1. INTRODUCTION

The hydrocarbon and chemical process industries have made enormous efforts in the past 15-20 years to improve safety performance. This has been driven by major accidents in Europe, the USA and elsewhere (e.g. vapor cloud explosions at Flixborough, Pasadena, and Kuwait; a AN explosion at Toulouse, toxic releases at Bhopal, Seveso, Texas City; environmental accidents at Sandoz and Alaska; and major offshore accidents in UK, Norway and Brazil). Regulations, specifically addressing major accidents, have been developed, primarily in Europe and the USA, but other countries have adopted aspects of this regulatory approach as well.

While there is no uniform regulatory approach, there has been a shift in focus from occupational health to Process Safety Management. The UK probably has made the greatest effort to integrate different industries in a common regulatory format – based around the Safety Case. Key process and offshore industry regulations include:

- Europe: Seveso 2 Directive (updating original Seveso 1 Directive of 1984)
- Offshore: UK Offshore Safety Case Regulations, Norway NPD regulations

Some key non-Governmental activities and information dissemination have been associated with: the Center for Chemical Process Safety (administered by AIChE), the European Process Safety Centre, the American Chemistry Council, and many others.

Expenditures on safety have been variable. In the USA the focus was initially to bring drawings up to date and to carry out thorough process hazard analyses (mostly HAZOPs). Major investments have occurred for hydrogen fluoride and some polymerization facilities and more generally for occupied buildings in hazard areas. In the North Sea, a common major problem was identified around the proximity of hazards to occupied modules and major expenditure was necessary to address this issue. The Safety Case 1992 regulations were estimated by Aberdeen University to have cost the industry over £1.5 billion. Similar large expenditures also occurred in Norway.

This paper demonstrates that process safety management approaches work well in reducing personnel injuries, but have for the most part failed to deliver significant major accident risk reductions. An exception is the UK North Sea Safety Case regime which has reduced major leaks significantly and which implements several features not present in the other approaches. A number of companies have adopted this approach, but running these systems today is cumbersome.

2. WHAT HAS WORKED

In the period, the process industry has achieved a much better understanding of accident causation, safety management systems, barrier approaches, behavior-based safety, etc. The idea of the Management Loop (as in ISO14001) is deeply ingrained in these systems. However, the results of these efforts have been mixed. Some aspects of safety and environment have improved significantly, particularly those around individual safety, but major accidents remain a serious challenge.

2.1 PSM Strengths – Personnel safety

The major accident regulations have been broadly successful in getting all players to document their facilities and hazards in a systematic way, and support this with formal safety management systems. This has driven accident rates downward. The following chart (Figure 1) shows Total Recordable
Injuries in the period 1993-2002. These data have been obtained from the Company websites. Data represent for the most part minor injuries.

**Figure 1. Trends in safety results in the Process Industry**

![Trends in safety results in the Process Industry](image)

Note: Data for this chart was obtained from each Company’s public website – see reference section for website details. Scaling was used to make the dataset consistent where there was a change in recordables definition.

Although there are differences in the recordables statistic, some useful conclusions can be drawn. Clearly, personal injury trends have improved significantly. In the broad petroleum industry (e.g. API) the improvement has been about 30% over the decade 1993 to 2002. Conversely the “industry leaders” have achieved a 70% reduction result as shown by the average trendline above. Within the industry leaders, major improvements have been achieved even with excellent starting positions (e.g. Dow, ExxonMobil, ConocoPhillips). All of these companies have ongoing improvement targets which call for further major improvement.

### 2.2 PSM Weakness – Major Accidents

The area of major accidents would be categorized as a failure to improve for most companies. The last 5 years have seen several major accidents affecting the process industry. These include: major accidents at KNPC Kuwait, Conoco UK, Atofina Toulouse, Petrobras Brazil, and the Prestige off Spain. Prof Ale (2003) provides several examples from the Netherlands of declining performance in the area of major accidents. This evidence is confirmed in statistics collected in Europe and the USA.

The USA Environmental Protection Agency requires 5 year accident histories to included with Risk Management Plan submissions. Kleindorfer et al (2003) have analyzed this data, but they were unable to identify any downwards trend.

The EU Major Accident Hazards Bureau maintains the MARS Database (Major Accident Reporting System) which includes data from all 15 members of the EU. Duffield (2003) provided a graph showing reporting frequency to the MARS database current 2002. This shows no reduction in rate of reporting major accidents (Figure 2) – the slight fall-off in slope in 2002 is due to delayed reporting and has been seen in prior plots in this form from MARS. MARS also shows no change to average severity based on the 7 point severity scale.
The Norwegian Petroleum Directorate has reviewed major accident and other safety performance in their sector of the North Sea (NPD, 2003) and they find disappointing results, particularly indicators on major accident (e.g. hydrocarbon major leaks). They found their composite safety indicator was not improving and hydrocarbon leaks – a key indicator of major accidents – was increasing at a statistically significant rate.

A common model for major accident risks was developed by Heinrich and extended by Bird (2004). This showed a fixed ratio between minor and major accidents. The idea was that by attacking smaller incidents and personnel accidents that the improved “safety culture” would reduce major accidents in the same ratio. As no one site had sufficient statistics on major accidents, it was not possible to verify this assertion. In fact the recent EU and USA data do refute this fixed ratio. The approaches used to enhance personnel safety do not specifically address the barriers which control major accidents and thus it should be no surprise that the two do not correlate well.

If the process industry is to achieve desired major accident rate reduction, then it must do so by techniques focusing on major accidents, not relying on other piggy-backing off other EHS measures. This approach has been found not to work.

3. THE UK OFFSHORE DIFFERENT APPROACH

An interesting difference to this negative trend is the experience of the UK North Sea offshore oil sector. This zone is managed by a safety case regime (HSE, 1992) with some significant differences to the Seveso 2 onshore process industry safety report approach.

Hydrocarbon leaks have been monitored thoroughly following a requirement from Lord Cullen in his Piper Alpha inquiry report. The HSE data, shown in Table 1, show a steady downwards trend in major hydrocarbon leaks. Interestingly, medium leaks reduced less and minor leaks increased. This is discussed below.

<table>
<thead>
<tr>
<th>SEVERITY</th>
<th>97/98</th>
<th>98/99</th>
<th>99/00</th>
<th>00/01</th>
<th>01/02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>13</td>
<td>15</td>
<td>12</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Significant</td>
<td>139</td>
<td>134</td>
<td>127</td>
<td>117</td>
<td>109</td>
</tr>
<tr>
<td>Minor</td>
<td>66</td>
<td>85</td>
<td>95</td>
<td>145</td>
<td>128</td>
</tr>
<tr>
<td>TOTAL</td>
<td>218</td>
<td>234</td>
<td>234</td>
<td>270</td>
<td>241</td>
</tr>
</tbody>
</table>

The whole focus of the UK Offshore Safety Case regime is to address major accidents and it does through mechanisms not present in the EU Seveso 2 Directive, the USA PSM / RMP regulations, or the NPD requirements. Major accidents occur too infrequently to judge success in the UK sector alone, but major leaks are believed to be a good indicator of the potential for a major accident.
The Offshore Safety Case regime was developed in 1992 and the HSE and the industry had the opportunity to learn from deficiencies in the Seveso 1 Directive. Some specific differences in this regulation compared to other regulations are believed to contribute to the specific success on major leak reductions.

Table 2. Comparison of major accident regulations requirements

<table>
<thead>
<tr>
<th>Regulatory aspect</th>
<th>UK Offshore Safety Case 1992</th>
<th>Seveso 2 Directive</th>
<th>USA OSHA PSM / EPA RMP</th>
<th>NPD Offshore requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Management system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Risk assessment</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quantitative Risk Assessment demonstrating meeting a defined risk target</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Identification of Safety critical element (critical barriers)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Performance standard for all Safety Critical Elements</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Lifecycle program to maintain critical barriers (Written Schemes of Examination)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

This is a simplified table as each regulation has many requirements, and earlier text identified some key successes for personnel safety driven by these regulations. The key difference relates to the focus on critical safety and environmental barriers, termed Safety Critical Elements. There is a growing awareness of the need to focus on barriers in safety programs, based on the well known “Swiss Cheese Model” of Reason, by CCPS on Layers of Protection Analysis, and the new IEC 16511 standard. Only a few process facilities have converted their hazard identification studies to address these concepts. Reason’s Swiss Cheese model is a good metaphor for barrier controls. In it, the more barriers (the number of slices) and the higher their reliability (the size of the holes), the less likelihood that a safety challenge can bypass all the barriers and lead to a major accident.

The UK regime uses the risk assessment to identify the Safety Critical Elements. In simple terms these are the safety controls (hardware, people systems, or software) that deliver a disproportionate improvement in safety (and conversely, when not functional lead to a disproportionate increase in risk). Typically these are a manageable number – 50 to 100 items per facility. Each of these must have a specific performance standard – a defined level of reliability / availability / functionality – that ensures that the overall risk target is met based on all foreseen safety demands. This is demonstrated in the risk assessment. The performance standard can only be achieved by ongoing efforts through the lifecycle – inspection, maintenance, training, testing, etc. The purpose of the Written Scheme of Examination is to define the specific program of activities to maintain the safety critical elements. This allows these to be planned, resourced and monitored through life.

The author believes this focus on major accident barriers, defining their required reliability, and the means by which this will be achieved is a key factor in the success of the UK regime. This is not to say the UK regime is perfect and a conference in Nov 2003 addressed a need to modify the regulations to create a stimulus for continuous improvement, to revitalize the safety case process, to enhance workforce involvement, and to reduce bureaucracy.
4. RISK-BASED OPERATIONS

Risk-based approaches

The process industry has started to implement risk-based strategies for parts of its activities that have returned good value. Examples include: Risk-Based Inspection (API 580 and 581) and Risk-Based Maintenance (an extension of Reliability Centered Maintenance). Risk-based inspection analyses risks and revises inspections for fixed equipment to match the inspection type and frequency to the need. Reducing fixed inspection intervals has driven out significant operational cost through fewer inspections and by extending turnaround intervals. Similarly risk-based maintenance reviews equipment reliability and targets preventive and predictive maintenance at higher risk items (either safety or business interruption) rather than relying on traditional breakdown maintenance.

Risk-based operations (RBO) is a developing technique to deploy knowledge gained in Hazard reviews and deploy this in a manner that maximizes uptime and operational throughput consistent with a previously established safety target. It uses a proven methodology from the North Sea but extends the approach and links in to other risk-based approaches (RBI and RBM).

Risk-based operations steps
1. Extend the current HAZOP focus on causes and safeguards to address necessary mitigations if safeguards are degraded
2. definition of safety environmental or business critical safeguards
3. definition of threats
4. create real-time metrics for safeguards and threats
5. create data links to enterprise, site and individual databases to compile metrics in near-real time
6. review real-time metrics in routine operational planning meetings
7. where the combination of threats and safeguards condition leads to excess risk deploy risk reduction measures using a suitable decision framework

How it works

Typical scenario for Monday morning planning meeting:

Operational preference:
To carry out routine operations at 100% capacity, plus undertake an unusual catalyst regeneration cycle, plus cope with simultaneous turnaround activity on the site.

Threats:
Construction activity means three times the normal number of hot work permits need to be issued, plus 15 contractor vehicles and 200 contractors within the process area. One senior foreman is sick but a replacement is available from a different unit.

Safeguards status:
10% of relief valves are 6 months beyond their nominal test interval, the gas detection system is operational but has not been calibrated according to the planned sequence, the fire protection system is in test and part of the system will be blocked in for testing.

Decisions required:
   a) is this ok with normal resources
   b) are extra operational resources required
   c) should some activities be limited or some processes be shutdown

Today this decision is mainly judgmental by experienced operational managers and supervisors. Some oil companies have developed decision trees (e.g. Matrix of Permitted Operations) that address to some degree the type a) or c) decision but only if specific critical safeguards are completely non-functional. They are poor for type b) decisions and dealing with extra threats and degraded safeguards.

Often the potential accident will not be related to the direct activity, but the overall workload (extra permits, contractors on-site) means supervisor attention is insufficient and problems can arise that
cannot be diagnosed quickly. Interaction between the extra work and the accident may be hard to predict.

- e.g. Longford accident – insufficient technical expertise available when needed due to an unusual operational condition
- e.g. P-36 accident – unusual operation leads to an accident while simultaneous inspection activity has opened a void space for inspection while some compartmentalization safeguards are degraded

Risk-based operations approach
- Calibrate penalty factors for degraded safeguards
- Calibrate penalty factors for current threat
- Calibrate risk factors of proposed activities
- Apply decision framework
  - Is the risk level above a predetermined critical threshold?
  - Operations can proceed as normal, operations can proceed with additional safeguards, operations cannot proceed without some shutdown
- Develop operations plan maximizing output within agreed risk framework
- Refer to HAZOP for pre-developed solutions approach

5. EXAMPLE RISK-BASED APPROACHES

**Bow Tie Barrier Approach**

Zuijderduijn (1999) describes the Hazards and Effects Management process and the use of barrier diagrams (termed Bow Ties) at the Shell Pernis site. This process is used by Shell globally. The Bow Tie concept is provided in Figure 3.

**Figure 3. Bow Tie example**

This figure identifies the main threats on the left hand-side and demonstrates in a “bow tie” shape how barriers prevent the escalation of the initial threats to one of several final outcomes. Safety critical barriers are identified and each of these is assigned to a business group with an individual responsible.
Some Shell sites use a feature called Matrix Of Permitted Operations which defines in matrix format what activities may or may not be done if the relevant barrier is not functional. This is a form of risk-based operations, but it focuses on forbidden operations and it is understood the approach has not found favor in operating sites as it is too restrictive on operations.

Dalzell Mohell and Ditchburn (2003) describe the barrier approach being used by BP offshore. This employs a sophisticated management system to support the barrier concept. It does not use real-time metrics for operations decision making.

Prototype Risk-Based Operations - North Sea Threat and Safeguards Status

Kortner et al (2001) describe a near real-time barrier measurement approach used by Statoil in the Norwegian North Sea sector. Statoil management sought a tool that would:

1. Map and describe the technical safety condition at all facilities offshore and on land operated by Statoil.
2. Develop methods to map and monitor the technical safety condition of safety barriers, safety systems and equipment, inclusive predicting safety development trends.

Kortner et al describe four types of measures:

1. **Lagging measures** Statistical accumulations of actual incidents or near miss events for a facility. Typically these are slow moving and make sense only over longer time periods (e.g. annual averages).
2. **Leading measures** Measures of PSM management system elements that support EHS, such as management of change systems, training systems, etc. These are mainly assessed by 2-3 year audits. These are slow moving measures not well suited for day-to-day operational management.
3. **Barrier measures** Measures of the status of EHS barriers from fully functional to seriously degraded or non-functioning. Suitable candidate for real-time measure.
4. **Threat measures** Measures of the degree of threat to the facility. These are typically EHS challenges at a rate higher than anticipated in the risk assessment that underlies the safeguarding system. These can be determined by monitoring / predicting weather, nearby ship traffic, work permit activity, contractors on board, etc. This is also a suitable candidate for real-time measure.

The assessment looked at 19 safety barrier classes (ranging from containment systems, firefighting systems, ship collision prevention, etc) for 16 North Sea platforms. Each barrier was assessed for a performance requirements in terms of its: function, integrity (or unavailability), vulnerability to the event, and management/ documentation. Each barrier was assessed by audit, observation, test, or other suitable means and a 6 point rating assigned ranging from A – Better than Reference Level to F – Intolerable Condition. A total of 5000 ratings were generated. These did give a moment-in-time status of barriers but the logistics are too large to maintain this live as real-time data. It is more used as a priority to fix deficient items.

Facility Simultaneous Operations and Construction Risk Management

Statoil is using the idea of real-time measures to control risks at one of their major facilities (Hundseid and Brien, private communication). This facility is undergoing a major expansion with simultaneous normal operations. The site has developed a system for operational risk control that balances threats against risk. Operational control applies to three controllable variables: the number of hot work permits, the number of contractors on site, and the number of contractor vehicles on site. These are manipulated on a day-to-day basis based on a quantitative risk assessment prediction.
The risk measure is based on the FAR statistic (Fatal Accident Rate – fatalities per 100 million man-hours worked) which itself is calculated from the Potential Loss of Life metric (a non-normalized fatality rate). The FAR is calculated from a quantitative site risk model which uses the formula:

$$FAR_{HC} = \frac{(PLL_{\text{day}} \cdot H_{\text{day}} \cdot Fwp_{\text{day}}) + (PLL_{\text{night}} \cdot H_{\text{night}} \cdot Fwp_{\text{night}})}{H_{\text{day}} \cdot N_{\text{day}} + H_{\text{night}} \cdot N_{\text{night}}} \cdot \frac{1}{8760} \cdot 1E8$$

- $FAR_{HC}$ = Fatal Accident Rate for hydrocarbon related accidents
- $PLL_{\text{day}}$ = Potential Loss of Life (frequency per year)
- $PLL_{\text{night}}$ = Potential Loss of Life (frequency per year)
- $H_{\text{day}}$ = Fraction of Construction Shift in operation (= (10hrs/24hrs)*((25days per month*12months per year)/365days per year) = 0.34
- $H_{\text{night}}$ = Fraction of Night Shift in operation (= 1-0.34 = 0.66)
- $Fwp_{\text{day}}$ = Factor expressing the degree of "exposure to process risk" during the Construction Shift (0.6). This factor is determined based on information on site.
- $Fwp_{\text{night}}$ = Factor expressing the degree of "exposure to process risk" during the Night Shift (0.2).
- $N_{\text{day}}$ = Average number of man-hours per site hour during Construction Shift
- $N_{\text{night}}$ = Average number of man-hours per site hour during Night Shift

The quantitative model is run in the DNV Neptune Risk package which allows for combinations of different accident types, event trees, compiled consequence models, and basic subroutines or spreadsheet calculations.

While this example approach does give genuine risk-based operations, it is not directly linked to safeguards / barrier status, primarily to threat status. Thus it is not yet a full implementation of a 4 parameter model suggested by Kortner (2001).

6. CONCLUSIONS AND NEXT STEPS

Although general safety as measured by lost-time injury statistics has improved significantly in the past 10-15 years, major accident safety performance has stagnated. This was demonstrated by reference to several examples. The most successful of the major accident approaches, currently the North Sea safety case regime, is based on quantitative barrier management. Tentative examples have been developed in the oil industry to show how real-time metrics, derived around barrier ideas would be used for risk-based operations.

Several additional steps need to be demonstrated to develop a full Risk-Based Operations approach. These additional steps are:

- Development of a framework for combining the four real-time metric types: lagging, leading, threat, and safeguards status.
- Development of a qualitative model based on risk penalties (to reflect increased risk) and risk bonuses (to reflect reduced risk)
- Development of a quantitative model based in combined quantitative measures (personnel, environment, and business interruption).
- Combining the measures to newly available “real-time” measures from Enterprise databases (e.g. SAP, PeopleSoft, etc.), corporate and site data compilations (e.g. Access or Excel), site operational data (e.g. Process Information Managers linked to the process control system).
- Development of a real-time decision framework (qualitative and quantitative) that can be used at regular Monday morning meetings.
7. REFERENCES


HSE (1992) Offshore Safety Case Regulations


