On future ship safety – people, complexity and systems

V Pomeroy MA, CEng, FI MechE, FIMarEST, FRINA, Southampton
Marine and Maritime Institute, UK

This paper considers the characteristics of risk and the important influences of the human element, innovative solutions and complex engineered systems on the future of maritime safety. Residual risk remains once all practicable steps have been taken to manage the risks associated with any undertaking. For complex engineered systems, and these include modern merchant ships, there will always be a limit on the attainable level of safety, where human performance and technical issues such as complexity and novelty will dominate the residual risk and the causes of incidents. Recent work has also shown a divergence between the historical record and the perception of risks held by a range of maritime professionals. This divergence may explain some of the maritime incidents that appear to be the consequence of apparently inexplicable acts.

The paper sets out some of the issues relating to residual risk. It concludes by considering the future of ship safety, and the effective regulation of safety for future ships, taking into consideration people, systems and the management of risk.

AUTHOR’S BIOGRAPHY

Vaughan Pomeroy began his engineering career with a major aircraft manufacturer, British Aircraft Corporation, and subsequently worked with an international practice of consulting engineers, Mott, Hay and Anderson. He then spent over thirty years with Lloyd’s Register, ultimately as the marine technical director responsible for the technical policy of the marine business of the classification society. He has been a visiting professor at the University of Southampton since 2004 and is the independent non-industry member of the Safety Improvement Advisory Group of the UK Civil Aviation Authority.

INTRODUCTION

This paper is based on the presentation made at the Symposium on the Future of Ship Safety by the author. The paper is, essentially, a position paper because of its origin but the opportunity has been taken to develop the thinking to provide a sound basis for the conclusions that were presented. It does not develop proposals for resolving the issues that are identified, leaving this to further papers.

The future of ship safety will depend on a large number of interacting factors that will define the business of shipping at a chosen future point in time. It is reasonably certain that shipping, for at least the foreseeable future, will continue to provide the principal means for transporting materials and goods around the planet to support global trade. Whilst some high value, lightweight goods and items where speed of delivery is critical will be transported by air and landward transport will depend predominantly on road and rail, it seems unlikely that any competing mode of transport will be created that can move the total volume of materials and goods as cost-effectively as modern shipping or with such flexibility. However, it is likely that trade patterns will change over time as the relative importance and magnitude of individual markets adjusts to reflect changes in relative wealth and population. It is also quite possible that the materials and goods that are transported by sea will change, both in volume and description.
So, whilst it appears reasonable to work on the assumption that the future business of shipping might look very similar to that seen today it is also reasonable to assume that the design and operation of ships will probably change significantly. The pursuit of greater logistical efficiency with reduced operating costs, which are currently dominated by the cost of fuels and are likely to remain so, and reduced environmental impact will all lead to change, in both design and operation.

It is essential that the ships that are operated in the future are safe, fulfilling the expectations of society in terms of safety of life, property and the environment. Safety can be measured in a number of ways. The total loss rate, including both actual and constructive total losses, for ships over 100gt for the period 1980–2010 is shown in Fig 1. This graph, based on data from Lloyd’s Register¹, shows the improvement over the period of the loss rate per thousand ships at risk, for all causes.

Since 2002, the indication is that the graph has flat-lined, or is possibly even showing signs of the loss rate increasing, and the challenge for the future is to re-establish the downward trend that has been characteristic of the maritime industry for a very long time. Possible reasons for this stagnation will be discussed later in this paper as, after the previous two decades of steady and continuous improvement, some postulated explanation is desirable.

Similar trends can be shown for other safety indicators, such as loss of life and serious losses involving insurance claims for damage and loss other than total losses, with the latter according to the International Union of Marine Insurance (IUMI) showing a quite distinct upward trend in the current millennium².

The inference is that after a prolonged period of improvement in maritime safety further gains are proving to be elusive, and yet it is also apparent that society expects better. Against this background this paper explores residual risk and, in particular, the critical importance of a range of issues, including the human element, complexity and the impact of technology change. These three facets are all important now, and will all be even more relevant in the ships of the future.

**The human element, complexity and changes in technology**

The human element has been recognised as a major factor in ship safety by the International Maritime Organization (IMO) and others for a long time. This has been recognised formally through the adoption of a resolution by the IMO Assembly setting out the vision, principles and goals relating to the human element. After subsequently revising this, the current vision set out by IMO³ is ‘to significantly enhance maritime safety and the quality of the marine environment by addressing human element issues to improve performance.’

Despite many efforts to address the human element, the accident record remains dominated by navigational errors and other incidents that result predominantly from human fallibility. The broad definition of the human element by the IMO encompasses more activities than those by the people on the ship. Schager⁴ discusses both errors made by operators and those made by designers and manufacturers in relation to technological aids intended to assist mariners in the safe navigation of ships, taking the grounding of *Royal Majesty* in 1995 as an illustrative example. His conclusion is that ‘there is a certain human misconception that can lead us astray in an increasingly technological world’ that leads to the disregard of normal observational data when presented with the direct ‘information’ from a technological solution. This example can be readily referenced to the entire modern ship, where the pervasion of technology is evident. This observation leads directly to the next of the three challenges – complexity.

Complexity is not often associated with ships, apart from those that are viewed as complicated, such as cruise ships or specialist ships involving dynamic positioning or other sophisticated capabilities. In reality modern ships and, more significantly, their operation are complex. Complexity has been created by the adoption of increasingly interlinked, software intensive systems to manage the ship efficiently. Complexity has also been created over a long period without deliberate and obvious choice through the increase in the number of organisations and stakeholders who are necessarily involved in ship operation, through a web of links and interactions. This complexity of hardware and organisation is noted as critical by Perrow⁵ who writes specifically about merchant shipping ‘Although it is obvious that there is a great problem, it is not clear that any of the usual solutions such as better inspection, training, equipment, personnel or integrated policing agencies will make much difference. The problem, it seems to me, lies in the type of system that exists. I will call it an “error-inducing” system: the configuration of its many components induces errors and defeats attempts at error reduction.’

The impact on ship safety of change in technology is less obvious, and in some ways it is entwined with the human element and the ability of people to adapt to new technologies. However, the rate of change of technology will continue to be rapid, not least due to the search for responsible actions to deal with challenges posed by global climate change and the demand for improved environmental protection, and these changes will have a major impact on the people who make the industry function, both at sea and on land, throughout the life-cycle of a ship.

These three different aspects will be explored later in this paper. These will also be used to illustrate how a different approach to safety regulation could prove beneficial in terms of restoring the trend to improved ship safety in the future for ships of the future.

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¹ Lloyd’s Register
² IUMI
³ IMO
⁴ Schager
⁵ Perrow
Residual risk
As far as the public is concerned they expect safety of life and property and the environment, not just at a good level but absolutely. Risk is perceived as a reality, although undesirable, and the result is a public fear that comes as a consequence. So, for any organisation managing risk at an acceptable level is a critical part of staying in business. As an example, the nuclear power industry has fared badly when low probability events, most of which were predicted and accepted at the time of design and build, actually resulted in a major, or significant, accident. The potential for an adverse public reaction to a single disaster becomes evident from events such as those associated with Three Mile Island and Fukushima Daiichi nuclear power plants.

Perrow3 provides an insightful analysis of the Fukushima Daiichi incident and draws attention to the opposing viewpoints of the risk analyst and the society impacted by the event. Whilst the assessment of risk relies on probabilistic analysis and the determination of acceptability is based on the calculated risk the societal reaction is only interested in the consequences. Perrow concludes: ‘It is true that the Fukushima plants’ performance exceeded design standards in three respects: they kept running without offsite power longer than required; they survived a wave that may have been three times as high as they were expected to confront; and they survived an earthquake much larger than their design anticipated. But in this “success”, hailed by industry and academic nuclear experts alike, we are seeing radiation levels that—if not yet catastrophic—are devastatingly high.’

On a much wider perspective, despite the positive contribution to producing low carbon electricity there is a lack of popular and political will to build more nuclear power stations, and after the Fukushima Daiichi event, even some existing plants are being permanently shut down. Public reaction is rarely informed by the probabilistic models of safety that are used by the professional community but it is largely based on the collective perception of risk, measured by the potential extreme consequences of failures.

As a further indicator of the impact of public perception, popular reaction has also resulted in airlines going out of business when customer confidence has been lost after accidents which appear to suggest that the operator is unsafe.

Of course, there are many examples that clearly demonstrate that the perception of risk of the public, and by inference that of their elected governments, does not reflect the actual risk. Some risks, generally associated with hazards that are outside the control of the individual, are routinely overestimated whilst those within the control of the individual are underestimated. Choice, such as which mode of transport to use, is effected by individual perception. So, it follows that the understanding of residual risk involves not only the industry experts, who are familiar with the underlying concepts but also the general public and politicians who are less well informed on risk issues and who react on individual and collective perception of what that risk might mean to them.

The term residual risk is less familiar in a maritime context than it is in financial circles but it is a useful concept in discussions on maritime safety. It provides a very clear focus on what level of risk remains, once steps have been taken to manage the total risk portfolio, and that is the risk that is associated with loss of safety – failures, incidents, accidents and disasters.

Residual risk is managed in financial terms within a corporate situation through one of a number of established strategies that can be selected by the executive, taking cognizance of the business environment. Some risk can simply be taken within the operating budgets, with the consequential cost of any event reducing the profit for the accounting period. Some risk can be financed through a contingency fund that is built up and maintained off balance sheet and drawn down when events occur, thereby not affecting in-period profits or balance sheet value. In extreme situations, money can be borrowed in the markets to fund unforeseen costs, although this is unusual. Some risks can be covered through insurance, either through policies placed with individual insurance companies or through some sort of collective arrangement, such as the mutual insurance arrangements that are familiar within the shipping business. When insurance is the chosen route some provision must be made for the consequences of risks that exceed any excess on the policy, balancing the likelihood of exceeding the excess against the premium cost of increasing the quantum that is covered.

The total risk portfolio will contain a large section where risks have been identified and appropriate arrangements put in place to remove, reduce, manage or mitigate the consequences. That means that residual risk is the unmanaged, and possibly unmanageable, element of the total risk portfolio, remembering that the management of risk includes the impact of good regulation, sound engineering and effective management practices. This is illustrated in Fig 2. That residual risk can lead to undesired outcomes, which will be dependent on the actual situation when the risk is manifested, and emergency response is the action taken to mitigate the consequences.

So, if a proper risk management process has been invoked why do we end up with residual risk? In some cases the residual risk is simply the summation of risk contributors where explicit choices have been made to accept that risk – where for instance a risk cannot be mitigated at all or at reasonable cost. Some residual risks will exist because the chosen risk control option is not perfect, perhaps relying on human activity where it is well known that failures must be taken into account. The contributors to residual risk that are often forgotten include those risks that were not identified,

![Fig 2: The importance of residual risk](image)
not fully understood, underestimated or where the chosen risk control option simply did not work effectively when the demand occurred. It is the latter elements that are explored in this paper.

**Ineffectiveness of risk control**

When selecting risk control options, the relative effectiveness of different available solutions is often not sufficiently considered, or it may even be totally disregarded. Sometimes it appears that risk control is less about making choices and more about finding a single solution to a problem. The ranking of the effectiveness of different families of risk control options is illustrated in Fig 3. Clearly, if a hazard can be eliminated then the risk is removed completely and the chosen solution is completely effective, as shown in Fig 3.

An example might be the choice of fire suppression systems for an engine room where choice of, for example, a water mist system eliminates the suffocation hazard that would be present with a CO₂ arrangement. However, the maritime industry is subject to many hazards that cannot be eliminated, either due to excessive cost or lack of available options. Usually the focus is on reducing risk through effective control and hence adopting one of the five options shown in Fig 3. Substitution, minimisation and engineering of the risk are different approaches to risk control that can be taken by design – the arrangements can be designed to control the risks by:

1. The selection of systems that afford inherently lower risk (perhaps substituting a CO₂ fire suppression system with one using a Halon gas, although noting this option has environmental impact).
2. The reduction of inventories, for example, to reduce fire hazards.
3. The introduction of engineered systems, such as improved detection and monitoring to identify potentially hazardous conditions.

The last two categories move away from safety by design and deal with protecting the individual and procedural control of human behaviour.

In Fig 3, the red portions of each bar represent, diagrammatically, the residual risk that remains once the chosen risk control option has been implemented. With the exception of total elimination of the risk it is useful to note that the impact of human activity on the effectiveness, and by inference the residual risk, increases as the effectiveness decreases. Unfortunately, the maritime industry is rather too keen to adopt the less effective controls. Reliance is placed on the use of placards, procedures and personal protection – which are known to be the less effective solutions, even where a properly engineered solution is available.

As an example, the use continues of notices on engine control stands advising of barred speed ranges, determined to avoid critical speeds for torsional vibration, which do not preclude continued operation within these potentially dangerous conditions. Automated controls that ensure that propulsion systems are taken through these critical speed ranges quickly are not commonly fitted, with some industry concern about loss of flexibility during critical manoeuvring. It should not be surprising that since these solutions are often very dependent on human intervention under high stress situations that brings with it a vulnerability to the fallibilities of people and issues that impact on human performance such as complexity and unfamiliarity.

**Management of residual risk**

It follows that when determining for any undertaking whether the risk has been properly managed, a judgment has to be made about the acceptability of the residual risk. The usual tests, involving the problematic and, sometimes, controversial concepts of reasonable practicability, best available technology and not exceeding excessive cost apply, but allowance has to be made for great uncertainty in the prediction of residual risk, which often relates to very low probability events with potentially very high consequences. Whilst in current parlance every effort must be made to detect the ‘black swans’, brought to wide attention by Taleb, these highly improbable events are also unpredictable and their occurrence has unpredictable consequences. Once such a very rare event, which may be a success story as likely as a disaster, has actually happened the tendency is to make it appear to be less random and more predictable than it is, often including these facets into models for the predication of future risk. In some respects it might be reasonable to regard the loss of *Titanic* to be a ‘black swan event’ since an analysis of collisions between ships and icebergs shows a high degree of survivable damage for steel vessels.

The extent of the loss of life might reasonably have been thought as highly improbable. The stranding of modern well-designed and maintained ships under full command for no clear reason (the maritime equivalent of the controlled flight into terrain category of aviation accidents), such as the loss of *Costa Concordia* might equally have some characteristics of a black swan event. Although, like the financial crises of recent years, these events can become obvious and fully explainable with hindsight before these tragic stories unfolded the marine professional community, given the collected knowledge of the time, had good reason to dismiss these as highly improbable, if not impossible. The key issue in determining whether an event is a real black swan is could it have been predicted and could more have been done to

![Image](image_url)
prevent it. In most cases the post-event analysis shows that accidents such as the loss of Titanic and Costa Concordia were foreseeable, preventable and likely to happen, although highly improbable. Nevertheless, the black swan analysis remains useful in a maritime context. However, risk analysis can become self-defeating if the right balance is not struck and care must be taken to avoid what have sometimes been termed ‘red swans’, which are those hazards that get identified as possible but which are really absolute fantasy and totally non-existent.

In considering the concept, design, realisation and operation of a complex maritime system, it must be recognised that engineering and management judgments have the potential to increase the residual risks. By way of example, consider the devastation that followed the tsunami that struck south east Asia on Boxing Day in 2004. The built environment, resulting from engineering and business choices, had significantly changed the risks, even when the underlying hazard remained unaltered. It is understandable that there is a demand for waterfront buildings and this results in the removal of the natural protection of mangroves and salt flats, but the consequence can be extreme damage. The comparison of satellite images clearly illustrates this effect.

This example demonstrates how impressive technology solutions can be deployed to meet a demand without always determining the associated change to the total risk profile. The adoption of double hull construction for oil tankers to reduce the risk of accidental pollution of the marine environment following grounding also possibly decreased safety through changes to well-established hull structural design, the creation of corrosion hazards and the potential for hydrocarbon gases entering double bottom spaces and posing an explosion hazard. The determination of the acceptable level of safety will always be a balancing exercise but the ultimate test is whether the residual risk is tolerable, and that requires establishing what that total risk profile might be for the chosen solution.

Given the well-voiced expectation of society, and their political leaders, as expressed following any major incident involving pollution or loss of life that ‘this must never happen again’, it is necessary to consider whether there is an irreducible minimum level of safety. With strong technical capability and the wealth of accumulated experience is it possible to improve the current level of safety? Of course, there is in practical terms an uncomfortable balance to be made between cost, technical capability and expectation. In formulating a future safety regulatory system, given the current knowledge about risk issues and the investment in the development of fundamental analysis tools and risk based design methodologies, it follows that the maritime industry does possess the capabilities required for carrying out a systematic assessment of the various factors that influence the achieved safety level and for making rational judgments that are founded on strong evidence. However, the rational evidence-based risk assessment might not satisfy the wider community, particularly following a major incident.

One important factor that influences the practical limit of achieved safety level at any point in time is ‘industry learning’ or ‘race memory’: that is the collective wisdom that the industry has acquired and routinely applies in conducting its normal business. Duffey and Saull proposed a Universal Learning Curve, which models the cumulative learning within an industry that develops from collected experience through operation. They showed that industries appear to learn and this learning leads to a reduction of accidents over a period where the basic technology remains constant, although improvements are progressively incorporated. Their analysis showed that, whilst all industries learn through experience, the accident rate never asymptotes to zero. The data for ships shown in Fig 1 fits very well with this theoretical Universal Learning Curve. Duffey and Saull postulated that the asymptotic incident rate that is inferred by the definition of the Universal Learning Curve is always dominated by issues involving complexity, people and systems. The implication is that, even with perfect technology that will never fail, accidents will still occur. Some of those incidents will relate to failures in design, build and maintenance as well as operation. Duffey and Saull re-examined more recent data for the marine industry and considered specifically the cases investigated by the UK Marine Accidents Investigation Branch. They showed that for both merchant ships and fishing vessels the same experience-based error rate prediction applied, confirming that their Universal Learning Curve does fit the available data.

In fact, Duffey and Saull go even further and use their theory to demonstrate that in mature industries where significant, safety-enhancing technology changes occur, and a step change might be expected in safety performance, the loss rate does not show the expected improvement. They predict that society must expect shipping losses to continue. This conclusion appears to dismiss the corrective benefit of introducing new technologies, or indeed better operational management methodologies, which are focused on providing significant risk control effects, but the gain that is delivered in terms of improved safety might be tempered by the dominant effect of the human element in its widest manifestation.

So the inference from the work of Duffey and Saull is that in any modern technical system some incidents, including some with significant unwelcome consequences, should be expected. Perrow takes this argument forward in his Normal Accident Theory, suggesting that in complex technological systems some accidents will be inevitable. Although shipping is often regarded as a mature and simple industrial technology (relative to aviation or nuclear power, for example). Perrow found shipping, as an industrial endeavour, to be very complex as discussed above. More specifically he refers to the shipping industry as high risk because he found it to contain some major error-inducing factors, including the division of responsibilities between many independent parties. Whilst Perrow develops a compelling argument cautioning society to accept a level of incidents as inevitable, when the level of technical complexity increases his Normal Accident Theory may no longer be totally valid. Leveson et al suggest there becomes a need to supersede Normal Accident Theory, and indeed High Reliability Organization Theory, with a systems approach to safety that embraces human activity, throughout the asset life-cycle, as an active component of the system.

Complexity has already been mentioned in this paper as a major contributory factor in residual risk. Complexity is, however, not a single readily discernable characteristic and
it comes in a number of forms. For example, complexity can result inadvertently from the employment of multiple layers of sub-suppliers or contributors and a lack of really effective systems integration. In these situations:

1. Interfaces between component parts are not necessarily well understood.
2. Manuals are available only for components from single suppliers or contributors and not for the complete configured system.
3. Software is just treated as a black box.
4. Validation of performance against an agreed system requirements definition is limited by the lack of time available.
5. Progressive integration testing and validation is limited by time and cost constraints and the lack of a structured approach to testing and validation.

Complexity makes the operator’s job more difficult and requires a different type of person with different level of education to operate the system. With the adoption of increasingly complex marine systems in modern ships, and probably even more complex arrangements in the ships of the future, the operator will have to be a marine professional who is continually kept up to date with any change and with the effect of that change and who is capable of making balanced judgments. The skills base required will evolve as the technology that is employed develops and advances, requiring changes in both the generic training of seafarers and the specific training provided by shipowners for individual solutions and applications. At the same time the workload will continue to become less participative and more heavily dominated by monitoring and recording, and this progressive change is already evident and may be a cause of discontent amongst some seafarers who complain about the burden of administrative tasks.

Perception of risk, and impact on human performance

The maritime industry relies on people to be an active link between parts of the technology and to provide the primary risk control function when major degradation takes place within the technology, through incident, damage or failure. However, people react in accordance with how they perceive the risks that they face, and not how the risk assessment assumed they might react. It is, therefore, important to understand how risk is perceived across a range of people in different roles across the maritime industry, particularly those who have a direct influence on maritime safety. In this section the available data on risk perception will be discussed along with some of the implications that the information derived from that data might have in a risk-based safety management scenario.

It is quite common to find comparisons between the public perception of risk and the statistical ‘reality’ and an example is shown in Fig 4. These illustrative presentations differ in content and style but all demonstrate that there is a big gulf between reality, as determined by historical data, and public perception. In the example shown in Fig 4 there is a great deal of useful information. The sources of global energy production are ranked in three ways – scale, number of deaths in delivering the energy and public fear. The comparison between, for example coal and oil shows clearly that oil has greater significance in terms of contribution to the global energy mix (indicated by the size of the circle in the top right segment of the plot) but that coal has a far greater cost in terms of lives lost in production. The public dread, or fear, axis is interesting showing that gas is feared more than oil and more than coal, which perhaps reflects current public fears caused by shale gas recovery and fracking. Nuclear, not unexpectedly, heads the public fear scale, despite low costs in terms of real human risk.

Of course, when assessing risks and safety levels at an operational level the maritime professional is only peripherally interested in public perception, with that interest basically limited to determining the acceptability of risk to society. It is more interesting to understand how seafarers and ship managers (and probably designers, constructors, regulators and surveyors) think and behave, based on their perception of the risks that are present. If these people do not understand the risk landscape the evidence is that they will react by worrying about the wrong things. Fortunately, the results of a research project carried out by the Seafarers International Research Centre (SIRC), within Cardiff University, provide some interesting evidence and advance the understanding of the problem that the industry faces and will face to an even greater extent in the future.

The maritime industry has largely relied on anecdotal evidence in relation to the impact of the human element on incidents, and evidence concerning incidents that involve issues such as software and systems is often difficult to elicit.

**Fig 4: Public perception and reality (Image by Susanna Hertrich)**

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It is evident that there is a significant difference between the reality, which is derived from historical accident data, and the perceptions held by the 2372 respondents. Whilst different rankings can be derived from the various data sources that are available of casualty information, there must be good reasons for this very clear discrepancy. It has been postulated that the perceived high risk of fire might derive from the emphasis placed on fire safety training, which could result in seafarers assuming that this implied a very high level of risk. The relatively lower rankings of the most common accidents (collisions and groundings) may be significant if the consequence is that less attention is paid during situations where these events are more likely to occur.

Similar data is shown in Tables 2 and 3 with an analysis by role and age, which approximates for exposure to learning opportunities. Interestingly there is evidence of considerable variation when analysed by role, with shore-based managers matching most closely with reality, possibly as a result of dealing with insurance claims and the consequences of incidents. The analysis by age is counter-intuitive since the implication is that exposure for a longer time does not change perception, implying the experience is gained quickly and the perception of risk does not change over a long period of exposure. The difference in the oldest age group might reflect differences in the training regimes or, perhaps, a different approach to lifelong learning and the personal interest in the acquisition of ‘potentially useful’ information from a variety of sources.

### Table 1: Relative ranking of risks associated with major casualty events

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<thead>
<tr>
<th>Event</th>
<th>Accident database</th>
<th>Respondents</th>
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<tbody>
<tr>
<td>Collision</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Grounding</td>
<td>2</td>
<td>4</td>
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<td>Contact</td>
<td>3</td>
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<td>Sinking</td>
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<tr>
<td>Fire</td>
<td>5</td>
<td>1</td>
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<tr>
<td>Explosion</td>
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The publication of the results of research by Bailey et al.\textsuperscript{13,14,15} which set out to compare the perceived risk with the actual risk provides a valuable insight into the way that risks are perceived by the very people who are directly involved in ship operation, both at sea and on shore. The results are useful in informing decision makers, since these give an insight into the way that people may behave. The published results give some clues as to why some of the acts that lead to human element incidents might have seemed entirely logical and sensible at the time to the people involved. At the most basic level, Bailey et al compared the relative ranking of the risks associated with major casualty events, and the summary is shown in Table 1.

### Table 2: Relative ranking of risks by role

<table>
<thead>
<tr>
<th>Accident database</th>
<th>Shore based managers</th>
<th>Onboard senior officers</th>
<th>Onboard junior officers</th>
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<tr>
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### Table 3: Relative ranking of risks by age

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The impact of this research on engineering decision making, and on maritime operational decisions, is that there is now some evidence of how people in the industry perceive risks. The data provided is only outlined here to provide background to the argument that is developed. The evidence from a study of accidents and failures is that the behaviour of people may differ from the assumptions made during design. The effectiveness of risk control options often depends on the behaviour of the operator, under unusual and stressful situations. The designer, and possibly the ship managers, may arrive at solutions that are undermined by the behaviour of the operators, in the widest sense of that term, which is heavily influenced by the individual perception of risk.

At a personal level, a good indicator is to compare the perceived and actual risks relating to occupational health and safety. A comparison between data held by a shipping company and the perception of seafarers is shown in Table 4, again taken from Bailey et al\(^{14}\). The discrepancies are obvious, but are not readily explained.

The inference that can be drawn from this very limited extract from the study by Bailey and his colleagues is that perception of risk is influenced by the experience of the individual, acquired during formative training and education and thereafter through exposure to working situations. The differences can be explained, intuitively, but more work would be helpful to improve the understanding of this important facet of seafarers and others involved in maritime operations. This is really important as it is well understood that human behaviour is dominated by perception of risks and hazards, not the reality that is reflected through historical statistics.

Impact of risk perception on a risk-based safety regime

The evidence on risk perception that is now available calls into question some of the risk assessments which are based on historical data and often rely on the introduction of risk control options based on active involvement of operators. In accidents there is often evidence that appears, with hindsight and expert analysis, to suggest that the behaviour of the operators was ‘inexplicable’ or even ‘incredible’. However, whilst conducting risk assessment studies the author has found experts readily dismissing as ‘incredible’ such acts as not following standard operating procedures. If it is assumed that the results of Bailey et al do reflect the perceptions of the population responsible for maritime operations, and there is no better information available, there does seem to be some rational evidence that begins to explain why ‘experience’ might not lead to the ‘right decisions’, particularly at times of high stress. Bailey et al\(^{16}\) give some insight into different safety management practices and how people at various levels perceive the messages from senior managers, which helps to explain some variations between different shipowners and operators. Bailey\(^{17}\) looks further, focusing on the impact of the International Safety Management (ISM) Code and its key objective of risk assessment. He notes that ‘Such differences are known to impact on safety-related behaviour and responses to management-led safety initiatives’ and the effective management of these differences requires ‘engagement by the workers in the process of risk identification and abatement.’ However, there is a large quantity of evidence available from the work of Bailey et al. It might not yet have sufficient detail to provide answers to all possible questions but it is better than that which is available in most other industries in terms of providing a window through which some understanding can be gained about how the people directly involved in running the shipping industry think about risks.

It is important to understand why people worry about the wrong things. If people do not understand the risk environment in which they are engaged then they will probably focus on the wrong things, with the distinct possibility that they will miss something that really is significant and misdirect resources. It will also impact on organisations since these are simply an agglomeration of people. More importantly it will impact on engineering decisions, since there will be differences in the understanding of the risk reality and the effectiveness of risk control measures. And who is making the contribution to the risk assessment? Not usually the possibly young, possibly inexperienced seafarer whose perception of the risks might make the difference. And that presents a challenge to the industry and to the regulators.

Now the industry is faced with major challenges to improve performance and reduce environmental impact and that will bring in new technology where the industry does not have the benefit of historical data, so it would be expected that failures will occur that have not been anticipated. This extends far beyond the generally voiced concern about the relevance, or not, of using historic data to assess future risks. Whereas in the past the risk analyst has been able to source failure data, providing details of failure modes and incident frequencies, from industry databases the change of technology over recent years has created a very real challenge. Methodologies are available for estimating the probability of failure, and some of these have been demonstrated through a robust programme of collaborative research to derive more useful event data from first principles, as described by Papanikolaou et al\(^{19}\).

There is, however, a non-hardware aspect that needs to be considered when introducing new technologies that relates to the imaginative ways that people find to use the new

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<td>Use of ladders and gangways</td>
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<td>Engine maintenance at sea</td>
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Table 4: Comparison of perceived and actual occupational risks
capabilities which often differ from the designer’s intentions. Another study by SIRC, reported by Bailey et al.\textsuperscript{9} which studied the implementation of the mandatory Automatic Identification System (AIS) has confirmed that new maritime solutions do indeed get used in unintended ways. New technology can also be found providing distraction and diversions – as demonstrated by mobile phones, laptops and even with AIS. The fact is that the ordinary seafarer can afford to bring to his or her workplace personal devices with a serious ability to distract, or at least occupy the mind, and it is impossible to remove this hazard other than by working with each individual.

The maritime industry is not alone in facing the challenge of adopting technologies that create a major change in the operational scenario and also dealing with the behaviour of people, which has a greater significance in contribution to the cause of incidents as the reliability of equipment and systems improves. In an annex to the report of the US Presidential Commission\textsuperscript{20} tasked with studying the loss of the Space Shuttle ‘Challenger’, the Nobel-laureate Richard Feynman identified the discrepancy between launch risk figures obtained from managers and those from the engineers for the shuttle, and the impact of these assumptions in dealing with critical risk control challenges. We now see in the problems encountered with Lithium-ion batteries on the Boeing 787 Dreamliner some further evidence of underestimating the risks associated with the adoption of new technology.

Complex systems and novel technologies
Some observations in relation to both complexity and innovative solutions have already been made within the argument. However, there are some more specific comments that are helpful.

The maritime regulatory framework is founded on the basic principle that a crew trained and certificated in accordance with STCW is competent to operate a ship that complies with SOLAS, MARPOL and related standards. There have always been variations between ship designs but the basic technology was relatively universal, and it was not unreasonable to assume that seafarers could be posted to any ship and, after a short period of familiarisation, could operate that ship safely. For many years systems were relatively simple and technology was stable, with any changes taking place over extended periods. That situation no longer applies and the industry, and more importantly the regulatory system, must react accordingly, recognising that the interactions between people and technology will face changes that are often unintended and unforeseen.

It seems natural at this point in time to link complexity and innovation, at least when referring to the ship itself. This misses out, however, the inherent complexity, noted emphatically by Perrow, of the maritime industry. This non-technical complexity is identified in the major study carried out by consultants COWI for the Danish Maritime Authority\textsuperscript{21}, which concluded that ‘seafarers find a range of work tasks to be unnecessarily complex and time consuming compared to the value they are perceived to add.’ It is evident that in some cases this more a case of lack of perceived value that actual lack of value but the implication is that a more straightforward system would be helpful in reducing workloads. Shaw\textsuperscript{22} reaches similar conclusions based on experience predominantly within oil tanker operations, stating that ‘Complexity comes from a variety of sources both internally and externally. It is not always apparent to the organisation where complexity comes from. To push back complexity the organisation needs to stop things getting worse, identify what drives complexity and redesign the organisation to achieve the required sophistication without unnecessary complexity.’

This form of operational system complexity can be experienced with any type or age of ship, and with the expectation of increased maintenance activity burden with ageing technology might even be of greater safety significance with older ships. The increased impact of human factors on occurrence rates for older ships has been demonstrated by Gemelos and Ventikos in relation to Greek coastal shipping\textsuperscript{23}. Whilst no doubt this is due to a number of factors the relationship with age of ship would support the idea that complexity is a contributor.

Moving to the complexity that comes from modern ship design the proposed actions by Shaw are equally valid, as is the comment that infers that complexity can just appear, without any apparent source. Regulatory change can inadvertently cause complexity, perhaps by adding a need for additional sophisticated equipment, such as ballast water treatment plant, or seeking additional functionality.

In recent years the merchant shipping community has moved, very quickly, from a tradition of ultra-conservatism to a willingness to embrace innovative and, arguably, under-developed solutions. This period has also seen the introduction of new upgrades of existing equipment in such short time scales that there has been little, or even no, experience with one model before the next is entering service. This rapid refresh of the technology base is a major challenge to the people who are tasked with operating the ship, both at sea and ashore. Innovation has generally increased complexity, particularly in the chase for improved fuel efficiency, reduced pollution and reduced overall operating cost. Very rarely does innovation deliver a more simple solution that is easier to understand and operate, although it might appear to reduce workloads by extending repair and maintenance intervals or through more sophisticated automation.

In general, the adoption of novel technologies, which are not supported by a wide industry knowledge and culture, and systems with greater complexity both bring additional risks. In common with the human element issues that are widely discussed, but not necessarily fully understood, these issues must be addressed in a future regulatory system, and within management systems, if the effect is not to be continued stagnation or deterioration in the achieved levels of ship safety.

RESULTS
Current risk levels?
So is the residual risk reducing or increasing? There would seem to be some factors that might increase risk through changing working practices or rapidly changing technology and the corresponding lack of understanding of how it all works within the total system.

It is evident that standard training course syllabuses may not be sufficient. The assumption within the regulatory framework
is that an averagely, or arguably acceptably, competent seafarer holding the required certificates of competency is capable of operating any ship that has been constructed and maintained in accordance with the relevant international requirements of the IMO. With a continual rapid rate of change, training, and education is lagging behind the technology and the gap is growing faster than the providers can update their provision. Furthermore, lack of systematic updating of certificated seafarers is an issue that has been identified in some incident investigations.

The other aspect, which has not been discussed in any depth but was indicated on Fig 2, is the management of emergencies. When an incident occurs the emergency response becomes the primary route whereby the consequences can be managed, and minimised. Without emergency response the consequences will be uncontrolled and the outcome will simply take its own course. The emergency response will depend on the ship’s crew and any available external resources that can be mobilised. The people involved in responding to any emergency will be faced with a confused and confusing picture. Depending on their assessment of the risks, as the situation develops, they will take decisions and act accordingly. The actions taken can result in:

1. Recovery to a condition where normal operation can be restored and the voyage continued safely.
2. Recovery to a safe condition without any external impact but with significantly reduced operational capability.
3. Recovery to a condition which prevents further external impact but which requires external support.
4. Progression of situation to further damage and permanent disablement with minimal external impact.
5. Progression of situation to further damage and permanent disablement with continuing, significant external impact.
6. Uncontrolled damage and loss.

There are many examples of minor failures and emergencies where the ship’s crew, assisted where necessary by external resources, has resolved complex issues without any significant adverse consequences. However, major marine incidents are usually the result of a number of factors coming together and there is evidence in incident investigation reports that the situation escalated from the initial cause as a result of poor decision-making. Reasons include lack of familiarity, lack of understanding of design intentions and inadequate usability. The training of the people who are tasked with managing emergencies may not be appropriate for the situations that may be faced. Again, the training, and this is more than the statutory provision related to certification, has to be updated at the same pace as the technology. There is great hope placed in the use of computer-based training, as a cost-effective solution to delivering training to people at the workplace, but does this approach deliver the same benefit as being faced with real hardware and a screwdriver?

The graph shown in Fig 1, and the evidence provided by IUMI, suggests that maybe the residual risk is increasing as incidence rates appear to be increasing. The challenge that this conclusion presents suggests that the limitations of the current regulatory safety regime have been reached and a new approach will be necessary to make the gains that the industry expects society will demand.

CONCLUSIONS

The future of ship safety, and future ships and future people

At any point in time the level of safety can be examined and determined made of its acceptability. The acceptability of the chosen safety level to future generations can only be presumed, and that may not turn out to be correct. Abell wrote: ‘This last reduction of risk brought about in so short a time suggests that the ship is becoming nearly as safe as she is ever likely to be...’ He then cites the changes that had brought about that improvement in ship safety and identifies the contribution made by the skills of the shipwright and, more specifically, radio communication. That confidence simply serves to underline the challenge of discussing future expectations for ship safety, and indeed the possible developments that will bring improvements. However, in the previous sections of this paper some key issues have been discussed and form the basis of the following propositions that could improve the future safety of future ships. Discussion about the future of ship safety is critical to the future of shipping.

The IMO took a major step forward in the way that regulations are developed by the adoption of Formal Safety Assessment. The IMO took further steps in adoption regulations that specifically permitted the use of alternative approaches, based on the demonstration of equivalence in safety terms using risk assessment. More recently the first use of goal setting, in the development of Goal Based Standards for ship design and construction, has been adopted. Although most of the regulatory regime for shipping is still prescriptive and based on reaction to incidents there have been significant change, embracing risk-based and goal setting philosophies where appropriate. However, to take maritime safety to the next level in the future the challenges outlined in this paper will need to be tackled effectively, without imposing an unaffordable or impractical burden on the industry and those who work within it.

The future people will certainly need to possess a really good understanding of complex systems, including the people who will still form an important part. They will have to understand what happens when they go beyond the intentions of the designer, which means that they will have to understand the safe operating limits. There may be systems that provide support by keeping operators within safe envelopes, but even these have limitations. Monitoring, recording and interpretation skills will be more important than the ability to manufacture spare parts, dismantle and refit. Managing residual risk is central, but understanding those risks is very challenging. Emergency response services should not be activated very often but when these are needed they will have to cope with unimaginaged situations, and some new ones that have never been created before. This implies changes in the way that we educate, not train, the future marine professional. Education will need to be systems based, to include a significant element about people and how people work in a high technology situation. Education must be continuous throughout the career, and of high quality.
Future ships will require a different regulatory regime and if future safety is to be improved some radical new approaches will be necessary. That will mean that the regulations governing shipping – design, construction, operation and maintenance – will need to be matched to the industry that these regulate. The current largely prescriptive format will not cope with technology and operational change.

The future regulatory system should be goal-based, defining the standards of performance that the ship and its systems must satisfy. The move from the well-established largely prescriptive regime to a system that will meet the needs of future ship safety will inevitably bring challenges, and the new arrangements must be demonstrably at least as good, in terms of the achieved safety level, as those that are replaced. The change will not be unique, and lessons can be learned from others who have trodden this path before. Penny et al.\textsuperscript{25} examine the practicalities of goal-based safety regulation, in relation to the commercial aviation sector, and identify very clear advantages, in particular the clarity with which safety goals and regulatory goals must be identified. They also note that such a paradigm shift, which is typified by a move from a tick-box mentality to an argument-based mind-set, is challenging, suggesting that the transition can be facilitated by close working between the regulators and the regulated, preparation during development of the new regime of training and guidance documentation and the development of model safety argument examples that are reusable.

The IMO has some experience with developing goal-based standards and performance-based standards which will inform the development of the future-proofed regulatory regime to serve the maritime industry in the future. The future is, in effect, here right now as new technology and novel operational modes are introduced, particularly in respect of efficiency gains and emissions reduction. IMO, therefore, needs to act quickly to develop a framework for future regulation so that swift progress can be made towards the replacement of the current regulatory framework without detriment to the effectiveness and success of the industry or to the achieved level of safety.

Achievement of a safe sustainable shipping system in the future will need ships that are designed to make best use of available technology but designed with the real user in mind. Future proofing will demand flexibility to allow reaction to market changes. Future safety will require far more attention to human centred design, people across the industry who understand the risk profile and fit-for-purpose through career education, and training, solutions. The support of an effective regulatory regime will be required that can give assurance of an acceptable, and improved, level of safety whilst being capable of immediate relevance to new technology and novel solutions.

The author,\textsuperscript{26} referred, in the second Lord Kelvin Lecture delivered to the Institute of Marine Engineering, Science and Technology in December 2009, to the challenge of zero tolerance and the need to focus on systems and people. That focus must remain, but without taking attention away from the need for sound engineering and management.

Fields\textsuperscript{27} showed that the maritime industry has reacted, often retrospectively, to lessons learned but has an enviable reputation for improving safety through effective regulation. That must continue to evolve to meet the challenges of the future.

ACKNOWLEDGEMENTS

The author thanks Koji Sekimizu, the Secretary-General of the IMO, for the opportunity to make the presentation on which this paper is based at the Symposium on the Future of Ship Safety, held in London on 10/11 June, 2013.

The author also thanks the Institute of Marine Engineering, Science and Technology for promoting the presentation with their support as a Non-Governmental Organisation in consultative status at IMO. In particular the comments and contributions of David Smith, Bob Maxwell, Paul Doherty and other members of the Human Element Working Group of the Technology Leadership Board of the Institute of Marine Engineering, Science and Technology are gratefully acknowledged. As usual the author is grateful to his wife, Ann Nussey, for her support and her constructive criticism, adding as always infallible logic to his writing.

The author is grateful to Susanna Hertrich for permission to use her information graphic in Fig 4 (see www.susannahertrich.com for further examples of her work).

The views expressed are those of the author and not those of any organisation with which he is or has been associated.

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