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Design as a contributor to chemical process accidents

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ABSTRACT

The paper discusses the design errors in chemical process industry (CPI) by analyzing major equipment related accident cases from Failure Knowledge Database (FKD). The aim is to recognize the contribution of design to chemical process accidents and to evaluate the time of occurrence of the errors in a plant design project. The analysis of accident cases found out that the contribution of design to accidents is very significant: 79% of accident cases analyzed were contributed by design errors. The most critical design errors were poor layout (17%), insufficient consideration of chemical reactivity and incompatibility (16%) and incorrectly chosen process conditions (16%). The design errors were initiated at basic (32%), detailed (32%) and preliminary (22%) design phases of the project. Errors in fundamental aspects of chemical processes e.g. route selections are more severe (as compared to others errors class) and might creates many similar errors in later phases of design project. Based on the accident information gathered, a straightforward point-to-look list for error detection and elimination was suggested for process lifecycle stages.

1. Introduction

The aim of this paper is to analyze the contribution of design to chemical process accidents. Several accident analyses indicate that the contribution of design to accidents is significant in many area of engineering e.g. infrastructure, aviation, railway, and nuclear industries (Kinnersley & Roelen, 2007; Lopez, Love, Edwards, & Davis, 2010; Love, Lopez, Edwards, & Goh, 2011). They claimed that about 50–90% of the accidents and incidents are caused by errors during the design stage.

In the CPI, the research on design error has been largely neglected (Bourrier, 2005; Busby, 1998). Only a few statistical data or lessons learnt have been presented (Hale, Kirwan, & Kjellen, 2007a; Taylor, 2007a). In fact, in 1970s, many designers refused to accept the term of 'design error' (Taylor, 2007b). This situation is nowadays changed when design quality control and design review are well accepted and a common practice in a design project. However, many of design firms are reluctance to discuss the errors due to legal aspects, company image, and personal reasons. It is generally accepted that even the designers have given their best; there are still considerable gaps in design to be improved. Therefore, it is been suggested that more studies should be done in this area to enhance and share the specific design knowledge (Hale, Kirwan, & Kjellen, 2007b).

Our previous technical analysis of major accidents in the CPI (Kidam, Hurme, & Hassim, 2010) found that the design related errors are the main contributors to accidents. A detailed study on the contribution of design to accidents is still lacking. The goal of this paper is to identify the most critical design errors contributing to accidents. Also the link of root causes of design error to the plant design activities during the design lifecycle is studied. To disseminate the findings, a list of point-to-look and accident ranking is created. This design information helps the process developer and designer to focus on the critical design errors at the specific plant design phases.

2. Research approach

The research was done by studying 284 main equipment related accident cases gathered from Failure Knowledge Database (FKD, 2011). The design errors are explored and their origins during plant design are identified. Matching the design errors identified with design tasks and the decisions made at each plant design phase gives an estimate on their origin and time of occurrence during the design activities.

A database study as a research approach has also challenges. Each accident database has some limitations in terms of accessibility, contents and accuracy. Kletz (2009) discussed the weaknesses of the accident reports. He finds that the majority of the

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accident reports are 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). This will affect the result of the analysis and accuracy of lessons learnt generated.

The Failure Knowledge Database (FKD, 2011) was selected for the study in order to minimize the problems mentioned above. The accident database covers the most significant accidents all over the world. The accident database is managed by experienced academia. Majority of the accident reports contain detailed technical information on the accident such as process flow diagram, plant layout etc., which enables to identify the design errors associated with the accidents. Hatamura, Ilno, Tsuchlya, and Hamaguchi (2003) discussed the aims, basic structure, accident classifications and case expression of the database.

3. Process lifecycle phases

The details of the stages and tasks involved in the design project have been discussed by Hale et al. (2007b), Hurme and Rahman (2005) and Taylor (2007b). The plant design starts with *research and development phase* where the process concept from laboratory to pilot plant is developed. The chemical & physical property data and reaction chemistry are studied in detail. Design data and process information is complied for process scale-up. In *preliminary engineering*, the process concept is defined and process alternatives are generated. The process flow diagram (PFD) is developed and pre-dimensioning of major unit operations is done. The basic process information such as process conditions, raw materials, mass and energy balance, materials of construction and major unit operations are chosen to provide information needed for a feasibility study.

In the *basic engineering phase*, the details of process package are determined. Process package contains process flow sheet, piping and instrumentation diagrams (PID), equipment specifications, and process description. Process data for all equipment, piping, control system, and utilities needed are decided to provide input information for the detailed engineering phase. The detailed PID is developed and the detailed equipment and instrument specifications are finalized. Hazard and operability study (HAZOP) is done.

Detailed engineering phase includes the design for construction of the mechanical, electrical, civil etc. engineering disciplines. Three dimensional plant layouts are developed and full process safety analyses are carried out. The process designer prepares the operating manual of the process. This includes work procedures and instructions, safety and emergency guidelines of process. The operation manual is intended for process operation, process start-up and operator training.

In the *construction and start-up phase*, the chemical plant is be built as designed, started and the test runs are made. In the *operation phase*, the plant is operated and maintained according to guidelines. Since the plant requires improvement or capacity increase, modifications are made. Here the management of change is important.

The design targets, tasks, decisions, and safety issues involved for each design phase are summarized in Table 1.

4. Design error

Humans are prone to make errors due to many reasons e.g. misunderstanding, poor communication, miss-thought, in-hurry, lack of knowledge, lack of checking etc. Since engineers are humans, they make mistakes in spite of all the efforts of making a satisfactory design. According to Kletz (2003), designer makes error because they usually have a limited time to check their work. The design process is inherently error prone, since at some stage something is probably overlooked (Haastrup, 1984). On the other hand creative processes such as process development, lead to creative and novel errors (Taylor, 2007b). Earlier the concept of design error was difficult to accept by the engineers. The attitude was; others companies may make design errors but not ours (Haastrup, 1984). Nowadays the attitude has been largely changed (Hale et al., 2007b; Taylor, 2007b).

As mentioned earlier, limited scientific research has been done in this area, especially related to CPI. There is no standard definition of design error available so far (Hale et al., 2007b). In general, design error is a feature of design, which makes it unable to perform according to its specification (Taylor, 2007a). The process performance criteria are presented in the design specification document of the process called the ‘basis of design’. It includes process performance criteria such as plant capacity; product quality; health, safety and environmental criteria e.g. emission limits and maximum occupational air concentrations of toxic chemicals. In addition, several design standards, regulations and others technical guidelines are needs to be followed.

As can be understood from above, not all design errors are safety related, but may be related to product capacity, quality etc. Even from safety related errors, only a small percentage reaches the stage where they cause an accident (Taylor, 2007a). Therefore, for accident analysis purposes a more applicable definition is (Taylor, 1975):

> “… a design error is deemed to have occurred, if the design or operating procedures are changed after an incident has occurred”.

This definition includes as design error both design and operating procedure changes after an accident. The operating procedures are created during the design stages for start-up, operation, shutdown, and maintenance of the process; and presented in the operating manual. The errors in operating procedures represents considerable part in Taylor’s (2007a) data, since it come from nuclear industry. When technical design errors caused 35% of nuclear accidents in 1970s and 46% in 1980s, there were in addition of 10% and 15% procedure errors caused accidents, respectively (Taylor, 2007a).

The third aspect related design errors are the errors in operator—technical interface. Their share in chemical industry accidents has been found to be large; on average 23% of accident contributors (Kidam & Hurme, in press). The operator-technical interface means how clear and friendly is the equipment/system interface to the user. For example, if the piping arrangement is clear and the control system display is easily understandable, the likelihood of human error is lower.

The difference of design error and error in the operator/technical interface can be described in the following way: In operator/technical interface error there is no faults strictly from the technical point of view but still the design has lead to an accident by causing an operating error due to being confusing, misleading or un-logical to the user; and therefore causing an misinterpretation of the physical process or control display.

5. Design as accident contributor

284 accident cases from FKD database related to piping, reactor, storage tank, process vessel, heat transfer and separation equipment in process industry were analyzed to find out the contribution of design related errors to process accidents. In this study the design error definition of Taylor (1975) was used (see the previous section). Therefore, a design error was committed if the accident

Table 1
Typical characteristic of the design stages in the CPI.

Phase	Target	Main tasks and decisions	Main design and safety issues
Research and development	Development of process concept and scale-up to industrial scale.	- Idea generation and process creation/innovation. - Laboratory and simulation studies on reaction mechanism and kinetics. - Examination of raw materials (pure and industrial grade). - Laboratory & reaction calorimeter tests. - Process alternatives generation - Bench and pilot scale tests. - Market survey. - Legal and patent check.	- Use of hazardous material as feedstock. - Fail to choose the safer state of feedstock. - Incorrect data on the reaction kinetic and reaction behavior. - Incorrect data on runaway reaction potential. - Overlook the chemical reactivity and incompatibility. - Under estimate the effect of impurity, by-product and contaminants. - Unclear mechanism to control the unwanted/runaway reaction. - Inaccurate scale-up.
Preliminary engineering	Preliminary process design for the feasibility study.	- Process concept selection and flow sheet development. - Selection of unit operations. - Preliminary sizing of equipment. - Preliminary selection of construction material. - Site selection. - Final feed/product specifications. - Feasibility study.	- Complicated and extreme routes selection (high temperature and pressure). - Unsuitable types of unit operations. - Unsafe operating conditions. - Overlook the chemical reactivity and incompatibility at process equipment level. - Lack of safety analysis on the chemical contaminations.
Basic engineering	Creation the process data for detailed engineering.	- Detailed process design and optimization. - Process design of equipment and piping system. - Basic automation and instrumentation engineering. - Preliminary layout design. - Utilities design. - Waste minimization. - Hazard and operability study.	- Inappropriate layout, positioning and physical arrangement. - Incompatible heat transfer medium. - Incorrect heating/cooling sizing. - Inadequate safety and process protection. - Wrong or inaccurate process data for equipment etc. - Unsuitable material of construction. - Fail to consider corrosive environment. - Inappropriate mechanical/physical and chemical resistance specification. - Incorrect material flow set-up. - Lack of safety analysis.
Detailed engineering	Design of the physical process (equipment, piping etc.) for acquisitions and construction.	- Detailed piping design. - Detailed layout design. - Instrumentation and automation design. - Mechanical design of the equipment. - Structural and civil engineering. - Electrical design. - Design of utilities/services.	- Inappropriate piping layout and protection. - Inappropriate internal shape of equipment/component. - Incorrect location and positioning of support/attachment/venting of process equipment. - Inadequate electrical, mechanical and structural/foundation specification. - Inadequate static, lightning and ignition sources control. - Inadequate detection, automation and instrumentation. - Inadequate operating, start-up, shutdown and emergency manuals. - Wrong specification of 'buy item'. - No back up for utilities failure.
Procurement, fabrication, commissioning and start-up	Acquisitions, construction and installation of the process. Starting up the process and make it to meet the specification.	- Contracting and bidding. - Contractor selection. - Procurement. - Installation. - Inspection. - Testing. - Field changes.	- Part or components miss-match. - Wrong installation or poor work quality. - Incorrect positioning of sensor/instruments. - Accessibility. - Lack of monitoring and supervision of contractor. - Miss communication between designer, contractors and plant owner.
Operation/Plant modification	Safe operations within design specifications and capacity. Improvement of the process.	- Selection of safe operation and maintenance principles. - Gathering experience. - Process optimization. - Process improvement - Record keeping on plant histories and technological up-date.	- Poor planning. - Lack of safety analysis. - Lack of technical and reaction knowledge. - Poor safety culture. - Poor inspection and maintenance. - Poor management of change.

Table 2
The classification of design error.

Design error	Description
Process condition	Inappropriate process condition selection due to lack of knowledge/data, inadequate analysis, wrong assumption/interpretation of process data, environmental/surrounding input overlook/ignored etc.
Reactivity/incompatibility	Lack of analysis of chemical reactivity and incompatibility hazard at normal and abnormal process conditions as well as an ignorance of possible process contamination, unintended chemical mix-up and process/environmental changes.
Unsuitable equipment/part	Unsuitable equipment, components or parts selection that creates operational problems (e.g. wrong application, uneven flow or blockage) or increase the risk of accidents.
Material of construction	Wrong specification of material construction selection in term of physical, mechanical, chemical resistance and environmental/surrounding characteristics.
Sizing	Inappropriate sizing (oversize or undersize) of process equipment and its piping system that affect their function and reliability during normal and abnormal process conditions (e.g. flow related or two-phase phenomena).
Utility set-up	Wrong utility selection and its realization especially related to maximum heating/cooling capacity, incompatible heat transfer medium and its flow/handling/control mechanism.
Protection	Inadequate design for safety due to lack of analysis and limited process information especially related to thermal safety, relief types and sizing as well as overall mitigation system.
Layout	Errors on plant layout, physical arrangement, positioning, equipment accessibility, visual obstacles, operator/technical interface and color-coding etc.
Automation/instrumentation	Inadequate automation and instrumentation especially during abnormal process conditions for proactive process deviation/hazard detection, response and mitigation.
Operating manual	Wrong work procedures that jeopardize the safe operation of process equipment such as wrong sequence of work, wrong/unclear direction/instruction, and wrong hand tool or material used.
Fabrication/construction/installation	Design oriented problems related to welding defect, thermal expansion phenomena, stress, and miss-match of process equipment with their connectivity. Some of major equipment has a long delivery time that needs to be ordered early. In some cases, their detailed design is not fit to as built.

report recommended changes into the process or its designed operating procedures. Both technical and procedural errors were included in this study; however, any corrective actions due to human and organizational failures were not included. The errors were divided into 11 categories as presented in Table 2.

The study found that about 79% (224 out of 284) of accident cases involved at least one design error. The majority (72%) had multiple design errors resulting in 526 errors recorded in total, giving an average of 2.35 design errors per case. About 59% of the design changes involved changes in equipment or process such as minor structural modification, change in layout, replacement of construction material, use of safer or compatible heat transfer medium, re-sizing, or installing safety protection systems. The remaining 41% are classified as non-hardware related changes including equipment setting, adjustment of automation limits, design documentation, operational setting, safety and operation manual, and emergency preparedness and mitigation.

Table 3 compares the result with earlier studies on design errors. Earlier papers have studied design mainly as the *primary cause* of accidents. From this point of view design is responsible for 50–60% of accidents (average of studies in Table 3 is 56%). The earlier studies have much lower average i.e. 25% of accidents as reviewed by Haastrup (1984). For the *total contribution* of design to accidents Drogaris (1993) and HSE (2003) give both about 70% share, to which our result of 79% contribution can be compared. The difference can be explained by the more detailed analysis made here (we found 2.35 design errors per case, compared to Drogaris' study 1.4 and HSE's study with 1.3 design errors per case). In our study, there was a pre-selected set of main equipment related accidents, in which the share of design error is potentially higher.

Table 3
The literature data on design error (% of accidents).

Publication	Industry	Design error, %	
		As primary cause	As contributor
Drogaris (1993)	Chemical	–	70
Duguid (2001)	Chemical	52	–
HSE (2003)	Industry	59	71
Present study	Chemical	–	79
Average		56	73

Some earlier studies (Nivolianitou, Konstandinidou, & Michalis, 2006; Sales, Mushtaq, Christou, & Nomen, 2007) list the share of design errors as *% of contributors*. The average of these values are for the design & analysis errors is 25% of contributors. Taylor (2007a) reports 35–45% of contributors to be design based and 10–15% procedure based in nuclear industry.

Design is seldom the only contributor to accidents. In the previous study (Kidam & Hurme, in press) it was found that the share of design among all contributors is about 25%. Based on Table 3, in average, design contributes 50–60% of accident as a main contributor and is present in 70–80% of accidents as a main or sub-contributor. In the larger number, all the design related errors such as 'unsuitable equipment', 'excess corrosion', 'equipment failures', and 'improper procedure' are included as design errors. This is a matter of point of view, since especially earlier some company classified e.g. 'bad weather' as the root cause of accident. However, in reality the damage caused by bad weather is directly related to bad design. In this aspect, the designer failed to consider the environmental factors and did not design the equipment based on worst-case scenario (Taylor, 2007a).

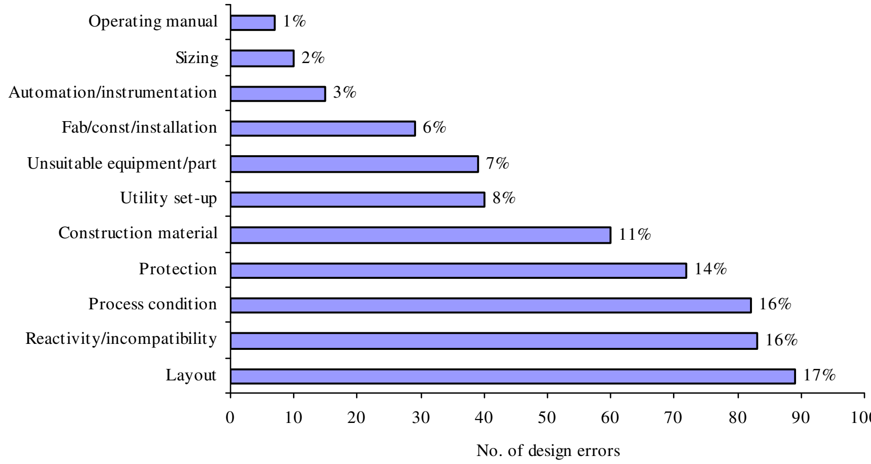

Fig. 1. Distribution of design errors in the CPI (% of design errors) (Number of cases with design errors = 224; Number of design errors = 526).

5.1. Design errors of major equipment in the CPI

The distribution of design errors of the six major equipment types were analyzed based on categories presented in Table 2. The results are presented in Fig. 1. As seen from the figure, majority of the design errors is associated with poor process layout (17% of design errors), followed by inadequate analysis of chemical reactivity & incompatibility (16%), incorrect process conditions selected (16%), lack of safety protection (14%), unsuitable construction materials (11%), inappropriate utilities set-up (8%), unsuitable equipment, parts or components (7%), and poor installation (6%). Inadequate process control (3%), incorrect sizing (2%) and insufficient operating manual (1%) only contributed a small share of design errors. The root causes of the design errors that caused accidents are presented in Appendix 1 in detail.

In general, poor *layout* can be divided into two categories, which are plant layout arrangement of the major equipment (such as reactors, columns etc.) and detailed layout (e.g. pipes, their connections, valves etc.). As presented in Appendix 1, the share of *detailed layout* caused accidents is the largest (69% of layout accidents). Typical examples are dead-end of pipes (16%), shape that accumulates substances (11%), support arrangement (9%) and shared pipelines (8%). In the *plant layout* category (31%) the largest contributor is physical arrangement of equipment (24%) and vertical positioning (7%).

Detection and elimination of the chemical *reactivity & incompatibility* errors can prevent reactive chemical incidents. Most of accidents under this category are due to process contamination (e.g. reactions with contaminants, 24%, or with waste or residue, 8%) and followed by unwanted reactions (secondary reaction, 13%; hazardous material generation, 13%; and heat generation 7%). Reactions with heat transfer medium are also a very usual cause of accidents (11%).

Optimum *process conditions* (i.e. right temperature, pressure, chemical concentration etc.) are crucial for safe and profitable chemical process operations. Common design errors that trigger unwanted events include process contamination (33%), high temperature (11%), uneven flow/dry condition (9%) and inadequate process material flow (e.g. ventilation, blow-out, exhausting, vacuum etc., 7%).

Accidents also occur due to lack of process *protection* for fire and explosions such as no provision for nitrogen blanket (26%), static electricity control (24%) and inadequate positive isolation from a high-pressure system (e.g. single valve, 14%).

Majority of mechanical failures of equipment or piping are due to wrong *construction material* (11% of accidents) especially by mechanical specification (27%), chemical resistance (25%), sizing & thickness (17%), and poor conductivity (15%).

In *utility set-up* (8%) heating and cooling equipment related errors include selection of too high/extreme temperature or heating capability sources (23%), incompatible heat transfer medium (18%) and hazardous material (18%).

Design errors associated with *unsuitable equipment/component/part* (7%) are mainly related to dust/powder handling (e.g. feeding, 13%), and static electricity control (e.g. non-conductive part, 10% and spark generation, 10%).

Appendix 1 presents a statistical distribution of design errors. The top ten of most common underlying causes of design errors are summarized in Table 4. The typical lacks in design are insufficient safety analysis and design for safety especially related to process contaminations and physical arrangement (layout) and ignition prevention.

Table 4
The most common underlying causes of design errors in the CPI (% of errors).

Design errors	No. of errors	Percentage
1. Process contaminations	27	5.1%
2. Physical arrangement	21	4.0%
3. Reaction with contaminants	20	3.8%
4. No nitrogen blanket	19	3.6%
5. Static charge electricity	18	3.4%
6. Mechanical specification	16	3.0%
7. Chemical resistance specification	15	2.9%
8. Dead-end	14	2.7%
9. Sizing/thickness	10	1.9%
10. Secondary reaction	10	1.9%

Total number of design errors = 526.

5.2. Typical errors of equipment design

This section discusses the specific design errors at equipment level. The result of the analysis is summarized in Table 5. The most common design error categories are bolded. As seen from the table, each type of process equipment has unique design errors. The root causes of most common design errors are discussed in the following.

Table 5 shows that most common design errors in the ***piping system*** are related to the design (e.g. poor layout, 44 cases; and unsuitable construction materials, 37 cases). Among critical *layout* aspects are physical arrangement, (line-up) shape and dead-end of piping. Some of these errors are considered as human–technical

Table 5
The distribution of the design errors per types of process equipment.

Design errors	Piping system	Reactor	Process vessel	Storage tank	Separation eq.	Heat transfer eq.	Total
Layout	**44**	9	12	**14**	3	**7**	89
Reactivity/incompatibility	4	**17**	**29**	4	**22**	**7**	83
Process condition	10	**16**	**15**	3	**25**	**13**	82
Protection	9	**12**	**19**	**17**	8	**7**	72
Construction material	**37**	5	3	**11**	1	3	60
Utility set-up	1	**13**	4	7	11	4	40
Unsuitable equipment/part	3	7	10	**13**	3	3	39
Fab/const/installation	11	2	4	5		**7**	29
Automation/instrumentation		**11**			3	1	15
Sizing		5	3		1	1	10
Operating manual	1	3		3			7
Total	120	100	99	77	77	53	526

interface induced errors (e.g. misleading piping shape and physical appearance). Incorrect specifications of *construction material* (e.g. mechanical and chemical resistance specification) as well as less than adequate sizing and wall thickness increase the probability of piping failure. The main issue here is the consistency of the pipe specifications between main pipelines with their connection/attachment components.

Designing a ***reactor*** is difficult due to the complex and dynamic reaction behavior. Analysis shows that the fundamental errors for reactor design are inadequate safety analysis that hampers the safe design. The most critical design errors are related to chemical *reactivity & incompatibility* (17 cases), *process conditions* selection (16 cases), *utility set-up* (13 cases), *protection* system (12 cases), and *automation & instrumentation* (11 cases). In many cases, the design errors are inter correlated to chemical reactivity, stability, incompatibilities, and process deviations.

Design errors of ***process vessels*** are very similar to reactors especially in chemical *reactivity & incompatibility* (29 cases), *protection* system (19 cases) and *process conditions* (15 cases). Depending on the purpose of the vessel, the design errors occur because of the desire for process flexibility, sharing or multipurpose usage and complex connectivity between process units. The demand for process flexibility, plant modification and multiple usages also affects the protection system of the process vessel. During equipment design, the designer may only consider the main purpose and chemicals handled.

The contribution of design to ***storage tank*** failures is significant (77 cases). According to Table 5, among critical design errors are lack of *protection* (17 cases), poor *layout* (14 cases), *unsuitable parts usage* (13 cases), and wrong *construction material* specifications (11 cases). Typical protection issue is related to ignition control in the tank. Static accumulation and discharge are very common causes of accidents. The fire risk is very high if nitrogen blanket is not available. Another important design issue for storage tanks is layout.

The most significant design errors associated with ***separation equipment*** failure are related to the *process condition* details (25 cases) and *reactivity & incompatibility* of chemicals (22 cases), which is quite similar as with chemical reactors. Variation in composition, excess and un-reacted reactants, impurities and formation of trace or hazardous compounds make the separation system more complex and difficult to design.

For ***heat transfer equipment*** failures, inappropriate *process conditions* (13 cases) is the most critical design error; followed by *protection* system, poor *fabrication, construction & installation*, poor *layout*, and chemical *reactivity & incompatibility* (7 cases each).

6. The origins of the design errors

The aim of the paper is to improve the consideration of safety aspects in design process. Hence, the design errors identified were linked into design project stages by recognizing their time of origin, i.e. the design stage when the design error was made. The timing of plant design activities used is presented in Table 1. The tasks partly overlap or are repeated since the nature of design is interactive and stage-wise becoming more accurate when the project proceeds. Therefore, the decisions are made typically first in a preliminary way e.g. for pre-design and later finalized in basic and detailed engineering stages. In this study, error is considered being committed when the final decision was made.

The time of origin of design errors is presented in Table 6 for each equipment type and the number of design errors at each plant design stages is summarized in Fig. 2. As seen from Fig. 2, majority (59%) of the design errors occur in the process design related phases; basic engineering (32%), preliminary engineering (22%) and research and development (5%). Errors in detailed engineering are also significant (32%). However, design errors during construction & start-up (5%) and plant modifications in the operation phase (4%) are low.

This result can be compared with the Haastrup (1984) even he presents only a design task based and not a stage-wise classification. The similarities are the low share of design errors in operation stage (i.e. modifications) 3% of errors (in our study 4%); and the share of errors in PID stage 32% of errors (in our study basic engineering, 32%). Haastrup however gives a much larger share of design errors in detailed design stages, and much lower in first stages (flow-sheeting and none in R&D stage). He has also large share of errors in procedures than we. This may be because of

Table 6
Origins of the design errors based on final design decisions.

Design errors	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
Construction material	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

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

different point of view. For instance a runaway accident may have been classified as error in reactor equipment specification in a later design stage, instead of insufficient chemical reactivity analysis in a first design stage as we considered.

Appendix 2 presents details of errors done in design phases. It is interesting to note that the *research & development* and *preliminary engineering* phases have common design errors, which are chemical reactivity & incompatibility and process conditions in a 50/50% ratio. The most critical issues are related to process contaminations. Process contaminations appear in both reactivity & incompatibility and process condition design error classes, because the hazard of contaminants can be from the chemical itself (i.e. reactivity & incompatibility) or from the influence of process environment (i.e. process conditions such as temperature, pressure etc.) that trigger unwanted event such as runaway reaction, decomposition, polymerization etc.

As seen from Appendix 2, the basic issue in both design phases is the inadequate analysis of reactivity & incompatibility (47–50%); e.g. the impact of chemical contaminations, secondary reactions, reactive or incompatible of utility media with process fluids and construction materials, and incorrect selection of process conditions (47–50%); e.g. process concentrations, uneven flow or dry conditions, temperature and corrosiveness. The chemical property information is created and its effect on the chemical processes is analyzed in the research and development phase. Process information produced will be used as the basis of the process and equipment design. Therefore, if there are errors in this basic information, also the design is erroneous.

Although the first two design phases have similar errors, their frequency is still different. As seen from the Fig. 2, the share of design errors originated from research and development is low (5%), but high at preliminary engineering (22%). The reason for the difference is related to the number of design decisions made at each stage. In research and development, large conceptual decisions are made on process route and operating conditions but their number is still small. Not many engineering decisions are made at this stage. In preliminary engineering (e.g. flow-sheeting), much more design decisions are done especially related to the unit operations, their pre-dimensioning and processing conditions; creating the first change of larger number of design errors.

The process design concludes with the *basic engineering phase* and a large number of design decisions were made here. Among critical design errors in this phase are wrong construction material (25%), poor layout (18%), and inappropriate utility set-up (16%). The integrity of the process equipment depends directly on the chemical (35%) and mechanical (33%) specifications of construction materials. Mistakes on these will increase the corrosion and erosion rate, which creates material leakages, process contaminations and unwanted chemical reactions. On other hand, proper site and equipment layout with enough spacing between processing units will eliminate domino or knock-on hazards (Khan & Abbasi, 2001). Faults in selection of heat transfer system such as over design of heat transfer system (26%) and employment of incompatible heat transfer medium (22%), are usual design errors of utility set-up.

Detail engineering phase represent 29% of design errors. The most common design errors are related to the internal layout design of equipment & piping (34%) and protection systems (28%). Design errors such as dead-end, shape errors, inappropriate positioning, erroneous connection, and inadequate support create accidents. Many of the process failures occur due to the corrosion, erosion, vibration, and flow restriction problems. In flammable systems, consideration should be given to eliminate the ignition sources such as static discharge, friction/spark generation and use of non-explosion proof equipment/hand tools.

In *construction and start-up phase* only 5% of design errors were identified. The majority of the errors is related to poor fabrication, construction and installation (88%) such as mechanical stress (39%), poor fabrication or construction quality (22%), welding defects (17%), and bolt tightening related (13%). Most of the problems are related to on-site design changes needed during construction and installation. However, sometimes these site-changes are not well documented and worst, no safety evaluation were made prior changes are made.

Accidents because of plant modification or process changes are grouped into *operations phase*. Majority of them involve plant improvement and debottlenecking. In general, the design procedure is the same as for new plant but the design scope, tasks and decisions are smaller. As seen from the Fig. 2, only 4% of design errors are identified in the operations phase. There are reasons for the small share. In principle the knowledge of the process is large based on the plant operation history, which makes the confidence level of the proposed project higher. Normally, the process changes involve the existing reaction chemistry. However, accidents still happen due to inadequate design consideration during plant modification. Analysis shows that the most critical design error in the plant modification are the lack of analysis on the effect of chemical reactivity & incompatibility (27%), process condition (23%), construction material (18%), and utility set-up (14%). The risk is that the original design knowledge is not transmitted to those, who make the plant modification years later. Therefore, some critical aspect is potentially neglected.

In summary, the study shows that the most critical design errors are process conditions and chemical reactivity & incompatibility in R&D and preliminary engineering phases; construction material and layout in the basic engineering, and detailed layout design and

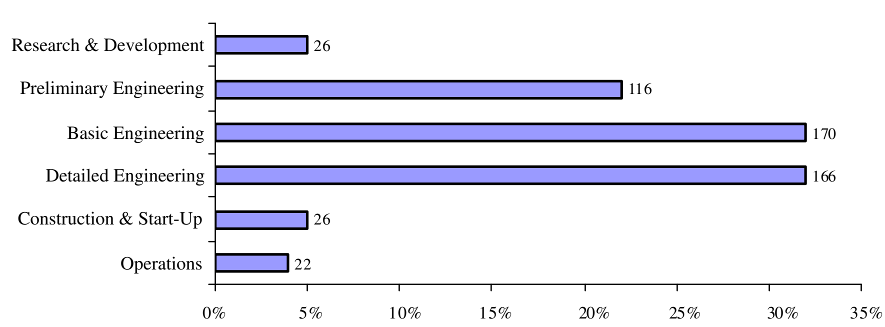

Fig. 2. The number and share of the design errors throughout plant lifecycle (Total of design errors = 526).

protection in detailed engineering. In general, most of errors are done in the basic and detailed engineering phases.

It seems that not enough design reviews were conducted throughout the process lifecycle. The design errors should be more systematically detected and eliminated. According to Taylor (2007a, b) the existing safety review methods eliminate 80–95% of design errors. The remaining design errors are present in most of the accidents. This is because the existing methods have their limitations. The most common design review method is Hazard and Operability Study (HAZOP), which is based on PID diagrams. Typically, it does not deal with mechanical errors, rarely with dimensioning errors (Taylor, 2007a) and procedure errors (Duguid, 2001).

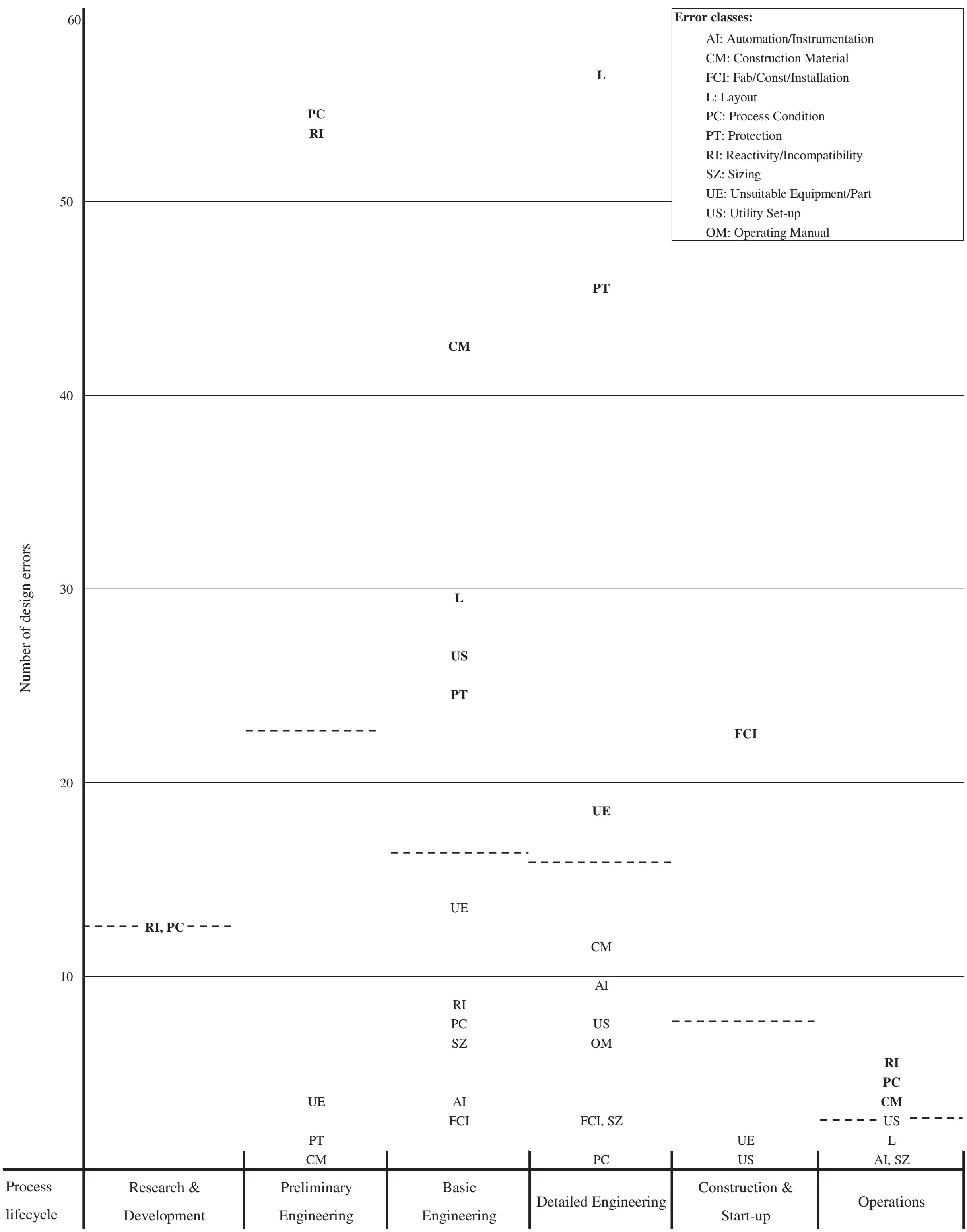

Fig. 3. Frequency of errors per error categories in design lifecycle (dotted line is the average frequency).

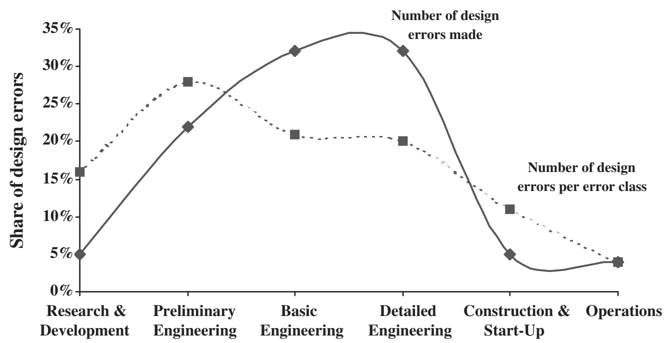

Fig. 4. Relative frequency of design errors and errors per error class.

7. Points-to-look for safer design

In this section, a point-to-look list for improving safety in design throughout plant design lifecycle is presented based on the accident data gathered. In Fig. 3 the number of design errors in various error categories is plotted to the plant design timescale. These values represent the importance of a category in each design stage. The average number of design errors per category is presented by a dotted line for each design phase. The average value can be used as a benchmark for comparing the importance of error categories.

As seen from Fig. 3, the average frequency of design errors (dotted line) reaches the maximum in *preliminary engineering* (23 errors) and decreases gradually with design project progression. Therefore, in preliminary engineering a large number of design errors are done on few fundamental process related selections, even the highest number of design errors is made in the basic and detailed engineering phases, as shown by Fig. 2. This is because in later phase of plant design, much more design decisions are made but they are less fundamental. Therefore, the error rate is later high but the average importance of design decisions probably less. See also Fig. 4, which illustrates the frequency of design errors.

Fig. 3 reveals the types of design errors, which should be focused in accident prevention in each design stage. The design error categories, which have highest frequency in each stage, are presented in bold in the figure. The result has been summarized in Table 7 as a priority list for safer design. The most common design error categories to be focused in accident prevention have been marked with five asterisks. The most error prone design aspects are; selection of process conditions and consideration of reactivity & incompatibility issues in preliminary engineering, and the selection of layout and protection equipment in detailed engineering.

Table 7
Priority list for design error elimination.

Error category	Conceptual & preliminary design	Basic engineering	Detailed engineering	Construction & start-up
Layout		**	****	
Process conditions	*****			
Reactivity & incompatibility	*****			
Protection		*	***	
Construction material		***		
Utility set-up		**		
Fab/const/installation				*
Unsuitable equipment/part			*	

***** = highest priority; **** = higher than average; *** = average; ** = lower than average; * = low.

As seen from Table 7, the proper consideration of process conditions and chemical reactivity & incompatibility aspects in R&D and preliminary process design phases is very important for the safety of the chemical process, since these selections fundamentally affect the later stages, where detailed design such on equipment types, materials of construction (chemical resistance etc.), utility set-up (compatible heat transfer medium etc.), protection (e.g. relief system), and plant layout are done. Errors e.g. in reaction system specification create more errors in basic engineering stage and even more in detailed design. If proper process analysis is carried out at early phase of process the combinatorial explosion of effects of erroneous process data can be eliminated in later design stages.

The presented point-to-look list (Table 7) helps to conduct safety related design checks more effectively by focusing on the most error prone aspects in each design stage. Focusing the safety efforts is needed, since design projects have typically tight schedules. A more quantitative view on the importance of error categories is provided by Fig. 3. The details of error types in design phases are presented in Appendix 2.

8. Discussion and conclusions

A study of design errors in chemical process industry was carried out by analyzing past accident cases on major equipment. The study confirmed that the contribution of design to accidents is very significant. The study found that nearly 80% of the accident cases are contributed by at least one design error. Majority of them has more then one design error. About 60% of errors are related to the process equipment & piping and 40% to non-hardware such as automation and documentation. This study found that design contributed to more accidents (79%) than the earlier studies found (70%). This is possibly because the design cases were pre-selected to represent six major types on process equipment. There was also more design errors found per accident compared to earlier results (2.3 vs. 1.3–1.4 earlier). This was obviously due to the design oriented point of view of the study and the deeper analysis done. There is also not exact distinction between design error and other accident categories. For example if 'bad weather' caused an accident, was it a design error, if bad weather was not considered enough.

The most common design error classes found are related to poor layout, followed by poor consideration of chemical reactivity & incompatibility and wrong process conditions (such as pressure and temperature) selected. Layout errors are mainly related to piping systems, and reactivity & incompatibility errors to process vessels, separation equipment and reactors. Process conditions related design errors are typical to separation equipment, reactors and process vessels. The most common underlying causes are process contaminations.

The result of the analysis shows that nearly 2/3 of design errors are done in basic and detailed engineering phases. However, the number of design errors done per one design aspect is largest in the preliminary design indicating that many errors are done in the fundamental process engineering decisions such as process conditions and chemical and reactions involved. More focus should be obviously given to these process related decisions at the early phase of plant design to enhance safety.

A point-to-look list for error detection in design lifecycle was created based on the information on past design errors, which led to accidents. The list helps the design engineers to focus on the design error types that were most commonly overlooked during the design of chemical process plant earlier. Proactive design errors detection and elimination throughout process design lifecycle makes the chemical plant safer and robust to accidents.

Appendix 1. The distribution of design errors of major equipment in the CPI.

1 LAYOUT, 89 design errors out of 526 (17%)

1.1 Physical arrangement, 24%
1.2 Dead end, 16%
1.3 Physical shape error, 11%
1.4 Support arrangement, 9%
1.5 Share piping, 8%
1.6 Vertical positioning, 7%
1.7 U-shape-de, 7%
1.8 Flow restriction, 4%
1.9 Venting shape, 3%
1.10 Positive isolation, 2%
1.11 Trap condition, 2%
1.12 Accessibility, 1%
1.13 Direct connection, 1%
1.14 Similar appearance, 1%
1.15 Single valve, 1%
1.16 Too closed, 1%

2 REACTIVITY/INCOMPATIBILITY, 83 out of 526 (16%)

2.1 Reactions with contaminants, 24%
2.2 Secondary reaction, 13%
2.3 Reactive with HTM, 11%
2.4 Hazardous material generated, 10%
2.5 Contaminated/reactive waste, 8%
2.6 Unstable at high temperature, 8%
2.7 Heat generated, 7%
2.8 Reactive with cleaning agent, 6%
2.9 Incompatible raw material, 5%
2.10 Unstable in dry condition, 2%
2.11 Unstable by-product, 1%
2.12 Unstable new material, 1%
2.13 Unstable off-spec product, 1%
2.14 Water reactive, 1%

3 PROCESS CONDITION, 82 out of 526 (16%)

3.1 Process contaminations, 33%
3.2 High temperature, 11%
3.3 Uneven flow/dry condition, 9%
3.4 Inadequate ventilation /exhaust, 7%
3.5 More corrosive, 7%
3.6 Secondary reaction, 6%
3.7 Hold too long, 5%
3.8 Flow velocity, 4%
3.9 Effect of physical condition, 2%
3.10 Hazardous material generation, 2%
3.11 More reactant, 2%
3.12 Store at high temperature, 2%
3.13 Wrong reaction data, 2%
3.14 Effect of by-product, 1%
3.15 High pressure, 1%
3.16 Hold too short, 1%
3.17 Long usage/aging, 1%
3.18 Unbalance reactant ratio, 1%

4 PROTECTION, 72 out of 526 (14%)

4.1 No nitrogen blanket, 26%
4.2 Static electricity, 24%
4.3 Single valve, 14%
4.4 No check valve, 7%
4.5 Non-explosion proof, 7%
4.6 Friction/impact, 6%
4.7 No coating/painting, 3%
4.8 No flame arrester, 3%
4.9 Aging/tear & wear, 1%
4.10 Drain without cap, 1%
4.11 No gas treatment, 1%
4.12 No inhibitor, 1%
4.13 No insulation, 1%
4.14 No relief valve, 1%
4.15 No vacuum breaker, 1%
4.16 Reactive with iron rush, 1%

5 CONSTRUCTION MATERIAL, 60 out of 526 (11%)

5.1 Mechanical spec, 27%
5.2 Chemical resistance spec, 25%
5.3 Sizing/Thickness, 17%
5.4 Non-conductive material, 15%
5.5 Thermal expansion, 7%
5.6 Friction/impact, 5%
5.7 React with content, 3%
5.8 Fire rating, 2%

6 UTILITY SET-UP, 40 out of 526 (8%)

6.1 High heating sources, 23%
6.2 Incompatible HTM, 18%
6.3 Flammable sealing/cleaning agent, 8%
6.4 No cooling/natural, 8%
6.5 Difficult to clean, 5%
6.6 Positioning, 5%
6.7 Power failure - no back up, 5%
6.8 Blockage-gummy material, 3%
6.9 Corrosive HTM, 3%
6.10 Direct connection, 3%
6.11 Flow restriction, 3%
6.12 Incompatible purging medium, 3%
6.13 No mixing effect, 3%
6.14 No vacuum/exhaust, 3%
6.15 Normal condition sizing, 3%
6.16 Sharing cooling source, 3%
6.17 Single valve, 3%
6.18 Under construction, 3%
6.19 Waste handling, 3%

7 UNSUITABLE EQUIPMENT/PART, 39 out of 526 (7%)

7.1 Feeding mechanism, 13%
7.2 Non-conductive part, 10%
7.3 Spark generation part, 10%
7.4 Sampling tools, 8%
7.5 Mechanical spec, 5%
7.6 Miss-used, 5%
7.7 Shape miss-match, 5%
7.8 Small volume, 5%
7.9 Under construction, 5%
7.10 Waste handling, 5%
7.11 Chemical resistant spec, 3%
7.12 Difficult to clean, 3%
7.13 Heating/cooling error, 3%
7.14 Lack of sensor, 3%
7.15 Lack of vacuum/exhaust, 3%
7.16 Measurement error, 3%
7.17 Mixing affects, 3%
7.18 Open storage, 3%
7.19 Open tank, 3%
7.20 Part positioning, 3%
7.21 Wrong absorption system, 3%

8 FAB/CONST/INSTALLATION, 29 out of 526 (6%)

8.1 Stress concentrated, 31%
8.2 Poor work quality, 17%
8.3 Welding defect, 14%
8.4 Bolt tightening, 10%
8.5 Foundation weak, 7%
8.6 No insulation, 7%
8.7 Lack of detection, 3%
8.8 No coating/painting, 3%
8.9 Support arrangement, 3%
8.10 Wrong connection, 3%

9 AUTOMATION/INSTRUMENT, 15 out of 526 (3%)

9.1 Setting error, 33%
9.2 Lack of detection, 27%
9.3 Sensor failed, 20%
9.4 No interlock, 13%
9.5 Uneven speed, 7%

10 SIZING, 10 out of 526 (2%)

10.1 Small volume, 50%
10.2 Size miss-match, 20%
10.3 Normal condition sizing, 10%
10.4 Small overhead volume, 10%
10.5 Smaller after modify, 10%

11 OPERATING MANUAL, 7 out of 526 (1%)

11.1 Maintenance/repair, 43%
11.2 Waste handling, 29%
11.3 Cleaning, 14%
11.4 Transfer mechanism, 14%

HTM – heat transfer medium.

Appendix 2. Design errors associated with plant design phases.

A) RESEARCH & DEVELOPMENT, 26 design errors out of 526 (5%)

1.0 Process Condition, 13 (50%)
- 1.1 Process contaminations, 23%
- 1.2 Uneven flow/dry condition, 23%
- 1.3 High temperature, 15%
- 1.4 More corrosive, 15%
- 1.5 Hold too long, 8%
- 1.6 Unbalanced reactant ratio, 8%
- 1.7 Wrong reaction data, 8%%

2.0 Reactivity/incompatibility, 13 (50%)
- 2.1 Reactions with contaminants, 31%
- 2.2 Incompatible HT medium, 23%
- 2.3 Unstable at high temperature, 15%
- 2.4 Heat generated, 8%
- 2.5 Incompatible raw material, 8%
- 2.6 Reactive with cleaning agent, 8%
- 2.7 Unstable in dry condition, 8%

B) PRELIMINARY ENGINEERING, 116 out of 526 (22%)

1.0 Process Condition, 55 (47%)
- 1.1 Process contaminations, 40%
- 1.2 High temperature, 13%
- 1.3 Secondary reaction, 9%
- 1.4 More corrosive, 7%
- 1.5 Hold too long, 5%
- 1.6 Uneven flow/dry condition, 5%
- 1.7 Effect of physical condition, 4%
- 1.8 Hazardous material generate, 4%
- 1.9 More reactant, 4%
- 1.10 Store at high temperature, 4%
- 1.11 High pressure, 2%
- 1.12 Hold too short, 2%
- 1.13 Long usage/aging, 2%

2.0 Reactivity/incompatibility, 54 (47%)
- 2.1 Reactions with contaminants, 26%
- 2.2 Secondary reaction, 19%
- 2.3 Contaminated/reactive waste, 11%
- 2.4 HM generated, 11%
- 2.5 Heat generated, 9%
- 2.6 Unstable at high temperature, 9%
- 2.7 Incompatible raw material, 6%
- 2.8 Unstable by-product, 2%
- 2.9 Unstable in dry condition, 2%
- 2.10 Unstable new material, 2%
- 2.11 Unstable off-spec product, 2%
- 2.12 Water reactive, 2%

3.0 Unsuitable Equipment/Part, 4 (3%)
- 3.1 Measurement error, 25%
- 3.2 Mixing effects, 25%
- 3.3 Open storage, 25%
- 3.4 Open tank, 25%

4.0 Protection, 2 (2%)
- 4.1 No inhibitor, 50%
- 4.2 Reactive with iron rush, 50%

5.0 Construction Material, 1 (1%)
- 5.1 React with content, 100%

C) BASIC ENGINEERING 170 out of 526 (34%)

1.0 Construction Material, 43 (25%)
- 1.1 Chemical resistance spec, 35%
- 1.2 Mechanical spec, 33%
- 1.3 Sizing/Thickness, 23%
- 1.4 Friction/impact, 7%
- 1.5 Non-conductive material, 2%

2.0 Layout, 30 (18%)
- 2.1 Physical arrangement, 70%
- 2.2 Share piping, 23%
- 2.3 Positive isolation, 3%
- 2.4 Single valve, 3%

3.0 Utility Set-up, 27 (16%)
- 3.1 Over design HT capacity, 26%
- 3.2 Incompatible HT medium, 22%
- 3.3 Flammable sealing/cleaning agent, 11%
- 3.4 No cooling/natural, 11%
- 3.5 Blockage-gummy material, 4%
- 3.6 Corrosive HT medium, 4%
- 3.7 Incompatible purging medium, 4%
- 3.8 No mixing effects, 4%
- 3.9 Normal condition sizing, 4%
- 3.10 Sharing cooling source, 4%
- 3.11 Single valve, 4%
- 3.12 Waste handling, 4%

4.0 Protection, 25 (15%)
- 4.1 Single valve, 40%
- 4.2 No check valve, 20%
- 4.3 Friction/impact, 16%
- 4.4 No flame arrester, 8%
- 4.5 No gas treatment, 4%
- 4.6 No insulation, 4%
- 4.7 No relief valve, 4%
- 4.8 No vacuum breaker, 4%

5.0 Unsuitable Equipment/Part, 14 (8%)
- 5.1 Mechanical spec, 14%
- 5.2 Miss-used, 14%
- 5.3 Small volume, 14%
- 5.4 Waste handling, 14%
- 5.5 Chemical resistant spec, 7%
- 5.6 Difficult to clean, 7%
- 5.7 Heating/cooling error, 7%
- 5.8 Lack of sensor, 7%
- 5.9 Lack of vacuum/exhaust, 7%
- 5.10 Wrong absorption system, 7%

6.0 Reactivity/incompatibility, 9 (5%)
- 6.1 Incompatible HT medium, 56%
- 6.2 Reactive with cleaning agent, 44%

7.0 Process Condition, 8 (5%)
- 7.1 Inadequate ventilation, 63%
- 7.2 Flow velocity, 38%

8.0 Sizing, 7 (4%)
- 8.1 Small

9.0 Automation/Instrumentation, 4 (2%)
- 9.1 Lack of detection, 100%

10.0 Fab/Const/Installation, 3 (2%)
- 10.1 No insulation, 67%
- 10.2 Lack of detection, 33%

D) DETAILED ENGINEERING, 166 out of 526 (29%)

1.0 Layout, 57 (34%)
- 1.1 Dead end, 25%
- 1.2 Physical shape error, 18%
- 1.3 Support arrangement, 14%
- 1.4 U-shape-de, 11%
- 1.5 Vertical positioning, 7%
- 1.6 Flow restriction, 5%
- 1.7 Venting positioning, 5%
- 1.8 Venting shape, 5%
- 1.9 Accessibility, 2%
- 1.10 Direct connection, 2%
- 1.11 Positive isolation, 2%
- 1.12 Similar appearance, 2%
- 1.13 Too closed, 2%
- 1.14 Trap condition, 2%

2.0 Protection, 46 (28%)
- 2.1 No nitrogen blanket, 41%
- 2.2 Static electricity, 39%
- 2.3 Non explosion proof, 11%
- 2.4 No coating/painting, 4%
- 2.5 Aging/tear wear, 2%
- 2.6 Drain without cap, 2%

3.0 Unsuitable Equipment/Part, 19 (11%)
- 3.1 Feeding mechanism, 26%
- 3.2 Spark generation part, 21%
- 3.3 Non-conductive part, 21%
- 3.4 Sampling tools, 16%
- 3.5 Shape miss-match, 11%
- 3.6 Part positioning, 5%

4.0 Construction Material, 12 (7%)
- 4.1 Non-conductive material, 67%
- 4.2 Thermal expansion, 25%
- 4.3 Fire rating, 8%

5.0 Automation/Instrumentation, 10 (6%)
- 5.1 Setting error, 40%
- 5.2 Sensor failed, 30%
- 5.3 No interlock, 20%
- 5.4 Uneven speed-de, 10%

6.0 Utility Set-up, 8 (5%)
- 6.1 Difficult to clean, 25%
- 6.2 Positioning, 25%
- 6.3 Power failure - no back-up, 25%
- 6.4 Direct connection, 13%
- 6.5 No vacuum/exhaust, 13%

7.0 Operating Manual, 7 (4%)
- 7.1 Maintenance/repair, 43%
- 7.2 Waste handling, 29%
- 7.3 Cleaning, 14%
- 7.4 Transfer mechanism, 14%

8.0 Fab/Const/Installation, 3 (2%)
- 8.1 No coating/painting, 33%
- 8.2 Support arrangement, 33%
- 8.3 Wrong connection, 33%

9.0 Sizing, 3 (2%)
- 9.1 Size miss-match, 67%
- 9.2 Small venting, 33%

10.0 Process Condition, 1 (1%)
- 10.1 Inadequate ventilation/ exhaust, 100%

E) CONSTRUCTION & START-UP, 26 out of 526 (5%)

1.0 Fab/Const/Installation, 23 (88%)
- 1.1 Stress concentrated, 39%
- 1.2 Poor fab/const. quality, 22%
- 1.3 Welding defect, 17%
- 1.4 Bolt tightening related, 13%
- 1.5 Foundation weak, 9%

2.0 Unsuitable Equipment/Part, 2 (8%)
- 2.1 Poor/under construction, 100%

3.0 Utility Set-up, 1 (4%)
- 3.1 Poor/under construction, 100%

F) OPERATIONS, 22 out of 526 (4%)

1.0 Reactivity/incompatibility, 6 (27%)
- 1.1 Hazardous material generated, 33%
- 1.2 React with contaminances, 33%
- 1.3 Contaminated/reactive waste, 17%
- 1.4 Secondary reaction, 17%

2.0 Process Condition, 5 (23%)
- 2.1 Process contaminations, 40%
- 2.2 Effect of by-product, 20%
- 2.3 Uneven flow/dry condition, 20%
- 2.4 Wrong reaction data, 20%

3.0 Construction Material, 4 (18%)
- 3.1 Mechanical spec, 50%
- 3.2 React with content, 25%
- 3.3 Thermal expansion, 25%

4.0 Utility Set-up, 3 (14%)
- 4.1 Flow restriction, 33%
- 4.2 High heating sources, 33%
- 4.3 Incompatible HT medium, 33%

5.0 Layout, 2 (9%)
- 5.1 Flow restriction, 50%
- 5.2 Trap condition, 50%

6.0 Automation/Instrumentation, 1 (5%)
- 6.1 Setting error, 100%

7.0 Sizing, 1 (5%)
- 7.1 Smaller after modify, 100%

HT – heat transfer
HM – hazardous material

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