Process safety can help provide better assurance for communities, and for refinery, petrochemical and chemical plants, through the use of a hazard and operability (HAZOP) study, a method of identifying both deviations to process design that could cause potential hazards, and safeguards required in order to reduce potential hazards.

The HAZOP study is traditionally a qualitative study. To give it more quantitative character, dynamic simulation is sometimes used to complement the HAZOP study. Combining HAZOP with dynamic simulation provides the means for investigating (and demonstrating) the consequences of deviations from normal operating conditions. This article presents a few examples using dynamic simulation in a HAZOP.

HAZOP
Companies and the public are increasingly asking for better assurance that sites and communities will not be adversely impacted as a result of fires, explosions or releases from oil refineries and chemical plants. The banking and insurance industries are also increasingly asking for this assurance. Process safety can help reassure these companies, industries and communities through the use of a HAZOP study. The HAZOP study is recognised worldwide as a primary methodology for hazard identification conducted for the oil, petrochemical and chemical industries for satisfying two basic requirements. The first is checking a new design for safety and operability problems whilst it is at the process instrumentation diagram stage. The second is the identification of latent safety and operability problems in
HAZOP study

Methodology

UOP HAZOP studies are well documented and include all of the supporting information used during the HAZOP sessions in a way that is useful to the owner and the contractor.

HAZOP studies of UOP process units are conducted with a team of experts including a chairman/HAZOP team leader, process design engineer, process engineer, technical service engineer, control engineer, and the project engineer. Specialists to be consulted on specific points may include an electrical engineer, piping engineer, research scientist, civil engineer, chemist, and the flowsheeting specialist, as necessary (Figure 1).

HAZOP is carried out as a structured study. The method relies on using guidewords (such as no, more, less) combined with process parameters (e.g., temperature, flow, pressure) that aim to reveal deviations (such as less flow, more temperature and so on) of the process intention or normal operation. Ideally, HAZOPs should be carried out early in the project.

Consequences

The consequences are then risk rated based on their severity and likelihood. Figure 2 shows a risk ranking matrix that is used in all of the HAZOP reviews. The risk ranking matrix has four levels of risk which are the following:

- Risk ranking D: risk not acceptable.
- Risk ranking C: risk acceptable with additional administrative or engineering controls that lower the risk ranking to ‘A’ or ‘B’.
- Risk ranking B: risk acceptable with additional administrative or engineering controls.
- Risk ranking A: risk acceptable even if no further action taken.

If during the HAZOP a risk ranking of ‘D’ or ‘C’ is determined by the HAZOP team, the HAZOP leader may engage the flowsheeting specialist to see if a dynamic simulation could determine a better understanding of the issue and the severity. The dynamic simulation may determine that the severity may not be as severe as the HAZOP team determined by qualitatively assessing the severity quantitatively, so may potentially move the risk ranking to an ‘A’ or ‘B’.

The application of the HAZOP technique to a detailed process unit design is a complex and lengthy task. UOP has created a model where the HAZOP worksheets are pre-populated by an experienced HAZOP leader who, during consultations with skilled experts, will allow the company to make the HAZOP reviews more efficient and less time consuming during the HAZOP meetings.

Using dynamic simulation in HAZOP reviews

In the past 30 years, much research effort has been dedicated to the development of the dynamic analysis. The dynamic analysis approach for a HAZOP of a process unit seems to be the most straightforward procedure that gives quantitative results.
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Usually, the HAZOP analysis does not consider the duration and magnitude of the deviations generated during the operation. However, what exactly does the deviation ‘less flow’ mean: 80% or 10% of the usual operation value? Does the deviation occur as an immediate (step) decrease of the flow lasting five minutes or more, or is it only an impulse? Is this decrease continuous at some rate? Answers to these questions can be obtained using dynamic simulation, which is one of the newer features. Consider the example where a valve is left open on a line going to a storage tank. Dynamic simulation will assist on the duration of how long it will take to overfill that tank even if there are multiple inlets to the storage tank. In dynamic simulation, the extent of the deviations can be easily incorporated and possible consequences investigated.

The dynamic analysis serves for analysing the time and direction of shifting from one steady state to another one due to a failure deviation. It is also very useful for the investigation of dynamic behaviour of the system with respect to the time and length of the failure. The results of safety analysis can be used in HAZOP studies. HAZOP, with dynamic simulation, has the potential to become a very practical and robust tool. The company illustrates this by presenting examples of dynamic simulation for conventional column on loss of reflux for UOP’s Phenol™ process operating pressure evaluation.

However, it is important to point out that the implementation of dynamic simulation for any chosen system is dependent on an adequate steady state model; this is dependent on: physical properties, kinetics, mass and heat transfer behaviours. During a HAZOP study, possible deviations are generated by rigorous questioning, prompted by a series of standard ‘guidewords’ applied to the intended design. After the guideword is matched with a parameter, a deviation is generated. The next step in the HAZOP study is to look for potential consequences. At this moment, the application of dynamic analysis is useful in order to find quantitative consequences.

The HAZOP study is traditionally a qualitative study. By definition, a dynamic simulation is the imitation of the operation of a real world process or system over time, which means that in principle it should be a realistic way of representing an actual process. Combining HAZOP with dynamic simulation does provide the means for investigating and demonstrating the consequences of deviations from normal operating conditions. Dynamic simulation now provides the UOP HAZOP team the ability to quickly investigate and test the effectiveness of various suggested strategies dealing with high risk situations (intolerable levels of risk).

By having a dynamic simulation of the process as a support tool, an extensive, easier and more complete study can be accomplished. That provides a systematic screening of process deviations associated with possible high risk events, determining the threshold values that may lead to such events and enabling the examination of a particular design for the adequate safe range of operation. Dynamic simulation should be seen as a tool that complements the traditional HAZOP procedure and does not replace it. There are still many processes that cannot be modelled accurately enough due to a lack of quantitative information, particularly in emergency situations.

Process safety is paramount in the secure and viable operation of any refinery, petrochemical or chemical process plant. Many techniques and methodologies have been defined over the years to undertake steps that will ensure a safe operating environment at a chemical facility. However, until now, process simulation has found very little or no use in safety-related studies such as HAZOP. In this article, a systematic framework is introduced based on a quantitative HAZOP (that is, HAZOP supported by dynamic simulation related to process malfunctions). The quantitative HAZOP differs from standard HAZOP in documenting results, classification of frequency and consequences of process deviations, and application of a risk potential matrix (risk ranking matrix).

Dynamic simulations can be used to support the HAZOP in the following ways:

- An important part of the HAZOP procedure is to think of the consequences of a certain deviation.
- For complex and nonlinear systems, it is not straightforward to assess the consequences. Hence, the use of dynamic simulation with the deterministic models can be helpful in assessing the effect of faults on the operations and dynamics of the process.
- The purpose of the methodology is to determine the effect of operational disturbances on the safety of the plant and devise ways to reduce the risk of the consequences.

HAZOP can provide qualitative answers regarding the magnitude of the deviations that will lead to severe consequences. It cannot provide the time it takes to reach a ‘no return’ stage of an accident after the deviation has
occurred, or the action that can be taken in order to prevent the accident. Dynamic simulation can provide this information that a traditional HAZOP could not provide. Dynamic simulation in HAZOP can provide quantitative assessment of the consequences of abnormal operating conditions.

Dynamic simulation and HAZOP analysis

Background

Steady state process templates (flowsheets) are used extensively in the engineering design workflow for all UOP process technologies. UOP engineers utilise the Honeywell UNISIM® Design Suite of process modelling tools1-3 in the preparation of a process design package to users called Schedule A. This suite of tools allows for the development of steady state and dynamic process models.

In the process phase of the Schedule A workflow, there was development of a large database of validated steady state process templates for all UOP process technologies. Modifications to these templates are made based on customer specific requirements. All the equipment and piping associated with a project are sized based on flow rates, calculated from steady state heat and mass balances, which interface all of the engineering sizing tools. Simulation results are downloaded to the standalone hydraulic tools to determine line sizes and generate tabulation reports. If needed, various parts of the steady state template can be checked using the equivalent dynamic simulation template.

Dynamic simulation templates

Transitions from the converged steady state templates to dynamic simulation templates requires a different approach towards specifying unit operations. In the implementation of dynamic templates a sequence of important actions are required to insure a successful high fidelity dynamic analysis:

- Converge a realistic steady state simulation of the problem to be studied.
- Add valves and pipes to ensure pressure-driven flow between unit operations.
- Set terminal feed and product pressures.
- Determine approximate, or include exact, dimensions of all process equipment.
- Specify sizing data for all pipe runs (lengths, diameters, etc). Size the CVs.
- Include nozzle elevations for all valves, piping and process equipment.
- Add all necessary controllers (TICs, TICs, etc.) to all control loops.
- Run the dynamic simulation: tune the controllers, check pressure drops, and line out the model to match the original steady state performance.
- Add events to the event scheduler to model upsets and other conditions.

The above steps need to be completed only once and serve as the starting point for dynamically evaluating all normal and upset operating scenarios.

Each of the dynamic models is preconfigured to include upset conditions, strip charts and tabulate historical data. In UNISIM®, the event scheduler is used to model the preconfigured dynamic upset scenarios. Additional upsets are also manually activated as a dynamic run is proceeding during time integration.

Over the years, a strategy and timetable have been established to implement dynamic simulation methods into the current UOP process workflow. The use of dynamic process templates has been introduced to supplement the work as needed during the Schedule A projects. Various sections of these dynamic templates are used to identify specific design issues for each project (e.g., a project HAZOP review, emergency shutdown events, customer inquiries, etc.) that normally would not be recognised through the use of steady state simulators.

Sections of the dynamic templates are utilised to explore transient behaviour around individual equipment, e.g., reactors, columns, etc. There are many different levels of fidelity possible when creating dynamic flow sheets. In UOP engineering dynamic templates are used that implement the basic regulatory control schemes shown on all the process flow diagrams for all UOP process units.

From a full dynamic template of a UOP process unit, the process engineer is able to break down the process flows and create smaller process snapshots for analysis. To consider and evaluate time dependent behaviour in the Schedule A work process, a separate group of flowsheeting skill specialists are utilised on Schedule A projects to assist in preparing and designing these dynamic flowsheets.

The recently included flowsheeting specialists support the internal HAZOP team reviews. This support includes the preparation and evaluation of dynamic models as needed from the working HAZOP worksheets. Supporting data (e.g., strip charts, tabular historical data of key events/new hazards/safety issues) from these dynamic runs are included in the reports. Additional dynamic runs are made to address any user's concerns after the reports are issued.

With the use of dynamic templates from the steady state design templates, quantitative testing can now evaluate the effectiveness of proposed strategies for emergency situations. Furthermore, dynamic analysis has helped to identify new unknown hazards and safety issues. The consequences of any
deviations can now be accurately determined from normal design. Dynamic analysis has also been included in the HAZOP reviews of new technologies, as proposed by the R&D process design and development groups.

**Dynamic HAZOP analysis**

Over the years, dynamic analyses has been performed to support the internal HAZOP reviews. Most of these are very detailed and require specific user information such as 'as built' equipment and line size data as well as detailed valve performance data. Other flowsheets are more simply configured and are used occasionally in HAZOP analysis to confirm and/or support the qualitative conclusions normally encountered during the reviews. The following examples illustrate some process scenarios typically encountered during HAZOP reviews.

**Conventional column: loss of reflux**

The majority of process units utilise two and three phase conventional separation columns. These columns typically have an overhead condenser with a receiver and a bottoms re-boiler circuit.

In a typical HAZOP analysis, there could be potential hazards associated with the installation of engineer controlled emergency isolation valves. In those situations, an evaluation will be conducted to determine whether the installation of the engineer controlled emergency isolation valves provides the safer option for personnel, the environment or surrounding equipment than if these valves were not installed. As shown in Figure 3, these isolation valves can be local or remote manually operated and are typically not interlocked to other instrumented devices.

From the database of UNISIM® templates, a dynamic model of the conventional column follows a standard process flow diagram view of equipment, piping and basic piping and instrument diagram control designations. This model has event schedules preconfigured with a number of upset scenarios. If needed, adhoc scenarios can easily be added to the model during the HAZOP team analysis.

To simulate an upset event, a manually operated isolation valve is inadvertently closed during normal operation. First, the column is lined out to steady state conditions; then the isolation valve is triggered to fully close. Through a sequence of events, the overhead vapour from the column immediately spikes upward, then moves downward rapidly as it is displaced by the increasing liquid level in the receiver. After 3.5 mins the liquid level completely fills the receiver and overflows through the vapour line at a large rate. With no reflux flow returning to the column, the liquid level in the sump starts to decrease. The liquid level ultimately drops to zero after another 7.5 mins. During this upset the column operating pressure increased close to the pressure safety valve set pressure but did not open.

Obviously, during normal operation, the appropriate trip activation or operation actions in response to safety alarms would have been in place to mitigate any severe operating scenarios such as the one performed in this simple example. As this example shows, the continued use of dynamic simulation in the HAZOP reviews has allowed for quantitative evaluation of the effect of time on process safety issues, particularly as they relate to equipment failures, startup and shutdown scenarios. Vendor data can also be readily incorporated to validate performance. For instance, the actual valve flow coefficients CV and stroke time data is used for all control and isolation valves whenever dynamic simulation work is being implemented in HAZOP analysis.

**Phenol process: operating pressure evaluation**

Dynamic studies are also performed for users based on internal HAZOP reviews. One user requested the possibility of running oxidiser tanks at higher pressures, so as to increase product flow, should be evaluated.

The process flow diagrams for the oxidiser section were taken from a library of design templates and modified to include all user specific information. Figure 4 shows a dynamic model representation of a section of the oxidiser feed train. Piping and instrument diagrams were also used to accurately define the placement of all control and isolation valves as well as control logic systems in the dynamic simulation. Some elevations and line sizing information were also extracted from the drawings. The remaining data was obtained from previous hydraulic reports. Equipment sizes were also incorporated into the model.

The air feed valve/isolation valve configurations utilised the 'as built' detailed valve performance data provided by the user.

The results of the dynamic analysis showed that the user could run their unit at higher operating pressures. A greater pressure trip point was recommended for the oxidiser shutdown system, as this would still prevent overpressure of the oxidiser tanks from reaching their set relief pressures. Based on the 'as built' stroke time valve data obtained from the customer, it is clear that the valves can perform quickly in avoiding pressure relief of the oxidiser tanks at the highest possible operating pressure.

**Conclusion**

The combination of traditional HAZOP analysis with dynamic simulation facilitates accurate determination of the consequences of deviations from normal design. Potential hazards and safety issues can be better identified. By dividing the problem model into smaller, independent flowsheet sections, the level of complexity associated with the dynamic simulations can be reduced.

HAZOP teams can now test the effectiveness of mitigation strategies for many emergency situations. The use of dynamic simulation as a process safety/risk assessment tool provides significant added value to HAZOP reviews and reports.

**Notes**

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**References**