LAYERS OF PROTECTION ANALYSIS FOR HUMAN FACTORS (LOPA-HF): AN IMPROVED METHOD FOR ADDRESSING HUMAN FAILURES IN PROCESS HAZARD ANALYSIS

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Abstract

Process hazard analysis (PHA) performed to meet the requirements of OSHA and EPA regulations must address human failures and human factors. Unfortunately, this has been difficult to accomplish and, consequently, PHA often focuses instead on equipment failures and external events. This is unfortunate since it is well established that human failures are the dominant contributors to risk from processes. An improved approach for identifying human failures in PHA and the human factors that determine their likelihood is presented in this paper. The method described is an extension of the simplified risk assessment technique, Layers of Protection Analysis (LOPA).

Introduction

Process hazard analysis (PHA) is used to identify *hazard scenarios* for a process. These are specific, unplanned events or sequences of events that have an undesirable consequence resulting from the realization of a hazard. Processes can contain many different types of hazards, for example, chemical, e.g. toxic materials; physical, e.g. high pressure; mechanical, e.g. rotating equipment; electrical, e.g. high voltage power supply, etc. While PHA can be used to address any type of hazard, typically, in process safety, it is used to address the major hazards of fires, explosions and toxic releases.

For PHAs performed to meet the requirements of OSHA's Process Safety Management (PSM) standard, 29 CFR 1910.119 and EPA's Risk Management Program (RMP) rule, 40 CFR Part 68, it is required that "the PHA shall address human factors". It is generally accepted that PHA must:

- Account for human failure as a cause of hazard scenarios and,

- Consider factors that impact human performance.

It is important that PHA address human factors since human failures are believed to dominate the risk in processes(1). OSHA is concerned about such human factors as the accessibility, clarity and usability of controls and instrumentation; task overload; and work schedules. The influence on the performance of people of both the person-process and person-person interfaces must be considered.

PHA teams brainstorm the causes of hazard scenarios. They may be human failures, equipment failures or external events. Current practice is for the PHA team to identify the principal factors that affect the human failures identified by using checklists. Unfortunately, this approach has several disadvantages:

- If the checklists are kept simple, human factors may be missed.
- Lengthy checklists are cumbersome to use and quickly become repetitive and tiresome.
- Checklist approaches do not provide much structure or guidance for the human factors analysis.
- PHA team members have difficulty using such checklists.
- Checklists produce only a simplistic analysis of human factors.

Consequently, this approach is susceptible to producing inadequate results. An improved approach, called Layers of Protection Analysis for Human Factors (LOPA-HF), has been developed(2).

LOPA-HF

LOPA-HF utilizes the framework of Layers of Protection Analysis (LOPA)(3). LOPA is a simplified risk assessment method. It provides an objective, rational and reproducible method of evaluating scenario risk and comparing it with risk tolerance criteria to decide if existing safeguards are adequate, and if additional safeguards are needed. LOPA can be viewed as an extension of PHA.

LOPA-HF analyzes the impact of human failures and human factors on process risk by examining how people are involved with individual hazard scenarios. Figure 1 depicts the constituent elements of a hazard scenario. The initiating event can be an equipment failure, human failure or external event. These are the “causes” of a PHA study such as the Hazard and Operability (HAZOP) method. Intermediate events can include operator actions as well as automated responses of the process control and safety systems. Many intermediate events are safeguards that can prevent, detect, or mitigate the scenarios. LOPA typically considers safeguards that are Independent Protection Layers (IPLs), defined as those whose failure is independent of any other failures involved in the scenario. This provides a conservative analysis.

Enabling events or conditions can include human factors issues such as an error-inducing environment, for example, work overload, or human failures such as miscalibrated instruments. The consequence is the effect of the scenario on people (on-site or off-site), property (on-site or off-site), the process (downtime, product quality, etc.), the environment, etc.

In order to address human factors and failures properly in PHA, their impact on each individual element of a hazard scenario must be determined, namely:

- the initiating event
- intermediate events
- enabling events or conditions
- the consequence

Human factors that influence each part of the hazard scenario are identified using simple issues lists. These lists are prepared in advance and tailored for each situation that may be encountered. They provide structure, guidance and completeness for the analysis. The approach allows analysts to focus quickly on the principal human factors issues that influence a scenario without the need to wade through a PHA human factors checklist.

The way this is accomplished in LOPA-HF is described below for each scenario element for an example involving unloading hexane from a tank truck into a storage tank using a pump[(2)]. In this example, the storage tank is surrounded by a dike. The storage tank is equipped with a level indicator and a high level alarm that annunciates in the control room. Two operators are typically involved in the unloading operation. A field operator initiates the transfer with the truck driver, and a control room operator monitors and operates various process functions from a computer interface. The truck driver is required to supervise the transfer. The scenario used in the example is overfilling the hexane storage tank with the spill not contained by the dike.

<u>Initiating Event</u>

Initiating events that are human failures can arise from various human factors. In LOPA-HF, analysts use simple Issues Lists to identify the dominant human factors contributors to the failure rate, existing protective measures and any recommendations for additional protective measures. This information is recorded in a LOPA-HF worksheet (see Figure 2). The initiating event considered for the example is “Delivery of hexane when there is insufficient room in the storage tank due to a failure in the inventory control system”.

For this initiating event, the LOPA-HF analysts consider items in an Issues List, such as:

HUMAN FACTORS ISSUES LIST
Incorrect Action By Person
Work overload/underload
Insufficient training
Inadequate skills
Inadequate resources
Inadequate procedures
Inadequate labeling
Equipment not easily operable
Displays/controls not visible/heard
Displays/controls confusing
Displays/controls not accessible/usable
Inadequate communications
Environmental issues (temperature, humidity, light, noise, distractions)
Error (wrong action, no specific reason)
Mistake (wrong action, misunderstood)
Other?

These Issues Lists are provided for various types of human failures that may be initiating events and are typically standardized so that LOPA-HF analysts become accustomed to working with them, although they can also be customized for particular types of processes and/or specific companies' cultures. LOPA-HF analysts may flag more than one applicable issue.

The human factors identified as contributing to the initiating event for the example were a mistake in ordering due to work overload and a mistake in gaging the tank contents due to inadequate training (see Figure 2).

The LOPA-HF analysts next consider protective measures that may be in place for the initiating event. They consider the items on an Issues List, such as:

PROTECTIVE MEASURES ISSUES LIST
Incorrect Action by Person
Training
Procedures
Equipment labeled
Check
Other?

Existing protective measures for the example were the unloading procedures, the level indicator and the high level alarm (see Figure 2).

The LOPA-HF analysts next consider whether additional protective measures are needed. The LOPA-HF analysts use the Protective Measures Issues List as a guide. Recommendations made in the example were to improve training of the operators and the truck driver, and consider installation of a high level trip for the feed pump and an inlet shutdown valve to help prevent overfilling accidents (see Figure 2).

Initiating events resulting from equipment failures and external events may also have human factors contributors. For example, a pump may fail off due to inadequate maintenance or an object may be dropped from a crane and rupture a line due to inadequate training of the crane operator. Human factors issues for these types of initiating events are handled in a similar way to human failures.

Independent Protection Layers

IPLs may be automated systems that operate without human involvement, manual systems triggered by alarms, or a combination of both. Failure rates of both types of systems can be influenced by human factors. The analysis of IPLs is similar to that for initiating events. The LOPA-HF analysts consider the items on the “Incorrect Action By Person” Issues List that could cause the failure of each IPL, the protective measures that may be in place already, and those that may be needed. The LOPA-HF worksheet is completed for each IPL in the scenario.

For the example, IPLs are the dike and operator response to alarms (Figure 2). There were no human factors issues identified for the dike. In the case of the operator response to alarms, an inadequately designed computer control interface was identified as a pertinent human factor. The level indicator was identified as weak protection and the recommendation to install an automated trip was made again.

Enabling Events/Conditions

Enabling events/conditions do not directly cause the hazard scenario. They make possible another event in the scenario. They must be present or active for the scenario to proceed, for example, a process being in a particular mode, phase or step. Enabling events/conditions frequently can be influenced by human factors, for example, disabled alarms. Human failures such as incorrect maintenance may leave the process in an unsafe state that may not be detected until an initiating event occurs.

LOPA-HF addresses enabling events/conditions in a similar way to initiating events and IPLs. However, there is an additional first step of identifying applicable enabling events/conditions since they may not have been identified or considered in the PHA. This is done by reviewing an Issues List of enabling events/conditions, for example:

ENABLING EVENTS/CONDITIONS ISSUES LIST
Installation of incorrect seals, gaskets, etc.
Process left in incorrect state after turnaround, maintenance, sampling, or other operation
Disabled alarms
Overrides
LOTO not effected
Startup/shutdown/operating/emergency mode, etc.
Other?

The LOPA-HF analysts consider the items on a Human Factors Issues List for the type of enabling events/conditions applicable to identify those human factors that could result in the enabling events/conditions. They also identify protective measures that may be in place already by reviewing a “Protective Measures” Issues List and recommend those that may be needed. The LOPA-HF worksheet is completed for the enabling events/conditions in the scenario.

For the example, the enabling condition of “high temperature alarm overridden” was identified for the scenario (see Figure 2). A human factor impacting this condition was the alarm left inoperable after process adjustments owing to the lack of a check. There were no existing protective measures. Therefore, a recommendation was made to revise the process optimization procedure to confirm operation of the alarm after completion of adjustments.

Consequence

LOPA-HF identifies human factors issues and protective measures for consequences by using Issues Lists for the appropriate type of consequence.

The consequence of the scenario for the example was “hexane release outside the dike that could result in fire and/or injury”. Human factors impacts identified for the consequence were the lack of awareness of this hazard by process personnel and the lack of a smoking prohibition outside the area of the tank farm where the spill could reach (see Figure 2). No existing protective measures were identified. Recommendations were made to address this hazard in the initial and refresher training for all affected personnel and to restrict smoking to designated locations.

Risk-Based Decision Making With LOPA-HF

PHA uses engineering judgment to identify the possible need for additional safeguards based on the adequacy of existing safeguards in achieving an acceptable, or tolerable, level of risk. It has been found, in practice, that this subjective approach can lead to disagreements, and possibly inappropriate measures to reduce risk. This led to the development of LOPA[3] so that decisions on risk remediation measures could be made more objectively by estimating scenario risk and implementing recommendations to achieve specified risk tolerance criteria. Similarly, recommendations relating to human factors resulting from a LOPA-HF study can be used to assist in reaching a tolerable risk level.

To approximate the risk of a scenario, LOPA typically uses order of magnitude categories for the initiating event frequency, the likelihood of failure of IPLs and the consequence severity. Scenario frequency is determined by combining the initiating event frequency, IPL failure probabilities, and probabilities of enabling events / conditions. Scenario risk is determined by combining scenario frequency and consequence severity and is compared to risk tolerance criteria to determine if additional risk reduction is required to reach a tolerable level.

Evaluation of Human Failure Probabilities in LOPA-HF

Once the human factors issues that adversely affect the performance of the constituent elements of the hazard scenario have been identified, the contributions of corrective actions to reducing the scenario likelihood can be assessed. Their effects will combine together through reductions in the likelihoods of the initiating event, intermediate events, enabling events/conditions and consequences.

Human failure probabilities (HFP) can be used to represent the probability of failures by people such as operators when faced with the need to act. They address both inaction and incorrect action (errors of omission and commission). They are analogous to the Probability of Failure on Demand (PFD) used for IPLs in standard LOPA. The PFD is the probability the IPL fails to perform its required safety function on demand.

Alternatively, an approach can be used in which credits are assigned for each type of human factors improvement according to its effectiveness. The approach involves assigning credits to human factors recommendations so that, for example, improvement in the accessibility of a control is worth 3 credits and improved training is worth 2 credits. When aggregated, each 10 credits of improvements contributes an order of magnitude reduction in the scenario likelihood. A target risk level can be met by accumulating sufficient credits and the analysts can decide which of various possible combinations are preferred. Standard tables of credits can be established using human performance data.

The use of credits can be demonstrated with the previous example. The recommendations for human factors improvements identified by LOPA-HF are shown in the table below.

SCENARIO ELEMENT	EVENT	RECOMMENDATIONS	CREDITS
Initiating event	Delivery of hexane when there is insufficient room in the storage tank due to a failure in the inventory control system.	Improve training of the operators and the truck driver.	2
		Consider installing a high level trip for the feed pump and an inlet shutdown valve to help prevent overfilling accidents.	4 + 4
IPL1	Dike	None	-
IPL2	Operator response to alarms	Consider installing a high level trip for the feed pump and an inlet shutdown valve to help prevent overfilling accidents.	4 + 4
Enabling condition	High temperature alarm overridden	Revise the process optimization procedure to confirm operation of the alarm after completion of adjustments.	3
Consequence	Hexane release outside the dike that could result in fire and/or injury.	Address this hazard in the initial and refresher training for all affected personnel.	2
		Restrict smoking to designated locations.	1

If we assume that standard LOPA identified the need for a reduction in the scenario likelihood by 1×10^{-1} then, if we want to accomplish this through human factors improvements, we must find 10 human factors credits. Credits have been assigned to each recommended improvement in the table. Various choices are possible to reach 10 credits. For example, the company may wish to improve training of the operators and the truck driver (2 credits) and install a high level trip for the feed pump and an inlet shutdown valve (8 credits). Other alternatives are also possible.

Conclusions

LOPA-HF offers a number of advantages over the conventional checklist approach for addressing human factors issues in PHA. These include:

- Considers a wide range of human factors issues but in an organized and manageable way using simple Issues Lists.
- Focuses on the specific human factors issues that contribute to the risk
- Provides a structured analysis.
- Builds on PHA.
- Can be performed using qualitative methods but can be refined using quantitative analysis where high risk levels may warrant.
- Easily used by people experienced with PHA or LOPA .

The analysis of human factors for hazard scenarios using LOPA-HF can be performed as an adjunct to a standard LOPA study or independently.

References

1) Baybutt, P. "Human Factors in Process Safety and Risk Management: Needs for Models, Tools and Techniques", P. Baybutt, Proceedings of the International Workshop on Human Factors in Offshore Operations, US Minerals Management Service, New Orleans, pps 412 - 433 (December, 1996).

2) Baybutt, P. "Layers of Protection Analysis for Human Factors (LOPA-HF), Process Safety Progress, 22, 119, 2002.

3) Layer of Protection Analysis, Simplified Process Risk Assessment, AIChE/CCPS, 2001.

Figure 1. Constituent Elements of a Hazard Scenario

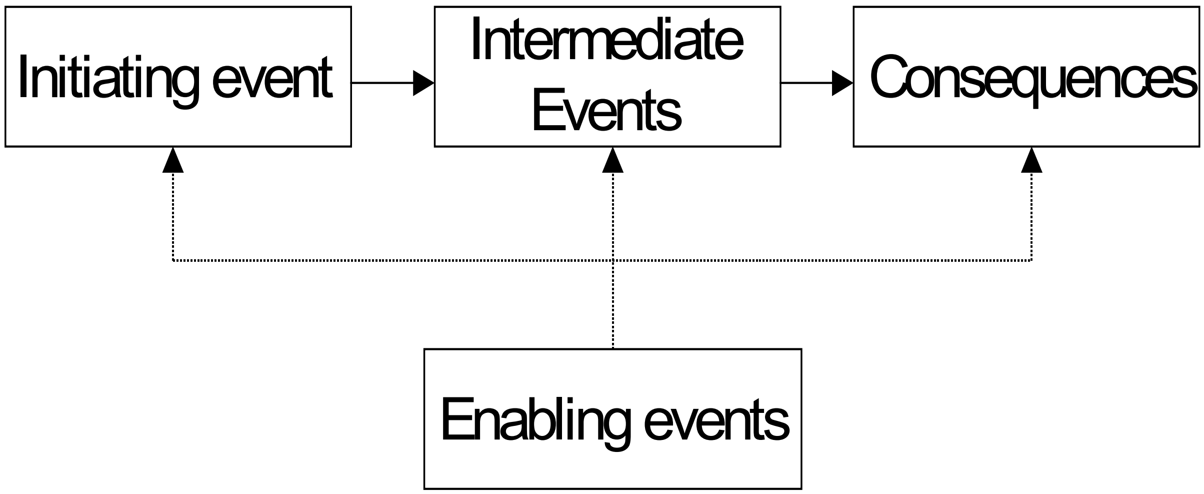

Figure 2. Example of Completed LOPA-HF Worksheet

<table>
<tr><td colspan="2">LOPA - HF WORKSHEET</td></tr>
<tr><td colspan="2">Scenario Description: Overfilling the hexane storage tank with the spill not contained by the dike.</td></tr>
<tr><td colspan="2">Initiating event: Delivery of hexane when there is insufficient room in the storage tank due to a failure in the inventory control system.</td></tr>
<tr><td>Human Factors:</td><td>Mistake in ordering due to work overload.
Mistake in gaging the tank contents due to inadequate training.</td></tr>
<tr><td>Protective Measures:</td><td>Unloading procedures.
Level indicator.
High level alarm.</td></tr>
<tr><td>Recommendations:</td><td>Improve training of the operators and the truck driver.
Consider installing a high level trip for the feed pump and an inlet shutdown valve to help prevent overfilling accidents.</td></tr>
<tr><td colspan="2">IPL1: Dike</td></tr>
<tr><td>Human Factors:</td><td>None</td></tr>
<tr><td>Protective Measures:</td><td>N/A</td></tr>
<tr><td>Recommendations:</td><td>N/A</td></tr>
<tr><td colspan="2">IPL2: Operator response to alarms</td></tr>
<tr><td>Human Factors:</td><td>Inadequately designed computer control interface.</td></tr>
<tr><td>Protective Measures:</td><td>Level indicator (weak)</td></tr>
<tr><td>Recommendations:</td><td>Consider installing a high level trip for the feed pump and an inlet shutdown valve to help prevent overfilling accidents.</td></tr>
<tr><td colspan="2">Enabling event/condition: High temperature alarm overridden</td></tr>
<tr><td>Human Factors:</td><td>Alarm left inoperable after process adjustments owing to the lack of a check.</td></tr>
<tr><td>Protective Measures:</td><td>None.</td></tr>
</table>

Recommendations:	Revise the process optimization procedure to confirm operation of the alarm after completion of adjustments.
Consequence: Hexane release outside the dike that could result in fire and/or injury.	
Human Factors:	Lack of awareness of this hazard by the process personnel. Lack of a smoking prohibition outside the area of the tank farm where the spill could reach.
Protective Measures:	None.
Recommendations:	Address this hazard in the initial and refresher training for all affected personnel. Restrict smoking to designated locations.