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INTRODUCTION

Scope

The identification of hazards in chemical plants has become increasingly important. Not only have plants become larger and more complex, but some countries now have regulations requiring that some form of formal hazard identification be performed. Environmental regulations have been tightened as the public has become aware of the dangers posed by large chemical plants. One of the most popular techniques for hazard identification is a hazard and operability study (HAZOP).

A hazard and operability study (or HAZOP) is a systematic, critical examination by a team of the engineering and operating personnel with the intention to assess the hazard potential of individual items of equipment and the consequential effects on the facility as a whole. The essential feature of the HAZOP Study approach is to review process drawings and/or procedures in a series of meetings, during which a multidisciplinary team uses a defined protocol to methodically evaluate the significance of deviations from the normal design intention.

The Hazard and Operability (HAZOP) Analysis technique is based on the principle that several experts with different backgrounds can interact in a creative, systematic fashion and identify more problems when working together, than when working separately and combining their results. The HAZOP study focuses on specific points of the process or operation called “study nodes,” process sections, or operating steps. The HAZOP procedure involves taking a full description of the process and systematically questioning every part of it to establish how deviations from the design intent can have a negative effect upon the safe and efficient operation of the plant.

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General Design Consideration

A hazard and operability study (or HAZOP) is a systematic, critical examination by a team of the engineering and operating intentions of a process to assess the hazard potential of mal-operation or mal-function of individual items of equipment and the consequential effects on the facility as a whole. By the word, hazard is any operation that could possibly cause a release of toxic, flammable or explosive chemicals or any action that could result in injury to personnel. Operability is any operation inside the design envelope that would cause a shutdown that could possibly lead to a violation of environmental, health or safety regulations or negatively impact profitability.

Examples of hazards at work might include:

- Loud noise - it can cause hearing loss;
- Breathing in asbestos dust because it can cause cancer.

Hazards in the process industry might include:

- The level of liquid in a vessel: a high level may result in an overflow of liquid into gas streams, or an overspill of a dangerous chemical or flammable liquid; a low level may result in dry running of pumps, or gas blow by into downstream vessels.
- The pressure of liquid in a vessel: high pressure may result in loss of containment, leaks or vessel rupture.

The essential feature of the HAZOP Study approach is to review process drawings and/or procedures in a series of meetings, during which a multidisciplinary team uses a defined protocol to methodically evaluate the significance of deviations from the normal design intention.

HAZOP were initially 'invented' by ICI in the United Kingdom and started to be more widely used within the chemical process industry after the Flixborough disaster in 1974 that killed 28 people and injured scores of others. The system was then adopted by the petroleum industry, which has a similar potential for major disasters. This was then followed by the food and water industries, where the hazard potential is as great, but of a different nature, the concerns being more to do with contamination rather than explosions or chemical releases.

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HAZOP is a structured and systematic technique involving a multi-disciplinary team for examining a defined system, with the objective of:

- identifying potential hazards in the system. The hazards involved may include both those essentially relevant only to the immediate area of the system and those with a much wider sphere of influence, e.g. some environmental hazards;
- identifying potential operability problems with the system and in particular identifying causes of operational disturbances and production deviations likely to lead to nonconforming products.

Safety Issues

- To identify scenarios that would lead to the release of hazardous or flammable material into the atmosphere, thus exposing workers to injury
- To check the safety of the design
- To improve the safety of an existing and or modified facility

Operability Issues

- To decide where to build/install
- To check operating and safety procedures
- To verify that safety instrumentation is designed optimally
- To facilitate smooth, safe prompt start-up & shut-down
- To minimize extensive last minute modifications
- To ensure trouble-free long-term operation
- Operability problems should be identified to the extent that they have the potential to lead to process hazards, result in an environmental violation or have a negative impact on profitability.
- In practice, more operability related recommendations are made in a HAZOP study compared to safety

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Key features of HAZOP examination include the following.

- The examination is a creative process. The examination proceeds by systematically using a series of guide words to identify potential deviations from the design intent
- The examination is carried out under the guidance of a leader who ensure comprehensive coverage of the system under study
- The examination relies on experienced specialists from various disciplines
- The examination should be carried out in a climate of positive thinking and frank discussion.
- Solutions to identified problems are not a primary objective but are recorded for consideration by those responsible for the design.

Although the design of the plant relies upon the application of codes and standards, the HAZOP process allowed the opportunity to supplement these with an imaginative anticipation of the deviations which may occur because of, for example, process conditions or upsets, equipment malfunction or operator error.

In addition, the pressures of project schedules can result in errors or oversights and the HAZOP allows these to be corrected before such changes become too expensive. Because they are easy to understand and can be adapted to any process or business, HAZOPs have become the most widely used hazard identification methodology.

HAZOP should be held in these conditions:

- During various stages of plant design
  - ✓ At the beginning of the project as a ‘safety and environmental specification’
  - ✓ Towards the end of process definition, when the Process Flow sheets are available as a Safety and Environmental Review
  - ✓ When P&IDs are at ‘Approved for Design’ stage (Final design HAZOP)
- During construction site inspections ensure that recommendations arising from the HAZOP or other safety and environmental reviews are being implemented.
- A pre-commissioning study reviews plant procedures and perform a conventional safety audit

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- Once operational, an audit of plant and procedures at regular interval ensures ongoing safety awareness

The HAZOP study is traditionally performed as a structured brainstorming exercise facilitated by a HAZOP study leader and exploiting experience of the participants. A traditional HAZOP study has the following phases (Skelton, 1997):

- Pre-meeting phase

  The purpose and objective of the study is defined. The leader of the HAZOP study gathers information about the facility, such as process flow diagrams (PFD), piping & instrumentation diagrams (P&ID), a plant layout, chemical hazard data etc., and proposes a division of the plant into sections and nodes. For each node - or for the plant as a whole - the leader identifies relevant process variables and deviations from design intent or normal operation based on either past experience or company guidelines.

  The leader also identifies the participants, who will participate in the review of the different sections of the plant, and ensures their availability. Typically, this group includes the process design engineer, the control engineer, the project engineer and an operator besides the experienced team leader. All these people have large demands on their time during a project. The team leader schedules a sufficient number of half day HAZOP meetings.

- Meeting phase

  At the start of the HAZOP meeting the technique is briefly reviewed, and the specific scope of the present study is stated. The overall facilities are described e.g. using a 3D computer model. Then the team considers each P&ID or PFD in turn. The team leader ensures that process variables and deviations are considered in a rigorous and structured manner, that results are recorded, and that all areas meriting further consideration are identified by action items.

- Post-meeting phase

  After the HAZOP meeting all actions items are followed up by the persons assigned to them during the meeting and the results of the follow-up is reported to the team leader.

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The team might call a review meeting to determine the status of all actions items, and decide if additional efforts are needed.

The HAZOP procedure involves taking a full description of the process and systematically questioning every part of it to establish how deviations from the design intent can have a negative effect upon the safe and efficient operation of the plant. The procedure is applied in a structured way by the HAZOP team, and it relies upon them releasing their imagination in an effort to identify credible hazards. In practice, many of the hazards will be obvious, such as an increase in temperature, but the strength of the technique lies in its ability to discover less obvious hazards, however unlikely they may seem at first consideration.

HAZOP procedure

1. Begin with a detailed flow sheet. Break the flow sheet into a number of process units. Thus the reactor area might be one unit, and the storage tank another. Select a unit for study.
2. Choose a study node (vessel, line, operating instruction).
3. Describe the design intent of the study node. For example, vessel V-1 is designed to store the benzene feedstock and provide it on demand to the reactor.
4. Pick a process parameter: flow, level, temperature, pressure, concentration, pH, viscosity, state (solid, liquid, or gas), agitation, volume, reaction, sample, component, start, stop, stability, power, inert.
5. Apply a guide word to the process parameter to suggest possible deviations.
6. If the deviation is applicable, determine possible causes and note any protective systems.
7. Evaluate the consequences of the deviation (if any).
8. Recommend action (what? by whom? by when?)
9. Record all information.

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Figure 1 shows the typical of HAZOP procedure.

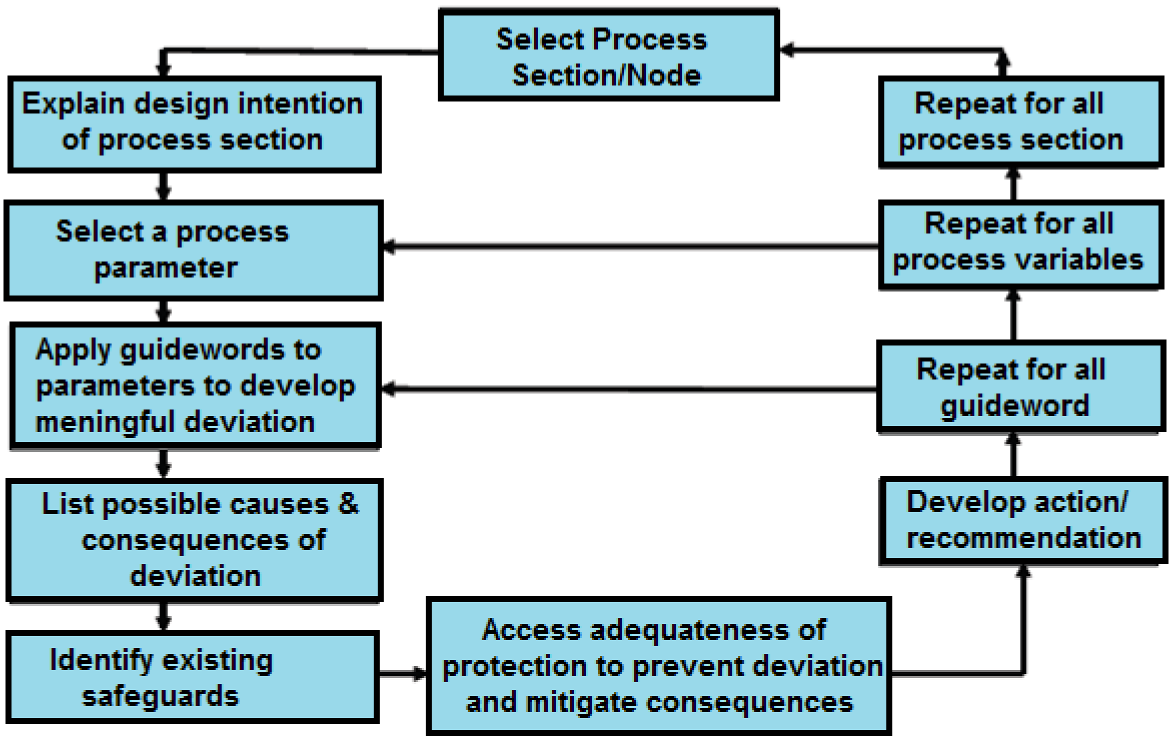

Figure 1: Typical HAZOP Procedure

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It is important that a HAZOP team is made up of personnel who will bring the best balance of knowledge and experience, of the type of plant being considered, to the study. A typical HAZOP team is made up as follows:

- Independent leader (e.g., not from plant studied). Preferred but complete independence not essential. The responsibility are:
  - ✓ Plan sessions and timetable
  - ✓ Control discussion
  - ✓ Limit discussion
  - ✓ Encourage team to draw conclusion
  - ✓ Ensure secretary has time for taking note
  - ✓ Keep team in focus
  - ✓ Encourage imagination of team members
  - ✓ Motivate members
  - ✓ Discourage recriminations
  - ✓ Judge importance issues
- HAZOP Secretary/Scribe. The responsibilities are:
  - ✓ Take adequate notes
  - ✓ Record documentations
  - ✓ Inform leader if more time required in taking notes
  - ✓ If unclear, check wording before writing
  - ✓ Produce interim lists of recommendations
  - ✓ Produce draft report of study
  - ✓ Check progress of chase action
  - ✓ Produce final report
- Project engineer. The responsibilities are:
  - ✓ Provide details of cost and time estimation and also budget constraints.
  - ✓ Ensure rapid approval if required

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- Operations representative. Plant operation
  - ✓ Plant Engineer or Manager
    - ➢ Provide information on compatibility with any existing adjacent plant
    - ➢ Provide details of site utilities and services
    - ➢ Provide (for study on existing plant) any update on maintenance access and modifications
  - ✓ Shift Operating Engineer or Supervisor
    - ➢ Provide guidance on control instrumentation integrity from an operating experience view point
    - ➢ Provide (for study on existing plant) information on plant stability at the specified control parameters
    - ➢ Provide information on experienced operability deviations of hazard potential
- Discipline engineers. Process, instrument/ electrical, mechanical/ maintenance, project engineer. The responsibilities are:
  - ✓ Process Engineer: Provide a simple description; Provide design intention for each process unit; Provide information on process conditions and design conditions
  - ✓ Mechanical Design Engineer: Provide specification details; Provide vendor package details; Provide equipment and piping layout information
  - ✓ Instrument Engineer: Provide details of control philosophy; Provide interlock and alarm details; Provide info on shutdown, safety features
  - ✓ Maintenance representative: Needed where maintenance of the plant is complex or hazardous. Many operability problems are associated with maintenance and many accidents occur during maintenance
  - ✓ SHE expert: represent the interest of occupational safety and health and may be required to serve as an independent observer to see that the study proceeds in a satisfactory manner
- Other Specialists. They provide expertise relative to the system and the study as needed. This may only require limited participation but the team leader will have to decide on the times when such persons are needed. Likely candidates include:
  - ➢ Research chemist for new processes
  - ➢ Electrical engineer

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- Environmental pollution specialist
- Effluent treatment specialists
- Safety specialist
- Control system software engineer
- Chemist,

- Contractor and client representatives: If the plant is being designed by a contractor, the HAZOP team should contain representatives from both contractor and client. This may result in some duplication of the above the roles but is generally necessary do to the alternative perspectives of the parties

Table 1: The Potential Members of a HAZOP Study Team

Chemist Civil engineer Construction representative Corporate safety manager Electrical engineer Environmental engineer Expert from another plant Fire protection engineer Hazard evaluation expert/leader Human factors specialist Industrial hygienist Inspection engineer/technician Instrument engineer/technician Interpreter Maintenance supervisor Maintenance planner Mechanic/pipefitter/electrician	Mechanical engineer Medical doctor/nurse Metallurgist Operations supervisor Operator/technician Outside consultant Process engineer Process control programmer Project engineer Recorder/secretary/scribe R&D engineer Safety engineer Shift foreman Toxicologist Transportation specialist Vendor representative

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The HAZOP process uses guidewords to focus the attention of the team upon deviations of the design intent, their possible causes and consequences. These guidewords are divided into two sub-sets:

- Primary Guidewords which focus attention upon a particular aspect of the design intent or an associated process condition or parameter i.e. flow, temperature, pressure, level etc.;
- Secondary Guidewords which, when combined with a primary guideword, suggest possible deviations i.e. more temperature, less level, no pressure, reverse flow etc.

The entire technique depends upon the effective use of these guidewords, so their meaning and use must be clearly understood by the team. A list and their meaning are provided.

- The intention can fail completely and nothing at all happens. This is prompted by NO or NOT. For example, a "no flow" situation can exist if a pump fails to start.
- If there is a quantitative variation, it may be described by MORE or LESS. This refers to quantities, physical properties and activities. For example, more of a charge of reactant, a high mole ratio in a reactor, less reaction, and so forth.
- If the intention is changed, a qualitative deviation results. An additional activity may occur AS WELL AS the original intention. If a motor starts-up on auto start, a drop in the power supply may upset other equipment.
- The intention may be incompletely achieved, that is to say, only PART OF what was originally intended may be completed. A diesel fire-pump may start-up, but fail to reach full speed.
- The exact opposite of what was intended may occur, giving the REVERSE of the intention. Reverse flow is a common occurrence, very often in spite of the use of check valves. In a reaction kinetics situation, the reverse reaction may occur.
- OTHER is a guide word used as a final catch all. It is used to identify something completely different. Following the reaction kinetics thought, a different reaction mechanism may be more important under certain conditions. OTHER is also used to call up requirements for maintenance, start-up, shut-down, catalyst change, etc.

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Table 3: A list of Guidewords

Guide Word	Meaning	Example
NONE	Negation of Intention	No forward flow when there should be, i.e. no flow or reverse flow.
MORE OF	Quantitative Increase	More of any relevant physical property than there should be, e.g. higher flow (rate or total quantity), higher temperature, higher pressure, higher viscosity, etc.
LESS OF	Quantitative Decrease	Less of any relevant physical property than there should be, e.g. lower flow (rate or total quantity), lower temperature, lower pressure, etc.
PART OF	Qualitative Decrease	Composition of system different from what it should be, e.g. change in ratio of components, component missing, etc.
AS WELL AS MORE THAN	Qualitative Increase	More components present in the system than there should be, e.g. extra phase present (vapor, solid), impurities (air, water, acids, corrosion products), etc.
REVERSE	Logical Opposite	A parameter occurs in the opposite direction to that for which it was intended e.g. reverse flow.
OTHER THAN	Complete Substitution	Complete substitution e.g. sulphuric acid was added instead of water.
EQUIPMENT WORDS “OTHER”		What else can happen apart from normal operation, e.g. start-up, shutdown, uprating, low rate running, alternative operation mode, failure of plant services, maintenance, catalyst change, etc.

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The guidewords are applied to a range of process parameters. The most common process parameters are:

Flow	Time	Frequency	Mixing
Pressure	Composition	Viscosity	Addition
Temperature	pH	Voltage	Separation
Level	Speed	Information	Reaction

Typically, a member of the team would outline the purpose of a chosen line in the process and how it is expected to operate. The various guide words such as MORE are selected in turn. Consideration will then be given to what could cause the deviation. Following this, the results of a deviation, such as the creation of a hazardous situation or operational difficulty, are considered. When the considered events are credible and the effects significant, existing safeguards should be evaluated and a decision then taken as to what additional measures could be required to eliminate the identified cause.

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Figure 2 illustrates the logical sequence of steps in conducting a HAZOP

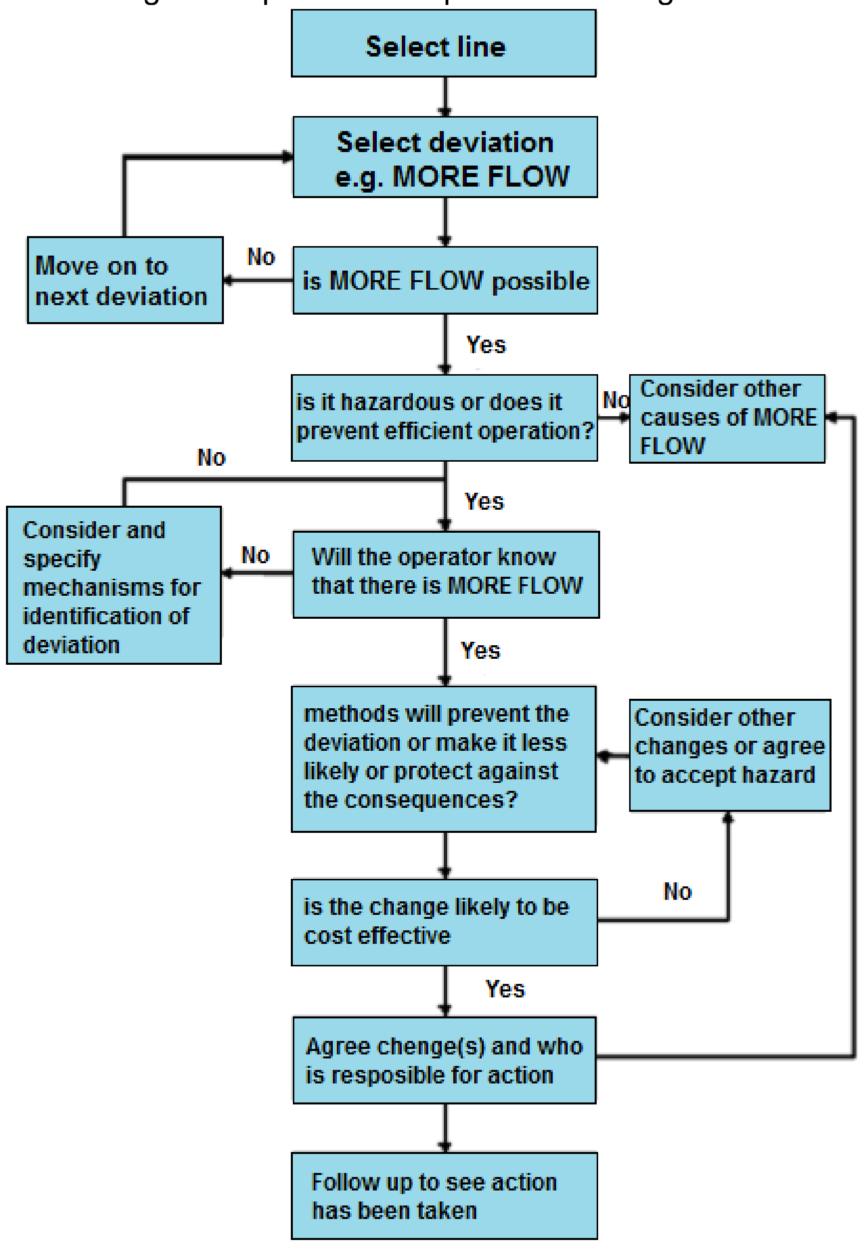

Figure 2: Flow Chart of the Study Method

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The primary advantage of the brainstorming associated with HAZOP Study is that it stimulates creativity and generates new ideas. This creativity results from the interaction of a team with diverse backgrounds. Consequently, the success of the study requires that all participants freely express their views and good supportive teamwork practices are adopted. Participants should refrain from criticizing each other to avoid smothering the creative process. This creative approach combined with the use of a systematic protocol for examining hazardous situations helps improve the thoroughness of the study.

The success or failure of the HAZOP depends on several factors:

- The completeness and accuracy of drawings and other data used as a basis for the study
- The technical skills and insights of the team
- The ability of the team to use the approach as an aid to their imagination in visualizing deviations, causes, and consequences
- The ability of the team to concentrate on the more serious hazards which are identified.

Strength of HAZOP

- HAZOP is a systematic, reasonably comprehensive and flexible.
- It is suitable mainly for team use whereby it is possible to incorporate the general experience available.
- It gives good identification of cause and excellent identification of critical deviations.
- The use of keywords is effective and the whole group is able to participate.
- HAZOP is an excellent well-proven method for studying large plant in a specific manner.
- HAZOP identifies virtually all significant deviations on the plant, all major accidents should be identified but not necessarily their causes.

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Weakness of HAZOP

- HAZOP is very time consuming and can be laborious with a tendency for boredom for analysts.
- It tends to generate many failure events with insignificance consequences and generate many failure events which have the same consequences.
- It takes little account of the probabilities of events or consequences, although quantitative assessment are sometime added. The group generally let their collective experiences decide whether deviations are meaningful.
- HAZOP is poor where multiple-combination events can have severe effects.
- When identifying consequences, it tends to ignore contributions that can be made by operator interventions

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DEFINITIONS

Actions (or Recommendations) - Suggestions for design changes, procedural changes, or areas for further study (e.g. adding a redundant pressure alarm or reversing the sequence of two operating steps)

Availability - The probability that an item of equipment or a control system will perform its intended task

Causes - Reasons why deviations might occur. Once a deviation has been shown to have a credible cause, it can be treated as a meaningful deviation. These causes can be hardware failures, human errors, unanticipated process states (e.g. change of composition), external disruptions (e.g. loss of power), etc.

Consequences - Results of deviations (e.g. release of toxic materials). Normally, the team assumes active protection systems fail to work. Minor consequences, unrelated to the study objective, are not considered.

Deviations - Departures from the design intention that are discovered by systematically applying the guide words to process parameters (flow, pressure, etc.) resulting in a list for the team to review (no flow, high pressure, etc.) for each process section. Teams often supplement their list of deviations with ad hoc items

Design freeze – No further changes can be made to the design

Emergency shutdown - Commonly used terminology to refer to the safeguarding systems intended to shutdown a plant in case of a process parameter limit-excess.

EUC (equipment under control) - Equipment, machinery, apparatus or plant used for manufacturing, process, transportation, medical or other activities.

EUC control system - System which responds to input signals from the process and/or from an operator and generates output signals causing the EUC to operate in the desired manner.

Guide Words - Simple words that are used to qualify the design intention and to guide and stimulate the brainstorming process for identifying process hazards

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Hazard - any operation that could possibly cause a release of toxic, flammable or explosive chemicals or any action that could result in injury to personnel.

HAZOP - Term applied to the structured and systematic examination of a process or system of parts to find possible hazards and operability problems. A process hazards analysis procedure originally developed by ICI in the 1970s. The method is highly structured and divides the process into different operationally-based nodes and investigates the behavior of the different parts of each node based on an array of possible deviation conditions or guidewords.

independent protection layers (IPL) - This refers to various other methods of risk reduction possible for a process. Examples include items such as rupture disks and relief valves which will independently reduce the likelihood of the hazard escalating into a full accident with a harmful outcome. In order to be effective, each layer must specifically prevent the hazard in question from causing harm, act independently of other layers, have a reasonable probability of working, and be able to be audited once the plant is operation relative to its original expected performance.

Intention - Definition of how the plant is expected to operate in the absence of deviation. Takes a number of forms and can be either descriptive or diagrammatic (e.g., process description, flowsheets, line diagrams, P&IDs)

Likelihood - The frequency of a harmful event often expressed in events per year or events per million hours. One of the two components used to define a risk. Note that this is different from the traditional English definition that means probability.

Operability - any operation inside the design envelope that would cause a shutdown that could possibly lead to a violation of environmental, health or safety regulations or negatively impact profitability

Operating Steps - Discrete actions in a batch process or a procedure analyzed by a HAZOP analysis team. May be manual, automatic, or software-implemented actions. The deviations applied to each step are somewhat different than the ones used for a continuous process

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Piping and instrumentation drawing (P&ID) - Shows the interconnection of process equipment and the instrumentation used to control the process. In the process industry, a standard set of symbols is used to prepare drawings of processes.

Process Parameter - Physical or chemical property associated with the process. Includes general items such as reaction, mixing, concentration, pH, and specific items such as temperature, pressure, phase, and flow

Process Sections (or Study Nodes) - Sections of equipment with definite boundaries (e.g., a line between two vessels) within which process parameters are investigated for deviations. The locations on P&IDs at which the process parameters are investigated for deviations (e.g. reactor)

Proof test - Testing of safety system components to detect any failures not detected by automatic on-line diagnostics i.e. dangerous failures, diagnostic failures, parametric failures followed by repair of those failures to an equivalent as new state. Proof testing is a vital part of the safety lifecycle and is critical to ensuring that a system achieves its required safety integrity level throughout the safety lifecycle.

Redundancy - Use of multiple elements or systems to perform the same function. Redundancy can be implemented by identical elements (identical redundancy) or by diverse elements (diverse redundancy). Redundancy of primarily used to improve reliability or availability.

Reliability - The probability that no functional failure has occurred in a system during a given period of time.

Safeguards - Engineered systems or administrative controls designed to prevent the causes or mitigate the consequences of deviations (e.g. process alarms, interlocks, procedures)

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NOMENCLATURE

C&E	Cause and Effects
EUC	equipment under control
HAZOP	hazard and operability study
IPL	independent protection layers
P&ID	piping & instrumentation diagrams
PFD	process flow diagrams
PIC	Pressure Indicator controller
R&D	research and development

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