THE MANAGEMENT OF SAFETY OF WARSHIPS

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ABSTRACT

This article outlines the procedure set up by the Chief Naval Architect of the Ministry of Defence to ensure the safety in service of surface warships and submarines from deficiencies in design and maintenance. The philosophy for each aspect, such as fire resistance or structural strength, is outlined and the means by which it is monitored described. Safety Certificates are issued against documented evidence for which individuals are personally responsible. The Chief Naval Architect has the sole authority to issue or withdraw the Safety Certificates.

Background

The increasing delegation to industry of responsibility for the design and refit of warships has led to re-examination of safety standards and procedures within the Ministry of Defence. It is essential that safety requirements are clearly set out and that their achievement is monitored at all stages of the ship's life. In particular, it must be clear who is responsible for all aspects of inspection and approval.

The Controller of the Navy is the Design Authority for all warship procurement throughout the life of a ship. Project management of surface ships and submarines is directed by two Chief Executives whilst the Chief Naval Architect (CNA) is responsible for setting standards in naval architecture, materials technology and related subjects. CNA staff endorse their aspects of the design as technically valid at various stages and, in particular, they ensure that all relevant safety standards are met. On completion of the vessel a number of safety certificates are issued each of which has an expiry date by which time that aspect must be revalidated by a survey, inclining experiment or some other investigation. If at any time a modification is made which affects safety, a new certificate has to be issued.

It is suggested that the safety of a *warship* is philosophically more complex than that of a commercial vessel. Legislation exists covering most aspects of *merchant ship* safety and, if these provisions are strictly complied with, builder, owner and operator are deemed to have acted safely[1, 2]. The value of ship and cargo is insured and loss of the ship will not usually have a great effect on the shipowner, who can hire a replacement. Although safety rules exist for warships, they must be interpreted flexibly so that such vessels can carry out tasks that are inherently dangerous, for example night exercises without lights or radar. In the Royal Navy there are relatively few ships of any one type, individually very valuable and which would take many years to replace. In consequence, there is a far greater emphasis on preventing the loss of an asset, while merchant practice is less concerned with that and concentrates on minimizing loss of life.

The first part of this article discusses the general problem of acceptable risk as related to warships, together with possible causes of accidents. The latter part, from page 521 onwards, then considers some specific potential hazards in more detail.

Acceptable Risk

The acceptability of risk in all walks of life is not easily evaluated. Three types of risk management have been identified[3]—theoretically absolutely safe levels, best available technology levels, and levels derived from a balance between risks and benefits. Under the first come for example the use of food additives while the second would include the purity of drinking water. Engineering structures tend implicitly to come under the third category for the obvious reasons that the first is impossible and the second is too costly, even probably for nuclear installations which might originally have been treated as category two. However, the balance between risk and benefit is extremely difficult to set, especially if it involves putting a price on human life, and in practice the levels tend to evolve through accidents and the subsequent legal processes to statutory regulations (for example, the effects of the capsize of the *Herald of Free Enterprise*[4] or the King's Cross Underground fire).

In the case of warships it is even more difficult to set a standard. Losses, except due to enemy action, have been very infrequent in the R.N. since the earlier part of the century, and while it is possible to establish the cost of loss or damage to a ship it is not possible to define benefits numerically. Neither is it possible to balance loss of earnings against the cost of insurance since there are no earnings and warships are not insured. During the period 1945 to 1984 the accidents to H.M. ships listed in TABLE I were reported[5], including figures for losses as shown. In addition several ships amongst those listed have been so severely damaged that repair was uneconomic.

TABLE I—*Accidents to H.M. Ships—1945-1984*

	Total	*Losses*
Explosion	27	1 submarine
Fire	approx. 10/year	3 minesweepers
Collision	115*	1 submarine, 1 minesweeper
Grounding	50	
Flooding	1	1 submarine
Docking accident (storm)	2	1 frigate, 1 submarine

*Excluding 10 'Cod War' incidents.

In the event of a disaster, the success or otherwise of the design authority's activities is judged, first by a naval Board of Inquiry and then by Parliament, representing public opinion. The inquiries have sometimes led to calls for improving particular aspects of design but there has been no overall verdict that the standards of safety are too low. Safety measures can often be expensive and it is possible to spend far beyond the point of diminishing returns. The number of reported fires, structural cracks, abnormal rolls and other incidents which could have led to disaster suggest also that current standards are not too high. Such standards are regularly compared with those of other NATO countries and only slight differences are found.

The level of risk to personnel is another problem which has been difficult to standardize across industrial activities, but perhaps it is the commonly acceptable standards which can yield the best guidance to the ship designer. Here it is necessary to differentiate between 'accepted' and 'acceptable' risk[6]. The first is a level which may exist in a particular activity, frequently a voluntary one such as motor cycling or rock climbing, which is *accepted* by those undertaking the activity but which would not be *acceptable* to the majority of the population and in some cases to legislators. Acceptable risk is that which is reasonable to impose on a group of people who accept it involuntarily and usually have no choice if they wish to lead a normal life, and may not even be aware of it.

To the crews of warships the hazards of war are an accepted risk which they understand on joining and to some extent are paid for. However, the risks inherent in normal operation from, for example, the effects of weather and handling heavy machinery, may be construed in part as involuntary or at least be no worse than those run by personnel in similar walks of life. Consequently it is reasonable to look at the statistics of loss of life in a variety of activities and so to establish an appropriate region of risk level for warship design.

TABLE II—*Average annual accidental death rate per million at risk (1974–1978 except as stated)*

Activity		*Death Rate*
Vehicle manufacture		15
Chemical and allied industry		85
Shipbuilding and marine engineering		105
Construction industries		150
Coal mining		210
Mining (not coal)		750
Offshore oil and gas (1967–1976)		1650
Glider flying	(1970–1978)	400
Power boat racing	(.. ..)	800
Hang gliding	(.. ..)	1500

Note. No account is taken of the actual hours/year spent in the activity

TABLE II has been derived from a Royal Society Study Group report[6]. The figures are normalized to one million individuals at risk per year. In presenting and analysing risk statistics it is particularly important to make allowance for not only that subset of the population that is at risk, but also the proportion of time at which they are at risk. Much available data is imprecise in both these areas and the Royal Society report goes to particular pains to ensure that like is compared with like.

In U.K. merchant shipping the number of fatal accidents to crew members has been about 2 in 1000 annually of which about 3 in 10 000 are associated with the loss of a ship[7], that is 300 in one million for comparison with TABLE II. The remaining fatalities are mainly associated with operator error[8]. In heavy industry as a whole the fatal accident rate is about 100–300 per million at risk each year[9]. Consequently, any numerical definition of risk for personnel on warships should be expected to be of the same order.

It is not feasible in something as complex as a ship to start with a value of risk and work backwards to a safety factor. What is more, the majority of margins used in ship design are not expressed as probabilities and so the apparent risk cannot be readily derived. However, in recent years it has become the norm to define the extreme design load on a Royal Navy ship as that which has a 1% probability of exceedance in a ship's life, which is itself defined as 30 million wave encounters (at a mean period of 7–8 seconds). The extreme load is derived from measurements taken from ships at sea and extrapolated, using partial safety factors associated with assumptions on the statistical distribution of extremes, to the 1% probability design point[10]. The hull is designed so that its ultimate strength matches this load without any further margins, but assuming the worst case for parameters such as material properties and typical values for initial deformations and residual stresses.

However, by making some rather sweeping assumptions on the effect of the strength being exceeded (the ship is not necessarily lost), the number of men at risk and the likely fatalities amongst those men, it can be deduced that the level of risk is between about 100 and 500 on the scale of TABLE II. It is also not unreasonable to assume that other critical characteristics of warship design have similar safety levels insofar as they have all evolved together; intuitively, with the competing claims of reduced cost and greater personnel safety over the years, there must be a tendency towards design standards of fairly consistent safety levels. In very broad terms therefore it may be taken that current R.N. design standards lead to acceptable levels of safety equivalent to levels which are accepted in other comparable walks of life as indicated above.

Consequently, current effort is put into ensuring that designs meet the established standards, and, by applying a policy of regular in-service surveys, providing a level of knowledge of the material state of ships which is supported by documentary evidence and manifested in the form of 'Safety Certificates'.

All warships are exposed to risk from:

- fire,
- collision,
- structural failure,
- capsize,
- magazine explosion,

and, in addition, submarines have risks associated with:

- loss of control,
- flooding at depth.

Each of these risks is covered by appropriate safety certification and procedures, the form of which differs to suit the nature of the risk. Examples of two of these are given in FIGS. 1 and 2.

This article is mainly concerned with accidents but warships are designed to fight, withstanding damage as well as inflicting it. The resistance to damage expected in war in many, but not all, cases ensures a high degree of resistance to peacetime incidents. For example, the extent of flooding caused by a torpedo is far greater than that associated with most collisions.

Routes to Disaster

Disasters arise from failures in the fields of design, construction or operation; sometimes through a gross error in one field, more often from a combination of errors in more than one field. Common failures and some examples are given in the following paragraphs.

Design

Errors will come under one of the following descriptions:

(*a*) The designer has produced a very refined design with low safety margins.

(*b*) The designer has not allowed for the actual operating environment or life cycle.
(*c*) The designer has not understood all possible modes of failure or has extrapolated existing knowledge unwisely.
(*d*) The designer decides not to incorporate extant safety measures for financial or other reasons. This can often occur when safety standards are improved retrospectively.

CERTIFICATE OF SAFETY - STRUCTURAL STRENGTH

HMS ....

VALID UNTIL 12 September 1990

1. The structural strength of the above vessel is adequate to meet operational requirements without danger to the safety of the vessel or to personnel on board, except as noted below.

2. A margin of safety to allow for normal degradation of structure is included. Any abnormal change or defect should be notified immediately to the Operating Authority and MoD(PE).

3. The most recent structural survey reports are:

D171 dated 12 September 1987

signed

CHIEF NAVAL ARCHITECT

Notes

1. The cracking of the superstructure front reported in the survey documentation is likely to re-occur. Ship's Staff are to monitor the area carefully and report any such cracks to CinC Fleet (FNCO2) and MoD(PE).

2. Extensive corrosion of the transom plating and structure is noted. As a result, full astern power is only to be used in an emergency and high astern speeds are to be avoided. The area is to be inspected daily when seas are below sea state 3 and hourly above sea state 3 for any further degradation or cracking.

3. OPDEF ME 20/86 has not been repaired in accordance with A&A 20-21. The repair carried out is not the approved procedure and is to be replaced by insert at the earliest opportunity.

FIG. 1—STRUCTURAL STRENGTH CERTIFICATE

HMS ....

STATEMENT OF STABILITY

Based on Inclining Experiment conducted on HMS .... on 21 August 19..

	DEEP CONDITION	LIGHT SEAGOING CONDITION	LIGHT HARBOUR CONDITION
Mean Draught	7.88 ft.	7.01 ft.	6.98 ft.
Metacentric Height	2.17 ft.	2.20 ft.	2.14 ft.
Angle at which ship reaches her maximum righting moment and beyond which the righting moment diminishes.	45°	38°	37°

NOTES

1. The conditions are defined on the back of this form.
2. The mean draught is the mean of the draughts at the forward and after marks.
3. The ship is assumed to be undamaged with all external openings closed.

LIQUID LOADING RESTRICTIONS

a. The ship must never be brought below the Light Seagoing Condition except when in harbour, ie. when at sea a minimum of 15 tons of Dieso must be retained in tank H3.

b. When docking in the Light Harbour Condition, the trim should be reduced to normal limits.

c. The number of slack tanks should be kept to a minimum.

signed

CHIEF NAVAL ARCHITECT

DEFINITION OF CONDITIONS

The conditions for which stability information is given overleaf and on the accompanying curves of statical stability assume the ship fully equipped and with consumable items in the state tabulated below.

ITEM	DEEP CONDITION %	LIGHT SEAGOING CONDITION %	LIGHT HARBOUR CONDITION %
Main Fuel Tanks	95	15 tons in H3	0
Fuel Service Tanks	Normal Working Level		
LO Storage Tanks	95	95	95
LO Drain Tanks	0	0	0
Fresh Water Tanks	95	0	0
Naval Stores and Spare Gear	100	50	50
Provisions	100	0	0
Ammunition	100	0	0
Misc. Minor Tanks and Systems	Normal Working Level		

The stability of these ships rapidly becomes unacceptable when ice forms and they should not be employed in areas where icing is likely. Should they be caught unexpectedly in icing conditions, as many tanks as possible are to be pressed full and every effort made to remove the ice as quickly as possible.

FIG. 2—STABILITY STATEMENT (FRONT AND BACK)

Some of these design failure modes are obvious but others are not. The safety margin against buckling of stiffened panels is diminished by manufacturing distortions, particularly if the stiffeners are small in relation to the plating thickness. Changes in design, after the original design staff have moved, are a particular hazard; the new designer will often not fully understand the design philosophy and may make changes without fully understanding their implications. Last minute attempts at weight saving may also lead to structural weakness.

Calculation errors must be accepted as inevitable. In days gone by, this was recognized and vital calculations were carried out by two calculators, working independently. Comparison between their calculations made errors fairly easy to detect. The use of computers should prevent arithmetical errors, but wrong assumptions, incorrect data input and undetected errors in big programs are still fruitful sources of error. It is much more difficult for senior staff to spot errors in a print-out than in a work book and the increasing tendency for such officers to see themselves as managers rather than designers increases the risk. In fact with their experience and 'feel' for a design it is more important than ever that they look over the numerical results of a calculation and ask pertinent questions, although it has to be said that even design managers' experience in the details of design is now diminishing.

Construction

Construction errors will be included in the following headings:

(*a*) The builder has not understood the standards of construction intended or expected by the designer.

(*b*) Such standards are impossible to achieve.

(*c*) The quality control exercised by the builder was inadequate.

Details are particularly important in structures required to resist explosion: asymmetric sections and joints are to be avoided and malalignment is an even more serious fault. Too often, such features have been introduced to save a little on the cost. It is also difficult to limit the use of wood and other flammable materials to the extent intended by designers. They are such convenient materials for builders and operators to use that their extent is hard to control. It has not yet been demonstrated that quality control methods are as effective as rigorous inspection by customers' representatives.

Operation

Faults during operation will be included in the following:

(*a*) The operational conditions are different from the designer's assumptions.

(*b*) The design life has been exceeded.

(*c*) The operators or maintainers are not fully aware of the implications of the designer's assumptions, or are negligent.

There are many cases in which new operational tasks and new equipment force a ship to be used in ways for which she was not designed. The use of towed sonar arrays forces ships to stay on a steady course and speed regardless of sea conditions. Measurements show that this can lead to a significant reduction in fatigue life. The significance of overloading or of failure to ballast when required is all too often not appreciated. The crew's very reasonable wish to make their living quarters more comfortable brings too much flammable material into ships as well as adding top weight.

Risk Assessment

Failure in any one of the aspects in the above three paragraphs can cause an accident but for a disaster to occur it is usually necessary for serious faults to be present in more than one area simultaneously. For example, in one recent case a frigate came close to structural collapse due to some minor design faults combined with poor inspection and bad maintenance but disaster was averted because the operators realized that a dangerous condition was present and took the correct measures.

Techniques of risk assessment involve assigning probabilities to all the above contingencies and if a high probability exists in one area outside the control of the authorities then every effort is made to reduce the probabilities in other areas so as to minimize the total risk. Thus risk management consists of the following general actions:

(*a*) Identification and assessment of the risk.

(*b*) Establishment of the acceptability of the risk.

(*c*) Decisions on the control of the risk.

TABLE III—*Merchant ship losses (no. of vessels)—1978–1986*[11]

	1978	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*
Foundered	169	164	152	120	142	127	131	108	99
Missing	9	4	8	10	3	1	4	2	7
Fire/explosion	85	83	55	67	79	58	57	48	47
Collision	56	47	39	41	32	35	35	35	21
Wrecked, etc.*	144	153	127	110	114	99	76	84	56
Lost†	10	14	6	11	32	20	24	30	35
Total	473	465	387	359	402	340	327	307	265

*includes stranding and collision with fixed objects (contact).
†includes war losses.

Risk identification and assessment is usually based on experience from accidents, failures or near failures of components or complete systems. Mathematical risk analysis is available but has been little used to date in the maritime field due to lack of suitable data in a usable form. Data banks of accidents in the merchant ship field are maintained by various authorities in the U.K. in particular the Department of Transport and Lloyds Register of Shipping[11] from which the examples in TABLE III have been extracted. Few accidents can be investigated because evidence is commonly not available, and, even when it is, only those accidents resulting in significant loss of life or cost to the community, for example with pollution, are investigated in depth. Frequently for total losses of ships distant from land the cause of loss can only be conjectured. Fortunately, incidents in warships are rare but even so evidence on accidents is kept by CNA for use in design assessment.

Beyond the gathering of risk statistics the use of numerical risk assessment is gaining acceptance to an increasing degree especially in the offshore industry. It is often the only solution to the management of safety for novel designs or structures where no precedent exists, such as tension leg platforms. In the merchant ship field, risk analyses have only been applied to the transport of hazardous cargoes such as liquid natural gas (LNG)[12]. The technique has been used in the Navy to establish the risk to divers' lives in the novel diving system in H.M.S. *Challenger* as well as to establish the safety level of nuclear installations. Numerical risk assessment is also increasingly being used in the design of critical submarine systems.

Mathematical risk prediction involves assessing all modes of failure and analysing each to find the probability of its occurrence. Where failure modes are independent this is relatively straightforward although very time consuming. Also some of the data input must inevitably be of doubtful accuracy when there are few real failures against which to check the estimates. In the case of warships with many possible failure modes in many systems and with many of the modes interdependent, the analysis is not only time consuming and expensive but extremely complex and costly in resources, and of doubtful validity. It can only be justified where there is a clear need for a numerical risk assessment as an alternative to engineering judgement, for example for nuclear safety, and even then the final answer can only be comparative, depending as it does on a number of subjective assessments of component reliabilities and system failure dependencies.

In practice, however, where probability limits are set it is almost always to ensure a design that is no less reliable than that produced from existing deterministic design procedures, so that although there may be consistency within a particular engineering field there is unlikely to be any global consistency. In addition, it is not realistic to talk about an acceptable probability of failure without considering at the same time the concomitant benefits and costs. Taken to its logical conclusion, emphasis on safety without thought to consequent costs would lead to the impossible requirement of zero risk. It is obviously undesirable to attempt to reduce an already small risk by pouring in talent and resources when there are other major problems requiring attention.

For warships the aim must be to maintain adequate safety whilst minimizing cost. The current numerical level of safety is not certain, but it has been deduced from minor failures on frigates that the probability of disastrous structural failure in one ship life as defined above is equivalent to about one in 1000 in one ship year. In addition, there is a considerable, but unquantifiable, margin of safety concealed within the definition of 'effective structure' used in strength analysis. The safety level is consistent with that required by the Civil Aviation Authority for the probability of loss of a civil airliner of not more than one in 1000 in a year's operation. Further, as no British warship has been lost due to such a design failing since the loss of the *Cobra* in 1901[13, 14], the risk of loss may be seen as satisfactorily low. On the other hand, there are too many examples of serious cracking for complacency.

Ideally the user might demand that the designer should allow for all possible malpractices in construction and all likely modes of maloperation. In other words, it would then not matter what happens during construction and service, the ship would remain safe. Unfortunately, even if this were theoretically possible, which is doubtful, it would be totally uneconomic to achieve such a design. It follows, therefore, that the shipbuilder and the operator must take their share in the achievement and maintenance of a safe ship. This subject is discussed in the context of merchant ships by Meek *et al.*[1].

The designer starts with the knowledge of the level of quality control that the shipbuilder should apply, for example in the assembly of structural details, and then allows a small safety margin for uncertainties mainly for the analysis of such details. It is assumed that the quality is assured and it is clearly of prime importance that the overseers and shipbuilder achieve the expected quality, or one of the three safety areas is lost straightaway. Submarine quality control is set at a higher level than for surface ships and is applied rigorously to all systems that are known as 'first level systems', whose failure could lead to disaster. There are normally no such systems in a surface warship and a slightly less demanding standard of quality assurance is acceptable.

Perhaps more importantly, the designer starts with assumptions about the environment the ship is likely to encounter in her life, what that life is and how much of the life is spent at sea. Here there is a traditional standard of a 20 year life, 33% of which is spent at sea, with North Atlantic weather conditions sufficing as an ill-defined average environment. More margin will be allowed than for construction as there is clearly a greater level of uncertainty, but it is essential that if Naval Staff expect a greater proportion of life to be spent at sea or a longer—or indeed shorter—life then the designer must know at an early stage. If a shorter life is quoted the designer has to look ahead and decide whether he really believes a ship will be taken out of service in, say, 15 years or will circumstances be such that when the nominal end of life is reached the ship will be required to run on. At the design stage, the cost of building in a few extra years of life is likely to be very small, but maintaining a shorter life ship beyond her design age can be very costly.

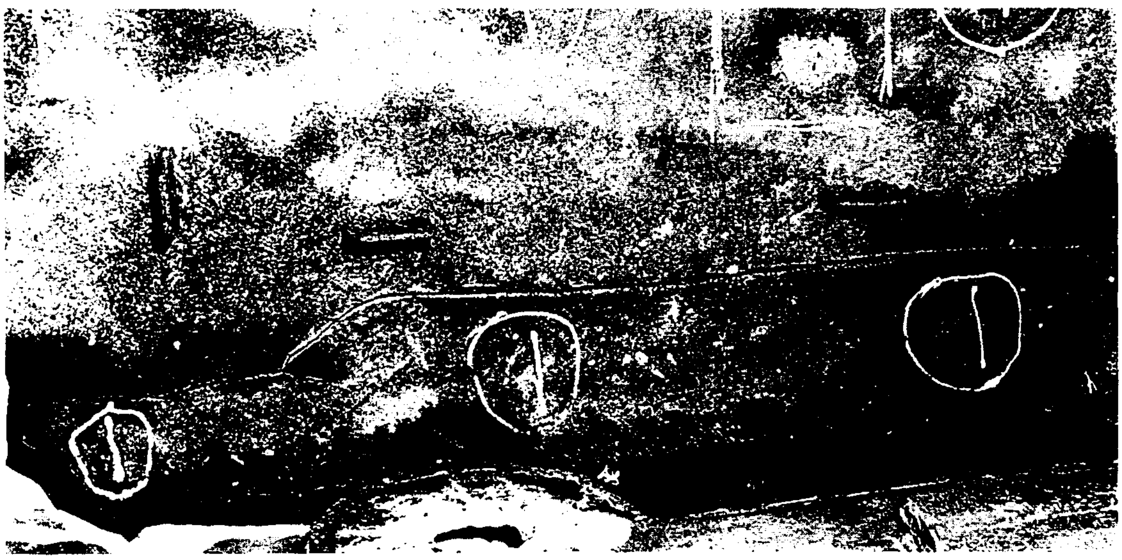

FIG. 3—FATIGUE CRACK IN DECK

Older frigates, some of which are well over 20 years old, show what can happen when insufficient attention is paid to the importance of the age of ships and to the maintenance of the knowledge of ships' material state. One such ship nearly suffered a disaster when a crack ran across her upper deck during an exercise in the North Atlantic in late 1982. The ensuing Board of Inquiry found that the ship had never been refitted in the same place twice and that there had been no continuity of repair action or of feedback to the design authorities. It was also likely that due to the age of the ships a class problem existed as the defects were due to fatigue and corrosion; this was indeed found to be the case. FIGS. 3 and 4 illustrate some typical defects found. It is failures of this sort, resulting in significant loss of strength, that the structural safety certification procedure is designed to protect against.

It is therefore important that the operator understands the limitations under which the ship was designed. It is also important that the operator and maintainer have enough understanding of the significance of defects that occur, to distinguish between those which might be expected at that time in a ship's life and which have been allowed for in design, and those which are unexpected and may be jeopardizing safety. The safety certificate (FIG. 1) will draw attention to any known ship and class defects such as areas where fatigue cracking is likely to initiate.

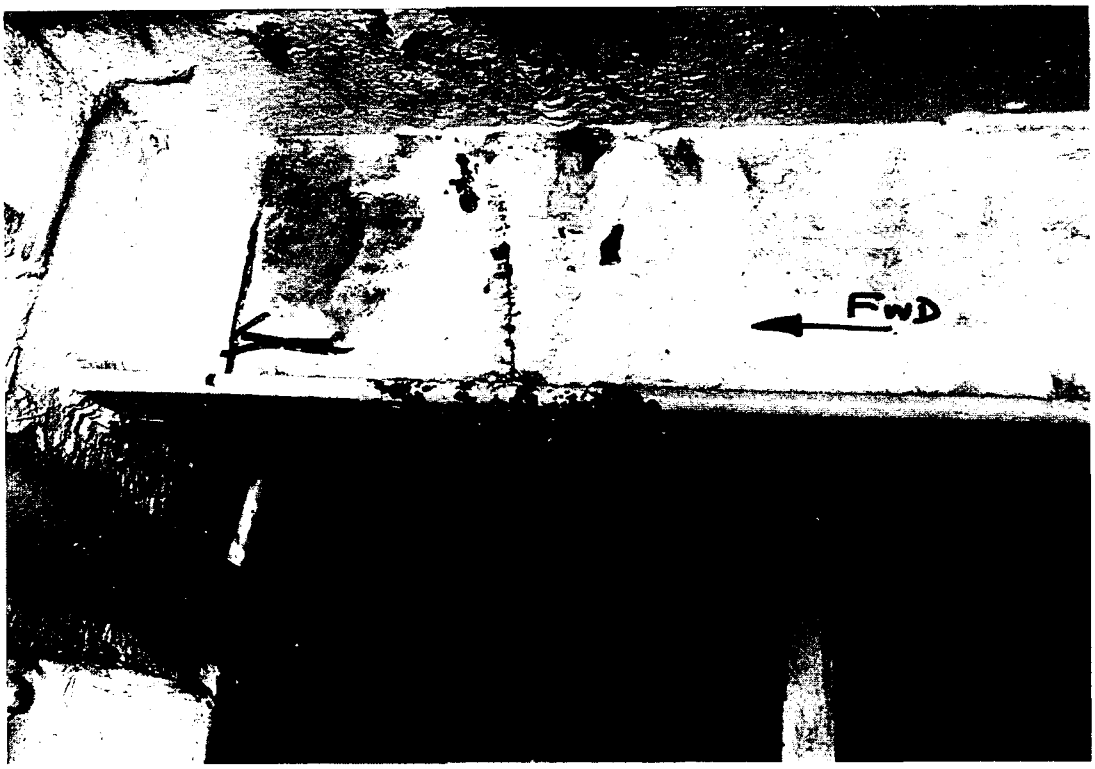

FIG. 4—FATIGUE CRACK IN STIFFENER

It is essential, therefore, that a thorough knowledge of the material state of each ship is maintained at all times if hazards to safety are to be minimized. Surveys must be mandatory and not undertaken only when convenient and of easily accessible areas. Reporting of defects both by ship's staff and by dockyard must be timely and if there is any doubt as to significance of a defect the design authority must be informed immediately. In recent years this feedback has been satisfactorily achieved, and all concerned now have a far clearer understanding of the material state of the naval architecture of the Fleet than previously.

Surface Ship Stability and Capsize

The last British warship to capsize in peacetime was the battleship *Captain* in 1871[15]. This led to the requirement for all new ships to be inclined and for the results to be issued formally to the commanding officer as a 'Stability Statement' (FIG. 2) listing metacentric heights over a range of displacements (with GZ curves attached) and setting out any restrictions on the use of fuel. The acceptability of the stability parameters was judged by senior officers of Naval Construction Department on the basis of personal experience which, with a big navy and frequent new designs was satisfactory, as demonstrated in two World Wars.

In 1944 the U.S.N. lost four destroyers from capsize in bad weather and the investigations into their loss led to the stability criteria of Sarchin and Goldberg[16] which, with modifications, have been adopted by the R.N. and some other NATO navies. It was necessary for the R.N. to adopt more formal standards because the reducing size of the navy and consequently fewer designs had diminished the level of experience available, and because standards were needed as part of the contract for ships designed by industry. Differences between present MOD standards and those of Sarchin and Goldberg lie mainly in the MOD requiring more area under the GZ curve at small angles.

Three of the four U.S. destroyers were lost in the great typhoon of December 1944[17, 18] and their capsize was due to the combined effect of a large steady heel caused by a beam wind and heavy rolling in beam seas. Comparison of the GZ curves of the ships lost with those of ships which survived gives strong support to the use of an energy balance, quasi-static, approach for this capsize mode.

Resonant rolling in head seas is not seen as a credible capsize mode for warships with good initial stability and freeboard. As with all ships, stability is much reduced when a frigate is balanced on the crest of a wave moving from astern at the same speed of the ship but both calculations and experience indicate that this mode, too, is not a serious hazard. Broaching which leads to a large half roll is not well understood. Warships are sometimes constrained by operational considerations to continue on a course at a speed which seamen know to be unwise and broaches are not uncommon. Some reassurance is obtained from the number of events which have occurred without disaster but the severity of the angles adopted justify current work in hand to study broaching.

In many modes, it is clear that damping, by bilge keels, contributes to safe operation and efforts are being made to define a suitable criterion. It seems that the roll criterion proposed by Monk[19], based on crew effectiveness, is of the right order for safety against capsize.

During the design phase the height of the metacentre and the large angle righting levers can be calculated with precision, and errors are rare. Control of weight and the height of the centre of gravity is more difficult. Almost always weights of novel equipments are underestimated or heavier equipments are fitted than those originally envisaged. Additionally, the changing threat will often lead to pressure for additional military equipment. Strict discipline in design and weight control, based on weighing during build, are essential but the wise designer will still include a margin on weight and KG in his original estimates. The rigorous cost limits on recent ships have helped considerably to control such growth. The use of flared hull forms provides a most valuable protection against the problems of growth in service. It is usual to re-incline representative ships of a class after 10 years in service and the initial stability statement is valid for this period using an estimated rate of weight growth (0.5% per year of displacement) and rise of KG (0.3% per year of KG).

Warships are required to retain a substantial amount of stability (defined as area under the GZ curve) after flooding from damage extending over 21 metres or 15% of the length whichever is the greater. This amounts to a 3–4 compartment standard with a typical layout and is often more demanding than the intact criteria. In addition, bulkheads are unpierced below the intact waterline except for fuel lines: watertight doors rarely remain watertight after damage.

The whole subject of stability and capsize has been treated in more detail in this *Journal* a few years ago[20].

Structural Strength of Surface Ships

The design of the hull to withstand wave loading is based on a specified probability of ultimate strength being exceeded within an agreed ship life, measured in wave encounters[10]. Additionally there are a number of other criteria, for example transverse hull strength and main transverse bulkhead strength, which, either from lack of statistical data or because the loading is deterministic, are based on acceptable stresses or deflections. All these criteria are laid down by CNA.

The criteria themselves are mainly based on historical data, strain measurements from ships at sea, and from the practical knowledge gained from structural failures—or lack of them. There is therefore a moving and developing data base, and acquisition of new knowledge or modification to operating parameters, for example the way in which ships operate while towing arrays, often lead to minor adjustments to standards. It is however important that step changes are avoided or it will be difficult to compare the response of ships designed after the change with that of earlier vessels, and so evolution and indeed reliable use of the design criteria will be disrupted.

The structure of the ship is then designed, usually now by contractors, to meet the criteria laid down and it is the responsibility of the design authority, that is the MOD ship project, to provide assurance to CNA that the criteria are met. While the end of the process requires CNA's signature on an endorsement document, the work leading up to that point involves much interaction between CNA and project personnel for interpretation of standards, agreement on aspects that need specific analytical checks and occasionally check calculations by CNA staff in the nature of an audit.

It is the responsibility of the shipbuilders' quality assurance staff, audited by the local Naval Overseer working with the ship project, to ensure that the structure is built in accordance with drawings and specifications. CNA will be involved from time to time if a change to the design is needed, or a concession has to be granted to cover a constructional error. It is the ship project's responsibility to draw CNA's attention to any such changes or concessions.

On completion, a ship will be given a final build survey by the Naval Overseer, and on the basis of that survey and in the knowledge of any changes or concessions agreed during build, CNA will issue the ship with a structural safety certificate. This certificate will have an expiry date, generally 3 to 4 years ahead, when a further survey will be required before re-certification is granted. Survey intervals are matched to docking and repair intervals but a full hull survey can only be undertaken during refit, currently at about every 6 years for modern warships. Surveys at intermediate dockings are inevitably limited in scope and are restricted to known ship and class risk areas which include, as ships get older, regions of fatigue cracking and corrosion, which can lead to an increasing risk of fast fracture especially if steel with no specified toughness standard is used[21]. These in-service surveys are carried out by Commander-in-Chief Fleet technical staff initially, backed up by contractors' staff when the ship is taken in hand for maintenance or refit. It is primarily from the reports of these surveys that CNA re-issues the Structural Safety Certificate for a further period.

Towards the end of a ship's life structural deterioration will accelerate, for example see FIGS. 3 and 4, and it is sometimes necessary for a safety certificate to include recommended operational restrictions in terms of maximum speed, sea state or sea area. In these cases local surveys of the critical suspect areas will usually be undertaken by CNA staff. It may even be necessary to refuse a safety certificate and to propose that a ship be taken out of service and either retired or extensively replated. The final decision however lies with the C-in-C Fleet and must depend on operational requirements, although it would need very strong reasons to for him to run the risk of operating a ship when CNA has reservations about the strength.

Fire

Safety against fire requires a multi-stage procedure which will include the aspects considered below. However, because of the complexity of the subject, no single fire safety certificate has been produced but all aspects are documented.

Fire Resistant Materials

A 4000 tonne frigate will carry about 700 tonnes of fuel, 45 tonnes of ammunition and some 100 tonnes of other flammable materials. The safety of fuel depends on secure stowage, low in the ship where it is least likely to be ignited by enemy attack and where it is more easily extinguished by a foam blanket.

Other flammable materials can be divided into:

- those designed and built into the ship;
- furniture and fittings;
- stores, paper and books (including packing cases, etc.);
- personal effects;
- unofficial improvements.

The first of these groups includes linings, deck coverings, thermal and electrical insulation, and paint. In many cases, superficial area of flammable material is a better measure of risk than is weight, and tests take account of this. All materials built into the ship are tested for flammability and smoke generation and those that are most satisfactory are selected. There is an inherent conflict between 'easy-clean' surfaces and fire resistance and some compromise is necessary. The decision should be, and is, heavily biased towards safety.

Furniture and fittings have changed in recent years and now have only a very small proportion of hazardous materials and that well protected. Stores, books and paper and similar substances are kept to what is seen as a necessary minimum but the paper war is not easy to win. Personal effects and 'do-it-yourself' improvements are not easy to control since the sailor is proud of his home and likes to improve it. Greater awareness of the hazards of introducing flammable sleeping bags, carpets and other furnishings is spreading, albeit slowly.

Zoning

More recent ships are divided into four or five independent zones, with separate ventilation systems, fire pumps and other systems to contain the fires.

Firefighting

The crew of a frigate is numerous and well trained and exercised in fire fighting. Systems and equipment are frequently updated; in particular, since the Falklands war, great improvements have been made in locating fires (thermal imaging cameras), and in communication (internal radio). New fire suppression techniques have been tried with encouraging results. Smoke extraction fans are fitted to remove smoke once the fire is out, and evacuation routes are planned and marked.

Magazine Safety

The safety of ship's magazines from accidental explosion rests on a two stage assessment undertaken by the Magazine Safety Committees. The ordnance inspectorate must first show that the weapon is intrinsically safe; that it may be moved, even dropped, subjected to heat and fire, and to radiation, and will not readily burn. It should also be resistant to bullet and splinter impact.

Consideration is then given to the magazine and the juxtaposition of one weapon with another and the likely levels of electronic emission and other radiation, together with their effects on the explosive, ignition and guidance systems. Should a missile motor ignite—an almost incredible accident in peacetime—the venting must be adequate to prevent the ignition of the remaining contents.

Submarine Safety

Structural Integrity

The safety of the main hull structure is, philosophically at least, a simpler problem than that of surface ships since the loading is determinate. Margins are small and structural imperfections such as 'out of circularity' and rolling tolerances are more important. Fatigue life will be an important design criteria, limiting the use of high strength steels. Regular and extensive non-destructive examination is essential.

Hull Penetrations

A nuclear submarine has quite a large number of holes in the pressure hull for torpedo tubes, cooling water, waste disposal and other systems. Smaller openings are closed by hull valves usually of a copper-based alloy, such as nickel aluminium bronze, but larger openings such as for hatches are invariably of steel. These can deteriorate due to problems such as crevice corrosion and inspection is necessary at dockings.

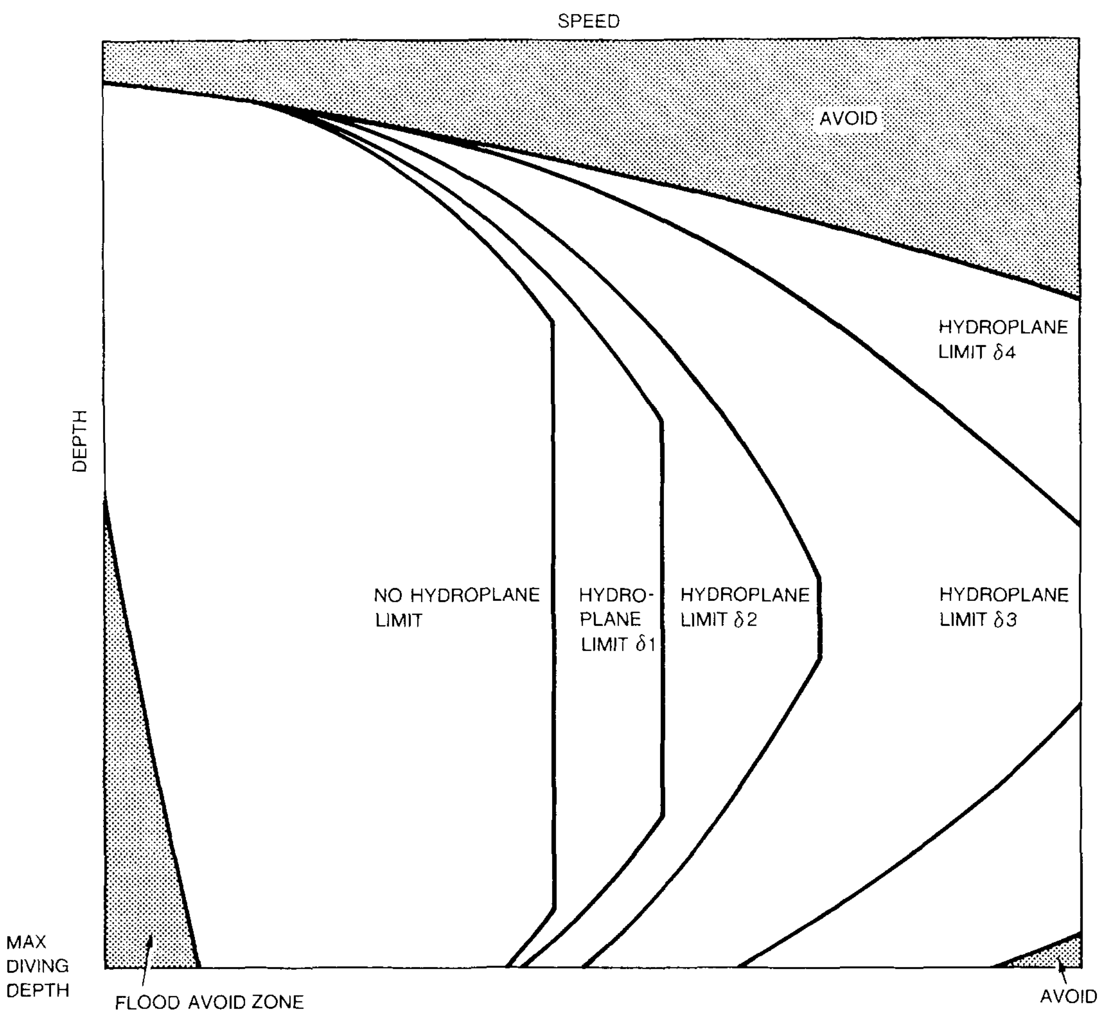

FIG. 5—TYPICAL MANOEUVRING LIMITATION DIAGRAM FOR A SUBMARINE
δ values indicate maximum hydroplane angles

Manoeuvring

A submarine at speed can change depth very rapidly. Accidental depth excursions can be caused by hydroplane jam, system malfunctions or human error. The chances of an accident are reduced by design, checked by fault tree analysis, but the possibility of a depth overshoot cannot be excluded and is allowed for in safety margins.

Depth Control

A manoeuvring limitation diagram (MLD), for example FIG. 5, is produced showing safe speeds at various depths. Too slow a speed makes surfacing from a flooding accident difficult, too fast will cause unacceptable depth changes. Below the design diving depth (DDD) there is a margin which allows for overshoot whilst keeping the submarine above the minimum collapse depth (MCD). The MCD assume all parameters at their worst permitted tolerance (rolling, circularity, etc.) and includes a factor of safety for unavoidable lack of precision in calculation (but *not* for errors).

Conclusions and Safety Plan

The foregoing discussion establishes that the standard of structural safety of surface warships is roughly consistent with the level of safety which is acceptable in equivalent industrial and transport fields, and the broad assumption is made that parallel evolutionary design leads to other areas having an acceptable, but not too high, safety standard.

By laying down standards based in part on theory, but mainly as a result of experience of hazards and accidents, and from historical evidence, CNA has a basis against which to judge new designs. These designs are monitored informally by CNA staff to a plan known as the Safety Plan which is based on the design programme prepared by the ship project, and formally at prescribed intervals by CNA himself, leading to a signed 'design endorsement' stating that all relevant safety (and other) standards have been met or deficiencies accepted. Departures from safety standards can be agreed only by CNA professional staff and are recorded by a concession procedure.

For ships in service, safety documentation requires formal signature at senior level in both the project and CNA, and supporting documents have formal signatures by officers at a number of lower levels, making individuals personally responsible for their statements. The safety certificates, which are held by the ship and the headquarters project group as well as by CNA, have expiry dates and must be renewed. Renewal depends on an appropriate survey or test, for example an inclining experiment, carried out by an engineer appropriately qualified and experienced. If CNA is not satisfied that the ship is adequately safe he can recommend operational restrictions and in an extreme case he has the right of access to the Controller of the Navy.

No system can be perfect but it is believed that the process described gives a reasonable, pragmatic guarantee of warship safety, without leading to unjustifiable cost penalties. CNA is however pursuing more detailed numerical studies into structural safety with the intention of extending them to other areas when adequate experience is gained.

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