

SAFETY MODEL WHICH INTEGRATES HUMAN FACTORS, SAFETY MANAGEMENT SYSTEMS AND ORGANISATIONAL ISSUES APPLIED TO CHEMICAL MAJOR ACCIDENTS

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This paper introduces a model called PyraMAP which is focused on human performance in hazardous systems. It was developed for the UK Health and Safety Executive. The model integrates the role of Human Factors in safety within a wider context of safety management and organisation to enable more cohesive and better structured approaches to analyzing the performance of Major Accident Prevention (MAP). The paper also looks at the model in the context of the Texas City refinery accident of 2005.

1. INTRODUCTION

Investigation and analysis of accidents and their underlying causes has a dependency on knowledge and models of cause and effect. In recent years analysis has targeted underlying causes of accidents, influenced by ideas such as the Swiss cheese model of Reason (1990, 1997) and the concept of the organisational accident. Failures of front line operators in hazardous systems are no longer to be regarded as sufficient single cause for an accident.

This paper describes a structured approach to integrating the different levels of the human contribution to accidents and their prevention, in particular concentrating on major hazard chemical and petrochemical accidents. The approach is based on extensive previous work (Bellamy et al, 1989, 1999, 2006a, 2006b, 2007a, 2007b; Bellamy & Geyer, 1992; Bellamy & Brouwer, 1999; Baksteen et al 2007; White Queen, 2003) and is the next step in structuring and defining the role of Human Factors in Major Accident analysis and prevention.

2. TEXAS CITY ACCIDENT

For illustrative purposes the paper looks at a recent accident, the BP Texas City refinery accident (U.S. Chemical Safety and Hazard Investigation Board, 2007) where 15 people were killed and 180 injured. According to the investigation report the accident in BP's refinery was caused by overfilling of a raffinate splitter tower resulting in the release of a flammable liquid from a blowdown stack that was not equipped with a flare. During start-up of the tower operators were unaware that it was overfilled because the level transmitter was inaccurate and the redundant high level alarm failed to activate. In addition the tower level sight glass was dirty and unreadable. The control board display did not provide adequate information on the imbalance of flows in and out of the tower to alert the operators to the dangerously high level. "The Board Operator truly had no functional and accurate measure of tower level on March 23, 2005" says the report.

The accident triggered an enormous amount of interest in the fundamentals of safety organisation and management, leading to a review in the US of BP's refineries by an independent safety review panel documented in the so-called Baker panel report (Baker 2007). In this paper we will analyse the conclusions of this report along the lines of the PyraMAP model.

3. PYRAMAP MODEL – PYRAMID OF MAJOR ACCIDENT PREVENTION (MAP)

The PyraMAP model was developed for the Health and Safety Executive in the UK with the purpose of having a framework for a more integrated approach to safety (Bellamy & Geyer 2007). In addition the Deputy Unit Head for major hazards policy at the Ministry of Social Affairs and Employment in The Netherlands provided independent review and advice of the work. In particular he was critical of current applications of human factors science in assisting with major accident prevention.

The purpose was to have a generic safety model that integrated human factors within its wider context of organisation and safety management. The model should be applicable to different hazards and industries but the initial focus was on major hazards. PyraMAP stands for *Pyramid of Major Accident Prevention*.

The generic pyramid is shown in Figure 1.

The socio-technical issues comprise 3 taxonomies – organisation, safety management and human factors – and any aspect of risk control, such as a measure or a barrier or a procedure. A theme is a set of items from the 3 taxonomies built round the hub of risk control. The theme defines a the selection of the elements from the taxonomies which are connected together in some way.

The idea of having taxonomies is to make it clear what is being addressed in each area. In particular there was a need to define human factors because non specialists had difficulties understanding what it meant. Good human factors in practice is about optimising the relationships between demands and capacities in considering human and system performance. Whether there is good fit or there is mismatch will be reflected in behavioural outcomes. The human factors taxonomy therefore focuses on these demands, capacities and outcomes. The organisational taxonomy came from literature identifying organisational aspects of accidents (Bellamy, Leathley & Gibson, 1995). However, what makes the model major hazard specific is the safety management taxonomy, the technical aspects of

Figure 1. Generic socio-technical pyramid (Bellamy & Geyer 2007) with its three taxonomies – Organisation, SMS and human factors

the system and the hazards. In the major hazards application the safety management taxonomy used the UK COMAH regulation Safety Report Assessment Manual criteria series 4 as a basis (Health and Safety Executive, 2003) The detailed taxonomies can be found in Bellamy & Geyer 2007). An overview is shown in Figure 2.

4. MAJOR HAZARD THEMES DERIVED FROM ACCIDENTS

The taxonomies of the generic PyraMAP are used to make specific warning triangles which function to highlight socio-technical aspects that come together to create strengths or weaknesses in the system. This coinciding of factors is called a theme. The major hazards pyramid has 4 themes. Each theme describes the recurrence in major accidents of a specific group of socio-technical issues identified from the taxonomies. These 4 themes are coming from the analysis of 8 major accidents with detailed accident reports. They are:

1. Failure by people with major hazard responsibilities to understand the risks and the risk controls in MAP, particularly involving the information derived from risk assessment and the allocation of roles and responsibilities where understanding of the risks is key.
2. Failure to competently perform tasks related to the integrity of MAP risk control measures because of failures to deliver appropriate competences to persons in the organisation carrying out MAP tasks

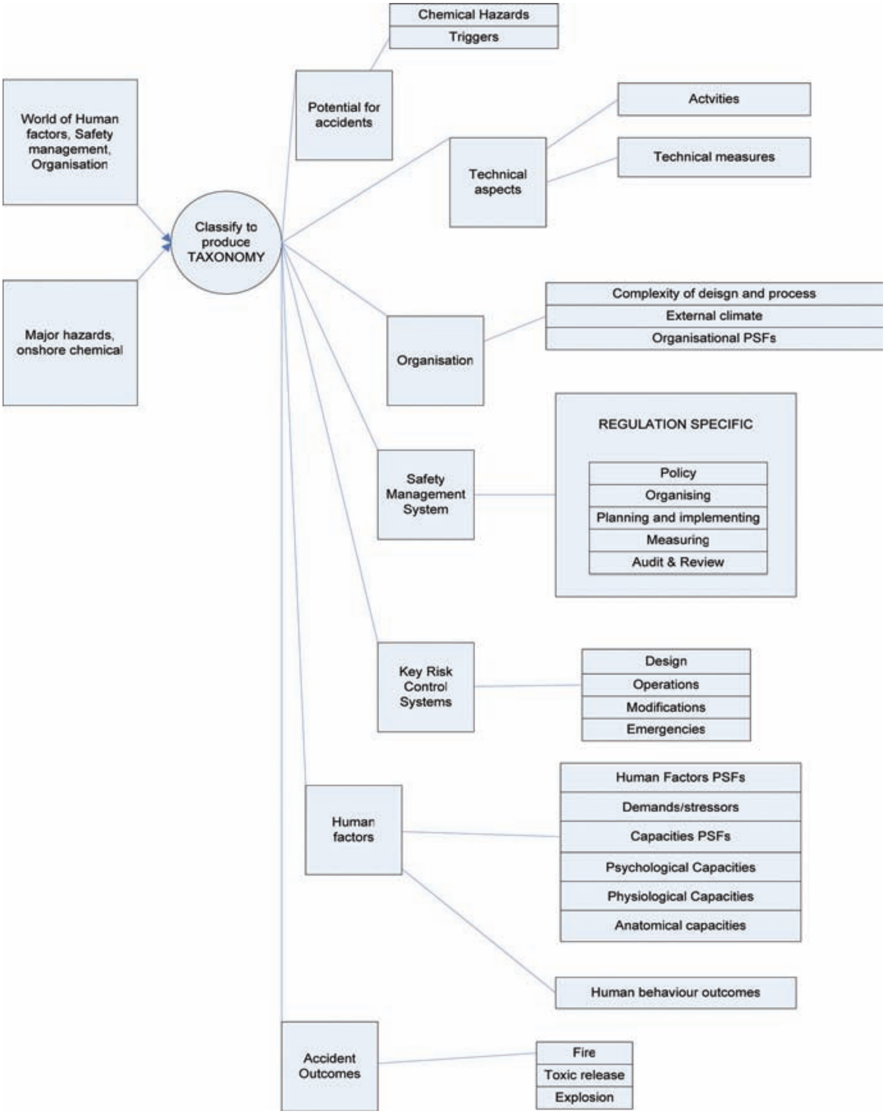

Figure 2. Basic taxonomy structure of the major hazards PyraMAP emphasising human factors, safety management, organisation and regulation

3. Failure to prioritise and give due attention to resolving demands on human performance capacities which conflict with MAP particularly through communications and workforce involvement
4. Failure to give assurance that there is a knowledgeable, learning organisation where behavior in relation to the MAP goals and procedures is being measured and improved.

The 4 themes of the PyraMAP, the 4 "warning triangles" are shown in Figure 3. Accident contributors identified in the reports were identified in the taxonomies such that each accident then had a list of taxonomy elements whose failures were related to causing the accident. The accidents analyzed were:

– Flixborough (UK, 1974): Explosion due to release from a temporary bypass assembly of inadequate design operated by insufficiently competent people

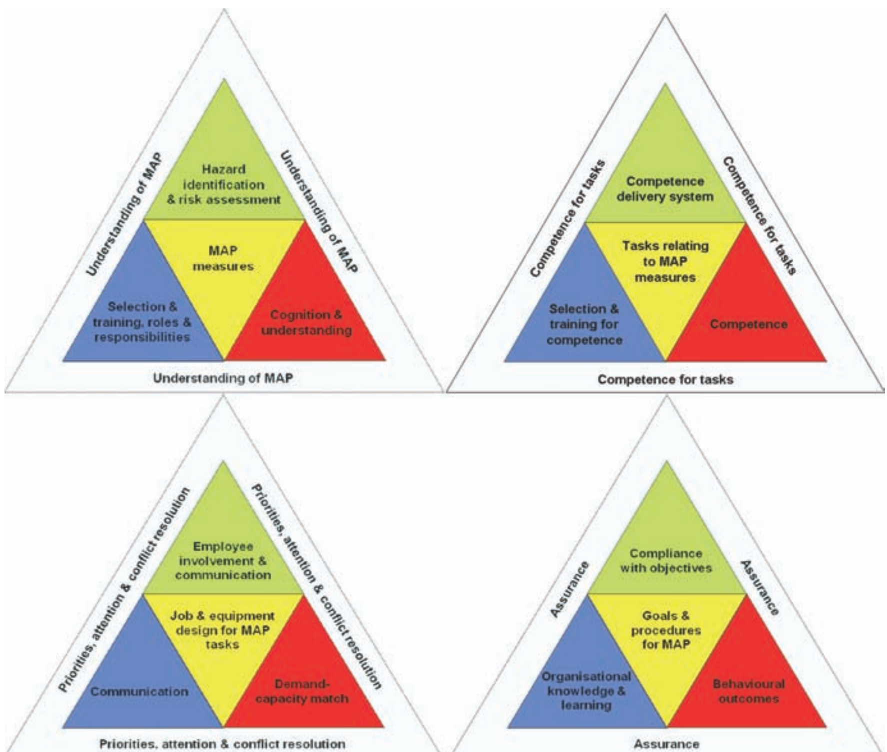

Figure 3. The 4 themes of the PyraMAP for major accidents (Bellamy & Geyer 2007) as derived from the analysis of 8 major hazard accidents

- Grangemouth (UK, 13 March 1987): Fire due to passing valve (poor design) and inadequate isolation procedures
- Allied Colloids (UK, 1992): Fire following misclassification of chemicals and failure to segregate incompatible substances in storage
- Hickson and Welch (UK, 1992): Jet fire following runaway reaction during non routine vessel cleaning due to lack of awareness of risks and inadequate precautions (Health and Safety Executive, 1994).
- Cindu (The Netherlands, 1992): Explosion due to runaway reaction in a batch processing plant. Trainee using wrong recipe in an old poorly designed plant
- Associated Octel (UK, 1994): Fire due to poor awareness of risks in complex poorly maintained plant
- Texaco (UK, 1994): Explosion and fires due to incorrect control instruments, poor MMI and alarm system and a lack of management overview
- Longford (Australia, 1998): Failure to identify hazards and properly train operators. Insufficient understanding led to a critical incorrect valve operation

Analysis of major accidents using showed the four dominant socio-technical themes mentioned earlier contributing to ***crucial mistakes*** that triggered those accidents. Failures in these four are considered to be archetypical of chemical major accidents and possibly can be more generally applicable.

5. USING THE PYRAMAPS

The use of the PyraMAPs and their themes is to encourage the pulling together of key aspects of an organisation surrounding a risk control system in an integrated way. From Figure 3 the PyraMAPS could be combined to make a 3-D pyramid, an organising structure for pulling together indicators of safety performance, the strength and weaknesses. The point of having the 3-D pyramid concept is to reinforce the idea that all the components combine to create a new whole. The purpose is to encourage holistic thinking in preventing major hazard accidents.

When laid out side by side the hallmarks of the dominant socio-technical archetypes become very obvious and predictable in major accident reports. If there are patterns then that might offer the opportunity to use the predictability to look for performance indicators which will fit the archetypes.

In order to get to grips with the organisation as a whole and its potential for a major accident, performance indicators need to be generated and this is where the PyraMAPs can be used as domains for generating indicators for risk control measures. In the working method for the PyraMAPs the analyst starts with a selected safety barrier, procedure, job design factor, or goals & rules and generates indicators across the 3 components within the specified theme. An example is shown in Figure 4 for the subject of *Ability of the Organisation to Learn*. This theme was considered to be a good test of the model because it is a broad issue. It was possible to map onto the structure the key attributes and key issues at a high level using the domain expertise of HSE inspectors.

Figure 4. PyraMAP of the subject "ability of the organisation to learn" (from Bellamy & Geyer 2007)

Selected Risk Control Tasks: – Recognition of risk/danger from failure to learn – Identification of learning sources – Identification of learning tasks	**Safety Management System:** – Arrangements to identify and access sources of learning (internal/external & international and other sectors) – Assignment of responsibility and accountability for learning – Arrangements to assess and implement improvements from learning – Competence
Organisation: – Actively seeking learning opportunities (including external) – Willingness to apply learning – Commitment at senior level	**Human Factors:** – Use learning to train individuals (direct and awareness) – Individuals provide ideas for learning

The steps to go through in order to generate PyraMAP warning triangles are:

1. Identify measures specific to the risks. Analysis of near misses, incidents and accidents in context of the barriers model, can be used to iterate the model.

2. Develop PyraMAPs for (selected) measures. Sufficient measures have to be selected to reflect the whole sociotechnical system.
3. Specify relevant indicators. A combination of domain experts is needed.
4. Gather evidence of the level of performance for these indicators and make a set of warning triangles.
5. Use as an inspection or safety management tool to identify safety barriers and the important sociotechnical elements surrounding them.

For example the risk control chosen is flow discharge from a particular containment and associated indicators of failure/overfilling for that containment. Where are the strengths and weaknesses in the sociotechnical system of which they are a part? When these are identified can they be validated using other measures i.e. are they systematic. Taking each theme in turn:

1. Understanding: Were there criteria for inclusion of failure of this system in a risk assessment? Were the hazards and risks of failure in flow discharge included in training? Who understands its importance in terms of preventing overfilling e.g. in terms of recognition of maintenance and monitoring requirements, or in terms of what the indicators mean? Who are the ones making the decisions Do they have an understanding of the risks? Do maintenance personnel understand the importance of the measures? Do decision makers allocating personnel resources know what the knowledge requirements are for those job positions which have a role in MAP?
2. Competence: What are the associated tasks for provision, use, maintenance and monitoring of the overfilling prevention measures e.g. Were designers of the indicators for overfilling competent? Were competence requirements identified for identifying and responding to deviations? Do users get training in following procedures and in recognising and responding to the indicators for that particular containment? e.g. is it safe to start up if flow discharge is blocked? Were they trained in an appropriate way? Do they get refresher training? Are there training and performance criteria?
3. Priorities, attention and conflict resolution: Are the overfilling identification and response tasks within capacity, or are there competing demands, overload, distractions, insufficient manning, communication failures, etc that could conflict? Could capacities be reduced through fatigue or attention to other tasks? How could a person report problems? Do they? What kind of response would they get? Is safety being shown to be a priority? In effect is there workforce involvement in safety or is there emphasis on production?
4. Assurance: What are the goals & standards and rules & procedures of the organisation that apply to the overfilling prevention of the containment in question? What are they based on? Is it a sound basis? Have there been any symptoms of mismatch in the performance of people interacting with this system? Violations? Omissions? Fatigue? Have there been failures in flow discharge before? Is the organisation learning to do things better with respect to overfilling scenarios – better knowledge, training, interface?

The answers to these questions for a small part of the system can provide the start of a creative pattern identification process. This can be taken further by actively tracking the main line strengths and weaknesses in other systems.

6. APPLICATION OF THE PYRAMAP TO THE TEXAS CITY ACCIDENT

After elaborating on each PyraMAP theme, some examples of relevant CSB investigation and Baker panel findings are given below (US CSB 2007, Baker 2007).

1. UNDERSTANDING OF (MAJOR) ACCIDENT PREVENTION

The most important aspect of the technical system is the control measures themselves, the equipment and process controls which are the necessary measures of major accident prevention and the safe boundary of operation. This is where hazard identification and risk assessment comes in. The safety management processes make use of organisational resources and assessment criteria to undertake these risk assessment activities. An output of these processes is information on hazards and risks as criteria and inputs to other processes such as training. This provides an understanding of what the measures and safe boundaries are and why they are there. Processes such as selection and training and job allocation provide as outputs managers and supervisors in jobs of authority who understand the risks and the risk controls. These processes include providing criteria for manning specific activities and replacing absentees. The ultimate goal is to have the understanding of the risks and risk controls present whenever MAP measures could be affected by human intervention in any of the life cycle phases.

When contributors to this sociotechnical system fail people who do not understand the risk control measures could end up in a situation which demands a judgement or recognition which they do not have in order to keep the MAP measures in place.

The Texas City investigation report (US CSB, 2007) stated that:

"A lack of supervisory oversight and technically trained personnel during the startup, an especially hazardous period, was an omission contrary to BP safety guidelines."

"Occupied trailers were sited too close to a process unit handling highly hazardous materials. All fatalities occurred in or around the trailers."

In particular:

"BP had used a rigorous pre-startup procedure prior to the incident that required all startups after turnarounds to go through a PSSR26. While the PSSR had been applied to unit startups after turnarounds for two years prior to this incident, the process safety coordinator responsible for an area of the refinery that includes the ISOM was unfamiliar with its applicability, and therefore, no PSSR procedure was conducted. …. The PSSR required sign-off that all non-essential personnel had been removed from the unit and neighboring units and that the operations crew had reviewed the startup procedure."

The Baker panel (Baker 2007) believed that BP

– has active programs to analyze process hazards but " the system as a whole does not ensure adequate identification and rigorous analysis of those hazards. The Panel's examination also indicates that the extent and recurring nature of this deficiency is not isolated, but systemic." (PyraMAP 1)
– "have delegated substantial discretion to U.S. refinery plant managers without clearly defining process safety expectations, responsibilities, or accountabilities" (PyraMAP 1)

2. COMPETENCE

People undertake tasks which should keep the measures in place by making them available, by using them correctly, maintaining them and monitoring them so that the technical system remains within the safe envelope. It is important that people are competent to do these tasks.

People require both theoretical and practical training. Competence requirements are criteria for selection and training. Safety management makes use of organisational resources and criteria like selection and training systems, job and task analysis and job descriptions in processes which deliver competences to tasks which support the MAP measures. The workforce (which includes managers) needs the knowledge, procedures and skills to do their tasks competently.

The Texas City investigation report (US CSB, 2007) stated that:

"The operator training program was inadequate. The central training department staff had been reduced from 28 to eight, and simulators were unavailable for operators to practice handling abnormal situations, including infrequent and high hazard operations such as startups and unit upsets."

The Baker panel believed that BP:

– "has not effectively defined the level of process safety knowledge or competency required of executive management, line management above the refinery level, and refinery managers" (PyraMAP 2)
– "has not adequately ensured that its U.S. refinery personnel and contractors have sufficient process safety knowledge and competence." (PyraMAP 2)
– "over-reliance on BP's computer based training contributes to inadequate process safety training of refinery employees" (PyraMAP 2)

The competence PyraMAP applied to the Texas City accident is shown in Figure 5. Here the findings of the Baker panel are shown according to the triangle components. The point is that these weaknesses combine to weaken the barrier integrity, not just in competences to use barriers effectively, but underlying competences in the organisation from the leadership downwards through the line management indicating an organisational incompetence to manage process safety.

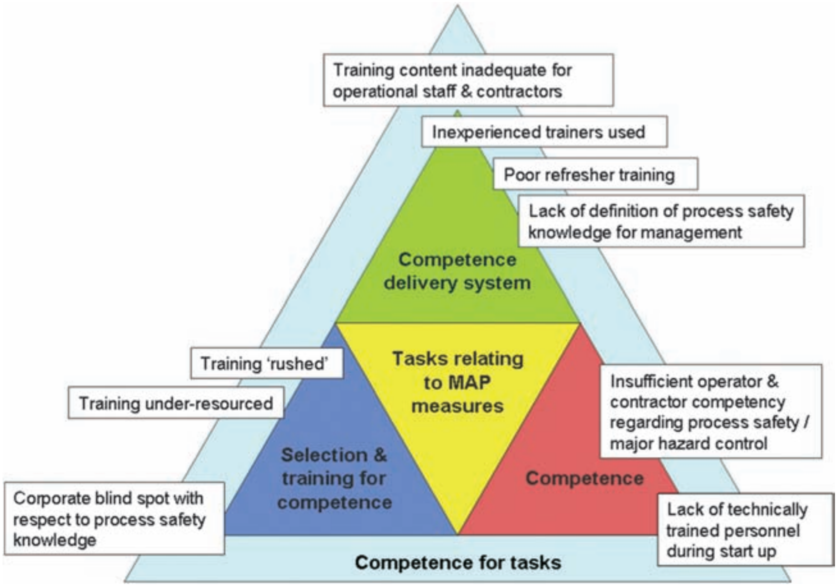

Figure 5. Baker panel and investigation report elements in the competence PyraMAP

3. PRIORITIES, ATTENTION & CONFLICT RESOLUTION

Performance on risk control related tasks should be supported by job and equipment design to prevent excessive demands which could lead to a demand-capacity mismatch. Mismatch means that a person is unable to perform psychologically, physically or physiologically in order to meet the task requirement like not being able to reach something because it is too high, being unable to analyse something because insufficient information is supplied or being unable to attend to something because it is lost in noise. These tasks should also be supported by information and communications that emphasize the criteria for what tasks should be given priority and attention. These communication systems should allow feedback and involvement of operators to indicate demand-capacity problems and help identify possible solutions as input to adjustment processes. Sometimes communications emphasize the wrong things because production pressures compete for time and attention or because the communication is badly designed and is giving the wrong message. Workload on operators, poor interface design, the stress of handling process deviations, insufficient procedural support can all cause attention and prioritizing problems in the use of resources.

The investigation report indicated that:

"An extra board operator was not assigned to assist, despite a staffing assessment that recommended an additional board operator for all ISOM startups."

" Supervisors and operators poorly communicated critical information regarding the startup during the shift turnover; BP did not have a shift turnover communication requirement for its operations staff."

"ISOM operators were likely fatigued from working 12-hour shifts for 29 or more consecutive days."

The Mogford Report cites fatigue as one of the root causes of the Texas City accident:

"Some employees had worked up to 30 days of consecutive 12-hour shifts. The reward system (staff remuneration and union contract) within the site encouraged this extended working period without consideration of fatigue. There were no clear limitations on the maximum allowable work periods without time off."

The Baker panel believed that BP

– in some refineries, including Texas city, "has not established a positive, trusting, and open environment with effective lines of communication between management and workforce" (PyraMAP 3)
– "operations and maintenance personnel … sometimes work high rates of overtime, and this could impact their ability to perform their jobs safely and increases process safety risk" (PyraMAP 3)

4. ASSURANCE

How do the behavioural outcomes relate to the goals, objectives and rules (procedures) of the organisation? It is often said that what gets measured gets better or gets done. What is measured should reflect the objectives of the organisation. Are the objectives, the goals, the procedures and the standards of risk control being met and are they good enough? Are there deviations, use of wrong objectives? Are there symptoms of mismatch? It is important to have appropriate MAP objectives for risk control and a system that ensures these are being achieved including learning systems for improvement. Organisational change can influence the ability to meet objectives. Loss of memory or knowledge separating it from the risk control system can be disastrous. For this reason monitoring, learning and adjustment is required in all areas affecting the processes whose outputs impact on MAP.

The Texas City investigation report stated that:

"Outdated and ineffective procedures did not address recurring operational problems during startup, leading operators to believe that procedures could be altered or did not have to be followed during the startup process."

"The process unit was started despite previously reported malfunctions of the tower level indicator, level sight glass, and a pressure control valve."

"The BP Board of Directors did not provide effective oversight of BP's safety culture and major accident prevention programs. The Board did not have a member responsible for assessing and verifying the performance of BP's major accident hazard prevention programs."

The Baker panel believed that BP:

- "has not provided effective process safety leadership and has not adequately established process safety as a core value" (PyraMAP 4)
- " did not always ensure that adequate resources were effectively allocated to support or sustain a high level of process safety performance" (PyraMAP 4)
- "does not effectively translate corporate expectations into measurable criteria for management of process risk or define the appropriate role of qualitative and quantitative risk management criteria." (PyraMAP 4)
- "does not effectively measure and monitor process safety performance" (PyraMAP 4)
- "does not effectively use the results of its operating experiences, process hazard analyses, audits, near misses, or accident investigations to improve process operations and process safety management systems" (PyraMAP 4)
- exhibits "instances of a lack of operating discipline, toleration of serious deviations from safe operating practices, and apparent complacency toward serious process safety risks at each refinery" (PyraMAP 4)
- "corporate safety management system does not ensure timely compliance with internal process safety standards and programs" or "timely implementation of external good engineering practices that support and could improve process safety performance" (PyraMAP 4)

7. CONCLUSIONS

The PyraMAP model closely matched the conclusions drawn by the Baker Panel in the analysis of BP's refineries Therefore, PyraMAP could be a useful tool in the analysis of major accidents with respect to the contribution of human factors. Human factors are now better related to major hazards accidents. In general the relation between human factors and accidents has not been described in a systematic way. The PyraMAP model is a step towards bringing structure into this relation. Accident analysis at a detailed level, across a significant number of accidents, can increase understanding of the sociotechnical patterns which make up major accident prevention or causation. PyraMAPS provide a framework, with the 4 dominant themes of accidents described in this paper, for creative thinking "outside the box" in prevention of major accidents. They might provide a basis for generating indicators of safety on the wider organisational influences on human performance, whether at board, line management or operator level for a specific technical system. In the Human Factors context, based on this model, such indicators would be placed on the organisation and management aspects which influence the match between the capacities of and demands on front line operators with the end result of reducing the likelihood of the technical system failing.

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