How to Efficiently Perform the Hazard Evaluation (PHA) Required for Non-Routine Modes of Operation (Startup, Shutdown, Online Maintenance)

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Abstract

Process safety is about controlling risk of failures and errors; controlling risk is primarily about reducing human error. All elements of Risk-Based Process Safety (RBPS) and alternative standards for process safety (such as US OSHA's standard for Process Safety Management [PSM] or ACC's Process Safety Code™ [PSC]) have many elements, and each of these in turn help to reduce the chance of human error or else limit its impact. One core element is the process hazard analysis (PHA), also called a hazard identification and risk assessment (HIRA). PHAs have been performed formally in gradually improving fashion for more than five decades. Methods such as HAZOP and What-If Analysis have been developed and honed during this time. But, one weakness identified twenty years ago still exists in the majority of PHAs performed around the world; most PHAs do not thoroughly analyze the errors that can occur during startup mode, shutdown modes, and other non-routine (non-normal) modes of operations. This is despite the fact that most major accidents occur during non-routine operations (about 70%), even though the process/plant may only be in that mode of operation for 5% or less a year. Instead of focusing on the most hazardous modes of operation, most PHAs focus on normal operations. In a majority of both older operations and new plants/projects, the non-routine modes of operations are not analyzed at all. This means that perhaps 60 to 80% of the accident scenarios during non-routine operations are being missed by the PHAs. **If the hazard evaluation does not find the scenarios that can likely occur during these non-routine operations, the organization will not know what safeguards are needed against these scenarios.**

This paper shows practical ways to efficiently and thoroughly analyze the step-by-step procedures that are used to control non-routine operating modes, as well as those for batch and between batch operations. This paper builds upon the methods and rules provided in papers beginning in 1993 and brings them up-to-date. Experienced PHA leaders should be able to use the rules and approaches provided in this paper to improve their PHAs. And others will be able to use the results of this paper to estimate the number of accident scenarios they may be missing and to estimate the time it would take to complete an efficient and thorough PHA of the non-routine modes of operation.

1. Introduction

During the period 1970 to 1989, 60% to 75% of major accidents in continuous processes occurred during non-routine modes of operation (principally startup and online maintenance modes).[1] This trend has continued unabated for most the process industry to the present day. A compilation of 47 major process safety accidents in the past 23 years is given in Appendix A; of these, 66% occurred during non-routine operations. In addition, a poll of over 50 clients indicates that 70% of their moderate and major accidents occurred during non-routine modes of operation. This data is particularly disturbing when factoring in the time at risk, since most continuous processes are typically shut down 5% or less per year. Therefore, for many continuous processes the workers and other stakeholders are 30 to 50 times more likely to have a major accident during the time frame of startup, shutdown, or on-line maintenance modes of operation. One reason for processes being at higher risk during these operating modes is many of the safeguards (independent protection layers) are bypassed or may not be fully capable. A hazard evaluation is necessary to help a company identify the layers of protection necessary to lower the risk to acceptable levels. To fulfill this need, a company operating a continuous process should **Fully** evaluate the hazards during **All** modes of operation. Unfortunately, in the first four decades of hazard evaluation use (beginning after the Flixborough disaster in the UK in 1974 – another accident that occurred during startup in a temporary configuration), many companies have done a poor job of identifying and evaluating accident scenarios during startup, shutdown, and online maintenance modes of operation, while usually doing a good job of evaluating hazards of normal modes (continuous or normal batch modes) of operation.

Recent US OSHA PSM National Emphasis Programs underscore the need for companies to identify potential accident scenarios during non-routine modes, and to reduce the frequency and consequences of such errors as part of an overall process safety management (PSM) program. Paragraph (e) of the US OSHA regulation on PSM, 29 CFR 1910.119,[2] and similar requirements in US EPA's rule for risk management programs (RMP), 40 CFR 68.24,[3] specifically require that PHAs consider human factors and address all hazards (stated as "during all modes of operation, both routine and non-routine," in Appendix C to the OSHA PSM regulation).

How does someone responsible for coordinating or performing hazard evaluations (including PHAs) uncover potentially important accident scenarios during all modes of operation without consuming too many resources? To correctly answer this question, we must (1) understand the root causes of human error and (2) develop a strategy for systematically finding the scenarios that are caused by human error, during all modes of operation. The strategy must be thorough, yet provide for a practical allocation of resources. This paper provides a strategy that uses widely accepted hazard evaluation techniques (such as those referenced by OSHA and EPA for PHAs, which include what-if analysis and hazard and operability [HAZOP] analysis). This strategy has proven effective for hundreds of facilities over the past two decades since it was first published.[4] In addition to identifying accident scenarios during non-routine modes; this approach helps to more fully address human factors, which is a specific requirement of OSHA's PSM regulations and EPA's RMP rule.

Human factor deficiencies can make operations during non-routine modes extremely hazardous – since operators have less operating experience for non-routine modes, and these times of operations rely heavily on operator decision-making and tasks. In addition, there are less layers of protection in effect during non-routine operations. Analyzing procedure steps can identify steps where the operator is most likely to make mistakes and suggest ways, ranging from adding hardware to improving management systems, to reduce risk of an accident scenario.

The approach outlined in this work applies equally to any hazard evaluation where the steps for a non-routine mode of operation are well defined (i.e., written), including PHAs of existing units, hazard evaluations during preliminary and detailed design phases of projects (for new/revised processes), and large or small management-of-change hazard reviews.

2. Background: What are Human Factors?

Human error in research, design, construction, installation, operation, maintenance, manufacturing, inspection, management, etc., can be considered the cause of almost all industrial accidents. (Experts typically quote that about 85% of accidents are caused by human error, though some say that except for natural disasters this figure is 100%.) However, simply attributing these accidents to "human error" without evaluating the root cause implies that the errors are inevitable, unforeseeable, and uncontrollable. Nothing could be further from the truth.

Human errors are sometimes mistakenly called procedural errors. This is not true anymore than saying all equipment errors are due to design errors. People make mistakes for many reasons, but experts estimate that only about 10% of accidents due to human errors in the workplace occur because of personal influences, such as emotional state, health, or carelessness. Over the past five decades of research and observation in the workplace on human error, we have come to know that human error probability depends on many factors. These factors (described in more detail in *Human Factors Missing from PSM* [5]), include:

- Procedure accuracy and clarity (the number one, most sited root cause of accidents):
    - A procedure typically needs to be 95% or better accuracy to help reduce human error; humans tend to compensate for the remaining 5% of errors in a written procedure.
    - A procedure must clearly convey the information (there are about 25 rules for structuring procedures to accomplish this) and the procedure must be convenient to use.
    - Checklist features – These should be used and enforced either in the procedure or in a supplemental document.

- Training, knowledge, and skills
    - Employees must be selected with the necessary skills before being hired or assigned to a department.
    - Initial Training – There must be effective, demonstration-based training on each proactive task and each reactive (e.g., response to alarm) task.
    - Ongoing validation of human action is required and usually must be repeated (in either actual performance or in drills/practice) at least once per year *(*as discussed later in this paper). For human IPLs, the action must be demonstrated to be "fast enough" as well.
    - Documentation – the human performance must be documented and retained to demonstrate the error rates chosen are valid.

- Fitness for Duty – Includes control of many sub-factors such as fatigue (a factor in a great many accidents), stress, illness and medications, and substance abuse.

- Workload management – Too little workload and the mind becomes bored and looks for distraction; too many tasks per hour can increase human error as well.

- Communication – Miscommunication (of an instruction or set of instructions or of the status of a process) is the second or third most common cause of human error in the workplace. There are proven management systems for controlling communication errors.

- Work environment – Factors to optimize include lighting, noise, temperature, humidity, ventilation, and distractions.

- Human System Interface – Factors to control include layout of equipment, displays, controls and their integration to displays, alarm nature and control of alarm overload, labeling, color-coding, fool-proofing measures, etc.

- Task complexity – Complexity of a task or job is proportional to the (1) number of choices available for making a wrong selection of similar items (such as number of similar switches, number of similar valves, number of similar size and shaped cans), (2) number of parallel tasks that may distract the worker from the task at hand (leading to either an initiating event or failure of a protection layer), (3) number of individuals involved in the task, and (4) judgment or calculation/interpolation, if required. For most chemical process environments, the complexity of the task is relatively low (one action per step), but for response actions (human IPLs) there are almost always other tasks underway when the out-of-bounds reading occurs or the alarm is activated.

In addition to the human factors listed, other considerations for use of a human as an IPL include (1) time available to perform the action and (2) physical capability to perform the action. Table 1 lists the main human factors as well as the multiplying effect of deficiencies in control of these human factors.

Table 1. Summary Human Factor Categories[a]

Human Factor Category	Human Factor Issue/Level	Multiplier for Cognitive & Diagnosis Errors
Available Time (includes staffing Issues) – for responses only	Inadequate time Barely adequate time (≈2/3 x nominal) Nominal time 1 Extra time (between 1 and 2 x nominal and >than 20 min) Expansive time (> 2 x nominal and > 20 min	P(failure)=100% 10 1 0.1 0.01
Stress/ Stressors (includes staffing issues)	Extreme High Nominal	5 2 1
Complexity & Task Design	Highly complex Moderately complex Nominal Obvious diagnosis	5 2 1 0.1
Experience/ Training	Low Nominal High	10 1 0.5
Procedures	Not available Incomplete Available, but poor Nominal Diagnostic/symptom oriented	20-50 20 5 1 2
Human-Machine Interface (includes tools)	Missing/Misleading Poor Nominal Good	20-50 10 1 0.5
Fitness for Duty	Unfit (high fatigue level, illness, strong medication, not physically capable of job today) Degraded Fitness Nominal	10-50 5 1
Work Processes & Supervision	Poor Nominal Good	2 1 0.8
Work Environment	Extreme Good	5 1
Communication	No communication or system interference/damage No standard for verbal communication rules Well implemented and practiced standard	10 5 1

[a] Based in part on *The SPAR-H Human Reliability Analysis Method*, NUREG/CR-6883.[6] Another US NRC initiative, NUREG/CR-6903, *Human Event Repository and Analysis (HERA)*, 2007[7], builds on the human factors categories described in SPAR-H in order to develop a taxonomy for collection of human error data from events at nuclear

power plants. PII has modified the list to account for general industry data and terminology and to incorporate PII internal data.

These human-error causes (human factors), which in turn result from other human errors, are all directly within management's control. When using human error data for controlling initiating events (IEs) and independent protection layers (IPLs), the site must ensure that the factors above are consistently controlled over the long-term and that they are controlled to the same degree during the mode of operation that the PHA, HAZOP, What-if, FMEA, or LOPA covers. For instance, if the workers are fatigued following many extra hours of work in a two week period leading up to restart of a process, then the human error rates can increase by a factor of 10 times or 20 times during startup.

3. Overview of Methodology for Hazard Evaluation of Non-routine Modes of Operation

The hazard evaluation of non-routine modes of operation involves reviewing procedures using a HAZOP, simplified HAZOP, or What-if analysis to uncover potential accident scenarios associated with non-routine operations, for continuous or batch operations. As mentioned earlier, human error is more likely and more critical during non-routine operations. By analyzing procedural steps where human error is more likely, and where human error or component failure could lead to a consequence of interest, risk can be reduced. The hazard evaluation team objective is to evaluate the risk associated with skipping steps and performing steps wrong.

FMEA cannot be applied to procedure-based deviations, unless you create a “human” component, in which case you have simply merged HAZOP deviations for “steps” into FMEA. Pre-Hazard Analysis (P_rHA) and other hazard evaluation methods are not applicable for accomplishing a detailed hazard evaluation of non-routine modes of operations.

Checklist of human factors issues (see an earlier paper[4] and also in the Guidelines for Hazard Evaluation Procedures[8]**)** can be very useful after the detailed hazard evaluation of deviations of steps. Such analysis can indicate where generic weaknesses exist that can make errors during any mode of operation more likely, or that can make errors during maintenance more likely. Such human factors checklists are normally used at the end of the analysis, they can be done piecemeal during an analysis (on breaks from the meetings) by individuals on the team, and then the results of each individual review can be discussed as a team at the end.

As with scenarios uncovered during continuous modes of operation, the company may need to perform analysis (including quantitative analysis such as LOPA or HRA) to more fully address any unresolved or complex issues raised in the hazard evaluation of non-routine modes of operation.

Case studies illustrate the analysis approach and the usefulness of this strategy.

4. Purpose of Hazard Evaluation of Procedures-Based Modes of Operation

Although incorporating human factors considerations into hazard evaluation studies of continuous operation is straightforward by asking why the human might make a mistake that leads to a parametric deviation, this approach only addresses a small fraction of the potential human errors that can affect process safety. Many analysts have tried to find accident scenarios in non-routine modes of operations by adding generic guide words such as "deviations during startup" and "deviations during maintenance/sampling" to the hazard evaluation of equipment nodes/sections. Unfortunately, this only catches a fraction of the accidents that can occur in non-routine modes since a hazard evaluation team is focused on "continuous" mode of operation during HAZOP or What-if of equipment sections/nodes.

From an informal survey of more than 100 companies, most do not currently perform process hazard evaluations of procedures, although many do perform some type of job safety analysis (JSA). The JSA is an excellent starting point for an evaluation of procedures because a JSA identifies the tasks that workers must perform and the equipment required to protect workers from typical industrial hazards (slips, falls, cuts, burns, fumes, etc.). Unfortunately, a typical JSA will not usually identify process safety issues or related human factors concerns. For example, from a JSA perspective, it may be perfectly safe for an operator to open a steam valve before opening a feed valve; however, from a process safety perspective, the operator may need to open the feed valve before the steam valve to avoid the potential for overheating the reactor and initiating an exothermic decomposition. The primary purpose of a JSA and other traditional methods for reviewing procedures has been to ensure that the procedures are accurate and complete (which is required of employers in 29 CFR 1910.119(f)(3)[2]).

By contrast, the purpose of a hazard evaluation is ***not*** to ensure the procedures are accurate and acceptable, but instead, to ***evaluate the accident scenarios if the procedures are not followed***. Even the best procedure may not be followed for any number of reasons, and these failures to follow the prescribed instructions can and do result in accidents. In fact, in the chemical industry and most other process industries the chance of an operator or other worker making a mistake in following a procedure is greater than 1/100, and in some cases much greater. When taking into account common human factor deficiencies that accompany non-routine operations, such as fatigue, lack of practice, the rush to restart and return to full production, etc., the probability of errors can climb to 1/10 chances per task (a task being about 1 to 10 detailed steps). Table 1 presented earlier lists the factors that can increase or decrease human error rates.

The purpose of a hazard evaluation of non-routine modes of operation (governed by written procedures) is to make sure an organization has enough safeguards for the inevitable instance when a step is either performed wrong or skipped (inadvertently or due to shortcutting or other reasons)

Regulators have repeatedly recognized the need for full evaluation of hazards during all modes of operations. US OSHA obviously recognized the importance of this category of hazard evaluation when emphasizing in CPL 2-2.45 (Systems Safety Evaluation of Operations with Catastrophic Potential)[9] that a human error analysis should address:

1. *Consequences of failure to perform a task.*
2. *Consequences of incorrect performance of a task.*
3. *Procedures and controls to minimize errors.*[9]

In the first major PSM inspection in 1992 using 29 CFR 1910.119[2], OSHA assessed a serious violation when the PHAs did not address "human factors such as board operator error, line breaking mistakes, and improper lockout and isolation of process equipment,"[10] all of which are errors originating from failure to either perform tasks or perform them correctly.

In another citation[11] OSHA alleged a serious violation because the company did not address all of the hazards of a process. In particular, the company was cited for **not** evaluating the hazards (during the unit-wide PHA) associated with non-routine procedures such as "startup, shutdown, emergency shutdown, and emergency operations." There were several other violations assessed in this citation because these non-routine procedures did not (allegedly) address the **consequences** associated with operators failing to follow the prescribed procedures. The OSHA inspector was convinced that a hazard evaluation of the non-routine operating procedures should have been part of the PHA scope.

In an article by Woodcock (an OSHA staff member) entitled, "Program Quality Verification of Process Hazard Analysis"[12] (for use in OSHA's training program for PSM inspectors), the author states that a PHA should include analysis of the "procedures for the *operation* and *support* functions" and goes on to define a "procedure analysis" as evaluating the risk of “skipping steps and performing steps wrong.”

In the Risk Management Program rule (40 CFR 68.24)[3] EPA also recognizes the importance of procedural analysis, by defining the purpose of a PHA to be to "examine, in a systematic, step-by-step way, the equipment, systems, and *procedures* (emphasis added) for handling regulated substances."

Industry has found that a HAZOP or what-if analysis, structured to address procedures, can be used effectively for finding the great majority of accident scenarios that can occur during non-routine modes of operation.[4, 8, 13, 14] Experience shows that reviews of non-routine procedures have revealed many more hazards than merely trying to address these modes of operation during the P&ID driven hazard evaluations.

> ***Example:*** *For the BP Texas City, Texas refinery, pre-2005, if the isomerization unit had a hazard analysis of the startup mode (using What-If and 2-Guide Word analysis [explained later in this work]), the team would have likely identified that the high-high level switch in the column was a critical safety device. They also may have recommended moving the switch to a location higher in the column and then interlocking the high-high level switch to shutdown feed to the column. However, the site performed a parametric deviation HAZOP of the equipment nodes which focusing on continuous mode of operation, and so the team decided that the high-high level switch was not critical since devices in upstream and downstream process units (during continuous operation) would indicate possible level problems in the column – and besides, the operator would certainly notice the high-level condition on the sight glass during the rounds twice per shift. Unfortunately, these are not necessarily safeguards during startup of the column (1) since the routine practice was to overfill the bottoms (raise the level above the upper tap of the level controllers transmitter and above the nozzle for the high-high level switch and (2) since swings in upstream and downstream units are expected (and so likely such swings would not have led to intervention by the operators of the other units).*

To reinforce the need for and to explain the method for analysis of deviations of steps in a procedure, Section 9.1 was included in the 3rd Edition of *Guidelines for Hazard Evaluation Procedures*, 2008[8]; this was one of the major changes to the hazard evaluation procedures**.**

5. HAZOP Method for Analyzing Deviations of Procedural Steps

The Hazard and Operability (HAZOP) method has two major variations; one for the continuous mode of operations (where the team brainstorms what would happen if there were deviations of parameters) and procedure-based (where the team brainstorms what would happen when the steps of a procedure are not followed correctly). The procedure-based variation of HAZOP is the oldest form of HAZOP (from ICI in 1960s). It was an expansion of a Hazard Evaluation method based strictly on asking:

- **What happens if the step is skipped?**
- **What happens if the step is performed wrong?**

In turn, the "pre-HAZOP" method for brainstorming accident scenarios from not following procedures (including because the procedure is itself wrong) is based on the understanding that human errors occur by someone not doing a step (errors of omission) or by doing a step incorrectly (errors of commission). So, simply asking what would happen if the operator omitted a step or performed a step wrong is one way to structure a hazard evaluation of a step-by-step procedure. ***(We will discuss the usefulness of this simple approach to hazard evaluation of steps later.***)

5.1 Seven (7) Guide Word method

In an effort to be more thorough, the inventors of HAZOP (at ICI) broke these two types of errors into subparts and agreed on using the following 7 Guide Words:

Omission:	**Skip (or Step Missing)**
	Part Of
Commission:	**More**
	Less
	Out of Sequence
	As Well As
	Other Than
	Reverse

In the early 1990s, the guide word Skip was augmented by adding the option of discussing "are there any steps **missing** from the procedure."[4]

Table 2: Definitions of 7-8 Guide Words for HAZOP of Procedure-Based (non-continuous mode) Operation

Guide Word	Meaning When Applied to a Step
Missing (optional guide word)	A step or precaution is missing from the written procedure prior to this step (similar to “Out of Sequence”, except the missing step is not written)
Skip (No, Not, Don’t)	The specified intent of this step is not performed
Part-of	A portion of the full intent is not performed. Usually only applies to a task that involves two or more nearly simultaneous actions (“Open valves A, B, and C”.)
More	Too much of the specified intent is done (does not apply to simple on/off; open/close functions); or it is performed too fast
Less	Too little of the intent is done, or it is performed too slowly
Out of sequence	This step is performed too early in the sequence
As well as	Something happens, or the user does another action, in addition to the specified step being done correctly (could be a short cut)
Other than (or Reverse)	The wrong device is operated, selected, read, etc., or operated in a way other than intended. Or the wrong material is selected or added. “Other than” errors always imply a “Skip” as well.

To apply HAZOP to procedural steps for startup, shutdown, online maintenance, and other modes of operation, the facilitator (or team) must first divide the procedure into individual actions. This is already done if there is only one action per step. Then, the set of guide words or questions is systematically applied to each action of the procedure resulting in procedural deviations or what-if questions. The guide words (or procedural deviation phrases) shown in Table 2 above were derived from HAZOP guide words commonly used for analysis of batch processes. The definition of each guide word is carefully chosen to allow universal and thorough application to both routine batch and non-routine continuous and batch procedures. The actual review team structure and meeting progression are nearly identical to that of a process equipment HAZOP or what-if analysis, except that active participation of one or more operators is even more important and usually requires two operators for a thorough review; a senior operator and a junior operator. For each deviation from the intention of the process step (denoted by these guide words applied to the process step or action), the team must dig beyond the obvious cause, "operator error," to identify root causes associated with human error such as "inadequate emphasis on this step during training," “responsible for performing two tasks simultaneously,” "inadequate labeling of valves," or "instrument display confusing or not readable." The guide word *missing* elicits causes such as "no written procedural step or formal training to obtain a hot work permit before this step," or "no written procedural step or formal training to open the discharge valve before starting the pump."

5.2 Two (2) Guide Word Method for Analyzing Deviations of Procedural Steps

A more streamlined guide word approach has also proven very useful for (1) procedures related to less hazardous operations and tasks and/or (2) when the leader has extensive experience in the use of the guide words mentioned previously and can therefore compensate for the weaknesses of a more streamlined approach. The two guide words for this approach (as defined in Table 3 below) encompass the basic human error categories: errors of omission and commission. These guide words are used in an identical way to the guide words introduced earlier. Essentially "omit" includes the errors of omission related to the guide words "skip," "part of," and "missing" mentioned earlier. The guide word "incorrect" incorporates the errors of commission related to the guide words "more," "less," "out of sequence," "as well as," and "other than" mentioned earlier. Note that these two guide words (Table 3) fill the basic requirements for a human error analysis as outlined in OSHA's CPL 2-2.45.[9]

Table 3: 2 Guide Word (Guide Phrases) for Modified-HAZOP of Procedure-based Operation

Guide Phrase	Meaning When Applied to a Step
Step not performed	The step is not done or part of the step is not done. Some possible reasons include the employee forgot to do the step, did not understand the importance of the step, or the procedures did not include this vital step
Step performed wrong	The employee's intent was to perform the step (not omit the step), however, the step is not performed as intended. Some possible reasons include the employee does too much or too little of stated task, the employee manipulates the wrong process component, or the employee reverses the order of the steps.

Table 4: Example of 2 Guide Word HAZOP of a Critical Step in a Procedure

Drawing or Procedure: SOP-03-002; ***Cooling Water Failure***	**Unit:** HF Alkylation	**Method:** 2 Guide Word Analysis	**Documentation Type:** Cause-by-Cause

Node: 23	**Description:** STEP 2: Block in olefin feed to each of the 2 reactors by blocking in feed at flow control valves

Item	Deviation	Causes	Consequences	Safeguards	Recommendation
23.1	Step not performed	Operator failing to block in one of the reactors, such as due to miscommunication between control room operator and field operator; or control valve sticking open or leaking through	High pressure due to possible runaway reaction (because cooling is already lost), because of continued feeding of olefin (link to 11.7 - High Rxn Rate; HF Alky Reactor #1/#2) High pressure due to high level in the reactor, because of continued feeding olefin (link to 11.1 - High Level; HF Alky Reactor #1/#2)	High temperature alarm on reactor High pressure alarm on reactor Field operator may notice sound of fluid flow across valve Flow indication (in olefin charge line to reactor that is inadvertently NOT shutdown) Level indicator, high level alarm, and independent high-high level switch/alarm	
		Operator failing to make sure bypass valve is also closed, since this precaution is not listed in the written procedure; or the bypass valve leaks through	High pressure due to possible runaway reaction (because cooling is already lost), because of continued feeding of olefin (link to 11.7 - High Rxn Rate; HF Alky Reactor #1/#2) High pressure due to high level in the reactor, because of continued feeding olefin (link to 11.1 - High Level; HF Alky Reactor #1/#2)	High temperature alarm on reactor High pressure alarm on reactor Field operator skill training requires always checking bypasses are closed), when blocking in control valves Field operator may notice sound of fluid flow across valve Flow indication in olefin charge line (but likely not sensitive enough for small flows) Level indicator, high level alarm, and independent high-high level switch/alarm	
		Operator failing to close flow control valve manually from the DCS because the phrase "block in" is used instead of the word "close"	Valve possibly opens full at restart, allowing too much flow to reactor at restart, resulting in poor quality at startup and/or possibly resulting in runaway reaction and high pressure	Control room skill training requires always manually commanding automatic valves closed before telling field operator to block in control valve	37. Implement best-practice rules for procedure writing, which includes using common terminology.
23.2	Step performed wrong	Operator closing the olefin charge flow control valves before shutting down the charge pump, primarily because the steps are written out of the proper sequence	Deadheading of charge pump, leading to possible pump seal damage/failure and/or other leak, resulting in a fire hazard affecting a small area (link to 5.12 - Loss of Containment; Olefin Charge Line/Pump)	Step 3 of procedure that says to shutdown charge pump The step to shut down the charge pump (Step 3) is typically accomplished before Step 2 (in practice)	41. Move Step 3 ahead of Step 2.
		Field operator closing both upstream and downstream block valves	Possible trapping of liquid between block valve and control valve, leading to possible valve damage (due to thermal expansion)	Field operator skill training stresses that only one block valve should be closed	

6. What-if Method for Analyzing Deviations of Procedural Steps

The What-if method for analyzing procedure-based modes of operations is free brainstorming without the aid (or constraints) of guide words. This method is described in detail the *Guideline for Hazard Evaluation Procedures (CCPS)*[8]. The hazard evaluation team using this method would read the procedure and then answer the question: "What mistakes will lead to our consequences of interest?" The team would list these mistakes and then brainstorm the full consequences, causes, and existing safeguards – the same analysis approach described for the guide word approaches mentioned earlier in this section. What-if brainstorming **is not** applied to each step of the procedure, but rather covers the entire task (procedure) at one time.

7. Choosing the Right Method for Analysis of Non-Routine Modes of Operation

Obviously the What-if approach takes far less time than the 2-Guide Word method, and the 2 Guide Word method takes much less time than the 7-8 Guide Word method of HAZOP of procedures. Experience has shown that hazard evaluation facilitators, newly trained in the three techniques above, tend to overwork an analysis of non-routine procedures, so a tiered approach is best. In this tiered approach, the first step in choosing the right method of analysis in the hazard evaluation of procedures is to screen the procedures and select only those procedures with extreme hazards. These procedures should be subjected to a detailed HAZOP analysis (7-8 guide word set) presented above. The 2-Guide Word set is efficiently used for less complex tasks or where the consequences are lower. The What-if method is applicable to low hazard, low complexity, or very well understood tasks/hazards.

Experience of the leader or the team plays a major part in selecting the procedures to be analyzed, and then in deciding when to use each guide word set.

Figure 1 shows the typical usage of the three methods described above for a typical set of operations procedures within a complex chemical plant or refinery or other process/ operation. Most of the procedures are simple enough, or have low enough hazards to warrant using the What-if method. Currently, the 7-8 Guide Word approach is used infrequently, since most tasks do not require that level of scrutiny to find the accident scenarios during non-routine modes of operations.

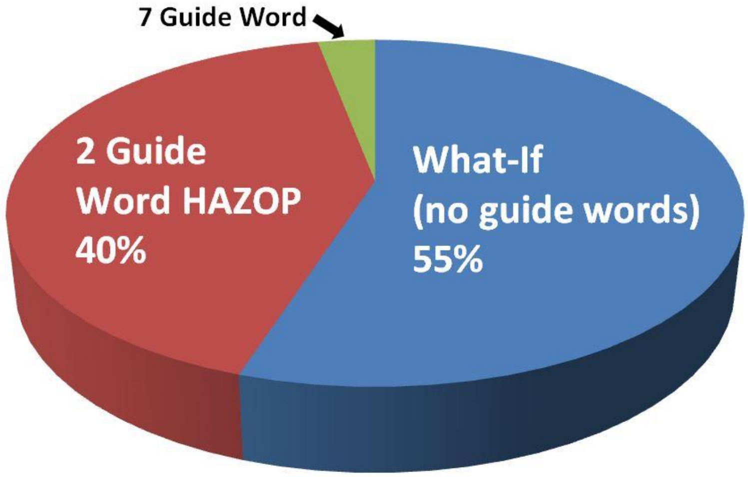

Figure 1. Relative Usage of Techniques for Analysis of Procedure-Based Modes of Operation

The experience of the leader or the team plays a major part in selecting the method to use for each task/procedures to be analyzed. However the first decision will always be "Are these procedures ready to be risk reviewed?" If the procedures are up-to-date, complete, clear, and used by operators, then the best approach for completing a complete hazard evaluation of All modes of operation, including routine modes of operation, is shown in Table 5 below:

Table 5. Example Choice of Methods for Hazard Evaluation of all Modes of Operations if the Operating Procedures are More Than 80% Accurate[15]

For Continuous Mode	For Discontinuous Mode (batch, startup, shutdown, on-line maintenance, emergency shutdowns)

• HAZOP of Parameters of Continuous Mode
• FMEA of Continuous Mode
• What-if of Simple Sub-systems
	• HAZOP of Steps
	  ○ 7 Guide Word
	  ○ 2-3 Guide Word
	• What-if of Simple Tasks

Notes: Do this first for a continuous process. Do not do this at all for a Batch process.	Note: Do this second for a continuous process. For a batch process, use Only this analysis approach.

If you do **not** have accurate procedures then the best approach is to develop accurate and up-to-date procedures as quickly as possible and in the meantime follow the approach shown in Table 6 below:

Table 6. Example Choice of Methods for Hazard Evaluation of *Partially All* Modes of Operations if the Operating Procedures are Less Than 80% Accurate[15]

For Continuous Mode	For Discontinuous Mode (batch, startup, shutdown, major maintenance, emergency shutdowns)
• HAZOP of parameters of Continuous Mode • FMEA of Continuous Mode • What-if of Simple Sub-systems	You may find 10% of the scenarios that can occur during non-routine operations by adding guides such as "Deviations During On-line Maintenance" to your set of Parametric Deviations.
Note: After this "incomplete" PHA, you must develop accurate operating procedures (better than 80% accuracy) and the you can complete the PHA by either What-If or HAZOP methods applied to these accurate procedures	

Any procedure (even a computer program) can be analyzed using these techniques. Reviews of routine procedures are important, but reviews of non-routine procedures are even more important. As mentioned earlier, the nature of non-routine procedures means that operators have much less experience performing them, and many organizations do not regularly update these procedures [though this should change as companies comply with 29 CFR 1910.119(f)][2]. Also, during non-routine operations, many of the standard equipment safeguards or interlocks are off or bypassed.

Using the approaches above, a company doing a complete hazard evaluation of an existing unit will invest about 65% of their time to evaluate normal (e.g,, continuous mode) operation and 35% of their time for evaluating the risks of non-routine modes of operation.

Many companies do **not** perform a thorough analysis of the risk for startup, shutdown, and on-line maintenance modes of operation; the reason normally given is that the analysis of these modes of operation takes "too long." Yet, actually, the hazard evaluation of the normal mode is taking too long and so the organization feels it has no time left for the analysis of procedures for startup and shutdown modes of operation. But, if these hazard evaluations for the normal mode of operation are **optimized** (such as using rules presented elsewhere[16]), the organization will have time for thoroughly analyzing the non-routine modes (typically discontinuous modes) of operation and the organization will still have a net savings overall! This point is critical since 60-75% of catastrophic accidents occur during non-routine modes of operation. Figure 2 illustrates (for a continuous process unit) the typical split of meeting time for analysis of routine mode of operation versus non-routine modes of operation.

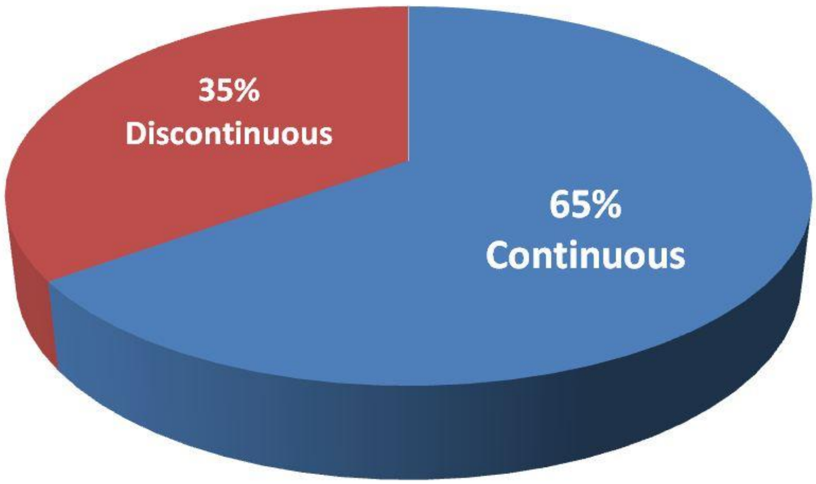

Figure 2. Relative Amount of Meeting Time Spent for Analysis of Routine and Non-routine Modes of Operation for a Continuous Process

8. General Guidelines for Analyzing Non-routine Modes of Operation or Batch (Step-by-step) Processes

- Define the assumptions about the system's initial status. "What is assumed to be the starting conditions when the user of the procedure begins with Step 1?"
- Define the complete design intention for each step. "Is the step actually 3 or 5 actions instead of one action? If so, what are the individual actions to accomplish this task?"
- Don't analyze safeguard steps that start with ensure, check, verify, inspect, etc., or where the consequence of skip is "loss of one level of safeguard/protection against ….." There is no reason to analyze these steps since they will show up as safeguards of deviations of other steps. This approach is similar to not analyzing a PSV during a HAZOP of continuous mode (parametric deviation analysis); instead the PSV is shown as a safeguard against loss of containment.
- Together with an operator before the meeting, identify the sections of the procedures that warrant use of:
  - 7-8 Guide Words (extremely large consequences can happen if deviations occur)
  - 2 Guide Words (the system is complex, mistakes are costly, or several consequences could occur)
  - On others, use What-If (no guide words or guide phrases; for use on simpler or lower hazard systems)
- Decompose each written step into a sequence of actions (verbs)
- Apply guide words directly to the intentions of each action

The Following Preparation Steps May Also Be Needed:

- Walk through procedure in the plant with one or more operators to see the work situation and verify the accuracy of the written procedure. This is optional and should have also been performed as part of validation of the procedure after it was originally drafted.

- Determine if the procedure follows the best practices for "presentation" of the content; the best practices will limit the probability of human error.
- Discuss generic issues related to operating procedures, such as:
  - staffing (normal and temporary)
  - human-machine interface
  - worker training, certification, etc.
  - management of change
  - policy enforcement
- Review other related procedures such as lock out/tag out and hot work.

9. Case Studies

The following case studies illustrate the usefulness of the process outlined in this paper.

9.1 Case Study 1: Phillips Polyethylene Plant 6, Pasadena, Texas

In 1991-1992, a PHA was performed for the first of the rebuilt polyethylene plants at the Pasadena, TX, Phllips 66 plant. The accident there two years prior claimed 24 lives, injured hundreds of others, destroyed all three polyethylene plants, and cost Phillips an estimated $1.4 billion. Following the investigation of the accident, one of the requirements of the settlement agreement between Phillips and the US government was to ensure the PHA of the rebuilt units addressed hazards during ***All modes of operation***.

The PHA team varied in size, but always included at least two operators. The team leader was a process engineer with 15 years of experience, who was also trained in human factors. The PHA first covered the continuous mode of operation for the approximately 200 nodes of equipment (from feed stock through pellet handling) using the "parametric deviation" form of HAZOP (and some What-If). Then, to complete the analysis of all modes of operation, the PHA team performed a step-by-step analysis of all steps of all startup and shutdown and online maintenance procedures (about 700 steps changed the state of the system and each of these steps were analyzed) using the 7 Guide Word HAZOP method (2 Guide Word analysis was not known to the team at this time). For deviations such as "operator skips a step," the causes identified by the team included "the operator doing this step miscommunicates with the operator who performed steps earlier in the day and went to the wrong reset panel/switch in the field". In this example, an "other-than" error led to the "skip" error; so two errors occurred at once: the wrong switch was flipped and the correct switch was not flipped. Other causes included: "label not distinct enough" or "thinking/believing the previous operator completed this step." The additional safeguards suggested by the PHA team sometimes lower the likelihood of the error by addressing a human factors weakness. But in many cases, the solution was a change to the hardware or instrumentation, including adding new interlocks (these would be called Safety Instrumented Functions today) and adding mechanical interlocks and installing larger relief valves. In a couple of cases, isolated sections of the process were redesigned to lower the inherent risk, such as adding error-proofing (Poke Yoka) features.

The 7 Guide Word HAZOP of non-routine modes of operation took 2.5 weeks of meetings, 40 hours a week. This was in addition to the 3.5 weeks of meetings to complete the parametric deviation analysis HAZOP of the continuous (normal) mode of operation (as mentioned before, 200 nodes of equipment). *Note that if the team had known of and been trained in 2 Guide Word HAZOP for procedure steps, they likely would have chosen that for many of the tasks and it is estimated that the meeting time for analysis of non-routine procedures would have been reduced to less than 2 weeks, with little or no loss of thoroughness.* The completed PHA report was submitted to US OSHA for review and was approved almost immediately; OSHA particularly reviewed the analysis of all modes of operation and coverage of human factors.

After the PHA was completed, the settlement agreement also required a quantified human reliability analysis (HRA) of the online maintenance task of clearing a plugged settling leg – mistakes during this task led to the accident in 1989. The HRA was performed similar to as required for nuclear reactor risk assessments, using a human reliability event tree to model the error probability for the task. The HRA results indicated that if the three IPLs in the new design are maintained, the probability of a similar event occurring when using this procedure was less than the risk of fatality when driving to work. This report was also approved by OSHA.

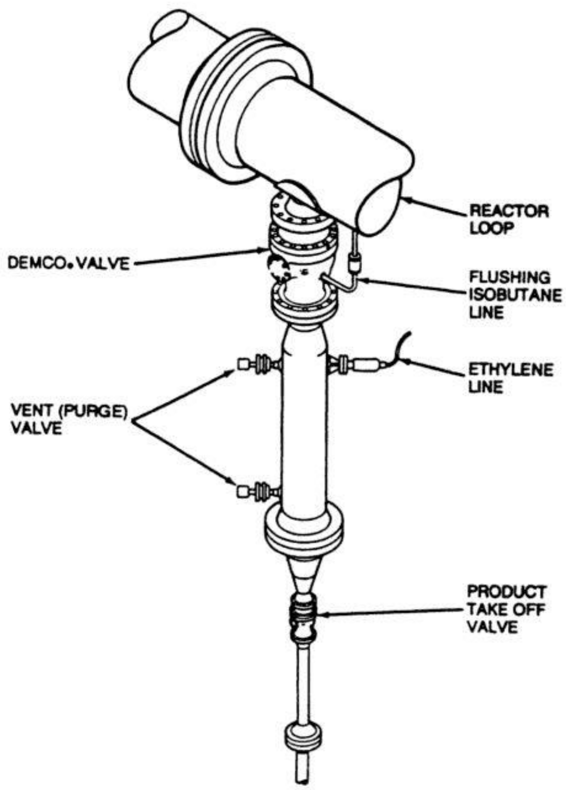

Figure 3: Typical Settling Leg Assembly for Phillips Polyethylene Reactor

The HRA shed light on new aspects of making errors and recovering from the errors during this task, but the HRA results did not result in changes to the process steps (at least not much), or the training program, or the human factors engineering, or the hardware/IPLs. In this instance, the HRA validated the results of the 7 Guide Word HAZOP, but did not make new recommendations. The HAZOP of the procedures had already found the major accident scenarios and had already identified well enough the changes needed to reach tolerable risk.

9.2 Case Study 2: Catalyst Addition System

After several near misses and accidents, a company completely upgraded its PSM program. Detailed operating and maintenance procedures were written for all non-routine tasks. Training experts were called in to ensure that workers understood these new procedures. During process design, particular emphasis was placed on reducing human error. The company also decided to perform PHAs (using the HAZOP analysis technique) to uncover potential accident scenarios in its process design and procedures, with the PHA teams instructed to focus on human error sources. Detailed human reliability analysis was reserved for critical, complex tasks identified by the PHA teams as having potentially severe consequences.

The following results were taken from the analysis of a continuous catalyst addition system for a reactor, shown in Figure 4. Though the normal mode of operation was continuous, the addition system was frequently isolated, depressurized, refilled, and then restarted while a standby addition system maintained feed flow to the reactor. It was interesting to note how the team's perception of "likelihood" for a given human error scenario changed after the procedures were reviewed.

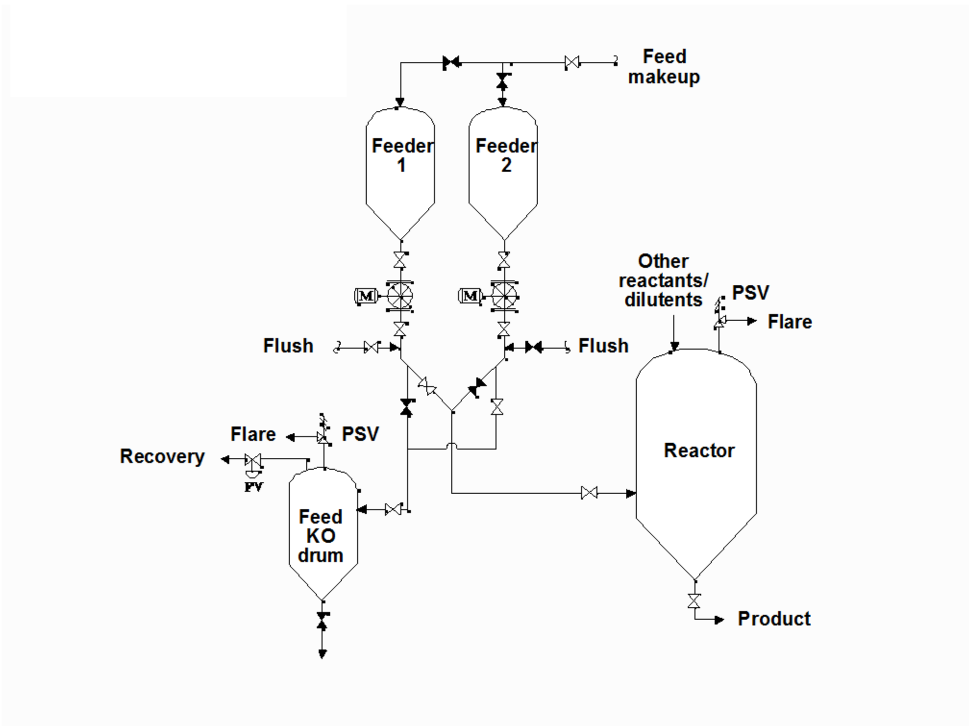

Figure 4: Catalyst Addition System for Reactor

The HAZOP review of the procedures for switching between feeders indicated that the steps telling the operator to close the drain line valve, and later to verify the drain valve was closed, were both "missing." Also, the operators recalled that formal (classroom) training did not mention the operation of this manual valve and field training did not always cover operation of this valve. The senior operators on the review team began to realize that an inexperienced operator might not understand that the sound made by the rushing backflow of fluid is abnormal and might react too slowly to prevent over-pressurization. Therefore, the team concluded that if hands-on training failed to correct the procedure deficiencies, backflow from the reactor to the KO drum was a likely accident scenario, especially with new operators. The team recommended the procedures be modified to (1) reflect the proper sequence of steps and (2) emphasize the consequences of leaving the drain valve open and then later opening the feed line to the reactor. A checklist of the proper sequence of steps was recommended for this procedure. In addition, a recommendation from the continuous mode HAZOP involving the relief valve on the KO drum was modified to ensure the relief valve was also capable of handling reverse flow from the reactor (the relief size was ultimately increased).

Note about 3% of the relief valves across the entire chemical complex (which contained more than 3000 relief valves) were resized to account for accident scenarios that were only found during analysis of non-routine modes of operation.

9.3 Case Study 3: Urea and Ammonia Plants in the Arabian Gulf Region

Several ammonia and urea plants had hazard evaluations performed using HAZOP of nodes (parametric deviations for continuous mode of operation) and then non-routine modes of operation were analyzed using What-if and 2-Guide Word analysis for selected, critical procedures. The HAZOP of nodes (which focuses necessarily on the continuous mode of operation) missed many accident scenarios that were later found during review of non-routine modes of operation. The analysis of critical procedures resulted in a number of new recommendations to reduce the risk of accident scenarios (these accident scenarios were not identified during the HAZOP of the nodes a few days before). One example was the recommendation to install a second, independent level transmitter on the urea reactor to prevent overflow to the high pressure scrubber which will lead to overpressure of the entire synthesis loop and poor reaction kinetics during startup and normal operation.

Another example related to the start-up of high pressure ammonia pumps in the synthesis section of the ammonia plant follows. A recommendation was made during the analysis to include more detail on the required rate of temperature increase together with notes explaining the potential consequences for heating too quickly. In this case, a high heating rate may damage the 316L stainless steel liner in vessels and would have caused corrosion, deformation and ultimately a vessel failure.

It was also identified during the analysis that the development of trouble-shooting guides should be considered for responding to severe system upsets, including control valve failure, sticking of a hand valves, and to address contamination issues. These can be developed with the help of the PHA tables, which contain 40% of the scenarios and information related to trouble-shooting guides.

10. Conclusion

Qualitative analyses of non-routine operating procedures is an extremely powerful of tools for uncovering deficiencies that can lead to human errors and for uncovering accident scenarios during all modes of operation. This approach of step-by-step HAZOP and/or What-If analysis is not new to industry and regulators have required similar approaches for decades. And regulators continue to note lack of analysis of the risk of non-routine operations and lack of risk review of changes to procedures.

> ***From the Wall Street Journal[17] referencing the presidential commission investigating the Deepwater Horizon accident of April 2010:*** *BP had rules in place governing procedural changes, but its workers didn't consistently follow them,*

according to BP's September [2010] internal report on the disaster and the report released earlier this month [January 2011] by the presidential commission on the accident. "Such decisions appear to have been made by the BP Macondo team in ad hoc fashion without any formal risk analysis or internal expert review," the commission's report said. "This appears to have been a key causal factor of the blowout."[17]

From CSB Report on August 2008 Bayer CropScience Explosion: [17] *"The accident occurred during the startup of the methomyl unit, following a lengthy period of maintenance … CSB investigators also found the company failed to perform a thorough Process Hazard Analysis, or PHA, as required by regulation…In particular, for operational tasks that depend heavily on task performance and operator decisions, the team should analyze the procedures step-by-step to identify potential incident scenarios and their consequences, and to determine if the protections in place are sufficient."*

Further, such analyses make it easier to provide a thorough consideration of human factors. Regardless of what hazard evaluation technique is employed, it is imperative for PHA teams to ask, "Why would someone make this mistake?" whenever a human error is identified as a cause of a potential accident. "To err is human" may be a true statement, but the frequency and consequences of such errors can be effectively reduced with a well-designed strategy for analyzing risk of non-routine operating modes.

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Appendix A. Random Selection of Major Accidents versus Mode of Operation; limited to Processing Facilities[a,b]

Yr	Event	Company	Location	Deaths	Injuries	Losses (USD)	Mode of Operation
1987	Overpressure of and release of distillate from LP Separator, resulting in explosion	BP Oil	Grangemouth, Scotland	2	2	+50 million	Online maintenance
1987	External impact and release of HF	Marathon Oil	Texas City, TX	0	100+	4000 evacuated	Maintenance turnaround
1988	Natural gas explosion and fire	Occidental Petroleum	North Sea, Near UK	167	61	+2 billion	Startup after maintenance
1989	Release and ignition of isobutene and ethylene	Phillips	Pasadena, TX	24	300+	1.4 billion	Online Maintenance
1990	Internal explosion of waste water tank	ARCO Chem.	Channelview, TX	17	5	100+ million	Online Maintenance
1990	Explosion and fire	BASF	Cincinnati, OH	3	40	1.1million in fines Site closed	Non-routine batch
1992	Release and explosion	Texaco	Wilmington, CA	0	107	73 million	Normal Operation
1992	Ignited sludge sending a jet of flame over 50m-long through the plant control building into the site's main office block	Hickson & Welch	Castleford, UK	5	18	Unreported	Non-routine procedures - Removal of sludge
1993	Internal explosion of fired heater	Ashland Oil	Catlettsburg, KY	2	NA	Unreported	Startup
1994	Release of ammonia and nitric acid	Terra Ind	Port Neal, IA	4	18	Unknown	Start-up
1994	Release of hydrogen cyanide	BASF	Seal Sands, UK	0	11[(]	Not significant	Startup
1994	Series of fires and then explosion	Texaco	Milford Haven, South Wales, UK	0	26	>700 million	Startup after emergency shutdown
1995	Explosion and fire	NAPP Tech	Lodi, NJ	5	4	Unknown	Non-routine batch steps
1995	Explosion and fire with flammable hydrocarbons	Pennzoil	Rouseville, PA	5	1	40 million	Online maintenance
1997	Phenol/Formaldehyde explosion	Georgia Pacific	Columbus, OH	1	13		Normal operation, wrong sequence

Yr	Event	Company	Location	Deaths	Injuries	Losses (USD)	Mode of Operation
1997	VCE from spill of LPG	Hindustan Petroleum Corporation (HPCL)	Visakhapatam, India	50	Unknown	64 million	Normal Operation
1997	Release and ignition of distillate	Tosco	Martinez, CA	1	46	6 million	Online maintenance
1997	Spill of HCL	Surpass	Albany, NY	0	43	Unknown	Startup
1997	ETO fire and explosion	Accra Pac	Elkhart, IN	1	65	Unknown	Shutdown
1998	Release and ignition of natural gas	Esso	Longford, Australia	2	8	1.1 billion	Startup, after maintenance
1998	Release of flammable and ignition	Morton	Patterson, NJ	0	9	Unknown	Normal Operation
1998	Catastrophic vessel failure, release and ignition	Sonat	Pitikin, LA	4	0	Unknown	Normal Operation
1998	Release of more than 4 tons of sulfur dioxide and hydrogen chloride	Nipa Laboratories	Lancashire, UK	0	3	> 100,000	Normal Batch operation
1998	Explosion and fire in refinery coker	Equilon	Anacortes, WA	6	Unknown	Unknown	Startup
1999	Release of distillate and ignition	Tosco	Martinez, CA	4	1	Unknown	Online maintenance
1999	Release, fire and explosion	Thai Oil-Royal/Dutch Shell	Sri Racha, Thailand	8	13	37 million	Normal Operation
1999	VCE resulting due to leak from valve failure	Chevron	Richmond, CA	0	0	79 million	Normal Operation
1999	Hydroxylamine explosion	Concept Sciences	Allentown , PA	5	14	4 million	Normal Operation (New Process)
2000	Release and explosion	Kuwait	Mina Al-Ahmadi, Kuwait	5	50	433 million	Normal Operation
2001	Release and ignition	BP Amoco	Augusta, GA	3	0	Unknown	Online maintenance
2001	Sulfuric acid tank explosion	Motiva	Delaware City, DE	1	8	Unknown	Maintenance
2002	Decomposition reaction in distillation column	First Chemical Corp	Pascagoula, MS	0	3	Unknown	Normal Operation

Yr	Event	Company	Location	Deaths	Injuries	Losses (USD)	Mode of Operation
2003	Benzoyl peroxide explosion and fire	Catalyst Systems	Gnadenhutten, OH	0	1	Unknown	Normal Operations
2004	Fire at explosion from LNG release	Sonatrach	Skikda, Algeria	27	74	Unknown	Startup
2004	Release of toxic allyl alcohol and allyl chloride	MFG Chemical	Dalton, GA	0	169	Unknown	Initial Startup
2004	Release and explosion of vinyl chloride	Formosa Plastics	Illiopolis, IL	5	3	Permanent closure	Cleaning during reactor shutdown
2004	Release of alkylate and explosion	Giant Industries	Cinizia (Gallup), NM	0	6	Unknown	Normal operation (switching pumps)
2005	Release and ignition of distillate	BP	Texas City. TX	15	170+	2+ billion	Startup
2006	Release and ignition of propylene	Formosa Plastics	Point Comfort, TX	0	16	Unknown	Normal operation (external impact)
2006	Release and ignition of flammable vapors	CAI/Arnel	Danvers, MA	0	10	Unknown	Normal operation
2007	Runaway reaction and explosion	T2 Labs	Jacksonville, FL	4	32	Unknown	Routine batch
2007	Release and ignition of natural gas	ARAMCO	Hawaiyah, Saudi Arabia	40	9	Unknown	Online maintenance
2008	Oleum release and evacuation of community	Occidental (INDSPEC Chemical Corporation)	Petrolia, PA	0	0	Unknown	Non-routine batch
2008	Runaway reaction and overpressure and explosion/fire	Bayer CropScience	Institute, W VA, USA	2	8	Unknown	Startup
2009	Solvent vapor release and explosion	Veolia	W. Carrollton, OH	0	2	Unknown	Shutdown
2010	Fire and explosion in crude oil distillation unit at Lindsey Oil Refinery	Total	Humberside, UK	1	2	Unknown	Maintenance turnaround
2010	Explosion and fire at oil refinery	Tesoro Corp	Anacortes, Washington State	5	2	Unknown	Startup after maintenance

[a] Data in the table excludes storage and terminals and also excludes exploration (drilling, etc.) and transportation
[b] Forty-seven major accidents are listed above, of which thirty-one are during non-routine operation