

A QUALITATIVE APPROACH TO CRITICALITY IN THE ALLOCATION OF MAINTENANCE PRIORITIES TO MANUFACTURING PLANT

C.J. Atkinson

Burgoyne Consultants Ltd., Burgoyne House, Chantry Drive, Ilkley,
West Yorkshire. LS29 9HU

Achieving an effective maintenance regime in a manufacturing plant is a strategic business issue. It is important to focus engineering priorities and effort onto the right areas in order to realise safety in operations and prevent loss. Quantitative techniques for doing this are available but they typically require specialised skills and are time consuming to apply - resources which are frequently unavailable to maintenance engineering departments. A simpler, qualitative approach to assessing criticality, which can be applied both to existing operating units and to new plants at the design stage, is discussed. It provides a simple ranking system and is easily applied by experienced engineering and production staff.

Keywords: Maintenance, criticality, priority, strategic, qualitative approach, simpler.

INTRODUCTION

Why should plant and engineering managers be seriously interested in maintenance as a strategic business issue? One answer to this question is provided by the management consultant, Peter Drucker, who said "The first duty of business is to survive and the guiding principle of business economics is not the maximisation of profit it is the avoidance of loss". Maintenance is about the avoidance of loss in the widest sense of the word.

The purpose of a maintenance system is to improve the reliability and safety performance of a company's capital assets (plant, equipment and structures). The aim is to strengthen the financial performance of the business by maximising the availability of productive capacity and by minimising the risk of unplanned and undesired events. The latter could include injury to people, both employees and the general public; damage to the environment; loss of operating materials and damage to capital assets. Other targeted benefits of an effective maintenance system would be improved service to customers and the avoidance of adverse publicity.

A systematic programme of maintenance can also reduce maintenance costs particularly by avoiding the secondary damage which may result if equipment is allowed to run to failure before anything is done, by avoiding unnecessary maintenance activity and by designing out recurrent problems.

A recent survey by the Institution of Chemical Engineers revealed that two thirds of the companies responding had such a systematic approach. However, it is clear that resources of time and money in implementing such a programme can represent a significant barrier to progress. An objective basis for assessing maintenance frequencies and the risk of "over maintaining" are also common concerns. Of the companies which were operating a system, over half were unhappy with the resources required to sustain it. There are, of course, a

variety of approaches to maintenance management and the issues of resources and effectiveness are significant to each of them. An approach which addresses these concerns will be helpful to managers seeking to secure the benefits of a systematic approach to maintenance.

In common with the management of other business activities, part of the function of maintenance management is to provide leadership. By this we mean not only ensuring that the right practices and procedures are followed in carrying out maintenance activities but also that the right maintenance activities are being given priority. The right activities are those which make maximum contribution to the avoidance of loss. Criticality ratings provide an aid to this function of leadership.

It is, of course, quite true that a comprehensive review of the maintenance requirements of a complex plant is a large task; any worthwhile system will require thought and mental application. However, there is more than one approach to analysing the maintenance needs of an operation. The area which this paper will focus upon is the identification, within defined plant boundaries, of critical systems and individual plant items which require priority in any maintenance programme. It develops a methodology for assessing the criticality of those items which is both easy to understand and simple to apply. The criticality ratings derived by the methodology can then be placed in rank order and used for the purpose of determining appropriate maintenance schedules.

The assessment of criticality may lead managers to consider other techniques such as Total Productive Maintenance (TPM) Wilmot (3), Nakajima (4) which focuses on a team approach generated by wider employee involvement and Reliability Centred Maintenance (RCM), Moubray (2) which is aimed at determining the maintenance requirements of physical assets in their present operating context: this is done using an approach similar to failure modes and effects analysis FMEA, Centre of Chemical Process Safety (5), British Standards (6). Managers will also need to consider the range of maintenance strategies available to them from *breakdown maintenance to the various planned and preventive maintenance options*. However, the primary step in leading the maintenance function to work on the right activities is that of taking an objective view of the relative importance (criticality) of the various elements of a manufacturing plant.

There are two principal methods which can be applied to assessing criticality. One is a rigorous, quantitative approach, typically fault tree analysis (FTA) Lees (1), Barlow et al (7), Shillon & Singh (8), within a Failure Mode Effects and Criticality Analysis (FMECA) (Refs. 1, 5, 6) methodology. This allows other factors such as human error to be taken into account. However, the analysis is both complex and time consuming. It is required for the analysis of major hazard plants but is less appropriate for dealing with the great number of lower risk plants to be found in the process industries. This approach also requires application by staff who are trained in reliability analysis.

A simpler, qualitative approach, still based upon FMECA (Refs. 1, 5, 6), can be applied to these lower risk plants. The methodology is considerably less complex than FTA (Refs. 1, 7 and 8) and, given appropriate training, lends itself to application by local analysis teams who know the plant well. This approach will sit well with a participative, team based company culture and allow the workload to be spread. Qualitative methods are also applicable as an initial screening process for the major hazard plants referred to above. They will allow

identification of those elements which require quantitative assessment whilst allowing the simpler qualitative methodology to be applied to the other parts of the operation. Qualitative analysis of criticality can be applied at the process and mechanical design stages of a new project to sharpen the focus on critical systems and plant items at the earliest possible point: key maintenance or design out issues can then be tackled before major costs have been incurred. The principles of assessing criticality at the design stage are the same as those for existing plants and this paper does not treat them separately. This latter qualitative approach for existing plants will now be developed in more detail.

THE QUALITATIVE APPROACH

The qualitative approach to allow criticality to be assessed is outlined in flow chart format in Figure 1. The result is a numerically weighted ranking so that it is possible to prioritise items of equipment in terms of criticality and, subsequently, of maintenance needs. It is also used to define the need for more detailed quantitative assessments.

It allows the benefits of a systematic approach to maintenance to be gained by using a relatively simple methodology. This is easy to apply and can be used by plant staff with no formal training in reliability analysis. The discipline of examining maintenance requirements in the manner described will prompt the investigation of problem areas and stimulate continuous performance improvement *within* the operation.

The steps in the methodology are set out below:

Define Plant Boundaries for the Study

The plant BOUNDARIES for the study should be defined so that everyone is aware of the extent of the study, which items/processes are to be included and which are not. It is important to ensure that adequate consideration is given to the effect of plant failures on common systems and common system failures on the plant when establishing the boundaries for the study. Similarly, the effect that an incident on the plant could have on other production units will need to be considered.

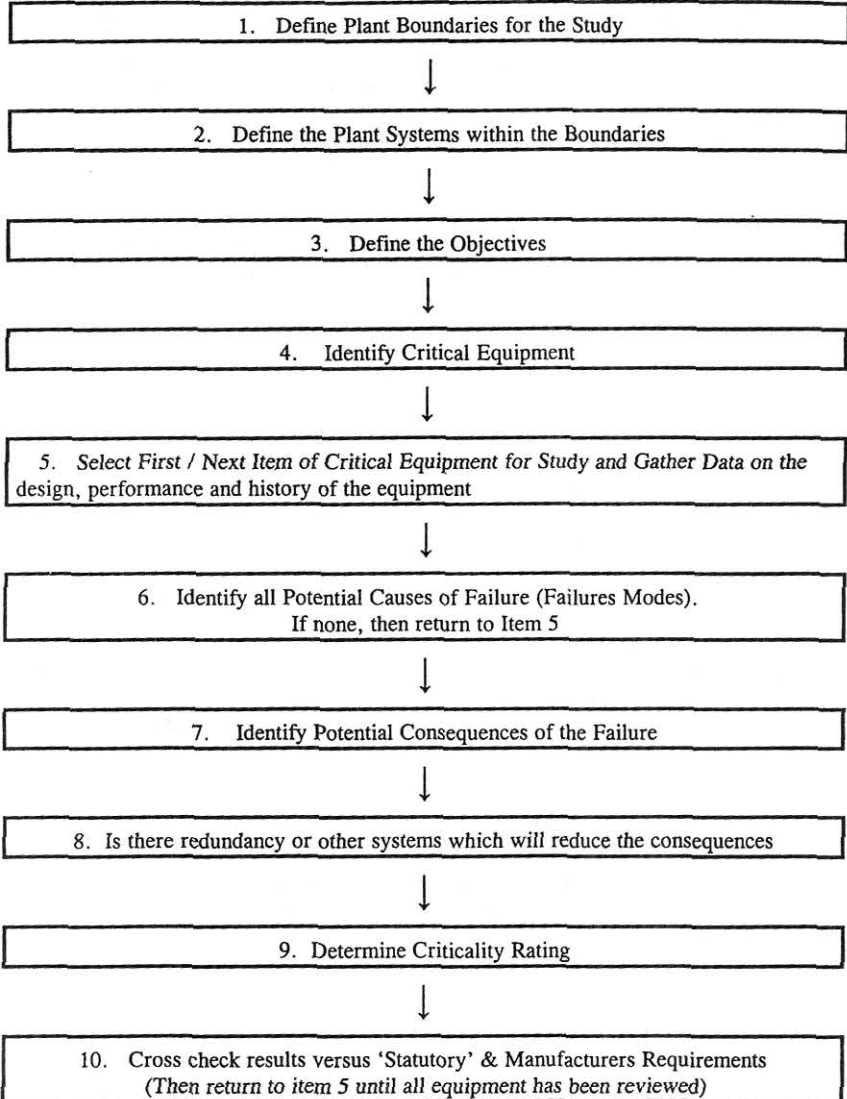
Define Plant Systems Within the Defined Boundary

The next step is to draw up a block diagram for all the systems of the plant within the defined study Boundaries. At this stage, if the SYSTEM BOUNDARIES are clear, identify any systems that are not critical. These would be systems which, should they fail would not produce a hazard to the public or plant staff or result in a high financial loss. Delete these systems from the study.

Define the Objectives of the Study

The purpose and the objectives of the study should be defined and understood by all the staff involved so that every one is pulling in the right direction. Objectives *might* take the form of:-

FIG. 1 - FLOW CHART OF THE METHODOLOGY



“To identify all critical items of equipment which can have an impact on production, safety and environmental concerns.”

“To assess the criticality of such items, evaluate the adequacy of existing maintenance policy and practice and identify the improvements which are required to develop a cost effective maintenance system.”

Identify Critical Equipment Within the Defined Systems

This is a first coarse assessment to identify equipment which, if it failed, would cause any of the following :-

- Harm to the public
- Harm to people within the site
- *Damage to the environment*
- Asset damage
- Lost production

A line diagram would typically be used to go through the process line by line and item by item. This step is not the same as an in depth Hazard and Operability Study (HAZOP), Kletz (9), CIHSC (10). If failure of the item could cause a problem it is simply listed for more thorough consideration in subsequent steps.

The potential for failure should be assessed by a team of people consisting, as a minimum, of the Plant Manager, Plant Engineer and a Safety Engineer. In the real world, the line diagrams may not be up to date and include all modifications. The key selection criterion for team members is that they collectively represent a thorough knowledge of the plant and how it operates in practice.

Select An Item of Equipment for Study

The assessment team should now select an item of equipment which they consider to be of high priority from their initial assessment. They should then gather data on the design, performance and history of the equipment so as to identify the purpose of the equipment, its design conditions and any previous history such as inspection reports, failures and manufacturers' recommendations. This latter activity has two principal benefits:

- it creates an up to date record that can be added to,
- it helps to identify all potential failures/hazards.

It is therefore important to make the best use of all available information. This step also provides valuable background data if excessive maintenance costs and downtime are identified when the criticality rating itself is being calculated.

Identify All Potential Causes of Failure

The assessing team should identify and list all potential failures. If no possible failures are identified the next item can be considered.

Potential failures can be identified by using one or more of the following methods:-

1. The past history of the equipment
2. The experience of people using the same or similar equipment
3. Brainstorming session
4. What if?
5. Hazard and operability study (HAZOP) approach (Refs 9,10).

The method used will obviously depend on the process, the potential for harm and the potential financial loss to the company of a failure. A What if? or brainstorm should be adequate providing that the study team consists of people who have a full understanding of the process, the basis of safety and the engineering aspects. This is a detailed assessment and the Assessment Team must include people who are closely involved with day to day operations; a minimum would be the Plant Manager, an Operating Supervisor, the Plant Engineer and a Maintenance Supervisor. For a more hazardous plant a HAZOP would be more appropriate. Advice should be sought from a Safety Professional on the type of study to be applied. This advice might be obtained internally or externally depending upon the resources available to the business.

The following points should be considered:-

1. Is the vessel or equipment designed to an approved standard or code of practice. If it is, then the chance of failure must be low.
2. Can the equipment be pressured above its design conditions by :-
 - a) overfill
 - b) runaway reaction
 - c) utilities failure
 - d) external circumstances such as fire
 - e) addition of materials other than those specified
 - f) being boxed in
 - g) operator error
 - h) maintenance error on pressure relief/control systems
3. Are there controls to prevent overpressure, are they adequate and are they maintained?
4. Are all the materials of construction compatible with all the process materials and products?
5. Is it possible to form an explosive mixture in a vessel or a system and if it is are the preventive controls adequate e.g. is there a nitrogen blanket and is the nitrogen supply secure, have all means of ignition been eliminated?
6. For the control of a reaction is the cooling water supply/coolant supply secure?
7. Are the control systems adequate for all potential deviations from design, are they installed and working as designed/intended? Are they understood by maintenance and process? Is there an adequate and meaningful test procedure?
8. Is there a modification procedure and has it been checked that no unauthorised modifications have been carried out?
9. Are the operating instructions and maintenance instructions written and understood?
10. Have staff been given adequate training to be able to identify deviations from the normal and take corrective action?
11. Is the electrical equipment to the required standard and is there a control?
12. Is all maintenance work covered by a permit to work and are all staff and contractors aware of this requirement?

13. Is a hot work permit required for any cutting or welding or the use of sparking equipment in a hazardous area?
14. Is there a procedure to deal quickly with a release of harmful material and have staff been trained in this procedure?

This list is for guidance only and should not be considered comprehensive. It covers some of the potential events that could result in a failure.

Identify Potential Consequences of the Failure

Having identified realistic potential causes for failure of an individual item, the team must now assess the effect of such a failure on the system under examination. These consequences might include fire or explosion, release of harmful materials, material losses, lost production, destruction of assets, creation of a dangerous situation such as a runaway reaction, etc.

The assessment of consequences will be primarily judgemental and hence qualitative. There will be occasions when the team will benefit from commissioning a more detailed quantitative assessment of consequences. Whilst such assessments are outside the scope of this methodology, the variables to be considered are:

1. The inventory that may be released
2. The pressure of the release
3. Whether such a release will be liquid or gas or both
4. The potential effect, toxicity, fire, explosion
5. An estimate of the potential distance of the effect
6. An estimate of the toxic level/discomfort to the public
7. An estimate of potential injury to the public and the numbers that could be affected
8. The potential release to water courses and the environmental consequences of absorption into the ground

Is There Redundancy Or Other Systems Which Will Reduce the Consequences

Protective systems such as alarms, trips, relief valves and non-return valves are installed to prevent hazards from occurring. When there is more than one independent method of performing the protective function, the protective system is said to contain redundancy. An example of such a system would be one where one of two trips with two independent measurement and trip channels will shut down a process safely. Such a system would be more likely to respond to a demand placed upon it than a single channel system. The consequences of the failure of a particular item might therefore be reduced. In considering this reduction of consequences, it is important to consider whether common mode failure such as a failure of instrument air or electrical power could affect the performance of both of the protective systems - are they truly independent?

Determine Criticality Rating

The criticality rating of an item allows it to be placed in rank order when considering the frequency with which it requires to be checked. It forms the basis of the initial test and inspection schedules for that item. This will, of course, be subject to review as the plant

history builds up. It is important to recognise that criticality ratings are part of a ranking process. They do not represent absolute frequency values for maintenance schedules but are used to assess the frequency of one item relative to others. This is a qualitative, not an absolute, methodology. Consistent application across similar areas is the key to obtaining meaningful criticality ratings. The work done in identifying the potential consequences of failure will also assist the assessment team in determining the appropriate type of maintenance activity which is required by an item as well as its relative importance.

Criticality rating also serves as a means of prioritising corrective actions identified by the study such as improving means of detection of system failure, minimising the effects on common systems and tackling root causes of excessive downtime.

Criticality must be rated by the assessment team. The ratings are assessed for seven areas which may be affected by the failure of the item. These are:-

- Injury to the Public
- Damage to the Environment
- Injury to people within the factory perimeter
- Loss of assets / profit
- Effect on common systems
- Excessive downtime and maintenance costs
- Reliability of detection and control systems

This rating system is targeted at operations where the consequences of failure are potentially significant hazards to people and the environment. It is also important to consider the impact of a failure on the public image of a Company. The perception of the consumer can have a major impact on, say, a food processor. A history of environmental incidents can damage any manufacturer whose clients do not wish to have their image tarnished by association. Perceptions are not always in proportion to reality and should never be underestimated.

The following subsections develop a scoring system based on three rating levels. These are set at 10, 5 and 1. These numbers are intended to serve as a guide. There is no reason in principle why a rating could not be scored as, say 7. However, such nuances are not likely to alter the results obtained in a significant way.

Injury to the Public. The following empirical ratings are probably appropriate :-

Potential effect high and many casualties, people feel sick or suffer serious discomfort	10
Minor irritation to the Public	5
May be aware of a release but suffer no ill effects	1

Damage to the company's public image should also be considered here particularly if this is likely to affect customer attitudes.

Injury to the Environment. Consideration should be given to a failure that could affect the

environment such that it would contravene the pollution regulations and cause serious damage to water systems, vegetation, animal life, clean and effluent systems such as storm water drains. Other areas to consider are the potential for flammable liquids and vapours getting into drains and common systems such that they can reach a source of ignition. The potential effects should be calculated or given an empirical rating as follows:-

Major event, clearly perceptible to the public, with for example:

- (a) Potential for serious, lasting damage to the environment.
- or
- b) The possibility that flammable vapours can reach a source of ignition. 10

Minor event, still perceptible to the public, with for example:

Potential for short term damage to the environment but flammable vapours cannot reach a source of ignition. 5

Minimal effects, containment within the factory and not perceptible to the public. 1

Public perception would relate to either direct observation of the event and/or indirect awareness through reports in the media.

Injury to People within the Factory Perimeter. Consider the potential for injury to people within the factory perimeter fence. This could be fatalities from fire, explosion, asphyxiation or being exposed to toxic materials or various degrees of injury from these effects. Injury because of poor access to the equipment for maintenance or operational reasons should be considered. The potential effects should be given an empirical rating as follows:-

Death or very serious injury/illness 10

Injuries/illness of a less serious nature such that recovery is possible within a few weeks 5

Minor injuries/illness 1

Loss of Assets/Profit. This will have to be assessed on a plant to plant basis. For the purpose of this exercise the following empirical ratings have been assumed:-

Loss of profits or assets in excess of £100,000 10

Loss of profits or assets in excess of £10,000 but less than £100,000 5

Loss of profits or assets in excess of £1,000 but less than £10,000 1

Common Systems. The effects of a failure of systems common to several plants such as services, vacuum, ventilation and liquid and gaseous effluents should be considered. Failure

of common systems might include a failure of supply from the common system which results in a hazard on the plant or a failure on the plant which results in damage to the common system and/or a knock on effect to other plants or processes. The potential effects of a cocktail of materials being created in the common system should be considered. If the potential failure could affect the manufacture of other products in the same equipment, this should be considered here. For the purpose of rating the following has been assumed:-

Effects of a service failure could result in a hazardous situation.
 An explosive mixture could form in the common system.
 A service failure could seriously affect other production units. 10

A service failure would have a minor effect in causing hazards on the operating units and it is unlikely that an explosive mixture could form in the common systems.
 A service failure would have minor effects on other plants. 5

A service failure would not cause hazard and an explosive mixture cannot form. There is no effect on other plants. 1

Present Maintenance Costs and Downtime are Excessive. It may be that some equipment is failing on a regular basis because it is not being operated as intended, there is a lack of preventive maintenance, it is not compatible with process materials/conditions or because of its age. Alternatively, the price of a low failure rate may be high maintenance expenditure. In either set of circumstances, whether or not failure could produce a hazard, an investigation should be carried out to determine the cause of the failures/cost of maintenance and a remedy suggested. This may involve replacement especially if the cost of maintenance is greater than the cost of replacement. When rating this element of criticality it is important to take into account not only failure frequencies and the potential consequences of these but also any high cost of preventive measures where failure frequencies are low. In other words, loss of profit arising from high maintenance costs as well as losses from the consequences of high breakdown frequencies should be considered when allocating the ratings defined below:-

Breakdown is occurring more than twice per year and can lead to a hazardous situation and/or major loss of profit 10

Breakdown is occurring at least once per year and results in loss of profit but not a hazardous situation 5

Breakdown occurs less than once per year 1

Reliability of Detection/Control Systems. Failures can be prevented if there are means of detection such as regular inspections by qualified staff, control systems to prevent a dangerous failure occurring or operator observation/intervention. The following ratings have been given as follows:-

No means of control or detection 10

Means of control are in place but no schedule to test that it is effective.

Operators not instructed in potential deviations and control	5
Means of control and a meaningful schedule of tests are in place.	
Operators are trained to detect and rectify deviations	1

Calculation of Overall Criticality Rating. The overall criticality rating is calculated by multiplying together the ratings scored in each of the seven sections described above. The highest rating is therefore 10^7 and the lowest rating is 1^7 . The overall criticality ratings can then be ranked and used for prioritising corrective action or redesign, for scheduling inspections and tests to detect hidden and potential failures, and for scheduling restoration tasks.

Criticality Ranking. A suggested relationship between Criticality Rating and Ranking is set out below.

Criticality Rating	Ranking
10^7 to 10^6	Very high
" "	High
" "	Medium
" "	Low
" "	Very Low
" "	Very Low

The criticality ratings will always be a clear guide to the priority which one item should receive in comparison to others but engineering management will still have to apply informed judgement according to the situation they are managing when determining the frequency of maintenance activities.

It is important to recognise that modern maintenance systems may call for function checks, visual inspection and incipient fault reporting on a daily or a shift basis. However, like all management systems, maintenance will require formal review activities such as proof testing of safety systems, specialist condition monitoring, statutory inspection, non destructive testing and item replacement routines, it is these formal review activities which are prioritised by criticality ranking.

Items which are identified as having a high criticality rating during a study at the design stage of a new project should be reviewed to see if it is possible to reduce criticality by using an alternative approach.

Cross Check Results Versus 'Statutory' Requirements

Some of the equipment will have had inspection frequencies assigned due to legislative requirements (e.g. Pressure Systems Regulations, IEE Regulations). Other items may be inspected under company procedures such as BS EN ISO 9000. Manufacturers may recommend maintenance schedules for their equipment. It should be checked whether these established activities call for more frequent inspection than required on the basis of the qualitative assessment described above. That dictating the more frequent inspection should be adopted. Statutory requirements will always be the minimum requirement.

The Final Steps

The results should be formally documented in an FMECA record table showing the outcome of the assessment for all items. A specimen table, for some items from a batch organic chemicals plant, is given as Table 1 in Appendix 1.

It is important, as stated above, to choose a maintenance policy appropriate to the plant under consideration. This paper does not set out to provide guidance on the selection of policy. However, in general, it is desirable that maintenance tasks be planned rather than undertaken ad hoc. It is, therefore, necessary to draw up a maintenance schedule table with a system to call items of equipment immediately in advance of their inspection or test and to register that the test has been completed and the results of the test/inspection. Resources must be available to carry out the test/inspection and to repair any defects. Instructions must be written giving the preparation procedure for the test/inspection and the method of carrying out the inspection/test and staff trained in these procedures.

It is important that a competent person monitors the schedule to ensure that it is being operated as intended and to identify any failings so that they can be rectified. As a history is built up it may, on evidence, be prudent to increase or decrease the inspection/testing frequency of a *piece of equipment*. *Change must only take place on the formal authorisation of a competent person designated by the operating company.* The maintenance system must be kept under review with a view to continuous improvement in performance.

Having established the criticality ratings of items of plant and equipment, these ratings need to be applied to scheduling within the appropriate maintenance policy. There is no universally applicable maintenance policy and there are considerable differences in the approaches to maintenance which are applied to process plant. This is of course a subject in its own right.

CONCLUSIONS

The Qualitative Assessment of Criticality presented in this training package will provide focus on those items which are critical for Health, Safety, Environmental or commercial reasons and the analysis carried out by the assessment team will assist in deciding which maintenance approach is most appropriate.

REFERENCES

1. Lees F.P. Loss Prevention in the Process Industries 2nd Edition (1996) Butterworth Heinemann.
2. Moubray J., Reliability Centred Maintenance II. Butterworth Heinemann.(1991)
3. Willmot P. Total productive Maintenance - The Western Way.
4. Nakajima S., Introduction to Total Productive Maintenance Productivity Europe Ltd.
5. Centre for Chemical Process Safety, Hazard Evaluation Guidelines (1985/1, 1992/9).

6. B.S. 5760 Reliability of Systems, Equipment and Components, Part 5: 1991 Guide to Failure Modes, Effects and Criticality Analysis (FMEA) and FMECA).
7. Barlow R.E., Fussell, J.B. and Sinpurwalle, N.D. (eds) (1975). Reliability and Fault Tree Analysis (Philadelphia, P.A.: Soc. for Ind. and Appl. Maths).
8. Shillon, B.S. and Singh, C., (1981) Engineering Reliability. New Techniques and Applications (New York: Wiley Interscience).
9. Kletz T.A. (1992) Hazop and Hazan 3rd ed. (Rugby : Institution of Chemical Engineers).
10. The CIA Guide to Hazard and Operability Studies (CISHC, 1977).

TABLE 1

COMPANY: PLANT:		TABLE 1							
COMPONENT	PURPOSE	FAILURE MODE	POTENTIAL CAUSE	POTENTIAL CONSEQUENCE	DETECTION/ CONTROLS	CRITICALITY RATING/ RANKING	PRESENT MAINTENANCE SCHEDULE	NEW MAINTENANCE SCHEDULE	
Reaction Vessel R1	To react feedstocks 1 and 2 and produce a range of products	Vessel failure Flange, manhole or agitator gasket	Design error corrosion, erosion, pressure above design. Gaskets, maintenance error.	Large spillage of toxic material. Small leak of toxic material	Inspection for pressure regulations. Flow ratio control/trip. High pressure trip. Low temperature trip.	12,500 Medium	For pressure vessel regulations.	Add an intermediate visual inspection every 6 months.	
In line mixer M1	Mixing of reactants in R1 by external circulation.	Seal damage. Bearings fail. Motor fails. Flange fails.	Wrong assembly. Wear and tear. Not suitable for duty.	Small spillage. Loss of production.	None.	250,000 High	None.	Three monthly. Known to fail often. Investigation required	
Flow Controllers FIC1, FIC2 and Ratio Controller RCI	Measures flow of feedstocks to reactor & controls the ratio between them.	Fails to safe. One feed valve could fail open but other should close.	Power failure. Element failure Blockage	Fail to danger. In worst case pressure would activate BD/RV and discharge to atmosphere.	Alarm. Valve closes, pump trips on ratio deviation. Valves close and pumps trip on pressure alarm.	12,500 Medium	None	Six monthly.	
Non-return valves NRV1 and NRV2 protecting site nitrogen and air systems.	Nitrogen for inert purging. Air for instruments / process.	Fail to danger. Hydro-carbon into site systems.	Failure of NRV flap.	Explosion / Fire.	None.	1,250 Low	None	Annual	