PERFORMANCE INDICATORS FOR MAJOR ACCIDENTS – LESSONS FROM INCIDENT ANALYSIS

Linda J Bellamy[a], Joy I.H. Oh[b], Henk Jan Manuel[c], and Vera Sol[d]
[a] Managing Director, White Queen Safety Strategies BV, PO Box 712, 2130 AS Hoofddorp, The Netherlands, linda.bellamy@whitequeen.nl
[b] Deputy Unit Head, Occupational Safety and Major Hazards Policy, Ministry of Social Affairs and Employment, Postbus 9080, 2509 LV Den Haag, The Netherlands, joh@minszw.nl
[c] Project Manager, Dutch National Institute for Public Health and the Environment (RIVM), PO Box 1, 3720 BA Bilthoven, The Netherlands, Henkjan.Manuel@rivm.nl
[d] Researcher, Dutch National Institute for Public Health and the Environment (RIVM), PO Box 1, 3720 BA Bilthoven, The Netherlands, vera.sol@rivm.nl

In the Netherlands use has been made of the software tool Storybuilder™ to analyse the causes and underlying causes of Loss Of Containment (LOC) accidents. In addition, work has been undertaken to investigate if, in the literature, there is any evidence of good measures of safety performance in a major hazard context. In the industry itself there are continuing concerns about the contribution of the organisational factor in accident causation, about keeping the number of key safety performance indicators to a minimum, about the value of using near miss data and about prioritising improvements. Can incident analysis be more targeted at resolving some of today's concerns? This is considered in the context of understanding the underlying causes of the low probability large consequence accidents in the chemical industry using Dutch and other European data, examining the technical and organisational contribution to deviations in the data set and considering how this fits into the wider context of measuring safety performance and the high priority areas.

1. INTRODUCTION

In the Netherlands there is an initiative by the policy unit for safety at work at the Ministry of Social Affairs and Employment to develop process safety performance indicators that the Labour Inspectorate can use as a monitors of Seveso company performance in safety management of it major hazards. The Ministry commissioned the National Institute for Public Health and the Environment (RIVM) to develop safety performance indicators (SPIs) based on a combined approach involving literature and guidance review of safety performance indicators for major hazards (RIVM, 2012), an evaluation by interview of a sample of Dutch Seveso establishments together with the experience of the Labour Inspectorate responsible for major hazard control and the development of a SMS norm derived from this background. This paper looks at the possible contribution of accident data to performance indicator development. The total framework is shown in Figure 1.

A major accident in the chemical industry concerns the release of a hazardous substance (major emission, fire or explosion) which causes, or could have caused, serious harm to people and the environment. While a number of major accidents occur in Europe every year, the bigger accidents are rare with well-known names associated with the accident locations – Flixborough in the UK 1974 (28 deaths, 89 injuries), Bhopal in India 1984 (2500 deaths reported within 5 days), Enschede in the Netherlands 2000 (22 deaths, 950 injuries) Toulouse in France 2001 (30 deaths, 10,000 injuries), Texas City, USA 2005 (15 deaths, 180 injuries), Buncefield in the UK 2005 (43 injuries). These accidents were unexpected occurrences that resulted in the need to improve the understanding and regulation of major hazard control. Current thinking is emphasising the use of leading indicators for monitoring major hazard safety performance. These should act as signals that make visible the boundaries of acceptable performance as well as showing if performance is moving to an unacceptable level in sufficient time to enable restoration to the acceptable state before getting to a point of no return.

To make the connection between safety and indicators it is generally agreed that in practice the safety performance indicator system should be linked to the risks. Grote (2009) suggests that central to the debate on SPIs is sound knowledge about cause and effect relations in order to predict safety performance from any set of indicators. Qualitative links with risk have been suggested in accident models such as the Swiss cheese model (Reason 1997 where indicators could point to the quality of the slices of cheese which represent lines of defence or risk controls (Broadribb et al 2009). The UK Health and Safety Executive's guidance on developing performance indicators (HSE 2006) makes use of this model built around the socio-technical concept of the risk control system. In practice companies are each developing their own indicators based on experience. Judgement based indicators predominated at the CEFIC/EPSC (2012) conference on safety performance indicators. Dutch industry and employers' associations have made promises to the government to come up with performance indicators for Seveso companies with registration of information starting in January 2012 (VNO-NCW et al 2011).

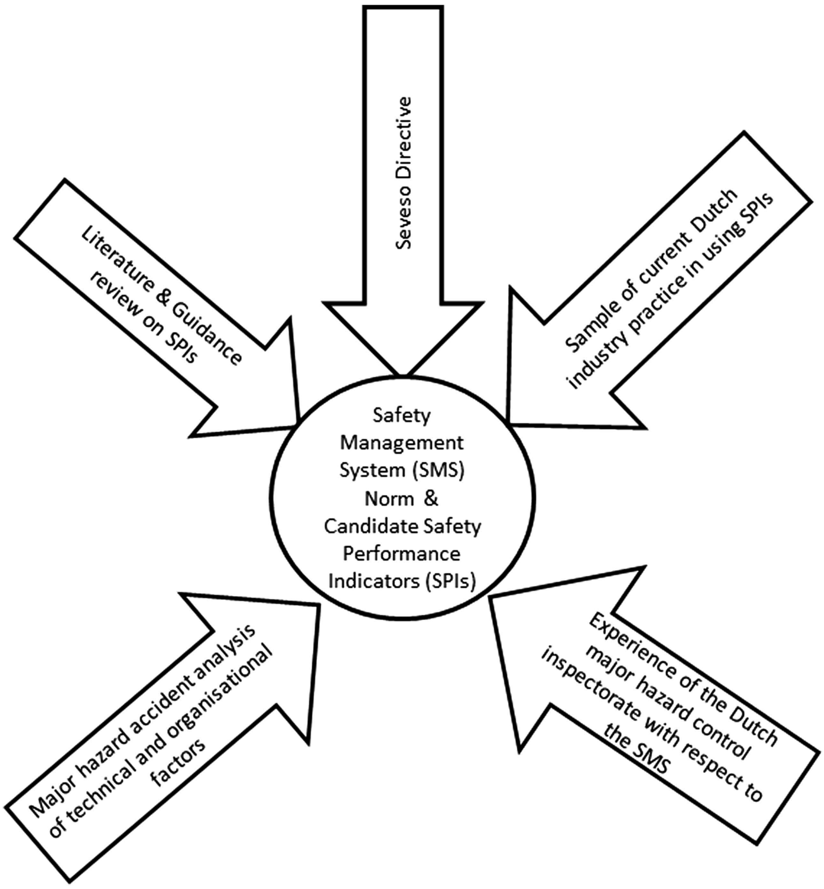

Figure 1. Framework for the development of Safety Performance Indicators for use by the regulator for monitoring the performance of Seveso sites in The Netherlands

2. BACKGROUND TO THE CURRENT WORK

In the RIVM (2012) review a distinction was made between indicators that a company might have and those that the regulator might use to evaluate company performance. 20 general points were made which performance indicators should ideally have based on literature and guidance in the area. 10 points were made with regards to the needs of the regulator, amongst which that the indicators should give signals for concern about future safety and should identify degradation in safety performance as early as possible. Identification of trends in a company's performance is important and measurement should be frequent enough to allow that to be possible. (See Annex I).

The strengths of the relationships between candidate leading indicators and safety performance are not generally known. Nonetheless factors like inspection backlogs, overdue training, management distanced from the work floor, inadequate knowledge of the risks, design failures, non-conformance with established procedures, routine violations, lack of accountability, procedural conflicts are examples of the kinds of organisational factors that have been associated with accidents at one time or another. After the fact we make sense of the events but there is a lack of scientific literature concerning the predictive success or otherwise of major hazard safety performance indicators. The obvious and predominant line of thinking is that deviations, plant failures and incidents provide a source of indicator information. Hopkins (2009) talks about failures which identify how well the process safety controls are functioning like plant trips and alarm rates, or delay to repair. Vinnem (2010) describes the indicators that are being used in the Norwegian offshore petroleum industry by the Petroleum Safety Authority based on the performance of technical safety barrier failures and the occurrence of major hazard precursors such as non-ignited hydrocarbon leaks. Technical safety barrier failures have also been used in a project coordinated by RIVM (2008) for the quantification of occupational risk and the principles of data analysis and modelling are now being applied to major hazard risks. The major hazard database model was built initially using data from the European MARS database (MAHB 2012) and subsequently incident investigations in Seveso plants carried out by the Dutch Labour Inspectorate (Arbeidsinspectie 2011, Mud et al 2011). As part of the development work a tool called Storybuilder^{TM} (Bellamy et al 2006, 2007, 2008, 2010) was developed in order to analyse the data arising from such investigations. The Health and Safety Laboratory in the UK have also used this model to analyse the Health and Safety Executive's RIDDOR accidents concerning Loss Of Containment (Lisbona & Wardman 2012; Lisbona et al 2011). The Storybuilder^{TM} software enables a graphic database to be built and scenarios are drawn as lines connecting identified events. These events are primarily safety barrier failures and loss of control events which occur in the technical system, and front line task and management failures for the human systems supporting these barriers. The model is described in Bellamy et al (2012) and contains the components shown in Table 1.

In analysing the data in Storybuilder^{TM} the following principles apply for the analysis of each incident:

1. Causes are represented as failures in or absence of *safety barriers* as can be identified in the report of the inspector and other information such as witness statements. A failed or absent safety barrier is defined as a failed or absent object, condition or state in the technical system which could have prevented the accident (in this case a loss of containment) or reduced its effects (such as by shutting off a release). Any additional data on the safety barrier are recorded as *incident factors* associated with each barrier, which can be viewed as holes in the Swiss cheese. The result of a failed barrier is a *loss of control event.*
2. The modelling of causes underlying the barrier failures are failures in the *barrier tasks* which are the human elements of the barrier functioning which serve to provide, use/operate, monitor and maintain the barrier's safety function. A sub element of these is where a human error has specifically been identified in the barrier task "Use".
3. The modelling of causes also includes identified failures in the delivery of 8 management resourcing systems which must be specific to the needs of the barrier tasks. The *management delivery systems* provide the outputs of the safety management system to deliver the needed resources to the safety barrier tasks.
4. Inadequacies in the Safety Management System (as specified by the Seveso Directive) are included in the evaluation of failed barriers where these were identified in the investigation.
5. A sequence of events (a scenario) in terms of barrier failures occurs from left to right in the graphical bowtie model. Failed barriers are from lines of defence which have been penetrated one after the other for the loss of containment and its effects to occur.

The basic components are shown in Table 1.

3. USE OF ACCIDENT DATA

Accident data are "lagging" indicators describing past safety outcomes of the population of plants from which they are derived. A lagging indicator of plant safety is most usually defined as the result of a loss of control which caused or could have caused harm or damage. CEFIC (2011), for example, provide guidance to companies to enable consistency in collecting lagging indicators on spills, injuries and material loss. Using the same framework provides the opportunity to benchmark and pool data.

It is generally agreed that lack of a major accident does not indicate that a plant is safe. For this reason so-called "leading" indicators are sought, these being indicators that are intended to say something about future safety performance. A whole controversy about what is leading and what is lagging has emerged although in effect all indicators are after the fact but the distinction is useful to separate early causes from effects.

In the examples of analysis described in this paper the underlying organisational factors associated with technical failures are illustrated. The 64 MARS refinery accidents

Table 1. Components of the Organisational-Technical model of the Storybuilder database. In the analysis of accidents the modeling process starts on the right and progresses left but in the model the implied causality structured from left to right as shown

Safety management system required components →	Management deliveries →	Barrier tasks →	Barriers →	Loss of control events (including bowtie centre event)
• Major Accident Prevention Policy • Organisation and personnel • Identification and evaluation of hazards • Operational control • Management of change • Planning for emergencies • Monitoring performance • Audit and review	• Procedures • Availability of people • Competence • Communications • Ergonomics • Motivation • Conflict resolution • Equipment	• Provide • Use • Maintain • Monitor	Conditions, states or objects in the technical system which perform a safety function to prevent or reduce the effects of loss of control events. When they fail they result in a loss of control.	Presence, build up or release of the hazardous agent/energy.

are Europe wide and span a period of 20 years from 1985–2004. The 118 Dutch Seveso site accidents are from 2006–2010 (note that 2006 is not a complete year. The MARS accidents are the more serious. Only 9 of the Dutch accidents were MARS reportable. The analysis results are only meant to show how incident data could be used to suggest areas where possible leading indicators could be developed. Prioritising is important because the regulator only wants a limited set of key indicators, ideally only one for each safety management system component.

3.1 TECHNICAL FAILURES

Figure 2 shows the barrier failures occurring in the first line of defence for Dutch Seveso site and European refinery data side by side. Despite differences in the sample, there is a similarity in the pattern of the numbers of first line of defence barrier failures of the two independent data sets which correlate 0.85. At its extreme, a correlation of 1 or −1 means that the two variables are perfectly correlated, meaning on could “predict” the values of one variable from the values of the other variable with perfect accuracy. One could say that the pattern of failures in the Dutch Seveso sites is a good indicator of the pattern of failures in MARS reportable refinery accidents. The refinery and Dutch accidents, although evaluated in a common model, are different sets of data, from different time periods and analysed by different analysts. The only common elements are 18 refinery incidents and 9 MARS reportable accidents in the Dutch data. There is only one Dutch reported accident in the refinery data set.

The refinery data are shown in Figure 3. There is no apparent upward or downward trend. Here the yearly accident frequencies (dark bars) for the 64 refinery accidents are given alongside the yearly frequency of the most frequent equipment condition barrier failures (light bars), which summed together occur in 42% of the 64 accidents:

- equipment material not suitable for conditions
- operating conditions not suitable for the equipment
- failure at connections (e.g. assembly, packing).
- inadequate design of equipment (e.g. configuration, vibration).

The 20 yearly frequencies for refineries and the subset of selected technical failures for this group of equipment barrier failures correlate 0.84 as shown in Figure 4.

Just using the accidents concerning equipment materials not suitable for withstanding the conditions (19% of the accidents), this alone correlates 0.77 with the total accidents over the 20 years of data. Using instead pre start-up safeguarding failures (plant is not made safe before start up or maintenance begins due to openings, leaks or failure to empty) which is also 19% of the accidents, the correlation with the total is 0.57 suggesting this is a less favourable all accident predictor despite being one of the most frequent barrier failure types. Adding this into the equipment condition failures gives no change at all to the correlation.

3.2 ORGANISATIONAL FAILURES

In around half the Dutch Seveso site accidents non-compliance with legal obligations were identified, amongst which failures in the safety management system. Inadequacies in the safety management system elements were identified in 66 of the accident investigations.

Management issues associated with equipment material conditions failures discussed in the previous section are shown in Figure 5. Inspection and maintenance management

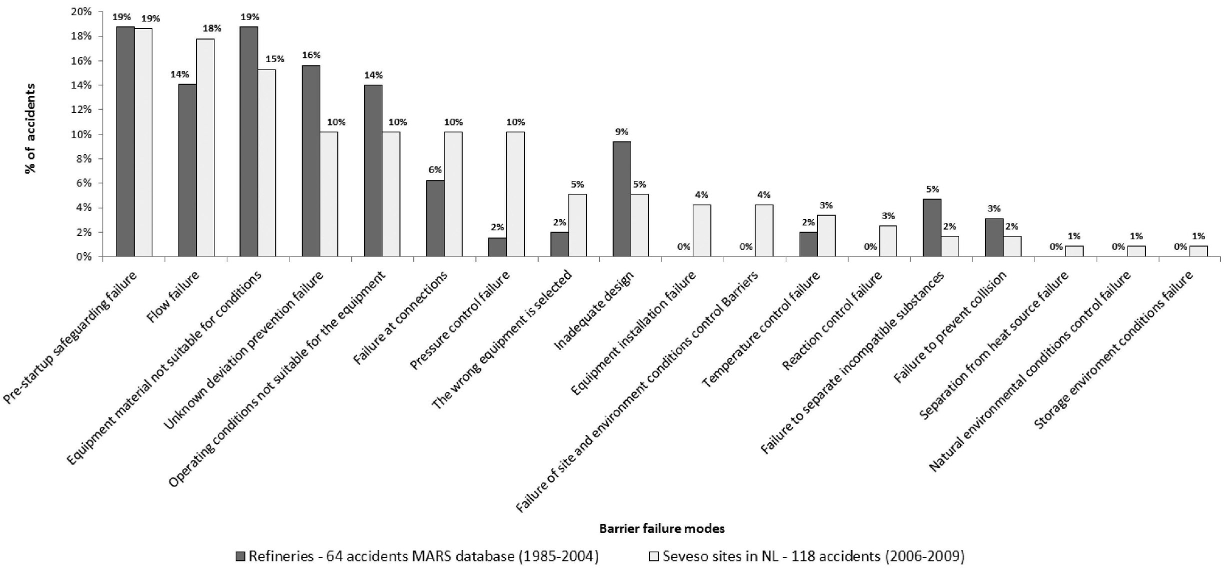

Figure 2. Percentage contribution of failures in the model’s first line of defence barriers for 64 Refinery accidents taken from the European MARS database 1985–2004 (dark bars) and 118 Seveso site accidents in the Netherlands 2006–2009 (light bars)

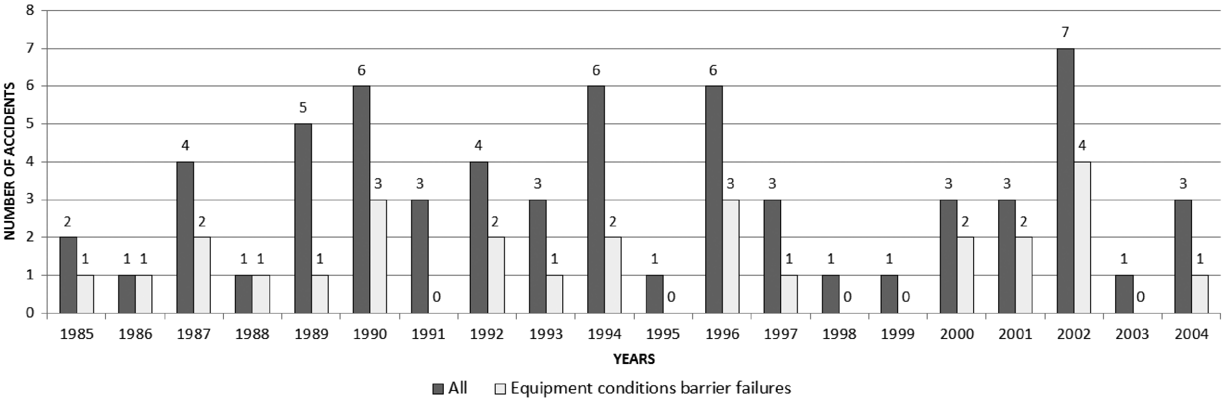

Figure 3. Sixty four refinery accidents distributed per year 1985–2004 showing all the accidents (dark bars) and the twenty seven accidents with equipment material/equipment conditions barrier failures (light bars)

inadequacies totally dominate operational control which is the leading SMS component here. Material failure is occurring because of the wrong specification of materials (61%), the lack of protection (22%) and inadequate welds (11%). Dominant barrier tasks and delivery system failures show these to be associated with equipment and motivation/awareness failures to provide the right materials and procedures and motivation to maintain, inspect and test the barrier. These data point to the question of how aware a company is of whether the materials of safety critical equipment have been correctly provided and maintained. A leading indicator might focus on the % of safety critical equipment that can be shown to have documented evidence that it is of the correct materials through records of appropriate procedures and equipment being applied in inspection, maintenance and equipment change.

Turning to the 22 safeguarding failures in the Dutch Seveso sites, 45% were failures to provide a safe system with hazardous materials removed through cleaning and ventilating That again turns out to be primarily failures in SMS component of inspection and maintenance to the task of providing the safe barrier through delivering procedures, equipment, competence, communications, and motivation to the task. Another 36% of safeguarding failures were failures in operational control and were directly caused by operator mistakes, 27% being rule based and 9% knowledge based mistakes. That is due to a mix of failures in the delivery systems, primarily procedures, followed by communication

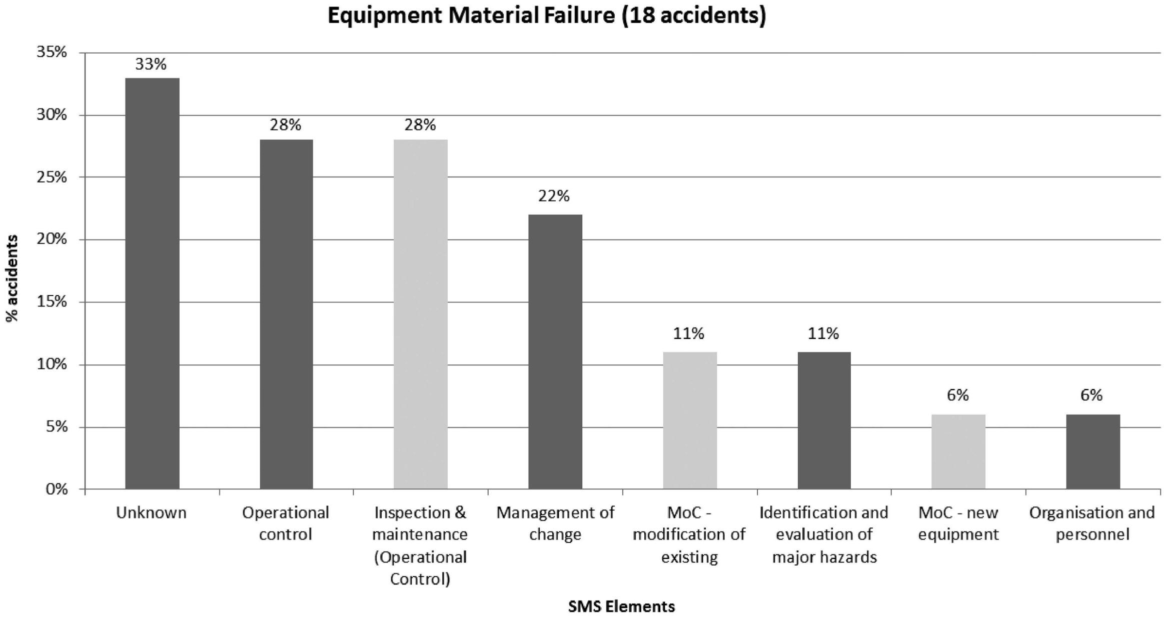

Figure 4. Yearly frequencies for 64 MARS refineries accidents over 20 years showing correlation (r) between equipment conditions barriers (y) and all accidents (x). The regression line is described by the formula $y = 0.4388x$

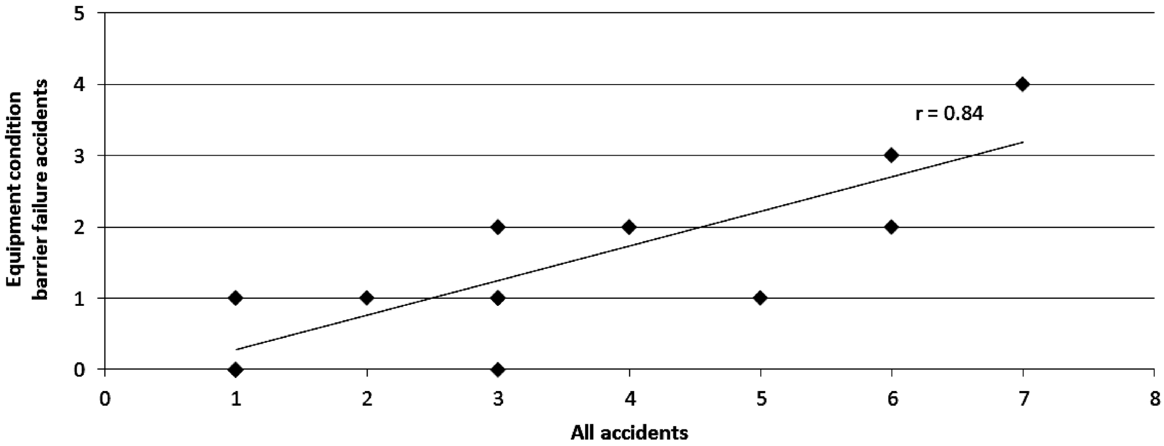

Figure 5. Distribution of safety management system aspects associated with Equipment Conditions failures in the technical system. Light bars indicate a subset of the main SMS category. The percentages are % of the 18 accidents

and awareness, then competence. Most of the mistakes appear to involve not closing valves. Taking these cleaning and open valve failures together, a leading indicator might focus on the extent to which a company can show it has sufficient checks on its resources, in particular procedures, communications and safety motivation for avoiding these failures before any operation is started.

Each one of the more predictive (correlating) barrier failures could be examined in this way to inform leading indicator development.

4. CONCLUSIONS

The analysis of the data shows potential for adding to the discussion on the selection of performance indicators in the Netherlands, with possible implications for the major hazard chemical industry as to how they could use their own data. It is not surprising that Dutch inspectors show concern for maintenance and inspection management and the state of equipment when involved in discussions about a safety management system norm and performance indicators. Their awareness is backed up by the detailed analysis of the data which show specific maintenance and inspection management issues are possible good indicators of future performance. The good correlation between technical causes of European refinery major accidents and the less serious more frequent Dutch Seveso site accidents is also supportive of the idea that looking at less serious accidents could say something about the more serious accidents.

If a single important indictor were to be chosen, that concerning the management of the hazardous substance bearing equipment conditions would be a good one. Management of four barrier types were suggested to take together in considering an organisational indicator for operational control management:

- equipment material suitable for conditions
- operating conditions suitable for the equipment
- good condition of equipment connections (e.g. assembly, packing)
- good design of equipment conditions (e.g. configuration, vibration)

The first barrier, equipment material suitable for conditions, is hypothesised to be a good standalone barrier to focus on. Consideration of other barriers whose performance correlates well with overall performance could be used for developing monitors for other organisational factors.

REFERENCES

Arbeidsinspectie, 2011, Incidentrapportage 2008–2010 Directie Major Hazard Control Arbeidsinspectie. Ministry van Sociale Zaken en Werkgelegenheid, the Netherlands, October 2011.

Bellamy L.J., Oh J.I.H., Ale B.J.M., Whiston J.Y., Mud M.L., Baksteen H., Hale A.R., Papazoglou I.A, 2006, Storybuilder: The New Interface for Accident Analysis. Proceedings of the 8th International Conference on Probabilistic Safety Assessment and Management [PSAM], May 13–19, 2006, New Orleans, ASME, New York, 2006, ISBN 0–7918–0244

Bellamy, L.J., Ale B.J.M., Geyer T.A.W., Goossens L.H.J., Hale A.R., Oh J.,Mud, M., Bloemhof A, Papazoglou I.A., Whiston J.Y., 2007, Storybuilder—A tool for the analysis of accident reports, Reliability Engineering and System Safety 92 (2007) 735–744

Bellamy L.J., Ale B.J.M., Whiston, J.Y., Mud M.L., Baksteen H., Hale A.R., Papazoglou I.A., Bloemhoff A., Damen M. and Oh J.I.H., 2008. The software tool storybuilder and the analysis of the horrible stories of occupationalaccidents. Safety Science 46 (2008) 186–197.

Bellamy L.J., Mud M., Damen M., Baksteen H., Aneziris A., Papazoglou I.A., Hale A.R., Oh, I.H., 2010. Which management system failures are responsible for occupational accidents? Safety Science Monitor, Volume 14, Issue 1, 2010.

Bellamy, L.J. Lisbona, D., Johnson, M., Kooi, E., Manuel, H.J., 2012, The Major Accident Failure Rates Project: Concept

Phase. HSE Research Report RR915, Health and Safety Executive, Bootle, UK.

Broadribb, M.P., Boyle, B., Tanzi, S.J., 2009. Cheddar or Swiss? How Strong are your Barriers? (One Company's Experience with Process Safety Metrics). Process Safety Progress, Volume 28, Issue 4, pages 367–372, December 2009.

CEFIC, 2011. Guidance on Process safety performance indicators. 2nd edition May 2011 http://www.cefic.org/Industry-support/Responsible-Care-tools-SMEs/3-Plant–Process-Safety/Cefic-Guidance-on-Process-Safety-Indicators/

CEFIC/EPSC 2012. International Conference on Process Safety Performance Indicators. Brussels, Jan 31-Feb 1 2012 http://www.epsc.org/content.aspx?Group=products &Page=pspi_conference

EU Council, 1996. Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances (Seveso II), amended by Directive 2003/105/EC of the European Parliament and of the Council of 16 December 2003.

Grote, G., 2009. Response to Andrew Hopkins. Safety Science 47 (2009) 478.

Hopkins, A., 2009. Thinking about process safety indicators. Safety Science 47 (2009) 460–465.

HSE, 2006, Health & Safety Executive, 2006. Developing process safety indicators. A step by step guide for chemical and major hazard industries. HSG 254. HSE Books, UK.

Lisbona, D. and Wardman, M., 2010. Feasibility of Storybuilder software tool for major hazards intelligence, Sudbury: HSE Books, http://www.hse.gov.uk/research/rrpdf/rr778.pdf (last accessed 26 April 2011).

Lisbona, D., Johnson, M., Millner, A., McGillivray, A., Maddison, T., Wardman, M., 2012, Analysis of a loss of containment incident dataset for major hazards intelligence using storybuilder. Journal of Loss Prevention in the Process Industries, Volume 25, Issue 2, March 2012, Pages 344–363.

Major Accident Hazards Bureau, 2012. eMARS Major Accident Reporting System, Database of "major accidents" reported under Seveso, OECD and UN-ECE Managed by the Major Accident Hazards Bureau (MAHB). https://emars.jrc.ec.europa.eu/

Mud, M., van Amen, J., Dijkshoorn, R., 2011. Incidentenanalyse Arbeidsinspectie Directie Major Hazard Control: Betreffende de ongevalsonderzoeken over de periode 1 Januari 2004 – 31 December 2010, report VRM11.8018. RPS Advies, Delft, The Netherlands.

Reason, J., 1997. Managing the Risks of Organizational Accidents. Ashgate Publishing Ltd., Aldershot, England.

RIVM, 2008. The quantification of occupational risk. The development of a risk assessment model and software.[Kwantificering van arbeidsveiligheidsrisicos. De ontwikkeling van een risicomodel en software]. RIVM – National Institute for Public Health and Environment – Report 620801001. P.O. Box 1, 3720 BA Bilthoven, the Netherlands. http://www.rivm.nl/milieuportaal/images/Quantification%20of%20occupational%20risk.pdf

RIVM, 2012. Safety Performance Indicators. Report by L. J. Bellamy and V. Sol, (in English). Dutch National Institute for Public Health and Environment, Ministry of Health, Welfare and Sport. http://www.rivm.nl/Bibliotheek/Wetenschappelijk/Rapporten/2012/juli/A_literature_review_on_safety_performance_indicators_supporting_the_control_of_major_hazards

Vinnem, J.E., 2010. Risk indicators for major hazards on offshore installations. Safety Science 48 (2010), 770–787.

VNO-NCW et al, 2001, Veiligheid Voorop. http://www.vno-ncw.nl/SiteCollectionDocuments/Meer%20informatie/veiligheid_voorop_2011.pdf

ANNEX 1: POINTS FOR THE DESIGN OF PERFORMANCE INDICATORS (RIVM 2012)

1. A link (usually causal) to the major hazard (process) risks, with appropriate coverage and priorities in the (safety) management system;
2. Sufficient in number and frequency to be able to identify trends (e.g. quarterly, yearly, 3 yearly), including any "Rasmussen drift" effects towards boundaries of safe operation to allow appropriate recovery in time;
3. Tailor-made for the company/site;
4. Metrics distinguish between good and bad in the population distribution (this also facilitates benchmarking);
5. Consideration of published guidance (HSE, CCPS, OECD, API, Deltalinqs, CEFIC etc);
6. Quantitative measureable indicators associated with defined objectives;
7. Precursor (prior to loss/harm) indicators of sufficient scope and sensitivity to give sufficient and timely "warning" of deviations from safe standards of design and operation.
8. Precursor indicators on management system inputs to major hazard risk control processes and indicators on related outputs of these processes;
9. Evaluation of management inputs, outputs and incidents for relationships, interactions, causes and major hazard risk potential;
10. Specification of indicator tolerances with justification in safe boundaries of operation and associated with action levels;
11. Specification of indicator targets, especially in relation to the objectives of the major accident prevention policy;
12. A selection of key indicators (KPIs) for reporting to the top management;
13. Indicators are actionable, in that there is a connection between the indicator and the actions which should affect it;
14. A reporting culture involving the whole workforce who have responsibilities in the control of major hazards;
15. Workforce involvement in indicator development and reporting programs;
16. A leadership which maintains the reporting culture and which ensures actions are carried out in time;

17. A leadership which positively influences safety culture through safety improvement (programs), measuring the effect on safety attitudes and awareness.
18. Consideration of metrics that could be sensitive to changes in the external system climate (such as economic pressures, takeovers, new knowledge) and their impact on safety at the plant.
19. Indicator review and improvement at least on a yearly basis.
20. Use of indicators also by external bodies about their own performance, particularly emergency response organisations.

With regards the development of indicators by the regulator, additional points to be considered are:

1. Leading Key Performance Indicators (KPIs) should give signals for concern about future safety.
2. Lagging key performance indicators should show past performance.
3. KPIs should identify degradation in safety performance as early as possible.
4. KPIs should be designed according to the way they are to be used by the regulator.
5. Consideration should be given as to whether indicators can be used standalone.
6. Aligning action levels with KPI measurement should be possible.
7. KPIs should be clearly defined and unambiguous to ensure accurate communications with stakeholders.
8. KPIs should not be capable of being manipulated.
9. Learning from the use of indicators may require changes in the set of KPIs used or associated action levels over time.
10. Standardisation, e.g. based on number of hours worked, could facilitate comparisons between companies.