IMPROVEMENTS IN PROCESS SAFETY REVIEWS PRIOR TO HAZOP

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Research has been carried out into ways of improving the process safety reviews carried out prior to HAZOP. Earlier studies on modelling incident scenarios have been refined with an improved model being developed with better emphasis on recovery mechanisms. Gaps in techniques have been uncovered for which modification of existing methods is appropriate.

The method developed for Preliminary Hazard Analysis can be used to generate fault trees and is particularly useful when applied to early P&I Diagrams. Selected incidents can be analysed in detail to indicate possible defects in the sociotechnical system of which the plant is a part.

Hazard Identification Process Design Risk Assessment Fault trees

INTRODUCTION

A process plant goes through many review stages from its initial development, through initial commissioning and into beneficial production. Two particular facets have been given attention in the present work. The first considers safety studies carried out as hazard identification exercises prior to the main HAZOP study, as it is appreciated that at the latter stage it is too late to efficiently carry out design changes. The second considers the root causes of incidents during basic engineering.

The main focus of this work has involved consideration of the development of an incident and the key events which should be considered. Particular attention is given to the recovery from any situation. This has resulted in the development of a variation of Preliminary Hazard Analysis and a technique for the initial analysis of a Process Sociotechnical System aimed at identifying necessary changes in the overall system of which the new plant is to be a part.

The release of process material is the dominant major hazard on chemical plants. This primarily occurs on loss of containment due to rupture caused by overpressure, overtemperature, low pressure (vacuum), very low temperature or deterioration of materials of construction or on simple discharge through an available opening to atmosphere. Such a release can be represented by the generalised model of an incident scenario given in Table 1. see Wells et. al. (1). This has served as the foundation of the current research reported here as how to carry out hazard analysis, risk analysis and safety oriented studies of the overall sociotechnical system of which the process plant is a part. This particular table does not include the root causes which affect every event. Root causes are considered in a subsequent section of the paper.

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Table 1 General Incident Scenario from Immediate Cause

IMPACT: HARM AND DAMAGE	Consequences categories (Appreciable to Catastrophic) Minor consequences / Near-miss
MITIGATION MEASURES FOR A RELEASE FAIL	Post incident emergency response inadequate Emergency Response Inadequate
ESCALATION BY TOXIC RELEASE	Secondary loss of toxic material Loss of toxic material
ESCALATION BY FIRE OR EXPLOSION	Escalation by fire or explosion Ignition of flammable mixture
COUNTERMEASURES FOR A RELEASE FAIL	Release fails to disperse Response by countermeasures inadequate Immediate response to release inadequate
SIGNIFICANT RELEASE OF MATERIAL	Release of material by rupture or discharge Release creates hazard or hazardous condition
FAILURE TO RECOVER THE SITUATION	Further action by operator fails to recover the situation Further action by operator fails to recover the situation
DANGEROUS DISTURBANCE OF PLANT	Dangerous disturbance leading to rupture Critical defect or deterioration in construction Flow through abnormal opening to atmosphere Adverse change in a planned product or other release
FAILURE TO CONTROL THE SITUATION IN EMERGENCY	Emergency control systems fail to correct the situation Action by normal control systems fails to correct situation Maintenance fail to correct the situation
HAZARDOUS DISTURBANCE OF PLANT	Hazardous disturbance of plant conditions Defect or deterioration in construction Abnormal opening to atmosphere Adverse change in a planned product or other release
FAILURE TO CONTROL THE SITUATION	Normal control systems fail to correct the situation Operators fail to correct the situation (on alarm?) Maintenance fail to correct the situation
PROCESS DEVIATION	Change in operating conditions Construction defective or deteriorated in service Abnormal opening in equipment Change in planned discharge or vent
INADEQUATE NORMAL CONTROL	Initial failure by control measures fails to correct situation Failure caused by inadequate control (see below)
IMMEDIATE CAUSES OF INCIDENT	Action by plant personnel inadequate Defects directly cause loss of plant integrity Plant or equipment inadequate or inoperable Control system or emergency control inadequate Change from design intent at point in the plant life-cycle Environmental and external causes of disturbance

CONCEPT SAFETY STUDIES

Concept Hazard Analysis should be dominated by consideration of the consequences of a release and consider material hazards, process route and main operations, inventory levels, release of material and its consequences, site and environs. It should identify the hazardous characteristics of the process and consider the historical record both specific to the process and with respect to the operations and activities involved. The use of keywords generates an appropriate discussion such that at the end of the review it is unlikely that an unconceived hazard will subsequently emerge and the plant has been driven in the direction of reduced risk. Several versions of the HAZOP 1 technique of ICI exist, see Turney and Owen (2). A sample from the range of keywords is given in Table 2.

The objectives of this study must be clear as they can vary from a basic safety review to examining maintainability, product quality or providing advice to the designer. For each project it is usual to select about ten keywords to review the process, and such selection need not be confined to this list. It has been found useful to list equipment problems which refer to dangerous disturbances frequently occurring on specific plant items; such as liquid blowby and gas blowby from a gas-liquid separator.

The initial Process Sociotechnical System Analysis may be project oriented and carried out at Project Review to consider the resources required for the project and the essential process and project know-how. It should consider the organisation and management needs of the project. The needs of Regulators and Local Authorities must be considered together with a study of the site, local experience and skill, consents for emissions and effluents and the revised emergency plans of the works.

Table 2 Keywords in Concept Hazard Analysis

SUBSTANCES:	REACTIONS	EQUIPMENT PROBLEMS
Hazardous health (COSSH)	Planned / unplanned reactions	Equipment knowledge base
Hazardous to environment	THERMODYNAMIC	Dangerous disturbances
Dangerous substance,CIMAH	Overpressure/underpressure	RELEASE OF MATERIAL:
HEALTH HAZARDS:	Overtemperature, overheat	Release on rupture
Substances hazardous health	Undertemperature, overcool	Deterioration in construction
Chemical contact	Stored energy, stress, strain	Release by discharge
Bacteria	MECHANICAL HAZARDS:	Defect in integrity
Exposure, asphyxiation	Structural hazards	Fugitive emissions
Noise	Collapse, drop, lifting	Periodic emissions
Illumination / glare	Laceration, crushing	Product misuse
FLAMMABLES:	EXTERNAL THREATS:	Accumulation / spill
Ignition sources	Accidental Impact	Handling / Entry
Fires, smoke	Use of machines	LOSS SERVICES/SUPPLY:
Explosion / detonation	Drop / Fall	Loss of process streams
POLLUTANTS:	Act of God / nature	Loss of electricity
Emissions	Extreme weather	Loss of water (all types)
Effluents	External interference	Other services
Waste	Loosening / vibration	MODE OF OPERATION:
Ventilation	Sabotage / theft	Start-up
ELECTRICAL/RADIATION	External energetic event	Shutdown
Electrical	External toxic event	Maintenance, inspection
Radiation	External contamination	Abnormal operation
Laser	External corrosion / erosion	Emergency

PRELIMINARY HAZARD REVIEWS

Preliminary Hazard Analysis should generally be a top-down study driven from the release of material through emergency control and normal control and in critical cases bounded by immediate cause. It aims to ensure that no major changes will arise during the detailed design.

It has been found that the best starting point of this search is at points defined by the dangerous disturbances of plant which lead to rupture or discharge. These are as given in Table 3.

The dangerous disturbances occur at a point when emergency control procedures where available have proved inadequate. Note how this differs from hazardous deviations as defined in HAZOP which occur prior to this point in the incident scenario.

Each dangerous disturbance is noted on a proforma, Table 4, and the hazardous disturbance(s) and the significant event are identified and recorded. The gaps on the proforma are then filled in, as shown here for an exothermic reaction on the Methanator of a Hydrogen Plant. Preliminary Consequence Analysis examines the impact of any release. The approach used in effect follows the requirements of the CIMAH Regulations augmented by the use of Event Tree Analysis. An appropriate proforma for the results can be designed based upon the generalised incident scenario. This study will not give an accurate assessment of the frequency of any incident not the methods used to control or avoid the release. It should however consider ways of dealing with the resulting emergency and instigating the emergency response.

Note that a short-cut risk assessment has been carried out. This is backed by the fault trees from Preliminary Hazard Analysis plus event trees from a Preliminary Consequences Analysis. The latter follows along the lines of a CIMAH report and is not detailed here. A summary of each scenario is prepared for the Preliminary Safety Schedule shown here in abbreviated form as Table 5.

Table 3 Dangerous Disturbances of Plant

Disturbances resulting in rupture on exceeding mechanical limits
• Physical explosion • Chemical explosion
• Overpressure • Underpressure
• Overtemperature • Undertemperature
• Machine overload or stress • Impact blow/drop
Critical defect in construction
• Critical defect left in construction • Critical deterioration in construction
• Loosening/vibration
Flow through abnormal opening to atmosphere
• Abnormal opening left in plant • Abnormal opening made in plant
• Entry into equipment
Adverse change in a planned product or other release
• Change before leaving plant • Change after leaving plant
• Incorrect transfer • Abnormal vent/spill
• Incorrect use or disposal

Table 4 PRELIMINARY HAZARD ANALYSIS SHEET

Plant: Methanator

Date: 1.1.94:

MPI: Reactor circuit

IMMEDIATE CAUSES	INADEQUATE NORMAL CONTROL	PROCESS DEVIATION	FAILURE TO CONTROL (ON ALARM)	HAZARDOUS DISTURBANCE	INADEQUATE EMERGENCY CONTROL	DANGEROUS DISTURBANCE	FAILURE TO RECOVER SITUATION	SIGNIFICANT EVENT
High inlet temperature to reactor	Control system inadequate or misset		Operator fails to stop trend on TAH by adjusting control (slower acting and runaway unlikely)					
High CO_2 in stream from absorber	Fault on absorber	**High temperature in reactor**	Operator fails to stop trend on COx or TAH by correcting absorber	**High-high temperature in reactor**	Operator fails to stop inflow High temperature shutdown system fails	**Over-temperature in reactor**	Operator fails to stop all flows	**Release by rupture on (over-temperature)**
Impurities in feed down start-up line (sneak path)	Inadequate isolation after startup		Operator fails to stop trend on TAH by isolation					

RECOMMENDATIONS, COMMENTS, ACTIONS

1. Do not depressurise on high temperature unless no flow through Methanator
2. Operator alerted by several alarms. New TAH in and out
3. Check if start-up line needed if heat exchanger circuit modified
4. Alter outlet location of start-up line. Add PAH and TR. Double block and bleed
5. Check catalytic activation
6. Improve absorber reliability

Table 5 Preliminary Safety Schedule

INCIDENT SCENARIO	IMMEDIATE CAUSES	INADEQUATE CONTROL OR ACTION	INADEQUATE EMERGENCY CONTROL / ACTION	FAILURE TO RECOVER THE SITUATION	SIGNIFICANT RELEASE	MITIGATION OF RELEASE	SEVERITY OF CONSEQUENCES
SCENARIO 3. Rupture on the Methanator circuit due to overtemperature leading to torch fire with possible escalation to rest of complex	High inlet temperature to reactor F = 0.1 High CO_2 in stream from absorber or impurities in feed down start up line or high inlet temperature to reactor F = 0.1 Impurities in feed down start-up line (sneak path) F = 0.01	Operator fails to stop temperature trend on TAH by adjusting control (slow- acting) P = 0.01 Operator fails to stop trend on QHA(COx) or TAH by correcting absorber P = 0.1 Operator fails to stop trend on QHA(COx) or TAH by correcting isolation P = 0.05	Hazardous temperature in reactor and high temperature shutdown system fails Demand on system: F = 0.01 Probability of failure of trip system = 0.05 P = 0.05	Operator fails to stop all flows into Methanator by isolation of flows in and out of system. System not to be depressurised until cooled. P = 0.5	Release on overtemperature of reactor and adjacent pipework on outlet Failure frequency of system F = 0.0003	Release self-ignites. Reactor strengthened such that pipework most probable failure. Impingement on adjacent vessels leading to further torch fire P = 0.1 Impingement on adjacent pipeline with pool fire and possible missiles to other part of plant complex P = 0.01	Major damage to plant, possible injuries whilst fighting fire Likelihood = 3/4 Severity = 3 Severe damage to plant with possible injuries to plant personnel or fatality. No danger to public due to location of plant Likelihood = 5/6 Severity = 4

NOTES:

Procedures on all alarms and on activation of emergency control system to be documented and training programme established

Personnel to stay clear of methanator area on trip being activated. Fire-fighting procedures to be evaluated further

Procedures for inspection and maintenance of emergency trip system to be documented. Note how risk is badly affected should this item fail. Action on downstream plants on failure of Methanator to be determined.

Table 6 Methodology of Preliminary Hazard Analysis

• Partition the plant and select a section • Select a dangerous disturbance • Identify and note the significant event resulting from the dangerous disturbance • Identify and note each hazardous deviation giving rise to this dangerous disturbance • Complete the inadequate emergency control actions and failure to recover the situation • Study the hazardous deviation down to an appropriate level of immediate cause and fill in the inadequate control actions. Avoid going into HAZOP detail at this stage • Expand from the significant event to carry out a consequence analysis (may be carried out as a separate action later) • Select another dangerous disturbance and complete the studies
Subsequent to the study carry out a short-cut risk assessment Modify values according to the results of a Process Sociotechnical System Analysis Prioritise incident scenarios for further study and when appropriate repeat the study of immediate causes in HAZOP detail. Document results and commence Preliminary Safety Schedule

The format used for Preliminary Hazard Analysis has proved invaluable as an aid for producing fault trees. We advocate short-cut risk assessment with prioritisation for further study of critical cases. For details see Allum and Wells(3). This is insufficiently accurate for assurance that the company standard for tolerable risk is not exceeded but nevertheless is a useful indication.

The procedure adopted for Preliminary Hazard Analysis is shown in Table 6. It is emphasised that the main use of Preliminary Hazard Analysis remains the identification of hazards. Any process can be rapidly analysed without going into HAZOP detail for the majority of immediate causes of incidents. This is aided by starting the study at the point of a dangerous disturbance rather than a process deviation. The whole proforma is rarely completed and indeed an abbreviated form of documentation is preferred. Only a number of the more important scenarios are identified further and studied to assess risk. Clearly for these it is sensible when completing the proforma to utilise at an appropriate time the HAZOP technique to examine process deviations.

PROCESS SAFETY SOCIOTECHNICAL SYSTEM ANALYSIS

A Process Safety Sociotechnical System Analysis can be carried out following Preliminary Hazard Analysis. A keyword approach can be adopted as a means of generating discussion on key elements affecting a system. The sociotechnical approach emphasises the individual, social, organisational and managerial facets of the plant. External influences are included in the study as these influence the way in which a facility is operated. The framework adopted in our work is shown in Figure 1 and is a further development of the earlier work by Hurst et al (4). It is possible to divide the system into more entities but this has been noted as counterproductive as the study becomes too unwieldy and large.

The review aims to investigate how deviations/variances within each subsystem affect incident scenarios and plant safety using the general procedure outlined in Table 7. Each subsystem is reviewed by applying keywords which are specifically directed at key safety issues, usually specific parts of an incident scenario. The keywords for use with each subsystem are given in Table 8, the subsystems are given in bold type.

These keywords are amplified by a list of preconditions for failure which represent the root causes of incidents, see sample in Table 9. These latent failures are often present in the system for a period of time and in combination with other factors can lead to a serious incident. They are listed separately in a proforma which has a column for the results of the initial discussion.

The main studies for a proposed plant should be carried out during basic engineering at a time when the Preliminary Hazard Analysis has been completed. The use of a specific incident scenario on which to focus attention is essential as the discussion can start by asking if an accident were to happen on this plant what factors would be identified as being deficient. This approach leads to a more structured development which relates to the specific problem and reduces the extent of discussion as compared with an audit style approach.

Table 7. Steps for Process Safety Review of a Sociotechnical System

- ☐ Collect information on the main characteristics of the process system and its environment. This should include data on:
  - general information on the organisation and site
  - information on the Safety Management System
  - plant information and the main inputs and outputs
  - key incident scenarios
- ☐ Select an incident scenario
- ☐ Use keywords to identify preconditions for failure for each subsystem
- ☐ Note the main variances and how they affect system safety
- ☐ Record the discussion and continue with next scenario

Table 8. Factors for Sociotechnical System Analysis

Subsystems and Keywords	
External systems	**Management control**
Industrial and government bodies	Resource allocation and development
Contractors/consultants	Competence/capability of management
External emergency facilities	Responsibility and accountability
General public	Management of change
System Climate	Supervision and control
Technical adsorption	Monitoring and quality control
Legislation/regulations	Appraisal
Political climate/pressure groups	Handling emergencies
Economic climate/business factors	**Communication and information**
Business focus	Information quality
Corporate Culture	Safety information
Safety Culture	Channels and media interface
Organisation and management	Incident reporting
Decision-making hierarchy	Emergency response
Commitment to safety	**Procedures and practices**
Interaction with internal systems	Working practices and procedures
Interaction with external systems	Safety studies
Resource provision	Quality control
Inadequate production resources	Emergency procedures
Site and plant facilities	**Working environment**
Site and its layout	Local environment
Engineering and process design	Welfare
Commissioning and realisation of plant	Safety Culture
Transport, storage, use, disposal of material	Immediate supervision and support
Engineering integrity	**Operator performance**
Quality of plant	Recruitment
Availability and maintenance	Training
Safety and operating margins	Personnel capabilities
Plant upgrading / modifications	Working discipline
Standards and codes	

Table 9. Preconditions for Failure Arising from External Systems

Sociotechnical Analysis	**External Systems**
Keywords	**Preconditions for Failure**
Governmental bodies	Impact of new safety legislation or regulations Impact of planning regulations Impact of external inspectors
Industrial bodies	Impact of local works Inadequate shared facilities Inadequate pressure or support from parent company Pressure from suppliers/customers
Contractors/consultants	Inadequate selection and control of contractors Inadequate co-ordination on safety and health Inadequate monitoring of third party activities Inadequate know-how or experience Inadequate financial arrangements
External emergency facilities	Inadequate relations with outside services Inadequate agreement on the services and equipment which will be rendered Inadequate procedures for notification Inadequate information of toxicology and treatment for chemical related injuries Insufficient joint training sessions and drills
General public	Pressure groups Excessive local building developments Environmental developments

SECTION OF A PROCESS SOCIOTECHNICAL SYSTEM ANALYSIS OF THE METHANATOR

The Review of the Sociotechnical System should take a meeting format and is initiated by looking at each of the subsystems within the Sociotechnical framework defined earlier. The system is analysed assuming that an incident has occurred at the current time. Using an incident scenario as guide, the group should focus their attention on factors which give rise to any undesired event. The root cause categories with the list of preconditions for failure is then utilised to identify latent failures or the lack of controls which should be in place to stop the hazardous events from escalating into a major accident. It is left to the discretion of the group as to which subsystem should be given consideration first. The chairman should introduce each keyword and ensure a check is made that in a free discussion each precondition for failure is noted and remedial actions proposed.

The method has been applied to study an exothermic reaction termed the methanator. The process is essentially a finishing operation to remove oxides of carbon from a stream of hydrogen containing low percentages of methane and water, see Allum and Wells (3). The Process Safety Sociotechnical System Review of the plant will be carried out after the Preliminary Hazard Analysis, PHA using the incident scenarios generated by the PHA study as its basis.

The study in this case was initiated by considering the 'Procedures and Practices' subsystem first The list of keywords that were be used include:

- working practices and procedures
- safety studies
- quality control
- emergency procedures
- incident reporting

For this particular case the root cause factors which affect the incident are listed in Table 10. The study then proceeds to ensure that appropriate actions are taken to deal with the deficiencies that are identified.

The study may then move on to consider another subsystem say, 'Operator Performance' and the keywords to be used include:

- recruitment
- personnel capabilities
- training
- working discipline

Failure preconditions which may arise and appropriate actions are given in Table 10.

The identification of these root cause factors at the early stage of design enables management to provide safeguards and plans for preventing the occurrences of such failure preconditions. It is the aim that by carrying out the Process Safety Sociotechnical System Review the organisation will be less prone to latent failures and should any exist these can be designed out. Any major deficiencies noted can be subjected to a process audit.

Table 10 Example of Root Causes Identified in the Case Study

Root Cause Category: Inadequate Procedures and Practices	
Preconditions for failure	***Project actions***
Inadequate plant manual	Ensure that the written procedures are backed by expert systems for all actions to recover from an unsafe situation.
Control of external threats	Ensure precautions in place for access to plant including control of maintenance vehicle access.
Inadequate task observation and analysis	Identify all critical tasks. A procedure must be developed to determine appropriate action should the shutdown system fail to be activated or to respond by appropriate valve action. Ensure that procedure is developed for start-up and making sure that sneak paths are prevented.
Failure to carry out safety studies on procedures	The written operating procedures should be reviewed when they are fully developed.
Inadequate quality control	Identify key safety barriers to prevent latent errors occurring. Review trip-testing procedures and ensure that operator actions are fully understood. Ensure necessary response of downstream plant to shutdown of the methanator is fully understood.
Inadequate emergency plans	Emergency plans are not yet available. Ensure that procedures exist to deal with all emergencies. Need to study the problem of escalation and report on action to be taken.
Root Cause Category: Inadequate Operator Performance	
Failure to recruit skilled staff	The technology is new to the company. It may be necessary to recruit at supervisor level. Check that operators have adequate qualifications for the job.
Inadequate safety awareness and culture	Arrange training visits to similar plants.
Inadequate rehearsal of safety procedures and emergency response	A schedule should be set up to ensure that all operators are familiar with the emergency response. This should include simulation of the incident scenario reported.
Inadequate task training and appraisal	Investigate training programme for all critical tasks with periodic appraisal once operational.
Neglect of safety procedures	Ensure that safety procedures are provided and not written in a purely formal manner.

SAFETY SCHEDULE

This research has been carried out into ways of improving the process safety reviews carried out prior to HAZOP. Earlier studies on modelling incident scenarios have been refined with an improved model being developed with better emphasis on recovery mechanisms. This has improved the technique here called Preliminary Hazard Analysis with the added bonus that it can be used as an aid to generating fault trees. Selected incidents can be analysed in detail to indicate possible defects in the sociotechnical system of which the plant is a part. The keyword approach works rapidly and has further uses when carrying out safety audits or incident investigation.

It is important to show the further development of the combined use of the techniques. Concept Hazard Analysis, Preliminary Hazard Analysis and the Process Sociotechnical System Review, along with other techniques, should be integrated to set up the Safety Schedule which is to be developed for the plant. Such a schedule contains specific information on material hazards and inventory, incident scenarios, the immediate causes of incidents and the engineered protection and mitigation systems. The schedule should include note of root causes. This should refer to specific factors and indicate how deficiencies can be measured using performance indicators and where specific engineered defences can be instigated. This document can be built up over the life of a plant and can be used to demonstrate in an auditable form the quality assurance measures carried out on the project.

The techniques described, along with Preliminary Consequence Analysis which has not been discussed here, involve investigation of the following features:

1. THE INCIDENT SCENARIO: The sequence of events leading to a specific undesired event.
2. INCIDENT INITIATORS: Selected events and their root causes.
3. INCIDENT CONSEQUENCES: The worst expected financial, environmental, and safety consequences of the unmitigated event.
4. PROTECTION SYSTEMS: The engineered safety systems which are designed to detect and correct (automatically).
5. MITIGATION SYSTEMS: The (engineered) safety systems which reduce the undesired consequences of the event.

Such considerations fit equally well into any project stage. For example if Preliminary Hard Analysis is used to identify the Scenario - Initiator - Consequence sequence, then this can be extended to define the required functionality and integrity of the engineered protection and mitigation systems and the events against which they are designed. This can then be used as a specification for the design engineers as the project continues. This information is also useful during precommissioning and production. The system is able to evolve as the project develops and different hazard identification methods are used. It demonstrates in summary form that the plant/process is viable at the early stages of the project. It forms the specification for the detailed design and later gives a summary demonstration of plant safety, environmental acceptability etc. It can be used as a safety audit tool in which the integrity and functionality of the safety system has been defined. and the audit can confirm that the actual design meets that specification.

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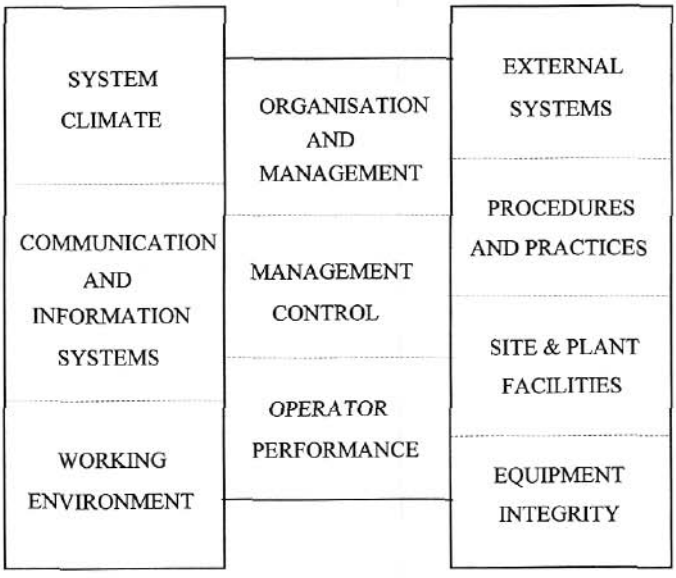

Figure 1 Subsystems within a Sociotechnical System