FUTURE ASW FRIGATE

CONCEPT STUDY
OF
A TRIMARAN VARIANT

BY

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This is an edited version of a paper describing work carried out by Mr SUMMERS *while on exchange in DFP(N) in 1993–94, and presented by the authors at IMDEX 95.*

ABSTRACT

The Director Future Projects (Naval) has carried out a design study into the applicability of the trimaran hullform as a contender for the Future Escort. This article:

- Presents a summary of the study.
- Discusses the potential benefits of the trimaran.
- Suggests that a cost saving of some 10% Unit Production Cost is possible, with no loss of capability as compared with the equivalent monohull.

The construction of a reduced size, but fully sea-going, demonstrator and the setting up of a research programme to verify the concept further, are recommended.

Introduction

As part of ongoing concept studies for future warships, the Director Future Projects (Naval) (DFP(N)) has been investigating potential designs for future frigates. These studies are aimed generically at a Future Escort (FE) and will eventually include the following designs:

- Monohull.
- Small Waterplane Area Twin Hull (SWATH).
- Trimaran.

This article describes the design of a trimaran option. The main purpose of these studies is to develop potential design solutions to perceived requirements, to have these costed and to investigate the cost effectiveness of trade-offs within the design. This information is then used to inform the creation of a staff target submission, which leads into setting up the procurement project.

These studies will also help DFP(N) to assess the relative merits of new technologies, alternative designs and unconventional hull forms. A reference design will be chosen to form a baseline to investigate the impact of research to either reduce cost or increase performance.

The studies are aimed towards a highly capable warship, optimized for the Anti-Submarine Warfare (ASW) role, with some self protection anti-aircraft features. It will carry a large towed variable depth sonar, helicopter and have a very quiet propulsion system. Its armament will be a mix of existing and new development. Commonality with equipment for the Common New Generation Frigate (CNGF) will be as great as possible. A reduced manning level policy will be followed, with maximum maintenance being carried out ashore. Table 1 lists the initial broad assumptions about the design characteristics and constraints.

TABLE 1—*Design requirements*

Broad characteristics and assumptions

Displacement	4,000–7,000 te.
Length	110 m +
Endurance	45 days at 15 knots
Top speed	27–30 knots
Seakeeping	Sea State 6 +

Weapon fit, taken from:

Hull mounted sonar (2050)
Towed Array (2057)
Low Frequency Active Variable Depth Sonar (LFAVDS)
Magazine Torpedo Launch System (MTLS) with
 Stingray/Advanced Lightweight Torpedo (ALWT)
Surface Ship Torpedo Defence (SSTD)
Very Short Range Air Defence (VSRAD)
32 Vertical Launch Seawolf (VLSW)
8 Surface to Surface Guided Weapons (SSGW) (Harpoon or similar)
Medium calibre gun
Small guns
1 x Merlin
'T23 like' command system
Seagnat
Surveillance radar
IFF
1007 navigation radar
Link 11,14,16
SCOT SATCOM
Radar/Comms Electronic Support Measures (RESM/CESM)

These studies are at present purely conceptual and are not related to a specific procurement programme. Naturally they will provide background information for more specific studies should they be undertaken, but should not be taken as indicating the nature of any potential staff requirement.

Background and scope

The trimaran concept for warships has grown out of work started by Professor D.R. Pattison then at University College London (UCL), where it has been pursued through several student design and research projects.

This article is intended to be more than a description of the design. It will include information about trimaran hull forms in general and will try to consolidate some of the work done at UCL on trimarans over the last several years. In addition it will propose ideas for further study in numerous areas, based on the authors' experience and having thought about trimaran designs for close to a year. The article details what was done and why, and proposes why the trimaran form has important advantages that merits its serious consideration for a FE.

Three primary factors are considered to have a significant influence on the next surface combat design:

- Cost.
- Survivability.
- Stealth.

The trimaran offers advantages over a monohull in:

- Speed.
- Seakeeping.
- Arrangements.

- Combat system layout etc.

But none of these is significant enough to overcome the simplicity and comfortable feeling of a monohull design. The areas that offer the significant advances, to make the choice of the trimaran hull form are:

- Survivability.
- Stealth.

Cost too is less than that of a monohull, as its configuration allows a greatly simplified propulsion and electric system. These benefits will be developed in this article. (FIG. 1) shows an artist's impression of a trimaran frigate.

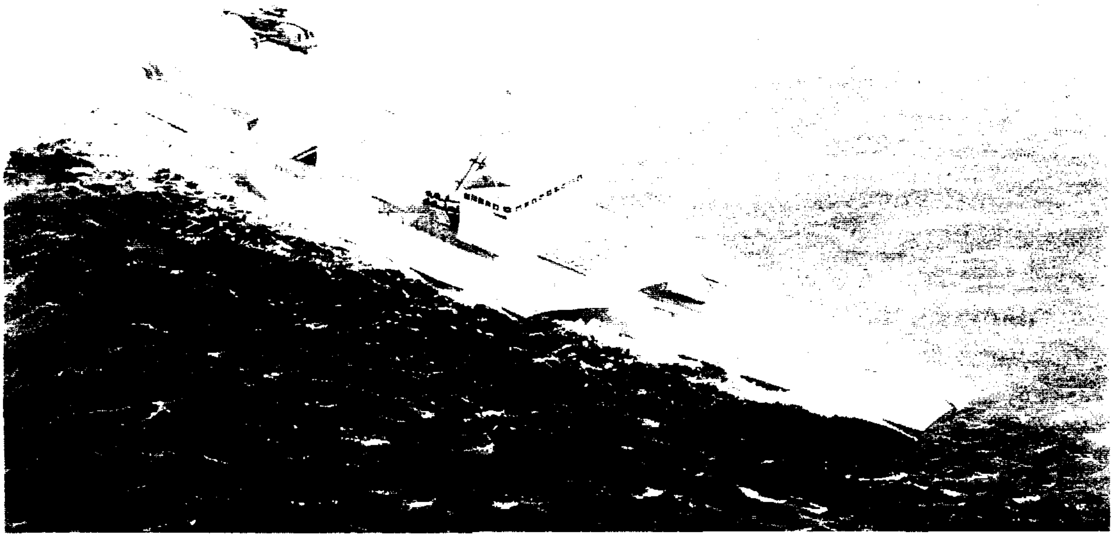


FIG. 1—TRIMARAN FRIGATE

ADVANTAGES AND DISADVANTAGES OF A TRIMARAN VERSUS A MONOHULL

The summary of advantages and disadvantages below have been developed from this and earlier work at the UCL and elsewhere, and is included to help in the overview of trimarans. It includes ideas from student reports as well as the authors'. The effort on trimarans over the last few years has been very effective in showing the benefits and problems of designing a trimaran. UCL staff and students are to be congratulated on an outstanding effort.

The pros and cons are based on studies of frigate size ships. The advantages change somewhat for other size and mission ships. For instance, a small patrol boat that requires high speed operation (high Froude number), gains significantly from the trimaran advantages in low power requirement at high speed, while this is less important in a frigate.

Advantages

Survivability

- Outer hulls partially shield the centre hull, thus vital equipment and magazines.
- Damaged stability.

Stealth

- Radar Cross Section (RCS)—more features can be incorporated.
- Infra Red (IR)—engine compartments shielded.
- IR— engine exhaust may be led between the hulls.
- Acoustics:
  - Machinery can be higher.
  - Side hulls shield noise of the centre hull.

Cost

- Lower for this design.

Power

- Low effective power at high speeds.

Improved seakeeping

- Reduced heave and pitch due to increased length.
- Probably reduced roll.
- Location of most personnel and equipment centred more amidships than a monohull.

Improved layout

- Internal arrangements are improved, with most area in the ship on one large deck.

Combat system

- Allows for the spreading out of weapons and sensors to reduce interference.
- Allows more modularity to easily upgrade systems.

Helicopter operation

- Large operating area.
- Low ship motion.

Future upgrade

- Greater scope for stability can be increased by widening the side hulls.

Disadvantages

- Manoeuvring.
- Risk.
- Berthing and dry-docking difficulty.

Optimization and Synthesis Model

In order to design the trimaran FE, without excessive manual calculations, a synthesis model was developed. As different configurations of the ships were tried, it quickly became obvious that the guidelines used in monohull frigate design for relationships between length, beam, draught, depth etc. did not help in trying to optimize a trimaran. Little by little the synthesis model became more sophisticated to overcome this.

The present model sizes trimarans between 4,000 and 7,500 tonnes. It is flexible enough such that it could be modified to other trimaran sizes and configurations, and uses the Microsoft EXCEL 4.0 spreadsheet.

NAVAL ARCHITECTURE AND MARINE ENGINEERING

This section is the major part of this article and describes the major features of the naval architecture and marine engineering of the design, and the rationale by which they were developed. Greatest emphasis is laid on the naval architecture, since this is fundamental to this novel concept. Substantial difficulties here are unlikely to be compensated by benefits in marine or combat system engineering, and would therefore lead to failure of the concept.

General

The principal ship characteristics are listed in Table 2.

TABLE 2—*FE (Trimaran) Characteristics*

Role

Future ASW Surface Combatant—service date 2010+.

Dimensions

Deep Displacement 5,830 tonnes.

			Centre Hull	Each side Hull
Beam overall	25.3	LOA/LWL	167/160	63/59.2
Depth	11.9	BWL	11.1	2.4
Box clearance	3.2	Draught	5.9	2.7
Box depth	2.8			

Machinery

2	Propulsion WR21 gas turbines.
1	Reduction gear, single FPP propeller.
1	2MW DC motor on centre hull shaft.
2	1MW DC motor, shaft and small propeller (1 for each side hull).
5	Turbomeca Makila T1 1.2MW gas turbine generator sets.
1	Set small fixed stabilizer fins.

Operational

Quiet cruise speed	15 knots.
Maximum speed	30 knots.
Range	8,000 nautical miles at 15 knots. 2,000 nautical miles at 25 knots.
Stores endurance	45 days.
Sea state	6+.

Payload

Weapons
- PDMS.
- VSRAD.
- Harpoon.
- MTLS.
- Medium calibre gun.
- 1 Merlin (with Stingray torpedoes).

Sensors

MFR.
EW as on CNGF.
Bow Sonar (2050).
Towed array (2057).
LFAVDS (like SLASM).

Decoys

SSTD (2070).
Seagnat.

Structure

Steel.

Accommodation

Officers	33
Senior Rates	81
Junior Rates	146
Total	260

Standards

Naval e.g.:

Stability	Naval Engineering Standard (NES) 109.
Accommodation	NES 107
FF/DC	NES 119

Other main features of the overall style of the design are:

- Underwater hull form is developed from the Type 23.
- Box length is the same as that of the side hulls.
- There is flare on all surfaces above the waterline, including transom and box sides.
- Waterline separation of the hulls is 4.2 metres.

Weights

The accurate prediction of weight is critical to the viability of the concept and credibility of the result. Weights were estimated at a 2-digit level, except for stowed liquids which were estimated at 3-digit level, using Naval Engineering Standard (NES) 163 weight breakdown. Only a summary is presented here and a comparison with the equivalent monohull is shown in Table 3.

TABLE 3—*Weight breakdown in tonnes*

	Trimaran	**Monohull**
Group 1—Structure	2012	2316
Group 2—Propulsion	437	566
Group 3—Electrical	155	351
Group 4—Control & Communications	466	474
Group 5—Auxiliary systems	456	476
Group 6—Outfit & furnishings	438	483
Group 7—Armament	77	77
Basic Light Ship (BLS)	**4041**	**4763**
Design & Building margin (3% BLS)	121	142
Contract modification margin (2% BLS)	81	95
Armour	65	65
Light Ship (LS)	**4308**	**5045**
Board margin (3% LS)	129	151
Group 8—variable loads	1390	1246
Deep Displacement	**5828**	**6442**

Monohull applicable

Although the trimaran is not a monohull, many of the weight groups can be accurately scaled from monohull data as the shape is less important than the volume, arrangeable area, length or accommodation. In other cases the centre hull could be looked at as a monohull with separate calculations made for the other parts. Weight algorithms were generally based upon the MoD's Concept Design program (CONDES) regression lines. These best fit lines were plotted and an equation generated for each group. In each case the ships selected for the regression analysis are those that represent as closely as possible the design standards and attributes to be included in the FE.

Not monohull applicable

Some weight groups were not deemed to be appropriately scaled from a monohull regression. These were analyzed separately.

Weights input directly

Typical combat system weights were obtained from the equipment managers. Many of the machinery weights were obtained from internal MoD data.

Structure

The structural design of the trimaran will be discussed in three parts:

- Centre hull and box (longitudinally).
- Box (transverse).
- Side hull.

This is the way the synthesis model is developed and the major issues on stresses break down this way. Reference 1 has been used extensively to determine requirements, but more importantly to understand the design methodology for monohulls, such that it could be extended successfully to trimarans. The structural design (FIG. 2) is a key feature of the concept and is therefore discussed at length.

The final design of this trimaran includes a transversely framed longitudinally stiffened centre hull, with the box structure contributing to the longitudinal strength. The box 1 deck is also transversely framed and longitudinally stiffened, while 2 deck is the opposite being longitudinally framed and transversely stiffened. This was done as the primary longitudinal stresses are higher in 1 deck than the conventional monohull structure, but 2 deck in the side hull sees high stresses in the transverse direction and therefore benefits more from this configuration.

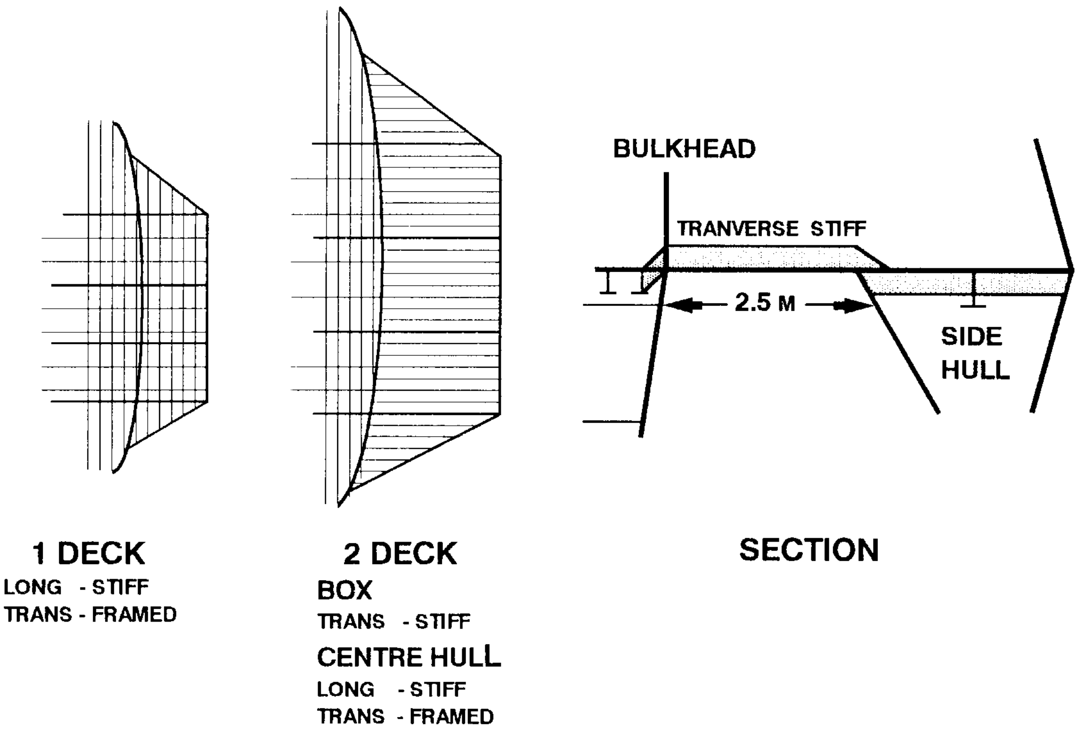


FIG.2—STRUCTURAL SKETCH

Centre hull and box longitudinal analysis

The detailed structural analysis is only summarized here. The analysis was performed using the relevant GODDESS routine, assuming an 8m trochoidal wave to give the wave bending moments, and 5,000 days at-sea operations to derive a fatigue factor from reference 1.

Two steels were used:

- 330MPa for 1 deck, the most heavily loaded.
- 275MPa elsewhere.

Using this information, the necessary midships section inertia was derived, and hence a midships section, which is shown in (FIG. 3). This is illustrative only at present and will clearly need refinement, but gives a first shot at structural weight.

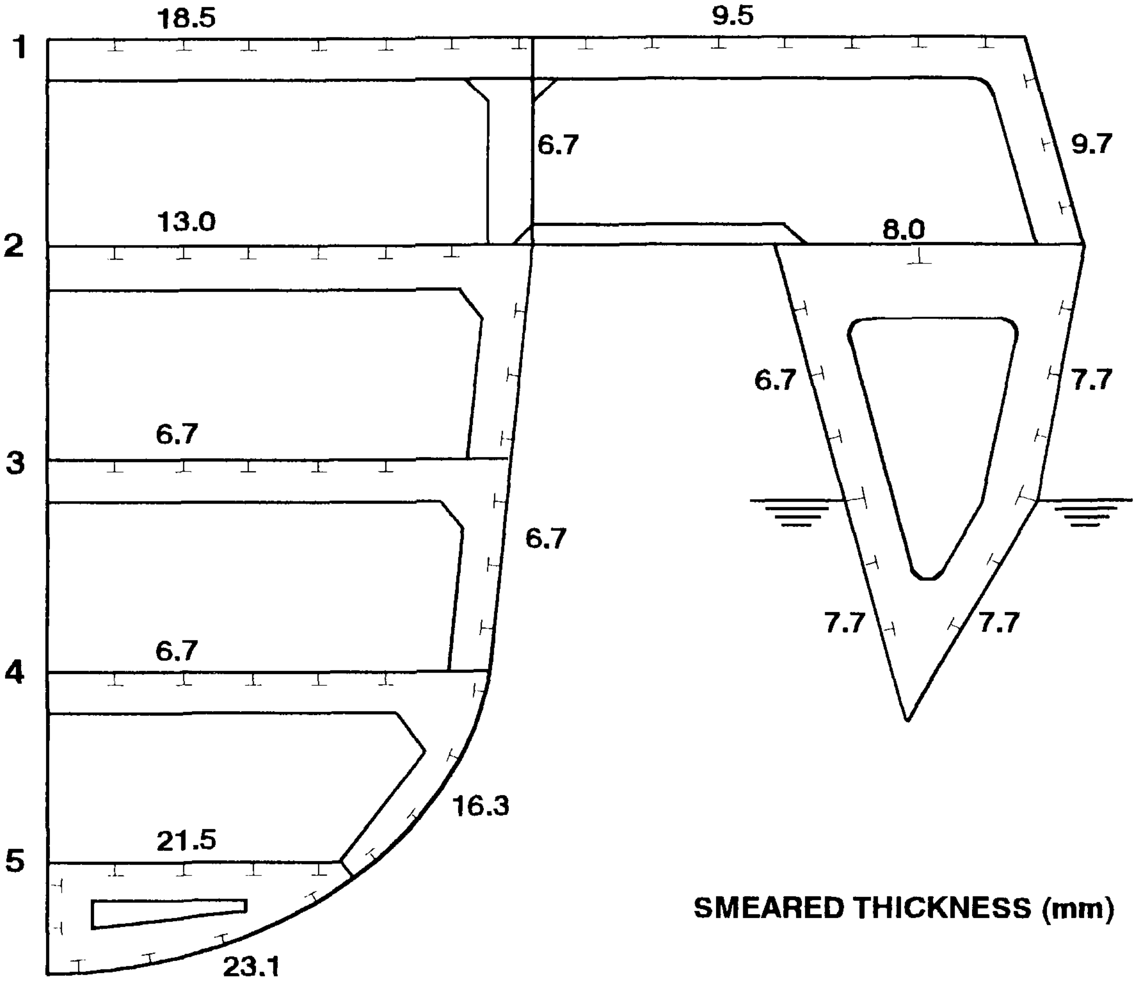


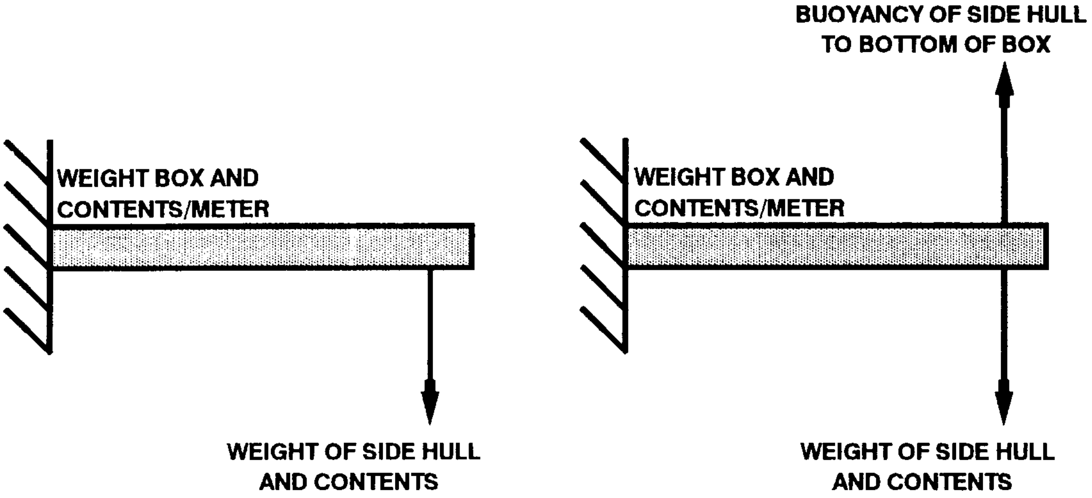
FIG.3—MIDSHIP SECTION

Box structure transverse calculations

Having derived the midships section scantlings, the transverse inertia of the box was calculated, assuming box and side hull cantilevered off the centre hull (FIG. 4). From this a first shot at the box and side hull structure was developed.

Future structural study

These are rough calculations of the structure in an early stage to try to understand thicknesses and to determine weights. There are numerous calculations such as torsion, shear etc., that should be done to better understand trimaran structures and



CASE 1 - SIDE HULL OUT OF WATER

CASE2 - SIDE HULL SUBMERGED TO BOTTOM OF BOX

FIG.4—SIDE HULL DESIGN CASES

weights. There was however nothing in the literature on trimarans or monohulls that suggested the structural design of a trimaran will not be straightforward. Several aspects of the structural designs have been identified as meriting further investigation.

Materials

The trimaran is basically like a monohull as far as material selection is concerned, but offers a few unique areas to investigate. The centre hull material selected is steel, with this frigate using a higher strength steel for 1 deck and a lower one for the rest of the hull and the box. This as explained above comes from the calculation showing maximum stresses being in the 1 deck.

The superstructure is in short sections longitudinally and therefore should eliminate much of the cracking concerns by shape alone. Steel has been selected for all the same reasons it is preferred in monohulls. A composite superstructure would fit quite easily into this ship as either the entire superstructure or as only one section of it.

The structure of the side hulls should be investigated. For this ship steel has been selected but only because it is conservative and easy to estimate for weight. A composite side hull has advantages in:

- Noise reduction.
- Shock mitigation into the box.
- Lower RCS.
- Potentially lower cost as this part of the ship requires complex structural shapes that are expensive and a tight area for welding access.

The composite would mechanically attach to the bottom of the box or at a lower point such as just above the waterline. The connection should see minimal stresses, and would be flanged steel with a flanged composite bolted and glued to it.

Space

In the sizing of a trimaran frigate, like a monohull. the area requirements are critical to the overall size of the ship. The ship is broken down into two main parts:

1. First area drivers such as living spaces and electronics spaces.
2. Second volume drivers such as tanks, and machinery rooms.

A ship that minimizes excess area (available arrangeable area minus required area), generally results in the minimum cost ship. The notes preceding the weights section also pertain to this section. Areas have been derived by a mixture of regression from monohull designs, calculations, and relevant standards.

Layout

The length of a monohull is usually the minimum length for topside arrangements, as this is usually the lowest cost ship that meets the requirements. For the trimaran two things are different:

1. Extra length over the monohull equivalent is added to increase the displaced volume of the ship to match the weight, without too wide a centre hull beam or too deep a draught.
2. This frigate design is unusual in that the uptakes are diverted between the hulls, thus reducing the length required on the topside dedicated to them. This can be seen in Table 4, where the minimum length for the topside is 128 m while the centre hull is 160 m on the waterline.

TABLE 4—*Topside minimum length*

Item	**Min Length metres**
Bow (anchor handling etc.)	16.0
Gun	10.0
VLSW	7.0
Bridge	12.0
Masts	5.0
Decoy launchers	2.0
RAS area	3.0
SSGW	7.0
Small calibre guns	3.0
Hangar	18.5
Flight deck	24.5
LFAVDS	20.0
Total	**128.0**

Beam of the centre hull was driven by:

- An adequate size for the machinery fit.
- Increasing displaced volume without excessive draught.

Overall beam was determined to optimize stability. This was done by varying side hull waterplane area (which optimized long length for survivability and narrow beam for powering) and the distance outboard of the side hulls. The distance between the centre hull and the side hulls is as large as possible to minimize wave interference effects.

A major design issue for this ship is the LFAVDS placement in relation to the flight deck. To satisfy this, the depth of the hull has been increased to 5 decks, as on the monohull, though the depth of the trimaran is slightly greater to provide box clearance over the water. As the trimaran flight deck is wider and further forward than on the monohull, it is easier to arrange both LFAVDS and helicopter operations to minimize interference.

Internal arrangements

An outline General Arrangement is as (FIG. 5). The trimaran configuration is a delight to arrange. Most of the area in the ship is in low motion locations close to midships, and all on a single deck. With dual passageways fore and aft, access is excellent. Even with the centre hull being long and narrow the arrangements are easy. Each deck level holds almost the entire requirement for a compartment, minimizing passageways on lower decks. The general philosophy for the arrangements was to maximize survivability by keeping as many items and people in the centre hull inboard of the side hulls or in the box. Only major spaces have been shown, but the extent of deck area available on 2 deck midships can be seen.

Side hull arrangement

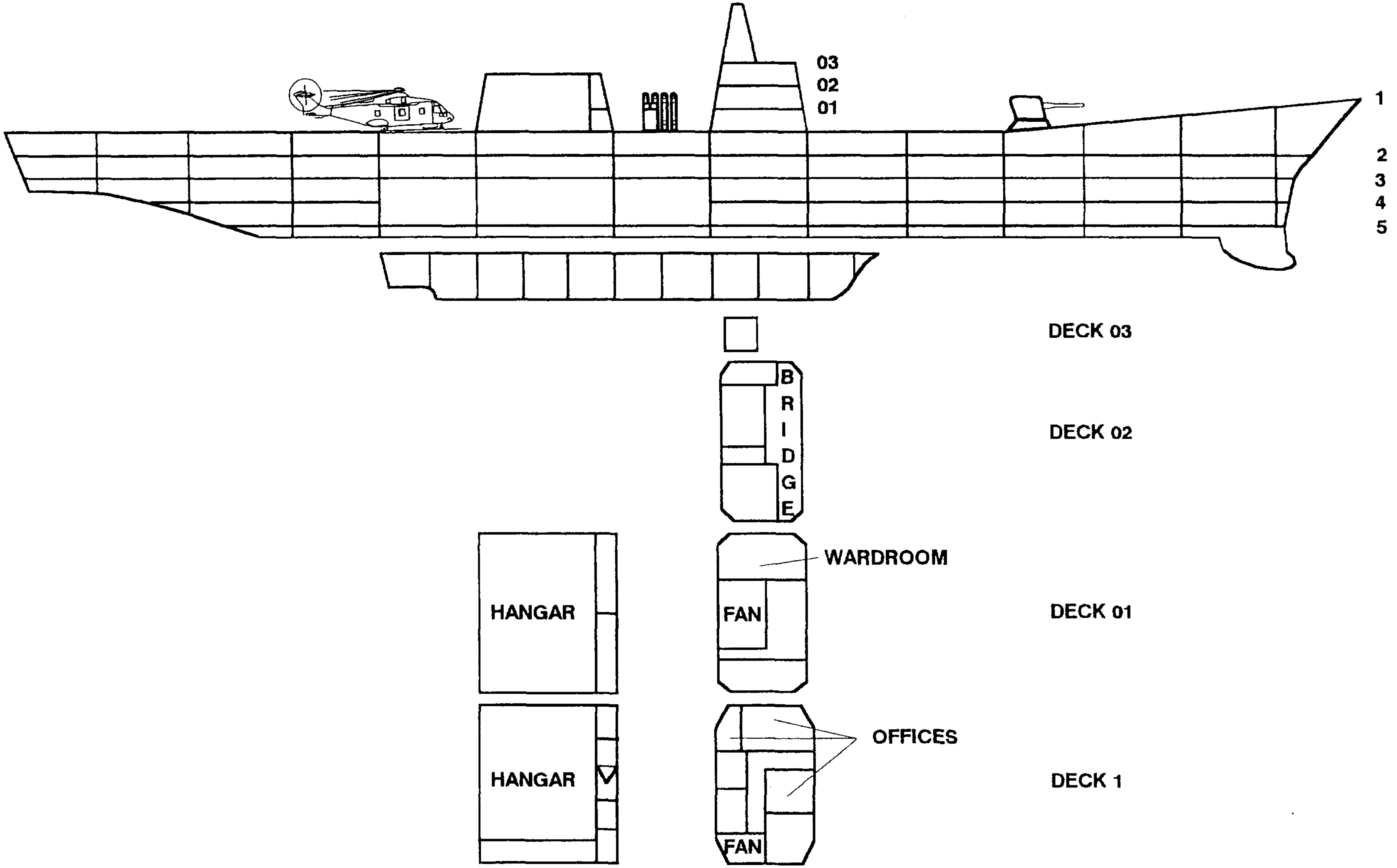
The side hull has bulkheads every 6 metres to reduce flooding in the damaged condition, this combined with its narrow beam leaves little area for arrangements. Thus the side hull is primarily voids and tanks, with the exception of the propulsion motor, fin stabilizer machinery, and access for accommodation ladders.

Topside arrangements

Little arrangement work has been done in this area but several key thoughts on topside arrangements are:

- The topside arrangements of the trimaran will be easier and should be an improvement over an equivalent monohull.
- The length of the trimaran allows spreading out both the weapons and antennae to reduce interference between them.
- The additional beam facilitates helicopter landing and arrangement of boats.
- The topside will exhibit those features necessary to reduce radar cross section as shown on *Sea Shadow*, and *La Fayette*, including sloping of all surfaces and concealing of all items topside.

Overall the trimaran offers a major step forward in internal and external arrangements.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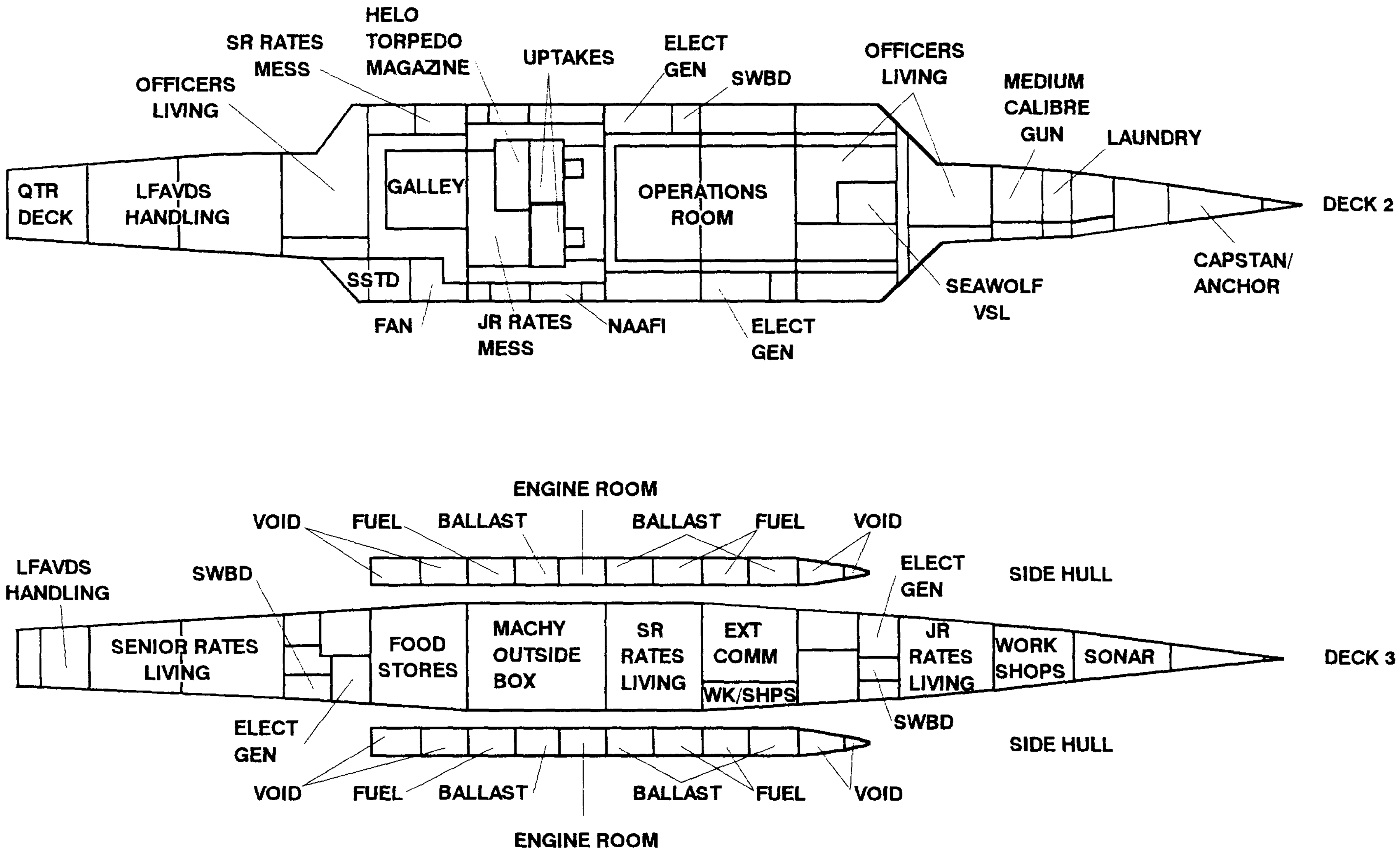
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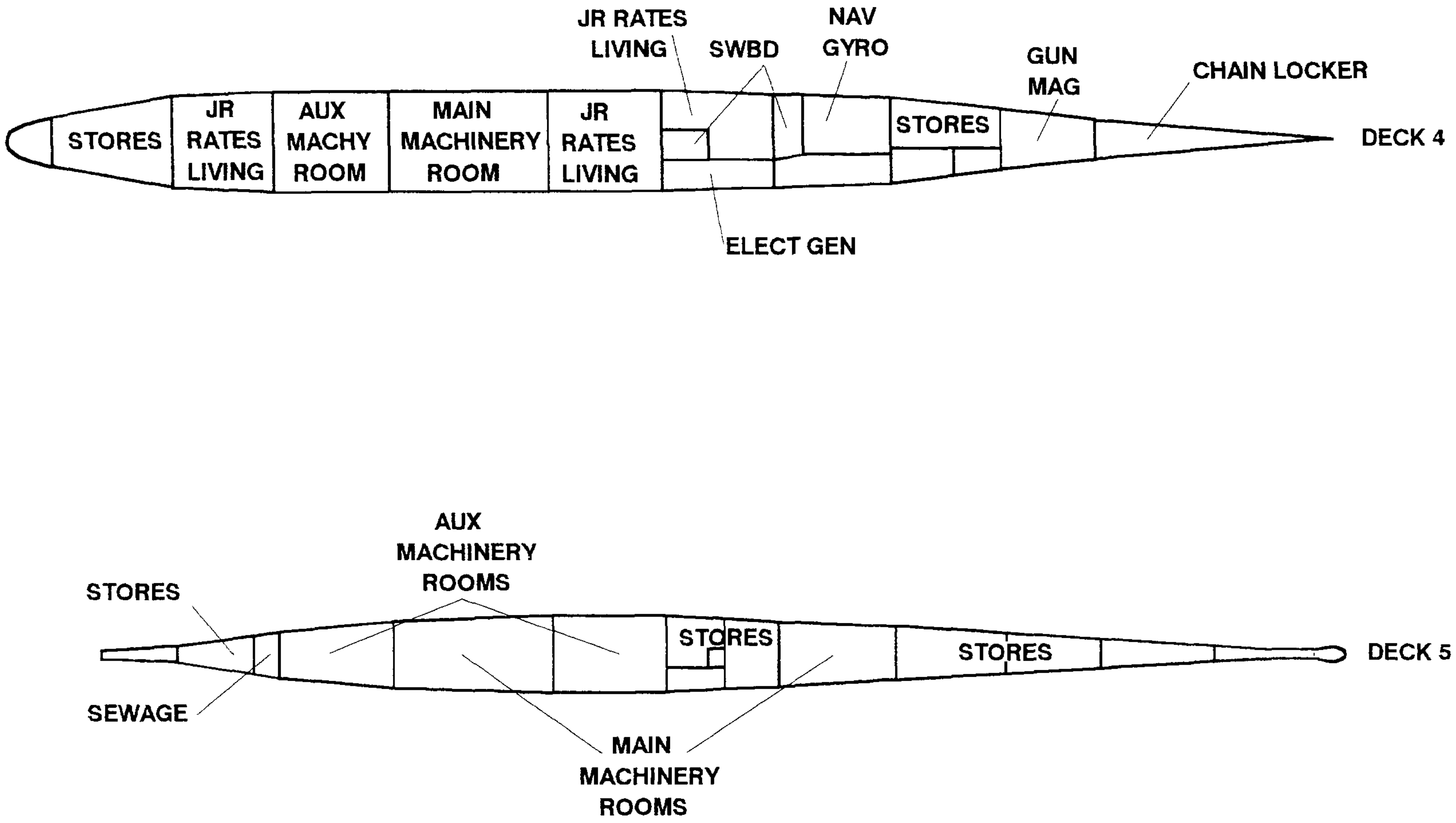

FIG.5—GENERAL ARRANGEMENT

Hull Form

Main hull

Series 64 is generally used for high speed hull forms, but as UCL discovered and the synthesis model work shows, Taylor series is a better choice for trimaran frigates as the Froude number is not very high due to a long length and moderate top speed.

Side hull

UCL has looked at the trade off between large, small, and SWATH shaped side hull shapes. The size of the side hull combined with the overall beam is what determines intact stability, such that a small† side hull set far out will be equivalent to a large side hull close in. Selection of side hull size involves the following:

- Volume for propulsion machinery (large better), if side hull has propulsion machinery.
- Flexibility in machinery arrangement (large better).
- Vulnerability effects (large better).
- Damage stability and reserve buoyancy (large better (especially long length), but small can control with extra ship beam).
- Low total resistance, interference effects with centre hull, resistance of side hull (small better).
- Manoeuvrability (small better).
- Flexibility in longitudinal side hull location (small better).
- Cost (small better).
- Box structure to hold ship together (small better).

Overall small side hulls have generally been preferred throughout the UCL studies, with the various studies converging on a size of each side hull displacing about 10% of the centre hull. The length of the side hulls has been about $^1/_3$ of the centre hull length. This study has found long thin side hulls to be preferred with their length equal to twice the damaged length and beam being as narrow as machinery and construction will permit.

Hull interactions

In general the studies have located the side hull midship just aft of the main hull midship, such that the LCFs are aligned. The results of the UCL small scale powering studies have shown that there is a definite effect from both longitudinal and transverse location of the side hull on resistance, which varies with speed. These studies, (reference 2), used small models to determine the interference effects between the hulls. The tests confirmed a 10% factor covered most of the cases (speed, location) and this 10% interference effect has been retained in this report and the synthesis model as being the best data available. It will be verified at one data point (but many speeds), by testing at the Defence Research Agency (DRA) Haslar.

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† Small is when the side hull is less than 15% of the displacement of the centre hull

Hydrostatics

These were calculated using the GODDESS computer program, and the synthesis model and are listed in Table 5.

TABLE 5—*Hydrostatic summary*

Centre hull		**Side hull (each)**	
LBP	160.0 m	LBP	59.2 m
Beam wl	11.1 m	Beam wl	2.4 m
Draught	5.87 m	Draught	2.7 m
Depth	11.925 m	Depth	6.0 m
Prismatic Coefficient	0.620	Prismatic Coefficient	0.600
Midship Coefficient	0.834	Midship Coefficient	0.640
Block Coefficient	0.517	Block Coefficient	0.384
Waterplane Coefficient	0.758	Waterplane Coefficient	0.735
L/B	14.41	L/B	24.65
B/T	1.89	B/T	0.89
L/D	13.4	L/D	10.0
LOA	167.1 m	LOA	63.0 m
Displacement	5526 tonnes	Displacement	151 tonnes
Centre and side hulls			
Displacement		5828 tonnes	
KB_T		3.6 m	
BM_T		6.3 m	
Beam wl		24.2 m	
Maximum beam		25.3 m	
Tonnes/cm		15.9	

Resistance, propulsion, and fuel estimate

The resistance estimate was based on the Taylor-Gertler series, suitably modified and with appendage corrections added. The speed power curve is at (FIG. 6). The shaft power was found by dividing the total effective power by the propulsive coefficient, which, for this single shaft ship with its long and very slender centre hull, was estimated as 0.65.

Two fuel calculations are made, one for Taylor-Gertler and one for Series 64. Only the Taylor-Gertler series results are used. The fuel is calculated at two different speeds, each with its own range requirement. The synthesis model selects the higher of the results and uses it for the weight report.

Intact stability

The intact stability of the trimaran offers the ship designer numerous options, when compared to a monohull. The stability of the trimaran can be easily changed by moving the side hulls farther out, or by changing the waterplane of the side hulls or to a lesser extent by changing the beam of the centre hull. The relative contribution to the overall waterplane inertia is:

$$\begin{array}{ll} \textbf{Inertia total} & = I_{\text{centre}} + I_{\text{side}} + I_{\text{side}} + I_{\text{side about itself}} + I_{\text{side about itself}} \\ \textbf{100\%} & = 30\% + 35\% + 35\% + 0.1\% + 0.1\% \end{array}$$

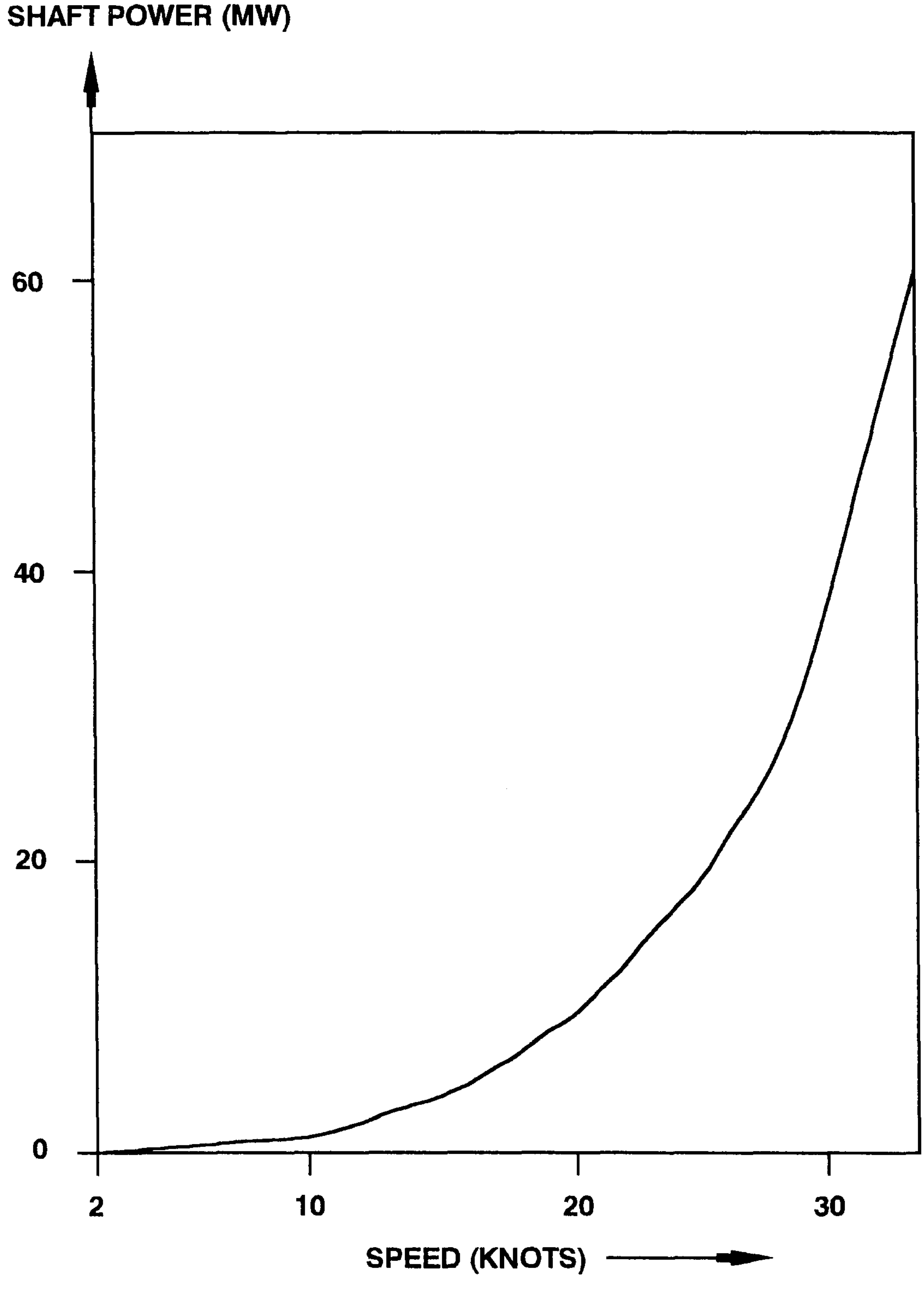

FIG.6—SPEED POWER CURVE

The intact Metacentric Height (GM) for the design was selected as 2 metres, based on an expectation that the motions, particularly roll acceleration, would be similar to that of a monohull, without being excessive as on a catamaran. The intact stability was checked using GODDESS against the requirements in NES109. The results are shown in Table 6.

TABLE 6—*Intact stability*

	Required	Achieved
Angle of heel limitation due to beam wind	<30°	5.6°
Heeling lever GZ/max GZ	<0.6	0.161
Absorbing/disturbing energy	>1.4	4.76
Area under GZ curve up to 30° (m rad)	>0.08	0.253
Area under GZ curve up to 40° (m rad)	>0.133	0.462
Area between 30° and 40° (m rad)	>0.048	0.209

Note that the ship is analyzed at the growth condition (end of life), and wind velocity 90 knots. The intact stability has been analyzed only for beam winds and not for icing, lifting heavy weights, high speed turns, or crowding of passengers. These have been looked at previously in UCL trimaran studies and shown to not be the critical case.

The capsizing criterion is no longer required by NES 109, but should be investigated for trimarans. This will be most effectively done as a series of model tests. The trimaran is very stable, yet capsizing in very high and steep waves is not a well understood science, for monohulls, much less so for trimarans. If the old criterion in NES109 for capsizing is calculated for this trimaran it is easily met by a factor of almost two.

Damage Stability

Acceptable damaged stability of the trimaran is critical to the concept being successful. The results of the various damage cases run show stability after damage far exceeds the monohull requirement. In addition the trimaran offers the potential to repair damage far more effectively than a monohull. This makes ship survival significantly greater than a monohull and ship war fighting ability after damage much more likely.

Six damage cases were run. All the cases had the following characteristics:

1. The damage involves a hole 15% of centre hull length or 24 metres. This floods a length of ship greater than 15%.
2. The side hull has watertight bulkheads every 6 metres to minimize the flooding from the 24 metre hole, thus the side hull is never flooded more than 30 metres.
3. The side hull being about 60 metres long has at least half its buoyancy left after damage in all cases.
4. A profile of the ship is used for wind heel calculations which includes the superstructure and mast.
5. The side hull has flare both on its inboard and outboard sides such that the GZ curve will increase with increasing heel angle. In an early try at a hull form with tumblehome on the outer side and an equal amount of flare on the inboard side, the ship did not meet the damage stability criteria.
6. All cases assumed displacement and Keel to Centre of Gravity (KG) at the end of life condition.
7. In all damage cases it is assumed that the structure in the box that remains is adequate to hold the side hull on. This should be analyzed but it is not considered to be a major problem, but is noted in the structural section requiring analysis.
8. The aft quarter deck is allowed to flood in all cases, though it does not go underwater in most.

9. Damage cases include side hull and centre hull damage, side hull without centre hull (but with box flooding), and centre hull without side hull damage. There are more cases run for the after part of the ship than forward, as these were considered the most critical cases.

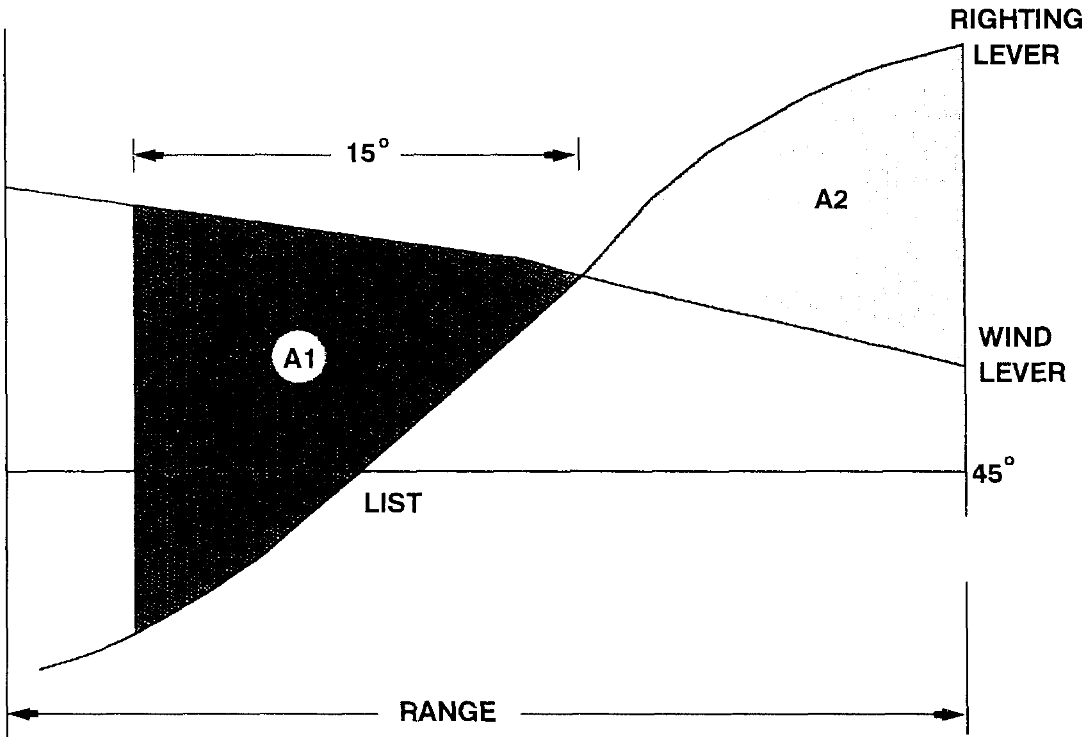

FIG.7—DAMAGED STABILITY CRITERIA

10. NES 109 damage stability standards for combatant ships were adhered to for all the studies. The following criteria after damage are required, and are shown graphically in (FIG. 7):
    - (*a*) Wind speed is 35 knots.
    - (*b*) All centre hull compartments are assumed to be empty thus have a 100% permeability, which makes the results conservative.
    - (*c*) After damage angle of list or loll must be <20°.
    - (*d*) GZ at point C must be <60% of maximum GZ (point C is where the wind curve crosses the GZ curve).
    - (*e*) Area A1 must be >0.5.
    - (*f*) Area A1 > 1.4 × A2.
    - (*g*) Longitudinal trim must be less than that for down flooding.
    - (*h*) Longitudinal GM > 0.
    - (*i*) GZ maximum is within the range of down flooding or 45° whichever is less.

TABLE 7—*Damaged stability criteria*

	Required	**DAM 1**	**DAM 2**	**DAM 3**	**DAM 4**	**DAM 6**	**DAM 7**
(*d*). Heeling lever to max GZ.	<0.6	0.081	0.089	0.034	0.022	0.021	0.031
(*f*). Absorbing/ disturbing energy	>1.4	3.26	3.36	4.06	4.48	6.42	3.16
(*e*). Energy ratio when damaged (ratio to 0.5)	>1.0	7.75	10.34	24.53	42.69	47.6	23.7
(*c*) Angle of list after damage	<20°	2.39	0.00	3.4	0.00	0.00	4.39

All cases of stability passed all criteria easily, a check of several revealed they would pass even at 90 knots of wind rather than the 35 required. The results are summarized in Table7, and a typical damage case is shown schematically in (FIG. 8).

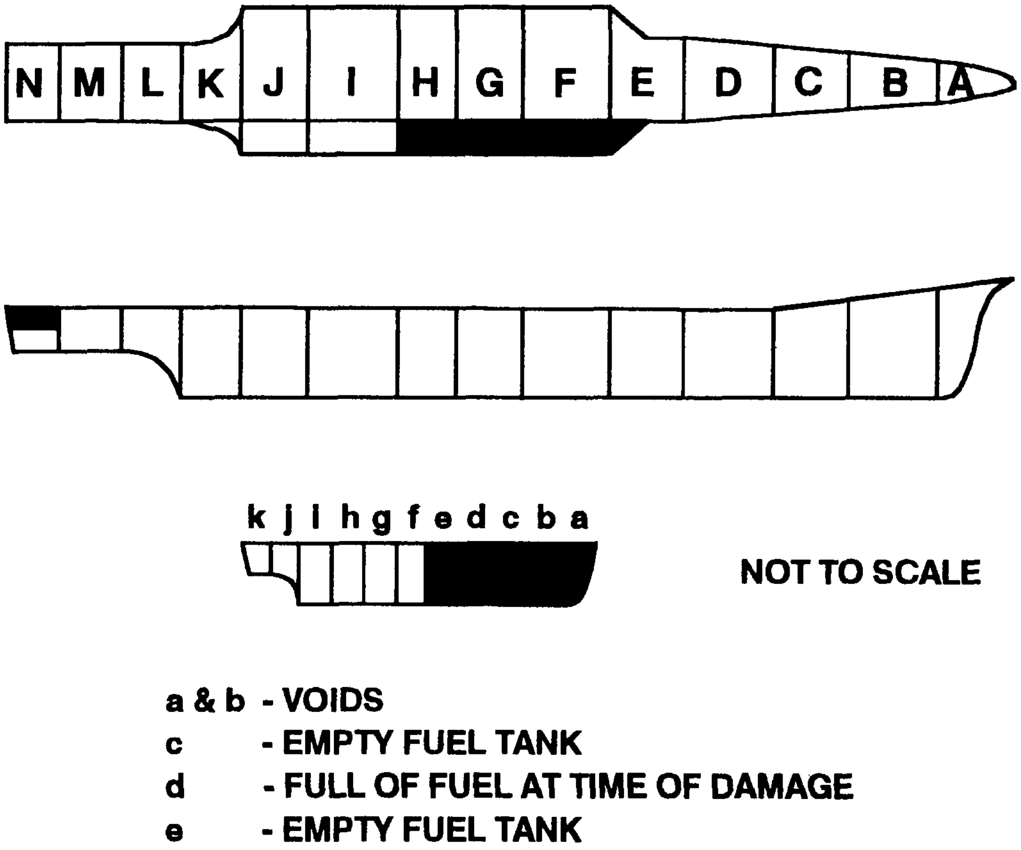

FIG.8—DAMAGE CASE DAM 2

As can be seen from the results damage stability was easily met in all cases. The small angle of list after damage is very unusual and requires the following explanation. The side hulls have fuel and/or clean ballast water in many of the compartments. In each case of damage of a side hull (cases 1, 2 & 3), it was assumed that the minimum number of tanks are full before damage, as this is the worst case. After the hit the full tank or tanks (which extend a considerable distance above the waterline) empty to the level of the new damaged waterline. As can be seen in DAM 2, an amount of fluid going out equals the amount that floods into that compartment and all others damaged, giving 0.0 degrees of list after damage. This is exactly what is wanted, thus resulting in no list.

There are some general conclusions from the damage stability results:

- There is very little list after damage in a trimaran.
- Case 1 is the most severe, which is damage to the side hull but no damage to the centre hull.
- The bulkheads of the centre hull could be moved further apart without failure of the criteria, this should be investigated as to how far. Or there could be longitudinal watertight bulkheads in the centre hull as the off centre flooding could be easily handled.

Seakeeping

There has not been any attempt to optimize this hull for seakeeping performance. The centre hull has been scaled from the Type 23 Frigate and includes bilge keels and fin stabilizers. As such this represents a baseline seakeeping performance and will be useful in comparisons with other hull forms.

The seakeeping performance has not been evaluated, due to the lack of a tool for evaluation. A head sea evaluation could have been done using the GODDESS strip theory, but it would not take into account the side hulls. However, an initial attack has been made on the problem by UCL.

There is no published work on trimaran seakeeping, but a successful method for monohulls, SWATH, and catamarans using linearized strip theory is expected to work well for slender trimarans. At UCL, a student analysis of the centre hull only or the centre hull with the side hulls incorporated to form a bulged centre hull, has shown that the pitch motions were better than the equivalent monohull, primarily because the trimaran is longer and length helps in reducing absolute motions. The relative motions at the bow and stern are greater due to the longer length. A key item to note is that even if the motions were the same the seakeeping of the trimaran would be considered better as far more of its arrangement space is near midships. Thus most of the crew and most equipment will see lower motions.

Wave slap on box

There is information from catamarans and SWATH on wave slap. The trimaran should be significantly better than these, as its cross structure is so far aft. A criterion, developed by UCL and modified, requires the clearance of the box above the waterline to be:

> ½ the sea state 6 wave height plus the amount of a bow down pitch.

This was estimated from several monohull seakeeping analyses done by the DRA. The DRA Haslar model tests should help to confirm this. The wave slap is of concern structurally, but more so it has an effect on the gas turbine exhaust between the hulls.

Roll period and GM

There is a need to test the relationship between roll period and GM, as a high GM is desirable from stability and KG growth during service life, but generally has an adverse effect on comfort for crew. There may not be as direct a relation as on a monohull. In addition the mass moment of inertia is quite different from a monohull.

A monohull radius of gyration is not easy to change but for a trimaran the fuel is in the side hulls to increase this term and increase the roll period for the same GM. A GM of about 2 metres is used for most of the UCL studies and has been maintained in this article as the ideal. It is considered that the 2 metre GM will give a better ride for the trimaran than the monohull with a 2 metre GM.