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Review Article

Hazard and operability (HAZOP) analysis: A review of basics

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Abstract:

Hazard and operability (HAZOP) methodology is a Process Hazard Analysis (PHA) technique used worldwide for studying not only the hazards of a system, but also its operability problems, by exploring the effects of any deviations from design conditions. Our paper is the HAZOP review intended to gather HAZOP-related literature from books, guidelines, standards, major journals, and conference proceedings, with the purpose of classifying the research conducted over the years and define the HAZOP state-of-the-art.

Keywords

HAZOP; Process Hazard Analysis; Hazard identification; Hazardous materials; Review; Pros & Cons; guide words; exothermic.

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Introduction

A **hazard and operability study** (HAZOP) is a structured and systematic examination of a complex planned or existing process or operation in order to identify and evaluate problems that may represent risks to personnel or equipment. The intention of performing a HAZOP is to review the design to pick up design and engineering issues that may otherwise not have been found. The technique is based on breaking the overall complex design of the process into a number of simpler sections called 'nodes' which are then individually reviewed. It is carried out by a suitably experienced multi-disciplinary team (HAZOP) during a series of meetings. The HAZOP technique is qualitative, and aims to stimulate the imagination of participants to identify potential hazards and operability problems. Structure and direction are given to the review process by applying standardised guide-word prompts to the review of each node[1] .HAZOP, or a Hazard and Operability Study, is a systematic way to identify possible hazards in a work process. In this approach, the process is broken down into steps, and every variation in work parameters is considered for each step, to see what could go wrong. HAZOP's meticulous approach is commonly used with chemical production and piping systems, where miles of pipes and numerous containers can cause logistical headache. The HAZOP technique was initially developed to analyze chemical process systems, but has later been extended to other types of systems and also to complex operations and to software systems. [2]

When to perform HAZOP

The HAZOP study should preferably be carried out as early in the design phase as possible - to have influence on the design. On the other hand; to carry out a HAZOP we need a rather complete design. As a compromise, the HAZOP is usually carried out as a final check when the detailed design has been completed. A HAZOP study may also be conducted on an existing facility to identify modifications that should be implemented to reduce risk and operability problems. [2]

A Brief History and Evolution of HAZOP

HAZOP were initially 'invented' by ICI in the United Kingdom, but the technique only started to be more widely used within the chemical process industry after the Flixborough disaster in 1974. This chemical plant explosion killed twenty eight people and injured scores of others, many of those being members of the public living nearby. Through the general exchange of ideas and personnel, 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. [3] HAZOP

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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) 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 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.

Materials & Methods

The method is applied to complex 'processes' for which sufficient design information is available, and not likely to change significantly. This range of data should be explicitly identified and taken as the 'design intent' basis for the HAZOP For processes plant, the nodes are chosen so that for each meaningful *design intent* can be specified and they are commonly indicated on piping and instrumentation diagram (P&IDs) and process flow diagram (PFD). The extent of each node should be appropriate to the complexity of the system and the magnitude of the hazards it might pose. However, it will also need to balance

study. For example, a prudent designer will have allowed for foreseeable variations within the process creating a larger design envelope than just the basic requirements and the HAZOP will be looking at ways in which this might not be sufficient. [1]

between "too large and complex" (fewer nodes, but the team members may not be able to consider issues within the whole node at once) and "too small and simple" (many trivial and repetitive nodes, each of which has to be reviewed independently and documented).

For each node in turn the HAZOP team uses a list of standardised guide-words and

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process parameters to identify potential *Deviations* from the design intent. For each deviation, the team identifies feasible *Causes* and likely *Consequences* then decides (with confirmation by subsequent risk analysis where necessary) whether the existing safeguards are sufficient, or whether an *Action* to install an additional safeguard is necessary to reduce the risks to an acceptable level.

The degree of preparation for the HAZOP is critical to the overall success of the review - 'frozen' design information provided to the team members with time for them to familiarise themselves with the process, an adequate schedule allowed for the performance of the HAZOP, provision of the best team members for their role. Those scheduling a HAZOP should take into account the review scope, the number of nodes to be reviewed, the provision of completed design drawings and documentation and the need to maintain team performance over an extended time-frame. The team members may also need to perform some of their normal tasks during this period and the HAZOP team members can tend to lose focus unless adequate time is allowed for them to refresh their mental capabilities.

The team meetings should be managed by an independent, trained HAZOP Facilitator who is responsible for the overall quality of the review, partnered with a dedicated Scribe to minute the meetings. "The success of the HAZOP study strongly depends on the alertness and concentration of the team members and it is therefore important that the sessions are of limited duration and that there are appropriate intervals between sessions. How these requirements are achieved is ultimately the responsibility of the study leader."(1)

For a medium-sized chemical plant where the total number of items to be considered is 1200 (items of equipment and pipes or other transfers between them) about 40 such meetings would be needed. [2] Various software programs are now available to assist in meetings.

The main advantage of this technique is its systematic thoroughness in failure case identification. The method may be used at the design stage, when plant alterations or extensions are to be made, or applied to an existing facility.

Potential Shortcomings of the Traditional Method [3]

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

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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 ¼ (likelihood severity) is acceptable or not.

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.

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(II) Introduce alternative deviation keywords based on

a. More material ¼ Positive changes in the steady state material balance for the envelope or any of its component parts.
b. Less material ¼ Negative changes in the steady state material balance for the envelope or any of its component parts.
c. More Energy ¼ Positive changes in the steady state energy content of the envelope or any of its component parts.
d. Less Energy ¼ Negative changes 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.

Guide words and parameters [1]

In order to identify deviations, the team applies a set of Guide Words to each node in the process. To prompt discussion, or to ensure completeness, it may also be helpful to explicitly consider appropriate parameters which apply to the design intent. These are general words such as Flow, Temperature, Pressure, and Composition. The current standard notes that Guide words should be chosen which are appropriate to the study and neither too specific (limiting ideas and discussion) nor too general (allowing loss of focus). A fairly standard set of Guide Words is given in Table 1 as follows:

Guide Word	Meaning
NO OR NOT	Complete negation of the design intent
MORE	Quantitative increase
LESS	Quantitative decrease
AS WELL AS	Qualitative modification/increase
PART OF	Qualitative modification/decrease
REVERSE	Logical opposite of the design intent
OTHER THAN / INSTEAD	Complete substitution
EARLY	Relative to the clock time
LATE	Relative to the clock time
BEFORE	Relating to order or sequence
AFTER	Relating to order or sequence

Table 1 Set of Guide words for HAZOP

HAZOP-type studies may also be carried out by considering applicable guide words and identifying elements to which they are applicable [3] or by considering the parameters associated with plant elements

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and systematically applying guide words to them.

The overview of commonly used guide word - parameter pairs and common interpretations of them is given in Table 2 as follows.

Parameter / Guide words	More	Less	None	Reverse	As well as	Part of	Other than
Flow	High flow	Low flow	No flow	reverse flow	deviating concentration	contamination	deviating material
Pressure	High pressure	Low pressure	vacuum		Delta-p		explosion
Temperature	High temperature	Low temperature					
Level	High Level	Low level	No level		Different level		
Time	too long / too late	too short / too soon	sequence step skipped	Backwards	Missing actions	Extra actions	Wrong time
Agitation	Fast mixing	Slow mixing	No mixing				
Reaction	fast reaction / runaway	slow reaction	no reaction				unwanted reaction
Start-up / Shut-down	too fast	Too slow			Actions missed		Wrong recipe
Draining / Venting	Too long	Too short	none		Deviating pressure	Wrong timing	
Inertising	High pressure	Low pressure	none			contamination	Wrong material
Utility failure (instrument air, power)			failure				
DCS failure			failure				
Maintenance			None				
Vibrations	Too low	Too high	none				Wrong frequency

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The role of labelling in HAZOP [4]

In the complex processes where the HAZOP approach is most effective, the size and intricacy of the system can be overwhelming. Analysis and maintenance, as well as ordinary, day-to-day operation, require workers to navigate these systems. To allow effective work, system components such as pipes, valves, instruments, and vessels must be identified and labelled.

Often, safely maintaining a system will require monitoring. When measurements must be taken at the same point in a system, it makes sense to clearly mark that point with an indication of the test to be performed. Bad data will ruin the usefulness of any monitoring system.

Opening the wrong valve, or cutting into the wrong pipe, have often been the causes of serious accidents. That's why the ANSI/ASME A13.1 standard is so widely used for labelling pipe systems; it requires clear, bold labels in a highly-visible placement scheme.

Where hazardous chemicals are used as part of the process, **OSHA's HazCom labelling rules** apply. The rules are meant to give workers the information they need to be safe, and effective labelling serves that goal.

The HAZOP Study Process

HAZOP study is to carefully review a process or operation in a systematic manner to determine whether deviations from the design or operational intent can lead to undesirable consequences. This technique can be used for continuous or batch processes and can be adopted to evaluate written procedures. The HAZOP team lists potential causes and consequences of the deviation as well as existing safeguards protecting against the deviation. When the team determines that inadequate safeguards exist for a credible deviation, it usually recommends the action be taken to reduce the risk. [5]

Objective of carrying out a HAZOP study:

- To check a design
- To decide whether and where to build
- To decide whether to buy a piece of equipment
- To obtain a list of questions to put to a supplier
- To check running instructions
- To improve the safety of existing facilities.

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Form a HAZOP Team

To perform a HAZOP, a team of workers is formed, including people with a variety of expertise such as operations, maintenance, instrumentation, engineering/process design, and other specialists as needed. These should not be "newbie," but people with experience, knowledge, and an understanding of their part of the system. The key requirements are an understanding of the system, and a willingness to consider all reasonable variations at each point in the system.

Team member and responsibilities [2]

HAZOP team leader

Responsibilities:

1. Define the scope for the analysis
2. Select HAZOP team members
3. Plan and prepare the study
4. Chair the HAZOP meetings
5. Trigger the discussion using guide-words and parameters
6. Follow up progress according to schedule/agenda
7. Ensure completeness of the analysis

The team leader should be independent (i.e., no responsibility for the process and/or the performance of operations)

HAZOP secretary

Responsibilities:

1. Prepare HAZOP worksheets
2. Record the discussion in the HAZOP meetings
3. Prepare draft report(s)

HAZOP team members

The basic team for a process plant will be:

1. Project engineer
2. Commissioning manager
3. Process engineer
4. Instrument/electrical engineer
5. Safety engineer

Depending on the actual process the team may be enhanced by:

1. Operating team leader
2. Maintenance engineer
3. Suppliers representative
4. Other specialists as appropriate

HAZOP meeting

Proposed agenda:

1. Introduction and presentation of participants
2. Overall presentation of the system/operation to be analyzed
3. Description of the HAZOP approach
4. Presentation of the first node or logical part of the operation
5. Analyze the first node/part using the guide-words and parameters
6. Continue presentation and analysis (steps 4 and 5)
7. Coarse summary of findings

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Focus should be on potential hazards as well as potential operational problems

Identify Each Element and its Parameters

The HAZOP team will then create a plan for the complete work process, identifying the individual steps or elements. This typically involves using the piping and instrument diagrams (P&ID), or a plant model, as a guide for examining every section and component of a process. For each element, the team will identify the planned operating parameters of the system at that point: flow rate, pressure, temperature, vibration, and so on.

Consider the Effects of Variation

For each parameter, the team considers the effects of deviation from normal. For example, "What would happen if the pressure at this valve was too high? What if the pressure was unexpectedly low? Would the rate of change in pressure (delta-p) pose its own problems here?" Don't forget to consider the ways that each element interacts with others over time; for example, "What would happen if the valve was opened too early, or too late?"

Identify Hazards and Failure Points

Where the result of a variation would be danger to workers or to the production process, you've found a potential problem. Document this concern, and estimate the impact of failure at that point. Then, determine the likelihood of that failure; is there a realistic cause for the harmful variation? Evaluate the existing safeguards and protection systems, and evaluate their ability to handle the deviations that you've considered.

Results

Final report

When the HAZOP study is completed, a final report will be prepared. The minimum requirements for the report are as follows: [6]

1. Description of applied procedures and HAZOP technique
2. Summary and description of approved HAZOP recommendations.
3. Summary of operational recommendations and limitations.
4. List and description of drawings and related documents studies.
5. Finalised HAZOP study work sheets together with reports from each study session including a list of participants.
6. Annotated copies of drawings together with supporting documentation which were used during the examination.
7. Recommended revisions of drawings and documents (or part thereof if more convenient) which show modifications, identified as necessary as a result of the HAZOP study.
8. Changes proposed by the HAZOP team, but not accepted, and the reasons why the proposed changes were rejected.

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HAZOP Pros [6]

1. The HAZOP process is a systematic examination.
2. The team approach to a HAZOP makes it a multidisciplinary study.
3. The HAZOP team utilizes operational experience.
4. The process covers safety as well as operational aspects.
5. Solutions to the problems identified may be indicated.
6. HAZOPs consider operational procedures.
7. HAZOPs cover human errors.
8. The HAZOP study led by independent person.
9. HAZOP study results are recorded.
10. For team members the process is easily learned and performed.
11. A HAZOP does not require considerable technical expertise for technique formulation.
12. As a systematic process it provides rigor for focusing on system elements and hazards.
13. The HAZOP process is a team effort with many viewpoints.
14. Commercial software is available to assist in HAZOP analysis.

HAZOP Cons [6]

1. A HAZOP focuses on single events rather than combinations of possible events.
2. The HAZOP focus on guide-words allows it to overlook some hazards not related to a guide-word.
3. Training is essential for optimum results, especially for the facilitator.
4. HAZOPs are typically very time consuming and thus expensive.

Discussion [6]

HAZOP is a hazard identification technique which considers system parts separately and systematically examines the effects of deviations on each part. Sometimes a serious hazard will involve the interaction between a numbers of parts of the system. In these cases the hazard may need to be studied in more detail using techniques such as event tree and fault tree analyses. Many systems are highly inter-linked, and a deviation at one of them may have a cause elsewhere. Adequate local mitigating action may not address the real cause and still result in a subsequent accident. Many accidents have occurred because small local modifications had unforeseen knock-on effects elsewhere. While this problem can be overcome by carrying forward the implications of deviations from one part to another, in practice this is frequently not done. As with any technique for the identification of hazards or operability problems, there can be no guarantee that all hazards or operability problems will be identified in a HAZOP study. The study of a complex system should not, therefore, depend entirely upon a HAZOP. It should

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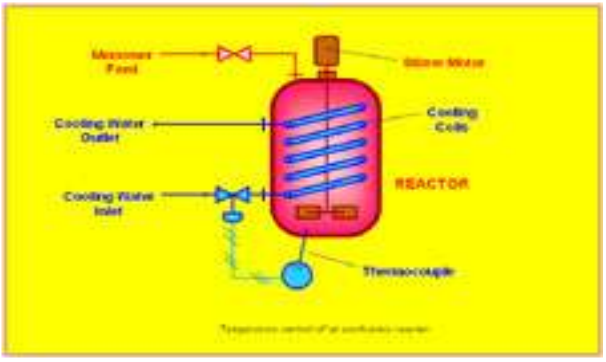
be used as a compliment to other suitable techniques. It is essential that other relevant studies are coordinated within an effective overall safety management system. The success of a HAZOP study depends greatly on the ability and experience of the study leader and the knowledge, experience and interaction between team members. HAZOP only considers parts that appear on the design representation. Activities and operations which do not appear on the representation are not considered.

Conclusion [6]

An important benefit of HAZOP studies is that the resulting knowledge, obtained by identifying potential hazards and operability problems in a structured and systematic manner, is of great assistance in determining appropriate remedial measures. While a HAZOP is not appropriate in all circumstances one of the major benefits that can be used to help justify the cost and time investment is that it also helps to avoid operating problems and can thus provide a clear return on the investment beyond the reduction in hazards.



The HAZOP analysis would reveal the following potential process modifications:

Case Study [7]

Example Exothermic Reaction System

A reactor system is shown in the Figure 1 to which the HAZOP procedure can be applied. This reaction is exothermic, and a cooling system is provided to remove the excess energy of reaction. If the cooling flow is interrupted, the reactor temperature increases, leading to an increase in the reaction rate and the heat generation rate. The result could be a runaway reaction with a subsequent increase in the vessel pressure possibly leading to a rupture of the vessel. The temperature within the reactor is measured and is used to control the cooling water flow rate by a control valve.

Performing a HAZOP on this process with the assigned task of considering runaway reaction episodes would lead to a completed form such as that shown in the Figure 1. The process is already small enough to be considered a single section. Four study nodes are cooling water line, stirring motor; monomer feed line, and reactor vessel.

1. Installation of a cooling water flow meter and low flow alarm to provide an immediate indication of cooling loss.
2. Installation of a high temperature alarm to alert the operator in the event of cooling function loss.
3. Installation of a high temperature shutdown system, that would automatically shutdown the process

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in the event of a high reactor temperature. The shutdown temperature would be higher than the alarm temperature to provide the operator with the opportunity to restore cooling before the reactor is shutdown.

4. Installation of a check valve in the cooling line to prevent reverse flow. A check valve could be installed both before and after the reactor to prevent the reactor contents from flowing upstream and to prevent the backflow in the event of a leak in the coils.
5. Periodic inspections and maintenance of the cooling coil to insure its integrity.
6. Evaluation of the cooling water source to consider any possible interruption and contamination of the supply.

In the event that the cooling water system fails (regardless of the source of the failure), the high temperature alarm and emergency shutdown system prevents a runaway. The review committee performing the HAZOP decided that the installation of a back-up controller and control valve was not essential. The high temperature alarm and shutdown system prevents a runaway in this event.

Similarly, a loss of cooling water source or a plugged cooling line would be detected by either the alarm or emergency shutdown system. The review committee suggested that all cooling water failures be properly reported. In the event that a particular cause occurs repeatedly then additional process modifications are warranted.

The basic form for the Hazop of this system is shown in the Table 3.

The first column, denoted "Item", is used to provide a unique identifier for each case considered. The numbering system used is a number-letter combination. The second column lists the study node considered, the third column the process parameter, and the fourth column the deviations (guide words). For example, the designation "1A" would designate the first study note "Cooling Coils" and the first guide word "NO" and the process parameter is "Flow". The designation "1B" is applied to the same study note (i.e. "Cooling Coils") for the same process parameter "Flow", but the guide word is "MORE".

The next 3 columns are the most important results of the analysis. These are the possible causes of the deviation in the process parameter, the possible consequences, and actions required.

This example demonstrates that the number of process changes suggested is quite numerous although only a single process intention is considered.

Table 3

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Project Name:	Date:	Page of	Completed:
Process:			No Action:
Section:	Reference Drawing		Reply Date:

Item	Study Node	Process Parameters	Deviations (Guide Words)	Possible Causes	Possible Consequences	Action Required	Assigned to: ↓	↓	↓	↓
1A	Cooling Coils	Flow	No	1. Control valve fails closed 2. Plugged cooling coils 3. Cooling water service failure 4. Controller fails and closes valve 5. Air pressure fails, closing valve	1. Loss of cooling, possible runaway 2. As above 3. As above 4. As above 5. As above	1. Select valve to fail open 2. Install filter with maintenance procedure Install cooling water flow meter and low flow alarm Install high temperature alarm to alert operator 3. Check and monitor reliability of water service 4. Place controller on critical instrumentation list 5. See 1A.1				
1B			High	1. Control valve fails open 2. Controller fails and opens valve	1. Reactor cools, reactant concentration builds, possible runaway on heating 2. As above	1. Instruct operators and update procedures 2. See 1A.4				
1C			Low	1. Partially plugged cooling line 2. Partial water source failure 3. Control valves fail to respond	1. Diminished cooling, possible runaway 2. As above 3. As above	1. See 1A.2 2. See 1A.2 3. Place valve on critical instrumentation list				
1D			As well as	1. Contamination of water supply	1. Not possible here	1. None				
1E			Part of	1. Covered under 1C						
1F			Reverse	1. Failure of water resulting in backflow 2. Backflow due to high back-pressure	1. Loss of cooling, possible runaway 2. As above	1. See 1A.2 2. Install check valve				
1G			Other than	1. Not considered possible						
1H			Sooner than	1. Cooling normally started early	1. None					
1I			Later than	1. Operator error	1. Temperature rises, possible runaway	1. Interlock between cooling flow and reactor feed				
1J			Where else	1. Not considered possible						
1K		Temperature	Low	1. Low water supply temperature	1. None – controller handles	1. None				
1L			High	1. High water supply temperature	1. Cooling system capacity limited, temperature increases	1. Install high flow alarm and/or cooling water high temperature alarm				
2A	Stirrer	Agitation	No	1. Stirrer motor malfunction 2. Power failure	1. No mixing, possible accumulation of unreacted materials 2. Monomer feed continues, possible accumulation of unreacted materials	1. Interlock with feed line 2. Monomer feed valve must fail closed on power loss				
2B			More	1. Stirrer motor controller fails, resulting in high motor speed	1. None					

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