The Strike Aircraft Carrier: Considerations in the Selection of Her Size and Principal Design Characteristics

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To select the size and principal characteristics of a strike aircraft carrier (CVA), the point of departure is the set of missions the weapons system is expected to execute. Of the possible CVA missions, the one that controls her design is the air strike against strategic or tactical targets. Given the military performance in the control mission, translation must be made thereof into engineering specifications of design features. The synthesis of these features results in a set of conceptual designs. The designs are first proportioned by solving for the static and dynamic conditions they are to satisfy. To this end, parametric design models are set up and solved for weight, volume, stability, power, structural integrity, and so on. The outcome is an initial set of CVA design characteristics. These characteristics are used to estimate the inherent degradation of the system from mechanical causes and from the environment. Military conflict situations are then postulated and for each the combat degradation is assessed. The combined degradation is employed in the iterative processes which converges to the prescribed value of military performance. Finally, the military conflict situations are weighted as to the probability of their realization. This weighting leads to a unique solution of CVA design characteristics.

Introduction

"The principal use of the attack carriers in the years ahead will be in the limited war role ..... There are many potential trouble spots in the world where the attack carrier is and will continue to be the only practical means of bringing our air striking power to bear."

Secretary of Defense
Robert S. McNamara
in testimony before the
Senate Armed Services Committee
25 March 1962

Purpose and Justification

In this presentation an attempt will be made to develop some arguments which enter into the selection of the size and principal design characteristics of a strike aircraft carrier (CVA). The reason for this choice of vessel as the subject of interest is that it leads to arguments that are timely and to a discussion that has a high degree of generality.

The timeliness of the arguments can, perhaps, be made plausible by a brief recount of past events. The aircraft carrier, hastily conceived during the First World War as a humble auxiliary naval weapons system (WS) of limited potentiality, developed during the ensuing interbellum to the point of becoming a generation later, during the Second World War, the chief instrument for projecting our strike air power overseas. Alternate means for the air delivery of weapons against the enemy, such as by land-based aircraft, tended

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Note: The ideas and opinions expressed in this paper are purely personal and are not necessarily in accord with stated philosophy, policy, and methodology of the Department of Defense and of the Navy.

to suffer somewhat in comparison because their then limited range required adequately spaced staging fields for operations to be carried out. The time required for preparing such fields made for a long lag from decision to execution of strike operations even in the absence of problems of negotiation with foreign powers for the exploitation of bases in their territory.

The advent of nuclear weapons during World War II and, since then, of the long-range bomber, of the intercontinental-range cruise and ballistic missiles, and of the large-capacity helicopter, and the expected imminent development of vertical take-off and landing (VTOL) aircraft of high performance are all having profound effects on the role of the strike aircraft carrier weapons system (CVA/WS). Both weapon lethality and tempo of operations have increased greatly and are continuing to increase. The obvious questions are being asked: Will CVA/WS's continue to have effective roles in modern warfare? If so, what are these roles? How should the systems be designed to best fulfill their assigned missions?

The degree of generality to be developed by an analysis of the CVA/WS might be brought out by observing that the carrier task force (CTF), of which the CVA is the kernel, is the most sophisticated and varied instrument of naval warfare extant. The CVA is a multipurpose ship which operates in an entourage of supporting ships, and the CTF has strategic, tactical, and logistic capabilities. This would seem to indicate that a logic for the selection of design characteristics of a CVA would require application of a rationale that is fairly general. And if a set of arguments can be developed for this case, there is a fair chance that they will be *a fortiori* valid when applied to most over naval WS's.

It is evident that in attempting to develop thoughts within the constraints of a brief presentation, I can hardly do justice to the subject. I can only hope to fail to do it altogether too much injustice.

Scope

The ideas presented are methodological rather than philosophical. The scope of the study is to outline a logic for selecting the size and principal design characteristics of the CVA component of the CTF.

The series of steps in the evaluation and selection process is presented in Fig. 1. The figure is incomplete. At each step one should read feedbacks links to preceding steps.

Of the questions being asked of the CTF, this study is intended to illuminate in part only the last of these questions; but to this end, the first two questions need be discussed for the purpose of developing the answer to the third.

Background

The Navy's basic philosophy has two tenets: The first is to strive for flexibility or versatility in its forces so as to cope with the complete spectrum of possible threats with a minimum amount of equipment. The second tenet, which is a corollary to the first, is that the equipment must be the most modern possible. It is essentially this philosophy that has led to the development of modern aircraft carriers of unprecedented displacements.

The aircraft carrier is a component in a WS which must be viewed as an integrated whole. A change in any component of the system affects all the remaining components to a greater or lesser degree. In past years, aircraft intended for carrier basing have grown in size and in complexity in order to achieve the performance required to carry out with confidence assigned missions against an enemy that is strong and ever growing in sophistication. This has resulted directly in the parallel growth of CVA's.

Since size is directly related to cost, there is, understandably, concern over this trend in aircraft carrier development. And because the aircraft carrier is not only a high-cost, but also a long lead-time, long life-time item, it becomes important to forecast her principal characteristics well in advance of developments in aircraft and equipments so that she may be designed to have a low rate of obsolescence and, eventually, low modernization costs.

Acronyms and Abbreviations

ACM = Acoustic Countermeasures
CTF = Carrier Task Force
CVA = Strike Aircraft Carrier
ECM = Electronic Countermeasures
ESS = Expected System Survivability
ETK = Expected Target Kill Value
VA = Attack Aircraft
VF = Fighter Aircraft
VTOL = Vertical Take-off and Landing Aircraft
VW = Search (Warning) Aircraft
WS = Weapons System
avfuel = aviation fuel
avgas = aviation gasoline
avord = aviation ordinance
shipord = ship ordinance

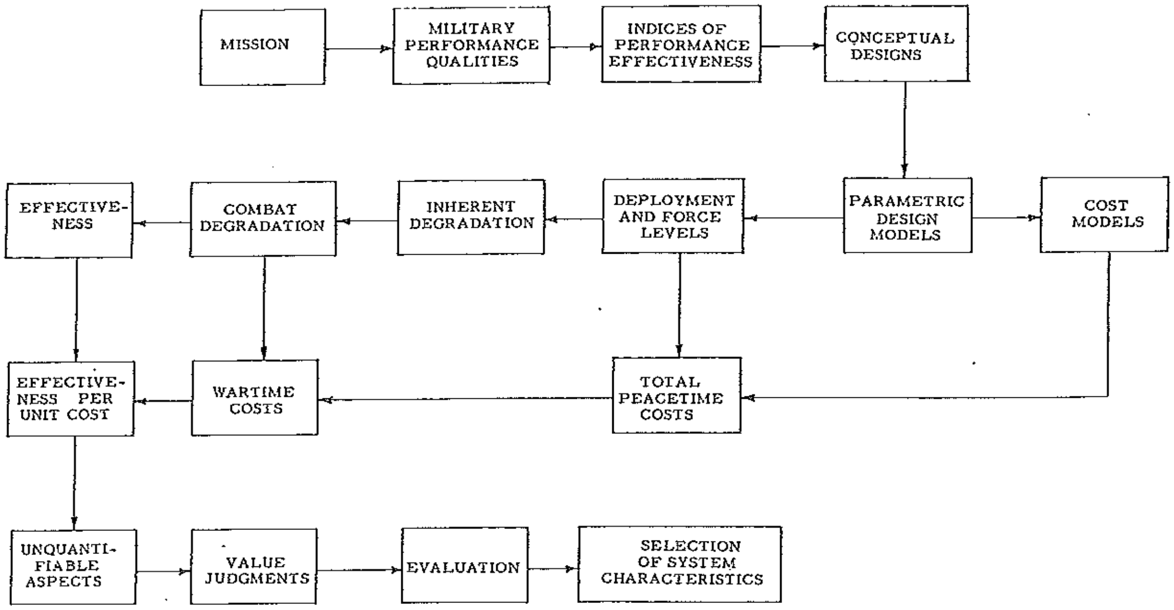

Fig. 1 Evaluation and selection process for aircraft-carrier-based weapons systems

Overview of the Rationale

When evaluating WS's or, more narrowly, alternative configurations of a same WS, their military effectiveness normalized on the basis of cost is usually introduced as a primary factor and solutions are sought that tend to maximize it. To the end of seeking such solutions, it is necessary to have a logic by which those elements which determine, or are related to, the system's military effectiveness are linked to those elements which determine its cost. If such a logic is developed for each serial component of a WS, then optimization of the WS may prove possible upon introduction of certain basic inputs derived from an examination of operational missions or reflecting technical experience.

In evaluating a military system (or, indeed, *any* system), the point of departure is its mission. This defines *what* the system is to do. To perform its mission, a WS must be endowed with certain qualities of military performance. *How well* a WS performs its mission is measured by the degrees to which it attains these qualities, i.e., by so-called indexes of performance effectiveness.

Military performance is sought by incorporating in the WS certain design features and by training the operating personnel to exploit the full potentiality of these features. This leaves as the next step in the process the important translation of military performance into engineering specifications of the design features.

The synthesis of these design features results in a set of conceptual designs which represent attempts toward an orderly integration of the features into coherent entities. They are hardly more than artist's sketches which, however, have the virtue of showing the geometries and mutual relationships of all the important components of the WS.

Proportioning and dimensioning of the design features (i.e., derivation of the design characteristics) is made by setting up and solving for each conceptual design, parametric design models which are derived from the static and dynamic conditions the designs are to satisfy (weight, volume, stability, power, structural integrity, and so on). Design constraints to be observed (maximum principal dimensions, and so on) are introduced at this point. The parametric design models yield the design characteristics that each system must have if it is to achieve a prescribed set of indexes of performance effectiveness.

The parametric design models are extended to yield cost. Relations are thus obtained which link initial investment and operating costs to any set of design characteristics.

Inherent degradation reduces military performance from that attainable in an ideal calm natural environment by an instantly reacting, flawless WS to that corresponding to a real WS operating in the real natural environment of a world at peace.

The next step is to specify the military environment, i.e., the military conflict situations. These

Table 1 Navy and Carrier Task Force Missions

Navy Missions	CTF Missions
1. Preservation of peace	
1.1 Deterrence	1.11 Show of force
1.2 Forestallment	1.21 Long range reconnaissance
	1.22 Blockade
2. Overseas Transport	
2.1 Logistics	2.11 Aircraft Transport
3. Defense[a]	
3.1 Own and allied territory	3.11 Antiair defense
	3.12 Antisurface defense
3.2 Own and allied fleets	3.13 Antisubmarine defense
3.3 Convoys	3.31 Antiair defense
	3.32 Antisurface defense
	3.33 Antisubmarine defense
4. Tactical attack	
4.1 Support of ground and amphibious forces	4.11 Close air support
4.2 Interdiction of enemy lines of communication	4.21 Deep air penetration (conventional warfare)
4.3 Attrition of convoys	4.31 Air attack
4.4 Attrition of enemy fleet units	4.41 Air attack
4.5 Attrition of enemy air units	4.51 Air attack
5. Strategic Attack	
5.1 Strike against counterforce targets	5.11 Air attack
5.2 Strike against countervalue targets	5.21 Air attack
5.3 Occupation of enemy territory	5.31 Close air support

[a] Air, surface, and submarine denote modes of attack delivery which the defense must blunt.

are conjectures of possible future ambients in which the WS's are to operate. Specifically, they define, for a projected time frame, both the enemy's as well as own geographic, social, economic, political, and technical status, and the military threat posed. The number of primary parameters required to describe a military conflict situation is quite large. Brutal reductions have to be made if the evaluation is to be at all tractable.

Finally, enemy counterstrategies and tactics are introduced in combat models and the combat degradation is assessed.

By this process one begins by specifying a level of military performance and one derives therefrom, in postulated military conflict situations, the expected military performance corresponding to a set of design characteristics and cost related to any conceptual design.

The final step in the evaluation process is that of assessing the probability of realization of military conflict situations so that the expected levels of military performance can be weighted to yield an index of evaluation for each design.

Military Performance

"System evaluation is judgment supplemented by inductive and numerical reasoning—it is only judgment, nonetheless."

E. S. Quade [1][2]

Point of Departure

Missions

The military effectiveness of a WS is its capability to bring to a successful conclusion military missions which it has been designed to execute. Since such missions are contemplated probabilities in an ever-evolving military environment, assessment of military effectiveness is essentially a problem of measuring uncertainties.

A mission is interpreted to be a military objective to be attained against possible opposition by an enemy: it is an end to be sought. The means of realization is through the choice of WS and strategy. Of the principal missions of the Navy, i.e., deterrence, defense of own and allies' territory, strategic and tactical offense, and overseas transport, the CTF is intended primarily for the third. (Command of the sea, sometimes referred to as a mission, is actually a condition of naval strength.)

A list of principal Navy missions is given in Table 1 which also gives particular CTF missions in support of the principal Navy missions. The listing of CTF missions includes: show of force, long-range reconnaissance, blockade, anti-air and anti-surface defense of own and allied territories, fleets and convoys, tactical ground support of ground and amphibious forces, tactical air strikes against enemy fleet and air units, and strategic air strike against enemy counterforce and countervalue targets in his territory.

Of course, in addition to these offensive missions, the CTF has the mission of self-defense against airborne, surface, and undersea threats.

The indexes of performance effectiveness define the capability of a WS to execute a mission. Insofar as possible, they should be measurable or, at least, rankable parameters.

The number of indexes of performance effectiveness related to the variety of missions that a CTF may execute could be fairly large with the result that an evaluation of the CVA/WS could be a fairly monumental endeavor.

Since such a general approach would be overburdensome, one inquires as to whether a simpler approach might be feasible and valid which would

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[2] Numbers in brackets designate References at end of paper.

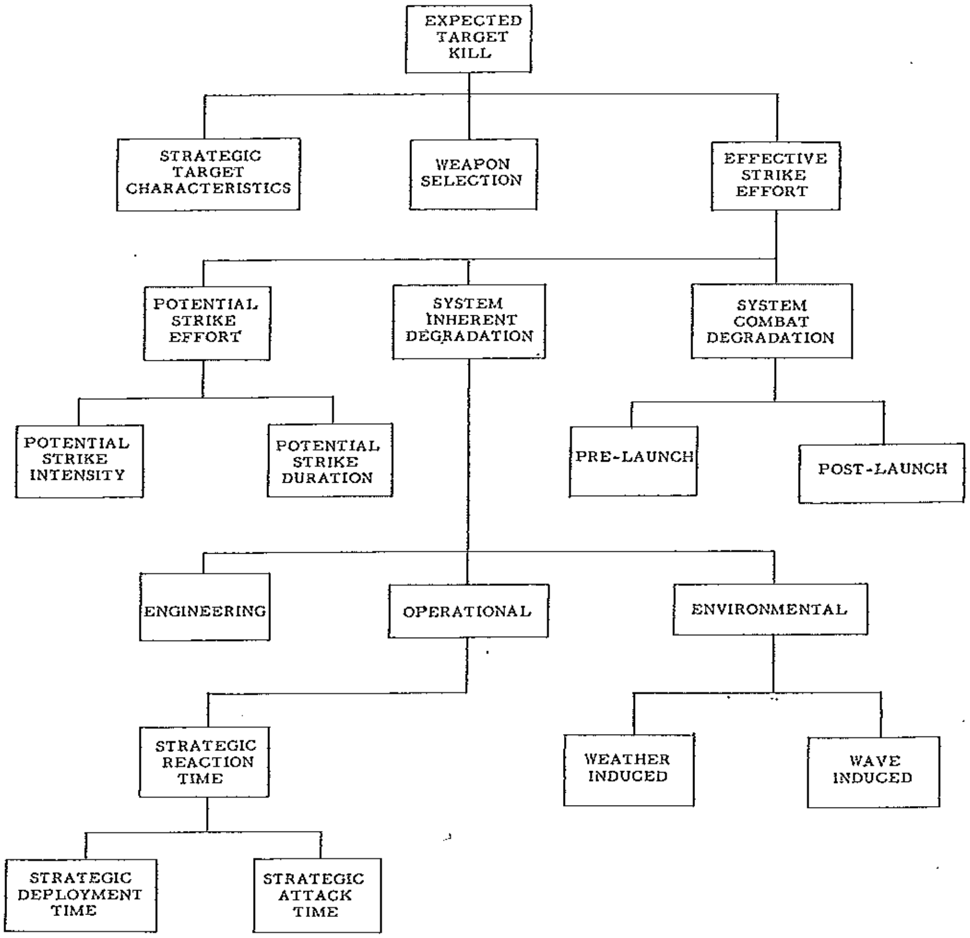

Fig. 2 Component items of attack effectiveness

rest on a powerful reduction in the number of missions and, therefore, in the indexes of performance effectiveness to be considered. Such an approach does obtain and is valid, but *only if there is a controlling mission.* Such a mission need not be the most probable one, but must have the virtue that if a WS is "optimized" for such a mission (insofar as any optimization is both meaningful and attainable), the WS will probably be satisfactory for all other missions in which it could be used.

Now advanced as a postulate is the hopefully defensible viewpoint that *for the purpose of designing the CVA* (at least for this purpose alone), the *air strike mission* is the controlling one. By "air strike" is meant the delivery of a set of weapons (either chemical or nuclear) against a set of strategic targets. Statement of the controlling mission leads directly to the indexes of performance effectiveness upon which to erect the rationale.

Approach

Given a controlling mission, one can either attempt a direct solution leading to a CVA/WS of optimum cost effectiveness or one can design a set of CVA/WS, derive their cost and performance effectiveness in postulated military conflict situations, and obtain the optimum by comparison. Of the two, the second process is somewhat simpler, straightforward, and unambiguous, but it is also exceedingly laborious and the optimum solution obtained by comparison is only the restricted optimum of the postulated set. If the set is not well designed, one obtains only the best among poor choices.

For this reason the suggestion is made that the logic should proceed from mission to design. This makes it necessary, at several points, to make selections from a range of possible choices. The method to be used is that of finding and applying a criterion that will yield the "local" optimum at any particular point in the process, i.e., the optimum for the immediate step to be taken. Although it is recognized that a final solution based on a sequence of local optima is not necessarily the "overall" optimum, yet it cannot be too far from this. The justification for this statement is to be found in the condition of "flat laxity" according to which a variation of the dependent variable in the neighborhood of an extremum (maximum or minimum) is small (indeed very small) for reasonably large variations of the independent variable.

The problem to be solved becomes, then, that of deriving the link between the indexes of performance effectiveness related to the air strike mission and the principal design features of a CVA. As a first step in the process, it is necessary to establish the indexes of performance effectiveness to be used. To this end, it is necessary to discuss the military qualities of the CVA/WS.

Military Qualities

In listing the military qualities with which the aircraft carrier (CVA) is to be endowed, one may begin by recognizing that she is the sea-based component of an offensive military system. The first purpose of an offensive military system is to force an enemy to submit to one's will, hopefully through the show of force, but, if ultimately necessary, through destruction of what he values. Thus, the first quality is that of attack: its measure is in terms of capability to destroy value.

But since it must be expected that the enemy will seek to prevent such destruction, enemy value destroyed will involve the risk of own value.

The obvious strategy is to seek to maximize the enemy value destroyed while at the same time minimizing the risk value to be paid (i.e., lost) for such destruction. This strategy may be termed maximization of net value destroyed.

Except for the now improbable case of duels between CVA/WS,[3] the targets assignable to these will differ in kind from those that an enemy is expected to seek. Also, an enemy will tend to assign a value to a target differing from the one we would assign thereto. Thus, the strategy becomes that of maximizing the net *weighted* value destroyed.

But value weighting presents a considerable number of problems which resist formulation, for value is a complex parameter: it has human, cultural, economic, political, and military aspects, and each belligerent tends to view and measure each aspect differently; there is no common scale; the units are quite different and changeable with time and the fortunes of war.

A powerful simplification obtains if only military value is considered, all other aspects being regarded as purely collateral and irrelevant. The items of pertinence are lives and military assets.

A basic assumption for setting up the evaluation process is that a maximum net value strategy is a valid one to apply to any particular mission. It is this assumption that permits rating the attack and defense qualities on the basis of relative importance.

Attack Effectiveness

In the attack mission, the effectiveness of a WS (i.e., the value destroyed) is measured by the expected target kill value (ETK). This is thought of as the expected fraction of target value destroyed by an attack, the target value used for reference being that obtaining at the time of receipt of command to attack.

The ETK is measured against a criterion of target destructivity which prescribes the level of damage to be inflicted on specific target systems. What this criterion should be is not examined here: It varies with each particular target, depending on its political, military, industrial, and civilian content, and on the political and military situation of the moment. It is an aspect of military doctrine. For an evaluation of competitive WS's it is only necessary to recognize that such a criterion is arbitrary but equal for all competitive systems.

The ETK depends on:

(*a*) Strategic target characteristics
(*b*) Weapon selection
(*c*) Effective strike effort

See Fig. 2.

Self-Defense Effectiveness

In the self-defense mission, the effectiveness of a WS is measured by the expected system survivability (ESS), which is defined as the expected fraction of system value saved from destruction by enemy attack.

The ESS depends on:

(*a*) Enemy attack effort
(*b*) Attack recognition and monitoring
(*c*) Weapon selection
(*d*) Effective defense effort
(*e*) Physical vulnerability of the system

See Fig. 3.

A desired level of military performance is obtained through the proper proportioning of attack and defense effectiveness. Since it is the system's

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[3] The World War II battles of Midway and of the Coral Sea are outstanding examples of such duels.

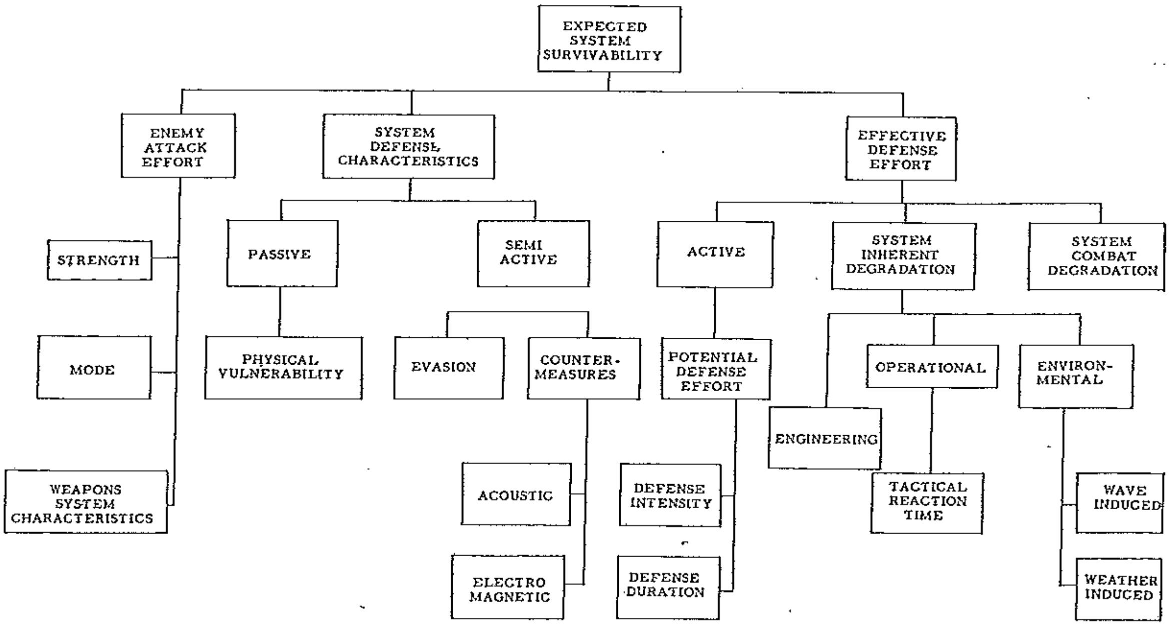


Fig. 3 Component items of self-defense effectiveness

attack and defense effectiveness that determines the military payload and features to which the CVA is to be designed, it is necessary to develop the factors entering into these measures of military performance.

Both ETK and ESS contain the common item of system combat degradation.

Target Characteristics

Targets are classed as either strategic or tactical. A strategic target is one for which the specific targeting authority is held in a unified command under the Joint Chiefs of Staff, such as the Commander in Chief, Pacific Fleet or the Strategic Air Command. Authority over a tactical target is held by a fleet command or unit thereof. Whereas a strategic target is stationary, although it may be of fleeting value, a tactical target is one of opportunity and its principal characteristic is its mobility.

Strategic-Target Characteristics

Only in the case of nuclear war are strategic target characteristics relatively easy to define, the essential variables in this case being few in number. For these, what is needed is the distribution over target geometry of:

(*a*) The densities of the target values of significance in nuclear war missions.

(*b*) Target resistance to the effects of nuclear weapons.

In addition to target-value distribution, an important characteristic is the permanency of such value. In this respect, targets are of two types: fleeting and stationary. The former are represented principally by the enemy's missiles, aircraft, and ships at base; the latter by the enemy's government and military control centers (including the missile, aircraft, and ship bases themselves), by population centers, industrial plants and stockpiles.

The ETK can be properly assessed only with reference to a particular target system. But since planning is necessarily by generalities, the target system is introduced only in terms of those features which are essential to the assessment. These are:

(*a*) Geography
(*b*) Geometry
(*c*) Physical vulnerability
(*d*) Defensive strength
(*e*) Fleetness

Target geography affects the deployment of the CTF, which, as will be brought out, affects in turn strategic reaction time (i.e., the time for the CVA/WS to react to a conflict situation and bring pressure to bear against enemy targets), force levels, logistics, and aircraft performance (from weather and altitude).

By target geometry is meant the total area and its configuration over which military value is distributed.

Physical vulnerability is defined in terms of the overpressure which will destroy the target, al-

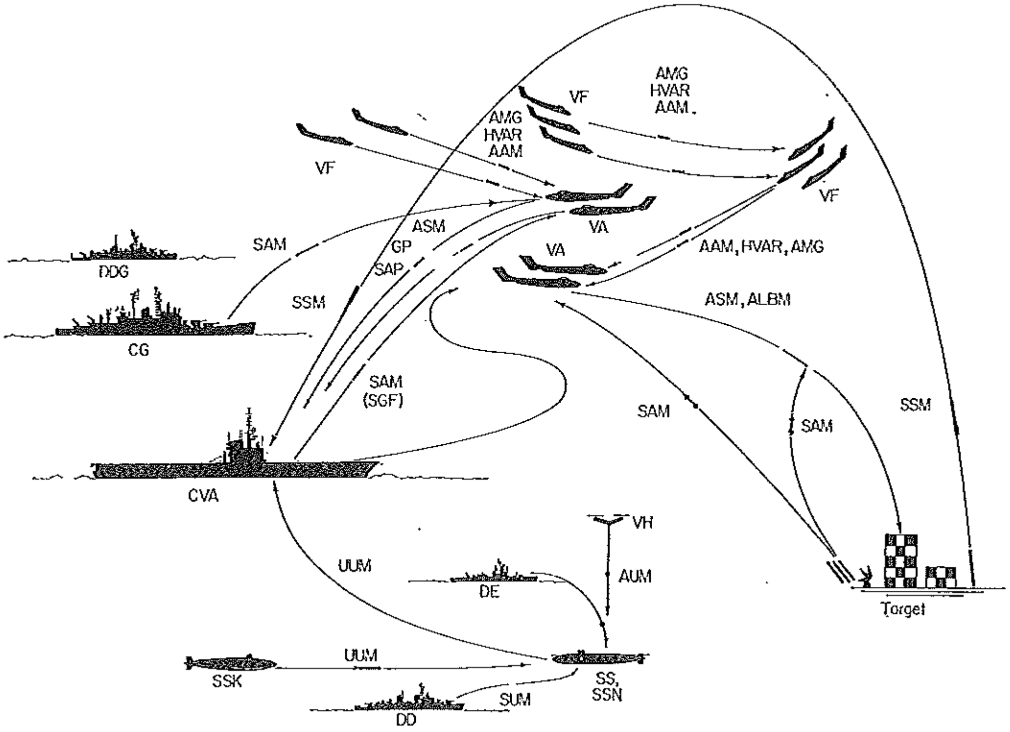


Fig. 4 Modes of CVA attack and defense

though other modes of destruction may prove more damaging in specific cases.

Such simple definition of physical vulnerability does not apply to non-nuclear conflicts. The absence in this case of a dominant mode of destruction amplifies the characteristics required to define this factor.

Defensive strength affects the penetrability of the attack aircraft (VA) and, therefore, the effectiveness of the strike effort. This, in turn, affects the number and types of aircraft to be embarked.

Fleetness (i.e., drop in target military value with time) is an important factor in determining what targets are assignable to the CVA/WS.

Tactical-Target Characteristics

Tactical targets are much more numerous and varied, but for the present scope one need only consider those targets which the CVA/WS may be designed to attack and those weapons which are designed to attack the CVA and against which self-defense measures are required.

Tactical Targets for Attack Missions

These are those targets that do not pose an immediate threat to the CVA/WS and which, therefore, must be sought out and destroyed. These are identified through aerial reconnaissance and must be attacked either immediately upon discovery or so shortly thereafter so as not to allow opportunity to the target to fleet. Trains, tanks, and even military forces fall into this category; they can move rapidly and distantly between reconnaissance missions.

Tactical Targets for Self-Defense Mission

These are the enemy's WS's intended for destruction of the CVA/WS.

The variety of WS's that might be available to a sophisticated enemy in a future time frame is fairly extensive, which makes identification of their relevant features an uncertain task.

Weapon Selection

This problem is solvable if the target system is known. For certain systems, for example, submarines and destroyer escorts, this is, indeed, the case, for they are relatively inflexible in this regard; but the CVA/WS is designed to cope with a spectrum of targets and the characteristics of these targets may not be known during the design planning stage. Since one cannot count on changing the aviation ordnance (avord) load carried by the CVA to insure optimum ETK and ESS, either because such a change may be infeasible for logistic reasons or because it may involve an unacceptable increase in reaction time, the CVA must be designed to carry a large assort-

Table 2 Weapons for Self-Defense

Mode of Enemy Attack	Enemy Vehicle	Vehicle Counterweapon	Enemy Weapon[a]	Weapon Counterweapon
Air		SGF[1]	GP[6], SAP[7]	
		SAM[2]	ASM[8]	SAM[2], VF + AAM[3]
	VA	VF + AAM[3]	ALBM[9]	AMM[11]
		VF + HVAR[4]		
		VF + AMG[5]		
	—		SSM[10]	AMM[11]
Surface	CG, CL	VA + GP[6]	SSM[10]	VF + AAM[3], AMM[11]
	DDG, DD	VA + SAP[7]	SUM[13]	—
	DDE, DE	VA + ASM[8]		
		VA + ALBM[9]		
Undersea		SS + UUM[12]		
		DD + SUM[13]	UUM[12]	—
	SS	VF + AUM[14]		
		VH + AUM[14]		
		VD + AUM[14]		

NOTES:

Type[b]

1 Surface gunfire: 5 in./38 cal, 20mm, 40mm guns.
2 Ship-to-air missile: Tarter, Terrier, Talos, Lance.
3 Air-to-air missile: Sidewinder, Sparrow, Phoenix.
4 High-velocity air rocket.
5 Automatic machine gun or 20mm cannon.
6 General-purpose bomb.
7 Semi-armor piercing bomb.
8 Air-to-surface or air-to-ship missile: Bullpup, Corvus, Hound Dog.
9 Air-launched ballistic missile: (Skybolt).
10 Surface-to-ship missile.
11 Antimissile missile.
12 Underwater missile: Torpedo, Hydrorocket, Subroc.
13 Ship-to-underwater missile: Torpedo, Asroc.
14 Air-launched underwater missile: torpedo, depth charge.

[a] American weapons cited.
[b] Present types listed. Types in parentheses have been discontinued.

ment of weapons to attack any target in a broad spectrum of possibilities, and to defend herself from attacks by a variety of enemy WS's. This makes for an ordnance load in excess of that required for a strike optimally designed against a particular target system and for a defense against a specific WS.

Attack Weapons

The expected kill value from weapons delivered against a strategic target is not proportional to their number and weight but is more complex and depends on weapon and target characteristics and total level of attack. Thus, unless we know or postulate these characteristics and level, ETK cannot be unambiguously related to avord delivered, hence to CVA design characteristics. In other words, although ETK is a cardinal measure by which to gage the effectiveness of the CVA/WS, it is somewhat ill adapted to a selection of CVA design features.

One can emerge to some extent from this unsatisfactory situation by basing the analysis on a target and weapon of reference, in which case the ETK becomes uniquely related to avord delivered on target and the former can be replaced by the latter. The effectiveness of the CVA with other weapons against other targets is directly related to that of the CVA with the reference weapons employed against the reference targets.

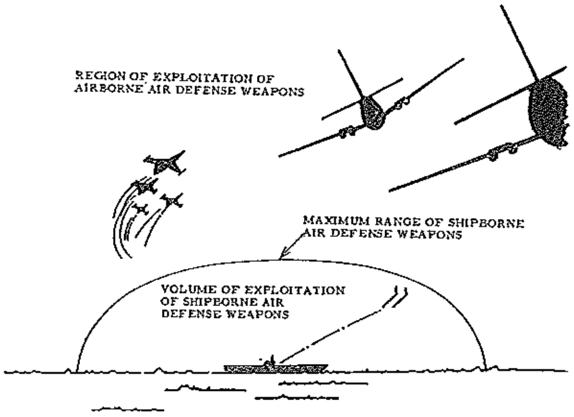
To be sure, it is arguable whether a fair choice can be made of reference weapon and target, for any choice tends to be regarded as a means to introduce bias. The choice of target is a particularly difficult one for, as will be brought out later under system reaction time, in addition to being characterized by hardness and size, the target may be of transient nature. But in the end, whether or not a convincing argument can be developed for substituting avord-on-target for ETK, one has little choice but to adopt the former as a measure.

Self-Defense Weapons

The types of WS that an enemy may employ for attack against the CVA/WS is fairly large; see Fig. 4 and Table 2. They may be classed according to whether the attack is air, surface, or undersea launched.

The types of weapons the CVA/WS could employ in self-defense are equally large. A first distinction is made as to whether they are CVA-borne or escort-borne. A second distinction is

Fig. 5 Zones of exploitation of shipborne and airborne weapons



made as to whether the CVA weapons are ship-launched or air-launched.

What defense weapon is to be employed against what enemy weapon depends on the medium of transit, on the range at which the enemy weapon reveals itself to the CVA, on its speed, and on whether the enemy weapon provides the defense WS with properties on which to home.

It is noted that airborne weapons are employed only beyond the volume contained within the maximum range of shipborne weapons, Fig. 5.

Effective Strike Effort

The effective strike effort is of three aspects:

1 Potential strike effort
2 System inherent degradation
3 System combat degradation

The last two aspects are common, in some respects, to the effective defense effort and will be discussed after other aspects of the effective defense effort have been considered.

The first two aspects constitute the unopposed strike effort.

Potential Strike Effort

The potential strike effort is the total weight of ordnance launched against a strategic target. It is given by the integral over strike duration of potential strike intensity:

$$E_{ps}(t_s) = \int_o^{s} I_{ps}(t)\,dt$$

where

$E_{ps}(t_s)$ = potential strike effort at time t_s after launch of strike, tons
$I_{ps}(t)$ = potential strike intensity, tons/hr
t_s = strike endurance

Potential Strike Intensity

This is the rate, undegraded from any cause, at which strike avord is loaded on the VA and launched against a strategic target. It is

$$I_{ps}(t) = \sum_i \left[N_{va}\cdot w_{ao}(r)\cdot \frac{d}{dt}o(r) \right]_i$$

where for each VA of type *i:*

$w_{ao}(r)$ = avord load for aircraft mission to radius r
$\frac{d}{dt}o(r)$ = rate of opportunity to fly in aircraft mission to radius r

where N_{va} is the total number of type i strike (VA) aircraft embarked and where the summation extends over all VA types.

The potential strike intensity is a function of aircraft mission radius and mission profile. Calculations are based on a reference mission radius to target (r_m) and a reference mission profile, the two being compatible and the latter being sea-level penetration all the way.

Potential Strike Endurance

This is the interval of time over which strike operations at the potential strike intensity level can be continuously maintained. This interval determines the onboard logistics of strike aircraft avord and of avfuel.

Effective Defense Effort

This is of two types: semiactive and active. The index of performance is the ESS.

Semiactive Defense Effort

This defense effort refers to the employment of countermeasures: evasional, acoustic, electromagnetic, and so forth.

Evadability

Evadability, or evasion capability, is definable in terms of CVA mobility (i.e., speed and maneuverability). It is proportional to area of uncertainty which depends on enemy weapon dead time (time from last fix on CVA to warhead detonation), CVA speed, and tactical radius.

Evadability against an enemy air attack is smaller than against undersea attack, for the weapon dead time tends to be shorter.

Against weapons employing terminal homing, evadability is small.

Acoustic and Electronic Countermeasures

The intent of these countermeasures is to degrade the enemy's capability to search and attack the CVA/WS. Their design and effectiveness is classified. However, they are introduced into the analysis in the simple form of empirical countermeasure factors obtained from fleet exercises. These are applied to the probability of success of that operation (detection, weapon conversion, and so on) they are designed to counter. Their effect on CVA size and principal design characteristics is negligibly small.

Effective Active Defense Effort

This is of two kinds depending upon whether the counterweapons employed are short range, ship launched, or long range, aircraft launched. As for strike effort, three factors are to be considered:

1. Potential active defense effort
2. System inherent degradation
3. System combat degradation

Potential Active Defense Effort

This is the total weight of ordnance launched against attacking systems. It is given by the time integral of a potential active defense intensity

$$E_{pd}\ (t_d) = \int_o^{td} I_{pd}\ (t)\ dt$$

where

$E_{pd}\ (t_d)$ = potential active defense effort at time t_d after activation of defense system, tons

$I_{pd}\ (t)$ = potential active defense intensity, ton/hr

t_d = defense endurance

Potential Intensity of Ship-Launched Defense

This is the undegraded rate at which defense weapons are launched against attacking systems. For ship-launched weapons this depends on number of weapon launchers, on weapon weight, and cycling time.

For aircraft-launched weapons, in lieu of weapon launchers, number of fighter aircraft (VF) embarked is used.

Potential Active Defense Endurance

This is the interval of time over which active defense operations can be continuously maintained. For airborne systems this interval determines the onboard logistics of fighter aircraft avord and avfuel.

Passive Defense Capability

This is defined in terms of the CVA resistance to weapon effects. It is measured in terms of ESS to airborne and undersea weapons (and to more complex weapons which transit both media).

The aspects of lethality are many. Obviously, sinking of the CVA is a sufficient condition of lethality, but it is not a necessary condition. The CVA/WS can be rendered inoperable in several ways: through damage to search and control sensors, which renders the CVA/WS deaf to control and blind to attack by the enemy; through damage to launch and recovery equipment (particularly the former), which inactivates the aircraft; through destruction of the ship's watertight integrity, thus possibly flooding vital spaces and disabling the ship, or at least altering trim to such an extent as to force cessation of operations; through damage to ship control equipment (rudders, propellers) which may yield the ship to the mercy of the elements; lastly (to close an incomplete list), through damage to the aircraft complement embarked.

All of these damages are discussed in terms of weapons effect radii, although not every item is equally susceptible to the same effect. For example, radars are rendered inoperative by lighter overpressures than catapults and they also serve, when radiating, as a cooperating instrument for guiding enemy passive homing missiles, which the catapults do not. The number of ship items to be considered when assessing CVA/WS lethality is large; the number of weapons that an enemy could employ against the CVA/WS is also large. This makes for a fairly intractable matrix of combinations to be examined. Again, simplification is sought by controlling combinations.

To an enemy's air burst weapon, the combining item is given by the aircraft complement, which is assumed to be uniformly distributed over the flight deck area. The effect radius introduced is that corresponding to the overpressure sufficient to render an aircraft inoperable. To an enemy's armor-piercing airborne weapon correspond the CVA vitals and those also correspond to undersea weapons (torpedoes, ASROC).

The effect radius of a weapon depends principally on its yield. Lacking intelligence on enemy WS (particularly future ones), one has no recourse in this regard but to assume that the enemy will have capabilities equal to our own projected ones for the same time period. This leads to the conclusion that the physical vulnerability of the CVA should be assessed in terms of the weapons carried by her own aircraft or embarked on her escort vessels. At least, some more realistic data are available for these than for the projected ones of a potential enemy.

System Inherent Degradation

The military performance of the CVA/WS suffers from inherent (noncombat) degradation from three causes:

1 Engineering
2 Operational
3 The natural environment

Engineering Degradation–Dependability

Engineering degradation is assessed in terms of its complementary aspect of dependability, which is defined as the expectancy that the CVA/WS will be technically able to carry out its mission.

Dependability is of two aspects:

1 Availability
2 Reliability

By availability is meant the engineering readiness of WS components to perform in a mission. This depends on the reliability of the system and on its maintainability. The most important WS components in this regard are the VA and VF.

Reliability is the expectancy that a system will not malfunction after orders to activate. Assessment of the reliability of a system yet to be designed is a problem in statistical uncertainty.

Operational Degradation—Reaction Time

Two reaction times are to be distinguished: strategic and tactical. The first is a measure of strategic attack timeliness, the second of tactical attack or, more importantly, of tactical timeliness of self-defense.

Strategic Reaction Time

This is the time interval from receipt of orders to strike to impact of warhead on strategic target. It is the sum of the time required for the CVA to transit from station in an area of deployment to an area of operations from which the VA can be launched and of the time required for the VA and their weapons to reach target. It is written as the sum of a strategic deployment and a strategic attack time.

Strategic reaction time may be an important factor in determining the attainable ETK. Its importance depends on whether the system to be targeted is stationary or fleeting (as well as on its reactive capabilities—whether passive or defensive or offensive). Strategic reaction time is least important when considered in connection with attacks on stationary, passive targets, such as industrial floor space and natural resources, and most important when in connection with attacks on fast-fleeting, offensive targets, such as intercontinental ballistic missiles and long-range bombers.

ETK degradation from target fleetness occurs either because (as in the case of missiles and air bases) the enemy launches his targeted items (his weapons or weapon carriers) in counterstrike operations, or because (as in the case of stationary targets) of attrition from attack by other competitive WS, our own or our allies'.

Since the attacker can attempt to kill only what fraction of initial target value is left at the instant of his attack, an increase in strategic reaction time usually tends to deprive him of the rewards for his risk and efforts. There is obviously a greater return from attacking all targets early upon the initiation of hostilities, but since a country's arsenal is usually insufficient to this task, the military planners formulate a targeting doctrine which establishes the priority for assigning weapons to targets and makes for delay in the time of attack on certain targets.

Strategic Deployment Time

This is perhaps the most important factor determining the CVA speed of deployment. It is the quotient of distance from station to area of operations and CVA speed of deployment. The numerator depends on:

(*a*) How early an advance intelligence is available as to a developing military conflict situation.

(*b*) The deployment pattern of the WS.

The first factor is obvious: early intelligence permits closing the distance from station to area of operations in advance of orders to strike. But early intelligence cannot be relied upon; the enemy may be uncooperative in giving us strategic warning. The second factor depends essentially on force levels.

As to speed, it is noted that high CVA speed is always of advantage, but the price to be paid for it may not always be appealing. The speed used herein is that at which the CVA and her escorts are deployed as a unit under conditions of urgency. This speed is selected on the basis of a compromise between quick strategic reaction time (which would require steaming at full speed) and good steaming range for the task force as a whole (to attain which, steaming at a slower speed is advantageous), the two qualities being somewhat contradictory. Thus, the speed for strategic deployment is not so much a ship parameter as it is a task force parameter, although occasionally the CVA does deploy unescorted.

Also, the speed of deployment to be given a CTF depends strongly on planned force levels, for scarcity in numbers of CTF must be made up by speed increase if strategic reaction time is not to be severely degraded.

The problem to be faced is that of weighing strategic deployment time against the cost of providing individual ships of greater power (hence also of greater rate of fuel expenditure) or, alternately, a larger number of ships.

Tactical Reaction Time

Tactical reaction time expresses how soon and how fast a CVA can launch strike or interceptor aircraft upon receipt of command or recognition of enemy attack and how soon the CVA shipborne armament can react to the attack. It is an essential element in the survivability of the CVA to air attack, particularly when the attack is fought off by own interceptors, which have a slower reaction time than shipborne armament.

Tactical reaction time for air operations is basically a function of airbase efficiency and of aircraft speed. It is a fundamental factor in the survivability of the CVA to air attack.

Tactical reaction time involves:

(*a*) Aircraft readying time
(*b*) Time to launch
(*c*) Time to intercept and kill

Tactical reaction time for ship-launched weapons is similarly made up of:

(*a*) Readying time of countersystem
(*b*) Time to localize or lock-on target
(*c*) Time to intercept and kill

For aircraft, the remaining times are small in comparison with readying time. However, during wartime cruising, some of the aircraft are in alert status, i.e., prepared for launch and for the initial response to an attack; the readying time is zero.

Environmental Degradation of Military Performance—Operability

The action of weather and waves tends to degrade the military performance of the CVA/WS and the measure to which the calm air and water performance is realized is given by the WS operability. This is defined as the expected degree of attainment of calm-environment WS performance.

When dealing with the CVA/WS, distinction is made between the degradation resulting from the response to the environment of the base itself (the ship), of base support equipment (sonars, radars), of the vehicles (the aircraft), and of the weapons.

Ship Operability

Ship operability is essentially determined by the magnitude of the oscillatory motions, and is defined as the expected time at sea that these motions will not exceed limiting values such that air operations must be temporarily curtailed.

Thus, ship operability is related to the yearly average fraction of time that the waves do not exceed certain dimensions. This relation is given by the transfer function (one for each motion) which depends, in a complex manner on the ship's geometry, on her weight distribution, and on her operations. In general, the larger the ship, the greater the operability.

At present, the criterion of limiting motions is stated in terms of pitching amplitude; namely, air operations are called off when the ship pitches more than ψ_ℓ degrees, the value of ψ_ℓ being determined from experience. Thus, to assess operability, it is necessary to determine the long-term cumulative frequency that the pitching amplitude will be less than ψ_ℓ. To this end, the following procedure is used:

(*a*) Synoptic material on sea conditions is examined to yield frequency of occurrence in the region of interest. The North Atlantic has been usually taken as the region of reference.

(*b*) The transfer function for pitch is obtained in terms of the ship's principal characteristics.

(*c*) The long-term frequency of occurrence of pitching amplitudes less than the limiting value is derived. This is the ship operability.

Ship operability does not necessarily correspond to the fraction of time that the environment may render the sensors, the aircraft, or weapons inoperative. In the evaluation of a WS, it is, of course, the joint operability that controls.

Sonar Operability

It has not been customary to install sonars in CVA, dependency for the detection of the underwater threat being placed in the tactically more flexible escorts. However, whether in CVA or escort, degradation of sonar performance as a function of sea state is similarly determinable depending, as it does, not only on the rise in ambient sea noise level, but also on the reverberation from entrapped air, on wave slap against the hull, and on the response of the ship to the state of the sea, the latter accounting for sonar emergence and bubble quenching of signals. Since sonars are bow mounted, sonar operability is a functional of vertical bow motion, i.e., of coupled heave and pitch. The criterion of sonar operability can be stated in terms of the expected long-term frequency of sonar or bow emergence.

Variable-depth sonar and sonobuoys suffer from similar causes, the latter from water on the antenna. In performance analyses, such degradation can be taken into account through an environmental performance factor.

Radar Operability

Performance degradation of a radar is related to ship angular accelerations and velocities, those of roll and pitch being of importance in this connection. The criterion is similar to that of ship operability, but since each radar degrades differently from ship motions from other radars, this condition must be taken into account when assessing the overall operability of the radar suit and of the subsystems to which each of its components is related.

Aircraft Operability

Aircraft operations are suspended when the wind intensity exceeds a critical speed ($V_{w,cr}$). The frequency of occurrence of such winds in any region is given directly in weather charts.

System Combat Degradation

"A gaming model cannot tell what the optimum response to a state of affairs is—it can only make us aware of uncertainties."

E. S. Quade (1963)

System combat degradation is of two aspects:

1. Personnel performance degradation
2. System attrition or vulnerability

The first is discussed under personnel combat effectiveness, the second under system survivability.

Personnel Combat Effectiveness

An estimate of how far the performance of a system in real combat falls below its performance predicted from analyses of exercises belongs to the class of problems for which the uncertainties are real, not merely statistical. Personnel combat effectiveness depends on discipline, training, morale, and alertness. These factors are intangible and difficult to quantify, as may be inferred from questions pertinent to this aspect; e.g., "Will the enemy surprise the CVA/WS?; or, Will there be warning and, if so, will the warning be believed?"

In evaluations in which the CVA/WS is compared with competitive WS of different concepts, personnel combat effectiveness could be an important factor, for it must be expected that some systems will suffer more than others in this regard.

However, for making a selection among essentially similar designs, the uncertainties as to performance degradation are likely to affect all alternatives more or less equally, so that this factor can be equated among them and hence is disregarded in the comparison.

Combat Survivability

The combat survivability of the CVA/WS depends on the type, level, and quality of the enemy attack, on the defenses that can be activated to counter it, and on the physical resistivity of the system. The large number of parameters required to define the attack and defense systems and their interaction makes even the formulation of an analysis of CVA/WS survivability an astronomical task even if number and capabilities of all systems are known.

To make progress, the number of parameters and the complexity of their interactions are reduced until what is left is manageable. This reduction is made by abstracting from the totality of factors defining real situations the essential or relevant aspects and considering these alone. This yields conflict or engagement models.

To be meaningful, the conflict models must account for the uncertainties which enter fundamentally into the evaluation. These uncertainties relate to a future enemy: the strength of his arsenal (equipment capabilities and force levels), his military doctrine, his battle strategy and operational tactics. Essential inputs on all of these are largely wanting and cannot be predicted with reasonable confidence. This forces one to depend on purely theoretical studies in which most inputs are a matter of judgment rather than the result of measurements.

There is one great handicap in the way of an analysis of warfare problems: an almost complete lack of methodology for obtaining practical answers even in those cases when the problems can be formulated, which is, indeed, rarely. In its essence, warfare analysis is concerned with the interaction of two opposing sides having conflicting aims, each side making sequential decisions based on its opponent's actions and neither side having at any time full information of its opponent's state.[4] This makes for looseness of behavior, complex logic of analysis, and uncertain prediction of results. At best, the path from mathematics to useful results is arduous. This

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[4] The author distinguishes between game theory in which each side has full knowledge of its opponent's state and warfare analysis in which this knowledge is, to a greater or lesser degree, wanting. This makes for a fundamental difference in methodology.

in itself calls for analysis by the simplest mathematical models reasonable. A philosophical essay on the subject is contained in Isaacs [2].

Conflict models are distinguished as suitable for long-range planning and for operational optimization. Only the former are of interest here: they provide an overall, not a specific, treatment of the problem. One is interested not in models that will play through tactical situations and eventually lead to preferred tactics, but with models that will lead to tactical "envelopes," i.e., to more general answers which are independent of specific decisions. The criterion to be used in selecting conflict models is whether they are useful for *designing* the CVA/WS. The problem is a narrow one, for it relates to a choice between alternative configurations of the same WS. For this purpose, not only are relatively unsophisticated conflict models adequate, but, indeed, they may not need to be solved at all, it being altogether sufficient to derive and compare the values of the constants of warfare entering into equations of combat.

It is necessary to distinguish between system combat degradation occurring prior to, and that occurring after, launch of aircraft. In the first case, the WS is concentrated and the survivability of the CVA/WS is identical to that of the CVA. After aircraft launch, this identity no longer obtains and separate assessments must be made.

The following remarks are on those aspects of survivability that affect the design of the CVA.

Of the various possible threats to the CVA/WS (Fig. 4), the most important are the submarine and the air attack. The discussion herein will be limited to these modes.

There are certain basic differences between the two modes of attack. These relate to number of attackers, their speed, their detection and classification ranges, their coordination, and their overtness. For the submarine, these parameters have low values, for the aircraft, high.

Whereas blunting of the air attack requires the destruction of the attacking aircraft or weapons, the submarine attack is blunted by simple detection and recognition of the presence of an enemy submarine in the waters in which the CTF is operating. Detection of the submarine will result in radical changes in defensive tactics to the point that the attack will have to be regenerated and a counterattack by the CVA escorts will be brought to bear against the submarine, thus changing him from stalker to quarry.

CVA Survivability to Submarine Attack

For the enemy submarine attacking the CVA, the problem is complicated by the condition that his target is mobile and he must first locate it. Thus, the first phase of a submarine attack consists of a search which must be covert. Also, the search is ordinarily carried out in an environment of false contacts. These may be either passive (e.g., merchantmen), involving no danger to the submarine should he expose himself, or active (e.g., CVA escorts), involving definite peril to him.

A successful search may not be followed immediately by a submarine approach to weapon launch position, but there may intervene a time interval during which the CVA is shadowed until the time to close in is considered to be opportune.

The next phase of the attack is the approach or closing in to weapon launch range. This is followed by weapon (i.e., torpedo or missile) interception or conversion, which is the phase from weapon launch to detonation. The last phase, the kill, takes into account the characteristics of the weapon and the physical vulnerability of the CVA.

Thus, the expectation of CVA survival to a submarine attack results as the product of seven principal probabilities:

$$S_u(t) = 1 - P_s(t)\cdot P_t(t)\cdot P_a(t)\cdot P_c\cdot P_k\cdot P_r\cdot Q_{acm}$$

where

P_s = probability of successful covert search by submarine
P_t = probability of successful covert shadowing (or tailing)
P_a = probability of successful approach to CVA
P_c = probability of successful weapon conversion
P_k = expected fraction of CVA value destroyed
P_r = overall reliability of submarine-based WS
Q_{acm} = probability that acoustic countermeasures will *not* be effective

Note that the first three probabilities are time dependent; hence, so also is the expected CVA survival.

Search by Attacking Submarines

Search is the process of upgrading intelligence on the location of the CVA to the point where a fix can be obtained.

There are three phases to the search:

1 Detection (first awareness of the probable presence of a target).
2 Classification (determination that the de-

tected signal or contact comes from an enemy ship).

3 Identification (the enemy ship is a CVA).

The ranges at which the CVA may be detected, classified, or identified depend on certain engineering and operational CVA characteristics, on the type and capability of the submarine sensing equipment, and on the environmental conditions surrounding the search.

CVA Shadowing by Submarine

If an enemy submarine identifies the CVA at a time earlier than that at which he may want to attack, he must lock-on and shadow her until ready to close in and kill. During this period the CVA may escape him and the success of his attack may be degraded thereby.

The degradation factor is difficult to determine. Its value depends on a large number of variables, among which one may list the CVA acoustic signature which depends on speed and course, on operating depth, and on physical properties of the water column; the performance of the submarine's sonar gear, which is a function of equipment, environment, and speed; and the CVA operational tactics, including maneuvers and decoys or jammers. In practice, this factor is empirically derived from analyses of fleet exercises, a correlation being made between surface-ship characteristics and tactics, on the one hand, and sonar equipment and submarine tactics on the other.

CVA Approach by Submarine

The locus of positions from which a submarine can attack the CVA with a prescribed probability of success is a quasi-circle whose radius is less than the weapon range. However, the sector of search area from which the submarine can approach the CVA to within attack radius is determined by the ratio of submarine to CVA speed (V_u/V_s). If the submarine speed is less than the CVA, the sectorial angle is

$$\psi = \sin \frac{V_u}{V_s}$$

but if larger, the submarine can approach from any direction.

Conversion on the CVA by Submarine-Launched Weapons

By conversion is meant that the weapon will be placed within effect radius of the target. In discussing weapon conversion, a first distinction is made between unguided and guided weapons. One distinguishes among unguided weapons further by separating them into homing and straight running.

The probability of conversion of submarine weapons depends on their effect radius, their attack error, and on the evasion tactics of the CVA. For unguided weapons (straight-running torpedo, ballistic depth charge), the error can be high and evasion tactics can seriously degrade conversion probability. Evasion from wire-guided torpedoes is more difficult because of the continuous upgrading of fix data. For homing torpedoes, the effect radius is equal to the weapon acquisition radius, while the attack error is negligibly small.

Physical Vulnerability

The resistivity of the CVA to influence torpedoes is a more complex problem, for the possible modes of failure are increased. The shock damage of contact torpedoes is supplemented by bubble pulses which may not only impair the watertightness of the bottom, but may break the ship's back.

CVA Kill by Submarine-Launched Weapons

The CVA value killed by a single weapon depends on the overpressure developed by the weapon and on the physical resistivity of the structure on subdivision and on damage-control measures. The first varies with weapon yield, which is a function of charge weight; the second depends on the torpedo protection installed.

To place her out of action, a nuclear weapon of sufficient yield must be detonated within the radius of effects which have been incorporated into the CVA design.

To discuss CVA resistivity to torpedo charges, these are classed according to whether they are detonated upon contact or through influences. The former are resisted by the side protection, the latter by the bottom protection and by the primary (or girder) strength of the ship.

The resistivity of the CVA to contact torpedoes is assessed in terms of the nominal charge weight she is able to withstand in contact explosions, this being defined in terms of its TNT equivalent.

A relation between number of torpedoes, weight of charge, and kill value remains to be established. The CVA value destroyed by a single weapon (single shot kill expectancy) is given by weapon lethality.

CVA Survivability to Air Attack

The expectation of CVA survival to air attack results as the product of six principal probabilities (five of which are already defined):

$$S_a(t) = 1 - P_s(t) \; P_a(t) \; P_c \; P_k \; P_r \; Q_{ecm}$$

where Q_{ecm} is the probability that electronic countermeasures will *not* be effective.

The air attack follows the same sequence as the submarine attack with the following significant differences. The attack is overt (albeit by surprise if possible), there is no shadowing, and the number of attackers can be large and their actions coordinated.

Search by Attacking Aircraft

Air search by the attacking aircraft is degraded by magnifying his detection and classification problem. The CVA is now recognized through her optical and electromagnetic signatures. The first is only effective at short range and only useful for positive identification should this be required. The CVA can do little to avoid optical identification, weather permitting. To avoid recognition through her electromagnetic signature, three courses are open: to weaken the signature, to mask it (by interference or jamming), and to introduce deceptive signals. The first alternative makes the initial detection more difficult, the second and last alternatives, the electronic countermeasures (ECM), make classification a greater problem.

Signal weakening can be achieved through operational means (emission control doctrine) which has no significant effect on CVA design.

Quantification of the influence of ECM against enemy air search is difficult and uncertain, since this influence depends on a large number of CVA characteristics (including size, configuration, and materials) and on environmental conditions (meteorological, oceanographic, and traffic). However, ECM makes but small demands on the military payload, so that its influence on CVA design is fairly negligible.

The enemy's air search may also be degraded by mobility; however, the ratio of speeds is such that, for the purpose of planning at least, mobility can be discounted.

The probability of CVA detection is determined as for the submarine search. Because of the relatively higher values of sweep range and speed as compared with those corresponding to the submarine case, the search is greatly accelerated.

CVA Acquisition by Enemy Aircraft and Conversion by Air-Launched Weapons

Interception of the CVA by enemy aircraft presents no kinematic problem as it does for the submarine, although there may exist a range problem.

Degradation of the enemy's aircraft and interception and weapon conversion capability can be sought by the passive means of electronic emission control and by the active means of counterweaponry, launched either by shipborne armament of the CVA or her escorts or from VF interceptors. The first is effective only against radar homing weapons; the second is discussed under the combat model.

Engagement of Enemy Aircraft by CVA Interceptors

If the air attack is detected in sufficient time, the CVA can launch in her defense the available VF complement and engage the enemy aircraft in an air battle, which they must survive to engage the CVA/WS shipborne defenses.

The outcome of such an air battle is determinable by Lanchester's square law. Application of such law requires knowledge of the exchange ratio (average number of VF lost to average number of enemy attackers lost). Such exchange ratio is derived from fleet exercises with own VF and VA and extrapolated to future conditions.

The exchange ratio depends on the ordnance loading of the attacking VA; i.e., on the proportion of their avord intended for the CVA as against that intended for self-defense against VF.

Of course, the VF interceptors can be met by attacking VF escorts in advance of the VA, with a more favorable exchange rate to the attacker.

Engagement of Enemy Aircraft by Shipborne Defenses

This occurs only within the shipborne defense boundary. The method is the same as for the engagement by CVA interceptors.

Expected Survivability of the CVA/WS in a Given Conflict Situation

The foregoing discussion leads to an estimate of the expected survivability of the CVA to attack by submarine or air (or by alternate modes). If the expectation that these attacks will be made against the CVA in a specific military conflict situation be respectively denoted by

$$P_u(i),\ P_v(i)$$

the surviving value of the CVA/WS in this conflict situation is

$$\begin{aligned} S_i(t) &= 1 - [1 - P_u(i) \cdot S_u(t)] \cdot [1 - P_v(i) \cdot S_v(t)] \ldots \\ &= 1 - \Pi_j \cdot [1 - P_j(i) \cdot S_j(t)] \end{aligned}$$

where j represents an attack mode.

Expected Survivability of the CVA/WS

There remains only the problem of giving proper weight to the expected occurrence of military conflict situations. If this expectation is defined by P_i, the expected survivability of the CVA/WS is

$$S(t) = 1 - \Pi_i[1 - P_i \cdot S_i(t)]$$

Some remarks on the problem of weighting are made in the last section.

Penetrability

The penetrability (or in-flight survivability) of the VA depends upon the quality and quantity of the enemy defenses, i.e., on their effectiveness against the aircraft and weapons. In assessing penetrability, the problem is not with the methodology, for this is the same as that of the defense of the CVA by her own battery and interceptors, but with the uncertainty as to what the enemy defenses might be. Again, one is left with no alternative but to postulate quality of own weapons and to introduce quantity parametrically. This has the advantage that the statistical uncertainty as to combat exchange ratios is reduced, since these can be estimated from own past exercise data and extrapolated to account for future conditions.

Parameters of Military Performance

The parameters of military performance entering into the statements of military effectiveness involve quantities, weights, speeds, operational data (reaction time, range, operability, dependability), and combat expectancies (exchange ratios) for the ship, aircraft, weapons, surface and submarine escorts, as well as own force levels and enemy threat.

Command, Control, and Communication (or C^3)

Underlying the discussion of the preceding section, devoted to military performance qualities, is the thought that proper control of these qualities exists at all times and that they can be brought into action, to any degree up to their full potential, at will. This step requires the ability to communicate and the exercise of authority. This makes for additional military features to be incorporated in the CVA/WS.

Communication

Communication comprises the reception from off-ship sources, the distribution on ship, and the transmission to off-ship receivers of orders and information.

The CVA/WS is designed to be distantly deployed from homeland and from fleet headquarters. This makes for a need to communicate, both openly and securely, possibly over great distances, for the preservation of ordinary ties and for the exercise of command authority and control measures.

Command

In a CTF, fleet units operate in an integrated manner in collective action. External direction of the CTF from the Chief of Naval Operations through Fleet Headquarters and internal direction of the CTF units is a command function. Command authority over the CTF units is usually vested in the CVA. Exercise of this authority requires the provision of CTF headquarters for a flag officer and his staff and communication capability of command.

Control

Control refers to the exercise of direction over performance of a system. It is this feature that integrates various components into one WS. In the CVA/WS, control is exercised over ship operations and air operations; the former including launching of shipord, the latter of aircraft and their avord.

Control is based on the receipt of command and of intelligence, the collection, analysis, and interpretation of the latter, and on choice of countermeasures, decision, and communication of orders to activate. Acquisition of intelligence, which is through search sensors (sonar, radar), collation, analysis, and interpretation, requires a combat information center (CIC). Execution of orders requires personnel complements for ship and air operations. Manning is discussed under military payload and base.

Nautical Performance

The essential difference between naval WS and those of the sister services is that the naval systems are *sea-based*. But the weapons and weapons carriers themselves exploit as medium of transit the sea, the air, the space, or (as in the case of Polaris) all three.

Sea-basing of the CVA/WS demands that the CVA platform be provided with certain nautical performance qualities. Air and space transit requires that the weapons and weapons carriers have certain aerodynamic and ballistic qualities, but these will not be discussed herein.

The nautical performance qualities define the ability of the CVA/WS to operate at sea. They consist of:

(*a*) Seaworthiness
(*b*) Seakindliness
(*c*) Deployability

Seaworthiness

By *seaworthiness* is meant insurance of the following provisions in the *worst* expected sea state encounterable:

(*a*) Extreme motions such as to allow adequate margin against capsizing and foundering.

(*b*) Structural strength sufficient to withstand with adequate margin the hydrostatic and hydrodynamic loadings imposed by the sea.

(*c*) Response to directional control.

(*d*) Safety in manning.

The foregoing apply to the CVA in the intact condition. Should the watertight integrity be compromised, then safeguards must be available to insure the unit's viability under certain conditions. For all damage less than that given by a prescribed criterion, the provision must hold in a sea state related to the worst that:

(*e*) Ship attitudes and motions will be such as to allow adequate margin against capsizing and foundering.

Seakindliness

Seakindliness is the property of a fleet unit to remain safely operational in all wind and sea states up to those of limiting intensity. Operability in this case comprises:

(*a*) Attitudes and motions below certain levels prescribed from experience as safe for carrying out operations.

(*b*) Absence of severe hydrodynamic impact (slamming).

Deployability

Deployability is the ability of a ship to operate at sea. It is a complex quality. Its two principal aspects are:

(*a*) Mobility
(*b*) Endurance

Mobility is interpreted in terms of:

(*a*) Sustained speed
(*b*) Course-keeping ability
(*c*) Maneuverability

Endurance consists of:

(*a*) Steaming range (unrefueled)
(*b*) Hotel endurance

Sustained speed is the average speed that a unit can maintain at full power in all the sea conditions it may encounter on route weighted by the relative frequency of their occurrence.

Course-keeping ability is the property of the unit to maintain any prescribed course in all environmental conditions up to that of limiting operability. For more severe environmental conditions it is only required that the unit maintain heading into the waves.

Maneuverability, or ability to change course, is defined by the tactical diameter attainable at full power in the annual average sea condition.

Steaming range is the distance the unit can travel unrefueled at a reference speed (usually the cruising speed) in the annual average sea state.

Hotel endurance is a statement of the length of time the unit can remain deployed without reprovisioning.

There is overlap between the factors making up the nautical quality of deployability and those entering into the military quality of strategic mobility.

Seaworthiness

Worst Expected Sea States

The design sea states are related to the extreme sea states expected. The 20, 25 and 30-year maximum sea spectra for the North Atlantic are shown in Fig. 6.

Expected Maximum Oscillations

The oscillations of importance in defining the environmental survivability of the CVA are roll and pitch (or, more accurately, combined pitch and heave). These are obtained as for the condition of ship operability. The sea spectrum to be used is *not* that corresponding to the severest expected sea state during the ship's lifetime, but to that sea which makes for the greatest response!

Structural Strength

The CVA must satisfy a criterion of adequate structural strength to insure that she will not come to grief when acted upon by waves no matter what their severity. The waves affect the nautical performance essentially through the hydrodynamic loading they impose on the vessel. This loading is of a transient nature, but distinction is made between such hydrodynamic loading that does and such that does not induce a vibratory response of the hull structure. The first is quasi-static: it gives rise to the rigid-body oscillations of the ship and to an elastic response of the hull structure varying with the frequency of the encountered waves, i.e., relatively slowly. The second type of hydrodynamic loading is impulsive: it generates vibratory response of the hull structure at the frequencies of its elastic modes. Thus,

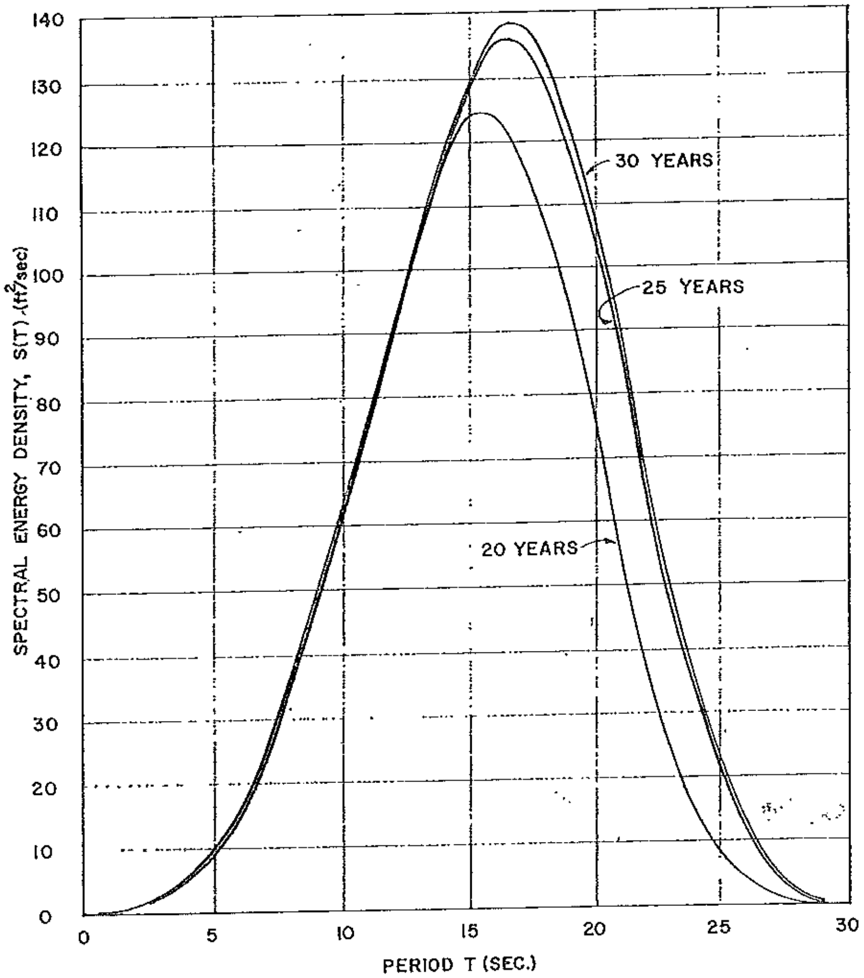

Fig. 6 Wave energy spectra for 20, 25, and 30-year intervals of observation

the condition of adequate strength is statable in terms of

(*a*) quasi-static strains
(*b*) impulsive strains

when these responses are related to those sea conditions that develop their maximum values (design sea states).

No reliable theory of wave-induced stresses has been developed, so that one is left to depend on empiricism.

Adequate strength is provided by insuring that the structure is subject to relatively low primary (ship bending) stresses, thus allowing a margin for the secondary (panel) and tertiary (plate) stresses and for the residual strains in the structure.

No separate criterion for impulsive stress has been formulated. They are grossly accounted for in the criterion of primary stress.

Response to Directional Control in Extreme Seas

Even in the severest sea, the vessel must have sufficient control to maintain heading into the waves in the hove-to condition. Thus, the ship must have steerageway sufficient to overcome the yaw induced by the design sea state.

Safety in Manning

When angular displacements or linear accelerations exceed critical values, manning becomes increasingly hazardous. No criterion appears to have been established for these values, but for a CVA, 20 deg roll and 0.75 g acceleration (uncombined) are probable critical values.

Provision Against Capsizing and Foundering in the Damaged Condition

The criteria for tolerable damage effects have been given by Sarchin and Goldberg [3]. For a CVA the reserve buoyancy is high and the critical effect is the angle of heel produced by the rapid asymmetric flooding (i.e., before the application of counterflooding) caused by torpedo damage.

Seakindliness

The limiting angle of pitch for aircraft operability has been discussed in the foregoing. No simple method is available for the quick insurance of freedom from slamming.

For structure and personnel, both of which are sensitive to acceleration, slow, gentle oscillations are preferable to faster oscillations of corresponding lesser amplitude. The important motion in this regard is roll.

Deployability

Sustained Speed

The problem of determining sustained speed in terms of power installed, sea states, and ship principal characteristics does not appear to have been solved, so that a crude rule of thumb is ordinarily employed which makes sustained speed 3 percent less than that which is obtained on the expenditure of 80 percent of full power.

Course-Keeping Ability

The CVA has no problem in this regard, her principal dimensions being such as to insure directional stability at all speeds.

Maneuverability

This is defined by the tactical radius (r_t).

Unrefueled Steaming Range

This is an arbitrary input. In recent conventional CVA designs, unrefueled steaming range (r_s) has been held at a fixed figure.

Hotel Endurance

This also is an arbitrary input and has been stabilized at a fixed nominal value.

Conceptual Designs

The military, nautical, and C^3 qualities do not describe the design of a system, but are in themselves only measures for:

(*a*) Insuring that the design is realizable and that the system will function properly.

(*b*) Evaluating the system's military effectiveness.

A statement of these qualities gives as yet nothing to evaluate. To proceed with the evaluation process, it is necessary that these abstract qualities be given visual configuration. This is accomplished by their synthesis into coherent systems or conceptual designs. The designs are then tested against the governing specifications and criteria to insure their validity and are proportioned to fit a selected set of indexes of performance effectiveness.[5] The flexibility that one has in developing system designs depends to some extent on the number of parameters and their allowable range of variation.

Essential specifications are:

1 The system's mission or missions
2 Design constraints imposed by:
    (*a*) Political factors
    (*b*) Economic factors
    (*c*) Military factors
    (*d*) Hydrographic factors

The possible effect of political factors is that of a denial of the use of bases in areas remote from home and of a denial of rights of overflight. These denials tend to make for an increase in the steaming range and endurance of the floating base; for a larger combat range of the aircraft, their weapons, or both; and for greater logistic support.

As to constraints imposed by economic factors, it is fairly obvious that the cost of the system itself is subject to budgetary restraints, particularly in these days of a fixed defense budget. All weapons systems are in strong competition for the defense dollar and a balanced program of funding of weapons for all foreseeable contingencies does not allow for all bets to be placed on a single system.

In addition to the economics of the system itself, the supporting systems must be taken into account. If a ship is to exceed 1100 ft in length or 140 ft in beam, new drydock facilities must be built.

Military restraining factors may be the compatibility of components with NATO or sister service standards.

Hydrographic constraints are imposed by the available depths of water in home ports.

As stated by Hovgaard [4], a design must in general be based on that of existing vessels with such modifications as follow from changes in the fundamental requirements and from improvements suggested by practical experiment or resulting from technical progress.

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[5] The specifications are conditions imposed on contemplated solutions by factors external to the system itself; the criteria are standards to be met or approached; the parameters are variables at the control of the analyst and designer.

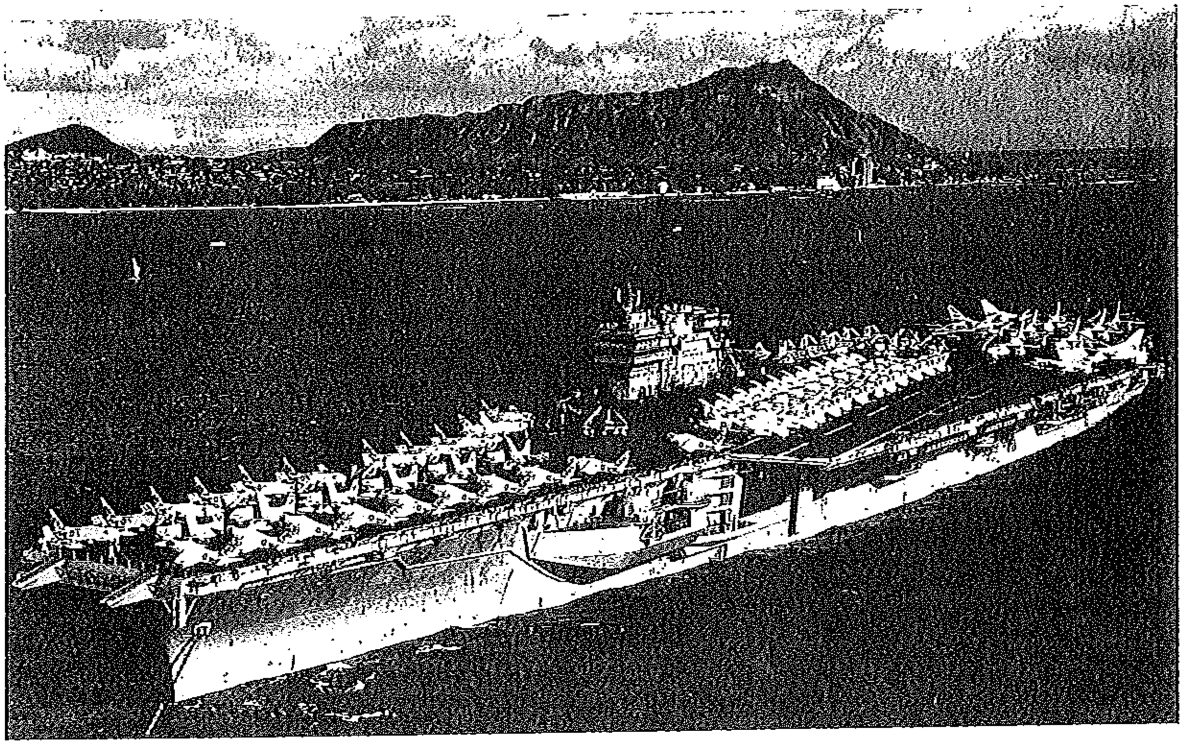

Fig. 7 USS *Ranger* (CVA-61) (Official U.S. Navy Photograph)

Recent CVA designs are shown in Figs. 7 and 8. They exhibit the following features:

- (*a*) Canted recovery area
- (*b*) Side elevators
- (*c*) Optical landing systems
- (*d*) Bow and waist catapults

In what follows, such a design concept will be used upon which to erect the parametric design model. If the concept is varied, the parametric design model must be designed to correlated with the design variation.

The Military Payload

To be entered into the design model, the features of military performance (including C^3) must first be converted into items of military payload, into weights and geometries of engineering features, into manning complement, and into constraints upon the design.

To this end, a pattern is introduced as follows: The CVA/WS is first divided into military payload and base. The sea deployability of the base makes it a naval WS.

The military payload subsystem is in turn subdivided into:

Division A—Weapons and aircraft (strike and active defense)

Division B—Base support and military features (support for strike and active defense; semiactive and passive defenses)

Division A—Weapons and Aircraft

Under weapons and aircraft come those transient or expendable items that leave the base. The latter are the weapons proper intended either for offense or defense; the former include aircraft, flight crew, and avfuel.

Weapons

The amount of strike avord is determined by the potential strike effort; the amount of defense avord and shipord follows from the potential defense effort. However, it is not these that are given as parameters of military performance but the effective efforts. This makes it necessary to proceed by iteration starting with an arbitrary (but reasonable) availability of aircraft, operability, and survivability factors.

The avord required for an effective air strike effort over a strike duration t_{as} is

$$(W_{ao})_{as} = \frac{E_{as}(t_{as})}{\ddot{a}_{va}(t_{as}) \cdot O_{va}(t_{as}) \cdot S_{va}(t_{as})}$$

The avord required for an effective air defense effort over a duration t_{ad} is

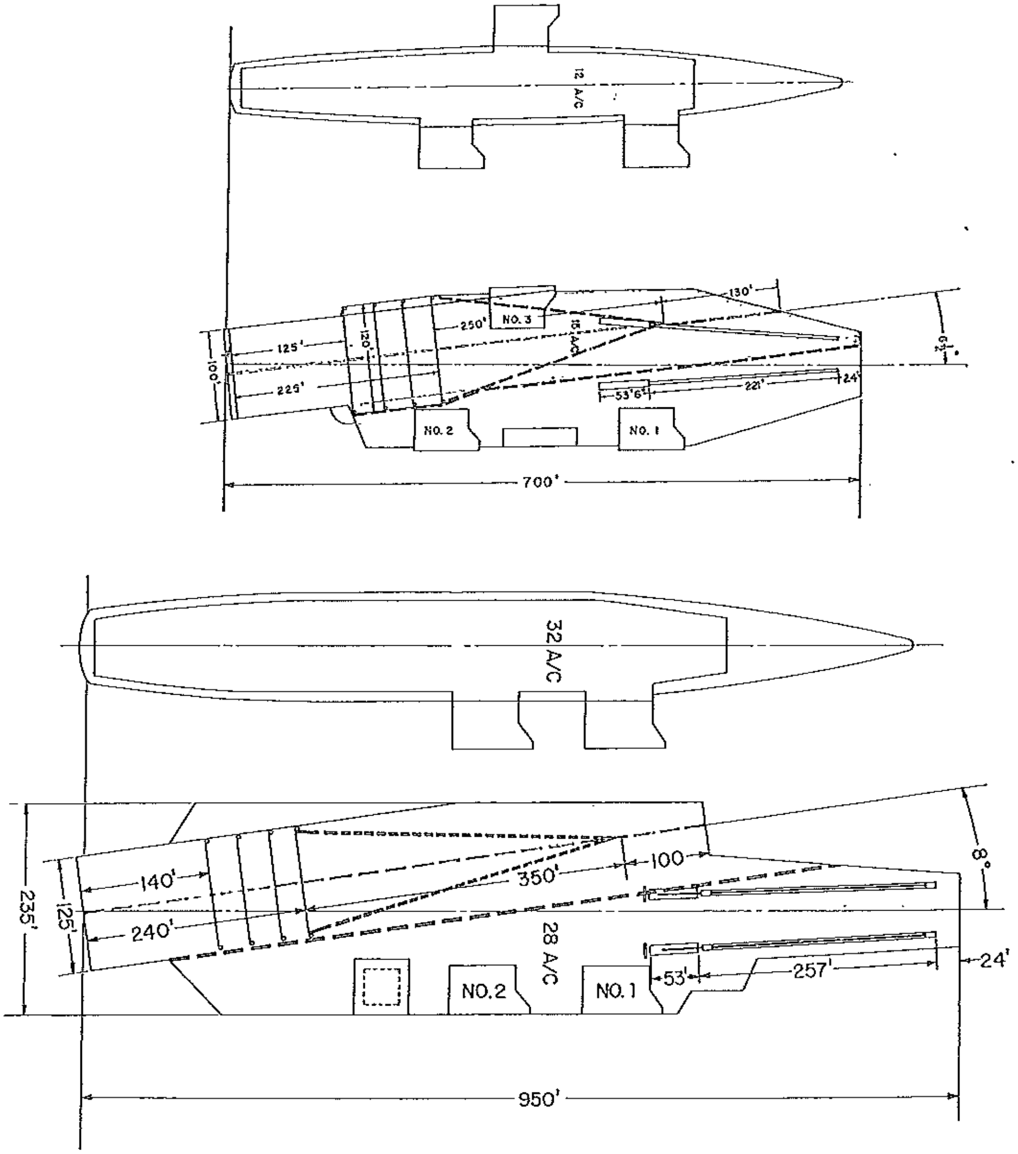

Fig. 8 Illustrative flight and hangar-deck layouts for two carriers

$$(W_{ao})_{ad} = \frac{E_{ad}(t_{ad})}{\bar{a}_{vf}(t_{ad}) \cdot O_{vf}(t_{ad}) \cdot S_{vf}(t_{ad})}$$

The shipord required for an effective ship defense effort over a duration t_{sd} is

$$W_{so} = \frac{E_{sd}(t_{sd})}{N_l \cdot W_m \cdot t_{sd}/t_c}$$

In the foregoing expressions:

E_{as}, E_{ad}, E_{sd} = air strike, air defense, ship defense efforts

t_{as}, t_{ad}, t_{sd} = air strike, air defense, ship defense durations

$a_{va}(t_{as}), a_{vf}(t_{ad})$ = sustained availability of attack and interceptor aircraft over air strike or air defense durations

$O_{va}(t_{as}), O_{vf}(t_{ad})$ = operability of attack and interceptor aircraft over duration of air strike or air defense operations

$S_{va}(t_{as}), S_{vf}(t_{ad})$ = penetrability of attack aircraft during strike and survivability of interceptor aircraft during engagements over air defense duration

N_l = number of missile launchers

W_m = missile weight

t_c = missile cycling time

The ordnance capacity to be designed into the ship is

$$W_o = (W_{ao})_{as} + (W_{ao})_{ad}(1 + \epsilon_{ao}) + W_{so}(1 + \epsilon_{so})$$
$$= W_{ao}(1 + \epsilon_{ao}) + W_{so}(1 + \epsilon_{so})$$

where ϵ_{ao} and ϵ_{so} are margins.

The unknown factors are the availabilities $\bar{a}(t_{as})$ and $\bar{a}(t_{ad})$ and the degradations $O_{va}(t_{as})$, $O_{vf}(t_{ad})$, $S_{va}(t_{as})$, $S_{vf}(t_{ad})$. These are estimated pro tempore and introduced into the design. The operational and conflict models are applied to derive new estimate and the process is repeated to convergence.

Aircraft

The airsuit embarked reflects the intended mission of the CVA/WS and is always a mix of strike (VA), interceptor (VF), reconnaissance (VR), early warning (VW), and utility (VU) aircraft, with the first two types predominating to such an extent that the CVA characteristics are derivable upon consideration of these alone with an empirical allowance being made for the remainder.

The aircraft and airsuit features required for the analysis are all derivable from the principal independent parameters of maximum take-off weight and maximum sea-level speed, and the secondary parameters of maximum sinking speed, stalling speed, and type of weather performance (all-weather, limited-weather, or day attack).

Because several types of VA and VF are usually embarked, the values assumed by these parameters for a specific airsuit are many, with resulting complication of the analysis. With the view to simplification, the concept of a *control* aircraft is introduced, i.e., an aircraft for which the parameters of interest all attain maximum values. Thus, the CVA is designed to a specific number of control aircraft. One speaks of a CVA having capability to operate N_v aircraft of take-off weight W_v and maximum sea-level speed V_v. The CVA capability to operate any other airsuit is determinable from conversion tables.

The aircraft suit imposes severe constraints on the design of the CVA, particularly on the length of her flight deck. These are as follows:

(*a*) *Minimum Length of Flight Deck.* The approach glide path must be such as to allow a safe ramp clearance (10 ft) and shallow angle (3.5 to 4 deg) for structural integrity. This establishes a median touchdown point at 143 to 163 ft from the ramp.

Four arresting wires are required to give a high probability of engagement. For a spacing of 40 ft (to avoid double engagements) with the center at the median, the added length is 60 ft.

To absorb the kinetic energy of the landing aircraft without jeopardizing the aircraft structure requires a runout of 350 ft.

Room for turning equal to length of controlling aircraft plus turn radius adds 70 + 40 = 110 ft at present.

Launching of aircraft with structural safety and safe margin of speed requires 273 ft.

Minimum length—based on a glide angle of 4 deg and no overlap of recovery and catapult areas.

$$l_{fd} = 143 + 60 + 350 + 110 + 273 = 936 \text{ ft}$$

(*b*) *Aircraft Parking Area.* The required parking area is given by

$$A_p = \frac{N_v \cdot A_v}{0.85}$$

where

A_v = spotting area
0.85 = packing coefficient

(*c*) *Hangar Deck Area.*

$$A_h = \frac{1 - a_v(t_s)\, N_v A_v}{0.85}$$

where $A_v(t_s)$ is the aircraft availability at the end of strike operations.

Aircraft require avord and avfuel. These consumables are derivable from the aircraft number (N_v) and principal characteristics (W_v, V_v), and from the operational factors of cycling time (t_c), duration of strike (t_c), air defense (t_{ad}) and ship defense (t_{sd}) operations and margins.

The number of VA of controlling design required to attain a prescribed effective strike intensity under sustained conditions is

$$N_{VA} = \frac{I_s}{w_{ao}(r_m) \cdot \frac{d}{dt} o(r_m) \cdot \bar{a}(t_s) \cdot O_{va}(t_s) \cdot S_{va}(t_s)} = \frac{I_s}{I'_s}$$

Here

I_s = effective strike intensity
I_s' = effective strike intensity of single aircraft
$w_{ao}(r_{va})$ = avord load in single aircraft for mission to reference mission radius (r_{va})
$\frac{d}{dt} o(r_m)$ = rate of opportunity to fly to reference radius at no operational degradation

$$\frac{d}{dt} o(r_m) = \frac{h}{(t_c)_{\min}}$$

h = potential operating hours per day (of each aircraft). For day aircraft, $h = 12$; for all-weather aircraft, $h = 24$

$(t_c)_{\min}$ = minimum cycling time

$$(t_c)_{\min} = \frac{2r_m}{V_v} + t_f + t_r$$

$$= \frac{2r_m}{V_v} + k_{af} \cdot w_{af}(r_m) + k_{ao} \cdot w_{ao}(r_m)$$

t_f, t_a = times required to fuel and arm
k_{af}, k_{ao} = empirical constants
w_{af}, w_{ao} = weights of avfuel and avord per plane for mission to reference radius
V_v = maximum sea-level speed of VA

The number of VF required to attain a prescribed effective air defense intensity is similarly calculated. Note, however, that the reference mission radius of the VF (r_{vf}) will differ from that of the VA (r_{va}). In the former case, the reference radius is half the combat radius.

The ship avfuel capacity is

$$\left[E_{as}(t_{as}) \cdot \frac{W_{af}(r_{va})}{W_{ao}(r_{va})} + E_{ad}(t_{ad}) \frac{W_{af}(r_{vf})}{W_{ao}(r_{vf})}\right](1 + \epsilon_{af})$$

where ϵ_{af} is a fuel margin.

The flight crew is

$$(N_{va} + N_{vf}) \cdot c_v(1 + \epsilon_v)$$

where c_v is the flight crew per plane and ϵ_v is a flight crew margin

Division B—Base Support and Military Features

The items included in this division are those base facilities which are incorporated either in support of the weapons and aircraft of Division A or to endow the WS with additional military features. They consist of:

(*a*) Flag Control (CTF Command Center)
(*b*) Weapons and Aircraft Base Support
(*c*) Weapons Countermeasures
(*d*) Protection
(*e*) Flag, Airbase, and Combat Complement

Flag Control

This includes the command center for CTF operations (as separate from CVA/WS operations) and its communication system.

Weapons and Aircraft Base Support

Weapons and aircraft base support is of two forms: equipment and activities. The equipment consists of:

(*a*) Sensors (Electronic Suit)
    Search radars
    Sonars
(*b*) Weapons support
    Stowage (avord and shipord magazines)
    Transfer (bomb elevators)
    Maintenance and checkout (ordnance shops)
    Launchers (ship battery) (shipborne armament suit)
    Control (fire control and target illumination)
(*c*) Aircraft support (Air Base)
    Stowage (parking area)
    Transfer (aircraft elevators)
    Maintenance and checkout (hangar and shops)
    Readying (fueling and arming stations)
    Avfuel transfer and stowage (transfer system, avfuel tanks)
    Launchers (catapults)
    Recovery (arresting gear)
    Control (air control radar)

The activity is that of operations coordination and requires a combat information center and communication systems.

Weapons Countermeasures

Weapons countermeasures are ECM and ACM. Some of the former are part of the electronic suit. Altogether their effect on military payload is negligibly small.

Protection

Protection (or passive defense) is of two kinds: torpedo and ballistic. Full protection (torpedo and ballistic) is provided only for the vitals (machinery spaces, avfuel compartments, magazines, and steering gear), although the armor can be so disposed to provide some protection also to the hangar. The rule in providing protection should be to achieve a compromise between weight of ballistic material allocated to a space and acceptable risk. When penetration of a compartment might not disable a ship (as occurs, for example, when one of several machinery spaces is penetrated), a greater risk is acceptable than when it might result in such disablement (as occurs, for example, in the case of the steering gear compartment), or when it might result in the probable loss of a ship either through explosion or through fire (as obtains when magazines or avgas compartments are penetrated). Such a rule can be easily followed when providing ballistic protection, but the shape of the hull and internal arrangements make it of difficult realization for torpedo protection. In the latter case, uniformity of protection is more readily achieved.

Electronic Suit

This is the engineering aspect of the communication, command and control qualities, and of ECM and ACM. The chief contribution comes from the radar and sonar suits (should the latter be fitted). How the electronic suit affects design is developed by Sherwin and Miller [5].

Radar installations on CVA have grown considerably in sophistication and size. In nuclear CVA, the absence of uptakes permits the installation of fixed-array systems of considerable capacity.

Shipborne Armament Suit

In recent designs, guns have given way to missiles and depth charges to rockets.

The number of launchers required to attain a prescribed effective ship defense intensity is

$$N_1 = \frac{I_{sd} \cdot t_c}{w_m \cdot \bar{a}_m(t_{sd}) R_m S_m}$$

where

w_m = weight of missile
t_c = missile cycling time
$\bar{a}_m$ = expected availability of missile
R_m = missile reliability
S_m = expected missile penetrability

Missiles impose design constraints through their requirements for stowage volume, handling gear, and support equipment. As to the first, the stowage density is considerably lower than that of bombs and this increases the size of magazines.

Airbase Items

These are the elevators, avord loading and avfueling stations, catapults, and arresting gear.

The airbase items of greatest weight and internal volume are the elevators and the catapults. Both vary with weight of control aircraft; the first also with the aircraft length and folded wing span, and the second with the kinetic energy of the aircraft.

The larger the number of elevators, the greater the flexibility of airbase operations; however, geometrical constraints impose a limit to their number. It has been found feasible to fit four elevators in CVA of displacement greater than 70,000 tons, but only three otherwise. The weight of an elevator system is about 10 times that of the control aircraft if ballistic protection is excluded, so that the elevator weight amounts to

$$10\, N_e W_v$$

where N_e is the number of elevators.

The number of catapults also varies with displacement and is approximately

$$N_c = \left[\left[\frac{\Delta}{20{,}000}\right]\right]$$

(where the double bracket indicates the closest integer to the expression). The weight of a catapult system is from 1/60 to 1/80 times the kinetic energy of the control aircraft at take-off, so that the total catapult weight is approximately

$$\frac{1}{70} N_c \cdot \frac{W_v V_{to}^2}{2g}$$

where

V_{to} = take-off speed, fps^{-1}
g = gravitational acceleration

In recent designs the recovery installation contains the same number of arresting gears (4), the capacity of which is dictated by the kinetic energy of the control aircraft at landing. The total weight for such an installation is

$$\frac{1}{70} \frac{W_v V_r^2}{2g}$$

where V_r is the speed at recovery (engagement speed at no wind over deck).

Flag, Airbase, and Combat Complement

This includes all CTF command personnel (admiral and staff), all air personnel except flight crew, and ship's personnel for manning the airbase facilities, for controlling the aircraft, for manning the ship's battery, the sensors, and the countermeasures.

Military Payload Complement

This is the sum of flight crew and flag, airbase, and combat complement. Since to each person correspond berthing and messing spaces, medical corpsmen, stewards, commissaries, personnel stores, air conditioning, provisions, potable water and outfit, all these items are prorated parts of the military payload!

Flag complement is a function of task force size ($c_f = k_f$).

Air personnel (air operations, air control, maintenance) depends on the number and size of control aircraft [$c_a = f_a(N_v, W_v)$].

Airbase support personnel varies with the number of aircraft [$c_{as} = f_{as}(N_v)$].

Ship combat crew is determined by the number and type of launchers [$c_{sc} = f_{sc}(N_l)$].

The Nautical Features

For use in the design model, the nautical performance qualities are also to be translated into weights and geometries of engineering features, manning complement, and design constraints.

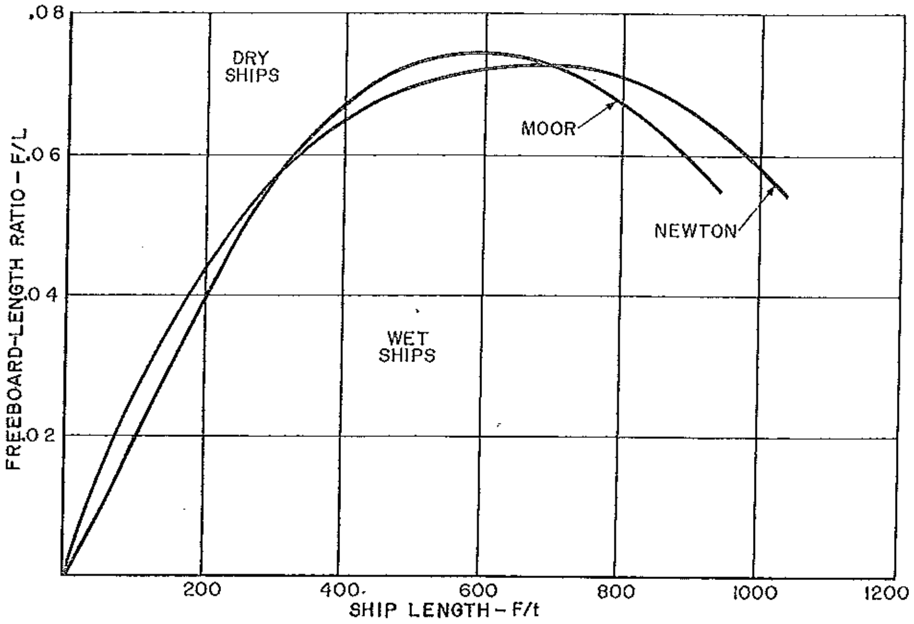

Fig. 9 Freeboard-length ratio of dry ships according to Newton and Moor

The nautical performance qualities are translated into statements of:

(*a*) Strength, hence of weight of hull structure.

(*b*) Motions, hence hull geometry.

(*c*) Power, hence machinery weight and hull form.

(*d*) Ship control, hence weight of auxiliaries.

(*e*) Unrefueled steaming range, hence weight of ship fuel.

(*f*) Base complement, hence weight and geometry of furnishings and consumables.

(*g*) Endurance, hence weight of consumables.

Structural Strength

The high depth-to-length ratio of CVA ($D/L = 0.10$) makes for the easy attainment of adequate primary (hull girder) strength for resisting the action of the sea. Such strength is enhanced by the torpedo and ballistic protection, and the primary stress numerals that obtain are quite low.

Motions

The requirement of adequate stability to prevent capsizing in the damaged condition determines the minimum transverse metacentric height ($\overline{GM}_\phi$) to be provided in the *undamaged* condition. The requirement of safety against foundering establishes the distribution of *minimum* reserve buoyancy, hence minimum freeboard amidships and at the ends.

The double limitation on angle of oscillation and linear acceleration for safety in manning imposes constraints on transverse and longitudinal metacentric heights as well as on beam (B) and length (L).

For seakindliness, the motions must be gentle. An empirical criterion applicable to roll is that

$$\overline{GM}_\phi \cong \left(\frac{100}{80{,}000 + \Delta}\right) B^2$$

Also, the ship must be dry. Newton [6] gives an empirical relation between freeboard (F) and ship length (L) for dry ships which is represented in Fig. 9. Moor [7] gives a similar relation.

Power

The maximum and sustained speeds are related to power, displacement, and force. Given the maximum speed (V_m) of the CVA, the corresponding shaft horsepower is

$$P_m = (r_{d/l}) \frac{V_m}{326} \frac{1}{\eta}$$

where ($r_{d/l}$) is the drag/lift ratio and η is the propulsive coefficient. Since $L = 2240\Delta$

$$P_m = 6.87\ (r_{d/l})\ \Delta V_m \frac{1}{\eta}$$

The drag/lift ratio is a function of speed-length quotient ($V_m/\sqrt{L}$), Fig. 10. The propulsive coefficient can be taken as $\eta = 0.625$. It is obvious that the drag/lift curve presented and the constant propulsive coefficient cannot account for all reasonable possibilities of CVA form. Indeed, the curve is valid for a beam/draft ratio (B/H) of 3.5, a midship section coefficient (C_x) of 0.985,

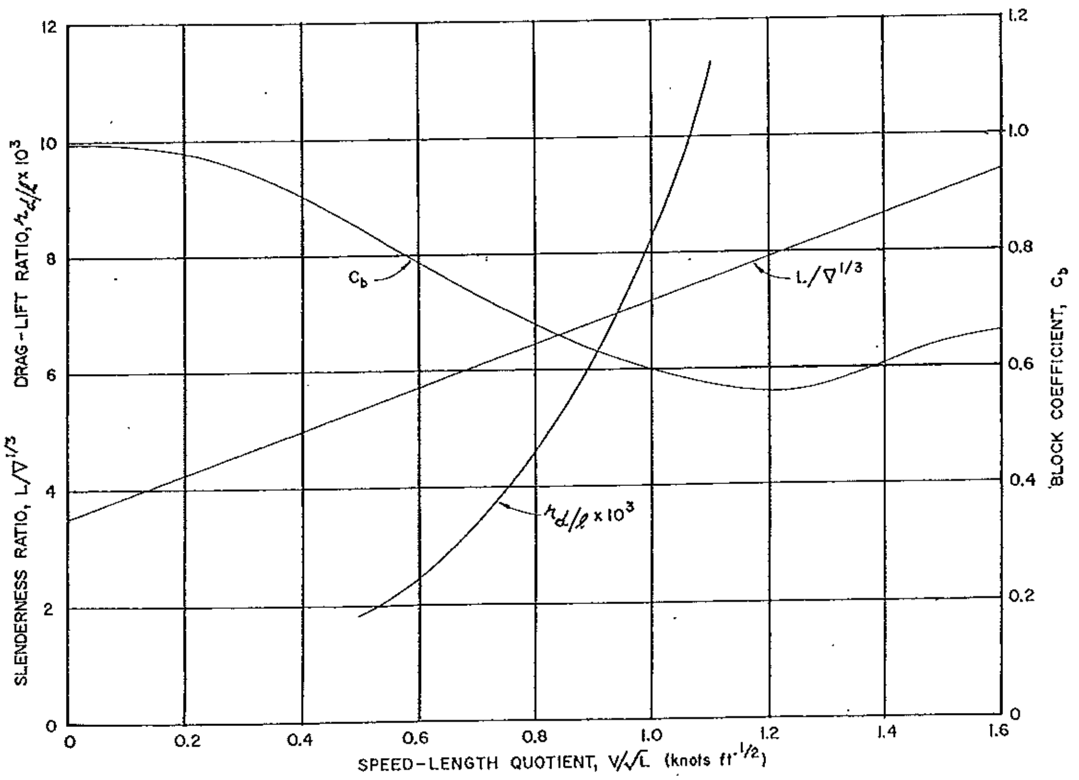

Fig. 10 Drag/lift ratio block coefficient and slenderness ratio as functions of speed-length quotient

block coefficient (C_b), and slenderness ratio ($L/\nabla^{1/3}$) given as functions of speed-length quotient ($V/\sqrt{L}$) as shown in Fig. 10, and for a hot-plastic paint finish. It may be noted that the paint finish has more influence on the power required than considerable variations in form.

Ship Control

The tactical radius (r_t) by which maneuverability is defined determines the required rudder(s) area (A_r). An empirical relation valid at cruising speed is

$$A_r = \frac{150}{r_t} \exp\left(-925\, C_b B/L\right) \text{ (ft}^2\text{)}$$

where C_b is the block coefficient.

Unrefueled Steaming Range

This item, which applies only to oil-fired CVA, is derived from an analysis of deployment area and logistics. The speed at which the unrefueled steaming range is made to correspond is the speed of strategic deployment, which, as brought out in the foregoing, is a CTF parameter.

Hotel Endurance

This is arbitrary. A nominal 90-day endurance is ordinarily used for determining personnel consumables.

The Base

The base is made up of those items that are introduced to insure the nautical qualities of the CVA/WS and those features, like deployability, which fall under both nautical and military qualities. The items are in great respect common to all ships. Of course, the ship personnel for manning the items and the hotel facilities of such personnel are part of the base as are all the consumables required for its operations.

The base is made up of fixed items, consumables, and base complement. The fixed items can be cast in the following pattern:

(*a*) Power Systems
  - propulsion plant and propellers
  - electric plant

(*b*) Ship Operational Control Systems
  - ship control and base communication
  - steering gear and rudder
  - mooring (anchor windless. . .)

(*c*) Base Maintenance
  - workshops and spares (hull, machinery, electrical. . .)

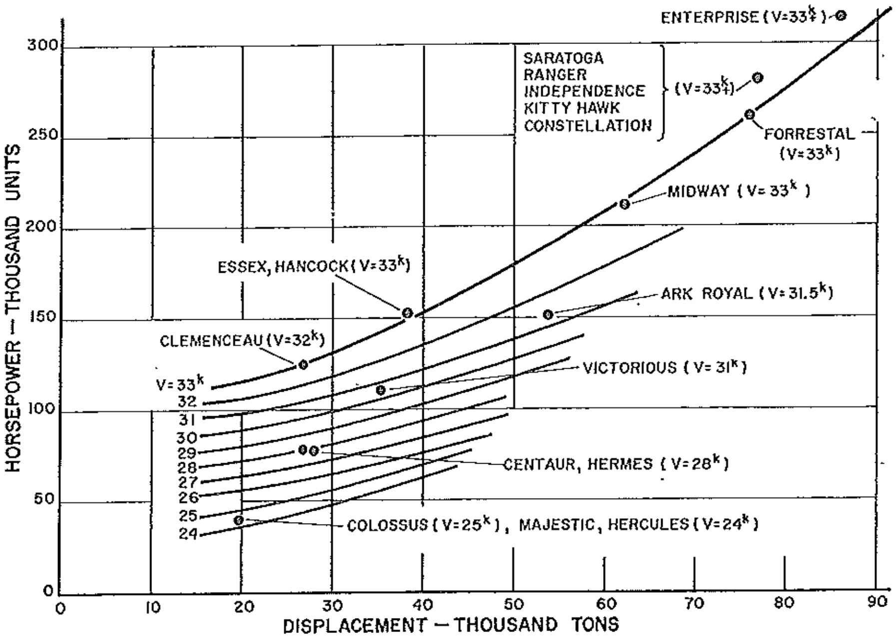

Fig. 11 Powering data. Source: *Jane's Fighting Ships*

(*d*) Base Stowage
  - tanks for ship fuel reserve feedwater and lube oil

(*e*) Logistics
  - replenishment and transfer gear

(*f*) Hotel Facilities
  - berthing, messing, store spaces, air conditioning, boats

(*g*) Base Envelope—Ship Hull
  - structural integrity (shell, decks...)
  - watertight integrity (watertight bulkheads, doors, counterflooding and damage-control systems)

The consumables are grouped according to:

(*a*) Machinery
  - fuel oil (if fossil fueled), reserve feedwater, lube oil...

(*b*) Hull
  - ship stores

(*c*) Electrical
  - electrical stores

The base complement consists of personnel for ship control, communication, navigation and engineering, and the service personnel (medical, commissary, and so forth) for their support.

Note that following the logic of this presentation, the hull structure (or base envelope) results in a terminal item on the list, not a lead item as usually considered. The hull is no more than the watertight wrapping for the functional, integrated entity which is the CVA/WS.

Some remarks follow on the relative important groups of propulsion plant and hull structure.

Propulsion Plant

The large size of the CVA and the high operational speed required of her for air operations result in propulsion plants of very high power. The only high-power prime mover available at present and, at least, for the immediate future is the geared steam turbine, although in the past the steam turboelectric drive has also been used (USS *Lexington*, CV2 and USS *Saratoga*, CV3). The steam-generating plant utilized to drive the turbine is either an oil-fired boiler or a heat exchanger coupled to a reactor. This combination gives rise to two types of power plant termed, respectively, conventional and nuclear.

The only novel propulsion plant that is within the present state of the art is the gas turbine. The British have fitted such a power plant in their "County" class of guided missile destroyers as a companion to a geared steam turbine installation to boost the high-speed performance of these ships. But although the power density of a dual steam and gas turbine installation would be higher, this gain may be incommensurate with the operating penalty imposed by the shorter operating periods between overhauls resulting from the reduced confidence in the reliability of the system stemming chiefly from its relative newness. At all events, installation in an aircraft carrier of a gas turbine power plant of high power output will need to be preceded by experience with lower power levels in smaller ships.

The power level of the propulsion system in present CVA ranges from the 150,000 shp of the *Hancock* class, through the 212,000 shp of the *Midway* class, to the 260,000/280,000 shp of the *Forrestal* and later classes. These powers give their respective ships maximum speeds of about 33 knots, Fig. 11.

Whether such speeds are excessive or inadequate for operations in future conflict situations is a problem in WS evaluation. However, it may be observed that the maximum power installed in *any* ship has grown but slowly with the years, so that on the basis of this history one might be reticent to predict a sudden increase in power installed. The power per screw has now reached the 70,000-shp level. Since at this level the threshold of cavitation is approached, it must be expected that increased power will not come without considerable development. The alternative of fitting more (say six) screws is unappealing from the point of view of machinery space arrangements and protection. At all events, the gain in speed to be achieved by increased power is a very slowly varying function of the latter.

The weight and volume of the propulsion plant are obtained by application of specific weights and volumes which depend on the power level.

In large installations the specific weight of conventional steam turbine power plants is about 30 lb per hp; for nuclear it is about 80 lb per hp at present [8]. The weight of conventional propulsion plants appears to vary with the square root of the power per screw or about as

$$2.8\ N_s\sqrt{P'}$$

where

N_s = number of screws
P' = power per screw

Their density appears to be about 30 lb-ft^{-3}.

The corresponding trend for nuclear plants is difficult to estimate because of the scarcity of data. At all events, it is the specifics for future installations that need estimating. For the conventional plant the downward trend will be slow because of the high degree of present development; for the nuclear plant the relative improvement may be greater.

Hull Structure

For CVA, the length is a weak function of the displacement for it is determined essentially by the length of the flight deck. Thus, on the basis of dimensional analysis, the condition of equal primary strength yields a ratio of unprotected hull weight to displacement which is approximately constant with size. Because this weight group accounts by itself alone for some 40 percent of the full-load displacement, it is important to estimate it with accuracy. For use in the parametric design models, the variation of this weight group with hull displacement must be known. Some plausible arguments have been made by Hovgaard [4], and by Manning [9], to the end that for geometrically similar ships the hull weight fraction can be treated as invariant with displacement. The point is that for geometrically similar ships of equal strength, when determined on the basis of computational method presently in vigor, the hull weight fraction should, indeed, increase with ship size, but this does not obtain because:

(*a*) The computational method underestimates the severity of the dynamic loadings imposed by the seaway on the smaller ships and overestimates such severity for the larger ships so that it is perfectly realistic to modify somewhat the scantlings derived upon the assumption of a fictitious sea condition upward for the small ships and downward for the large ones.

(*b*) The allowance for corrosion is independent of ship size and this tends to result in comparatively heavier scantlings in the smaller ships.

(*c*) Requirements of local strength impose minimum allowable thickness which must not be reduced. This has the same effect as the corrosion allowance.

The combined result of the foregoing factors (it is argued) is that the hull weight fraction of geometrically similar ships is invariant with size.

That such complex causes can cooperate to result in a constant hull weight fraction is indeed remarkable. What appears to be the case is that some rationalization is introduced to account for a reality that is, to some degree at least, inconsistent with design rules of thumb. Analysis of the weight schedules of other ship types reveals that the presented arguments are only well intended and not accurate: the hull weight fraction tends to decrease with size even for geometrically similar vessels and aircraft carriers do not remain geometrically similar as size is increased; they only affine. (None of the principal dimensions varies proportionally with the cube root of the displacement.)

The hull weight is expressible as

$$W_h = k_h\Delta^h$$

where h is empirically derived.

Complement

Base Complement

The base or ship complement is subdivisible into command and control, communication, navigation, engineering, commissary, and medical.

Command and control personnel is independent of size ($c_{cc} = k_{cc}$).

Navigation personnel is a function of displacement [$c_{sn} = f_{sn}(\Delta)$].

Personnel for ship communication varies slowly with complement size [$c_c = f_c(c)$].

Engineering crew appears to vary with propulsive power [$c_e = f_e(P)$].

Commissary and medical personnel are proportional to total complement [$c_{cm} = f_{cm}(c)$].

Total Complement

The total personnel complement, being the sum of the military payload and of the base complement, is consequently, expressible as

$$c = k_f + f_a(N_v, W_v) + f_{as}(N_v) + f_{sc}(N_1) + k_{cc} + f_c(c) + f_{sn}(\Delta) + f_e(P) + f_{cm}(c)$$

Since N_v, W_v, N_1, P, and c are related to displacement, the total complement can be written in terms of displacement. It appears the fit

$$c = 1800 + 0.027\Delta$$

is reasonable, Fig. 12.

Parametric Design and Cost Models

"The merit of empiricism is that it prevents one from making gross blunders."

G. Weinblum

In the preceding, the military performance capabilities or qualities of strike and defense and of command and control, and the nautical qualities of seaworthiness and sea-deployability have been translated first into a set of parameters of military performance, thence into items of military payload. These are now to be translated into features of ship design that are functionally related (structure, machinery, equipment, personnel complement, and so on). A parametric design model is then set up to yield the CVA principal characteristics, subject to the fulfillment of the criteria of seaworthiness, the requirement for deployability, and satisfying imposed constraints on the geometry of the solution.

The process consists in solving four equations: weight, volume, transverse stability and longitudinal stability, subject to constraints on dimensions and form, and to criteria of seaworthiness, seakindliness, and deployability. Application of cost factors to the weight schedule that results yields the initial investment cost. The complexity of the work makes the process iterative. Fortunately, it is computer adaptable.

The process includes the following steps:

1 Specify:

(*a*) Mission

(*b*) Military conflict situation

(*c*) Threat (air, sea, undersea)

(*d*) Military performance:

- Effective strike intensity and duration
- Passive defense capability
- Effective semiactive defense effort
- Effective active air defense intensity and duration
- Effective active ship defense intensity and duration

(*e*) Design and operational characteristics of control aircraft

(*f*) Design and operational characteristics of shipborne armament

(*g*) Electronic suit

- Radar
- Sonar

2 Determine military payload for assumed values of operability, reliability, and survivability (CVA, VA, VF).

3 Make first estimate of the displacement on the basis of weight data on other CVA and on other ships which are in some pertinent aspect similar to the CVA of the study. The data required for this purpose are the ships' weight schedules, which are an ordered weight listing of the components which make up the ship and her loading. The components are separated into functional groups which are related in specific manners to the input parameters and to the as yet unknown displacement (Δ).

4 Develop the flight and hangar deck geometries corresponding to the pertinent items of military payload.

5 Determine the CVA principal dimensions and form characteristics corresponding to the nautical performance qualities. This is done on the basis of the transverse and longitudinal stability equations, of the speed-form relation, and of the constraints imposed by flight and hangar decks, structural strength, and other causes.

6 Re-estimate the displacement on the basis of the first estimate of the principal dimensions and form coefficients. The volume equation is employed to this end.

7 Assess the inherent and environmental degradations of the CVA/WS on the basis of the derived dimensions and form.

8 Determine CVA/WS survivability (CVA, VA, VF).

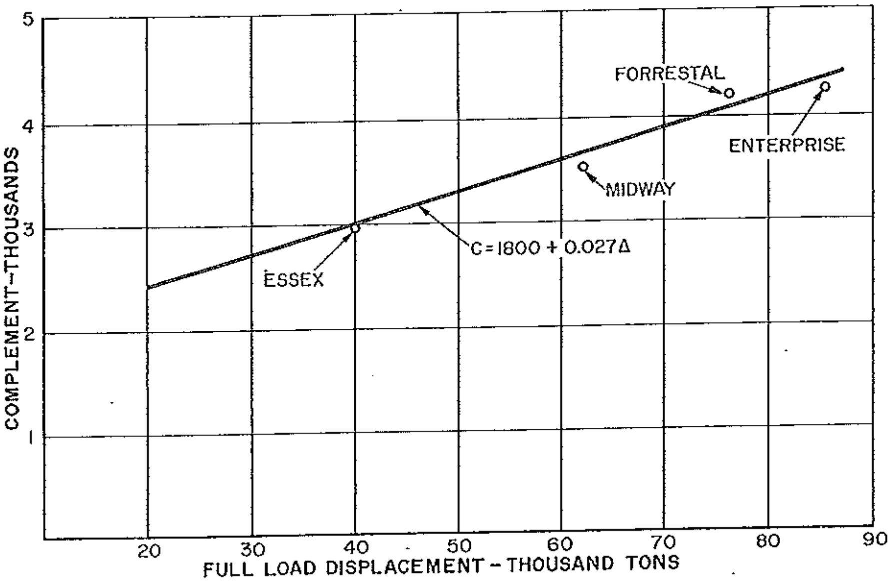

Fig. 12 Personnel complement of CVA's Source: *Jane's Fighting Ships*

Table 3 Weight Schedule

Military Payload	A	Weapons	avord	$W_{ao} = [E_{p/as}(t_{as}) + E_{p/ad}(t_{ad})]\cdot[1 + \epsilon_{ao}]$
			shipord	$W_{so} = E_{p/sd}[1 + \epsilon_{sd}]$
		Aircraft	aircraft	$W_v = N_v w_v$
			avfuel	$W_{af} = \left[E_{p/as}(t_{as})\frac{w_{af}(r_{ra})}{w_{ao}(r_{ra})} + E_{p/ad}(t_{ad})\frac{w_{af}(r_{rf})}{w_{ao}(r_{rf})}\right][1 + \epsilon_{af}]$
			flight crew entered under total complement	
	B	Flag Control		$W_f = k_f$
		Weapons and Aircraft Base Support	sensors	$W_s = k_s$
			weapon support	$W_{ws} = k_1\cdot N_1 w_1 + k_w\cdot N_w w_w$
			aircraft support	$W_{as} = k_v\cdot N_v w_v + k_c\cdot N_c w_c + k_r(w_v, V_r)$
		Weapons Countermeasures		W_{cm} neg
		Protection		$W_p = k_p\Delta^{2/3}$
		Payload Complement		entered under total complement
Base C		Fixed	main machinery plant	$W_m = k_m N_s^{1/3}\Delta^{1/3} V^{n/3}$
			electrical plant	$W_e = k_e\Delta$
			ship control	$W_{sc} = k_{sc} + k'_{sc}\Delta$
			base maintenance	$W_{bm} = k_{bm}\Delta$
			logistics	$W_1 = k_1$
			hotel facilities	$W_{hf} = k_{hf}c$
			hull	$W_h = k_h\Delta^h$
		Consumables	ship fuel	$W_{sf} = k_{sf}\Delta^{2/3}V_c^{n-1}\cdot t_e$
			machinery stores	$W_{ms} = k_{ms}W_m$
			electrical stores	$W_{es} = k_{es}W_e$
			provisions & personnel stores	$W_{ps} = k_{ps}c$
			ship stores	$W_{ss} = k_{ss}W_h$
		Complement		$c = k_c + k'_c\Delta$

9 Modify military payload to provide military performance qualities specified in step 1.

10 Repeat process to convergence.

11 To last weight schedule, apply cost factors and derive initial investment cost.

The specifications (item 1), military payload (item 2), and flight and hangar deck geometries (item 4) formed the subject of preceding sections. The method for making the first estimate of the displacement (item 3) is to be found, for example, in Hovgaard [4]. Its adaptation to the logic presented herein is outlined in the following. Brief comments are also made on estimating principal dimensions (item 3), on the re-estimate of displacement (item 6) and on the resulting CVA size.

First Estimate of Displacement

Weight Equation

The weight equation is

$$\sum_i W_i = \Delta$$

where W_i represents a weight component (fixed, transient, or consumable). In Table 3 the variations of these weights are shown for arbitrary parameters related to military payload and nautical performance and in terms of the displacement. The factors k and the indexes (n, h) are empirically obtained. The solution to the weight equation yields the first estimate of the displacement.

Vertical Moment Equation

The vertical moment equation is

$$\sum_i W_i \cdot z_i = \Delta \cdot \bar{z} = \Delta \cdot \overline{KG}$$

where

z_i = center of gravity above keel of weight component i

$\bar{z} = \overline{KG}$ = center of gravity above keel of hull

Estimate of Principal Dimensions

1 The minimum waterline length is governed by the flight deck length; hence

$$L_{\min} = k_{fd} l_{fd}$$

where k_{fd} is close to unity.

2 The minimum beam at the waterline is in part governed by the width of flight deck; hence

$$B_{\min} = k_{fd}' b_{fd}$$

where $k_{fd}' = 0.525$ in operational designs of canted deck CVA.

3 The minimum beam is also governed by the restriction on maximum draft $(H_{\max})$

$$B_{\min} = \frac{35\ \Delta}{C_b L H_{\max}}$$

4 The compatibility of beam and draft is given by the equation of transverse stability

$$\frac{5H}{6} - \frac{35\ \Delta}{3 C_w L B} + \frac{C_\varphi L B^3}{35} - k_d D = \overline{GM}_\varphi$$

where

$$C_\varphi = (0.0106 + 0.0727\ C_w) C_w$$

$$\overline{GM}_\varphi = B^2 \cdot \frac{100}{80{,}000 + \Delta}$$

$$D = H + F_x = H + K_f L$$

where K_f is obtained from Fig. 9.

5 Compatibility of displacement, length, and speed. Displacement, length, and speed are mutually related through the speed-length quotient $(V/\sqrt{L})$ as shown in Fig. 10.

6 Compatibility of beam and draft. Having obtained a compatible solution for length and displacement, the beam and draft must finally be selected. A constraint is imposed on their product.

$$BH = \frac{35\ \Delta}{C_b L}$$

where C_b is given by Fig. 10. An empirical relation between L and H is

$$H = 2.55\ \Delta^{0.233}$$

Second Estimate of Displacement

When certain principal parameters of form are available, it is necessary to:

(*a*) Re-estimate the displacement.

(*b*) Insure sufficiency of ship volume.

Second Estimate of Displacement

The weight of the components constituting the base can now be rewritten in terms of derived principal characteristics (L, B, D, and so on) and a more accurate estimate obtained. It is particularly important to do this for the hull structure, which accounts for almost half the displacement. The weight of the basic hull structure can now be written

$$W_h = k'_h L\ B\ D$$

Also, the power and hence the basic propulsion weight can now be obtained more accurately since the principal dimensions are known.

Volume Equations

The weight equation satisfies the displacement but does not insure adequacy of volume. This requires that a parallel equation be set up:

$$\sum_{i=1}^{4} v_i = C_v L\ B\ D$$

where

v_i = volume groups

c_v = volumetric coefficient

The groups are as follows:

1 Payload spaces (internal only) (magazines, hangar air operations, and weapons control).

2 Personnel spaces (berthings, messing, sanitary, administrative, storerooms, galley. . .).

3 Ship spaces (ship control, damage control, machinery, electrical equipment, fuel oil tanks, reserve feedwater tanks, steering gear, anchor handling. . .).

4 Miscellaneous (voids, allowance for access...).

These spaces impose geometric constraints. To the end of resolving these, they are classed according to height as follows:

1 Multideck (main machinery, missile magazines, hangar).

2 Single deck (berthing messing).

3 Partial deck (inner-bottom tanks).

Solution of the volume equation imposes a design constraint on minimum freeboard.

Technical Comments on CVA Size

The following generalized design results are obtained from the parametric design model.

The CVA displacement is determined, to a first approximation, by the flight deck length required for recovery and launching operations and by the flight and hangar deck areas required for parking and maintaining the embarked aircraft.

The length of recovery and catapult areas depends to some extent on aircraft weight and takeoff and landing speeds. Unless the CVA is designed for smaller aircraft or unless variable-sweep-wing or VTOL aircraft are introduced, no reduction from the present size appears possible.

High-speed, low-altitude aircraft tend to be long and force CVA size upwards.

Ship operability improves with size, but since the minimum ship length is large, the improvement in going from, say, 40,000 to 80,000 tons is not dramatic, although landing accident rate does appear to drop significantly with size.

The ratio of military payload to displacement increases with size. However, the point of zero payload is in itself high.

Conclusion

"The task of the military analyst is a monstrous one for it burdens him with a plethora of incertitudes which he cannot resolve: he is thus led to live a life of frustration. But it is as it should be: a retribution from the gods for his unwise choice of profession."

Anonymous

Some thoughts have been presented towards a logic for selecting the principal characteristics of a CVA, and a parametric design model has been outlined applicable to a CVA intended to carry an airsuit of VA of conventional (ground roll) design. The exposition is to some extent incomplete. For an adequate analysis it is necessary to investigate cases not considered herein, such as air defense of the CVA through employment of shipborne armament in escort ships, and other threats (a cruise missile is an example), and combinations of threats. Each kind of threat could introduce into the CVA defense features complementary to those already considered.

Should the complement of VA to be embarked be not of the conventional type, the process remains essentially unaltered, the only changes that may need be introduced being the removal or imposition of certain design restrictions chiefly on flight deck configuration. For example, if the CVA is to be designed to carry VTOL aircraft, the simple effect on the methodology would be to remove the restriction on the configuration of the flight deck imposed by the lengths of the recovery and catapult areas.

The alternate enemy threats and the CVA/WSC defenses against them are treated in a manner parallel to the attacks and CVA parry or evasion outlined in this presentation. What results from such an examination is a relation between CVA configurations and the intensity of the enemy attack for each postulated WS he may employ and for each combination of tactics he may choose.

This would lead to an open-ended set of possibilities which would be intractable. Fortunately, for the purposes of design selection, such a set can be collapsed to a small measure by simply limiting consideration to those combinations of weapons and tactics which satisfy certain prescribed levels of survivability. To illustrate, in the air threat, we could seek to determine the intensity of the enemy attack at optimum tactics that would reduce the expected survivability of the CVA below, say, 50 percent if the CVA were fitted with two sets of twin Terrier launchers.

Another way to effect brutal reduction in number of parameters to be considered is by application of sensitivity studies: these reveal the relative importance of the parameters. If the effect on ETK or ESS of variations in a parameter is small, the parameter is removed from further consideration; if the effect is large, attention must be focused on it. Collapse of the basic inputs to only a few important parameters is essential for the expenditure of reasonable effort in selecting a design. *And the criterion for retaining or excluding parameters is the measure of effectiveness in carrying out assigned missions!* Adoption of this pragmatic criterion may prove that long-held hallowed opinions are unsupportable. The importance of speed, for example, may be grossly overrated in these days of nuclear submarine threat. Similarly, heavy ballistic protection may no longer be warranted in view of the probability that the air threat will be essentially ASM delivered. Number of shops and personnel for aircraft maintenance may, indeed, have a greater impact on mission effectiveness. These thoughts are by way of speculation and are not opinions.

One can go a long way with sensitivity studies only when the uncertainties are engineering or statistical. But the greatest uncertainties are real: they relate to the world of tomorrow in which the CVA/WS will operate. The change in the technico-military environment may be slow, but is continuous.

In seeking combinations of weapons and tactics of tomorrow, we are constrained by the bounds of what may be technically feasible as well as operationally possible. As to the former, it is prudent to be realistic. Breakthroughs, no matter how appealing, cannot be depended upon for planning. As to the latter, since the tactics employed by an enemy against the CVA are at his option, it is again prudent to plan that he will employ optimal ones.

Each defense system added to the CVA increases her size and cost at a remarkably rapid pace. One result of this is that the force levels achievable within budgetary constraints are reduced and this reduction in force level has as an immediate corollary a decreased flexibility of operations. At what point a compromise is to be made rests with the decision maker, who is faced with the problem of weighting the factors which affect his choice. His difficulty is that the future can be only dimly perceived, if at all, through the web of contingencies that separate us from it.

To the extent that a degree of objectivity (however modest) can be introduced into the choice of the design characteristics of a future CVA/WS, the task of the decision maker is rendered less intuitive by that amount and it becomes easier for him to exercise the value judgments inherent in making a choice between alternatives. This presentation is a small effort in that direction.

The question still to be answered is whether the enemy will have the capability and the intent to allocate his military resources against the CVA/-WSC in sufficient quantity to reduce the CVA expected survivability below the level selected as a criterion. We are here trying to estimate his future arsenal and military doctrine. The only tool that the military planner has in this regard is the interpretation of intelligence in the light of historical trends. To do so he has, indeed, the assistance of numerous sacerdotes, but unfortunately no Delphic Oracle to consult.

References

1 E. S. Quade, "Military Systems Analysis," Memo RM 3452-PR, Rand Corporation, 1963.

2 R. Isaacs, *Differential Games*, John Wiley and Sons, Inc., New York, N. Y., 1965.

3 T. H. Sarchin and L. L. Goldberg, "Stability and Buoyancy Criteria for U. S. Naval Surface Ships, " TRANS. SNAME, vol. 70, 1962, pp. 418–458.

4 W. Hovgaard, *General Design of Warships*, E. and F. Spon, Limited, London, England, 1920.

5 S. A. Sherwin and R. T. Miller, "The Impact of Electroncis on Warship Design," TRANS. SNAME, vol. 70, 1962, pp. 597–628.

6 R. N. Newton, "Wetness Related to Freeboard and Flare," *Transactions Institute of Naval Architects*, vol. 102, no. 1, January 1960.

7 D. I. Moor, Discussion to Newton [6], 1960.

8 J. E. Kenton, "Our Growing Nuclear Navy," Nucleonics, September 1961.

9 G. Manning, *The Theory and Technique of Ship Design*, The Technology Press of MIT, Cambridge, Mass., and John Wiley and Sons, Inc., New York, N. Y., 1956.

Discussion

Lyndon Crawford, *Member:* With two great wars and two generations gone by to evolve the great fighting carriers, the whole idea still does not seem quite credible. Step topside on a carrier's island just after dusk with unadapted eyes. Listen to the screaming pandemonium and slambang absorption or release of enormous energies—all in the dark with a few vague lights and wispy figures. You don't know whether the thing is cost effective. What you wonder is whether it is going to work at all.

Cost effectiveness is meant to keep us honest—to sharpen the focus and prod the conscience and to insist that we seek real, not spurious, values for what we spend. And the discipline of the process, when properly employed, provides important check lists for a systems designer. It has its hazards. The notion of a "controlling mission," which is important here in this paper, calls to the virtues and the cautions.

Here we are trying to relate the technical design features of the ship to the raw, weapons delivery of the aircraft under the conditions of this controlling mission, and in so doing are striving toward the truth about the quality of our design. The first caution deals with completeness. Within this controlling mission alone, are all the factors significantly affecting the measures of effectiveness accounted for? Recent history can delude us. In both the Korean War and in the present work off Viet Nam, the carriers have had sanctuary. Still, the author's close concern for survivability and its various measures and control of effectiveness is well taken. The second caution departs off the tail end of the author's definition of the controlling mission to the effect that "... if such a weapons system is 'optimized' ... then it will *probably* be satisfactory for all other missions in which it could possibly be used." (Italics are the discusser's.) This pulls heavily on a designer's imagination. Don't we still have to be aware of some coefficients (visible or invisible) for any derived, numerical effectiveness to express *versatility* against the foreseeable roles that the ship may have to play? Or another to express doggedness and staying power? Still another to express the jeopardy that any such monster capital ship incurs; that is, the effect of total loss (however improbable) of such a large investment? Someone remarked years ago in one of the Naval Institute *Proceedings* something to the effect that: "Let no one think, because all we have for aircraft carriers are the *Lexington* and *Saratoga*, that the way we operate them now is the way we would operate a great fleet of these vessels." He was thinking of jeopardy, an important, if negative attribute. There are others. These matters humble us when we come to draw up charts of value against payment. The charts are really all right, but they are not the whole gospel, and I for one say that we who practice this business must be the first to address the unquantifiable, not our critics, even if we do not possess the ultimate decisions nor often the expertise to hazard significant judgements. The present author shows meticulous care in this regard.

Readiness or availability of aircraft appears here in the formulas. Aviation maintenance is absolutely imperative to the carrier's combat capability. It is an involved business and this reviewer suggests that there is quite a bit that we could be doing to arrange for aviation maintenance and much room for all sorts of ingenuity. Closely related are the provisions for moving the aircraft around the ship and for their stowage. I have a hunch that we have not scratched the surface on the possibility of improvements here. We are talking here indirectly about takeoff and landing rates, capabilities, and availabilities—all contributing mightily to the weapons system effectiveness.

One of the shocking realities of the present CVA's is the monumental manning bill. If I am not mistaken, we are going over 5000 men per ship when the air group is aboard—almost 1000 more than originally planned for the *Forrestal*. Surely some cold-blooded search can still be undertaken here.

There are a number of categories which properly belong as prorated items serving more than one main function of the ship itself: manning, energy source(s), electrical plant, ship service systems, foundation and internal closure structure, masting, external, secondary structure, repair and stores, and miscellaneous items. These all serve, variously, more than one of the principal functions which I have termed: principal hull structure (to resist the environment); main propulsion plant; command control; ship control (including liquid ballast); protection (peacetime and wartime); payload; and solid ballast (to balance-off the ship). This grouping is not far from the author's here. I have found it useful for submarine analysis, but I think it applicable to surface ships as well. In all events, if we are looking for the real costs (in terms of dollars and otherwise) of the functional equalities that we have been talking about, we have to acknowledge these cross-dependencies. Without getting into algebraic detail, the prorating over (of weights, volumes, dollar costs, and so on) into the six main functional groups listed in the foregoing is essentially only a matter of matrix multiplication and addition—easily accomplished by a computer if we grow tired.

But all this shows something else, too. To find what a service truly costs—directly *and* indirectly—someone has to have costs in much greater breakdown than most systems men can find today. When we get into such detail, proprietary rights intrude. It may be that the internal manipulations for dollars alone along the foregoing lines may have to be accomplished within the Government and made available only after processing of the kind I speak of here. When we come right down to it, the true costs of our big items—quality and quantity—are really wrapped in the fog. Surely this deserves the research spirit and zeal as much as anything else. Cost, we always want to know.

As I look at the aircraft carrier, as such, I cannot fail to remark on the enormous direct and indirect cost of ground roll of the aircraft. The immensity of these great mastodons connotes the wild speed these planes demand just to be airborne. The acreage of the flight deck is huge, and still the taxiing and spotting of aircraft is delicate and tricky. What is more, the individual crews demanded by these machines, by the LSO, and by primary fly control, watch by watch, along with protracted and exhaustive qualification procedures, all incurred by the ground-roll requirement, escalate expense along with all the backup manpower of bakers, cooks, and the horsepower and fuel to drive the whole apparatus along.

I am not against any of this. I think that we are going to need these great carriers for a long time to come. But, if we are going to go on about cost effectiveness and whole weapons systems, it would seem, for instance, that longer looks at ship-based VTOL systems are decidedly in order. Let us remember that, while VTOL's may tend to be fuel hogs, long-legged performance, as for such as the A3D's, may get less important and the whole system of ship and aircraft judged by first costs and operating costs may look quite favorable to complement the large ships. At any rate, I should like to see for once just what a new-construction design—tailored quite strictly toward VTOL's of reasonably high performance—would look like and how much they might cost.

I am talking about a serious, well-engineered study, not a prepreliminary sketch book. When all is said and done, we might not like it either as a system or a ship. But strong, exploratory design work conducted with a true research spirit is relatively cheap and badly needed in follow-on to more excellent papers such as this one.

R. K. McCandliss, *Member:* This paper treats an interesting and timely subject. My first reaction was that the author has chosen a most complicated example to treat, but, upon further consideration, I feel that the choice of any other mission for such an analysis would not have developed as completely the interfaces between the ship designer and the governing military factors.

It is refreshing to see the logic of the design of such a warfare system described in terms less hackneyed than the standard nomenclature used in the field, which has become dulled in meaning through constant use. Reading this paper, one sees new shades of emphasis on the process now becoming known in official circles as Ship System Formulation.

The requirements for quantification of military effectiveness specified by the Department of Defense in its procurement policies call for a "before the fact" evaluation of the design concepts in the military environment to replace the familiar evolutionary process. This task is a tremendous one, and would require war gaming exercises of the CVA/WS in enough repetitions of the attack mission under various environmental conditions, and against a range of threats, both real and projected, to develop reliable statistics on the probability of successful performance of each mission. Such a task can only be accomplished with extensive use of the computer for the calculations involved.

Various indices of effectiveness are used in different phases of the missions assigned the CVA. Each effectiveness index is based upon a different set of physical dimensions, thus rendering difficult comparisons between differing competing system concepts to accomplish the same mission. The Military Effectiveness Division at the David Taylor Model Basin has found that a more universal measure of effectiveness is the probability of successful performance of a specific mission against a specific threat in a specific environment. A table of such probabilities related to variations of mission, threat, and environment is completely general and can compare the performance of widely differing systems.

The Ship Concept Research Office at the David Taylor Model Basin is involved in the development of procedures to contribute to the accomplishment of such quantitative effectiveness assessments in various missions, not only of the CVA, but of other naval warfare systems. The experience relationships summarized in the latter part of this paper will be a valuable source of distilled data for the naval architectural aspects of CVA parametric studies to support such analyses in a projected future environment.

I confirm the use of sensitivity studies, mentioned in the conclusion. The Model Basin effectiveness participation in Ship System Formulation with the Naval Ship Engineering Center is geared to the generation of sensitivities of mission effectiveness to ship characteristics as parameters. This permits a trade-off selection of characteristics, with full knowledge of the capabilities bought for equipment prices paid. It also permits effectiveness studies to proceed concurrently with design studies, permiting some postponement of the commitment of the design to a given set of characteristics.

Prof. E. V. Lewis, *Member:* This paper deals comprehensively with the overall evaluation of a typical naval vessel as part of a weapons system. It can be expected that various aspects of this evaluation will be refined and improved and that modifications will be required in applying the principles to other ship types. This paper will be a basic reference for many years to come.

First, it is agreed that "ship operability" can be defined as "the expected time at sea that these motions will not exceed limiting values such that air operations must be temporarily curtailed." In fact, the same definition would apply to other ships with other controlling missions if the term "air operation" was replaced by "sonar operation" or "torpedo attack mission," and so forth. The techniques developed in the paper given by the author with Professor Pierson in 1953, in combination with elementary probability theory, can provide meaningful evaluations of ship operability.

In this case, a question only remains as to the choice of criteria of limiting motion. One wonders, for example, whether pitch amplitude suffices to describe the complicated situation of an aircraft landing on a carrier deck; and a question can be raised as to whether frequency of bow emergence is an adequate measure of sonar operability, since quenching may occur before the transducer emerges, and relative vertical velocity may be a significant factor.

Work at Webb Institute on the problem of ship operability in relation to a bow sonar mission has led to convenient graphical presentation of results that are entirely consistent with Dr. St. Denis' ideas. For several alternative designs, each at several forward speeds, the graphs show the percentage of time in a particular ocean area that certain limiting rms values of relative motion between bow and wave would be expected to be exceeded. One can then explore the effect of different limiting values of motion, expressed for example as the percentage of pitching cycles in which the sonar transducer approaches within a stated distance of the water surface. This leads to definite quantitative evaluations of operability. In a typical case, for example, it was shown that one design could be expected to carry out its sonar mission in the North Atlantic 81 percent of time at 20 knots and 89 percent at 10 knots, while a competing design could accomplish its mission only 68 percent of the time at 20 knots and 81 percent of the time at 10 knots.

The problem of extreme behavior, discussed under the heading of Seaworthiness, requires a much deeper treatment. In particular, it is doubted that the problem can be treated on the basis of "the *worst* expected sea state encounterable." Rather, as indicated in a later paragraph, "The sea spectrum to be used is *not* that corresponding to the severest expected sea state during the ship's lifetime, but to that sea which makes for the greatest response!" Furthermore, R. Bennet has shown that the highest wave-induced bending moment will probably occur in waves that are on the average not the most severe in terms of significant wave height, because the most severe waves occur rarely, and the probability of a high bending-moment value increases with the length of time the ship experiences a particular level of storm severity. Therefore, it is felt that the only valid basis for predicting extreme quantities such as bending moment is to evaluate the performance in seas of different levels of severity and then to determine the combined probability of exceeding different levels of bending moment.

Incidentally, it would be interesting to know both the source of the severe sea spectra shown in Fig. 6 and the basis of plotting, since we have been unable to compare the spectra with other published data.

Prof. Harry Benford, *Member:* The thinking that went into this paper indicates our Navy's growing awareness of the pervading importance of economics. Maximizing the probable effectiveness per dollar spent is clearly good sense and gives the designer a fundamental measure of merit on which to base decisions. Although no one can claim to have a truly valid measure of military effectiveness, even a crude approximation is better than none. The author deserves our thanks for outlining a logical approach to naval design based on such considerations. And, if he has left some tantalizing gaps (as in his two-line exposition on how to estimate investment cost), he has also presented much useful and original design data in other areas.

On the third page of his paper, the author states that parametric design models are extended to yield cost, and that initial costs and operating costs can be linked to any set of design characteristics. Now, although I located the aforementioned two-line explanation of how to estimate initial cost, nowhere did I find even one line on how to estimate operating costs. Perhaps the author would be good enough to develop that point somewhat. In addition, I should like to learn his views on what interest rate might be appropriate for the Navy in relating present and future costs.

Fig. 12 is something of a conversation piece. It shows that our larger aircraft carriers are manned by crews exceeding 4000 in number. If the Navy is looking for ways to save money, let it look here. Cutting that number in half would certainly save gross amounts in reduced hull size, lesser accommodation equipment, lower wages, lower victualing costs, and lower repair costs for accommodations. To those direct, though disguised costs we should add the social cost of 2000 skillful men who might otherwise be usefully employed in industry—and their concomitant contribution in way of the income tax. Does the author believe these points are worth study even though they defy exact analysis?

Dipl. Ing. Wilhelm Hadeler,[6] *Visitor:* This paper

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[6] Oberregierungsbauret i. R.

belongs to the best ones written to date on aircraft carriers or, for that matter, on warships of any type. Not only does it deal with the most difficult problems of designing aircraft carriers, but it also gives full particulars of the difficult problems of selecting the military characteristics of a man-of-war on the whole.

When more than 30 years ago the principal navies of the world began to project and to design aircraft carriers, there were only a few experiences with the details of this kind of warship. All of these experiences had been gained by practical trials with the carriers then afloat, which had been rebuilt from battleships, battlecruisers, and other vessels in peacetime. In time of war, no navy could dispose of experiences in the use of carriers and of a carrier-borne air arm. It seems that only the U. S. Navy and the Imperial Japanese Navy had already prepared or were preparing something in using for attack purposes. The Royal Navy in those days thought mainly of the control of shipping to protect it against raider attacks.

In the early thirties it was quite impossible to design an aircraft carrier in the conventional way by estimating the groups of weight: hull, armor, propulsion plant, armament, fuel, equipment, and so on. The main problem was always to build a deck for starting and landing the aircraft and to combine it with all the necessary accessories.

When the German Navy began to prepare the design of its only (never completed) carrier, the situation was still somewhat more difficult than in Great Britain, the U.S.A., or Japan. Until the British-German Naval Agreement of 1935, Germany had been forbidden by the Versailles Treaty to possess any military or naval aircraft. A few secret experiments with some single aircraft had only brought out some important points of view for naval aviation in general. Therefore we had to find out ways and solutions for every detail of the "Fluganlage" (flying plant) without any practical experience. We could only adapt the corresponding arrangements of an airfield to a ship. All difficulties, which the other navies had overcome in the course of more than ten or fifteen years, had to be mastered by the Germans during two or three years. An additional difficulty was the fact that there were neither naval officers nor naval architects with experience in carrier problems! Especially, there was no possibility of evaluating the problems systematically, as Dr. St. Denis has done.

Naval architecture is a special branch of shipbuilding that concerns engineers as well as naval officers. The engineers must have a large quantity of technical knowledge as well as knowledge of the main military problems. The naval officers on the other hand, besides their own activities, must know a good deal of the technical possibilities they can use. But, at first, both engineers and officers need an extremely careful preparation of all those demands which contain the military necessities of attack, self-defense-effectiveness, speed, sea-endurance, nautical features, and so forth. These elements of every design must be prepared by the military boards as completely and carefully as possible. The better this work is done, the better the final design will be!

The task of building the best and most accomplished fighting value for warships of every type is an extremely difficult one. In former years the knowledge of experienced senior naval officers was the best guidance in this work, but nowadays this is no longer sufficient. A well-balanced fighting value has become more and more urgent since the conventional capital ships and cruisers have begun expiring, since the aircraft carrier, together with the modern destroyer, has become the most important type of surface ship, and since the submarine danger is continually growing. As far as I know, Dr. St. Denis is the first to have succeeded in building up a scientific system of evaluation for every kind of necessity and experience to form the complicated "integral" called fighting value.

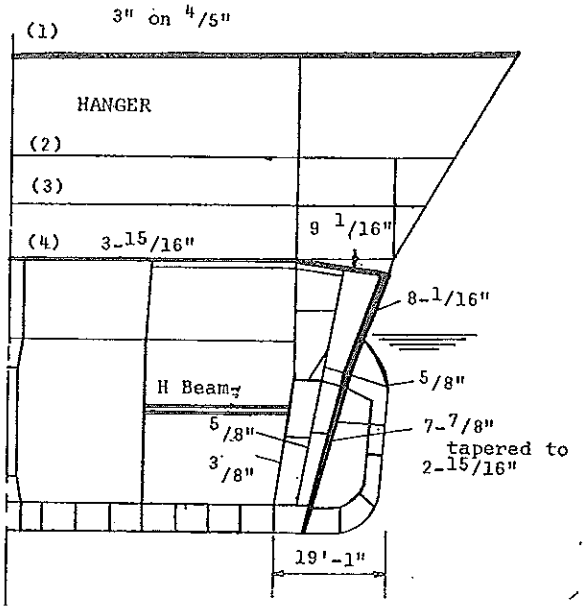
W. H. Garzke, Jr., *Member,* **and Lt. R. O. Dulin, Jr.,** *Member:* The CVA is a powerful, well-protected, fast warship derived from the optimization of three major requirements; namely, speed, protection, and offensive capability. The growth of an aircraft carrier's parameters was hindered before the last war by physical limitations such as canals, locks, and depth of harbors. World War II combat experiences, however, illustrated the need for multipurpose weapons systems, the crucial importance for the allocation of sufficient volume in the side-protective system, plus the necessity for a careful consideration of the demands for higher speed. Excessively high speed can demand a near-prohibitive price in terms of reduced military capabilities, unless the displacement and length of the strike aircraft carrier are permitted to increase. Table 4 illustrates the evolution of carrier design characteristics, although the trends in protection are not evident. High speed, good protection, and an effective weapons system were achieved in the American CVA's *Forrestal* and *Enterprise* by an increase in their parameters and displacements.

In the design of a CVA, it is most important that careful attention be given to the development of underwater protective systems equal in scope to

Table 4[a]

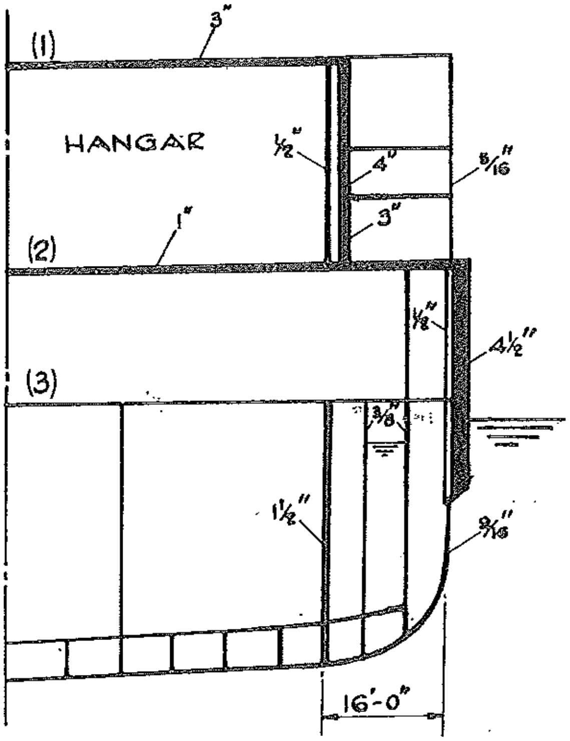
Carrier	Year Completed	Full-Load Displacement	LWL	Beam	Draft	SHP	V_{max}	Aircraft
Illustrious	1940	27,000	753	95	24	110,000	30	72
Graf Zeppelin	1940[b]	33,550	820.2	88.6	27.9	197,264	33.8	42
Shinano	1944	70,755	839.9	119.1	33.8	147,948	27.8	47
Midway	1945	55,000	900	113	32.8	212,000	33	137
Forrestal	1955	75,900	990	129.5	37	260,000	33	100
Enterprise	1961	85,350	1040	133	37	300,000	33	80

[a] Data unofficial.
[b] *Graf Zeppelin* was not fully completed



(1) Flight deck
(2) Hangar deck
(3) Upper deck
(4) Middle deck

Fig. 13 *Shinano*—midship section



(1) Flight deck
(2) Hangar deck
(3) Upper deck

Fig. 14 *Illustrious*—midship section

that given the military payload, so that this warship can continue her assigned missions with some degree of underwater damage. It is then mainly a question of space for the aviation requirements, particularly the length and width of the flight deck and size of hangars, and sufficient length and depth for the side-protective system. Some indication of the types of underwater protection possible can be inferred from an examination of the protective systems of two carriers noted in Table 4, the *Illustrious* and the *Shinano*, shown in Figs. 13 and 14. The use of armor in the protective systems is attributed to the fact that the protective systems of large carriers of the World War II era were frequently derived from those on modern battleships.

The *Shinano* represented a large aircraft carrier design with an extreme emphasis on heavy protection. During the conversion from a battleship to a carrier, it was decided to accept a reduced aircraft capacity in order to permit the provision of heavy protection. In the much smaller carrier *Illustrious*, armor and underwater protection were similarly emphasized. Despite a full-load displacement of only 27,000 tons, the *Illustrious* was provided with armor fully as extensive as that of the *King George V* class battleships, although of reduced thicknesses, and the torpedo defense system was of the same depth as that of the battleships. Both these carriers obtained improved resistance to damage at the expense of offensive capabilities. Only in the very large warships can an effective combination of high speed, good protection, and good offensive capabilities be attained, as is evident in recent development in American CVA design.

Recent technological developments have permitted the power per shaft to approach 75,000 shp, and the author has commented that further increases might be accompanied by the onset of cavitation effects. Obviously, should CVA displacements continue to increase or speed requirements increase, more than four shafts will be needed to provide sufficient power. The addition of a fifth shaft on the centerline would permit the provision of added power at the price of minimal added difficulties in arrangement. Lightweight gas turbine drives, for instance, might provide a sprint capability with a small weight penalty. All German heavy cruisers and battleships of the World War II era featured centerline shafts, and experienced no difficulties. High-speed warships require enormous machinery plants, and great care must thus be taken in the development of speed requirements to avoid unduly diminishing other attributes desired.

The specification of design characteristics, evaluated by methods of analysis similar to those presented in this paper, gives the designer a much better chance to develop an efficient design.

Prof. R. A. Yagle, *Member:* My concern with this paper is that the author may beguile others—as he has me in the past—into believing that once the problem can be stated it is in fact resolved. In this instance I have been laboring for some three years in attempting to dermine usable values for the k factors and the n and h indexes, or other expressions entirely, which he relegates to Table 3 and casually remarks must be obtained empirically. The volume equation is equally as involved and, were I a weapons system analyst, I am certain I would have great difficulty selecting values to use for the quantities in most of the other equations. Despite this, I would like to see more "broad brush" papers of this type presented so that all of the members of our profession can be made aware of the design philosophy behind particular, distinctive ship types.

Dr. A. H. Keil, *Member:* The author describes the basic steps leading from defined naval missions to the identification of the design characteristics for ships. He thus deals with the process of concept formulation and the application of systems analysis, which are now becoming formal steps in the decision making for the Navy's shipbuilding program.

Some will say that these thoughts are not new and that "we have always done it." There is no doubt that most serious thought has normally been given to the derivations of ship characteristics, and the success of the aircraft carrier, especially in recent operations, is proof of it. But concept formulations and system analysis are here to stay, requiring documentation of the thought processes and the quantitative analysis which lead to the selection of specific sets of ship characteristics.

The benefit of a methodology, as the author presents, is to illustrate the pattern of thought processes, to establish guidelines, and to drive home the complexity of such studies. I have read the paper again and again with great interest, but I still find it difficult to make specific comment, though the subject is not foreign to me.

Application of the methodology is, as the paper states, by no means simple and requires judgments during each step of the process and many iterations. I would like to add two brief specific comments. The aircraft carrier is, as the author states, a component of the Carrier Task Force for which the Navy has defined missions. By considering this Task Group in the spectrum of possible wartime environments, it becomes possible to identify the sensitivity of the performance of the CVA's and the Task Group to variation in design characteristics. This step is important because frequently considerable increases in "system effectiveness" become possible by implementing conclusions derived from the sensitivity study.

Application of the methodology developed in this paper is not restricted to the determination of ship characteristics alone. It permits also, especially if coupled with sensitivity studies, the determination of the impact of projected improvements and technological advances on the ship characteristics and on systems performance. Such evaluations are critical for identifying relevant areas for research and development efforts and their significance, thus providing focus and direction for the Navy's research and development effort.

I commend the author for undertaking the complex task of bringing this subject before the Society and for his skill in covering it so throughly.

Cdr. Richard Nielsen, Jr., USCG, *Member:* I am not qualified to discuss carrier design as such, but will confine my discussion to the principle of feasibility of design of ships. Much of the paper applies to selection of the size and principal design characteristics of any ship.

The Coast Guard is currently developing a computer program for the feasibility design of icebreakers. Hence, Dr. St. Denis' rationale on nautical performance, conceptual design, selection of nautical features, and base and parameter design and cost models is directly applicable. These sections will be studied with great care for incorporation within the icebreaker feasibility program.

Application of the military payload concepts to an icebreaker is not so clearcut, but, since an icebreaker as a carrier is a multimission ship, the same rationale can be applied.

W. N. Price, ***Member:*** Dr. St. Denis has done an excellent job in depicting the analytical approach, but the average engineering reader cannot help questioning whether or not the various mathematical formulas can really be quantified in a meaningful manner. I refer not only to the various probabilities, but also to the selection of parameters that determine basic functional relationships influencing the decision maker. Some further treatment would be desirable as to the approach to decision making under uncertainty in the applicable areas. Possibly, a deeper examination of the relationship of the CVA as a subsystem to the Carrier Task Force system would be in order. However, the paper now covers an extremely broad area, making some condensation and simplification essential. A full-length book would be required for really adequate converage.

C. L. Wright, Jr., ***Member:*** Of prime importance in this paper is the full consideration of the entire system of which the ship is a component part. In this case, the aircraft carrier is a component part of a weapons system. The consideration that should be made if the ship were a component of a transportation system, a communications system, or any other system is not too different.

This consideration includes a study of the place of the ship in the system, its optimum contribution to the system, its optimum characteristics, and an evaluation of its effectiveness. In each of these phases, empirical relations are used. It is evident that without the use of empirical relations the number of factors involved and the intricacies of direct studies would be too great for practical consideration, even with digital computers. But the use of empirical relations is sure to affect the reliability of the results.

The paper contains a quotation that "The merit of empiricism is that it prevents one from making gross blunders." My experience has been that it often leads to a critical accumulation of lesser blunders that could have been avoided if more direct thought had been given to the application. Empirical relations are no better than the information from which they are derived. Unless they are constantly revised, they do not reflect new developments in the state of the art. Reliance upon them will never lead to significant improvements in the fundamental aspects of ship design. In conceptual ship design, they provide the compromise between the results desired and the practical means for obtaining these results, but they should be used only with a full understanding of their limitations.

Relative to parametric design models for determining the optimum characteristics of the ship, the development of such models has been quite popular. Some of these models have been developed in considerable detail. In addition to a model developed by Dr. St. Denis, one developed by John W. Schmidt and another by Robert P. Whitten are specifically applicable to aircraft carriers. Before actually embarking on another development of such a model, it might be well to look into some of these already developed.

But these models cover only one phase of the study. With respect to the full scope of the study, I believe Dr. St. Denis has made an important (and to my knowledge unique) contribution to the profession.

Capt. R. L. Evans, USN (Ret.), ***Member:*** Dr. St. Denis has presented the systems analysis approach to the ship system concept in a clear and logical manner. This tool was not available, at least in its present form, until after World War II. The application of computer technology certainly permits many more situations to be investigated during the concept phase of a ship system design than was possible in prior years. In spite of the fact that this technology and methodology was not available in its present form prior to the ending of World War II, the informal and to a large extent undocumented manner in which the elements of the problem were treated then did produce ships which were useful and effective for the threats that existed during World War II.

The extremely rapid technological advances that have been made over the last two decades have complicated the problem of selecting the best ship system to meet our present requirements and perhaps still contain the flexibility in the concept to permit weapons system changes to counter the rapidly expanding arsenal which such advances make available. But because ship systems are expensive, and at least the hull and machinery are long lived, flexibility to permit weapons system change would be extremely desirable. The changes that have been made to the weapons systems in the *Essex* and *Midway* classes of aircraft carrier since their conception, even though expensive, are examples of this flexibility.

The considerations developed in this paper are similar to those performed in the advanced design, systems engineering, and operations research functions of most major aerospace firms. The methodology discussed has been developed over the past ten years for use in choosing combatant ship characteristics.

Five major concepts that affect the selection of design characteristics brought out by the author are:

(*a*) The mission is the point of departure in preliminary design.

(*b*) Effectiveness is determined by military performance in the control or *dominant* mission.

(*c*) Degradation of military performance by cause.

(*d*) Criterion for retaining or excluding parameters is the measure of effectiveness in carrying out the mission.

(*e*) Size is directly related to cost.

In addition, the author has provided a useful list of detailed items to be considered in developing principal characteristics. The breakdown of system inherent degradation, for example, into engineering, operational and natural environment, and the further breakdown of each of these classes, is useful.

The author states, "Collapse of the basic inputs to only a few important parameters is essential for the expenditure of reasonable effort in selecting a design." He also quotes from E. S. Quade as follows: "Systems evaluation is judgment, nonetheless." As evidenced by these quotes, the author certainly recognizes the costs during the study process of detailed investigation of all the sub-areas listed. The validity of the input data to this process must be known before accepting the output as real. There are areas where valid input data are extremely difficult to obtain, or where they are nonexistent. In such areas, judgement based on experience must be used. Unfortunately, the paper may be misinterpreted, as the implication can be drawn that detailed studies are required in all of the sub-areas of investigation. Instead, detailed studies of sub-areas are warranted only if they will significantly affect system evaluation or judgment. In many cases, the sub-area studies indicated can be deferred until after selection of principal characteristics. The process of selecting sub-areas to study is analogous to that of the overall problem of systems evaluation—it, too, is a judgment process.

As a guide to selection of principal ship characteristics, this paper is useful. We believe a number of the author's concepts can be used profitably in the analysis of ships' characteristics. However, it should not be treated as the only tool that will develop ship systems characteristics.

Author's Closure

I am grateful to Mr. Crawford for his elegant discussion, which helps very much to relate the problem of carrier design to the context of the real world.

That the evaluation process requires a new functional breakdown of weights and costs is clear. The one introduced in the paper is tentative. What is not tentative is that, to be used in the evaluation process, the weight and cost schedules must reflect the logic that the design of a system starts with its mission and continues with the determination of payload, base support, and base. A change in any index of mission performance is primarily felt in the payload and, normally, to a minor extent in the base.

Mr. McCandliss has raised the important point of how to assess military performance. There is full agreement over the necessity of determining probabilities of successful performance of specific missions against specific threats in specific environments. However, a table of such probabilities does not as yet provide a universal measure—not until the probability of occurrence of mission, threat, and environment has been assessed and the probabilities of performance have been properly weighted in accordance therewith. For specifics cannot well be interpreted until, through the application of statistics, they have been transformed into generalities. In the end, the performance of a system must be reduced to a very single number, for, unless this is done, the choice will be ambiguous.

There is a great temptation to assess military performance by playing war games. It is my opinion that, although war games have an essential role in training military personnel, they are simply a waste of time for design and for planning. These can be done more generally and far more expeditiously by application of warfare theory (Lanchester's law is an example).

I am pleased by the succinct way in which Capt. Evans has summarized the basic philosophy of the paper. His point that the validity of the input data must be known before the output can be accepted as real is well made but, unfortunately, applies only to measurable data. The great uncertainty in the evaluation process is over how to access the future, and the methodology must allow for this.

The statement that the informal and somewhat undocumented manner of analysis used prior to World War II did produce ships that were useful and effective for the threats that existed during that war is sufficiently general to be correct. However, it is my opinion that if the usefulness and effectiveness per unit cost of all our naval ships during World War II could be quantified and the types ranked accordingly, the battleships would sit at the bottom while the CVA's and landing craft would stand near the top. If this point be admitted for purpose of argument, the question to be asked is: "Could a systematic evaluation in advance of construction have brought this out?" If it could have, we would have found ourselves better off having built CVA's and landing craft rather than battleships. It is such questions that the system evaluation process seeks to answer.

I find myself in complete agreement with Prof. Lewis' remarks. The problem of extreme behavior of ships, long neglected in America, should be seriously pursued. There is promise of significant advances to be made in this area as our observations of the sea become more plentiful and our statistical techniques more acute.

The severe sea-state spectra of Fig. 6 were obtained as follows: The Bretschneider formulation of the sea spectrum is

$$S(T) \equiv 1.35\,\frac{h_s^2}{T_s}\cdot\left(\frac{T}{T_s}\right)^3\cdot\exp\left[-0.675\left(\frac{T}{T_s}\right)^4\right]$$

where T is the wave period and T_s the significant wave period. Note that the area under the spectrum is equal to the mean of the squared wave height.

$$S \equiv \int_0^\infty S(T)dT = \overline{h^2}$$

The assumption of a Rayleighian distribution of sea-state severity

$$f(S) \equiv \frac{1}{\sigma(2\pi)^{1/2}}\exp(-S/2\sigma^2)$$

leads to a worst sea state of one hour's duration to be expected during the ship's lifetime of t_l hours defined by

$$S = 2\sigma^2\cdot ln\left(\frac{t_l}{\sigma(2\pi)^{1/2}}\right)$$

For a fully developed sea the significant wave period is related to the significant height by the empirical formula

$$T_s = 2.13\sqrt{h_s}$$

where

$$h_s^2 = 2S$$

The roll data for the North Atlantic (see T & R Bulletin H-19) give $\sigma = 8.35$ ft. For a 20-year lifetime, the following figures obtain:

$t_l = 175{,}000$ hr
$S = 1390$ sq ft
$h_s = 52.7$ ft
$T_s = 15.4$ sec

Thus, the formula for the 20-year spectrum is

$$S(T) = \frac{(1.34)(52.7)^2}{(15.4)^4}\cdot T^3\cdot\exp\left[-0.675\left(\frac{T}{15.4}\right)^4\right]$$

In reply to Prof. Benford's criticism of the lack of cost data, the page limitation on the author did not permit a full development of this; however I shall send him the parametric design model used to derive the initial investment cost. The query on operating cost is readily answered, but at the expense of a great deal of bookeeping. In the brief space allowed me, I will provide some gross figures.

During peacetime operations, the greatest cost is the personnel pay. The salary scale is such that the cumulative cost of all personnel over a 20-year ship lifetime tends to equal the initial investment cost of the ship alone. This comparison is crude. If the comparison is based on initial investment cost of ship and aircraft (3 airsuits during a ship's lifetime), personnel cost dwindles to about one fourth of total investment cost.

The cost of fuel and other consumables for peacetime operations on our latest class of conventional CVA's is about ten million dollars a year. Remaining operating costs are small in comparison. I have no data as to maintenance and modernization costs.

During wartime operations there is to be added the cost of repairs. Such a cost is related to the survivability of the CVA/WS, but I have not as yet worked out the logic.

It is apparent that reduction of complement size would result in large savings, but it is not clear how much of a reduction can be made. The size of complement is dictated by the readiness condition of general quarters. In this condition, most departments of the ship are in full action and the remainder (e.g., the damage control party, the aircraft support) are on alert and ready for action if the ship is hit or if the returning aircraft have been damaged. The CVA/WS is an extremely complex WS and its operating efficiency, i.e., its effectiveness, depends chiefly on having available a sufficient number of the required type of specialists to keep the innumerable parts of the system going.

Cdr. Price is correct, of course, when he suggests that adequate coverage of the subject requires a full-length book. To prepare such a book, one needs only encouragement—both moral and financial.

The errors noted have been corrected.

May I assure Prof. Yagle that the k factors and the n and h indices have all been worked out. I owe this to the courtesy of the Naval Ships Systems Command in making available to me their elaborate weight and volume schedules. As to his remarks on beguiling, I protest that I have beguiled myself more than I have others.

Mr. Wright's remarks are noteworthy. I recall his stating once that "a ship is an accidental combination of well-designed components." This goes to the heart of the problem. The whole purpose of the evaluation process is to make the synthesis of a ship or of a system less accidental.

I warmly welcome Prof. Keil's able justification of the method presented in the paper. His remarks on logical extensions of the methodology are deeply appreciated. Perhaps this observation may be added: The philosophy behind the method is that intuition should be applied to those aspects of the process where deductive logic fails. Thus, instead of having to make an intuitive overall decision, one makes intuitive decisions of lesser caliber on several aspects which are all linked together by a chain of logic. The gain is that, the smaller the aspect that must be approached intuitively, the easier it is to exercise judgment.

Messrs. Garzke and Dulin raise the interesting point of protection and introduce the protective design particulars of the *Illustrious* and the *Shinano*. It is noted that in both ships a large fraction of the ballistic protection is horizontal and, therfore, directed against gravity bombs. Although, in World War II, CVA's have suffered, sometimes seriously, from air attacks in which gravity bombs were employed, it is a fair question to ask whether one should install such protection in future CVA's. The present tendency toward long-range homing weapons, both for attack and for defense, makes for flat weapon trajectories, and results in demands for vertical armor. How far one should go in this direction at the expense of horizontal armor is a point that can well be answered by the process discussed in the paper.

Mr. Hadeler introduces the term "fighting value," which is a very descriptive term for the overall quality of a WS. He brings out the difficulties in undertaking an analysis of fighting value in the absence of supporting empirical data. This is true, but only rarely does one operate in a vacuum. If data are lacking, one can always introduce hypotheses and then test the outcome for sensitivity to the hypotheses introduced and, in this manner, be guided.

I am heartened by Cdr. Nielsen's remarks that the Coast Guard will examine the method presented for applicability to their new icebreaker design. I will follow the application with keen interest.