HAZOP Tutorial

Introduction

A Hazard and Operability Study, commonly referred to as a HAZOP study, is a structured analysis in process design to identify potential process safety incidents that a facility is vulnerable to. A HAZOP study uses guide words to systematically determine possible failures that could result from operation of equipment outside of design conditions. This out of design condition can occur due to possible mal-operation or mal-function of individual items of equipment, instruments, or control system.

HAZOP studies are routinely performed on:

- New plants where the design is nearly firm and documented
- Existing plants as a part of a periodic hazard analysis or a management of change process

A list of necessary actions and recommendations will be prepared in the form of HAZOP report in order to improve the safety and mitigate the consequences of hazards.

This tutorial includes a HAZOP study for the explosion at the Caribbean Petroleum Company (CAPECO), which has been used in the first Material & Energy Balances Safety Module. A HAZOP study could have exposed flaws in the design and prevented the incident.

HAZOP Process

Step 1: Identify System

The first step in a HAZOP study is to select a piece of equipment or a section in which deviations from design set points are evaluated. Figure 1 shows a tank selected as the piece of equipment to analyze.

Figure 1. Select Equipment and Process Parameter

Step 2: Use Guide Words and Process Parameter

The next step is to identify each process parameter (e.g. flow rate) that is relevant to that equipment's operation. With the process parameter in mind, *Guide Words* are used to systematically consider all abnormal operating scenarios. Appropriate Guide Words must be systematically applied to the process parameter to analyze whether or not the scenario is possible. The HAZOP guide words are shown below in Table 1.

Table 1. HAZOP Guide Words and Definitions

No.	Guide Word	Meaning	Process Parameters	Example
1	No or Not	The complete negation of the intention from the design	Flow	*No* flow to Tank when there should be
2	More	There is a quantitative increase in whatever is being identified	Flow, Temp, Pressure, Level, Concentration	Gas Temperature *more* than normal operation
3	Less	There is a quantitative decrease in whatever is being identified	Flow, Temp, Pressure, Level, Concentration	Tank Level *less* than normal operation
4	As Well As	There is a qualitative modification, or a qualitative increase	Quality	-Impurities *as well as* expected composition -Extra phase present (gas *as well as* liquid) -Additional product formation
5	Part Of	There is a qualitative modification or decrease	Quality	Pump reaching *part of* full speed Another scenario: component missing
6	Reverse	Opposite of the design intent	Flow, Reaction	*Reverse* flow through check valve *Reverse* chemical reaction,
7	Other Than	There was a complete substitution	Quality	Acid added *other than* water
8	Early	Something occurred earlier than intended (clock time)	Applicable mainly for Batch Process	Cooling water started *earlier* than intended time
9	Later	Something occurred later than intended (clock time)	Applicable mainly for Batch Process	Cooling water started *later* than intended time
10	Before	A step was performed before it should have in the process sequence	Applicable mainly for Batch Process	Cooling step performed *before* heating step
11	After	A step was performed after it should have in the process sequence	Applicable mainly for Batch Process	Heating step performed *after* cooling step
12	Other	Encompasses general issues not well described by the other guide words	Start-up/Shut-down, Corrosion, Leak, Utility failure etc.	Tank Corrosion, Reboiler Changeover, Leak from valve, Power failure

In Figure 1, one of the process parameters is the inlet flow rate. The relevant guide words that can be applied to flow rate are "No, More, Less, Reverse". Other process parameters may include temperature, pressure, flow rate, pH, concentration, viscosity, volume, etc.

Using the guide word and parameter, we can analyze the deviations from normal operating conditions that the equipment could incur. *A deviation is any divergence from normal operating behavior.*

Guide Word + Parameter = Deviation

Here are some quick examples:

Guide Word	Parameter	Deviation
More	Pressure	More Pressure
Less	Level	Less level
No	Flow	No flow

Note: Not every guide word will apply to each scenario. For example, there is no physical meaning to a temperature reading being related to the guide word "part of".

Next step is to look into the Cause, Consequence, Safeguards provided, and any additional safeguard required.

<u>Step 3: Identify Cause</u>

The HAZOP team identifies the potential reasons which would result in the variation in process parameter. There could be several causes which can lead to a variation. All such causes need to be identified.

Table 2. Typical Causes of Deviations in Process Parameters

Guide word + Process Parameter = Deviation	**Typical Causes**
No flow	Valve Closed; Pump failure; Incorrect pressure difference, Major leakage etc.
Less flow	Pump cavitation, Fouling, partial blockage etc.
More flow	Valve full open, Increased pump speed, Increased pressure differential etc.
Reverse flow	Pump trip, Incorrect differential pressure, check valve passing
More (High) Pressure	Closed discharge, pressure control failure, excessive reboiling, loss of reflux
Less (Low) pressure	Pump/compressor failure
More (High) temperature	Heater control failure, Runaway reaction
Less (Low) temperature	Loss of heating, Fouled exchanger
More level	Level control failure, More input than output
Less level	Level control failure, Less input than output
Other Composition *Than* Usual	Leaking exchanger tubes, Feed Change, Wrong additives, additional reactions

Step 4: Identify Consequences

The HAZOP team identifies potential results of a deviation on the system in case it occurs. The result could be potential damage to equipment, personal injury, environmental impact. While writing consequences, the team does not consider any safeguards to be functioning.

Example: "High level (*deviation*) in tank leads to overfill of tank causing release of flammable material, fire and explosion." While writing consequences, any existing safeguards (e.g. high-level alarms, overfill protection system) are assumed to be not working.

Step 5: Identify Safeguards

The HAZOP team looks into the existing system to identify design and operating features **which have been implemented** to prevent the deviation, cause, or consequence. Safeguards could be an engineering or procedural barrier. All the existing protections should be identified and listed in the table.

Common Examples:

- Process alarms
- Standard operating procedure (SOP)
- Pressure safety valves

Step 6: Provide Recommendations

The HAZOP team evaluates whether the available safeguards are adequate to protect the system from proceeding to undesirable consequences. The number of safeguards required are calculated based on a risk matrix (not considered in this tutorial). If the existing safeguards are found inadequate, HAZOP team provides action plans to prevent/sense/mitigate the hazard/consequence. For the simplicity, we will list all the recommendations in our HAZOP study.

Examples:

- Addition of a trip action
- Adding a backup cooling water system in a reactor in case existing cooling water supply (safeguard) stops
- Overfill protection system in tanks

Note: *Safeguards* are protections in place while *Recommendations* are a lists of protections that should be added. Safeguards and Recommendations are different.

HAZOP Implementation

The HAZOP study forces engineers to consider all deviations from normal operating conditions and the associated hazards. After completing a HAZOP study, the next step is to implement protections or safeguards. Each safeguard must be capable of independently preventing the deviation.

While HAZOP is a qualitative study, a Layer of Protection Analysis (LOPA) is semi-quantitative. Engineers implement protections to the equipment that prevent the mathematically highest impact scenarios in terms of risk and probability. Please see the LOPA Tutorial for more information here.

A typical HAZOP worksheet will look like this:

GUIDEWORD + PARAMETER = DEVIATION	CAUSES	CONSEQUENCES	SAFEGUARDS	RECOMMENDATIONS

Note: Following *causes* are not considered in HAZOP study:

1. Simultaneous occurring of two unrelated incidents is not considered due to very low probability (e.g. more reactant level and failure of cooling jacket in a reactor)

2. Simultaneous failure of more than one independent protection devices is not considered due to low probability (e.g. simultaneous failure of high-level alarm and overfill protection system)

3. Natural Calamity (e.g. Earthquake, Flood, Cyclones etc.)

4. Sabotage

Note: An independent failure is one that does not influence the occurrence of a second failure and vice versa. For example, a pump and level transmitter could both fail on their own while a process in is operation. The failure of the pump did not cause the failure of the level transmitter.

While completing a HAZOP, please consider the following:

1. Failure of pressure safety valves/rupture discs are **Not** taken as a cause due to them being the last layer of defense. Pressure safety valves shall be considered as a safeguard.
2. Design related issues are **Not** considered as a cause because it is assumed that design calculations are correct. (e.g. incorrect line sizes in original designs)
3. It is assumed that all the equipment and control systems are working as per design intent. (e.g. we don't take incorrect pressure setpoints of relief valve)
4. In the case of multiple units of equipment (e.g. valves/Reboiler/Pumps), ensure to mention the equipment name defined in the figure (e.g. Valve X1, pump Y1) for clarification.
5. It is also possible that there is no safeguard present for a system. In this case, specify "None" in "Safeguard" column.
6. Standby equipment (pumps, reboilers etc.) can be considered as safeguards in the event of failure of existing equipment. This is because standby equipment can be taken inline to prevent any economic penalty or hazardous situation.
7. One "Deviation" can be a cause of another "Deviation" (e.g. *More* flow can be a cause of *More* level)
8. A protection system can be a cause and a safeguard for different cases. (e.g. level transmitter failure can be a cause for *high* level, but a level transmitter can act as safeguard in case of *more* flow)
9. Specify only those causes which can independently lead to a "Deviation" (e.g. a closed tank outlet valve and *more* inlet flow can independently lead to *high* tank level)
10. Standard Operating Procedure, if available, can be taken as safeguard when there is manual operation.
11. Do not consider cases where two unrelated/independent causes can simultaneously occur.

HAZOP Study for CAPECO

In the CAPECO explosion, the main gasoline storage tank was full, so an additional shipment of gasoline had to be stored in four smaller tanks using a highly manual process. One of the tanks had a broken level transmitter so "fill time" was manually calculated, and unfortunately overestimated. The tank liquid overfilled and created a gasoline vapor plume, which found a spark and rapidly exploded. Watch the video here: https://www.youtube.com/watch?v=41QMaJqxqIo and view the incident report here: https://www.csb.gov/file.aspx?DocumentId=5965

This section will investigate how a HAZOP study performed at the CAPECO facility could have exposed flaws in the facility's protective systems. Exposing these hazards may have resulted in actions to close gaps and prevent the tank overfill that resulted in the catastrophic explosion.

We will use Figure 2 below to carry out a HAZOP for the CAPECO explosion. We will consider a steady state scenario where gasoline was transferred *from* Tanker Ship *to* Tank 409 through a block valve X1. Pump Y1 was operating and withdrawing liquid from Tank 409. To monitor Tank 409 level, a level gauge and a level transmitter was installed.

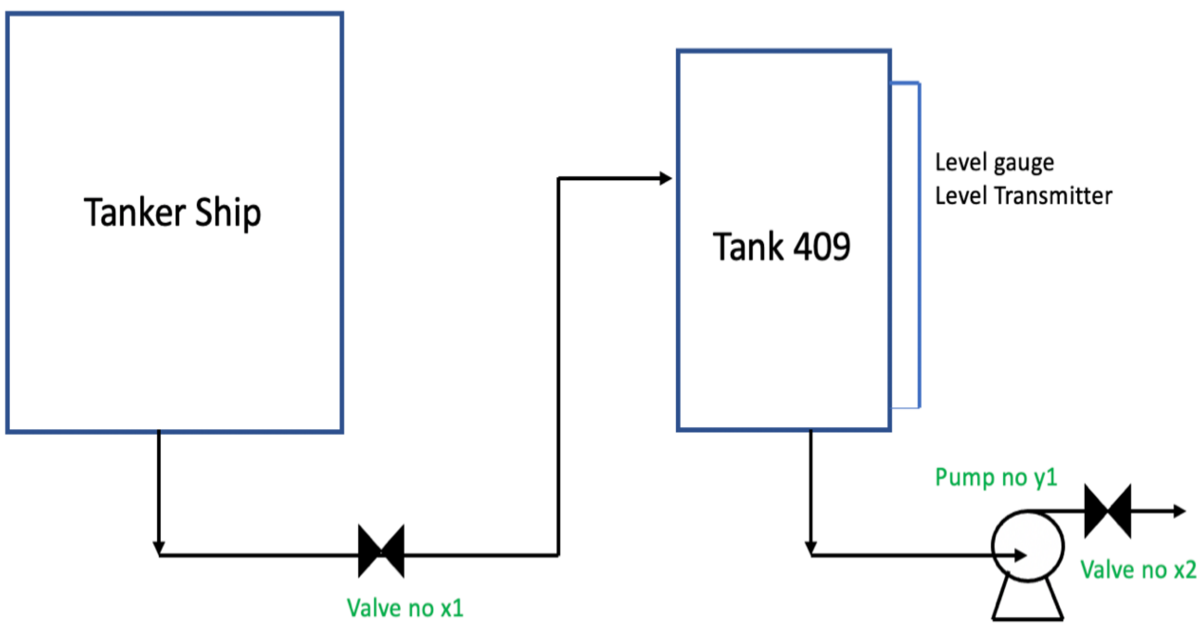

Figure 2: Simplified Process Flow Diagram

1. *Identify System*

Consider the system to be the secondary gasoline storage tank 409. This vessel is the one that overfilled and resulted in the explosion. While the system being considered is Tank 409, the surrounding valves X1 and X2 along with pump Y1 will be important for considering causes of different deviations for this system.

2. Choose a Guide Word and process parameter

We illustrate two scenarios below: (1) *no* flow and (2) *more* flow

#1 Guide Word: **No**, Process Parameter: **Flow**

The engineer would consider a scenario where there was *no* flow from the tanker vessel to the storage tank. They would need to assess what does a *no* flow scenario means, what could have caused the scenario, and what are the consequences and potential safety implications. After determining the potential consequences, the engineer would look to see what safeguards were in place to prevent them and what further actions could be taken to ensure safety.

#2 Guide Word: **More**, Process Parameter: **Flow**

The deviation *more* flow would describe an incident where more fluid than expected was offloaded into the tank. This scenario was the one that occurred in the CAPECO incident.

3. Go to Step 2, and repeat for all relevant guide words

The interactive HAZOP worksheet for this example can be seen here.

4. Write a short analysis after completing the HAZOP

Analysis: This tank was not equipped with an automatic overfill protection system that would have stopped the flow as soon as it detected overfill or diverted the flow to another tank. After considering the consequences caused by *more* flow, the engineers at the CAPECO facility may have determined that their facility is ill-equipped to measure and react to additional flow.

5. Gap Identification & Next Steps

Once we have identified all hazards, the next step is to apply a Layers of Protection Analysis (LOPA) to the highest risk and impact scenario. These safeguards could include any of the following:

1. Functional level transmitter communicating with an automatic flow diverter
2. Alarm system alerting when there is a high level in the tank
3. Alternative secondary containment besides the diked region
4. Gas detector in the vicinity of the tank farm
5. Total organic carbon composition detectors on inlet to water treatment facility

If implemented, each of these layers of protection could have prevented this event from occurring. More information on how to conduct a LOPA can be found in the LOPA Tutorial here.

References

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[4] Haugen, Stein, and Marvin Rausand. "Risk Assessment." 9. HAZOP. Department of Production and Quality Engineering. Norwegian University of Science and Technology, Department of Production and Quality Engineering. Norwegian University of Science and Technology, https://www.ntnu.edu/documents/624876/1277591044/chapt09-hazop.pdf/9e85796d-dc7f-41f8-9f04-9e13a4ce3893

Prepared in collaboration with Maeve Gillis