HAZOP STUDIES – A NEW APPROACH?

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The HAZOP method was originally developed within ICI almost 40 years ago and is now a de facto standard approach to identifying, and managing hazards on process plants in most developed countries.

There is no doubt that the technique deserves much credit for avoiding loss of life and costly accidents worldwide.

Because of the very comprehensive and painstaking keyword approach, a Hazop study requires a significant and dedicated human resource for the duration of the study which can be weeks or months on a large or complex facility.

The objective of the present paper is to present for examination some ideas how the technique might evolve – so as to retain the benefits but achieve them more efficiently and quickly. A by-product of this could be identifying hazardous situations that might otherwise be missed.

Finally some situations are identified where the new approach has limitations or needs further development. A hypothetical example of the new method is presented in an Appendix.

INTRODUCTION

The scope of this paper relates to steady state processes in the chemical process or energy industries. Batch processes are presently outside the scope of this approach.

The author has participated in Hazop studies in various branches of the Process industries ranging from oil and gas, to cryogenics and utilities and off sites. He has also assisted with providing Hazop training. The ideas and opinions described herein are entirely those of the author.

A BRIEF HISTORY AND EVOLUTION OF HAZOP

HAZOP became the industry standard acronym or abbreviation for Hazard and Operability studies following pioneering work at ICI by Trevor Kletz and Ellis Knowlton in the late 1960s and early 1970s. Since then Kletz (2006) [1] has kept the methods up to date and fresh via new material and mnemonic illustrations. The procedure quickly evolved to use a fairly standard set of keyword combinations to trigger a structured team analysis of new process designs and proposed revamps. Recently Crawley et al. 2008 [2] have advocated using 'guidewords' (more, less etc) together with 'parameters' (temperature, pressure etc) rather than the less precise 'keyword'. Whilst this clarification is welcomed, in the present paper, both terms are used interchangeably – hopefully without compromising the objective.

In the 1980s with the advent of PCs computer software was developed to record and review the excursions, consequences and assign actions to responsible parties to resolve. These days the draft report is typically prepared 'on the spot' by the secretary/leader using a laptop PC and projected on a screen in the meeting room, so the team members have an opportunity (and a duty) to approve what is being recorded. The Hazop report became a document with potential legal significance with the increased focus on HSE following a number of well-publicised accidents in the industry.

In the 1990s the likelihood-severity matrix commonly became used for prioritising issues unearthed during the study.

Safety Integrity Level – SIL reviews were adopted increasingly since the late 1990s and early 2000s. This technique needs more expertise on the part of the leader to achieve a successful review.

Process Simulation software is now available to help evaluate upset scenarios during the Hazop study to enable more rapid resolution of issues.

POTENTIAL SHORTCOMINGS OF THE TRADITIONAL METHOD

The traditional Hazop process uses a combination of guidewords and parameters (or keywords) for positive or negative deviations from normal measured operating variables such as temperature, pressure or level to trigger a team brainstorming session for potential hazards. Potential causes of the deviation are then solicited from the team, followed by a group assessment of the consequences. The adequacy of mitigating measures is then reviewed, and when the team is concerned that an unacceptable residual risk remains – an action is assigned to the appropriate team member.

This approach is normally applied to each pipe linking major items of equipment in turn until the entire scope of the study has been covered.

In this standard approach two potential drawbacks are apparent:

(i) A given hazardous scenario often has multiple symptoms and is therefore reached via several deviation guidewords or keywords. For example, a loss of coolant flow to a column reflux condenser can and will lead to increasing temperature and pressure, falling level in the reflux drum and loss of overhead purity. Each of these deviations will eventually lead the team to the same root cause.

(ii) The way that the process is subdivided into relatively small piping sub-systems, sometimes called 'nodes' means that adjacent sections may be affected by the same upset – again leading to repetitiveness, and slowing progress. Minimising this currently depends on the skill of the Hazop leader.

(The common use of the term 'node' in Hazop jargon for a section of pipe linking major equipment is an unfortunate misnomer. Node (from the same root as knot) should strictly refer to the *point* of interconnection of (for example) branches of a piping network.)

Repeatedly arriving at the same scenarios can lead to some tiredness or boredom on the part of team members, and it means that time and human resource are not used as effectively as possible. Some creativity may be lost as a result.

Recognition of these drawbacks prompted the author to consider how the Hazop process might be modified in order to minimise repetition and perhaps increase creativity, whilst retaining the benefits of a thorough review. Using the proposed new concept, the system under consideration is exposed to a small number of generic disturbances in turn and assessed for their feasibility. Where the disturbance is possible, all potential causes that the team can identify are listed followed by their likelihoods. The consequences of the disturbance and the severity of these consequences are then defined. Existing mitigating measures are then applied to assess whether the net overall risk = (likelihood × severity) is acceptable or not.

CONCEPTS THAT THE HAZOP TEAM MUST UNDERST AND TO APPLY NEW APPROACH

Although most of the team members will likely have some familiarity with the concepts of Material and Energy balances and steady-state operation, it is worth ensuring at the outset of a study that this is the case – since appreciating these concepts is fundamental to the success of the new method.

The tendency of systems to reach Equilibrium is a third concept that can give insights into how some hazards arise. Its understanding by the team members is not as essential as the other two concepts, but it may be useful in promoting creative thinking by Process Engineers or Hazop team leaders.

STEADY STATE

Steady state is the ideal operating mode for a continuous process. It cannot apply to a batch process. Steady state means that feeds flow into – and products emerge from the process – both at constant (steady) rates. Streams are heated and cooled and mixed, reacted or separated, but at each and every point in the process, the properties such as temperature, pressure, flow level, composition remain essentially constant. Minor perturbations are expected and limited by functioning and properly tuned automatic control loops. (Start-ups and shutdowns are clearly not steady state and need to be tackled separately.)

Hazards arise when this steady state condition no longer applies. In the traditional Hazop approach the guidewords with parameters are essentially the symptoms or triggers for the team to look for causes of the loss of steady state.

MATERIAL AND ENERGY BALANCES

At steady state, although materials flow into and out of a process – or into and out of a sub-system being considered, there is *no net change* in the mass hold-up or inventory of the process or sub-system.

In the same way, although energy may be added to a process (or sub-system) for example via steam heaters, electric heaters, pumps and compressors, and removed by coolers and heat losses through insulation, *at steady state*, there is *no net change* in the total energy content of the process or sub-system.

The perceptive reader will ask 'What about reactions?' These indeed need special attention since although mass is always conserved, the number of moles may change – affecting the volume of a gas-phase reaction, and the heat of reaction – positive or negative must always be taken into account.

These concepts are very familiar to the Process engineer, and need to be understood by the other Hazop team participants. Therefore at the start of the study a brief refresher is strongly recommended.

OTHER USEFUL CONCEPTS – EQUILIBRIUM

Equilibrium is often equated to the lowest energy state of a system. In nature, systems are generally close to equilibrium. If not nature can move quickly to correct this, and natural hazards can arise either directly or as a secondary consequence of the 'equilibration' – e.g. Storms, (leading to floods), lightning strikes (leading to forest fires when conditions are dry), earthquakes and volcanoes and so on.

A system can be in a state of dynamic equilibrium, where at a small scale or local level parts of the system are changing, but other parts are changing in the opposite sense, so that overall there is no net change. For example water continuously evaporates into the atmosphere from the oceans, lakes and rivers, but elsewhere condenses and falls as rain.

When we operate a chemical process, we are intentionally taking substances – both natural and man-made – away from a state of equilibrium with the environment. We concentrate and purify feed stocks – making them more reactive. We pressurise fluids to convey them and heat, react and separate them to enable their conversion into products that are more valuable to mankind.

Examples are evident in most of the so-called Unit Operations such as compressors, heat exchangers, reactors etc.

Clearly either taking substances away from a state of equilibrium with the environment, or dealing with process streams that are not equilibrium with each other is to some extent an essential feature of virtually all traditional chemical processes, but this displacement from equilibrium creates conditions with the potential for a spontaneous change – to restore equilibrium. ***Where or when we fail to control or prevent such a spontaneous change is exactly what causes an actual hazard.*** The failure can be a mechanical failure (heat exchanger tube ruptures, cooling water pump stops) or control system or instrument failure (valve sticks, instrument or software error) or human error (valve mal-operation).

(Chemists will recognise that the potential for spontaneous change is analogous to or in some cases identical to the Chemical Potential or Free Energy).

A continuous process may be considered to be in a state of dynamic equilibrium from which disturbances can lead to hazards. However, the main point of this section is that the conditions of dynamic equilibrium although steady, do not correspond to true equilibrium between process streams or equilibrium with the environment.

META-STABLE EQUILIBRIUM

We can be fooled into thinking that conditions are steady and that no potential for hazards exist, when in fact, parts of a system are far removed from equilibrium and a small nudge in conditions can lead to a rapid equilibration with unforeseen and undesirable consequences.

Examples include:

- Steam and cold condensate which suddenly contact each other leading to steam hammer and potential damage and loss of containment;
- Two phase flow in a pipeline where liquid is steadily accumulating at a low point and eventually forms a seal with the top of the pipe, which becomes a slug that is accelerated to the end of the line where damage can ensure if not anticipated.
- Cooling a cryogenic vessel or tank containing relatively warm vapour using cold liquid fed to the top. On contact with the cold liquid, the vapour tends to contract leading to a partial vacuum that pulls more of the cold liquid into the tank – the runaway situation can potentially lead to a collapse of the tank.

Although the concepts of equilibrium are not central to the new Hazop approach, they are mentioned here as they can be a useful additional tool for the Hazop leader to prompt the creative process.

OVERVIEW OF NEW PERSPECTIVE FOR HAZOP PROCEDURE

There are two ways in which I believe the HAZOP process can potentially be simplified and a thorough review of potential risks achieved with less time and effort. It will be seen that these two proposed changes are complementary.

(i) The definition of each sub-system under consideration by the team.

Instead of a pipe linking major equipment items [1], define a *system* of piping and equipment items which are interconnected in normal operation *and* which has a common mechanical design pressure, and typically a similar normal operating pressure.

At steady state this system can be envisaged as an *envelope* through whose boundaries material and energy pass, without any net change in the material or energy content of the envelope.

(ii) Introduce alternative deviation keywords based on

a. More material = Positive change in the steady state material balance for the envelope or any of its component parts.
b. Less material = Negative change in the steady state material balance for the envelope or any of its component parts.
c. More Energy = Positive change in the steady state energy content of the envelope or any of its component parts.
d. Less Energy = Negative change in the steady state energy content of the envelope or any of its component parts.

For each keyword, list and enumerate the local causes of the change, their consequences, any knock-on effects (perhaps in other linked systems) and mitigating factors – if any.

Note that the change in total energy content of the material within a system as a direct consequence of the change in material content itself is a trivial case.

BASIC PREMISE OF NEW PERSPECTIVE HAZOP

For ease of reference and to distinguish from the traditional approach, the author has chosen to coin the phrase – New Perspective (NP) Hazop. The basic premise underlying the (NP) Hazop is that any upset that can lead to a potential hazard, is a result of a deviation from normal steady-state operating conditions within the system under consideration, and this corresponds to a violation of the material and/or energy balance of the system.

Such a deviation is often linked to a corresponding disturbance in an adjacent directly or indirectly connected system. The linked systems may include the environment.

ORGANISATION OF AND PREPARATION FOR A HAZOP STUDY

It is well documented that a successful Hazop, – whether traditional or modified approach – requires P&IDs that have been developed to the IFE (Issue for engineering) or sometimes called IFD (Issued for Design) level. This means they are substantially complete and no significant

Table 1. Comparison between traditional hazop and new perspective

	Traditional approach		New perspective	
Division of plant into sections	Each line between major equipment items		Each subsystem having a uniform mechanical design pressure	
Method for triggering brainstorming analysis	Guideword	Parameter	Guideword	Parameter
	No	Flow	Increase	Material within system
	More	Flow	Increase	Individual Component
	Less	Flow	Decrease	Material within system
	Reverse	Flow	Decrease	Individual Component
	More	Pressure	Increase	Energy content of system
	Less	Pressure	Decrease	Energy content of system
	Reverse	Pressure (=vacuum)	Other factors	Various
	More	Temperature		
	Less	Temperature		
	More	Level		
	Less	Level		
	Other	Various		

changes are expected as a result of the Hazop, although minor changes are probably inevitable.

Plant layout, PFDs, heat and mass balance data and equipment datasheets should also be available to the team along with Cause and Effect diagrams and MSDS (hazardous materials data) if applicable.

As already stated, under the NP approach, each system considered comprises equipment items and piping that have a *common design pressure* and as such the system is bounded by a 'pressure break' – frequently by a line class break. These break points that define where the system 'envelope' is penetrated should be clearly marked, and colour coded on the P&IDs.

If using the proposed NP approach, the size of each system being considered may be larger than the traditional 'nodes' considered, and may well span several P&IDs, it is therefore recommended that the team makes use of an additional 'overview' type of flowsheet that is sometimes prepared as part of the project documentation. Where a single pressure system is considered too large to manage easily, the team or leader may elect to subdivide at a convenient point into two systems in series.

To facilitate the Hazop, particularly using the proposed new NP approach, it is suggested that a Process Safeguarding flowsheet PSFS be available *for each major system*. This should clearly show the major items within each system or loop, all safeguarding features – PSVs and trips together with their settings. Major control loops will also be shown. Additional detail such as vents and drains may be omitted but will be seen on the P&IDs. The objective of the PSFS is not to replace the P&IDs for the purpose of the Hazop, but to give the team a helicopter view of the system being considered, and to aid creativity when brainstorming potential excursions. In the absence of a PSFS, a set of colour-coded PFDs showing system limits can be helpful.

NEW PERSPECTIVE (NP) PROCEDURE

The basic principles of the NP Hazop method have been introduced above and the procedure is illustrated below by a simple flowchart, Figure 1.

A comparison of typical trigger keywords used in the traditional Hazop process and the NP Hazop is shown in Table 1.

A hypothetical example is presented using a simplified flow-scheme, Figure 2 for part of a process and the corresponding Hazop worksheets partially completed using the new method are shown in Table 2.

MAIN KEYWORDS

- **More Material** in envelope (System) – Extra input flow or Less Output flow
- More of a particular component
- **Less Material** in envelope (System) – Less input flow or more Output flow
- Less of a particular component

NB. Review flows to and from connections not in normal operation – drains, steam-outs; etc and possible flows in the wrong direction if feasible. Consider and list emissions to the environment and streams taken from the environment

- **More Energy in envelope (System) – Extra input or Less Output**
- **Less Energy** in envelope (System) – Less input or more Output

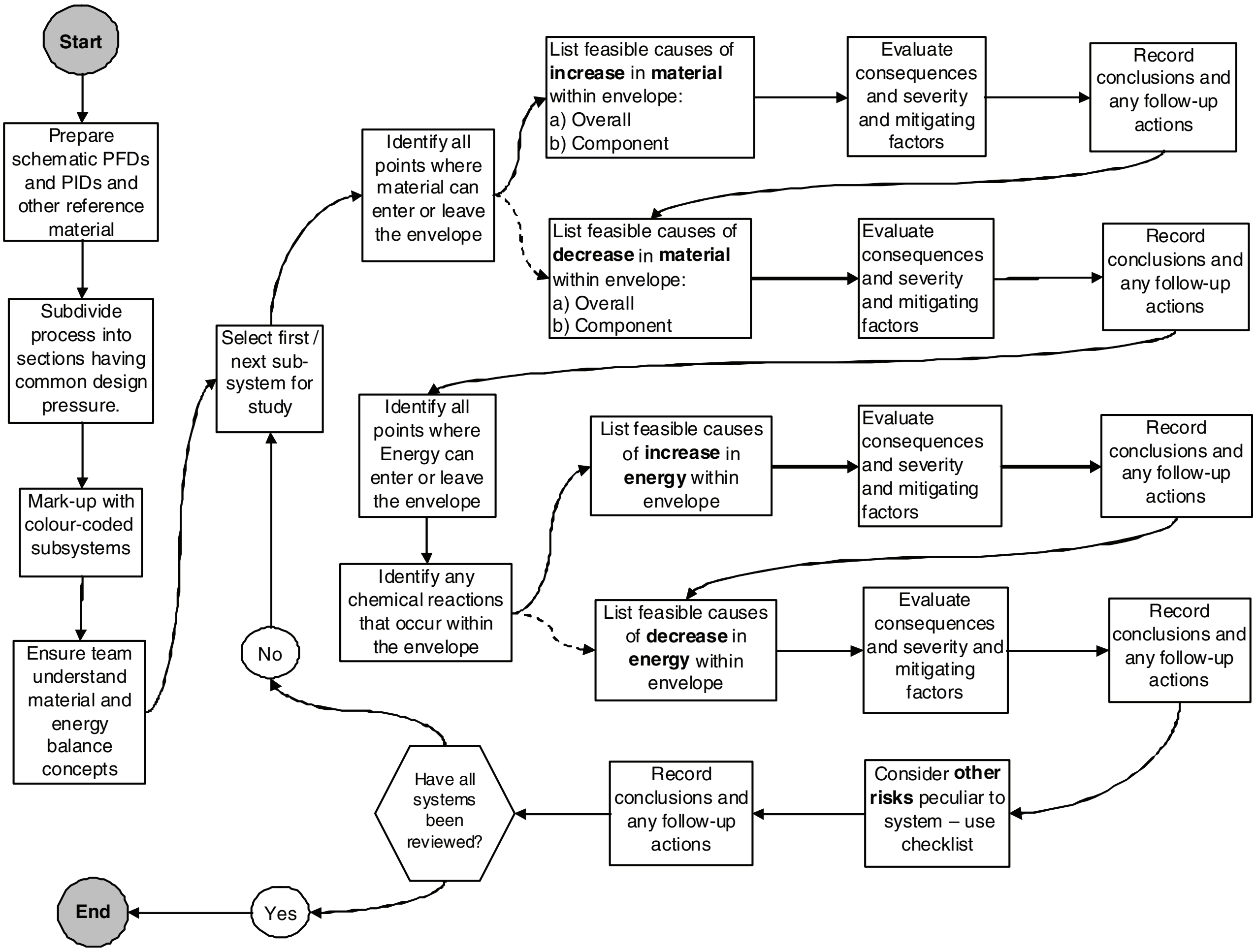

Figure 1. Flowchart for new hazop procedure

Consider energy exchange with the environment, and utility failures.

SUGGESTED OTHER KEYWORDS

- Input issues raised in Hazops of adjacent systems
- Start-up risks – review procedure
- Shut down risks – review procedure
- Load changes
- Reactions – effect of changes in feed flow and/or changes in feed composition
- Un-intended reactions? Corrosion/electrolytic effects/ solid precipitation
- Unplanned contact between systems removed from equilibrium
- Special maintenance requirements

Other situations and factors to be considered during the study are identified – often by the Hazop leader, such as: Filter change-over, offline vessel steam-out, maintenance, accessibility of instruments where operating procedures are important mitigating factors, corrosion, precipitation of solids, winterization, local environmental challenges such as dust storms, poplar pollen clogging air intakes, forest fires, hail, lightning, flooding, terrorist attack etc.

ISSUE BIN

In common with most meeting formats these days, disagreements often arise and without such conflicts there would be no progress. However big egos with entrenched positions can sometimes inhibit progress of the meeting and a skilled chairman or Hazop leader will anticipate these by having a flip chart for the 'Issue Bin' where all unresolved issues are clearly recorded and actions assigned at the end of the day. This will allow time outside the Hazop to gather more information and enable resolution on a rational basis.

COMPARISON

Identification of risks using conventional Hazop, the NP Hazop and third approach starting with the root cause can be compared. They may be considered respectively

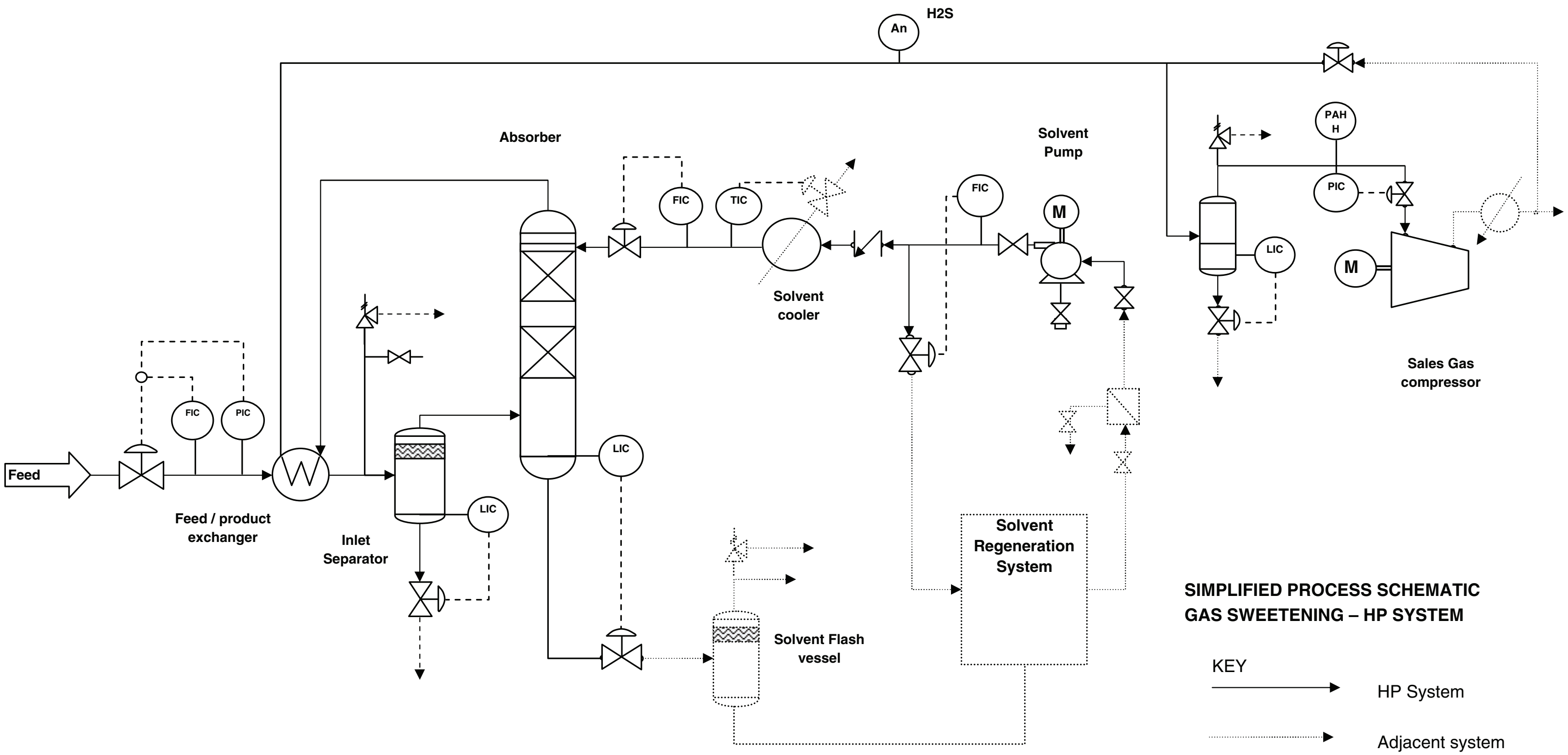

Figure 2. Process flow schematic for part of a Gas Sweetening plant

Table 2. Example worksheet

	NP Hazop Worksheet table - partially completed							
	System number	*Reference number*				**Key**		
	System	*Description of system being considered and its broad function*				Likelihood	High = 5, Low = 1	
	P&IDs	*List of all PIDs covered by this system*				Severity	High = 5, Low = 1	
	Other Flow diagrams	*For example safeguarding or schematic flow diagram for the system*				Net Hazard	Likelihood x Severity	
	System Des P (kPag)	*Design pressure for all components of the system being considered*						
	Overall Material Balance - increase of material within system - gas and liquid							
	Causes	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Sales compressor trips	5	Pressure rise in system	1		5	Inlet valve closes if on auto. Independent high pressure trip	
		5	Overpressure absorber - Loss of containment	5		25	PSV on absorber	
		5	Sales compressor loads up. IGVs open to try to maintain pressure	1		5		
		5	Solvent pump moves up curve. Min flow recycle may open.	1		5		
		5	Possible foaming or carryover from columns - damage to sales compressor	4		20	Suction scrubber	
2	Inlet Flow valve fails open	2	Pressure rise in system	1		2	Independent high pressure trip	
		2	Overpressure absorber - Loss of containment	5		10	PSV on absorber	check PSV capacity rated for full flow
3	Absorber Level valve fails closed	2	High level in absorber	2	May backflow into inlet scrubber	4	High level alarm on absorber bottoms	
4	Pump flow control maloperated	2		2		4		
5	Compressor antisurge valve opens	3	Pressure rises in system	2	Similar to compressor trip but less severe	6	Inlet valve closes if on auto. Independent high pressure trip	
	Component Material Balance - increase of specific component(s) within system - gas and liquid							
	Causes	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Increased acid gas in feed	5	Absorber may not be able to absorb - high acid gas ex absorber	1	Off specification sales gas. Potential corrosion in line to compressor and scrubber.	5	Alarm on Sales gas. Trip open gas to Flare.	Consider lining scrubber

Table 2. Continued

	Overall Material Balance - decrease of material within system - gas and liquid							
	Causes	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Inlet valve fails closed	2	Loss of feed, compressor goes onto recycle	1	Absorber may dump liquid giving high level	2		
2	Inlet separator level valve fails open	2	Loss of liquid seal - gas blow-by into condensate drain system. Potential overpressure and LOC	5	Check pressure rating of drain system	10		Check adjacent system downstream of separator LV
3	Absorber level valve fails open	2	Loss of liquid seal - gas blow-by into flash vessel. Potential overpressure and LOC	5	Check pressure rating of Flash vessel	10		Check adjacent system downstream of Adsorber LV
4	Compressor suction scrubber level valve fails open	3	Gas blowby into drain system. Potential overpressure and LOC	5	Check pressure rating of drain system	15		Check adjacent system downstream of scrubber LV
5	Solvent pump trips	4	Off spec sales gas. Dump to flare. Environmental emission.	2		8	Alarm on Sales gas. Trip open gas valve to Flare.	Consider standby pump with auto start.
6	Compressor suction pressure controller maloperates too far open	3	Pulls down pressures in system - possible liquid carryover from absorber, loss of purity	2		6	Alarm on Sales gas.	
7	Solvent cooler tube leak	1	Potential overpressure of LP coolant system and LOC.	5	Coolant side of exchanger designed for 77% of HP side, but consider piping.	5		Consider impact on coolant system Hazop
8	Inlet scrubber demister pad plugged	3	Reduced flow into absorber. Possible damage to demister pad if DP too high.	2	Inlet valve tends to open to compensate for restriction.	6	Pressure control override eventually prevents over pressuring inlet exchanger and scrubber.	Consider DPI with alarm across demister pad.
		1	If total blockage of pad - risk overpressuring inlet scrubber vessel	5		5	PSV on inlet scrubber - upstream of demister pad	Consider removing pad if blocking likely

	Component Material Balance - decrease of specific component(s) within system - gas and liquid							
	Causes	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Decreased concentration of absorbent solvent	5	Absorber may not be able to absorb - high acid gas ex absorber	1	Off specification sales gas. Potential corrosion in line to compressor and scrubber.	5	Alarm on Sales gas. Trip open gas to Flare.	Consider lining scrubber
							Monitor strength of absorbent solvent periodically	

Table 2. Continued

	Energy Balance - increase of energy within system							
	Causes	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Inlet gas temperature increases	4	Loss of performance in absorber	2		8	High temperature alarm Compressor inlet scrubber	
2	Solvent cooler fails	2	Loss of performance in absorber	2	Loss of coolant or failure of temperature control loop	4	High temperature alarm on solvent	
3	Solvent pump on recycle overheats	1	Damage to pump, loss of production	3		3		
	Energy Balance - decrease of energy within system							
	Causes	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Inlet gas temperature decreases	3	Loss of performance in absorber			0		
2	Loss of temperature control on solvent cooler	3	Excessive cooling of solvent - possible hydrocarbon condensation in absorber	4	Possible foaming in absorber, carryover to sales gas line	12	Compressor inlet scrubber	Add Low temperature alarm
3	Loss of heat to environment in winter	3	Potential freezing in stagnant aqueous systems	4		12	Heat tracing	Operating procedure to ensure functioning
	Other Disturbances							
	Causes / disturbance	**Like-lihood**	**Consequences**	**Severity**	**Remarks**	**Net Hazard**	**Mitigation**	**Action**
1	Corrosion due to acid gas	3	Failure - loss of containment	5		15	Choose appropriate materials especially for stagnant sections	Install coupons to monitor corrosion

top-down and middle of the road and bottom-up approaches. It should be apparent that each method should in most cases arrive at the same hazard, and that each has certain advantages. It is suggested that the NP approach offers a compromise that enables the risk to be caught with the same reliability as the traditional Hazop method, but with less repetition and with a more thorough screening than when starting from the predefined root cause.

CAVEATS AND CONCLUSIONS

The method as described has not attempted to address non steady-state conditions such as start-up, shut-down and load changes. Nor does it address batch processes. To assess whether the new approach can be adapted to render these important cases amenable needs further study.

The ideas contained in this paper have not yet been extensively tested. It is suggested that they might be tried in parallel with the conventional system to assess the relative efficiency, and whether or not the Hazop team finds it beneficial, and most importantly – whether it is as good as or better than the traditional method for identifying process hazards. Any challenge to an established and successful method of doing something, meets a natural resistance and the author is under no illusions that things will change overnight. However, by viewing a familiar object from a different perspective, new aspects of the object may become apparent.

ACKNOWLEDGEMENTS

The author would like to thank numerous colleagues in various disciplines and industry sectors that have collaborated during Hazop studies and sown the seeds of the concepts on which this paper is based.

ABBREVIATIONS

HAZOP	Hazard and Operability Study
NP Hazop	New Perspective Hazop
P&ID	Piping and Instrumentation Diagram
PFD	Process Flow Diagram
PSFS	Process Safeguarding Flow Diagram
SFD	System Flow Diagram
IFD/IFE	Issued for Design/Engineering (Basic design complete)
HP/LP	High Pressure/Low Pressure
SIL	Safety Integrity Level
MSDS	Materials Safety Data Sheet

REFERENCES

1. Kletz, T., 2006, Hazop and Hazan, 4th edn *(IChemE, UK).*
2. Crawley, F., Preston, M. and Tyler, B., 2008, Hazop: Guide to Best Practice 2nd edn *(IChemE, UK)*