Leading Indicators of Safety In Virtual Organizations

Submitted to:
Stig Johnsen
SINTEF Industrial Management
SP Andersens veg 5
NO-7465
Trondheim, Norway
47.957.27788 voice
Email: Stig.O.Johnsen@sintef.no

Submitted by:

Martha Grabowski
LeMoyne College
Professor, Director
Information Systems Program
1419 Salt Springs Road
Syracuse, New York 13214
315.445.4427 voice 4540 fax

Research Professor
Department of Decision Sciences & Engineering Systems
Rensselaer Polytechnic Institute
110 8th Street CII 5015
Troy, New York 12180-3590
518.276.2954 voice 8227 fax

email: **grabowsk@lemoyne.edu**
http://web.lemoyne.edu/~grabowsk

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1. Introduction

A primary purpose in measuring safety is to develop intervention strategies to avoid future accidents. Recognizing signals before an accident occurs offers the potential for improving safety, and many organizations have sought to develop programs to identify and benefit from alerts, signals and prior indicators. A recent study by the U.S. National Academy of Sciences focused on these signals, the conditions, events and sequences that precede and lead up to accidents, or the "building blocks" of accidents (Phimister, Bier, & Kunreuther, 2003, p.6):

> *In the aftermath of catastrophes, it is common to find prior indicators, missed signals, and dismissed alerts, that, had they been recognized and appropriately managed before the event, might have averted the undesired event. Indeed, the accident literature is replete with examples, including the space shuttle Columbia (Columbia Accident Investigation Board, 2003), the space shuttle Challenger (Vaughan, 1996),Three Mile Island (Chiles, 2002), the Concorde crash (BEA, 2004), the London Paddington train crash (Cullen, 2000) and American Airlines flight 587 to Santo Domingo (USA Today, May 25, 2003), among many others (Kletz, 1994; Marcus & Nichols, 1999; Turner & Pidgeon, 1997).*

In this paper, we address the challenge of identifying and evaluating leading indicators of safety in virtual organizations--organizations comprised of multiple, distributed members, temporarily linked together for competitive advantage, that share common value chains and business processes supported by distributed information technology (Davidow and Malone, 1992; Mowshowitz, 1997; Kock, 2000). Examples of virtual organizations in which risk mitigation processes are critical include health maintenance systems of doctors in widely dispersed managed care environments, medical societies, and electronically-linked members of Physicians On-Line (Physicians On-Line/Medscape, 2006); fire and emergency medical services units providing support in large-scale disasters (Weick, 1993; 1996); oil spill response teams responding to oil spills of national significance (Harrald, Cohn, & Wallace, 1992; Grabowski, Harrald & Roberts, 1997); aerospace conglomerates jointly developing mission- and safety-critical applications (Augustine, 1997; Spotts & Castellano, 1997); international oil exploration consortia merging in the North Sea (Herring, 2002) and developing oil fields in the Caspian Sea (*Oil and Gas Investor*, 2003), global telecommunications alliances providing 99% of the world's inter-bank financial transactions (SWIFT, 2006), offshore oil and gas exploration and drilling in Norway (Gulbrandsoy, Hepso & Skavhaug, 2002), and Danish offshore wind farm management consortia (Andersen & Drejer, 2005).

Risk in systems can exist because one or more components in the system are risky, or it can result from components that are themselves relatively safe, but interact in ways that increase risk. Perrow (1984) discusses such risk propensities at length, but generally for smaller systems than those that can be imagined as virtual organizations. Here we use the commonly used engineering definition of a risky event as one that is low probability but high consequence (e.g. Wenk, 1982).

Virtual organizations and systems of organizations are of increasing interest to systems and organizational researchers. The literature on inter-organizational alliances offers one paradigm for studying organizational systems (Barrett & Konsynski, 1982; Cash & Konsynski, 1985; Johnston & Vitale, 1988; Hagedoorn, 1993; Benasou &

Venkatraman, 1995), as does the literature on network organizations (Powell, 1990; Miles & Snow, 1992; Nohria & Eccles, 1992). More recently, researchers have begun to examine systems of organizations (e.g. Uzzi, 1997; Eisenhardt & Schoonhaven, 1996), and risk propensities in large-scale systems have received empirical attention (Perrow, 1984; Pauchant & Mitroff, 1992; Sagan, 1993; Vaughan, 1996; Grabowski & Roberts, 1996; 1997; 1999). The efficiency, effectiveness and trustworthiness of virtual organizations has also been the subject of recent research (Staples, Hulland and Higgins, 1999; Kasper-Fuehrer & Ashkanasy, 2001; Morris, Marshall & Rainer, 2002).

In this paper, we draw on research on high reliability organization (HRO's) (LaPorte, 1982; Roberts, 1990); risk, safety and leading indicator research (Shrivastava, 1986; Wildavsky, 1988; Sagan, 1993; Vaughan, 1996, Mearns, Whitaker & Flin, 2001, 2003; Phimister, Bier & Kunreuther, 2003); research on network organizations (Powell, 1990; Nohria & Eccles, 1992; Jarillo, 1988; Thorelli, 1986) and inter-organizational systems (Barrett & Konsynski, 1982; Johnston & Vitale, 1988; Konsynski & McFarlan, 1990); and virtual organization research (Davidow and Malone, 1992; Goldman, Nagel & Preiss, 1995; Preiss, Goldman and Nagel, 1996; Staples, Hulland & Higgins, 1999; Kock, 2000; Morris, Marshall & Rainer, 2003) in our exploration of leading indicators of safety in virtual organizations. We begin by discussing risk propensity in virtual organizations, and examine in detail characteristics of virtual organizations important to enhancing safety. We then discuss research to identify leading indicators of safety in virtual organizations, and conclude with a discussion of next steps and suggestions for how thoughtful management of leading indicators can enhance safety.

2. Risk Propensity in Virtual Organizations

The major distinction between virtual and other organizations is that the former are networked (usually electronically) organizations that transcend conventional organizational boundaries (e.g. Barner, 1996; Berger, 1996; Mowshowitz, 1997). The bonds among members of virtual organizations are temporary, and virtual organizations are noted for forming and dissolving relationships with other members of the virtual organization (e.g. Palmer, Friedland & Singh, 1986; Bleeker, 1994; Nohria & Berkley, 1994; Coyle & Schnarr, 1995). The traditional advantages attributed to virtual organizations include adaptability, flexibility, and the ability to respond quickly to market changes.

Although members of virtual organizations may occasionally meet face-to-face as well as electronically, members are not co-located, and virtual organization success hinges on shared, interdependent business processes that are designed to achieve shared business objectives. Virtuality thus has two features: the creation of a common value chain among the distinct entities of the virtual organization (Benjamin & Wigand, 1995; Rayport & Sviokla, 1995), and business processes supported by distributed information technology (Palmer & Speier, 1997; Kumar, 2001). Virtual organizations are distinguished from traditional network organizations by the temporary linkages that tie together the distinct organizations, and by the members' shared business processes and common value chains supported by distributed information technology. Network organizations, in contrast, generally establish more permanent linkages between members, and generally do not create shared value chains and interdependent business processes between members, as virtual organizations do.

Research shows that risk propensity in traditional organizations has its roots in a number of factors (Wenk, 1982; Perrow, 1984, National Research Council, 1996; Grabowski & Roberts, 1996; Tenner, 1996; Vaughan, 1996). One cause of risk is that the activities performed in the system are inherently risky (e.g. mining, medicine, manufacturing, airline transportation); another is that the technology is inherently risky, or exacerbates risks in the system (e.g. drilling equipment, high speed engines, nuclear propulsion systems). Yet a third cause is that the individuals and organizations executing tasks, using technology, or coordinating both can propagate human and organizational errors. In addition, organizational structures may encourage risky practices or encourage workers to pursue risky courses of action (e.g. lack of formal safety reporting systems or departments in organizations, or organizational standards that are impossible to meet without some amount of risk taking). Finally, organizational cultures may support risk taking, or fail to sufficiently encourage risk aversion (e.g. cultures that nurture the development of "cowboys" who succeed by taking risks, or of management practices that encourage new generations of risk takers) (Grabowski & Roberts, 1996).

Virtual organizations are characterized by several of the same factors that determine a traditional organization's risk propensity. Tasks executed by members of the virtual organization, although distributed, may still be inherently risky (e.g. oil exploration, fire fighting, eye surgery), as in traditional organizations. Technology used to execute the virtual organization’s tasks may also be inherently risky (e.g. drilling equipment, interacting chemicals, lasers, or infrared equipment). Human and organizational error can continue to propagate in virtual organizations as long as humans and organizations are a part of them. Organizational structures in virtual organizations may make risk mitigation difficult (e.g. virtual management structures can reduce physical oversight and contact, and organizational relationships presumably based on shared commitments to safety may not be equally shared among members of a virtual organization). Finally, organizational cultures may send confusing or contradictory messages to members about risk tolerance in the virtual organization (e.g. safety bulletins that celebrate the number of accident free days while the virtual organization simultaneously rewards workers for flaunting safety practices and "living on the edge").

However, risk propensity in virtual organizations has some interesting differences. Because virtual organizations are distributed, networked organizations with fluid and shared business processes, risk in the virtual organization can migrate between organizational members, making risk identification and mitigation difficult. Because virtual organizations are comprised of members with their own individual goals, policies, and cultures, and because the members are bound in temporary alliances that reflect changing marketplace opportunities, developing a shared culture of reliability and shared commitments to reliability goals is difficult, as the presence of simultaneous interdependence and autonomy creates an inherent tension in the virtual organization. Finally, because virtual organizations are large scale organizations with complex interactions between their members, precipitating incidents and accidents may have long incubation periods, making identification of a leading error chain difficult (Grabowski & Roberts, 1997; 1999). These risk propensities can provide important clues about effective risk mitigation in virtual organizations, and important motivation for examining leading indicators of safety in virtual organizations.

3. Leading Indicators

Safety performance has traditionally been measured by ‘after the loss’ type of measurements such as accident and injury rates, incidents and dollar costs. However, there is a growing consensus among safety professionals and researchers that lagging indicators, which means that an accident must occur or a person must get injured before a measure can be made, may or may not provide the necessary insights for avoiding future accidents. A low reported accident rate, even over a period of years, is no guarantee that risks are being effectively controlled, nor will it ensure the absence of injuries or accidents in the future (Lindsay, 1992).

Leading indicators, one type of accident precursor, are conditions, events or measures that precede an undesirable event and that have some value in predicting the arrival of the event, whether it is an accident, incident, near miss, or undesirable safety state. Leading indicators are associated with proactive activities that identify hazards and assess, eliminate, minimize and control risk (Construction Owners Association of Alberta, 2004). Lagging indicators, in contrast, are measures of a system that are taken after events, which measure outcomes and occurrences.

Examples of leading indicators include near hit reporting in anesthesia management (Pate-Cornell, 2003), accident precursor assessment programs in nuclear safety (Sattison, 2003), and hazard identification and analyses for offshore oil and gas in the United Kingdom (Step Change in Safety, 2004). Examples of lagging indicators include recordable injury frequencies, lost time frequencies, total injury frequencies, lost time severity, vehicle accident frequencies, workers' compensation losses, property damage costs, and numbers and frequency of accident investigations (Construction Owners Association of Alberta, 2004).

Leading and lagging indicators differ by granularity and focus, as seen in Figure 1 (Bergh, 2003). Leading indicators are primarily focused at the individual and perhaps departmental level. In contrast, lagging indicators are broader in scope and generally focus on organizational measures. Lagging indicators are seldom focused on individual performance; similarly, leading indicators are most often focused on small units of analysis (i.e., at the individual, group or departmental level). These differences have important implications for data collection, analysis and measurement of leading indicators.

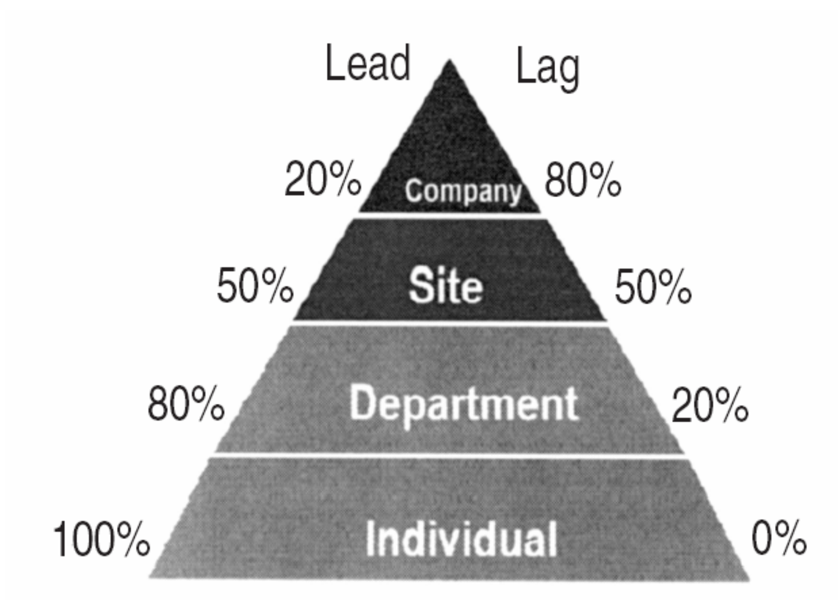

Figure 1
Units of Analysis for Leading and Lagging Indicators (Bergh, 2003)

Figure 1 also suggests the notion of shared leading and lagging indicators within the same organization or domain, ideas echoed by Bergh (2003), Petersen (1998), and Step Change in Safety (2004). Thus, both leading and lagging indicators coexist within the same domain, although they can be expected to focus on different units of analysis within that domain.

Indicator Characteristics

The links or associations between signals or indicators in a system and the onset of adverse events may take a variety of forms. Some indicators may precisely herald the onset of an adverse event in a predictive way; other indicators may be direct causes of adverse events. In either of these cases, the links or associations between indicators and events are direct, visible and demonstrable. An individual's presence could be an indicator, for instance; one such example of a causal link between an indicator and an adverse event is the recent case where a nursing home attendant was convicted of administering lethal doses of medications to patients in the home. The signal and cause were the presence of the attendant; the adverse event was clearly the death of the nursing home residents.

Historical accident analyses, however, reveal that accident causes are more often the result of interactions between interdependent elements in complex, high hazard systems (Perrow, 1984). Investigations into the dynamics of system interdependence and complexity are still the focus of much on-going research (Sagan, 2004). Thus, several indicators or signals can be correlated with the onset of an adverse event. These correlations might be links between single indicators and adverse events, or between groups or clusters of indicators and adverse events. Examples of correlations between leading indicators and adverse events include links between electrical system defects and main propulsion system failures. Examples of correlations between groups of leading indicators can be seen in links between large numbers of port state detentions, structural failures and substance abuse problems within a shipping company and an operational failure (Soma, 2005). Some indicators may serve as *proxies* or surrogates for other indicators. Proxy or surrogate indicators are substitutes or approximations for leading indicators; they are more easily measured, captured or analyzed than are the true leading indicators, and they have predictive associations with adverse events. Clusters and groups of indicators have also been used to develop *risk indices* to categorize and rank leading indicators of risk in a system. Each of these different types of relationships between indicators and adverse events can be considered in analyses of leading indicators for virtual organizations.

Previous Work with Leading Indicators

Leading indicators have been studied in many types of systems, with widely varying results (Leveson, 1995; Hollnagel, 1998). Many economic systems, including the U.S. economy, use composite indexes and economic series with leading, coincident, and lagging indicators of economic performance (Conference Board, 1997; 2004). In economic systems, leading indicators are those indicators that tend to shift direction in advance of a business cycle. Coincident economic indicators, such as employment and production, are broad series that measure aggregate economic activity, and thus define the business cycle. Lagging indicators tend to change direction after the coincident series.

In economic systems, lagging indicators are used to confirm turning points and to warn of structural imbalances in the economy.

Over the past thirty years, the medical community has developed increasingly sophisticated leading indicators of health in the United States. Initially, these efforts focused on identifying predictors of individual mortality; recently, the focus has shifted to include identifying leading indicators for improving the nation's health (Chrvala & Bulger, 1999), echoing the notion from the previous section that leading indicators can be individually and broadly focused within the same domain. The electric power industry has also evaluated the predictive validity of leading indicators of individual and group safety and performance in nuclear power plants (Gross, Ayres, Wreathall, Merritt, & Moloi, 2001; Ayres & Gross, 2002).

Some industries, such as aviation, have a relatively long history of seeking to identify leading indicators; others, such as blood banks and hospitals, are relative newcomers to the field. Nevertheless, each field uses similar information-gathering processes and weighs common design choices (Tamuz, 2003). Some of these industries discovered accident precursors based on their common experiences, such as having to draw on small samples of accidents (March, Sproull & Tamuz, 1991), while other industries developed signal detection programs as a result of learning by imitation (Levitt & March, 1988), such as medicine's Patient Safety Reporting System, which drew on aviation's experience with its Aviation Safety Reporting System (Tamuz, 2003). It is worthwhile noting that, although very little predictive validity has been provided with the use of leading indicators, attempts still continue to identify and validate such measures in a variety of safety- and mission-critical industries. One such example is given in the following section, where a pilot study to identify a framework for leading indicators in marine transportation is described.

4. Pilot Study: Leading Indicators for Marine Transportation

A pilot study was undertaken in 2004 to identify, evaluate and analyze a set of leading indicators of safety for marine transportation. Initially, the focus of the project was on domestic U.S. tanker operations. It was thought that such a pilot study could serve as the foundation for a broader study of leading indicators in virtual organizations, such as international shipping organizations, as well as remote offshore oil and gas operations.

Previous work in leading indicators suggests that the process of identifying leading indicators involves two steps: first, identifying significant safety factors, and second, identifying suitable metrics or leading indicators that correlate with the safety factors (Khatib-Rahbar, Sewell, & Erikson, 2000; Sorensen, 2002). In this pilot study, an expert elicitation technique, referred to as Value Focused Thinking, was utilized in order to identify significant safety factors in marine transportation. The initial safety factor structure elicited is shown in Figure 2 (Merrick, Grabowski, Ayyalasomayajula & Harrald, 2005).

Figure 2 illustrates each of the safety factors thought important by key decision makers in the pilot study's industry partner organization. The senior management team identified that hiring quality personnel, providing safety orientation, promoting safety through top management commitment, and developing a formal learning system were critical to improving an organization's safety culture. The vessel management team identified that responsibility, communication, problem identification, problem prioritization and a feedback system aboard the vessel were critical to improving a vessel's safety culture. Similarly, the safety, health and environmental team identified that individual empowerment, responsibility, and systems for anonymous reporting and feedback were essential to improving an individual's safety attitude. The items elicited in the expert elicitation sessions thus represent the initial safety factor structure.

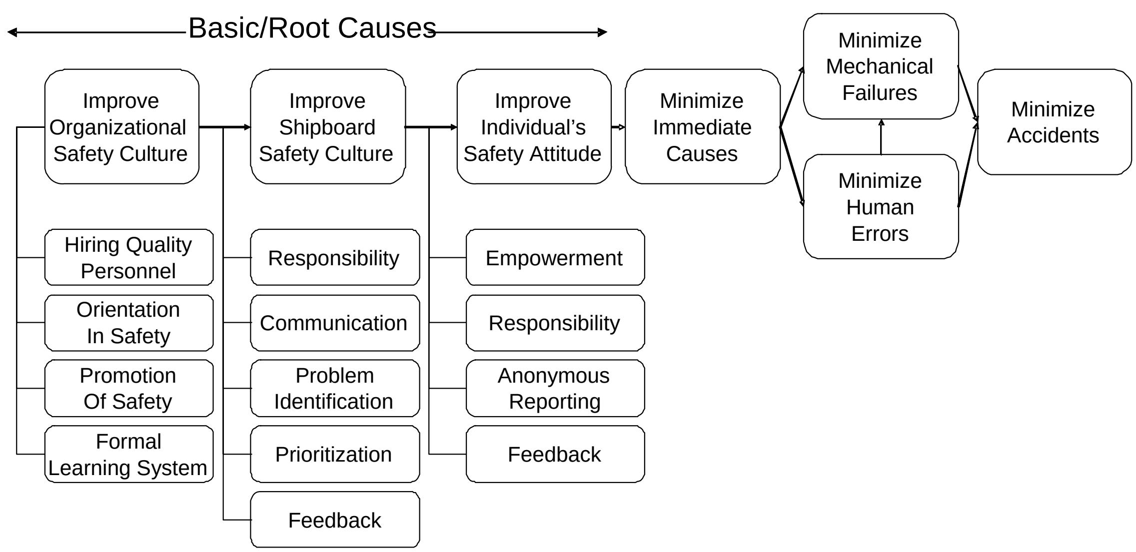

Figure 2. Initial safety factor structure

Figure 3 shows the research model constructed from the Figure 2 safety factors (Merrick, et al., 2005). The independent variables in the boxes to the left were derived from the expert elicitation sessions; the dependent variables listed under "Safety Performance" in the boxes on the right hand side of Figure 3 represent measures of safety performance commonly used in marine transportation (Mearns, et al., 2001; 2003; Soma, 2005). Each arrow in Figure 3 represents a causal relationship. For example, an improvement in organizational safety is hypothesized to lead to an improvement in vessel safety culture and an improvement in individual safety attitudes.

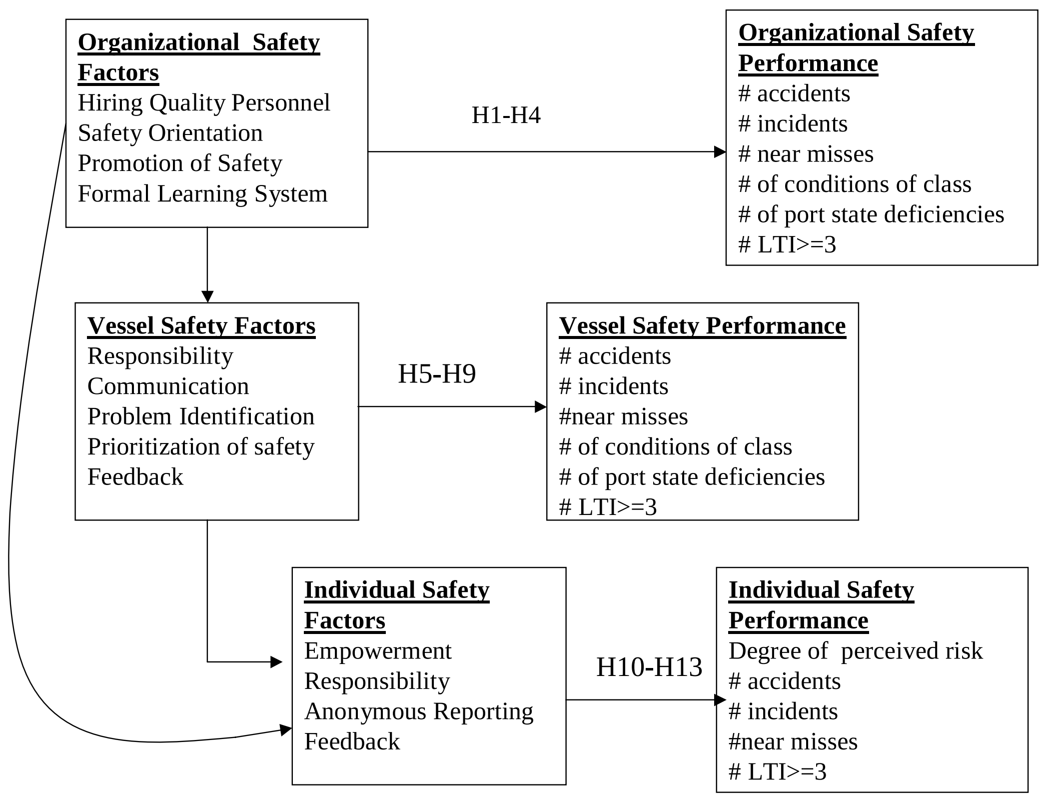

Figure 3. Research Model for Safety Factors for Marine Transportation

**H1 through H13 refer to hypotheses in the research model (Table 1)*

The research model hypothesized that improvements in safety performance can be linked causally to the organizational, vessel and individual safety factors. The organizational safety factors--Hiring Quality Personnel, Safety Orientation, Promotion of Safety and Formal Learning System—were proposed to influence the safety performance of organizations. Similarly, the vessel safety factors and individual safety attitudes were hypothesized to influence the safety performance of vessels and individuals, respectively. The hypotheses associated with the research model are listed in Table 1.

Organizational Hypotheses	
H1	**Hiring Quality People** at the organizational level will lead to an improvement in safety performance
H2	**Safety Orientation** at the organizational level will lead to an improvement in safety performance
H3	**An effective formal learning system** at the organizational level will lead to an improvement in safety performance
H4	**Promotion of safety** at organizational level will result in better safety performance
Shipboard Hypotheses	
H5	**Prioritization of Safety** at the shipboard level will result in better safety performance
H6	**Effective Communication** at shipboard level will result in better safety performance
H7	**Effective problem identification** at the shipboard level will result in better safety performance
H8	**Effective feedback** at the shipboard level will result in better safety performance
H9	**Responsibility** at shipboard level will result in better safety performance
Individual Hypotheses	
H10	**Employee empowerment** will result in better safety performance
H11	**Anonymous Reporting** by individuals will result in better safety performance.
H12	**Effective feedback** at individual level will result in better safety performance
H13	**Responsibility** at the individual level will result in better safety performance.

Table 1: List of Organizational, Shipboard and Individual Hypotheses

Both objective measures of safety and subjective safety climate measures were used to establish the statistical significance of the safety factors and identify the leading indicators. The correlations between the significant safety factors and safety performance were used to validate the leading indicators. In the past, guidance notes have been developed by research organizations that suggest the use of objective measures as leading indicators (Chrvala & Bulger, 1999; Step Change in Safety, 2004). However, the validity of these indicators has not been empirically established. Thus, one of the contributions of this pilot study was to empirically assess objective safety and subjective safety climate data to identify leading indicators of safety that are quantitatively validated and supported by the available data.

5. Leading Indicators in Virtual Organizations

The initial pilot study provided a research model and framework from which to consider the development of leading indicators of safety in virtual organizations. High reliability organization (HRO) research also suggests issues that merit attention in developing leading indicators for virtual organizations. In high reliability organizations, as in safety-critical virtual organizations, small errors can propagate into grave consequences, and risk mitigation processes are critical to the organization's survival (Roberts, 1990; LaPorte and Consolini, 1991; Sagan, 1993; Weick, 1987; 1993). Typical examples of high reliability organizations include flight operations aboard aircraft carriers, command and control organizations in battle management operations, the U.S. air traffic control system, and operations of some U.S. commercial nuclear power plants (Rochlin, LaPorte, & Roberts, 1987; LaPorte, 1988; Roberts, 1990; La Porte & Consolini, 1991).

Initially, four findings from high reliability research seem appropriate to consider in our examination of leading indicators of safety in virtual organizations (Grabowski & Roberts, 1999). First, high reliability organizations are characterized by *prioritization of* *safety and reliability as goals,* as such practices enhance a milieu of safe operations. High reliability organizations clearly define what they mean by safety goals and establish safety standards against which they assess themselves. For instance, at the Navy Aviation School in Monterey, California, aviation accidents are detailed on a large board adjacent to a chart showing the Navy's aviation safety record since the early 1950's. In safety-critical virtual organizations, prioritizing safety and reliability across the entire virtual organization is also important. Thus, *prioritizing safety* across the virtual organization is one example of a safety factor for improving safety in a virtual organization.

Operationalizing safety and reliability goals in high reliability organizations often takes the form of *redundancy in personnel and technology.* Pilots and co-pilots on commercial airliners can both fly the airplane, and both pilots and co-pilots are required aboard before commercial airliners will fly. In safety-critical virtual organizations, redundancy creates opportunities for system members to communicate, to cross check information, and to ensure that individual and business goals and plans are consistent with the goals and plans of the virtual organization, particularly in a dynamic environment. The geographical distribution of virtual organizations and the necessity for reliability enhancing organizations to prioritize safety goals and engage in redundancy suggest the necessity of paying attention to *organizational structuring and design* in the interests of safety in virtual organizations.

High reliability organizations are also noted for developing a high reliability culture that is decentralized and constantly reinforced, often by continuing practice and through training. For instance, nuclear power plants that run well build in high reliability cultures for regular employees, and try to build them in for additional employees who are brought in for scheduled outages. The building process involves continuing practice, continual training, and reinforcement through incentives and reward systems. Because interfaces are a key aspect of virtuosity and because trust and culture in the virtual organization are important for obtaining reliability, communication processes must be a point of focus. This suggests that leading indicators of safety in virtual organizations should therefore consider communication at the interfaces of the virtual organization. Because creating a common, reliable value chain is of primary interest to virtual organizations seeking to enhance safety, a leading indicator of safety in virtual organizations might be the degree to which such organizations develop a *shared organizational culture of reliability across all members of the virtual organization, utilizing effective communication at the organization's interfaces.*

A final non-variant process inherent in reliable operations is trust. The development of *trust* among members of virtual organizations is also critical to enhancing safety, and is a key safety factor. High reliability organizations continually attend the development of interpersonal trust. Incident command systems (ICS) in fire authorities, for instance, routinely publicize information about local, state and federal fire authority personnel who can be trusted. Trust is then further developed in the ICS fire authorities by training and encouraging firefighters to get to know each other. International shipping conglomerates have also been known to develop lists of ship's pilots who can and cannot be trusted with an organization's assets. Thus, trust is a critical safety factor in virtual organizations, and the degree to which it exists in virtual organizations may be a significant leading indicator of safety. These safety factors suggest a revised structure for virtual organizations, as illustrated in Figure 4. Figure 4 expands the initial safety factor structure to include safety factors to improve safety across a virtual organization: prioritizing safety, attention to organizational structuring and design, effective communication at the interfaces of the virtual organization, and developing a shared culture of reliability and trust in the virtual organization.

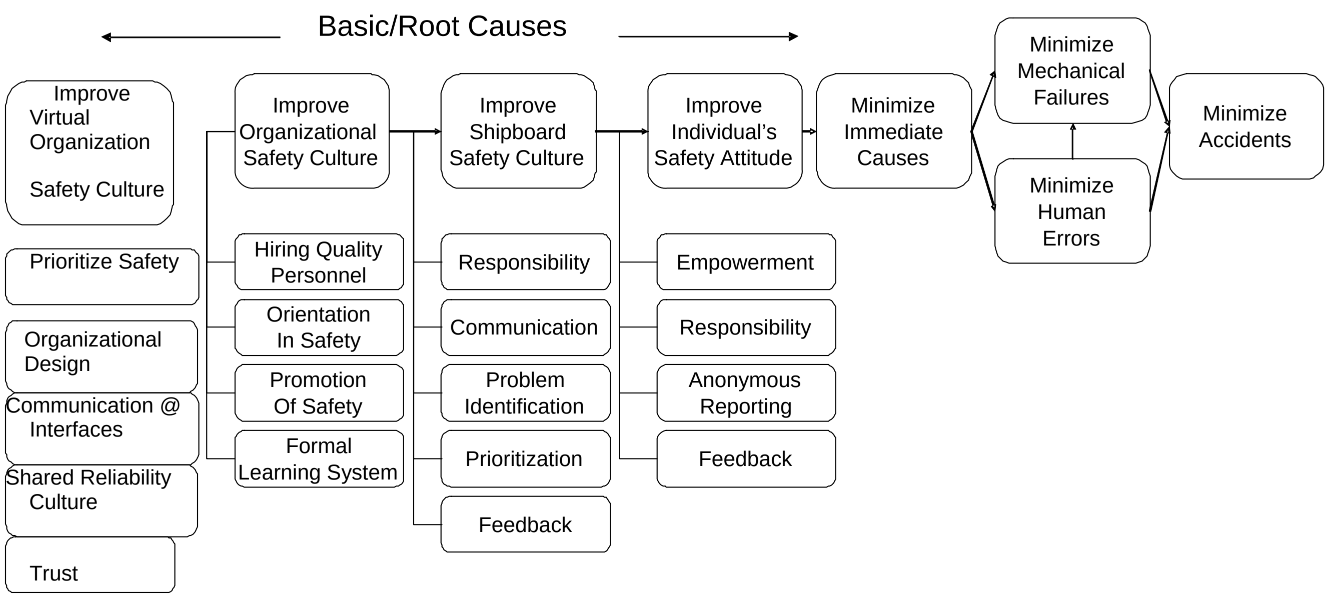

Figure 4. Safety Factors in Virtual Organizations

Taken together, these safety factors suggest a revised research model as well, as seen in Figure 5. The revised research model suggests that prioritizing safety, attention to organizational structuring and design, effective communication at the interfaces of the virtual organization, and developing a shared culture of reliability and trust across the virtual organization will influence the safety performance of the virtual organization, and of the systems and organizations that comprise it. The original safety factor model, incorporating individual, unit (vessel) and organizational elements, remains intact. The revised research model now includes safety factors thought important in virtual organizations.

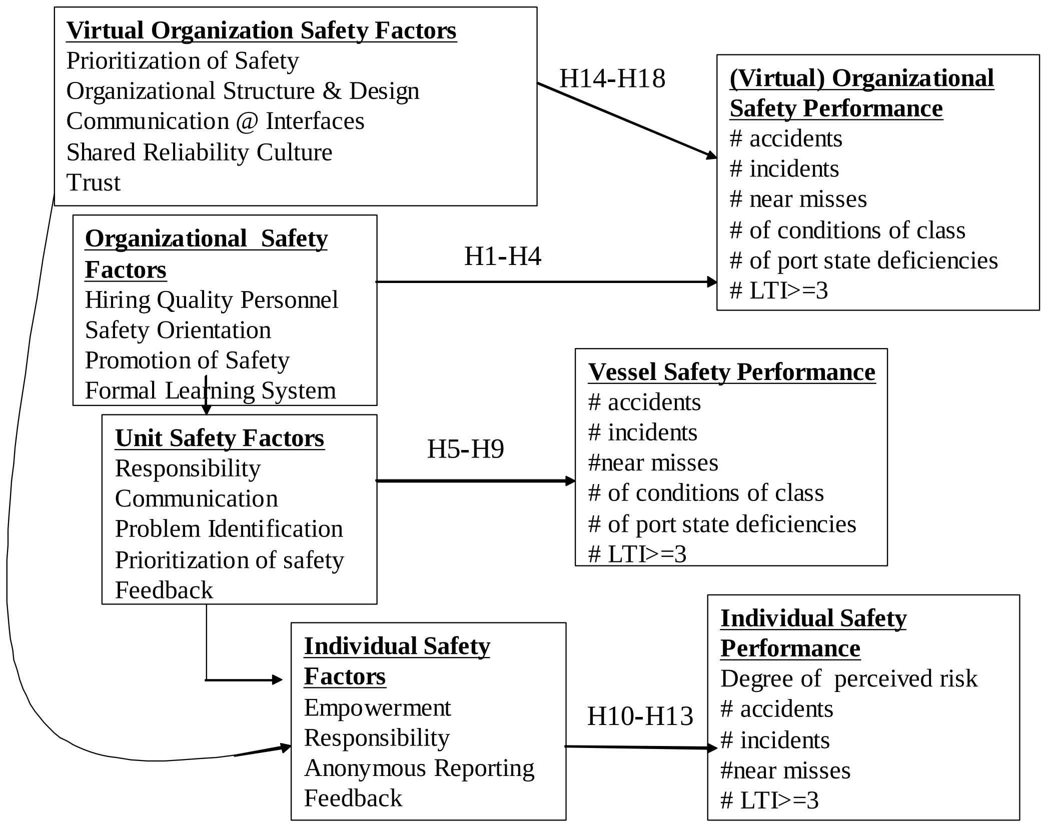

Figure 5. Research Model for Leading Indicators in Virtual Organizations

Identifying leading indicators of safety is critical in safety-critical virtual organizations. The revised safety factor structure and research model provide a starting point for this investigation. However, validating and measuring these predictors in the virtual world are difficult. For instance, insuring everyone in a distributed virtual organization has the same safety and reliability goals is difficult at best. While sheer numbers of persons and job functions in virtual organizations assures some redundancy, without careful attention to design, it is not clear the redundancies are of the form required to assure reliability. Geographical dispersion of virtual organizations constrains their ability to develop a shared, reinforced culture of reliability, and the lack of a shared culture inhibits the development of interpersonal trust in virtual organizations. These challenges underscore the need for both objective and subjective leading indicators as metrics of the safety factors, particularly in a dynamic virtual organization.

Enhancing safety in virtual organizations thus requires attention to and knowledge of the role of leading indicators, of risk and safety research and processes in conventional and high reliability organizations, as well as an understanding the nature and behavior of virtual organizations. With attention to these requirements, we propose investigation of the candidate leading indicators of safety in virtual organizations, focusing on the five characteristics just identified: prioritization of safety, attention to organizational structuring and design, communication at the interfaces, and developing a shared culture of reliability and trust across the virtual organization. Developing empirically validated metrics for the proposed safety factors, and establishing the links and correlations between and among the safety factors, leading indicators, and performance, is an appropriate next step.

References

Andersen, P. & Drejer, I. Distributed Innovation in Integrated Production Systems—The Case of Offshore Wind Farms. *Proceedings of the DRUID 10th Anniversary Summer Conference. Dynamics of Industry and Innovation: Organizations, Networks & Systems.* Copenhagen, Denmark: 27-29 June 2005. http:// http://www.druid.dk/conferences/summer2005/papers/ds2005-519.pdf, retrieved 5 January 2006.

Augustine, N.R. Reshaping an industry: Lockheed Martin's survival story. *Harvard Business Review.* 75, 1997, 83-94.

Ayres, T.J. & Gross, M.M. Exploring Power Plant Data Resources for Organizational Epidemiology. *Proceedings of the 7th IEEE Conference on Human Factors and Power Plants 2002.* Scottsdale, Arizona: 15-19 September 2002, pp. 10-1 to 10-16.

Barner, R. The new millennium workplace: Seven changes that will challenge managers—and workers. *Futurist. 30,* 1996, 14-18.

Barrett, S., & Konsynski, B. Interorganizational information sharing systems. *MIS Quarterly.* 1982, 93-105.

BEA (Bureau d'enquetes et d'anlayses pour le securite de l'aviation civile). Accident on 25 July 2000 at "La Patte d'Oie" in Gonesse (95), to the Concorde, registered F-BTSC operated by Air France. Paris: Ministere de l'equipment des transportes et du logement. http://www.bea-fr.org/docspa/2000/f-sc000725pa/pdf/f-sc000725pa.pdf, retrieved 18 October 2004.

Benasou, M., & Venkatraman, N. Configurations of interorganizational relationships: A comparison between U.S. and Japanese automaker. *Management Science.* 41, 1995, 1471-1492.

Benjamin, R. & Wigand, R. Electronic markets and virtual value chains on the information superhighway. *Sloan Management Review.* 36, 1995, 62-72.

Berger, M. Making the virtual office a reality. Sales and Marketing Management, *SMT Supplement*, June 1996, 18-22.

Bergh, V. D. Leading and Trailing Indicators : Occupational Safety. Paper presented at the *ISSA/Chamber of Mines Conference 2003 - Mines and Quarries Prevention of Occupational Injury and Disease*, Sandton Convention Center, Sandton, South Africa, 2003.

Bleeker, S.E. The virtual organization. *Futurist*. 28, 1994, 9-14.

Cash, J.I. & Konsynski, B.R. IS redraws competitive boundaries. *Harvard Business Review,* 63, 1985, 134-142.

Chiles, J.R. *Inviting Disaster: Lessons from the Edge of Technology.* New York: Harper Collins, 2002.

Chrvala, C.A. & Bulger, R.J. (editors). *Leading Health Indicators for Healthy People 2010: Final Report.* Washington, D.C.: National Academy Press, 1999. http://books.nap.edu/html/healthy3/, retrieved 13 February 2004.

Columbia Accident Investigation Board (CAIB). *Columbia Accident Investigation Board Report, Volume 1.* Washington, D.C.: National Aeronautics and Space Administration, 2003. http://www.caib.us/news/report. Retrieved 18 October 2004.

Conference Board. *Business Cycle Indicators.* Washington, D.C.: U.S. Government Printing Office. U.S. Department of Commerce, 1997.

Conference Board. *Business Cycle Indicator Project.* http://www.tcb-indicators.org/GeneralInfo/bciproject.cfm, retrieved 18 October 2004.

Construction Owners Association of Alberta. *Leading Indicators: Best Practices.* http://www.coaa.ab.ca/bp/xii/workshops/Workshop%202%20-%20Leading%20Indicators%20for%20Safety.pdf, retrieved 18 October 2004.

Coyle, J. and Schnarr, N. The soft-side challenge of the "virtual corporation." *Human Resource Planning.* 18, 1995, 41-42.

Cullen, W.D. *The Ladbroke Grove Rail Inquiry.* Norwich, U.K.: Her Majesty's Stationery Office, 2000.

Davidow, W.H. & Malone, M.S. *The virtual corporation: Structuring and revitalizing the corporation for the 21st century.* New York: Edward Burlingame Books/Harper Business Press, 1992.

Eisenhardt, K. & Schoonhaven, C.B. Resource based view of strategic alliance formation: Strategic and social effects in entrepreneurial firms. *Organization Science*. 7, 1996, 136-150.

Goldman, S.L., Nagel, R.N., & Preiss, K. *Agile competitors and virtual organizations.* New York: Van Nostrand Rheinhold Press, 1995.

Grabowski, M.R., Harrald, J.H. & Roberts, K.H. Decision support and organizational forms in a high velocity environment: Responses to catastrophic oil spills. In M.R. Grabowski & W.A. Wallace (Eds.) *Advances in Expert Systems for Management, volume 2,* Greenwich, CT: JAI Press, 1997.

Grabowski, M. & Roberts, K.H. Human and organizational error in large-scale systems. *IEEE Transactions on Systems, Man, and Cybernetics.* 26, 1996, 2-16.

Grabowski, M. & Roberts, K.H. Risk mitigation in large scale systems: Lessons from high reliability organizations. *California Management Review,* 39, 1997. 152-162.

Grabowski, M. and Roberts, K.H. Risk Mitigation in Virtual Organizations. *Organization Science,* 10:6, November/December 1999, 704-721.

Gross, M.M., Ayres, T.J., Wreathall, J., Merritt, A. & Moloi, D. Predicting Human Performance Trends. *Proceedings of the 7th Annual Human Performance/Root Cause/Trending Workshop,* Baltimore, Maryland, 4-7 June 2001. http://www.epri.com/attachments/266888_BaltHPmtext.pdf, retrieved 13 February 2004.

Gulbrandsoy, K., Hepso, V. & Skavhaug, A. Virtual Collaboration in Oil and Gas Organizations. *ACM SIGGROUP Bulletin.* 23:3, December 2002, 42-47.

Hagedoorn, J. Understanding the rationale of strategic technology partnerships: Interorganizational modes of cooperation and sectoral differences. *Strategic Management Journal.* 14, 1993, 371-385.

Harrald, J.R., Cohn, R., & Wallace, W.A. We were always reorganizing: Some crisis management implications of the Exxon Valdez oil spill. *Industrial Crisis Quarterly.* 6, 1992, 197-217.

Hollnagel, E. *Cognitive Reliability and Error Analysis Method,* Amsterdam, the Netherlands: Elsevier, 1998.

Herring, E. A European Union. *Chevron-Texaco.* 1:4, October/November 2002. http://www.chevron.com/news/publications/oct02/docs/pdf_european.pdf, retrieved 12 January 2006.

Jarillo, C.J. On strategic networks. *Strategic Management Journal*. 9, 1988, 31-41.

Johnston, H.R. & Vitale, M.R. Creating competitive advantage with interorganizational systems. *MIS Quarterly.* 12, 1988, 153-166.

Kasper-Fuehrer, E.C. & Ashkanasy, N.M. Communicating Trustworthiness and Building Trust in Interorganizational Virtual Organizations. *Journal of Management.* 27, 2001, 235-254.

Khatib-Rahbar, M., Sewell, R. T., & Erikson, H. *A New Approach to Development of a Risk-Based Performance Monitoring System For Nuclear Power Plants.* Paper presented at the Specialist Meeting on Safety Performance Indicators, Madrid, Spain, 17-19 October 2000.

Kletz, T. *Learning from Accidents.* 2nd edition. Oxford, U.K.: Butterworth-Heinemann, 1994.

Kock, N. Benefits for Virtual Organizations from Distributed Groups. *Communications of the ACM.* 43:11, November 2000, 107-112.

Konsynski, B. & McFarlan, W. Information partnerships: Shared data, shared scale. *Harvard Business Review.* 68, 1990, 114-120.

Kumar, K. Technology for Supporting Supply Chain Management. *Communications of the ACM.* 44:6, June 2001, 58-61.

LaPorte, T.R. On the design and management of nearly error free organizational control systems. In David L. Sills, C.P. Wolf, & Vivien Shelanski (Eds.) *Accident at Three Mile Island: The human dimension.* Boulder, CO: Westview Press, 1982, 185-200.

LaPorte, T.R. The United States air traffic system: Increasing reliability in the midst of rapid growth. In R. Mayntz & T.P. Hughes (Eds.) *The development of large technical systems.* Boulder, CO: Westview Press, 1988.

La Porte, T.R. & Consolini, P. Working in theory but not in practice: Theoretical challenges in high reliability organizations. *Journal of Public Administration Research and Theory.* 1, 1991, 19-47.

Leveson, N. *Safeware: System Safety and Computers.* Reading, Massachusetts: Addison Wesley, 1995.

Levitt, B. & March, J.G. Organizational Learning. *Annual Review of Sociology.* 14, 1988, 319-340.

Lindsay, F. D. Successful health and Safety Management. The Contribution of Management Audit. *Safety Science, 15,* 1992, 387-402.

March, J.G., Sproull, L.S. & Tamuz, M. Learning from Samples of One or Fewer.*Organization Science.* 2:1, 1991, 1-14.

Marcus, A.A. & Nichols, M.L. On the Edge: Heeding the Warnings of Unusual Events. *Organization Science.* 10:4, 1999, 482-499.

Mearns, K., Whitaker, S. M., & Flin, R. Benchmarking Safety Climate in Hazardous Environments: A Longitudinal, Interorganizational Approach. *Risk Analysis, 21*:4, 2001, 771-786.

Mearns, K., Whitaker, S. M., & Flin, R. Safety Climate, Safety Management Practice and Safety Performance in Offshore Environments. *Safety Science, 41*, 2003, 641-680.

Merrick, J.R.W., Grabowski, M.R., Ayyalasomayajula, P., & Harrald, J.R. Understanding Organizational Safety Using Value-Focused Thinking. *Risk Analysis,* 25:4, December 2005.

Miles, R.E. & Snow, C.C. Organizations: New concepts for new forms. *California Management Review.* 28, 1986, 62-73.

Morris, S.A., Marshall, T.E. & Rainer, R.K., Jr. Trust and Technology in Virtual Teams. *Advanced Topics in Information Resources Management.* Hershey, Pennsylavania: Idea Group Publishing, 2003.

Mowshowitz, A. Virtual Organization. *Communications of the ACM.* 40:9, September 1997, 30-37.

National Research Council *Understanding risk: Informing decisions in a democratic society.* Washington, D.C.: National Academy Press, 1996.

Nohria, N. & Berkley, J.D. The virtual organization: Bureaucracy, technology, and the implosion of control. in C. Hekscher & A. Donnellon (Eds.) *The post-bureaucratic organization: New perspectives in organizational change*. Thousand Oaks, CA: Sage, 1994, 108-128.

Nohria, N. & Eccles, R. *Networks and organizations: Structure, form and action.* Boston: Harvard Business School Press, 1992.

Oil and Gas Investor. The Caspian, A Giant in the Making. *Oil and Gas Investor 2003.* http://www.oilandgasinvestor.com/pdf/CaspianSR.pdf, retrieved 12 January 2006.

Palmer, D., Friedland, R. & Singh, J.V. The ties that bind: Organizational and class bases of stability in a corporate interlock network. *American Sociological Review.* 51,1986, 781-796.

Palmer, J.W. & Speier, C. A typology of virtual organizations: An empirical study. *Proceedings of the Association for Information Systems 1997 conference.* Indianapolis, Indiana, 15-17 August 1997.

Pate-Cornell, E. On Signals, Response and Risk Mitigation: A Probabilistic Approach to the Detection and Analysis of Precursors. in Phimister, J.R., Bier, V.M., & Kunreuther (editors). *Accident Precursor Analysis and Management: Reducing Technological Risk through Diligence.* Washington, D.C.: National Academy Press, 2003, pp. 45-59.

Pauchant, T.C. & Mitroff, I.I. *Transforming the crisis prone organization.* San Francisco: Jossey Bass, 1992.

Perrow, C. *Normal Accidents.* New York: Basic Books, 1984.

Perrow, C. *Complex Organizations: A critical essay*. (Second, Third Edition), New York: Random House, 1979, 1986.

Petersen, D. What Should We Use and Why? Measuring Safety System Effectiveness. *Professional Safety.* 43:10, October 1998, 37-40.

Phimister, J.R., Bier, V.M., & Kunreuther (editors). *Accident Precursor Analysis and Management: Reducing Technological Risk through Diligence.* Washington, D.C.: National Academy Press, 2003.

Physicians On-Line/Medscape. http://www.medscape.com/pages/public/help/index/index-pol, retrieved 13 January 2006.

Powell, W.W. Neither market nor hierarchy: Network forms of organization. LL. Cummins & B.M. Staw (Eds.) *Research in Organizational Behavior*. 12, 1990, 295-336.

Preiss, K., Goldman, S.L., & Nagel, R.N. *Cooperate to compete.* New York: Van Nostrand Rheinhold, 1996.

Rayport, J.F.& Sviokla, J.J. Exploiting the virtual value chain. *Harvard Business Review*. 73, 1995, 75-85.

Roberts, K.H. Some characteristics of high reliability organizations. *Organization Science.* 1, 1990, 160-177.

Rochlin, G.I., La Porte, T.L., and Roberts, K.H. The self designing high reliability organization: Aircraft carrier flight operations at sea. *Naval War College Review.* 40, 1987, 76-90.

Sagan, S. D. *The limits of safety: Organizations, accidents, and nuclear weapons.* Princeton, N.J.: Princeton University Press, 1993.

Sagan, S.D. Learning from *Normal Accidents. Organization and Environment.* 17:1, 2004, 15-19. http://oae.sagepub.com/cgi/reprint/17/1/15.pdf, retrieved 18 October 2004.

Sattison, M.B. Nuclear Accident Precursor Assessment: The Accident Sequence Precursor Program. In Phimister, J.R., Bier, V.M., & Kunreuther (editors). *Accident Precursor Analysis and Management: Reducing Technological Risk through Diligence.* Washington, D.C.: National Academy Press, 2003, pp. 89-100.

Shrivastava, P. *Bhopal: Anatomy of a disaster.* New York: Basic Books, 1986.

Soma, T. *A data interrogation approach for identification of safety characteristics determining whether a shipping organization is BLUE CHIP or SUB-STANDARD.* Unpublished Doctoral Dissertation, Norwegian University of Science and Technology, 2005.

Sorensen, J. N. Safety Culture: a survey of the state-of-the-art. *Reliability Engineering and Safety Science, 76*, 2002, 189-204.

Spotts, T.E. & Castellano, C. SmartBridge: Navigation Safety. *Sea Technology.* November 1997, 5-8.

Staples, D.S., Hulland, J.S. & Higgins, C.A. Self-Efficacy Theory Explanation for the Management of Remote Workers in Virtual Organizations. *Organization Science.* 10:6, June 1999, 758-776.

Step Change in Safety. *Leading Performance Indicators: Guidance for Effedctive Use.* http://step.steel-sci.org/publications/main_publications_fs.htm, retrieved 18 October 2004.

SWIFT. Society for Worldwide Interbank Financial Telecommunications (SWIFT). http://www.SWIFT.com, retrieved 11 January 2006.

Tamuz, M. Understanding Accident Precursors. in Phimister, J.R., Bier, V.M., & Kunreuther (editors). *Accident Precursor Analysis and Management: Reducing Technological Risk through Diligence.* Washington, D.C.: National Academy Press, 2003, 63-78.

Tenner. E. *Why things bite back: Technology and the revenge of unintended consequences*. New York: Alfred A. Knopf, 1996.

Thorelli, H.B. Networks: Between markets and hierarchies. *Strategic Management Journal.* 7, 1986, 37-51.

Turner, B.M. & Pidgeon, N. *Man-Made Disasters.* 2nd edition, London: Butterworth-Heinemann, 1997.

USA Today, May 25, 2003 in Phimister, J.R., Bier, V.M., & Kunreuther (editors). *Accident Precursor Analysis and Management: Reducing Technological Risk through Diligence.* Washington, D.C.: National Academy Press, 2003.

Uzzi, B. Social structure and competition in interfirm networks: The paradox of embeddedness. *Administrative Science Quartery.* 42, 1997, 35-67.

Vaughan, D. *The Challenger Launch Decision: Risky Technology, Culture an dDeviance at NASA.* Chicago: University of Chicago Press, 1996.

Weick, K.E. Organization culture as a source of high reliability. *California Management Review.* 29, 1987, 116-136.

Weick, K.E. The collapse of sense making in organizations: The Mann Gulch disaster. *Administrative Science Quarterly*. 38, 1993, 628-652.

Weick, K.E. Drop your tools: An allegory for organizational studies. *Administrative Science Quarterly.* 41, 1996, 301-313.

Wenk, E, Jr. *Tradeoffs: Imperatives of choice in a high tech world*. Baltimore, MD: The Johns Hopkins University Press, 1982.

Wildavsky, A. *Searching for safety.* New Brunswick, NJ: Transactions Publishers, 1988.