would provide a rapid estimate of the potentially bioavailable fraction of coal contaminants. Finally, more careful bioassays with marine organisms are needed to provide a convincing case that toxic effects from coal are negligible.

To help comparisons with previous and future studies, as many characteristics of the unburnt coal sample as possible should be recorded, such as rank, sulphur content, leaching duration, solid-to-liquid ratio in the raw, unfiltered leachate, and particle size. These variables greatly affect leachate properties and concentrations of some potential toxicants (e.g., metals). What is currently lacking is a comprehensive ecotoxicological comparison of different coal types and their leachates. A better knowledge of which types of coals have the potential to generate toxicity is central to effective, scientifically based mitigation of adverse effects.

Manipulative laboratory and field experiments

As discussed above, there are several missing links in the process of environmental risk assessment for coal. Furthermore, where coal is present in the marine environment, any potential ecotoxicological effects it may have are likely to be overwhelmed or confounded by more obvious physical effects, or by chemical effects of contaminants from other sources. Addressing these issues requires manipulative experiments in the laboratory and field to determine the bioavailability of coal-derived toxicants and to identify unambiguously their effects without the presence of confounding or obscuring factors. Field studies, including *in situ* toxicity testing and studies involving spiking coal into uncontaminated sediments, should be possible even at relatively large spatial scales because of coal's ease of handling. These studies could be extended to compare various types of coal, different degrees of weathering and particle size, and other factors that influence the toxic potential of coal.

Long-term monitoring and correlational studies

If, as predicted, demand for coal continues to grow, and new exporting and importing facilities are constructed, opportunities may arise for before-after/control-impact (BACI) studies of the effects of coal terminals on the surrounding environment. These studies would include monitoring of coal contamination, and any associated changes in the environmental concentrations of coal-derived contaminants (including those that are characteristic of coal and would allow clear identification of the source) and the health status of resident biota. They would include appropriately located and replicated control locations and would continue for a sufficient time before and after the start of coal-transporting operations for an adequate assessment of background temporal variation in the environment and its biota, and for any effects (physical and chemical) to emerge. Estimates of the time required for effects to emerge might be based on modelling of environmental input and fate of coal (e.g., Biggs et al. 1984) and of ecological responses (see, e.g., the discussion of modelling of effects of sedimentation on rocky-shore organisms in Airoldi 2003), and the results of manipulative experiments, such as those described above. Ideally, such studies would take place in the absence of other sources of impact, such as industrial discharges or spoil grounds, which might confound or obscure any effects of coal.

Needless to say, the above requirements are unlikely to be fulfilled in many situations. Most expansions of coal-transporting facilities are likely to occur by enlargement of existing ports rather than construction of new ones. In this situation, the environment is likely to be affected already, particularly at older ports where past environmental management practices were less strict than they often are today. Exceptions may occur where new coalfields are developed in areas where land transport infrastructure does not exist to allow transfer to an existing port, or expansion may involve construction of an additional terminal sufficiently far away from existing ones that it lies outside the field of effects. Such opportunities should be seized in order to minimise possible environmental effects and to advance our understanding of them. In practice, however, the perception, right or wrong, that coal is generally a low-risk contaminant in the marine environment seems to lead to the perception that such studies are not cost effective.

Conclusions

Despite coal's long and often conspicuous presence as a natural and anthropogenic contaminant in marine environments, its toxicological effects have received surprisingly little attention. As we have seen, this stems at least partly from a perception that the bioavailability of contaminants in coal is very limited and that at levels of coal contamination at which estimates of bioavailable concentrations of contaminants might give cause for concern, acute physical effects are likely to be much more significant. However, we have also seen that the very variable chemical properties of coal, and the environment in which it occurs, may give rise to circumstances in which contaminant mobility and bioavailability is enhanced. Understanding the mechanisms controlling bioavailability is probably the key to predicting and mitigating environmental effects of coal. It is a field that offers wide scope for experimental studies, as does investigation of biological responses to coal, particularly at higher levels of biological organisation.

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Safety at Seas: Bulk carrier structure

http://antipodeanmariner.blogspot.com/2012/09/safety-at-seas-bulk-carrier-structure.html

Another easy re-post from 'Safety at Sea' with photos from the AM's shipbuilding projects. Acknowledgements to the Author, Captain Dennis Barber and Cliff P. who has annotated some of the cross-sections of the ships under construction and has labeled the main structural components (double-click on the image to get the detail).

Antipodean Mariner

Safety At Sea Magazine Features (6th Sept 2012), Author Captain Dennis Barbour

Bulker safety: Structural strains
A decade ago, the IMO review of bulk carrier safety noted many structural risks facing such vessels. Safety expert Dennis Barber says it is time to review the stresses and strains that bulk carrier hulls still face

The bulk carrier safety debate intensified in the closing years of the 20th century, driven by a continuing attrition of large bulk carriers, many of which disappeared without trace. In response, IMO member states formed the International Collaborative Formal Safety Assessment of Bulk Carriers (FSA), which in the first decade of this century has brought together expertise from various countries and non-governmental organisations. It carried out an intense study using formal safety assessment techniques, and from this emerged measures intended to create safer bulk carriers. Not least of these was the addition of a whole new chapter (XII) to SOLAS that was dedicated to bulk carriers.

Among the many conclusions of the study, the ultimate cause identified for major losses in bulk carriers was loss of hull integrity (LOHI). Vessels of such size could only disappear without trace if they suffered LOHI. Put simply, if a vessel fills with water, it will sink – an obvious conclusion, perhaps, which makes it all the more surprising that LOHI was neglected in regulation until the FSA released its outcomes (for details, see ‘Sink or WIM’, SAS May 2012, p24).

The lack of any distress signal in most of the more than 500 cases studied indicates that

the vessels sank rapidly, so must have involved such a massive failure of the hull that the crew had no time to call for help.
The effectiveness of the FSA's work – which has been incorporated into SOLAS Chapter XII and also elsewhere, such as in the International Association of Classification Societies (IACS) Unified Rules – will be tested as time passes. As it is 10 years since the FSA released the first results of its research, with a new generation of seafarers and managers operating the world fleet, it is a good time to review the FSA's findings.

FSA findings revisited
Several dangers were addressed by the FSA. It pointed out that, structurally:
Air pipes, particularly those in the forward part of large bulk carriers, were insufficiently strong to resist the forces to which they could be exposed

Hatch covers were wholly inadequate to withstand the water pressures of over-topping (green) seas
Bulkheads in bulk carriers (as opposed to oil bulk ore carriers) were not strong enough to resist the head of water in a hold flooded to the waterline

Hull shell plating, being a single skin with limited access for close inspection, was highly vulnerable to failure
Freeboard forward was inadequate on low-freeboard vessels such as bulk carriers that were permitted to load to what are known as B-60 freeboards, similar to tankers.
Standards of corrosion control were inadequate to resist the degradation that could weaken shell plating and/or other structures, with the result that they could fail catastrophically.

'Derbyshire', lost with all crew in a typhoon

In the list above the causes of failures were not fully understood. Research into hatch cover failure was, until seafarer input was sought and incorporated, preoccupied with vertical forces. The evidence from the 1980 sinking of Derbyshire suggested that the hatches collapsed under weight of water. This may have been the case and it was officially acknowledged as such, but it was far more likely that the failure of hatches and air pipes came initially from the forward side of the hatch, not from above. Large waves overtopping the forward end would have enormous momentum that would have been capable of dislodging the hatch covers and shearing off the air pipes exposed to the rush of water across the relatively unimpeded foredeck.

Examination of hatch covers that were found in the hold of the wreck suggests this was indeed the cause. The hatch cover skirt was torn out horizontally, indicating that a large force struck it from ahead. Once dislodged, the cover would have been able to fall into the aperture of the forward hold that previously it had been protecting. It is probable that it would also have been exposed to the huge mass of water bearing down on it from above, and this, together with its own weight, would have projected it into the hold.

Forecastle adds reserve buoyancy

Reintroducing the forecastle

One issue that generated much agitation among mariners for many years was the loss of the forecastle in large vessel designs. A majority of modern Capesize and many Panamax bulk carriers are 'flush-decked'. The mitigating significance of the forecastle was identified by the FSA, but fell foul of the cost-benefit assessment part of the study.

However, IACS took the view that it was worth reintroducing the forecastle. Forecastles on all new bulk carriers were imposed in unified rules that came into force on 1 January 2004. At a stroke, the mariners' forward shelter was restored, albeit it would take several years for the flush-decked vessels to work their way out of the fleet.

A forecastle offers not only protection to the forward parts of the vessel (and incidentally to seafarers on deck) thus preventing the type of damage to forward hatches referred to above, but also provides valuable reserve buoyancy. The lack of forward reserve buoyancy was also identified in a study submitted by the China delegation at the IMO in 2001 looking at possible deficiencies in the International Convention on Loadlines. The IMO was alerted to the findings at the time of the FSA.

Mariners were not surprised. A favourite and high-scoring question in ship construction papers for the professional mariners' exams through the greater part of the 20th century was to describe the benefits of a forecastle. It is small wonder that mariners were quick to complain and curious that the design and construction part of the industry failed to see the significance of this simple but effective measure.

This brings us to another structural issue: shell plating strength. Before the 1980s, Capesize vessels typically had a shell plating thickness of 22mm or more, but by the early 1990s this had reduced to a about 15–17mm typically, ostensibly because high-tensile (HT) steel had replaced its low-tensile (LT) equivalent. The FSA revealed that corrosion was a probable factor in failure of shell plating and hatch covers and it should be noted that a 15mm HT steel plate will corrode at the same rate as 22mm LT steel plate. The proportion of degradation, however, is far greater in the thinner plate.

Capesize bulk carrier, annotated by Cliff P.

Berthing difficulties

Modern mariners will be familiar with the marks on the sides of large vessels. The tug pushing points are an admission that the side is not strong enough to resist the force imposed by a tug unless it coincides with a bulkhead. The professionalism of tug masters is thus the main mitigation against damage in this area. In the vast majority of cases, they get it right.

Tug push marks aligned with cargo hold bulkheads

The ship's side is not subjected solely to tug contacts, however. Design tends to concentrate on wave pressures, but this ignores other impacts such as fender pressures during berthing. Fenders fixed to the quayside are much less likely to coincide with bulkheads. If it is the case that the force of a tug pushing on side shell plating between bulkheads can cause damage, how much more potential for damage is there when the total mass of the vessel is concentrated on the single fender that inevitably is the first to make contact during berthing? A Capesize vessel regularly has a loaded displacement of up to 200,000 tonnes. If designers are relying on masters and pilots to ensure the vessel lands 'all along', they are almost certainly expecting the improbable.

Concentrated pressures on shell plating can also be experienced in loading ports where swells are regularly present and where even massive Capesize vessels are always on the move. The vessel's moorings will tend to become slack as the freeboard reduces during loading. Unless kept tight – something that is very difficult during the constant movement imposed by the swells – the vessel will lose contact with the fender face. It will then begin to yaw and alternately make contact at points forward and aft of the midship line. Typically in a nine-hold Capesize bulk carrier these contact points would coincide with No 3 and No 8 hold. It is significant that a number of side shell failures have occurred in these holds.

Spreading the load

With a heavy cargo the failure could be fatal, as a hold already carrying well in excess of 20,000 tonnes of cargo in a small heap in the bottom may take on another 10,000 tonnes of water as it fills the remaining space around the cargo. With a lighter cargo, the vessel may survive. The best mitigation for these potential failures is the avoidance of hard fenders that are concentrated on too small an area of the hull. Because there is no standardisation of hull design, it is impossible to align fenders with bulkheads on the vessels, but it is possible to use large pneumatic fenders that absorb loads and spread them over a larger area – precisely why they are routinely used between large tankers during ship-to-ship transfers. The same principal could be, and in some enlightened ports is, applied between bulk carriers and quaysides.

Some shell-plating failures have occurred in the forward-most hold. This area of the hull is particularly vulnerable on vessels entering locks and docks. The gentle nudge as the bow makes contact at the lock entrance on one shoulder or the other may be transmitting enormous forces into the plating in this area, where the lines of the hull converge towards the bow. A point load exerts pressure on a part of the plating not designed to take any force other than the seas, and the beginnings of a fracture may be imposed on the steel in this area. Failure may not occur straight away, but an undetected fracture may corrode on subsequent voyages until one day the strength of the overall plating fails.

Casualties and a few near-misses have occurred when shell plating around the bow has been breached or, more spectacularly, has fallen away. Such failures are often blamed on wave action – punching into heavy seas – combined with internal corrosion.

The forepeak tank

Another compartment that has a higher likelihood of failure is the forepeak tank, which on a Capesize vessel may be capable of holding 1,200 tonnes or more of ballast water. When the vessel is loaded, this tank would normally be empty, hence the suspicion that punching forces are the primary cause of the failure. Yet if the failure in such cases is invariably caused by external wave forces pushing inwards, the question remains as to why some surviving cases been found with plates distorted outward. The explanation is simple: the primary failure may well have been brought about by punching forces, but these may only have imposed a minor fracture, not a total catastrophic failure. The empty tank would then take on water through the fracture and, though not normally warned against in the vessel's stability book, sloshing in this tank would begin imposing increasing pressures on the corners of this triangular space as the tank fills.

When the tank is partially full, the pressures may literally blast the side out of the vessel, hence the outward distortions of the plating edges where they have been torn from the side shell. The vessel then suffers a major loss of reserve buoyancy, with the attendant risk of 'driving under'. This may account for a large number of losses during the night, when the bridge officer is unable to see the seas flooding over the bow. The FSA introduced water ingress monitoring in forepeaks as well as holds, and masters and managers would do well to ensure the systems are tested regularly.

An initial fracture may also result from impacts such as those from swinging anchors during anchoring operations; fractures in way of anchor housings in flush-decked ships where the anchors are very close to the waterline and may cause concentrations of force during punching into seas; and abrasions of anchor chains rubbing against the hull. It is worth noting that salvors use this as a method of cutting up wrecks!

It is evident that a few ports handling Capesize vessels in remote areas use anchor dredging as a means of controlling the vessel during berthing because the ports are not provided with tugs. The damage this could cause to the modern 15mm shell plating should be fully assessed. The ships look the same from the outside as their 22mm predecessors, but the reserve of material is considerably less.

Times change, hazards remain

The high-tensile, low-lightweight ships built in the 1990s are now getting very old and many will be reaching critical strength reduction. More recent vessels will have benefited from improved IMO and IACS regulations and rules, but the hazards remain.

Hold cross section, annotated by Cliff P.

Coatings that are strong and durable have certainly improved resistance to corrosion, but natural forces can still be dangerous. Climate change and the increasing occurrence of storms of unprecedented strength may well be making waves larger. Risks could thus be increasing for these large ships that cannot, because of their length, ride over them.

Mariners clearly have a part to play in ensuring that they learn as much as possible about their ship and its limitations.

Designers can contribute by recognising that they still might not have it exactly right. They could gather data from the mariners and spend more time on ships in ‘the big testing tank’. They could try harder to match the vessels better to their environments, both at sea and in port.

Port designers should perhaps pay closer attention to the way in which they fender their quaysides. That means doing more than ‘ticking the box’ and installing a proprietary fender that its manufacturer insists is suitable. Instead, they should closely observe berthing and calculate the loadings imposed on vessels’ hulls as they make impact, bearing in mind the enormous momentum involved.

Most of all, it is important to continue the work started at the FSA in IMO and to avoid the temptation to let matters stand still as though there is nothing more to be done. When it comes to issue of LOHI, the FSA was the start, not the finish.

Captain Dennis Barber, consulting partner in Marico Marine, was the contracted specialist project manager at the UK MCA for the recommendations of the RFI into the loss of

Derbyshire, serving as part of the project management team of the International Collaborative FSA for Bulk Carriers reporting to the IMO Maritime Safety Committee, 2001–2004

Bunker spill risk

Colin de la Rue, of Ince & Co, looks at the International Convention on Civil Liability for Bunker Oil Pollution Damage, 2001

Sometimes it comes as a surprise to people to hear that pollution from ships' bunkers can be nearly as serious a problem as major cargo spills from tankers.

There are various reasons why this is so. For one thing, bunker spills can of course occur not only from tankers but from most of the world's fleet. Dry cargo ships and other non-tankers are much more numerous than tankers so bunker spills are therefore a common source of oil pollution from ships.

Although only oil tankers can cause very large spills, many bulk carriers and container ships carry bunker fuel of 10,000 tonnes or more – these are larger quantities than many of the world's tankers carry as cargo.

Most importantly, ships' bunkers normally consist of heavy fuel oils, which in general are highly viscous and persistent. A relatively small quantity of highly persistent bunker fuel can be disproportionately damaging and costly to remove in comparison, for example, with a substantial cargo of light crude oil.

The record for the most expensive ever oil spill in terms of dollars per barrel was set by the 43,000 dwt wood chip carrier *Kure* when it struck the dock at a loading facility and ruptured a fuel oil tank in Humboldt Bay, California, in November 1997. The spill of 105 barrels of bunker fuel was followed by a response operation lasting 10 days at US$1m per day. The final cost reached $47m.

Other bunker spills in the US have been some of the most significant oil pollution cases since OPA 90 was introduced:

- the grounding in February 1999 of the woodchip carrier *New Carissa*, outside Coos Bay,Oregon;
- the bunker spill from the bulk carrier *Selandang Ayu*, which ran aground on Unalaska Island in the Bering Sea in November 2004; and
- and the spill of bunker fuel from the container ship *Cosco Busan*, which occurred when she struck the Oakland Bay Bridge in San Francisco Harbour in November 2007.

They have had significant political as well as financial consequences.

Outside the US, most bunker spills have until recently been outside the scope of any international compensation regime. Bunker spills from tankers fall within the 1992 Civil Liability and Fund Conventions, but those from other vessels have been governed only by domestic laws.

In many jurisdictions such laws have long been in place, but with few exceptions it has not been practicable for governments to impose their own independent rules to ensure that financial security is in place for payment of claims.

It was mainly for this reason that governments decided, after the HNS Convention had been adopted in 1996, that bunker spills represented a gap in international law which ought to be filled.

Work on the subject began at the International Maritime Organisation later that year and in March 2001 agreement was reached on the International Convention on Civil Liability for Bunker Oil Pollution Damage. This came into force on 21 November 2008

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after attaining the requisite ratifications 12 months earlier. A total of 25 states have ratified and now that the Convention is in force many more can be expected to do so.

The corner-stones of the Convention are strict liability, compulsory insurance and limitation of liability. Many provisions borrow heavily from familiar counterparts in the Civil Liability Convention 1992 (CLC), but there are some important differences.

Liability for bunker oil pollution

The Convention imposes strict liability for 'pollution damage' resulting from a spill of bunkers. This in itself is not remarkable. The limited exemptions from liability also match those in CLC. However there are differences concerning the party liable.

CLC imposes liability solely on the 'registered owner' of the vessel and excludes liability, whether under the Convention or otherwise, of various other parties, notably managers, operators, charterers, salvors, pilots and the owner's servants or agents.

This so-called 'channelling' of liability to the registered owner is a feature of CLC which simplifies the liability regime and is acceptable when supplemental compensation is normally available from the IOPC Fund if claims exceed the CLC limit.

By contrast, the Bunkers Convention is a single-tier regime and governments decided to preserve rights of recovery from other parties in addition to the registered owner. Liability is therefore imposed on the 'shipowner', defined as meaning 'the owner, including the registered owner, bareboat charterer, manager and operator of the ship'. Each of these parties may be held jointly and severally liable under the Convention.

In the same vein, the Bunkers Convention differs from CLC in that it does not contain any 'channelling' provisions excluding claims against other parties: the Conference decided against giving 'responder immunity' to salvors, but a compromise was adopted in the form of a Resolution calling upon governments to consider doing so when implementing the Convention in their domestic legislation.

Compulsory insurance and financial security

The compulsory insurance requirements of the Convention are very similar to those in CLC. Ships must carry on board a certificate issued by the flag state administration attesting that appropriate insurance or other financial security is in place to cover any liabilities incurred by the registered owner under the Convention.

The insurer or other guarantor named in the certificate is directly suable and may not rely upon policy defences other than wilful misconduct of the shipowner.

In this area the main differences from CLC are of a more practical nature. While it is one thing for flag state administrations and P&I Clubs to handle the paperwork required to certificate a few thousand oil tankers, the world's non-tanker fleet is far larger and the administrative burden involved is correspondingly greater. The Convention therefore contains provisions designed to avoid this burden becoming unnecessarily great.

One of these restricts the certification regime to ships of 1,000 gross tons or more; another excludes vessels engaged in purely 'domestic voyages'. Nonetheless, the number of vessels requiring certification has been very large, including many registered in states which are not parties to the Convention.

Although certificates can be issued by any contracting state, it was unclear, until a late stage before entry into force of the Convention, that there were contracting states with sufficient capacity to undertake this administrative work in addition to certificating their own vessels. Whilst significant problems have been avoided, the considerable work involved will need to be repeated, at least for vessels in International Group Clubs, to renew certificates from 20 February.

Limitation of liability

As always, insurance guarantees are available only if they are subject to clear limits. Consequently, as with CLC, the right of the shipowner and his insurer to limit liability goes hand in hand with the imposition upon them of strict liability and the compulsory insurance provisions.

In the Bunkers Convention the right of limitation is set out in Article 6, which provides:

'Nothing in this Convention shall affect the right of the shipowner and the person or persons providing insurance or other financial security to limit liability under any application national or international regime, such as the Convention on Limitation of Liability for Maritime Claims 1976 as amended.'

This arrangement differs from the limitation regime in CLC, in that it does not provide for a free-standing limitation fund dedicated to pollution claims. Instead the liability limit is linked to that applying under the national or international regime, if any, which applies in the state concerned in relation to liability generally for maritime claims. LLMC 76 has become the most widespread international regime of this type.

As the Bunkers Convention does not provide for a dedicated limitation fund, pollution claims against an LLMC fund will rank alongside various other claims which may arise from the same incident, eg collision damage claims.

Significant increase

However, given the significant increase in limits introduced by the 1996 LLMC Protocol, only in rare cases should the higher figures be insufficient to cover all claims.

Of course, it is in the rare cases that limitation is most important for shipowners, and Article 6 is not as clear on all points as some might have wished. One of the concerns is that LLMC does not explicitly grant a right of limitation for pollution claims.

It may be that many typical claims for pollution, such as for property damage and clean-up costs, would fall within the wording of one or other of the different categories of claim which are subject to limitation under LLMC. However there are others where the position may not be so clear.

In the UK, where strict liability for bunker spills was introduced some years ago, any room for doubt has been eliminated by a provision in the Merchant Shipping Act 1995 (s. 168) which stipulates that all claims for bunker oil pollution are to be deemed to be claims for property damage within the meaning of Article 2.1(a) of LLMC.

Other governments might usefully be urged to consider enacting similar provisions for clarity when enacting the Bunkers Convention in their national laws.

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Extreme Waves and Ship Design

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Abstract

Recent research has demonstrated that extreme waves, waves with crest to trough heights of 20 to 30 meters, occur more frequently than previously thought. Also, over the past several decades, a surprising number of large commercial vessels have been lost in incidents involving extreme waves. Many of the victims were bulk carriers. Current design criteria generally consider significant wave heights less than 11 meters (36 feet). Based on what is known today, this criterion is inadequate and consideration should be given to designing for significant wave heights of 20 meters (65 feet), meanwhile recognizing that waves 30 meters (98 feet) high are not out of the question. The *dynamic* force of wave impacts should also be included in the structural analysis of the vessel, hatch covers and other vulnerable areas (as opposed to relying on static or quasi-dynamic analyses).

Keywords

Extreme waves; Rogue waves; Ship design; Ship losses; Sinking; Risk.

Nomenclature

CSR, Common structural rules
ft, foot, feet (0.305 m)
grt, Gross register ton
H_{ext}, Extreme wave height, m
H_S, Significant wave height, m
HTS, high strength steel
HY, high yield strength steel
IACS, International Association of Classification Societies
m, meter
N, Newton
Pa, Pascal (N/m^2)
psf, pounds force per square foot
psi, pounds force per square inch
SSC, Ship Structure committee

Introduction

Recent research by the European Community has demonstrated that extreme waves—waves with crest to trough heights of 20 to 30 meters—occur more frequently than previously thought (MaxWave Project, 2003). In addition, over the past several decades, a surprising number of large commercial vessels have been lost in incidents involving extreme waves. Many of the victims were bulk carriers that broke up so quickly that they sank before a distress message could be sent or the crew could be rescued.

There also have been a number of widely publicized events where passenger liners encountered large waves (20 meters or higher) that caused damage, injured passengers and crew members, but did not lead to loss of the vessel. This is not a new phenomenon; there are well-documented events dating back to at least the early 1940s.

These two facts, vessel losses combined with knowledge that waves larger than previously considered likely may be encountered, suggest that reviewing vessel design criteria may be necessary. (Smith, 2006).

Ocean Wave Environment

Marine weather forecasts report the significant wave height (H_S), which is defined as the average of the highest one-third of the wave heights. A working definition for an extreme wave is one with a height greater than 2.3 times the significant wave height. In mathematical terms, this is:

$$H_{ext} = 2.3 \times H_S \quad (1)$$

Such waves are often referred to as rogue waves or freak waves, as their height lies at the extreme of what would be expected for a Rayleigh distribution of wave heights. Based on observations made by ship's crews and on limited data from offshore platform measurements and satellite observations, these waves are asymmetrical and have unusually steep faces. They may be preceded or followed by a deep trough.

Ship Design

Ship design is based on a set of prescriptive rules or standards. While this standardization ensures that designs meet operating requirements, it is important that these standardized requirements reflect the actual operating conditions that a ship will see during its service life. As a first approximation for structural design purposes, a seagoing vessel is considered to be a structural beam or girder. A fundamental difference is the fact that it is not connected to rigid supports, but rather is supported by fluid pressure. In addition, because a vessel is in constant motion, it is also subjected to dynamic forces.

Reduced to basic terms, the design of the vessel can be considered in two parts: first is the design of the hull as a girder capable of resisting the bending moments, shear forces, and torsion resulting from the cargo weight distribution and the forces of wind and wave. The second part is the detailed design of local structural elements such as hatch openings, hatch covers, engine and crane supports, bridge windows, and so on. The latter case is an important aspect of structural design whether for aircraft, civil structures, or ships. Failure often occurs at connections, local details, and other areas where stress concentrations can occur.

The reader is assumed to be familiar with ship design, so for conciseness I will not discuss it here. Readers interested in a general overview can consult my book (Smith, 2007), or for an excellent detailed discussion and comparison of ship design standards, see Kendrick and Daley (2007). Central to any design methodology is estimating the prevailing sea state and selecting a design wave height.

As larger and larger ships have been built, alternate methods of determining the design wave height have been used. Current design criteria generally consider significant wave heights less than 11 meters (36 feet). For example, the International Association of Classification Societies (IACS) has issued standard wave data—called IACS Recommendation 34—for use in the design of cargo-carrying vessels in the North Atlantic. (IACS, 2001). Table 1 in the IACS document indicates that most waves (88%) will have periods of 7 to 14 seconds and significant heights of 1m to 10.9 m (3.3 to 35.7 ft) or less. Only 0.2% of these significant wave heights will fall in the range of 11m to 17 m (36 to 55.7 ft).

Ship design necessarily must consider many service conditions, wave height being but one. Military vessels, for example, are designed to withstand shock and overpressure loads not experienced by commercial vessels. Basic ship design considers the moments and shear forces imposed by hogging and sagging loads with the vessel supported on or between waves having the maximum expected height.

The United States Navy uses a design wave height based on the length of the vessel (Fee, 2005), as noted in (Eq. 2).

$$H = 1.1\,(L_s)^{0.5} \qquad (2)$$

Here L_s is the length of the ship in feet. Thus, for a vessel 900 feet long, the design wave height would be (1.1)(30) = 33 feet high. Note: Converting the formula to metric units it becomes $H = 0.61\,(L_s)^{0.5}$, where now H and L_s are in meters. Historically, the U.S. Navy has taken the position that the largest wave likely to be encountered was 21.4 m (70 ft.) Based on more recent experiences the navy now believes that larger waves can occur, but that they are unstable and only last for a brief period. The possibility of extreme waves that are steeper and possibly do not have longer wavelengths is now recognized.

Once the loads are established, finite element methods are used to calculate the primary stresses in the ship's ribs, longitudinals, and other main structural elements, to ensure that the sizing of steel members is adequate for the expected loads. The navy's general criterion is built around a Sea State 8 condition. In Sea State 8, the significant wave height is about 14 m (45 ft). This is typical for most hurricanes. Hurricane Camille is one of the best recorded hurricanes, and the navy uses a wave scenario based on this hurricane in their ship models to check for dynamic stability and survivability. On the basis of other analyses, the navy has not had to make any fundamental changes in ship design as a result of the prospect of a wave greater than 21.4 m (70 ft). Naval vessels appear to already have sufficient strength built into them to survive an encounter with a larger wave using the existing criteria.

The energy carried by a wave is proportional to the square of its height. For this reason, a 30.5 meter (100 foot) high wave will hit a vessel with four times the force of a 15 meter (50 foot) high wave. If a high wave is traveling at 35 knots and a vessel traveling at 20 knots runs into it bow first, the combined velocity of the impact is 55 knots. The resulting slamming force has the potential to seriously damage the bow structure.

Consequently, other parts of the ship structure that may be subject to wave forces are also examined to ensure that they are sufficiently strong to resist the forces that will occur. The next step is the design of the deck plate for "deck wetness." Those areas subject to extreme deck wetness are the bow area and parts of the superstructure that encounter extreme wave loading due to wave slap and the dynamic load of large amounts of water pouring onto the deck in an extreme wave encounter. The basic design criterion is to assume a pressure of 24 kPa (500 psf) for any area that is prone to "green water" (wave slap). Most navy vessels are designed for at least 71.9 kPa (1500 psf), and some unique parts of a structure, such as the sponsons on an aircraft carrier, are designed for as high as 359 kPa (7,500 psf). In addition, a static head equivalent to a column of green water 2.4 to 3.1

meters (8 to 10 feet) high is designed in the forward part of the vessel that is likely to encounter waves. This is reduced linearly as you move aft from the bow of the vessel where a value of 30.6 kPa (640 psf) is used to a minimum value of 1.2 meters (4 feet) of head, equivalent to about 12.3 kPa (256 psf). Military vessels include additional design conservatism to account for the need to resist blast over pressure during combat operations.

Both military and commercial vessels are designed to stay afloat with one or more hull compartments flooded. In the case of commercial vessels, one or two flooded compartments is the norm, while for the navy it is three.

The military has progressed from using steel with a yield strength of 207 to 276 MPa (207 to 276 N/mm^2 or 30,000 to 40,000 psi) called HTS or high strength steel to using high yield strength steels (called HY steels) that have a yield strength of 551 MPa (80,000 psi). Submarines use 714 MPa (100,000 psi) HY steel. The norm for commercial ships is HTS at 276 MPa (40,000 psi). Further verification of ship designs is accomplished by carrying out model tests in wave tanks. Once the vessel is commissioned, it will undergo sea trials to verify performance and operational characteristics.

IACS Common Structural Rules

One of the vagaries of ship design is that there are no uniform codes or international standards as in the case of building design. Instead, ship design has evolved from centuries-old traditions where ship insurers inspected and classified vessels in accordance with the risks they perceived and the premiums they would impose. Over time this system evolved from vessel inspection to a classification system that stipulated design rules for a vessel to be eligible for rating in a specified class. Today there are more than 50 classification societies worldwide, each with different rules. The rules vary depending on the type of vessel as well.

In 1968 a group of classification societies formed the International Association of Classification Societies (IACS). Today the IACS membership consists of 10 classification societies representing China, France, Germany, Italy, Japan, Korea, Norway, Russia, United Kingdom, and United States. The IACS claims that its members collectively class more than 90 percent of all commercial tonnage involved in international trade. Historically IACS resolutions have not been mandatory for implementation by member organizations, which have been free to develop their own rules for ship design.

In response to growing discontent by ship owners concerned about the fact that ships being built today are less robust, three classification societies announced in 2001 that they would work together to establish common design criteria for standard ship types, beginning with tankers. Subsequently, a task force was formed to develop common structural rules for bulk carriers (IACS, 2006). As part of this effort, vessel inspection reports were reviewed to assess problem areas. The IACS reported that the majority of bulk carriers lost were more than 15 years old, were carrying iron ore at the time, and failed as the result of corrosion and cracking of the structure within cargo spaces, and as a result overstressing by incorrect cargo loading and cargo discharging operations. (IACS 1997). Curiously, there was no mention of extreme waves or rough seas as a cause of failure. The *Derbyshire*, only 4 years old, likely sank when 20+m (70 ft) high waves collapsed hatch covers (Tarman and Heitman, no date). Incidentally, bulk carriers continue to sink, the most recent example being May 2006 when 190,000 gt *M/V Alexandros T* broke up off the coast of South Africa in an area noted for extreme waves.

In 2004, the chairman of the IACS council, Ugo Salerno, issued a letter reporting on the status of common rules for oil tankers and bulk carriers. (IACS, 2004). Salerno stated that IACS's objective is that the new rules will be adopted and applied uniformly by all IACS members. The new ship design criteria—called *Common Structural Rules*—were released in April 2006, and will apply to tankers and bulk carriers designed and constructed after that date. The design wave loads in the new rules will be based on IACS Recommendation 34, described previously.

Should Design Loads be Increased?

Although the IACS Common Structural Rules (CSR) for bulk carriers state that they are based on IACS Recommendation No. 34, "Standard Wave Data," the relationship is not obvious. (IACS 2001). The CSR (see Chapter 1 page 17) defines a "wave parameter" C that is a function of vessel length and has a maximum value (dimensionless) of 10.75. The CSR rules specify material properties and design calculations that are required for vessel classification. The rules also contain a number of "check values" that stipulate certain minimum parameters, such as minimum hull plate thickness, that must be met by the design. In other words, the designer can use his or her own methods to size structural members but must ensure that results meet or exceed the checking criteria.

To get a feel for applying the CSR, I made a series of calculations for a hypothetical bulk carrier based on these parameters:

Rule length L = equal to 275 m (900 feet)
Breadth B = 45 m (147.5 feet)
Depth D = 23.8 m (78 feet) depth.
Draught T = 17.5 m (57.4 feet) displacement.
Displacement Δ = 161,000 metric tons

Here the nomenclature is as given in the CSR chapter 1 page 16.

Applying the CSR formula in this example gives a wave parameter of C = 10.625. (The maximum value of C = 10.75 is to be used for vessels 300 to 350 meters in length.) The wave parameter is used in various formulas in the CSR to calculate the bending moment and shear forces at various positions along the length and height of the hull and also in determining the hydrodynamic pressure at various locations. The procedures consider hogging and sagging as well as various sea states, such as bow-on, following seas, beam seas, et cetera.

In the CSR formulation the wave parameter is dimensionless but has a numerical value very close to the design wave height determined by the US Navy criteria (Eq. 2), i.e., $C = 0.61 (L)^{0.5} = 10.56$ meters when L = 300 meters.

Table 1 summarizes the results of my sample calculations. The notation "min or max" in the table means that this is a check value and the actual value calculated by the ship designer must be greater than or less than this value.

Table 1: CSR Sample Calculations

Material = AH steel with minimum yield stress 315 N/mm^2 and k= 0.78

Vertical wave bending moment, midship, deck level

- Hogging 4.98×10^6 kNm
- Sagging 5.68×10^6 kNm

Vertical wave shear force = 56,200 kN

Hydrostatic pressure, 8.75 m below waterline = 88 kN/m^2

Hydrodynamic pressure = 122 kN/m^2

Pressure on exposed decks and hatch covers = 35.8 kN/m^2

Normal stress due to vertical bending = 315 N/mm^2 (max value)

Shear stress = 154 N/mm^2 (max value)

Material thicknesses:

- Cargo area hull plate thickness, 22.6 mm
- Bow area, intact condition, 27.8 mm
- Bottom, inner bottom, 13.75 mm (min value)
- Weather strength deck, 10.0 mm (min value)
- Side shell, bilge, 14.1 mm (min value)
- Hatch cover plate thickness, 10 mm (calculated)
- Hatch cover plate thickness, 5-6 mm (min value)
- Note: thicknesses are "net" and must have a corrosion allowance of 2 to 4 mm added.

Lateral pressure, side of superstructure 29.9 kN/m^2

Pressure on exposed deck at superstructure level, 22.4 kN/m^2. Toughened window glass, 8 mm (min value).

The effort to develop the CSR is laudable, and hopefully will lead to greater consistency in the design of new vessels. One question is whether or not a maximum wave parameter of 10.75 is adequate.

Ship Failure Modes

There are several ways in which a large vessel could conceivably founder under the impact of wind and wave. Typically it is a chain of occurrences rather than a single event. For example, due to wave damage, a vessel could lose power or sustain rudder failure, which might then cause it to wallow in beam seas, in turn causing the cargo to shift and the vessel to list, take on water, and capsize. Or, wave damage to hatch covers, hatch coamings, deck equipment, or the hull itself could lead to flooding of holds or compartments, loss of freeboard, and eventual sinking.

Failure of structural integrity is common to several loss scenarios so it is of interest to estimate the order of magnitude of stresses imposed by large waves. Such stresses can be considered in three categories: hydrostatic loads, hydrodynamic loads, and impulse loads.

In Table 2 I compiled the hydrostatic force of a column of sea water of various heights. This could be considered the deck or hatch cover static load caused by green water flowing over the vessel (keep in mind that the actual load would be greater due to hydrodynamic forces acting in addition to the static load). The table also includes the original design criteria for the Derbyshire hatch covers, the Derbyshire hatch load at failure (as determined by SSC), typical deck and hatch loads using the CSR methodology (Chap. 4 pg. 23, Chap. 5, p.29) and some of the United States Navy guidelines mentioned above.

Table 2: Hydrostatic Load Points

Static Head (m)	Static pressure psi	Static pressure kN/m^2	Notes
1.0	1.46	10.1	
1.7	2.48	17.1	(1)
2.0	2.92	20.1	
2.38	3.47	23.9	(2)
3.0	4.37	30.2	
3.56	5.19	35.8	(3)
5.0	5.29	50.3	
5.32	7.76	53.49	(4)
6.0	8.75	60.3	
7.15	14.4	71.9	(5)
10	14.6	100	
15	21.9	151	
20	29.2	201	(6)
25	36.5	251	

Notes:

1. *Derbyshire* DnV design load.
2. USN 500 psf criteria.
3. CSR design load, decks, hatches.
4. *Derbyshire* hatch load at ultimate Stress (3.125 x design), (Tarman and Heitman).
5. USN 1,500 psf criteria.
6. *Derbyshire* hatch load likely during

Typhoon Orchid, (Tarman and Heitman).

Hydrodynamic loads ("wave slap") can impose greater stresses on marine structures than the hydrostatic load of green water. In heavy seas, an envelope of operating conditions bounded by predominant wave periods of 7 to 18 seconds, wave lengths of 50 to 250 meters, wave heights of 10 to 30 meters, and wave crest velocities of 10 to 35 meters/seconds would encompass dangerous conditions. Using Bernoulli's equation, the hydrodynamic loads for typical conditions can be found as noted in Table 3 using Eq. 3.

$$P_d = ½\, C_p\, \rho v^2 \qquad (3)$$

Where P_d is the hydrodynamic pressure in N/m^2, C_p is a factor to account for concentrated loads, ρ is sea water density, 1,025 kg/m^3, and v is velocity, m/sec. C_p is given the value of 3 for global loadings and 9 for local, concentrated loads. (Faulkner, 2001).

Table 3: Hydrodynamic Loads

Velocity	Pressures, kN/m^2		
m/sec		Global	Local
	C_p =1	C_p =3	C_p =9
10	51.3	154	461
15	115	346	1,040
20	205	615	1,850
25	320	961	2,880
30	461	1,380	4,150
35	628	1,880	5,650

In addition to the dynamic loads estimated above, plunging or breaking waves can cause short-lived impulse pressure spikes called Gifle peaks. These can reach pressures of 200 kN/m^2 or more for milliseconds, leading to brittle fracture of mild steel. Evidence for this type of failure was found when *Derbyshire's* wreckage was surveyed. (Faulkner, 2001).

As noted above in Table 2, the CSR design load for hatches is a static head of 3.6 m corresponding to a pressure of 35.8 kN/m^2. This value would be exceeded by waves 4 m high or by waves with an incident velocity of 10 m/sec. But would the hatch fail?

Are the CSR design criteria adequate?

The IACS CSR design criteria are intended to insure that stresses remain less than the yield stress of the selected material. This being the case, the expectation is that there is a safety factor of around 3 before the ultimate stress is exceeded and failure occurs. In the case of exposed decks and hatch covers this value corresponds to a wave 10.7 meters high or a pressure of 107 kN/m^2. Considering that the hatch covers, deck, and hull are structures fabricated of plates supported by beams and stiffeners, failure could occur by bending or shear.

In bending, the plate deforms elastically until some point reaches the yield point. In the case of a plate rigidly supported at the edges and uniformly loaded, yielding occurs at the center and edges. Plastic failure occurs when yielding and resulting plastic flow propagates throughout the section. This is known as a three-hinge plastic collapse because the three yield points at the center and edges act as hinges and allow the plate to collapse under the applied load.

To fail in shear, the applied load has to be considerably greater, sufficient to exceed the ultimate shear strength at the edge supports.

To check hatch failure for the hypothetical vessel described above, I made two further assumptions: hatch plate material thickness 12 mm (10 mm + corrosion allowance of 2 mm) and unsupported span distance b of 600 mm. Material is still AH steel with a minimum yield stress σ of 315 N/mm^2. Shear yield stress is taken as $\tau = \sigma/(3)^{1/2}$. Two potential failure modes to consider are the three-hinge plastic collapse and the edge shear yield.

The three-hinge plastic collapse pressure P_c in kN/m^2 can be found from equation 4 and the edge shear yield pressure P_e from equation 5. (Faulkner, 2001).

$$P_c = 4.5\, \sigma\, (t/b)^2 = 423\ kN/m^2 \qquad (4)$$

$$P_e = 2\, \tau\, (t/b) = 5{,}430\ kN/m^2 \qquad (5)$$

These results indicate that a large, fast moving wave ($v \geq 35$ m/sec) could possibly cause edge shear failure for a hatch designed in accordance with the CSR. However, and more importantly, plastic collapse would most likely occur first, either from the impact of a wave crest traveling at 20 to 30 m/sec or from the combined load of a slower moving wave with a head of 10 meters or so.

No doubt it can be argued that more sophisticated analyses can be made. Nonlinear finite element models of hatch covers can be developed and subjected to time-dependent wave loadings that more realistically simulate actual sea conditions. For example, in heavy seas, a vessel would be pitching up and down and the freeboard would not be constant. Also, if the vessel is underway, the impact velocity is the sum of the vessel velocity and the incident wave velocity. For a vessel underway at 16 knots and struck by a single rogue wave (as opposed to a vessel hove to in a storm) this velocity difference can be significant.

However, for the purposes of this study these refinements are not important.

The wave loads developed above suggest that vessels designed in accordance with CSR minimum values may in fact be vulnerable to high waves that can reasonably be expected in a 25 year service life. My conclusion is that the current design criteria spelled out in the CSR are inadequate and need to be increased. Specifically, hatch covers, coamings, wheel house windows and deck and bow structures and equipment subject to direct wave impacts should be designed to withstand the impact of fast moving waves 20 meters (66 feet) high.

Evidence for Higher Waves

Today there is considerable evidence for the existence of higher waves. In addition to observations by mariners at sea, there are measurements based on buoys, subsurface pressure transducers, wave height measuring instruments on offshore platforms, and satellite-based radar altimeters. Researchers are looking at installation of ship board wave height measuring instruments to gather more comprehensive data under actual conditions at sea. See Table 4 for examples ranging from 24 to 40 meters (80 to 140 feet).

Table 4: Some Evidence for Extreme Waves

Description and Location (Year)	Wave heights (m) Significant	Extreme
Sydney-Hobart Race (1998)	12-18	43 (M)
Weather ship data ca. 1980:		
Atlantic	13-23	40 (C)
Pacific	11-20	36 (C)
Offshore platforms		
North Sea	--	34 (C)
USS *Ramapo* N. Pacific 1933	--	34 (M)
East Dellwood N. Pacific 1993	12	31 (M)
Ocean Ranger N. Atlantic 1982	--	31 (E)
SS *Bremen S.* Atlantic 2001	--	30 (E)
Submarine *Grouper*, Atlantic	Calm seas	30 (M)
Caledonian Star S. Atlantic 2001	--	30 (E)
Athene Indian Ocean 1977	--	30 (E)
Queen Elizabeth 2 N. Atlantic 1995	--	29 (E)
Hurricane *Ivan* Atlantic 2004	--	28 (M)
Queen Elizabeth N. Atlantic 1943	--	27 (E)
Draupner platform N. Sea 1995	12	26 (M)
Esso Nederland Agulhas	--	25 (E)
MaxWave satellite study 2001	--	24+(M)

Notes: M= Measured, C=Calculated, E=Estimated
Source: Smith (2006) p. 215

Historic Ship Losses

A few decades ago, commercial vessels were lost at the rate of one per day somewhere in the world. Not all of these losses were attributed to heavy seas or extreme waves; the statistics indicated that 41% were wrecked, 28.5 % were lost to collisions, fire or explosion, 28 % foundered, and 2.5% simply disappeared and were never found, "missing and presumed lost." (Bascom, 1980). Today the size of the global merchant fleet is only about half the number of vessels that existed in 1980, but the cargo carrying capacity is actually increased through the use of larger vessels.

While many improvements have been made in vessel safety through improved operations, better weather forecasts, improved radar, and satellite navigation techniques, a surprisingly large number of vessels are still lost each year. For example, in 2006, a total of 261 vessels sank. Of this total, 75 were over 500 gross tons. These numbers are based on data that I have been able to gather; the actual losses are probably greater. Of the 75 vessels that sank, 25% were lost due to the effects of wind and wave. There were at least 10 rogue wave incidents reported in 2006, along with 15 other "large wave" incidents. I cite the following examples to show that the risks are real.

In May, 2006, bulk carrier *Alexandros T*, carrying iron ore from Brazil to China, broke up off the coast of Port Alfred, South Africa, a notorious location for rogue waves. Of the crew of 33, only 5 persons made it to life rafts before the vessel sank. A fishing vessel called *Super Suds II* capsized off shore from South Carolina after taking a big wave on the starboard bow, but the five crew members were rescued. Also in May, a large ferry, the *M/V Pont-Aven,* with 1,100 passengers on board, was hit by a rogue wave, breaking windows, flooding berths, and injuring 5 passengers. It was on its way from Plymouth, England to Santander, Spain, traversing the Bay of Biscay, another rogue wave hot spot. In August, the fishing vessel *Challenger* was swamped by a sudden, unexpected large wave and driven onto the rocks at the west end of Hoy, Orkney Islands, Northern Scotland. The two crewmen were saved. In November 2006, an offshore utility vessel called *M/V Hawk* disappeared off the east coast of South Africa, with no sign of the 4 crewmen. An empty life raft was later discovered. Its condition suggested that it was torn from the boat before any of the crew could get in, and they are lost and presumed drowned. November saw a large tanker, *M/T FR8 Venture*, with a load of crude oil from Scapa Flow, Orkney Islands, and headed for Houston, take a huge wave over the bow off the east coast of Scotland. Two seamen were killed and a third injured. Also in November, the German fishing vessel *Hohe Weg* was capsized by a huge wave in the North Sea, north of Bremerhaven. There was no time for the two crew members to escape; a month later their bodies washed ashore. A fishing vessel named *Joe Green* was hit by a rogue wave in the Atlantic Ocean off the coast of South Carolina, smashing bridge windows and damaging electronic gear, but the boat and crew survived. In November, a cargo ship 440 feet long, the *Westwood Pomona*, was hit by a wave 70 feet high that smashed in the windows on the bridge, damaged essential electronics, and forced the vessel to seek shelter in Coos Bay, Oregon for repairs. In December, a large wave came out of nowhere and smashed the tug *M/V Kathleen* in the Gulf of Mexico while it was offshore from Padre Island, Texas. It lost power and suffered one injured crewman, but was able to recover. Finally, in December the tall ship *Picton Castle* sailing from Nova Scotia to the Caribbean was hit by a rogue wave that washed a female crew member over board to her death in the Atlantic.

Risk-Benefit Considerations

Let's assume that the design lifetime of a new vessel is 25 years or 1300 weeks. During this period of time, we can anticipate at least five haul outs, each lasting four weeks. Assume that an average ocean crossing trip (Atlantic or Pacific) has a duration of three weeks with a one-week layover at each end. This corresponds to 75% sea time and 25% port time. The equivalent lifetime sea time for the vessel is 960 weeks or 581 million seconds.

Then assume that the vessel experiences waves with periods in the range of 7 to 14 seconds. On average during its lifetime, it would experience approximately 55 million waves. According to IACS Bulletin 34, Table 1, 99.8% of these waves would have a significant height less than 11 m (36 feet), and only 0.2% of these waves would fall in the category of 11 to 17 m in height. This suggests that 110,000 waves over 11 m in height could be encountered during the life of a vessel plying North Atlantic waters. The probability of waves over 17 m in height is not given.

The trend today is to make commercial vessels bigger and bigger. The *Maersk Emma*, reportedly the world's largest container ship at 397 m (1300 ft) long and 170,000 grt, is an example. Orders are in place to build more than ten additional container ships this size. Passenger ships keep getting bigger and bigger, with the new Royal Caribbean Line's *Freedom of the Seas* (339 m, 1,112 ft) and a 4,000 passenger capacity outpacing the *Queen Mary 2* (3,000 passengers). The largest double-hull tanker is the *Hellespont Fairfax*, at 380 m (1,246 ft); the largest bulker is the *Berge Stahl,* at 343 m (1,125 ft).

It would be of interest to see a comparative study demonstrating how these longer vessels fare in large, long wavelength waves, compared to vessels 200 to 250 meters long.

In the last several decades emphasis has been placed on increasing the cost effectiveness of vessels. More sophisticated computer design tools and the use of high strength steel alloys has enabled ship designers to reduce the quantity of structural steel per ton of cargo capacity. Using more advanced design techniques designers have also reduced areas of design uncertainty with the consequence that safety margins have also been reduced. The use of thinner plates and structural elements is advantageous, because it not only reduces shipbuilding costs but improves fuel economy. Improved corrosion protection methods and coatings have been developed that in theory reduce the likelihood of wastage of structural metal due to corrosion. However, with thinner sections, rigorous inspection and maintenance takes on an even greater importance, since there is less margin for error.

New vessel construction costs range from approximately $1,000/grt for container ships to $5,000/grt for cruise ships like the *Freedom of the Seas*. Designing for higher waves will mandate the use of more steel in critical structural components, increasing the cost of construction. The benefit of increased vessel reliability and a reduced risk of damage to the vessel and cargo, or of the loss of the vessel and its crew, must be weighed against this added cost. At first glance the incremental cost appears to be small, the benefit, huge.

Consider the cost of losing a *Maersk Emma* or a *Freedom of the Seas*. For the container ship, the value of vessel and cargo could easily exceed one billion dollars. For a giant cruise ship such as *Freedom of the Seas,* the vessel alone reportedly costs $800 million; the loss of thousands of passengers has an incalculable cost. In either case the damage to the marine insurance industry and the loss of public confidence in marine transport would lead to bankruptcies and increased government regulation.

Ship Losses and Vulnerability

Review of ship accident reports and US Coast Guard casualty reports indicates a number of areas where ships have been vulnerable to rogue wave damage. These areas should have priority for improved design. For bulk carriers, as discussed above, hatch covers and deck penetrations are extremely important, since they represent a potential path for seas to enter the vessel. In addition to the static load of green water on hatch covers, they should be designed to withstand the dynamic load of the impact of the design wave breaking on the vessel.

Consideration should also be given to installing seawater intrusion detection systems in forward sections of the vessel, as well as pumps that can be activated remotely from the bridge in the event leaks are detected.

In many of the reported rogue wave incidents, the wave smashed bridge windows and flooded instrument panels, disabling critical instruments and in a number of cases caused a complete loss of power. The obvious solution is to strengthen bridge windows. Less obvious is to weather-proof critical instrumentation systems within the bridge. Waves have also ripped lifeboats from their davits, suggesting that safety systems must be especially rugged.

Findings

I believe there is sufficient evidence to conclude that significant wave heights of 20 meters (66 feet) can be experienced in the 25-year lifetime of oceangoing vessels, and that 30 meter (98 foot) high waves are less likely, but not out of the question. Therefore, a design criterion based on an 11 meter (36 feet) high significant wave seems inadequate when risk of losing crew and cargo is considered. This is particularly true for large vessels that are intended for service in areas where extreme waves are likely to be encountered. IACS Recommendation 34 should be modified so the *minimum* significant wave height for design is at least

20 meters. The *dynamic* force of wave impacts should also be included in a dynamic structural analysis of the vessel, hatch covers and other vulnerable areas (as opposed to relying on static or quasi-dynamic analyses).

After selecting design loads, further steps are necessary to complete a ship design. An overall structural arrangement has to be selected; methods have to chosen to calculate the response of the structure (prescriptive rules, computer simulations, linear vs. non-linear analyses, et cetera); and finally the designer has to decide what are stress or deformations are acceptable, including determination of how much yielding or plastic response is allowable. Different classification societies take different approaches, with wide variation in results and safety factors. (Kendrick and Daley, 2007). This lack of consistency should be alarming to ship owners, insurers, passengers, and ship's crews.

Dedication

This paper is dedicated to the more than 2,700 merchant seaman, sailors, and passengers who lost their lives in marine disasters during 2006.

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Coal dust dispersal around a marine coal terminal (1977–1999), British Columbia: The fate of coal dust in the marine environment

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Abstract

A 1999 assessment of sediments, adjacent to the Roberts Bank coal terminal in Delta, British Columbia, Canada, shows that the concentration of coal particles (reported as non-hydrolysable solids or NHS) has increased substantially since a prior study in 1977. NHS concentrations have doubled from a mean concentration of 1.80% in 1977 to 3.60% in 1999. Overall the dispersal distance of coal has not increased over the 22-year period but rather the abundance of coal in the surface sediment within the dispersal area has increased. Since 1977 the main deposition of coal has occurred in the vicinity of the coal-loading terminals, where concentrations of 10.5% and 11.9% NHS (non-hydrolysable solids = coal) occur.

The settling properties of fresh and oxidized coal particles (<53 μm up to >2.36 mm) were examined in order to better understand the dispersal of coal in marine waters. No change in settling velocity of coal particles occurred with increasing oxidation. However, the proportion of buoyant coal particles decreases with oxidation in all size fractions, reflecting the decrease of coal hydrophobicity with oxidation.

The distribution of coal around the terminals agrees with measured particle settling velocity and current velocity, with coal concentration decreasing rapidly away from the terminal. Coarser sediment fractions contain the highest coal (NHS) concentrations and carbon/nitrogen ration when compared to finer fractions. Coal particles with >2.36 mm diameter (settling velocities ≤10.54 cm/s) settle out close to the terminal (depending on currents), whilst small (<53 μm) and weakly oxidized coal particles travel further and take longer to settle out (settling velocities ≥0.16 cm/s). This results in a wider dispersal of coal particles, and a corresponding decrease in the coal concentration.

Coal distribution would likely affect those benthic flora and fauna, most susceptible to coal dust coverage and possible anoxic conditions that might arise during coal oxidation within very close proximity (0–100 m) to the coal-loading terminal.

Keywords: Coal contamination; Coal environment; Coal settling velocity

1. Introduction

The Roberts Bank coal terminal has been in business for over thirty years and is presently operated by Westshore Terminals Ltd (Fig. 1). Located on Roberts Bank in the municipality of Delta, British Columbia, Canada, it is the first stage in a proposed development of a major bulk-loading port and industrial park, as the major terminals in Burrard Inlet (Vancouver, B.C.) exceed their exporting and development capacities.

However, Roberts Bank is not naturally a deep-sea port and is located in one of the most ecologically

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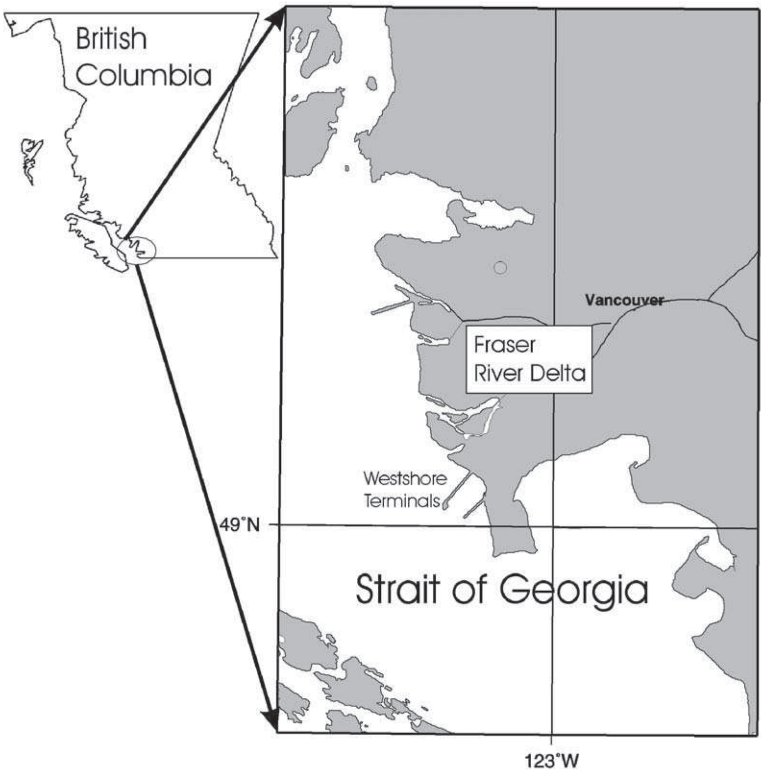

Fig. 1. Location of Westshore Terminals and Fraser River Estuary, British Columbia, Canada.

important estuaries on the west coast of North America. The construction of the coal terminal has had numerous effects on the local ecology, and the release of coal dust has had a detrimental impact on the region.

This paper investigates the coal content of the sediments in the vicinity of the coal loading facility, and reveals significant changes in sediment coal content and distribution in the 23 years since the previous study. An assessment of the settling properties and velocities of the coal particles in the water column were conducted to predict coal particle dispersal around the terminal, and these results are compared with the observed distribution of coal in the sediments adjacent to the coal loading facility. Some of the effects of this coal accumulation on the local ecology are also discussed.

2. History and previous studies

In April 1970, shipments of coal mined in the interior of British Columbia and Alberta began from the Roberts Bank coal terminal located south of the Main Arm of the Fraser River, just south of Vancouver (Fig. 1). The present facility consists of a 96-hectare man-made island situated at the end of a 4.8-km long causeway, serviced by a 20-m deep dredged waterlot and a large ship turning basin located between the terminal and the Tsawwassen Ferry terminal (Fig. 2).

Westshore Terminals handle approximately 30% of the shipping volumes of the British Columbia Lower Mainland. Approximately 90% of this volume is coal that is transported to the facility in unit trains, where the coal is unloaded and stored in large unprotected stockpiles. The coal is subsequently loaded aboard ships ranging in size form 45 000 deadweight tonnes (DWT) to 250 000 DWT for export from two major coal-loading terminals, referred to as pods #1 and 2 (Fig. 2). Coal shipments have increased from 10.6 million metric tonnes in 1980 to a maximum of 23.5 million in 1997. Estimates forecast a continued increase of 4% per annum until 2010 (Fraser River Estuary Management Program (FREMP), 1990a,b). Annual shipments are projected to reach 30 million metric tonnes of coal only with modification of Pod #3, as this terminal is presently being used as a bulk cargo terminal (Deltaport).

In 1975, Westshore Terminals Ltd. applied for a permit under the British Columbia Pollution Control Act, 1967 (Emissions), to discharge “unknown and immeasurable” quantities of coal dust to the air (Pearce and McBride, 1977) as they had previously operated

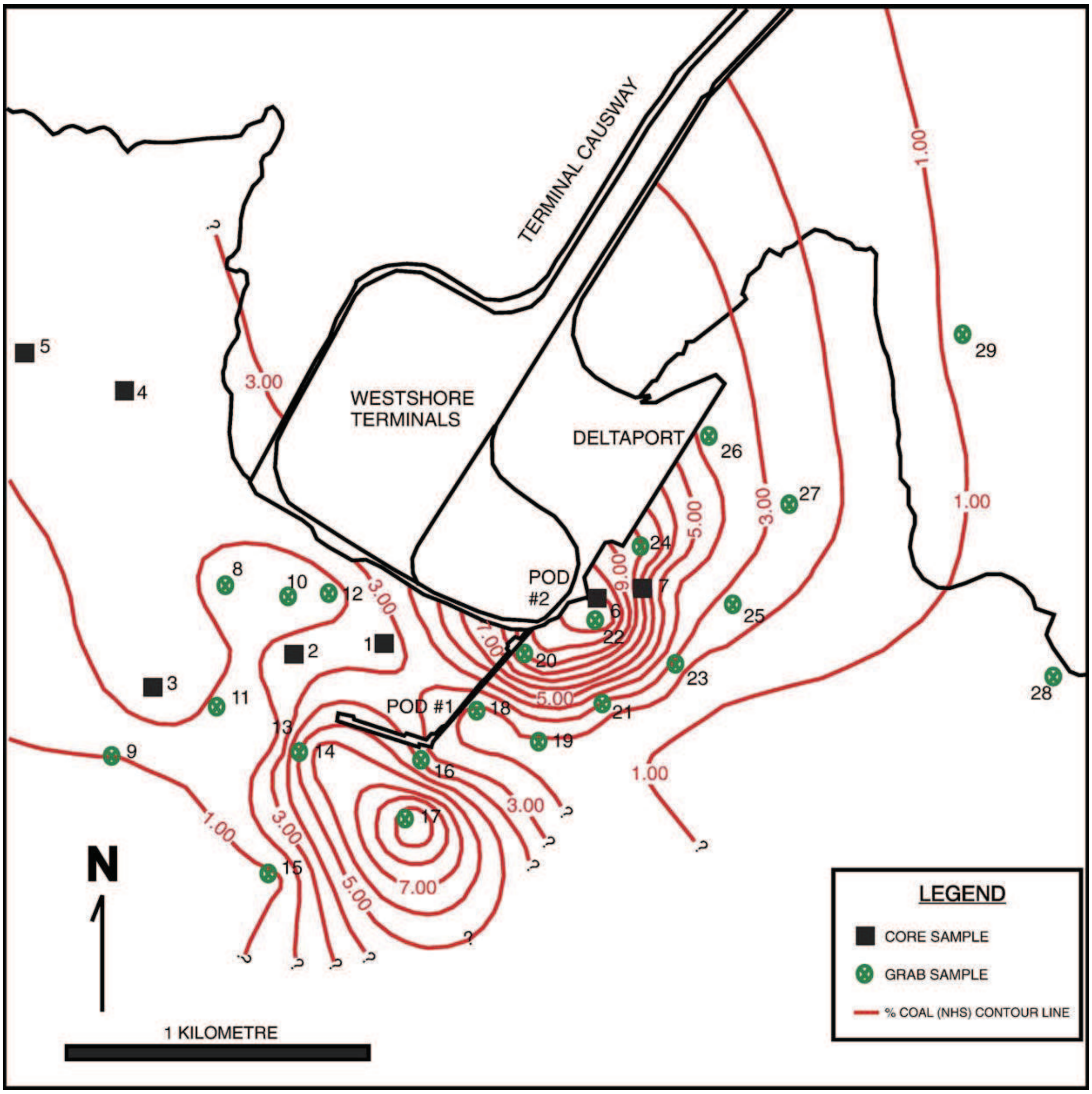

Fig. 2. Sample location and coal dust distribution in surface sediment as measured in weight percent NHS.

without a Pollution Control Branch permit. Local residents as far away as Pt. Roberts, have often complained of the coal dust escaping the terminal (Department of Fisheries and Environment Canada, 1978) from the incoming loaded rail cars, conveyor belts, and returning empty trains during the loading processes. Emissions from open stockpiles also contribute to the coal dust (especially during high wind periods), though it occurs to a lesser degree due to the use of resin binders such as polyvinyl acetate (Pearce and McBride, 1977).

Coal accumulation in bottom sediments, documented by Butler (1972) and Butler and Longbottom (1970) stimulated the Habitat Protection staff of the Fisheries and Marine Service to undertake a limited program in 1975 to study the further accumulation of coal in marine sediments around the terminal, and the possible effect of this coal accumulation on the local ecology. Pearce and McBride conducted the last of these studies in 1977 (Darrel Dejerdin, Vancouver Port Authority, Environmental Services, pers. Comm., 1999) and concluded that the coal content of the sediments adjacent to the Roberts Bank (reported as non-hydrolysable solids) increased only slightly in the five years since Butler's investigation.

3. Study area

Historically, man's encroachment upon, and development of the ecologically important Fraser Estuary/Delta has generally been both ad hoc and unrestricted. This uncoordinated approach to resource use, without regard to, or knowledge of effects on the environment has led to very significant changes in the environment. Since the 1800's, roughly 70% of the estuary's original wetlands have been lost to dyking, dredging, draining, and filling (FREMP, 1997). However, the total area of freshwater and brackish marshes on the outer estuary may have increased in the last century due to the accretion of mudflats on Sturgeon and Roberts Banks (FREMP, 1996).

3.1. Physical environment

Annual deposits on Roberts Bank of approximately 17 million tonnes of sediment are supplied by the Fraser River (FREMP, 1996), the largest river on the west coast of North America (Fig. 1). This sedimentation plays a vital role in the creation of much of the aquatic habitat on Roberts Bank, and is in a dynamic state due to interacting and variable river flows and tides. Constant dredging is necessary to maintain depths of navigable shipping lanes in the vicinity of Westshore Terminals, and recent applications (Westshore Terminals Administrative Department, 1998) have been submitted to dredge approximately 4000 m^3 in the immediate vicinity of Pod #2, (Fig. 2; Dariah Hasselman, FREMP, Project Review Coordinator, pers. comm.).

Roberts Bank comprises approximately 8000 of the total 14,000 hectares of tidal flat associated with the Fraser River Delta. The dominant platform of Roberts Bank is over 6-km wide and slopes gently from the dyked delta lowlands out to a distinct break in slope, approximately 9 m below the lowest normal tide level (Fig. 2). In the vicinity of the Westshore Terminals causeway, the intertidal area exposed between high and low water is approximately 3000-m wide. Tidal channels, current, and wave ripples interrupt the otherwise featureless bank (Luternauer and Murray, 1973; Luternauer, 1974.

3.2. Estuarine ecology

The Fraser River estuary is notable for its biological productivity. This is especially evident between the Roberts Bank Coal Loading Port and the Tsawwassen Ferry Terminal, home to tidal flats, wetlands and eelgrass beds. These habitats form the basis for populations of varied estuarine life forms (in addition to the large numbers of migratory salmon and waterfowl) including the benthos, plankton and fish (Federal Environmental Assessment Review Office, 1979; Fraser River Estuary Management Program, 1989, 1991a, 1991b, 1993, 1994).

The benthos, composed of organisms dwelling on the sea bottom and in sediments are the most greatly affected due to the disturbance of the bottom caused by deposition of coal particles. Anoxic conditions, evident from the presence of hydrogen sulphide, in the sediments receiving very high levels of organic input (including coal), caused by the consumption of oxygen during the degradation (oxidation) of organic matter, would likely have the most detrimental impact on the benthic florae and faunae.

The ecological contribution of bottom microinvertebrates is very significant, as larvae from clams, mussels, barnacles, and crabs drift out to sea and constitute a substantial proportion of the seasonal food for juvenile salmonids and herring. Damage to the benthos therefore has serious implications for both the mature invertebrate populations as well as those creatures that predate upon the benthic larvae.

The Fraser River and its estuary support one of the largest commercial, recreational, and aboriginal salmon fisheries in British Columbia, which includes salmon, surf smelt, eulachon, cutthroat trout, steelhead trout, white sturgeon, mountain whitefish, and Dolly Varden. The annual commercial fishery of Fraser River salmon between 1989 and 1992 was valued of over $115 million (Canadian dollars), with a post-processing wholesale value of over $230 million (Environment Canada and Fisheries and Oceans Canada, 1995). Additionally, sport fishing throughout British Columbia earns about $180 million/year in direct revenues, with Fraser River Chinook and Coho comprising a large percentage of this catch (Environment Canada and Fisheries and Oceans Canada, 1995). Furthermore, seven native bands (Musqueam, Tsawwassen, Semiahmoo, Coquitlam, Katzie, Matsqui, and Langley) participate in the aboriginal food fishery in the Fraser River Estuary.

On Roberts Bank, the Dungeness crab is the only species that is exploited commercially and recreationally, representing approximately 10% of the total catch in British Columbia (Environment Canada and Fisheries and Oceans Canada, 1995). The reported darker coal-coloration of some crabs taken from Roberts Bank is a concern of local fishermen who find the darker crabs more difficult to market.

4. Material and methods

4.1. Sediment and sample collection

A benthic sample of the sediments was collected from each of 29 subtidal sampling stations (Fig. 2). The station locations were established using a differential GPS device and cross-referenced with the Canadian Hydrographic Chart #3492 (Fig. 2) and were chosen at roughly 200 m intervals radiating from the two main coal-loading terminals (pods #1 and 2). Stations 28 and 29 were situated closer to the Tsawwassen ferry terminal to act as 'controls'.

A gravity impact corer was used to collect the first seven samples at high tide on October 22, 1999 and a Shipek© model sediment sampler was used to collect the last 22 samples on November 26, 1999.

Upon retrieval, the uppermost 2–3 cm (approximately 200 g) of the samples were removed and placed in sealed plastic bags while the remainder of the samples were placed in larger bags, or retained in the core tubes. The samples were transported immediately to the laboratory and placed in a freezer to prevent decomposition.

Two coal samples (samples 30 and 31) from the Balmer seam (R_0 ~1.4%) of the Early Cretaceous Mist Mountain Formation (Kootney Group) were used in both the sediment coal content and coal settling property analyses, as these metallurgical coal samples are representative of the majority of coal exported from the Westshore Terminals facility.

4.2. Analytical techniques

4.2.1. Sediment coal content analysis

Determination of the coal content in the 29 sediment samples (each measured in duplicate) was performed using a modified hydrochloric acid hydrolysis method, mimicking the analytical procedure of Pearce and McBride (1977). During this process hydrolysable protein and acid-soluble carbonates are removed by hydrochloric acid hydrolysis with the remaining non-hydrolysable organic matter being removed by hydrogen peroxide oxidation.

Coal is essentially unaffected by the peroxide oxidation and hydrolysis, and its concentration is determined by subsequent gravimetric analysis and ashing. Coal content is reported here as percent total non-hydrolysable solids (NHS), while the organic content is reported as the percent total hydrolysable solids (HS).

The percent NHS is not a measure of the actual coal content of the marine sediments, mainly due to the presence of hydrolysis-resistant organic material such as wood, charcoal, and bark. Post-hydrolysis combustion of such materials would provide an overestimate of the actual coal content by resulting in an elevated NHS value. Despite this source of error, investigations have shown that NHS values do provide an indication of the coal content in marine sediments (Pearce and McBride, 1977).

Two coal samples from the Balmer seam were also analyzed to allow an estimate of coal lost during the digestion process as well as determining the ash content.

4.2.2. Sediment particle size analysis

Sediment particle size analyses were performed on the seven core samples using the wet sieve method described by Morgans (1956) to minimize the loss of particles and reduction in their grain size. The sediments were sieved into five different size fractions and then dried at 50 °C for 3 h prior to being weighed. Cumulative weight percents were plotted against grain size values to obtain an estimate of the grain size distribution in the vicinity of Westshore Terminals, as well as the degree of sediment sorting. Individual sieve fractions were examined with a microscope to determine an estimate of the fractions in which most of the coal grains occur.

4.2.3. Sediment organic/inorganic carbon and nitrogen analysis

Upon completion of the sediment particle analysis, samples were ground to less than 53 μm using a mortar mill. The organic carbon content for the various sediment size fractions was determined from the difference between total carbon content and inorganic carbon (IOC) content, with IOC content being determined by coulometric analysis.

Sediment total organic carbon (TOC) and nitrogen content for the sediment size fractions were determined using an instantaneous oxidation of the sample by 'flash combustion' and subsequent chromatographic analysis.

4.2.4. Coal settling properties analysis

A series of settling velocity experiments were performed to determine the settling characteristics of coal under various conditions in an attempt to explain the distribution of coal in the sediments surrounding Westshore Terminals. The effects of moisture and various degrees of oxidation on the hydrophobicity of the coal particles were investigated to determine the conditions under which various size fractions would float or sink, as well as to determine their settling velocities.

Coal samples from the Mist Mountain Formation were crushed using a mortar and pestle, dry sieved to the desired size fractions, and placed in sealed plastic containers. Five, 1-g samples of the smallest coal size fraction (<53 μm) were gently placed on the surface of 200 ml of seawater in open jars, and left exposed to the atmosphere for a month without agitation.

The remaining samples of the larger size fractions were divided into four subsamples. One group remained in the sealed plastic containers; the second group was placed on open aluminum foil trays at approximately 25 °C; the third group was placed in open beakers an oven at 50 °C; and the fourth group was placed in open beakers in the oven at 100 °C.

Settling velocities were determined in a 1000-ml test tube filled with 25 °C seawater by dropping individual coal particles from 8 cm above the water surface (to partially overcome surface tension), and the settling time was recorded for individual particles to settle 30 cm in the test tube. Ten trials were run for each size fraction, and an average of the trials was calculated. The number of buoyant coal particles was also recorded, as well as whether agitation was necessary to initiate particle settling. Agitation of the samples involved gently pushing the samples below the water surface with a glass rod; their displacement being factored into the settling times.

The settling velocities of the thirteen different coal size fractions of the first group of 'fresh' (least oxidized) coal samples were measured immediately, while the other three groups were allowed to oxidize for a week at temperatures of 25, 50, and 100 °C. The '100 °C' group of coal particles was returned to the oven for further oxidation and their settling properties were measured on a weekly basis for the following two weeks. Oxidation was confirmed by measuring the loss of caking ability of the coal. Because of the fine particle size, petrographic observations of the samples by light microscopy was not possible.

The densities of the coal samples (larger than 2.36 mm) were measured for the fresh, saturated, and oxidized (25, 50, and 100 °C) groups by weighing the samples in air and in toluene. Specific gravities were determined from the particles' displacement in toluene.

5. Results

5.1. Sediment coal content

The coal and organic content of the sediments, expressed as the percentage of non-hydrolyzable solids and hydrolysable solids respectively, are shown in Table 1.

Based on the sediment NHS content, the subtidal coal distribution in the area around the coal terminal is shown in Fig. 2. The area of greatest accumulation (>11%) is located directly southeast of the Pod #2 coal-loading terminal. This region of high concentration is limited to within a hundred metre radius of the loading facility, and the coal concentration diminishes rapidly to less than 1% within 700 to a 1000 m. A second region of elevated coal dust concentration (>10%) is found approximately 200 m directly south of the Pod #1 coal-loading terminal. Samples were not taken closer to Pod #1 (between stations 14 and 16) because a large coal transport ship was moored at the terminal on both sample collection dates. This region around Pod #1 is

Table 1
Sample location with average total organic carbon content and average coal content (NHS)

Sample station	Average OM content (%)	Average coal content (%)	Sample station	Average OM content (%)	Average coal content (%)
1	17.98	2.74	16	18.62	3.02
2	12.71	2.66	17	31.47	10.47
3	14.46	2.97	18	18.92	1.20
4	14.47	2.52	19	15.45	1.61
5	15.61	2.31	20	14.02	9.90
6	15.17	10.85	21	19.60	2.14
7	22.92	4.22	22	16.12	11.90
8	23.95	1.74	23	16.48	1.95
9	18.28	0.91	24	23.10	7.80
10	17.01	1.62	25	18.26	2.48
11	15.79	1.52	26	24.26	3.29
12	20.74	1.82	27	31.70	2.58
13	14.86	1.04	28 (control)	14.02	0.77
14	14.02	6.72	29 (control)	13.71	0.65
15	13.06	0.92	30 (coal)	0.12	94.89
			31 (coal)	0.77	93.41

also characterized by a high NHS concentration gradient, dropping to levels less than 1% within 500 to 1000 m. An area of moderate accumulation (1–3%) completely surrounds the coal terminal and extends outward for at least 1000 m to the north (limit of sampling), west, and east, and 800 m towards the south. Contouring of Fig. 2 south of stations 15 and 16 is based on limited data. Subtidal control samples collected at stations 28 and 29 (near the Tsawwassen ferry terminal and causeway) contained low (<0.8%) NHS concentrations.

The coal content in the sediments decreased significantly with distance from the terminal (Fig. 3).

Concentrations of hydrolysable matter, assumed to represent organic matter (OM) content, consistently exceeded the non-hydrolysable (coal) content in the sediments in each of the twenty-nine stations sampled. OM was found to compose at least 12% (by weight) of the surface sediment content on Roberts Bank, with a maximum of 31 OM at station 17 (Table 1).

The two Mist Mountain coal samples have an average of 0.44% HS. However, this apparent hydrolysable solid content most likely represents the irremovable coal residue in the test tubes upon completion of the digestion process. The coal samples were analyzed to contain an average of 94.15% NHS, with the decreased mass likely representing the ash content of the coal.

5.2. Sediment particle size

Results from the physical analysis of the sediment samples from the core samples are presented in Figs. 4–6. Subtidal grain sizes range between silt and clay to medium grained sand (<53 to >355 μm). The sediments to the north and northwest of the terminal are primarily silt and fine sand (<53 to 250 μm), while the area to the south and east is dominated by fine to medium sand (125 to 500 μm). The nearshore area adjacent to the coal terminal in the lee of the Pod #1 terminal (Core #1) is dominated by fine sediments in the silt and clay range (<63 μm).

Quartz grains dominate the sand, though a high abundance of lithic grains, shell fragments and mica also occur. Large coal fragments (up to 2 cm in diameter) occur in several of the core and grab samples, and are especially abundant in sample locations 6, 17, 20, and 22. The sediments have a moderate to poor degree of sorting and the larger grains are predominantly subangular with a moderate degree of sphericity. Both the degree of angularity and the composition of these sediments are indicative of poor to moderate chemical and physical maturity.

5.3. Sediment organic/inorganic carbon and nitrogen content

Results from the analysis of the total organic carbon (TOC) indicate that the TOC is highest in the coarser sediment size fractions (>250 μm), with a maximum of 16.8% in Core #6 (Fig. 4). TOC values in the smaller size fractions are generally less than 2%, and the lowest values occur in the 150-μm size fraction.

The inorganic carbon (IOC) values are generally less than 0.7%, with a maximum value of 1.2% occurring in the coarsest fraction (355 to 500 μm) in cores 1 and 7.

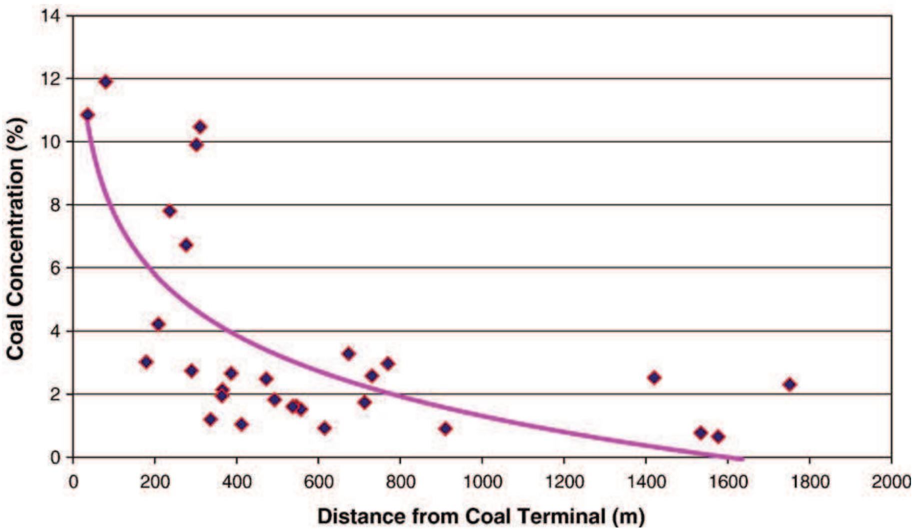

Fig. 3. Coal concentration (wt.%) with distance from the coal terminal.

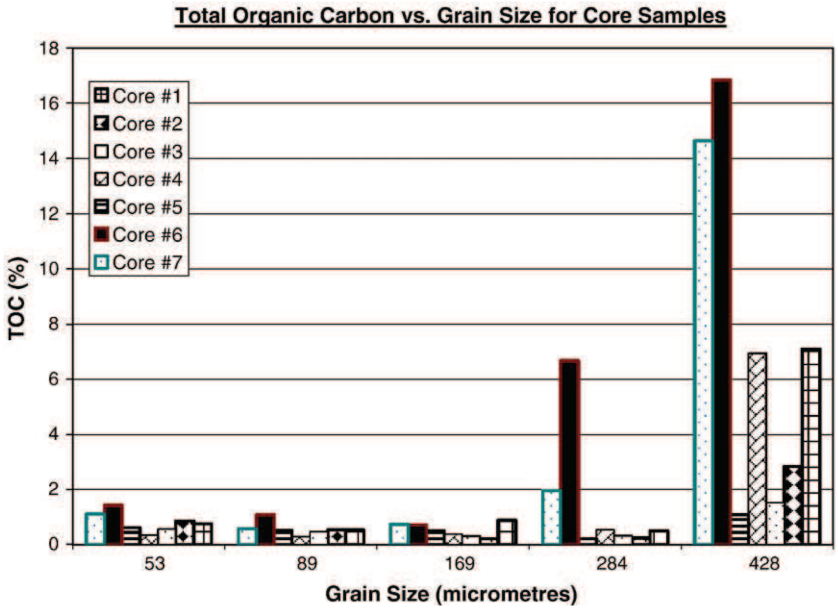

Fig. 4. Total organic carbon content vs. particle size distribution of samples for cores collected across study area (core locations are shown in Fig. 2).

Minimum values of IOC content are found to coincide with a grain size of approximately 200 μm, albeit a poor correlation.

Trends in the sediment nitrogen concentrations are found to generally conform to those of the TOC concentrations, although the nitrogen concentrations are considerably less (Fig. 5). Maximum nitrogen concentrations reached 0.34% in the largest size fraction (355 to 500 μm), while the nitrogen content in the majority of the other size fractions rarely exceed 0.10%. Minimum concentrations of approximately 0.03% nitrogen occur near the 200 μm size fraction.

A ratio between the carbon and nitrogen was plotted against the various core sample grain size fractions to determine whether or not the carbon being measured was from a terrestrial or marine source. Terrestrial carbon sources are known to generally have a higher C/N ratio than their marine counterparts (Mayer, 1994).

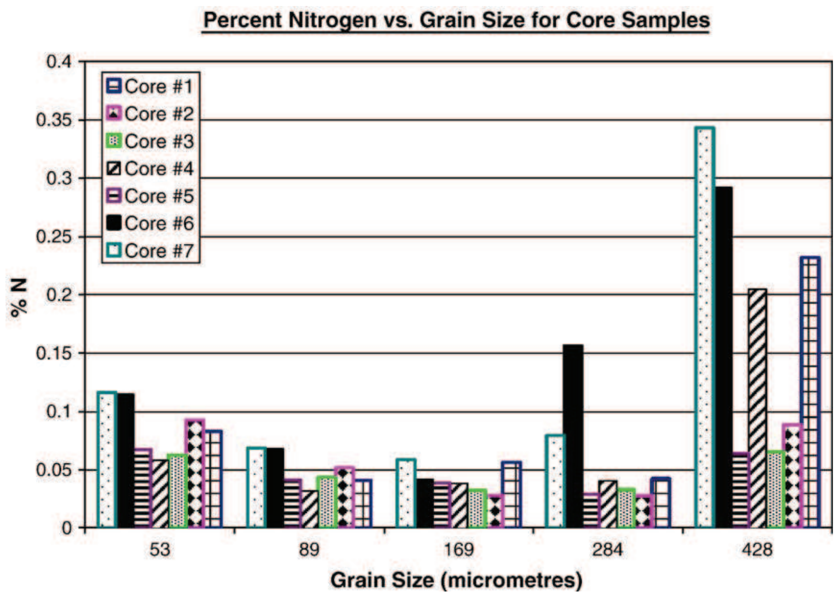

Fig. 5. Particle size distribution of samples vs. the total nitrogen content for cores collected across study area (core locations are shown in Fig. 2).

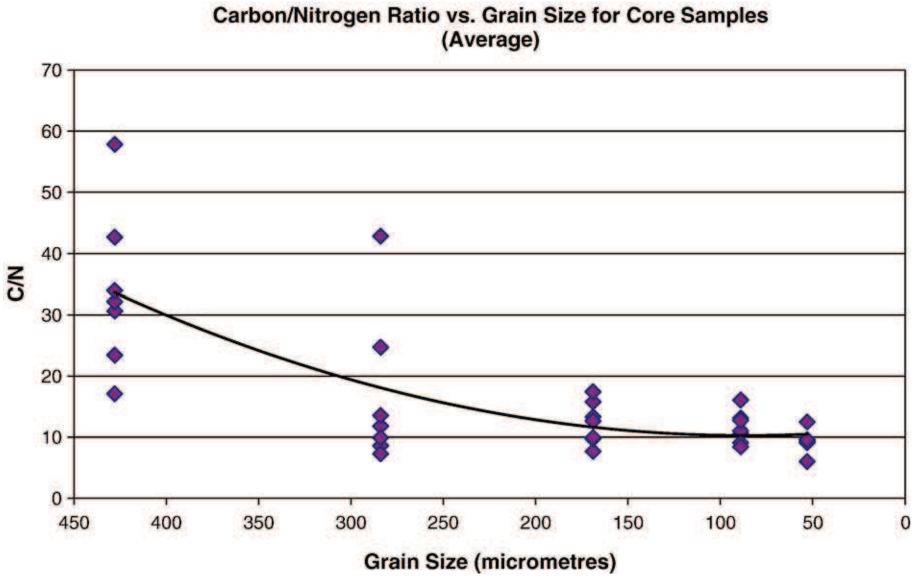

Fig. 6. Carbon to nitrogen ratio vs. grain size.

The highest C/N values occurred in the larger size fractions, and the C/N ratios generally decrease with decreasing particle size (Fig. 6). Cores 6 and 7 have the greatest C/N ratios, with a maximum value of approximately 68 for the 355 to 500 µm size fraction of Core 6. These elevated C/N values generally coincide with the maximum TOC and nitrogen values in the larger size fractions (Figs. 4 and 5), while the lowest C/N values have an approximate correlation with the minimum TOC and nitrogen values of cores 3 and 5 in the smaller size fractions. Cores 1, 2, and 4 lacked correlation between the TOC, nitrogen, and C/N values, although the same general trend can be observed.

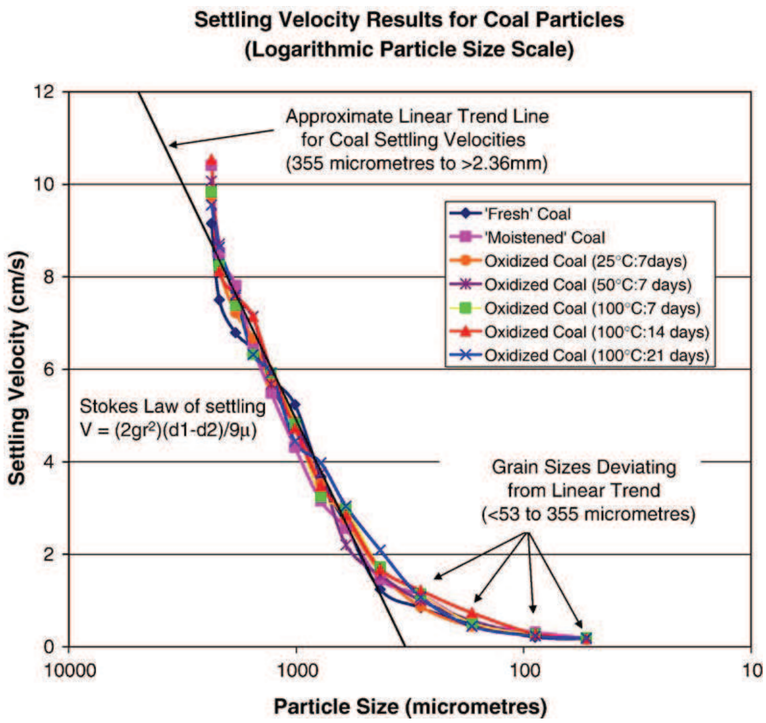

Fig. 7. Variation in coal particle settling velocity with particle size and degree of oxidation. For most particle sizes settling rates follow Stoke's Law.

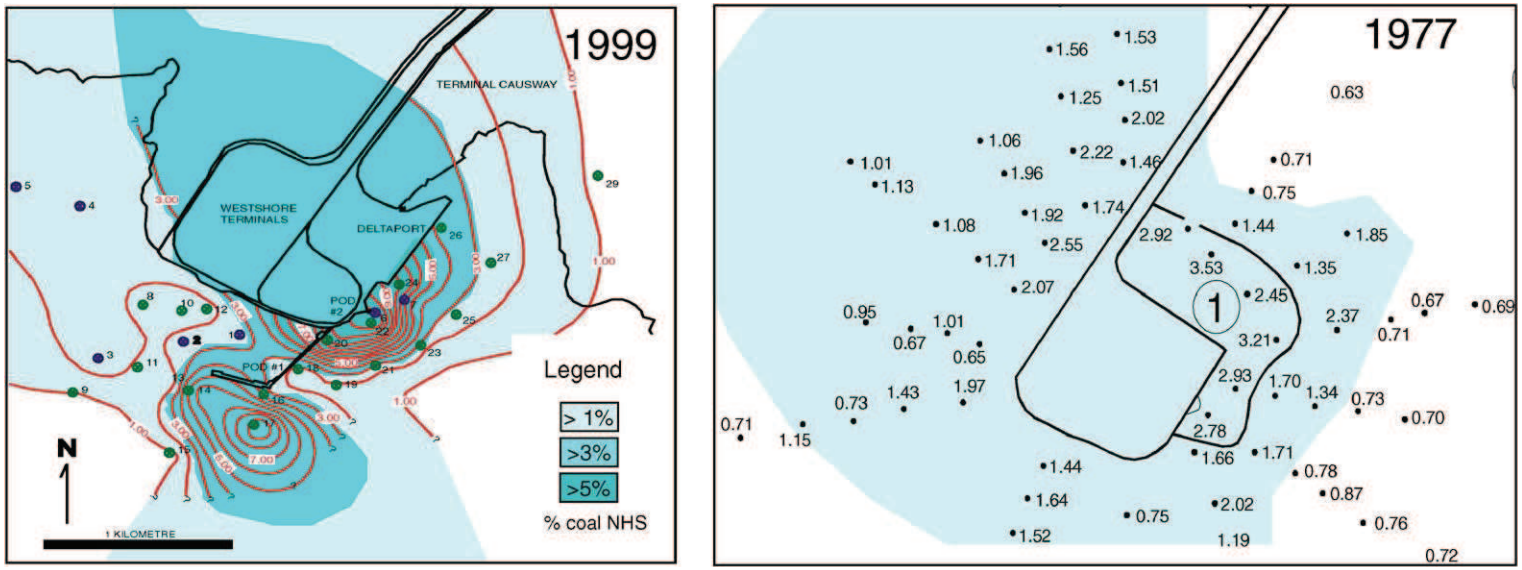

Fig. 8. Comparison of coal distribution (NHS) in 1977 and 1999 in the vicinity of the Terminal. Scale on each map is approximately the same. The aerial extent of the coal has changed little between 1977 and 1999 however the abundance of coal is markedly higher in surface sediments in 1999. The scale for both maps is the same.

5.4. Coal settling properties

The settling velocity results are presented in Figs. 7 and 8. The vast majority (>99%) of the five smallest samples (<53 μm) placed in open jars of quiescent seawater remained on the surface after a month; agglomerating into balls up to 1 cm in diameter. This agglomeration is likely the result of a weak electrostatic attraction between the fine coal particles as they also aggregate in a dry container, disintegrating only when shaken vigorously. The rest of the coal dust remained on the surface as a thin film, attesting to the hydrophobicity of the coal. The resistance to settling of the coal particles could also be due to surface tension, although one would expect this effect to be overcome when the particles were temporarily immersed in the water during vigorous shaking of the jars. Larger particles that did not settle, aggregated at the surface, even when initially separated by up to 5 cm. This attraction might be due to electrostatic forces and mutual repulsion from the water (hydrophobicity). The particles remained bound even after agitation and would settle at a greater velocity due to their combined radii.

The settling velocities of the different coal size fractions did not change significantly with oxidation, as illustrated by the similar trends in settling velocities in Fig. 7. Nonetheless, the settling velocities for the larger grain sizes (1.7 to >2.36 mm) increased slightly when the samples were moistened and exposed to various degrees of oxidation. The settling velocity for coal grains larger than 2.36 mm increased from a minimum of 9.15 cm/s ('fresh' coal) to 10.54 cm/s (100 °C: 14 days). However, exposure of the coal to 25, 50, and 100 °C oxidation conditions over the course of the experiment did not result in a consistent increase in settling velocity for the remaining grain size fractions.

As predicted by Stokes Law, the settling velocities decreased exponentially with decreasing particle size (diameter) for the majority of the grain sizes. The approximate linear trend line illustrated in Fig. 7 when the particle sizes are plotted on a logarithmic scale demonstrates this relationship. The smaller grain sizes (<53 to 355 μm) deviated from this trend, with a reduced rate of settling velocity increase with increasing particle size.

Although the settling velocities of the coal did not change significantly with oxidation, there was a consistent decrease in the size fraction where agitation was necessary. The least oxidized coal samples (based on time of exposure and confirmed by loss of caking ability) were found to have a greater proportion of particles that would float than those oxidized more thoroughly. Agitation was generally necessary for grain sizes smaller than 500 μm.

The specific gravities of the coal particles did not change dramatically under the various exposure conditions averaging 1.39±0.05 for all of the subgroups. However, the specific gravity did vary by as much as 0.10 within each group, attesting to the heterogeneity of the small coal samples.

6. Discussion and conclusion

An assessment of the benthic sediments adjacent to the Westshore Terminals coal terminal on Roberts Bank has shown that the concentrations of coal in the sediments (reported as NHS) has increased substantially since it was last investigated in 1977, having doubled from a concentration of 1.8% in 1975 to a mean concentration of 3.60% in 1999. NHS concentrations range from 0.65% in the 'background' samples 1.5 km away up to 11.90% in the immediate vicinity of the coal loading terminals. Since 1977 the main deposition of coal appears to have occurred in the vicinity of Pods #1 and 2 coal loading terminals, although limited samples were taken on the north side of the coal terminal causeway (Fig. 8). Coal concentrations in the sediments generally decrease rapidly with increasing distance from the terminal. Overall, the dispersal distance of coal has not increased over the 22-year period but rather the abundance of coal in the surface sediment within the dispersal area has increased.

The settling velocities of coal particles ranging from <53 to >2.36 mm did not change significantly with increased saturation and oxidation, although the saturated samples and those that were oxidized did settle faster in the largest size fraction (>2.36 mm). However, the proportion of buoyant coal particles decreased with increasing exposure to oxygen and temperature of heating throughout the range of coal size fractions examined, supposedly reflecting the decrease of coal hydrophobicity with increased oxidation.

Settling velocities for the coal particles in sea water analyzed in this experiment range from 0.16 to 10.54 cm/s for the <53 μm and >2.36 mm size fractions, respectively. These size fractions represent the majority of coal that could escape in the local winds (via deflation and saltation) during the loading processes and from the stockpiles themselves. Local winds average between 10–15 km/h throughout the year and attain speeds in excess of 60 km/h, especially during the winter months (Environment Canada, 1963–1990).

The regions around the coal terminal with the highest coal concentrations average depths between 5–20 m (Fig. 2). According to this experiment, the largest size