

# HAZOPExpert: An Expert System for Automating HAZOP Analysis

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*Hazard and operability (HAZOP) analysis is the study of systematically identifying every conceivable deviation from the design intent, and all possible abnormal causes, and adverse hazardous consequences that can occur in a chemical plant. This is a difficult, labor- and knowledge-intensive, and time-consuming analysis. HAZOP analysis is typically performed by a group of experts poring over the process P&IDs for weeks. An intelligent system for automating this analysis can reduce the time and effort involved, make the analysis more thorough and detailed, and minimize or eliminate possible human errors. Towards that goal, a model-based framework has been developed in which the knowledge required to perform HAZOP analysis is divided into process-specific and process-general components. The process-specific knowledge consists of the process material properties and the process P&ID. The process-general knowledge consists of the HAZOP-Digraph models of the process units which are qualitative causal models developed specifically for hazard identification. These models are developed in a context independent manner so that they can be used in a wide variety of processes. An inference mechanism is developed for appropriate interaction between these components in order to identify process-specific abnormal causes and adverse consequences. Based on this framework, an expert system called HAZOPExpert has been developed in an object-oriented architecture using the expert system shell G2. The salient features of the HAZOPExpert system and its performance on an industrial-scale sour water stripper plant case study are presented.*

## INTRODUCTION

Process Hazards Analysis (PHA) is the systematic identification and mitigation of potential process hazards which could endanger the health and safety of humans and cause

serious economic losses. This is an important activity in Process Safety Management (PSM) that requires a significant amount of time, effort, and specialized expertise. The importance of this activity is underscored by the Occupational Safety and Health Administration's (OSHA) PSM standard Title 29 CFR 1910.119 which requires initial PHAs of all the processes covered by the standard to be completed by no later than May 26, 1997 [1]. A wide range of methods such as Checklist, What-If? Analysis, Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis, and Hazard and Operability (HAZOP) Analysis are available for performing PHA [2]. Of these methods, the HAZOP analysis is widely used and recognized as a preferred PHA approach by the chemical process industry.

The basic principle of HAZOP analysis is that hazards arise in a plant due to deviations from the "design intent" or the normal behavior of the plant. In HAZOP analysis, process P&IDs are systematically examined by a group of experts, and the abnormal causes and adverse consequences for all possible deviations from normal operation are found. In order to cover all the possible malfunctions in the plant, the process deviations to be considered for this analysis are generated by systematically applying a set of "guide words" such as, *none, more of, less of, part of, reverse, as well as* and *other than*, which are qualitative deviations of process variables. The flow-chart of the guide word HAZOP analysis procedure is given in Figure 1. Detailed description of the analysis procedure with illustrative examples are given by CCPS [2], Knowlton [3], and Kletz [4].

HAZOP analysis is a laborious, time-consuming activity requiring specialized knowledge and expertise. For the analysis to be thorough and complete, the study team can not afford to overlook even the 'routine' causes and consequences which commonly occur in many plants. The importance of performing a comprehensive HAZOP analysis is clearly illustrated by Kletz [4, 5, 6] with examples of industrial accidents that could have been prevented if only a thorough PHA had been performed earlier on that plant.

A typical HAZOP study can take 1-8 weeks to complete, costing about \$10,000 per week. By an OSHA estimate, ap-

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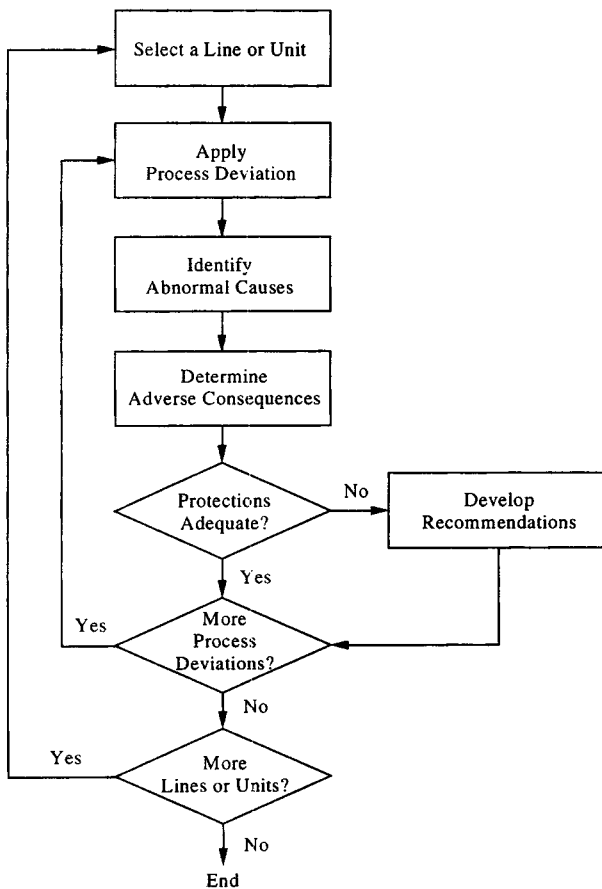


FIGURE 1 HAZOP analysis procedure.

proximately 25,000 plant sites in the United States require a PHA [7]. It is further estimated that a typical plant site might require five to ten PHA studies over the five year OSHA compliance schedule. If one uses HAZOP analysis for performing these PHA studies as it is commonly done, an estimated two billion will be spent collectively by the process industry between now and 1997, on PHA studies alone. This cost excludes getting the process safety information updated before the PHA can be performed.

Given the enormous amounts of time, effort and money involved in HAZOP reviews, there exists considerable incentive to develop an automated approach to the HAZOP analysis of process plants. An automated system that can reduce the time, effort and expense involved in a HAZOP review, make the review more thorough and detailed, minimize human errors and free the team to concentrate on the more complex aspects of the analysis which are difficult to automate is needed. Towards that goal, a knowledge-based system called *HAZOPEXPERT* has been developed. The salient features of *HAZOPEXPERT* as well as its performance on an industrial-scale sour water stripper plant case study are described here. For a more detailed discussion on the underlying model-based framework of *HAZOPEXPERT*, the reader is referred to Venkatasubramanian and Vaidhyathan [8] and Vaidhyathan and Venkatasubramanian [9].

#### KNOWLEDGE REPRESENTATION AND INFERENCE IN *HAZOPEXPERT*

The central ideas in *HAZOPEXPERT* are the separation of

the knowledge required to perform HAZOP analysis into process-specific and process-general knowledge, and the use of generic HAZOP models of process units. The overall architecture of *HAZOPEXPERT* is shown in Figure 2. The process-specific knowledge consists of information about the materials used in the process, their properties (such as corrosivity, flammability, volatility, toxicity, etc.) and the piping and instrumentation drawings (P&ID) of the plant. The process-specific knowledge changes from plant to plant and has to be provided by the user. The process-general knowledge consists of the HAZOP-Digraph (HDG) models of the process units which are qualitative causal models developed specifically for hazard identification [9]. These HDG models are the generic HAZOP models of the process units developed in an object-oriented and context-independent manner so that they can be used for a wide variety of processes. The HAZOP inference engine consists of the methods for finding abnormal causes, adverse consequences and for propagating process variable deviations. These methods allow for the appropriate interaction of the process-general and process-specific knowledge and identify only the abnormal causes and the adverse consequences which are realizable for a given process. The user interacts with the system through the graphical user interface (GUI), which consists of the P&ID graphical editor and the graphical HDG model developer for knowledge acquisition and augmentation.

#### HAZOP-DIGRAPH MODEL

Signed directed graph (digraph) has been used extensively as a tool for graphically representing the qualitative causal models of chemical process systems [10, 11, 12, 13]. A digraph consists of nodes connected by directed edges. The nodes represent process variables and a directed edge connecting two nodes represents the influence of a deviation in the first process variable on the second process variable. The process variables, and hence the digraph nodes, can have the values +, 0, and - indicating high, normal, or low compared to some normal value. The directed edges connecting the digraph nodes can have the gains + or - indicating the direction of influence of one process variable deviation on another. Digraphs of process

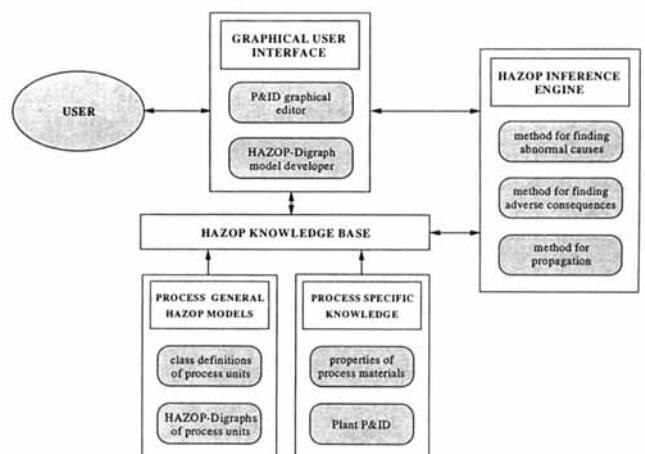


FIGURE 2 The architecture of *HAZOPEXPERT*.

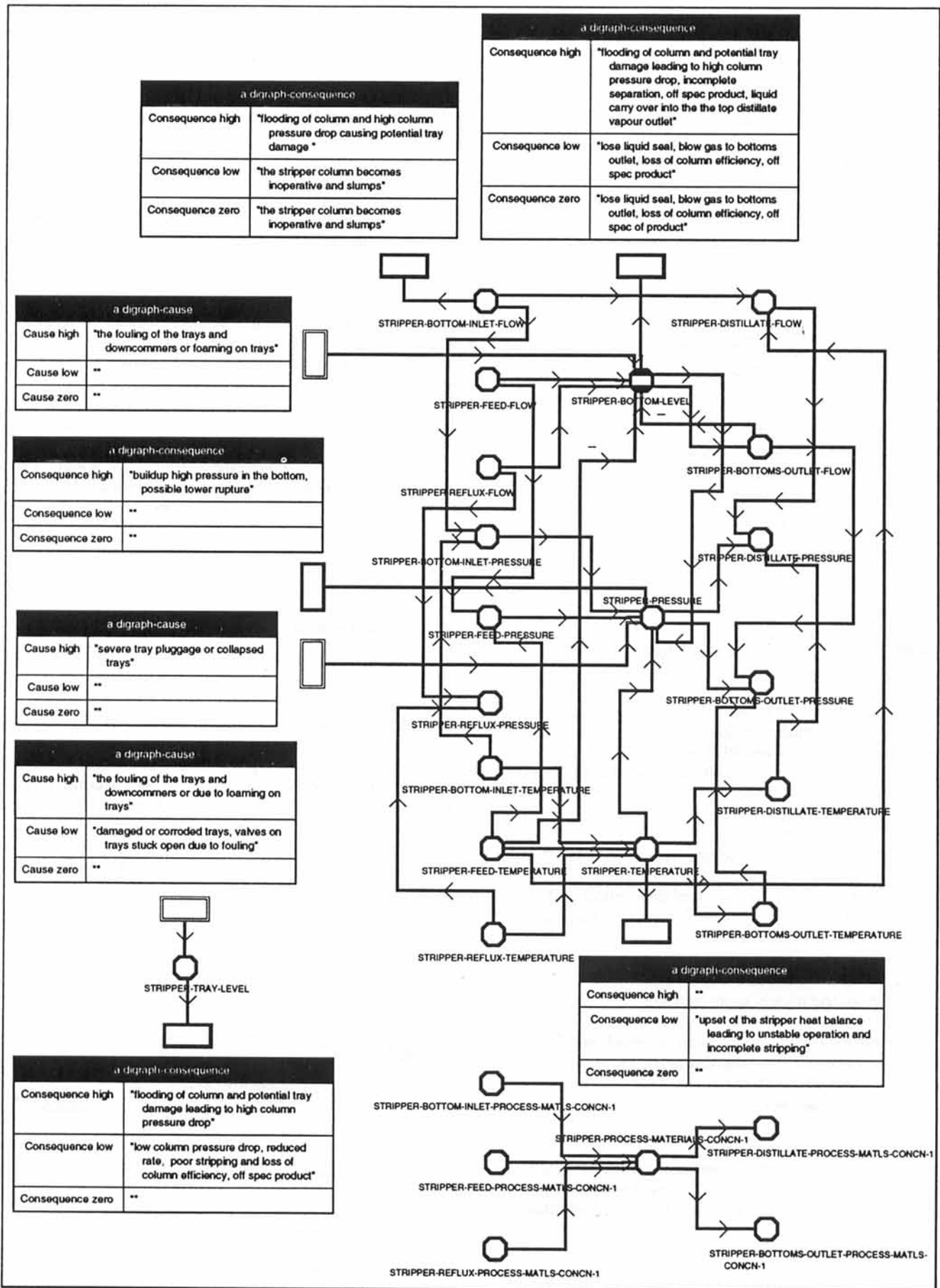


FIGURE 3 The HAZOP-Digraph model of a stripper in HAZOPExpert.

units can be derived from the material and energy balances or from expert's experience-based knowledge. The HAZOP-Digraph (HDG) model is a digraph-based model developed specifically for representing HAZOP knowledge in order to automate the analysis [9]. A HDG model is developed for each process unit in *HAZOPEXPERT*.

As an example, part of the HDG model of the stripper in *HAZOPEXPERT* is shown in Figure 3. The stripper model has digraph nodes (octagonal icons) representing the process variables of the stripper and the arcs connecting these nodes indicating the qualitative causal influence between them. The digraph nodes have a default NORMAL value, and can have the values HIGH, LOW and ZERO corresponding to the HAZOP guide-words MORE OF, LESS OF and NONE. The digraph-arcs have POSITIVE or NEGATIVE arc-gains. Most of the digraph-arcs have POSITIVE arc-gain and hence in Figure 3, only for arcs with NEGATIVE arc-gain, the "-" sign is shown by the side of the arcs. For example, the process variable, 'stripper-bottom-level' is controlled by manipulating the 'stripper-bottoms-outlet-flow' and hence these two process variable digraph nodes are connected by a negative feed-back loop.

The abnormal cause nodes (white rectangular icons) and adverse consequence nodes (black rectangular icons), consist of the knowledge about the process-general abnormal causes and adverse consequences for the process variable deviations in the stripper. These cause and consequence nodes are connected to the appropriate process variable digraph-nodes. For example, the abnormal cause node connected to the 'stripper-bottom-level' has the knowledge that "fouling of the trays and downcomers or foaming on trays" are possible causes for "High stripper-bottom-level". Similarly, the adverse consequence node connected to the 'stripper-bottom-level' has the knowledge that "flooding of column and potential tray damage leading to high column pressure drop, incomplete separation, off spec. product, liquid carry over into the top distillate vapor outlet" are possible consequences of "High stripper-bottom-level".

In addition to these process-general HAZOP knowledge represented in the HDG models, the *HAZOPEXPERT* system has predefined "process-material-cause" and "process-material-consequence" procedures which are used for finding process-specific causes and consequences which are realizable in a given plant. The "process-material-cause" procedure will find the causes of a variable deviation in a process unit due to the properties of the process materials present. For example, this procedure will identify, "blockage of the bottoms outlet from the stripper column due to the accumulation of solid process impurities," as a cause for "High stripper-bottom-level," or "leak in the stripper column due to the presence of corrosive process material," as a cause for "Low stripper-bottom-level."

Similarly, the "process-material-consequence" procedure will find the adverse consequences due to the hazardous properties of the process materials present. For example, this procedure will identify "fire hazard due to the presence of flammable process material" as a consequence for "High stripper-temperature." This procedure will also identify the hazardous consequences due to the loss of containment of toxic or flammable process materials. In addition, the *HAZOPEXPERT* system also has a predefined process-general, "control-loop-cause" procedure for finding the abnormal causes of process variable deviations in control loops due to controller failure, sensor failure, etc.

## HAZOP INFERENCE ENGINE

The top level goal of *HAZOPEXPERT* is to perform HAZOP analysis for a process variable deviation in a process unit or pipe. The abnormal causes for this deviation are found by executing the method for propagation and the method for finding abnormal causes for the process unit and its upstream process units. Similarly, the adverse consequences for this deviation are found by executing the method for propagation and the method for finding adverse consequences for the process unit and its downstream process units.

The method for propagation uses the HDG models to identify the process variable deviations in the process unit and in the pipes connected at the inlets of the process unit, which can cause the process variable deviations under consideration during the HAZOP analysis. In addition, this method also identifies the process variable deviations in the process unit and in the pipes connected at the outlets of the process unit, which can occur as consequences of the process variable deviations under consideration during the HAZOP analysis.

The method for finding abnormal causes for process variable deviations searches for any abnormal cause nodes connected to the deviated process variable nodes in the HDG model of a process unit and identifies the process-general causes. This method also finds the process specific abnormal causes by executing the *process-materials-cause* procedure which interacts with the properties of the process materials present in the process unit. In addition, for controlled variable deviations, the *control-loop-cause* procedure is executed to find the abnormal causes associated with the control loops.

The method for finding adverse consequences of process variable deviations searches for any adverse consequence nodes connected to the deviated process variable nodes in the HDG model of a process unit and identifies the process-general consequences. This method also finds the process specific adverse consequences by executing the *process-materials-consequence* procedure which interacts with the properties of the process materials present in the process unit.

## PERFORMING HAZOP ANALYSIS USING *HAZOPEXPERT*

*HAZOPEXPERT* has been implemented in an object-oriented architecture using Gensym's G2 real-time expert system shell. The Graphical User Interface (GUI) of *HAZOPEXPERT* is shown in Figure 4. This figure displays the essential features of the user interface, namely, the process unit HAZOP model library, the P&ID graphical editor and the HAZOP results windows. *HAZOPEXPERT*'s model library currently has the generic HDG models for 15 process units such as pump, tank, surge drum, heat exchanger, condenser, accumulator, reboiler, stripper, controller, valves, pipe, etc. The user can develop and add the HDG model of a new process unit to *HAZOPEXPERT*'s library using the graphical HDG Model Builder facility in the system. Also, experience-based cause and consequence knowledge of the experts can be added to the existing HDG models.

The P&IDs of the process and the process materials properties are the process-specific information that are to be supplied by the user. If the P&IDs of the process are available in CAD format, they can be automatically im-

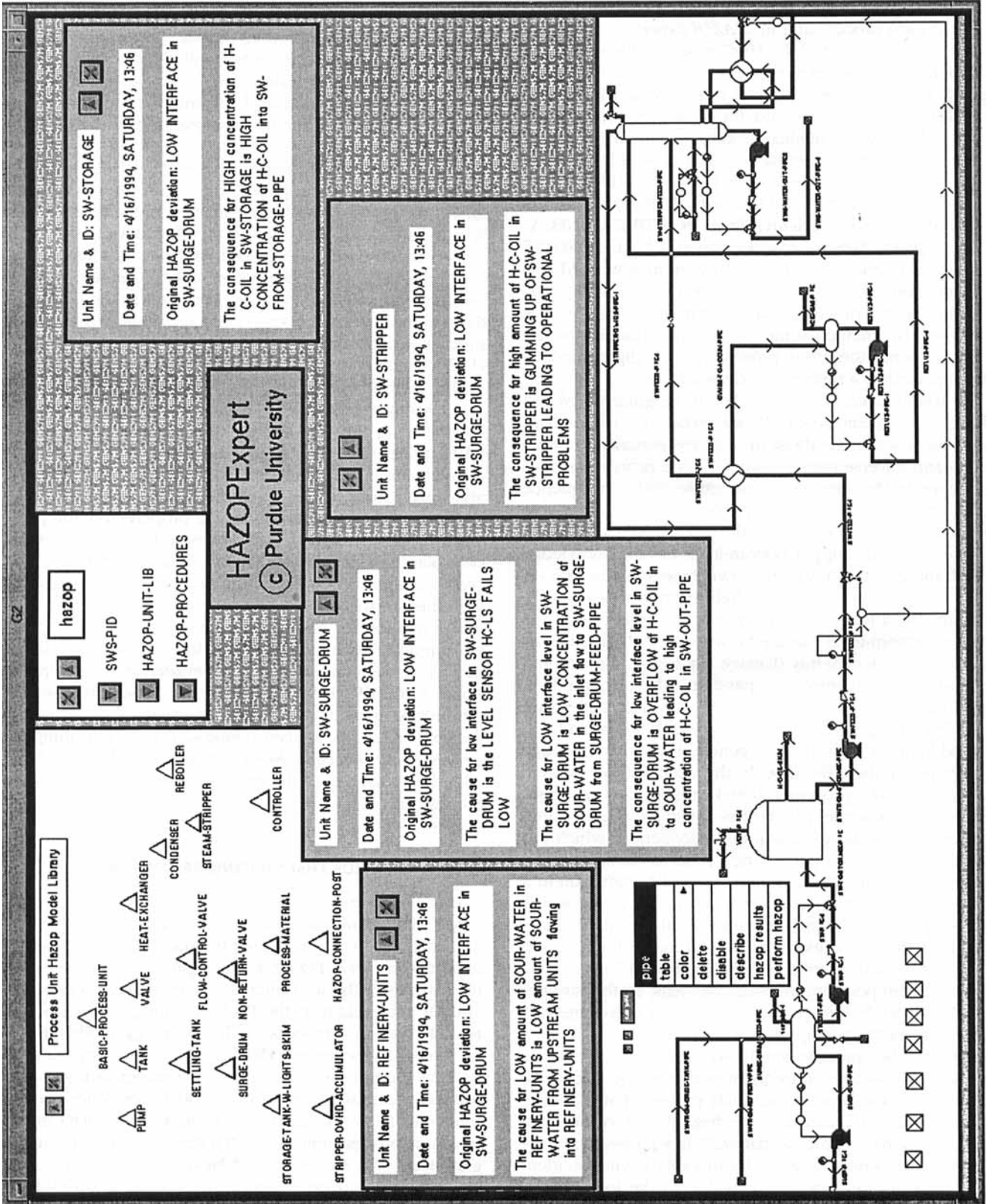


FIGURE 4 The graphical user interface of HAZOPExpert.

ported into *HAZOPExpert*. Otherwise, the user can draw the P&IDs of the process quite easily using the P&ID graphical editor in *HAZOPExpert*. Similarly, if the process material property data are available in any database format they can be automatically imported into *HAZOPExpert*. Once the P&IDs and the process materials property data are input into the system, the corresponding HAZOP models of the process units in the P&IDs get connected automatically internally in the appropriate manner. This greatly simplifies knowledge acquisition for a given process.

A process variable deviation in any process unit or pipe can be initiated by the user by changing the value of the corresponding process variable attribute (flow, pressure, temperature, level, composition, reaction, etc.) to high, low or zero. Thus the process deviations corresponding to the guide words "MORE OF", "LESS OF", "NONE", "PART OF" (change in compositions), and "AS WELL AS" (more components being present in the system, like contaminants, impurities, extra phase, etc.) can be created and analyzed by creating the equivalent process variable deviations in *HAZOPExpert*. Since the current version of *HAZOPExpert* cannot propagate consequences upstream and causes downstream, the HAZOP analysis for the guide word REVERSE (reverse flow, vacuum, etc.) cannot be performed. Also the HAZOP analysis for the non-process variable deviation related guide word OTHER THAN (what else can happen during maintenance, start-up and shut-down?) cannot be performed by *HAZOPExpert*. These features are currently under development.

*HAZOPExpert* will systematically perform HAZOP analysis for a process variable deviation and store the abnormal causes and adverse consequences, in the 'HAZOP results windows' of the process units and the pipes. These results are also stored in user-defined files which can be automatically imported into spreadsheeting software such as Microsoft Excel, or relational databases such as Oracle, or word-processing software such as Microsoft Word. These can be further manipulated and formatted in a user-defined manner for meeting regulatory compliance and other related requirements.

#### HAZOP ANALYSIS OF AN INDUSTRIAL CASE STUDY

The *HAZOPExpert* system has been tested on a number of processes of varying degrees of complexity. Results for the well-known Lawley case study [14], which deals with

the HAZOP analysis of the feed section of an olefin dimerization plant, have been reported elsewhere [8]. In this article, we present the results from applying *HAZOPExpert* to a more complex industrial case study and compare it with the results of a HAZOP study team.

This example involves the HAZOP analysis of a sour water stripping plant. The P&ID of the plant shown in Figure 4 was drawn using the P&ID graphical editor of *HAZOPExpert*. In this process, there are 26 pipes, 5 flow control valves, 5 non-return valves, 5 pumps, 1 surge drum, 1 storage tank, 1 stripper, 1 condenser, 1 stripper overhead accumulator and 6 controllers. This process contains a refinery sour water stream that is separated in a surge drum to remove slop oil from the sour water. The sour water is pumped into a storage tank where any carried over slop oil can be skimmed off. From the storage tank the sour water is pumped through a heat exchanger to a steam stripper where ammonia and hydrogen sulfide are stripped from the water. Hydrocarbon oil is a flammability hazard, and hydrogen sulfide and ammonia are toxic hazards. The release of these materials is a safety concern for the plant. Also, if there is poor separation of hydrocarbon oil from the sour water, the oil will escape into the stripper. This can gum-up the stripper which will cause operational problems.

The HAZOP analysis of this process had been performed earlier by a team using the conventional HAZOP review process. We performed the analysis using *HAZOPExpert* for all conceivable process variable deviations in all the units and pipes in the sour water stripper plant, and compared *HAZOPExpert's* results with the results obtained earlier by the HAZOP study team.

In a typical process unit, there are three deviations for flow (high, low, no), two deviations for temperature (high, low), two deviations for pressure (high, low), three deviations for level (high, low, zero), and three deviations each for the process materials concentration (high, low, zero). Thus, HAZOP analysis can be performed for a total of 734 deviations in all the process units and pipes in the sour water stripper plant using *HAZOPExpert*. The results provided by *HAZOPExpert* for all these cases are too numerous to be listed in this paper. Only some typical examples are given. For instance, the HAZOP results found by *HAZOPExpert* for the process variable deviation "low interface level in surge drum" are shown in the HAZOP results windows of the process units in Figure 4. Note that *HAZOPExpert* propagates the deviation all the way downstream to the stripper and has found the ultimate conse-

TABLE 1. HAZOP Study Team's Results

Unit-ID	Variable	Deviation	Causes	Consequences
SURGE-DRUM-1	INTERFACE-LEVEL	HIGH	Level sensor I-L-S fails, affects oil interface	Overflow of water into slop oil from SURGE-DRUM-1
SURGE-DRUM-1	INTERFACE-LEVEL	LOW	Level sensor I-L-S gets hung up	Overflow of hydrocarbon oil into sour water from SURGE-DRUM-1
SURGE-DRUM-1	LEVEL	LOW	Level sensor L-S hangs up in HIGH position	OIL-RECOVERY-PUMP never shuts down and pumps SURGE-DRUM-1 dry, pump overheats, seals fail
			Drain valve left open in SURGE-DRUM-1 drain line	Loss of sour water to sewer

quence, "gumming up of the stripper due to high amounts of hydrocarbon oil entering the stripper". In the HAZOP analysis performed by a team, it will be difficult for the team members to propagate the consequences through all the downstream units as far as *HAZOPEXPERT* does.

When a HAZOP team performs a conventional HAZOP analysis, it is not possible to consider all the 734 process variable deviations separately like *HAZOPEXPERT* did. Instead, the HAZOP team groups a number of connected pipes, valves, and pumps and other units into study nodes and perform the analysis for these study nodes. This way, the total number of deviations considered by the HAZOP team will be considerably reduced. This "study node HAZOP" is also emulated in *HAZOPEXPERT* by facilitating the

grouping of process units in the P&ID in to study nodes by marking them graphically using the graphical user interface. In the sour water stripper case study, 135 total process variable deviations in 12 study nodes were considered by the HAZOP team, and 32 abnormal causes and 32 adverse consequences were reported. For all these process variable deviations, *HAZOPEXPERT* was able to find the abnormal causes and adverse consequences that were identified by the HAZOP team. For example, the HAZOP results identified by the study team and the *HAZOPEXPERT* system for three process variable deviations considered in "surge-drum-1", are presented in Tables 1 and 2 respectively. It should be noted that Table 2 is the automatically collated HAZOP results in the standard regulatory compliance re-

**TABLE 2. HAZOPEXPERT System Results**

UNIT-ID	Variable	Deviation	Causes	Consequences
SURGE-DRUM-1	INTERFACE-LEVEL	HIGH	HIGH INLET-FLOW into SURGE-DRUM-1	HIGH LEVEL in SURGE-DRUM-1, filling-up and overflow of the surge drum, possibility of liquid entering vent
			LOW HEAVYS-OUTLET-FLOW from SURGE-DRUM-1	HIGH PRESSURE in SURGE-DRUM-1, possible release of flammable H-C-OIL (IMPURITY), into plant area due to leak, causing fire hazard
			HIGH PROCESS-MATERIALS-CONCN of the RAW-MATERIAL, SOUR-WATER in SURGE-DRUM-1	HIGH LIGHTS-OUTLET-FLOW from SURGE-DRUM-1
			LOW PROCESS-MATERIALS-CONCN of the IMPURITY, H-C-OIL in SURGE-DRUM-1	LOW HEAVYS-OUTLET-PROCESS-MATERIALS-CONCN of the IMPURITY, H-C-OIL from SURGE-DRUM-1
			Level sensor I-L-S fails LOW, or SURGE-DRUM-1 level controller H-L-C fails LOW with reversed control action	HIGH LIGHTS-OUTLET-PROCESS-MATERIALS-CONCN of the RAW MATERIAL, SOUR-WATER from SURGE-DRUM-1
SURGE-DRUM-1	INTERFACE-LEVEL	LOW	LOW INLET-FLOW into SURGE-DRUM-1	LOW LEVEL, leading to LOW PRESSURE in SURGE-DRUM-1
			HIGH HEAVYS-OUTLET-FLOW from SURGE-DRUM-1	LOW LIGHTS-OUTLET-FLOW from SURGE-DRUM-1
			LOW PROCESS-MATERIALS-CONCN of the RAW-MATERIAL, SOUR-WATER in SURGE-DRUM-1	HIGH HEAVYS-OUTLET-PROCESS-MATERIALS-CONCN of the IMPURITY, H-C-OIL from SURGE-DRUM-1
			HIGH PROCESS-MATERIALS-CONCN of the IMPURITY, H-C-OIL in SURGE-DRUM-1	LOW LIGHTS-OUTLET-PROCESS-MATERIALS-CONCN of the RAW MATERIAL, SOUR-WATER from SURGE-DRUM-1
			Level sensor I-L-S fails HIGH or SURGE-DRUM-1 level controller H-L-C fails HIGH with reversed control action	

(Continued on following page)

**TABLE 2.** Continued

UNIT-ID	Variable	Deviation	Causes	Consequences
SURGE-DRUM-1	LEVEL	LOW	LOW INLET-FLOW into SURGE-DRUM-1	LOW INTERFACE-LEVEL in SURGE-DRUM-1
			HIGH LIGHTS-OUTLET-FLOW in SURGE-DRUM-1	OIL-RECOVERY-PUMP motor trips out on overload, process upset
			Level sensor L-S fails HIGH or SURGE-DRUM-1 level controller L-L-C fails HIGH with reversed control action	Loss of NPSH, cavitation problem, and damage of OIL-RECOVERY-PUMP
			Drain valve left open in the drain line of SURGE-DRUM-1	Release of flammable H-C-OIL (IMPURITY), into plant area due to leak, causing fire hazard
				LOW HEAVYS-OUTLET-FLOW from SURGE-DRUM-1
				HIGH HEAVYS-OUTLET-PROCESS-MATLS-CONCN of the IMPURITY, H-C-OIL from SURGE-DRUM-1
				LOW LIGHTS-OUTLET-PROCESS-MATLS-CONCN of the RAW-MATERIAL, SOUR-WATER from SURGE-DRUM-1

ported spreadsheet format output from the *HAZOPExpert* system.

From Tables 1 and 2, it is evident that *HAZOPExpert's* results include those found by the study team. Also, *HAZOPExpert* found more number of causes and consequences than those recorded by the study team. This is partly due to the thorough nature of the analysis performed by the *HAZOPExpert* system. However the main reason for this is the strict qualitative reasoning approach for the analysis implemented in *HAZOPExpert*. Though HAZOP analysis is a qualitative approach, the experts in the study team filter their initial results using additional quantitative information in the form of the design specifications and normal operating conditions of the process units, and the quantitative properties of the process materials. Using this additional quantitative knowledge, the HAZOP team decides whether a process variable deviation will actually lead to the predicted hazardous consequences. In the absence of this additional knowledge, the *HAZOPExpert* system assumed the worst case scenario and hence found more number of consequences. These aspects of expert's reasoning have not been incorporated in *HAZOPExpert* yet and we are currently investigating these issues.

From a computational perspective, *HAZOPExpert* is quite fast. On a Sparc 1 class machine, for the sour water stripper case study, it generated all the causes and consequences for a given deviation in a matter of seconds. The entire HAZOP analysis considering all the 734 possible deviations can be performed in about an hour or so in an automated mode of the *HAZOPExpert*. Since the *HAZOPExpert* system is implemented using the expert system shell G2, it will run on any machine which runs G2. Currently G2 runs on Sun Workstations, SPARCstations, HP Workstations, DECstations and PCs (NT Windows).

#### CONCLUSIONS AND FUTURE WORK

A model-based expert system for automating HAZOP analysis called *HAZOPExpert* has been developed. One key feature of our system is the identification and the separation of HAZOP knowledge into process-specific and generic components. These two components interact with each other to cover the process-specific aspects of HAZOP analysis while maintaining the generality of the system as much as possible. The other important idea is the use of generic cause-and-effect HAZOP-Diagraph models of process units that are applicable to a variety of process configurations. Typical performance results are reported for an actual industrial HAZOP case study of a sour water stripper plant. *HAZOPExpert* generated the results that were obtained by conventional HAZOP analysis by a HAZOP team. The expert system is fast, and is quite easy to use and update. Further research is underway to include quantitative information and semi-quantitative reasoning for filtering the HAZOP results, and for the ranking of the various adverse consequences identified by *HAZOPExpert*. Efforts are also underway to make *HAZOPExpert* available as a commercial product.

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## LITERATURE CITED

1. **Department of Labor, Occupational Safety and Health Administration**, "Process Safety Management of Highly Hazardous Chemicals; Explosives and Blasting Agents; Final Rule," 29 CFR 1910.119, published in the Federal Register, pp. 6356-6417 (February 24, 1992).
2. **Center for Chemical Process Safety (CCPS)**, *Guidelines for Hazard Evaluation Procedures*, AIChE, New York (1985).
3. **Knowlton, R. E.**, *Hazard and Operability Studies: The Guide Word Approach*, Chematics International Company, Vancouver (1989).
4. **Kletz, T. A.**, *HAZOP & HAZAN Notes on the Identification and Assessment of Hazards*, The Institution of Chemical Engineers, Rugby, England (1986).
5. **Kletz, T. A.**, *What Went Wrong? - Case Histories of Process Plant Disasters*, Chapter 18, pp. 189-196, 2nd edition, Gulf Publishing, Houston, Texas (1988).
6. **Kletz, T. A.**, "Incidents That Could Have Been Prevented by HAZOP," *Journal of Loss Prev. Process Ind.*, **4**, (January, 1991).
7. **Freeman, R. A., Lee, R., and McNamara, T. P.**, "Plan HAZOP Studies with an Expert System," *Chem. Eng. Prog.*, pp. 28-32 (August, 1992).
8. **Venkatasubramanian, V., and Vaidhyanathan, R.**, "A Knowledge-Based Framework for Automating HAZOP Analysis," *AIChE Journal*, **40**, pp. 496-505 (1994).
9. **Vaidhyanathan, R., and Venkatasubramanian, V.**, "Digraph-Based Models for Automated HAZOP Analysis," *Reliability Engineering System Safety*, **50**, pp. 33-49 (1995).
10. **Lapp, S. A., and Powers, G. J.**, "Computer-aided Synthesis of Fault-Trees," *IEEE Trans. Reliab.*, **R-26**, pp. 2-13 (1977).
11. **Iri, M., Aoki, K., O'Shima, E., and Matsuyama, H.**, "An Algorithm for Diagnosis of System Failures in the Chemical Process," *Comp. and Chem. Engg.*, **3**, pp. 489-493 (1979).
12. **Shiozaki, J., Matsuyama, H., O'Shima, E., and Iri, M.**, "An Improved Algorithm for Diagnosis of System Failures in the Chemical Process," *Comp. and Chem. Engg.*, **9**, pp. 285-293 (1985).
13. **Oyeleye, O. O., and Kramer, M. A.**, "Qualitative Simulation of Chemical Process Systems: Steady-State Analysis," *AIChE Journal*, **34**, pp. 1441-1454 (1988).
14. **Lawley, H. G.**, "Operability Studies and Hazard Analysis," *Chem. Eng. Prog.*, pp. 105-116 (April, 1974).

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