ADDRESSING HUMAN ERRORS DURING PROCESS HAZARD ANALYSES

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This paper was basis for a presentation at the 1990/1991 PSM Symposium sponsored by CCPS/AIChE. A similar paper was published in May 1994 edition of Chemical Engineering Progress by the same authors.

ABSTRACT

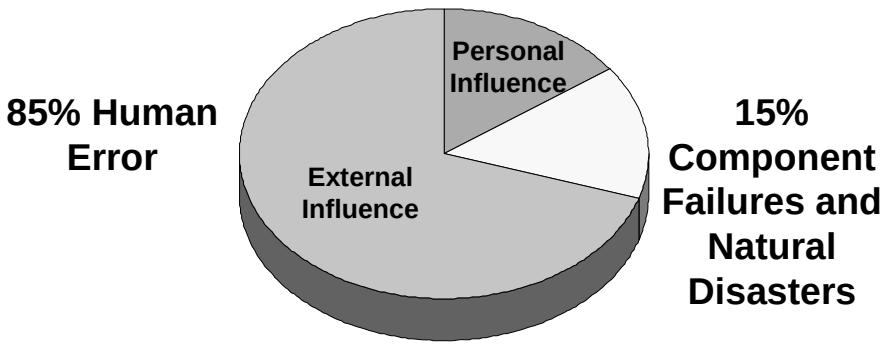
Recent accidents and new regulations underscore the need for companies to identify potential human errors and to reduce the frequency and consequences of such errors as part of an overall process safety management (PSM) program. But how does someone responsible for coordinating or performing process hazard analyses (PHAs) satisfy this need to uncover potentially important human errors without consuming too much time and too many resources? This paper describes an approach for integrating human factors considerations into hazard evaluations of process designs, operating procedures, and management systems. In the description of our approach, we cite OSHA's and EPA's definitions for consideration of human factors during PHAs. Critical issues related to human factors can be identified and addressed in different phases of a hazard evaluation. Case studies illustrate the effectiveness of this strategy.

INTRODUCTION

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.

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. Most mistakes made by people in the workplace result from external influences, such as:

- Deficient procedures
- Inadequate supervision
- Insufficient staffing
- Ineffective training
- Poor human-machine interfaces
- Poor physical work environment



These human-error causes, which in turn result from other human errors, are all directly within management's control.

Recent accidents and new regulations underscore the need for companies to aggressively pursue more effective ways to identify potential human errors and to mitigate their causes and/or consequences. This effort can be logically incorporated into each company's PSM program. Paragraph (e) of the OSHA regulation on PSM, 29 CFR 1910.119,[1] and EPA's proposed regulation for risk management programs, 40 CFR 68.24,[2] specifically require that PHAs consider human factors. But what does it mean to "consider human factors"? To correctly answer this question, we must (1) understand the root causes of human error and (2) develop a strategy for systematically examining each category of root cause. Our strategy must be thorough, yet provide for a practical allocation of resources. Another way to answer the question is to try to define what OSHA and EPA mean by "human factors." Since this term is not defined in the regulations, we must look for other clues, such as citations, settlement agreements, compliance directives, and clarifications (e.g., Appendix C of 29 CFR 1910.119). This paper provides a strategy for efficiently addressing human factors using widely accepted hazard evaluation techniques (such as those approved by OSHA and EPA for PHAs, which include checklist analysis, what-if analysis, failure modes and effects analysis [FMEA], and hazard and operability [HAZOP] analysis). In the description of each step of the strategy, we explain how this approach addresses OSHA's and EPA's definition of human factors. Although this paper focuses on the requirements of a PHA, the approach is equally effective for other hazard evaluations such as preliminary and detailed design reviews (for new/revised processes) and large management of change hazard reviews.

To implement this strategy, a four-step approach is suggested. Step 1, evaluating process design, requires the use of standard PHA techniques expanded to provide in-depth coverage of human factors. Step 2 involves having the PHA team perform a review of procedures using a HAZOP or what-if analysis to uncover potential human errors associated with routine and nonroutine operations. In Step 3, the management systems designed to control issues related to human factors (including those in Steps 1 and 2) are evaluated by using interviews, questionnaires, and checklists. Finally, in Step 4, a detailed human reliability analysis (HRA) is used to address any unresolved issues raised in Steps 1 through 3. This paper briefly describes Steps 1 through 4, and gives two case studies to illustrate the analysis approach and the usefulness of this strategy. Companies may incorporate any one, or all four, of these steps in their PHA programs. We typically recommend that Steps 1 and 2 be included as part of a PHA. Executing all four steps during PSM implementation (extending well beyond the PHA) will result in more complete identification and prevention of human errors.

STEP 1 - HUMAN FACTORS IN PROCESS DESIGN

Traditionally, hazard evaluations of process designs, using techniques such as checklist analysis, what-if analysis, HAZOP analysis, and FMEA, have focused on process chemistry and hardware. However, analysts can easily incorporate human factors considerations into any of these techniques. Incorporating human factors considerations helps identify not only the possible errors, but also reasons why the errors might occur — making it easier for managers to improve process safety.
Analysts frequently use a combination of techniques to ensure completeness of a hazard analysis. For instance, an analyst may use a checklist of global design issues (such as plant layout or emergency response) to augment an analysis based primarily on either a what-if analysis, HAZOP analysis, or FMEA. Checklists of this nature should (and easily can) include general human factors concerns as well.

During a review of the process design, the majority of human errors identified are those resulting from deficiencies in the human-machine interface. OSHA recognizes the importance of this category of human error causes. Specific examples of human-machine interface issues cited in the compliance directive [CPL 2-2.45A] to 29 CFR 1910.119 are:

> "... operator/process and operator/equipment interface, ... clarity and simplicity of control displays, automatic instrumentation versus manual procedures, ..."[3]

Various OSHA citations in the past three years have also listed human-machine interface issues such as inadequate control displays and inadequate labeling in specific violations.

Checklist Analysis

Checklists can be expanded to include human factors considerations and, when expanded, are a particularly effective aid in identifying human-machine interface deficiencies. Questions such as the following can easily be incorporated into a checklist:

- Are all controls accessible and easy to identify?
- Are workers provided with enough information to diagnose the cause of an alarm?
- Are all displays easy to see and read?
- Are related displays and controls grouped together?

The *Guidelines for Hazard Evaluation Procedures, Second Edition with Worked Examples,*[4] written by JBF Associates, Inc. for AIChE's Center for Chemical Process Safety, contains an excellent starting checklist. Other checklists are included in publications[5,6] available from the Chemical Manufacturers Association. The exhibit at the end of this paper is a checklist of questions we have found particularly useful for augmenting a PHA to better address "human factors engineering" issues. We typically use this checklist at the end of a PHA meeting (regardless of the primary hazard evaluation techniques chosen for the PHA) to ensure we have adequately covered these issues.

What-If Analysis

To include human factors considerations in a what-if analysis, team members must be sensitive to human factors issues. If the question, "What if the operator added too much catalyst?" reveals a potential problem, the team should ask, "Why would an operator add too much catalyst?" But the team should never simply accept superficial answers, such as "operator inattention," as the only reason. More specific answers, like "poor training," "previous shift failed to notify oncoming shift," or "defective weigh scale," should be considered; only then will the team address the true root causes of human errors. These answers also suggest possible solutions: more rigorous training may be required for new or transferred operators; perhaps a checklist should be developed to help operators keep track of where they are in the procedure; operators could keep a logbook noting the time of each catalyst addition; instrument maintenance personnel could check and calibrate the weigh scale periodically; or a redundant measuring device (e.g., independent weigh scale, flow totalizer) could be provided so that a false weigh scale indication will not mislead the operator into adding too much catalyst.

HAZOP Analysis

Incorporating human factors considerations into a HAZOP analysis is very similar to incorporating them into a what-if analysis. Whenever the team identifies "operator error" as the cause of any deviation, the HAZOP analysis leader must ask, "Why?" in order to continue the brainstorming process. For example, operator error might cause low flow in a pipeline. When asked why this occurred, the team might mention (1) the flow controller is difficult to adjust, (2) the flow indicator could give a false high reading, or (3) operators often step on the adjacent piping to reach some overhead valves, and can break or pinch the air supply line to the valve actuator. After considering any existing safeguards against these specific causes, the HAZOP analysis team could make specific recommendations for eliminating the identified human factors deficiencies.

FMEA

Because an FMEA generally focuses on hardware failures, incorporating human factors considerations into an FMEA can be more challenging than for other techniques. To successfully identify human factors issues, the analyst(s) must investigate such issues as: (1) hardware failures that could mislead the operator into taking inappropriate action, (2) hardware failures that could prevent an operator from accomplishing the desired action, and (3) hardware failures that could be caused by inappropriate operator action or inaction.

To successfully examine human factors issues, an FMEA must divide equipment into parts small enough for thorough investigation of issues (1) and (2) above. For example, the FMEA would have to investigate the consequences of a local pressure indicator reading falsely high or low, since a false reading could cause an operator to make a mistake. Often, an FMEA would not cover a local indicator at all because its failure would not directly cause a system failure. Similarly, an FMEA would not normally consider "valve handle missing" a meaningful failure mode, if the valve is manually operated and not used for process operation. But obviously, such a valve would be useless in mitigating a downstream rupture if the handle were missing.

FMEAs, as generally conducted, can effectively investigate human factors issues of the third type, as long as the analyst remembers that a failure mode like "valve closed" can be caused by either a hardware failure or a human error. The FMEA analyst, just like the what-if or HAZOP analysis leader, must then pursue the question, "Why?" to identify the root causes of operator error.

STEP 2 - HUMAN FACTORS IN PROCEDURES

Although incorporating human factors considerations into hazard evaluation studies of process designs (as discussed previously) is straightforward, this approach only addresses a small fraction of the potential human errors that can affect process safety. A recent European study concluded that most (about two-thirds of) process industry accidents happen during startups, shutdowns, on-line maintenance, and batch operations.[7] These results are not surprising, since it is precisely during these step-by-step operations that systems are most vulnerable to human error.

Most companies 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. (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 feed valve may need to be opened 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)]. However, even the best procedure may not be followed for any number of reasons, and these failures to follow the prescribed instructions can result in accidents.

OSHA obviously recognized the importance of this category of human error when they emphasized that training should address human errors by reviewing:

1. *Consequences of failure to perform a task.*

2. *Consequences of incorrect performance of a task.*

3. *Procedures and controls to minimize errors.*[8]

The PSM regulation [in 29 CFR 1910.119 paragraphs (f) and (g)[1]] and its compliance directive[3] also emphasize addressing this source of error by stressing the importance of (1) having written, step-by-step instructions, and (2) ensuring the written procedures are followed. Some feel that "human factors" related to PHAs [as mentioned in paragraph (e)] does not apply to procedural errors. However, in the first major PSM inspection using 29 CFR 1910.119, 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,"[9] all of which are errors originating from failure to either perform tasks or perform them correctly.

In a recent citation,[10] 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 PHA) associated with nonroutine procedures such as "startup, shutdown, emergency shutdown, and emergency operations." There were several other violations assessed in this citation because these nonroutine procedures did not (allegedly) address the **consequences** associated with operators failing to follow the prescribed procedures. Also, the citation mentioned "deficient procedures" as another human factor to consider. The OSHA inspector was convinced that a hazard evaluation of the nonroutine operating procedures should have been part of the PHA scope.

In a recent article by H. C. Woodcock entitled, "Program Quality Verification of Process Hazard Analysis"[11] (for use in OSHA's training program), he stated that a PHA should include analysis of the "procedures for the *operation* and *support* functions" and goes on to define a "procedure analysis" quite similar to the approach we describe in the following paragraphs.

EPA also recognizes the importance of analysis procedures, since they define the purpose of a PHA (in proposed regulation 40 CFR 68.24) as to "examine, in a systematic, step-by-step way, the equipment, systems, and *procedures* (emphasis added) for handling regulated substances."[2]

Procedure-Specific Guide Words (Applied to Each Step of a Procedure)

Guide Words*	Meaning
Missing	A step is missing from the procedure at, or just before, the step being examined (no written/verbal procedure)
Skip (No) Part of	This entire step in the procedure is not performed, or any part of the step is not performed (e.g., only two of the three specified valves are closed)
Out of Sequence	This step is performed either early or late in the sequence
As Well As	Some action or operation (outside of this procedural section) is performed simultaneously with this step, choosing the worst case combination
More and Less (Quantitative)	Combine these guide words with the appropriate process variable to arrive at a deviation (often not applicable for procedural steps). For example, *more* and *less* apply to a step requiring an operator to set a flow controller to 25% of scale, but they do not apply to a step to simply turn on a switch
Other Than	An improper process component (or control element) is manipulated, read, etc., usually due to similarities in appearance, function, or location

*These guide words can be used to develop either HAZOP deviations or what-if questions.

To identify potential human errors that may be overlooked by the more traditional hazard evaluation techniques discussed in Step 1 and those arising from a failure to follow the intended procedural steps, a process hazard evaluation technique for procedures is clearly needed. We have found that a HAZOP or what-if analysis structured to address procedures can be used effectively for this purpose.[12,13] First, the procedure under review is divided into individual actions. Then, a set of guide words or questions is systematically applied to each action of the procedure under review as procedural deviations or what-if questions. The guide words (or procedural deviation phrases) shown in the table below 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 and nonroutine procedures. The actual review team structure and meeting progression are 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. For each deviation from the intention (denoted by these guide words), the team must dig beyond the obvious cause, "human error," to identify root causes such as "inadequate emphasis on this step during training," "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." A checklist of global issues should be developed and used to ensure that topics (specific to each company or facility) such as procedure format, use of illustrations, use of warnings and notes, etc., are considered.

Streamlined Guide Words for Procedure Analysis

Guide Words*	Meaning
Omit	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.
Incorrect	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.

* These guide words can be used to develop either HAZOP deviations or what-if questions.

A more streamlined guide word approach has also proven very useful (1) for 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 the table below) encompass the basic human error categories: errors of omission and commission. These guide words are used in a fashion identical 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, omit and incorrect, fill the basic requirements for a human error analysis as outlined in OSHA's CPL 2-2.45.[8]

Any procedure (even a computer program) can be analyzed using this technique. Reviews of routine procedures are important, but reviews of nonroutine procedures are even more important. The nature of nonroutine 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)]. Also, during nonroutine operations many of the standard equipment safeguards or interlocks are off or bypassed. Clearly, OSHA understood these points when they stated in Appendix C of the regulation that PHAs should consider "human errors (routine and nonroutine)." They emphasize the importance of addressing errors during nonroutine operations several other times in Appendix C, and in the citations mentioned earlier. Our experience shows that reviews of nonroutine procedures have revealed many more hazards than reviews of routine procedures.

We have found that new PHA leaders trained in the techniques above will tend to overwork an analysis of nonroutine procedures, so we stress a tiered approach. A first step in the hazard review of procedures should be to screen the procedures to select only those procedures with extreme hazards. Then only these procedures should be subjected to a detailed analysis using either of the guideword sets

presented above. The two-guideword set is efficiently used for less complex procedural steps whereas the eight-guideword approach is appropriate for leading the analysis of complex procedure steps. Obviously, 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 guideword set.

STEP 3 - HUMAN FACTORS IN MANAGEMENT SYSTEMS

Most other sources of human error not specifically related to process design or procedures are related to management systems. These management systems establish guidelines and control:

- Hazard analysis programs
- Supervision of operators
- Employee selection and training
- Follow-up of safety suggestions
- Engineering design standards
- Safe work policies and practices
- Management of change
- Procedure and document control

Management system problems often surface during the analyses mentioned in Steps 1 and 2. However, many other problems or weaknesses can be determined by structured, questionnaire-based interviews with plant supervisors and managers. Similar questionnaire-based interviews with operators help to highlight differences in perception or underscore areas of common concern. The questions should be structured to be non-confrontational. Any identified weaknesses in PSM systems should be accompanied by suggestions for change or further study. The Chemical Manufacturers Association's guide to reducing human error[2] contains an abbreviated example of a general questionnaire. Questions should be tailored to the needs of each company or facility, and specific questions should be included to address administrative issues raised during execution of Steps 1 and 2. Typical questions related to the control of written procedures might include: "How often are procedures updated?" or "Who reviews procedures for correctness?" Questions regarding process design might include: "Are safety-related checklists used in the design of new equipment? If so, how is thoroughness ensured?" Questions related to the physical work environment should also be included, such as: "Are displays legible and do they use consistent units and scales?" or "Has adequate lighting and ventilation been provided to optimize worker alertness?" or "Can the unit be safely operated in foul weather?" These questionnaires can help address specific human factor concerns listed in the compliance directive, by facilitating "review of the number of tasks operators must perform and the frequency, evaluation of extended or unusual work schedules, ... and operator feedback."[3]

Many questions asked here overlap considerably with a quality audit of a PSM system. Therefore, the questionnaire and its results may be better kept with the PSM audit results rather than a particular PHA report. This is especially true since the results of the questionnaire will apply facility-wide (perhaps encompassing the scope of *many* individual PHAs). The current trend at most companies is to include this step in the PSM audit.

Don't expect any questionnaire to be complete. Questions should be modified and updated on a continual basis. In application, we find that much of the management systems questionnaire can be covered during Steps 1 and 2. In fact, the majority of the questions may simply provide a broader net for capturing general deficiencies in process design or procedures. However, follow-up interviews with management, and perhaps operators, will usually shed new light on management's philosophy and understanding of safety issues.

STEP 4 - DETAILED HUMAN RELIABILITY ANALYSES

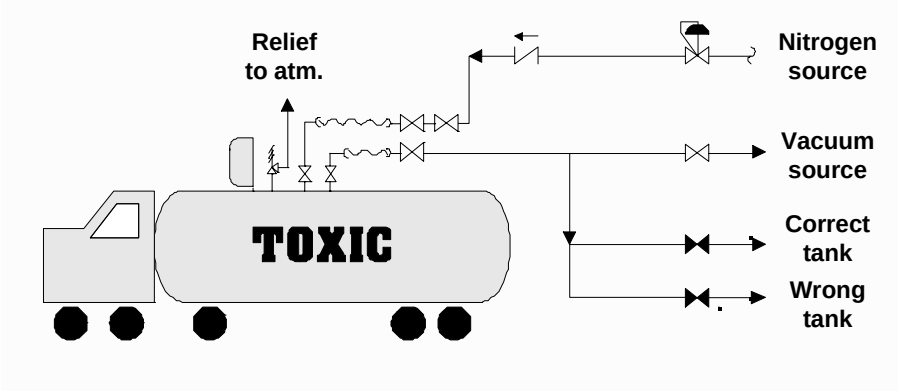
One product of the techniques described in Steps 1 through 3 above should be a list of potential accidents (or classes of accidents) caused by human error. From this list, companies may want to subject accident scenarios with particularly severe consequences to a detailed qualitative (or quantitative) HRA. This detailed analysis involves having an experienced human reliability analyst interview knowledgeable workers (operators, maintenance personnel, engineers, managers, etc., depending on the specific scenario), perform a task analysis, and evaluate the specific human-machine and human-human interfaces involved. By observing personnel during step-by-step process operations, and examining the ergonomic characteristics of process instrumentation and hardware, the human reliability analyst can identify important human factors issues overlooked by the other hazard evaluation techniques. As part of this review, the analyst may also evaluate other performance-shaping factors such as the shift rotation schedule, labor-management relations, and physical and mental stressors. The results of these analyses will likely identify both specific ways to improve human reliability on critical tasks and general ways to improve human performance throughout the facility.

CASE STUDIES

The following case studies illustrate the usefulness of the process outlined in this paper. They provide insights into how the various steps in the recommended approach complement one another.

Case Study 1

The company had traditionally performed checklist reviews of its process systems and JSAs of procedures. After an explosion that resulted in fatalities, the company embarked on an aggressive program of PHAs (using primarily the HAZOP analysis technique) of their process equipment and procedures. The following results were taken from a toxic material unloading system analysis.



Step 1 - Human Factors in Process Design

The HAZOP analysis of the unloading equipment considered the deviation "high pressure" in the tank truck, which could lift the truck's relief valve and release toxic material. The toxic material was delivered in various types of tank trucks, which could include tanks of different pressure ratings and relief valve setpoints. Investigation of possible causes revealed that high pressure in the truck could be a result of several human errors and mechanical failures, such as: (1) the truck driver overstating the truck's pressure rating, (2) the operator setting the nitrogen pressure regulator incorrectly, or (3) the nitrogen pressure regulator failing to throttle closed during a pressure surge from the nitrogen header. The review team recommended that a pressure relief valve be installed on the nitrogen line between the regulator and the truck and that this new relief valve be set below the lowest known relief valve setpoint of delivery trucks.

Step 2 - Human Factors in Procedures

The HAZOP review of the unloading procedure considered the guide word "less" as it applies to the step "pull vacuum in the unloading line before starting the unloading process." To complete this step, the operator had to align several valves and start a steam ejector system in an adjacent building. The review team realized that reading a vacuum gauge at the steam ejector did not ensure that a vacuum had been pulled in the unloading line out to the unloading rack. If the unloading line was not evacuated, leftover material in the line could contaminate other storage tanks (reducing product quality) and cause very rapid corrosion in other downstream equipment (likely resulting in a loss of containment). The team recommended installing a vacuum gauge at the unloading rack so the operator could verify that vacuum had been achieved and maintained at that location before starting to unload the truck.

Step 3 - Human Factors in Management Systems

During the analyses in Steps 1 and 2, the PHA team discovered that procedures had not been updated in a timely fashion. The operators had made several modifications (mostly improvements) to the procedures that had not been documented, and management was unaware of these changes. In addition, the procedures had not been reviewed for accuracy in over 2 years. Interviews revealed the existence of administrative requirements for (1) conducting periodic reviews of operating procedures and (2) implementing changes in design and/or operations documents, but management had not taken steps to ensure adequacy or compliance with these administrative controls. One remedy suggested by the team was to have the document control clerk issue a schedule and audit the status of procedure reviews. Also, it was suggested that the procedure

review team include both operators and engineers and that any procedural changes be subjected to a HAZOP analysis (as described in Step 2) by an independent team of similar composition.

Step 4 - Detailed Human Reliability Analysis

In Steps 1 and 2, the PHA team identified several operator errors that could cause a toxic release. As discussed above, improvements were made regarding some of the specific errors identified. However, company management felt that an additional, more detailed, qualitative analysis should be conducted. To accomplish this, a human reliability expert observed operators (on various shifts, with varying degrees of experience) performing routine operations. This qualitative analysis revealed several additional recommendations, including the following:

- Improving the outdoor lighting near the unloading rack
- Unloading only during daylight hours (when leaks are easier to see and emergency response personnel are more readily available)
- Locking the crossover valve closed to reduce the chance of material being unloaded into the wrong tank
- Providing a local indicator of storage tank pressure at the unloading rack (operators do not check the pressure frequently because the existing indicator is on top of the storage tank)

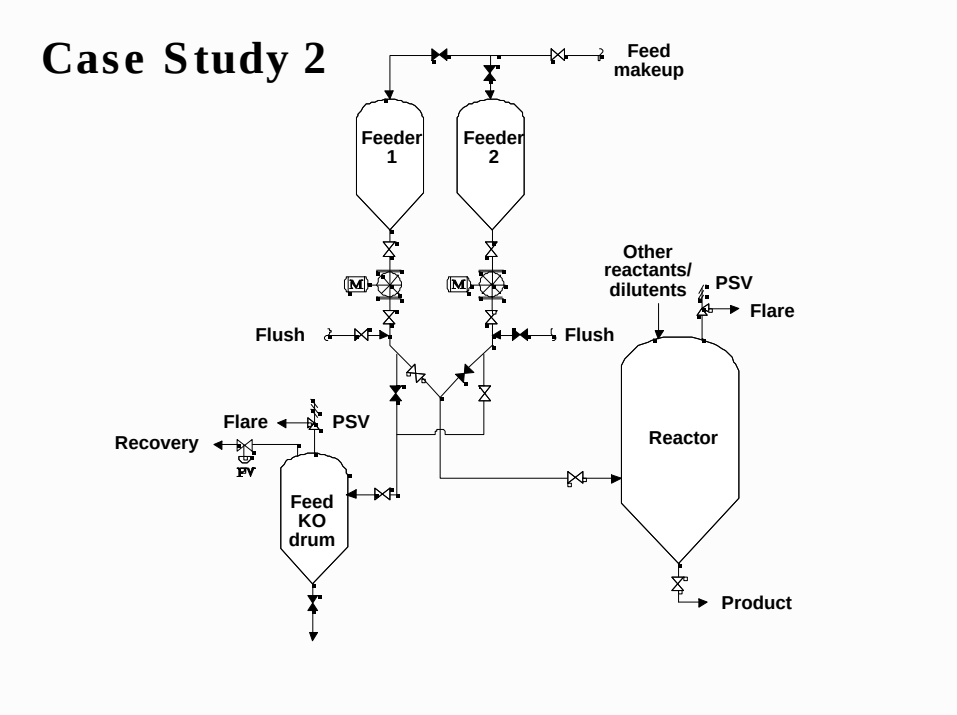
The detailed analysis was stopped at this point, since quantitative results were not necessary to reach a decision to implement the changes recommended.

Case Study 2

Another company had traditionally performed P&ID reviews for new processes only. These reviews used a streamlined form of the HAZOP analysis technique, but did not include operators in the team. In addition, these reviews were not repeated or revalidated in subsequent years. Instead, the company relied upon safety suggestion programs and routine safety audits to identify and correct potential safety hazards. JSAs were performed for a few tasks involving handling of extremely dangerous or toxic materials. Detailed procedures were not written for most nonroutine operations.

After several near misses and accidents, the company completely upgraded its PSM program. Detailed operating and maintenance procedures were written for all nonroutine 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 feed addition system for a reactor. 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.



Step 1 - Human Factors in Process Design

The HAZOP review of the feed addition system considered the deviation "high pressure" in the feed knockout (KO) drum. This low pressure vessel was used to collect a slurry material drained from the high pressure feeder after the feeder was isolated and depressurized, but before it was refilled with new material. One potential cause of overpressurizing the KO drum identified by the PHA team involved the operator failing to close the manual block valve in the drain line to the KO drum, before either pressurizing the line or aligning the feeder to the high pressure reactor. Reverse flow from the reactor, if not detected quickly by the operator, could overpressurize the KO drum. Operator training was identified by the team as the key safeguard protecting against this type of operator error. Although a fairly likely error, the team concluded that any operator would notice this mistake (e.g., by the sound made when the reactor depressurizes through the misaligned drain valve) and respond quickly enough to close either the drain valve or the reactor valve before the KO drum overpressurized. A check valve was suggested for the reactor feed line, but the idea was dropped because this device is ineffective in slurries. The team then deferred recommendation of any design changes until after a review of the procedures.

Another potential cause identified for high pressure in the KO drum involved failing to close the manual block valve in the drain line to the KO drum before establishing a high pressure flush of the feed line. Again, operator training was the primary safeguard protecting against this failure. The PHA team felt this last scenario was very likely, since in this case the flush flow (governed by a flow control valve upstream) could slowly increase, allowing the misaligned valve to go unnoticed until it was too late. After evaluating the effectiveness of the existing safeguards (including high pressure safeguards at the KO drum), the team recommended ensuring that the relief valve on the KO drum was large enough to handle full flow of the high pressure flush.

Step 2 - Human Factors in Procedures

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 overpressurization. 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, the Step 1 recommendation 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.

Step 3 - Human Factors in Management Systems

A review of management issues revealed that (1) procedures were in place and up-to-date, (2) operators were involved in generating the procedures, (3) previous recommendations had been followed, and (4) adequate training resources were provided. Morale was improved by management's attentiveness to operator concerns and by management's commitment to delay startup of the new unit until all PHA recommendations were addressed. One shortcoming noted was the lack of explicit requirements for supervisor involvement in nonroutine operations. The checklist and training safeguards suggested above would be more effective if they were occasionally audited by supervisors or management. The team recommended that a supervisor initial the checklist (recommended in Step 2) at specific critical steps in the procedure (e.g., before the step to open the manual block valve to the reactor).

Step 4 - Detailed Human Reliability Analysis

Because of the potential operator errors identified in the design and procedure review steps (Steps 1 and 2), plant management decided to proceed with a detailed HRA. As part of this effort, a human reliability expert observed several operators performing the tasks associated with switching feeders (isolating, depressurizing, and refilling the feeders) and flushing the feed lines. Results from observing the tasks and evaluating the equipment provided several additional suggestions, including the following:

- Color coding and labeling critical valves to ensure proper selection of the feeder and associated manual block valves
- Including a diagram in the procedure to clearly illustrate which valves to manipulate
- Adding the capability to double block the feed line to the reactor for steps related to decommissioning, such as for maintenance turnarounds
- Developing a checklist for operator use during routine rounds (this checklist should include items related to the feed addition system, such as checking the local level and pressure gauges on the KO drum to guard against leaky block valves)

The human reliability expert agreed that the procedural changes, checklist development, and increased management attention recommended in Steps 1-3 were important to help reduce the likelihood of the specific operator errors identified.

CONCLUSION

Human factors considerations are a vital element of process safety management that can easily be incorporated into popular hazard evaluation methodologies. 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 hazard. The two-step combination of qualitative analyses, possibly followed by a management system evaluation and/or a detailed human reliability analysis (either qualitative or quantitative), as outlined above, is an extremely powerful set of tools for uncovering deficiencies that can lead to human errors. "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 addressing human factors during process hazard analyses.

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3. OSHA Instruction CPL 2-2.45A, Compliance Guidelines and Enforcement Procedures (for PSM, 29 CFR 1910.119), Directorate of Compliance Programs, September 28, 1992.

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5. *A Manager's Guide to Reducing Human Errors*, Chemical Manufacturers Association, Washington, DC, 1990.

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11. Program Quality Verification of Process Hazard Analyses, Henry C. Woodcock, OSHA, 1993 (for instructional purposes only).

12. A similar approach for analysis of procedures is discussed in Chapter 8 of W. Hammer's book, *Occupational Safety Management and Engineering*, 3rd Ed., Prentice Hall, 1985.

13. A HAZOP approach to analyzing procedural steps is demonstrated in H. E. Kongso's article, "Application of a Guide to Analysis of Occupational Hazards in the Danish Iron and Chemical Industry," *International Conference on Hazard Identification and Risk Analysis, Human Factors and Human Reliability in Process Safety*, AIChE, Center for Chemical Process Safety, New York, 1992.

EXHIBIT

Human Factors Engineering Checklist

Item No.	Question
	Housekeeping and General Work Environment
1.1	Are working areas generally clean?
1.2	Are adequate signs posted in cleanup and maintenance areas?
1.3	Is the ambient temperature normally within comfortable bounds?
1.4	Is noise maintained at a tolerable level?
1.5	Is the lighting sufficient for all facility operations?
1.6	Is the general environment conducive to efficient performance?
	Accessibility/Availability of Controls and Equipment
2.1	Are adequate supplies of protective gear readily available for routine and emergency use?
2.2	Is communications equipment adequate and easily accessible? How would others know that a worker is incapacitated in the process area?
2.3	Are the right tools available and used when needed?
2.4	Are special tools required to perform any tasks safely or efficiently?
2.5	What steps are taken to identify and provide special tools?
2.6	Is the whole workplace arranged so that the workers can maintain a good working posture and perform a variety of movements?
2.7	Are all controls accessible?
2.8	Is access adequate for routine operation and maintenance of all equipment?
	Component Labeling
3.1	Is all important equipment (vessels, pipes, valves, instruments, controls, etc.) clearly and unambiguously labeled?

Item No.	Question
3.2	Does the labeling program include components (e.g., small valves) that are mentioned in the procedures even if they are not assigned an equipment number?
3.3	Are plant instruments and controls clearly labeled?
3.4	Are the labels accurate?
3.5	Who is responsible for maintaining and updating the labels?
3.6	Are emergency exit and response signs clearly visible and easily understood?
	Feedback/Displays
4.1	Is adequate information about normal and upset process conditions displayed in the control room?
4.2	Are the controls and displays arranged logically to match the expectations of the operators?
4.3	Are the displays adequately visible from all relevant working positions?
4.4	Do separate displays present information in a consistent manner?
4.5	Is all significant operating information logically arranged?
4.6	Are related displays and controls grouped together?
4.7	Is the information displayed in ways the operators can understand?
4.8	Are the operators provided with enough information to diagnose an upset when an alarm sounds?
4.9	Are the alarms displayed by priority? Are critical safety alarms separate from control alarms?
4.10	Is an alarm summary permanently on display?
4.11	What kinds of calculations do the operators perform when reading displays, and how are these calculations checked?
4.12	Do the displays provide an adequate view of the entire process as well as essential details of individual systems?
4.13	Do the displays give rapid feedback for all operational actions?

Item No.	Question
4.14	Do all mimic displays (board or screen) match the actual equipment configuration?
	Controls
5.1	Is the layout of the consoles logical, consistent, and effective?
5.2	Are the controls distinguishable and easy to use?
5.3	Do any controls violate strong expectations (color, direction of movement, etc.)?
5.4	Do the control panel layouts reflect the functional aspects of the process or equipment?
5.5	Does the control arrangement logically follow the normal sequence of operation?
5.6	What are the consequences of operator intervention in computer-controlled processes?
5.7	Are any process variables difficult to control with the existing equipment?
5.8	Does the control logic seem adequate?
5.9	Is there a dedicated emergency shutdown panel, and where is it located?
	Workload and Stress Factors
6.1	Are the operators only in the control room or do they work in a variety of locations?
6.2	How many manual adjustments must a worker perform during normal and emergency operations?
6.3	What is the normal operating shift duration? Is this duration appropriate based on its impact on alertness/fatigue?
6.4	How many extra hours must an operator work if his/her relief fails to show up?
6.5	How many hours do operators/maintenance personnel typically work on a shift during startup or turnarounds?
6.6	Has the operator's mobility been considered in selecting the design of protective gear for certain tasks, including emergency response?
	General Issues
7.1	Has the human/process interface ever undergone a human factors analysis?

Item No.	Question
7.2	Is there a formal mechanism for correcting human factors deficiencies identified by the operators?
7.3	How are designers made aware of human factors problems so they can improve future designs?
7.4	What means are provided to allow personnel to compensate for errors? Can personnel detect an error they or someone else makes with sufficient time to correct the error?
7.5	Have the operators made any modifications to the displays, controls, or equipment to better suit their needs?
7.6	Is the control room adequately located relative to the process?