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DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND

1 MARCH 1982

DDS 079-2

MINIMUM REQUIRED FREEBOARD FOR U.S. NAVAL SURFACE SHIPS

TABLE OF CONTENTS

079-2-a. References

1) Bales, Nathan K., "Minimum Requirements for Dry Fore Decks: A Design Procedure, "Society of Naval Architects and Marine Engineers, Presented at Star Symposium, Houston, Texas, April 25-29, 1979

2) Myers, William, "User's Manual for Standard Ship Motion Prediction Program, SMP" DTNSRDC Report (will be published later).

3) NAVSEA Freeboard Criterion, Report Number 6115-71.9.

4) DD08 Ship Synthesis Computer Program

5) Bhattacharyya, Rameswar, DYNAMICS OF MARINE VEHICLES, Wiley & Sons, pp. 337, 1978.

6) Rosenblatt, L.A. "The Design of Modern Oceanographic Research Ships," SNAME Spring Meeting Paper, 1960.

7) "Salvage Ship ARS-50 Preliminary Design Hull Form Development Report", NAVSEA Report, NAVSEA 3213-79-21, October, 1979

8) Comstock, Edward & Covich, Phillip, "CV Freeboard Design Criteria For Carrier Aircraft Elevators," NAVSEA Report No. 6136-74-19, 7 February, 1975.

9) Bales, Nathan K., "Strike Cruiser (CSGN) Above Water Bow Design Evaluation (U)", NSRDC Technical Memorandum, TM-15-76-45, July, 1976

10) Practical Application of Bales' Minimum Freeboard Requirements Design Procedures, NAVSEA Report 3213-81-05, February 1981

11) DDS 079-1, Stability and Buoyancy of U.S. Naval Ships, 1 August 1975.

12) Code of Federal Regulations, Chapter I, Subchapter E - Load Lines, 1 October 1979.

079-2-b. Nomenclature

C_B = Block Coefficient

FBD_{STEM} = Freeboard at Stem, Feet (meters)

FBD_o = Freeboard at Station 0, Feet (meters)

FBD_3 = Freeboard at Station 3, Feet (meters)

$FLARE_3$ = Flare at Station 3, Feet (meters)

F_G = Geometric freeboard measured vertically from weather deck or bulwark edge to the hydrostatic waterline

F_r = Leading component of F_G, it accounts for ship-to-wave relative vertical motion, r, as defined by

$$P_w = e^{-2 (F_r/r_{1/3})^2}$$

$\delta_1 F$ = Change of level correction resulting from trim and/or sinkage

$\delta_2 F$ = The change in freeboard caused by the ship's bow wave profile

$\delta_3 F$ = Effective freeboard factor resulting from the incorporation of flare, knuckle, or other special features of above-water bow design

LBP = Length of Ship between perpendiculars

LWL = Length of Ship at water line

n = Station number

P_w = The per-cycle probability of occurrence of deck wetness in random waves

r = Ship-to-wave relative vertical motion

r_k = Kinematic relative motion defined by the vector sum of vertical absolute ship motion and incident wave evaluation

$\delta_1 r$ = Change in relative motion due to dynamic swell-up caused by the oscillations of the ship at the free surface

$\delta_2 r$ = Change in relative motion due to distortion of the incident waves caused by the presence of the ship

T = Draft of ship, Feet (meters)

$(T_w)_o$ = Modal wave period

V = Ship speed, knots

Δ = Ship displacement, Long Tons

$(\tilde{\zeta}_w)1/3$ = Significant wave height

079-2-c. <u>Minimum Required Freeboard Calculation During Concept and Preliminary Design</u>

079-2-c(1). <u>Combatant Ships</u>

This method evolved from the more advanced studies in freeboard design presented in Reference 1. As presented in this method, the prominant factors in the determination of minimum freeboard are ship length and draft. The pitch component of absolute ship motion causes ship length to have the major influence on acceleration and slamming characteristics. Ship draft has a major influence on slamming characteristics and has been shown in Reference 1 to effect required freeboard. The minimum required freeboard at Station 0 is calculated using the following equation:

$$FBD_o = 10.5 + .045\,(LBP-150) - .00002(LBP-150)^2 - .20\,[(LBP/T) - 27.5]$$

where, min FBD_o, LBP and T are all in meters.

This equation can be applied to combatant ships of all types as a preliminary design method. Figure 4 presents this equation in a graphical format. If the design in progress is a destroyer type hull, the following specific processes may be applicable.

079-2-c(2). <u>Destroyer (only) Type Ships</u>

In recent years, freeboard requirements have been satisfied for destroyer type ships through the alternative use of either of the two methods presented below. The first of these methods, by Gale, Shen and Walker (Reference 3) calculates required freeboard as a function of ship length and draft. It is based on motion studies which results in a balance between deck wetness (wetnesses/hour at Station 0) and slamming (slams/hour at Station 3) characteristics such that slamming and wetness limits are reached at the same time. This method is currently being used in the DD 08 ship synthesis computer program (Reference 4).

The equation for determining the required freeboard by this method is:

$$100FBD_o/LBP = 1.011827\,(100T/LBP) - .000636215(LBP) + 2.780649$$

This method is restricted to destroyer type ships satisfying the following criteria:

$$150 < LBP < 1300$$
$$2.5 < 100T/LBP < 5.2$$
$$30 < \Delta/(.01LBP)^3 < 120$$

Figure 1 presents this equation in a graphical format.

The second method presented was empirically derived from fleet reports on deck wetness characteristics for destroyer type hulls. It makes use of a graph of ship length as a function of the freeboards at the stem and Station 3 and the flare at Station 3. (See Figure 2 for definitions)

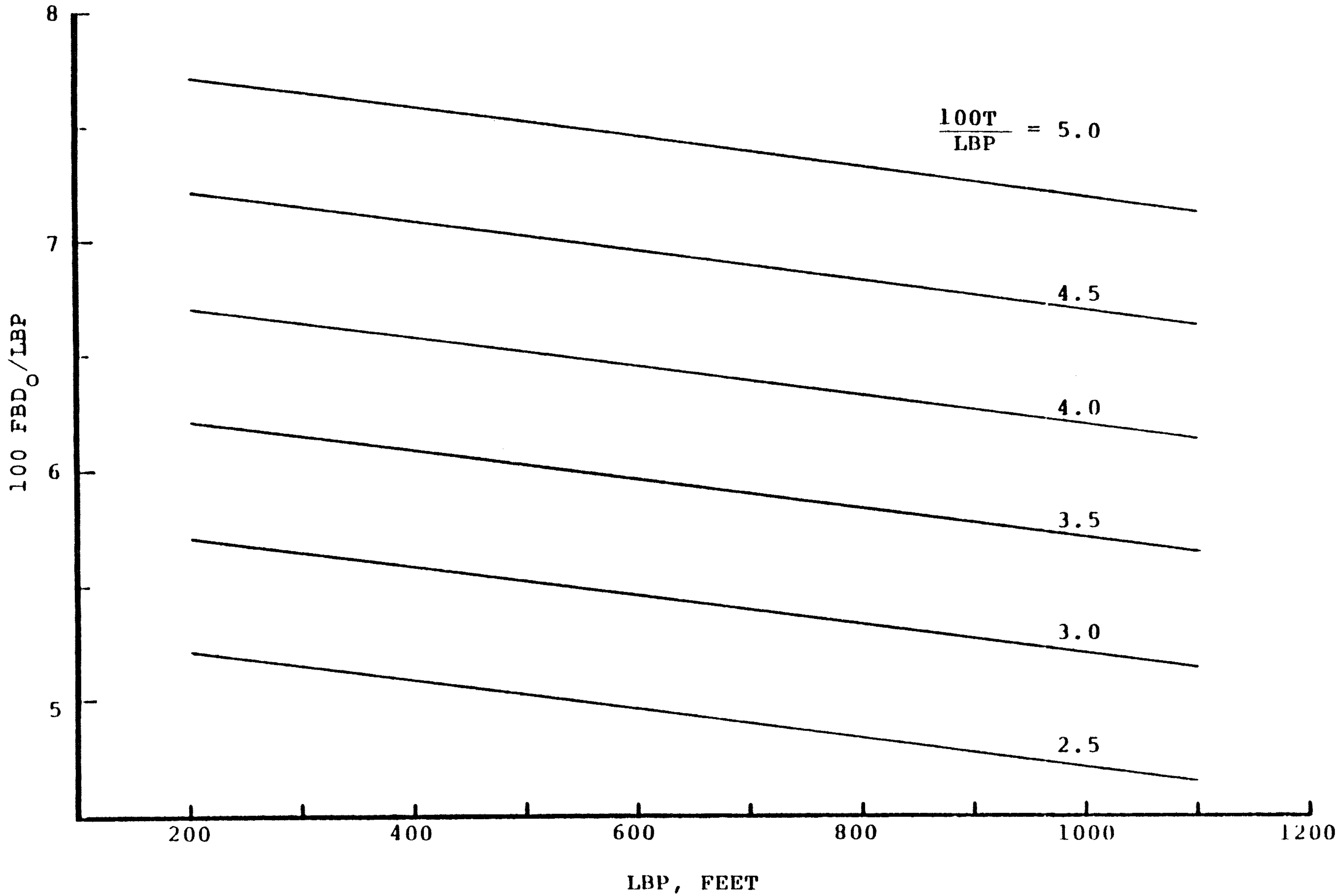


FIGURE 1 - Freeboard As a Function of Ships Length and Draft

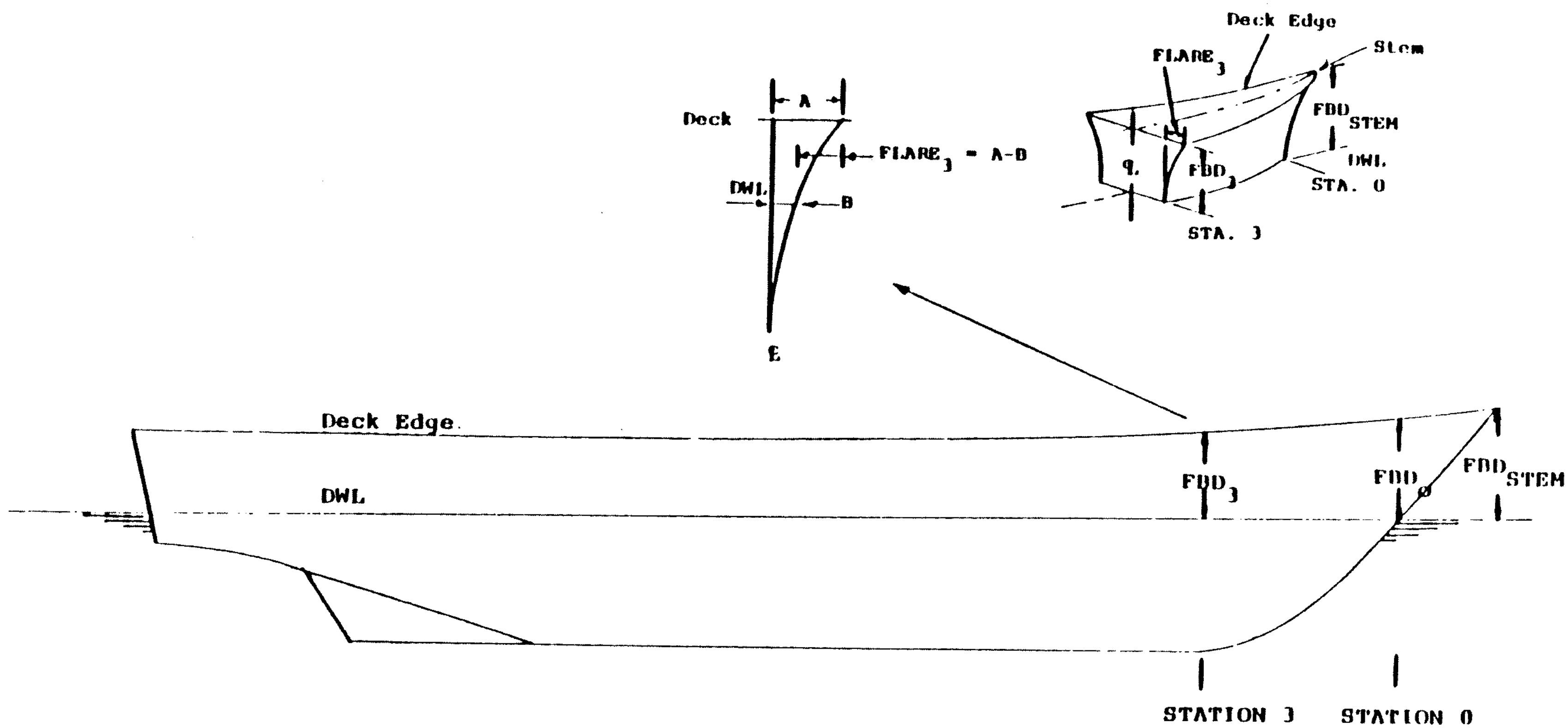
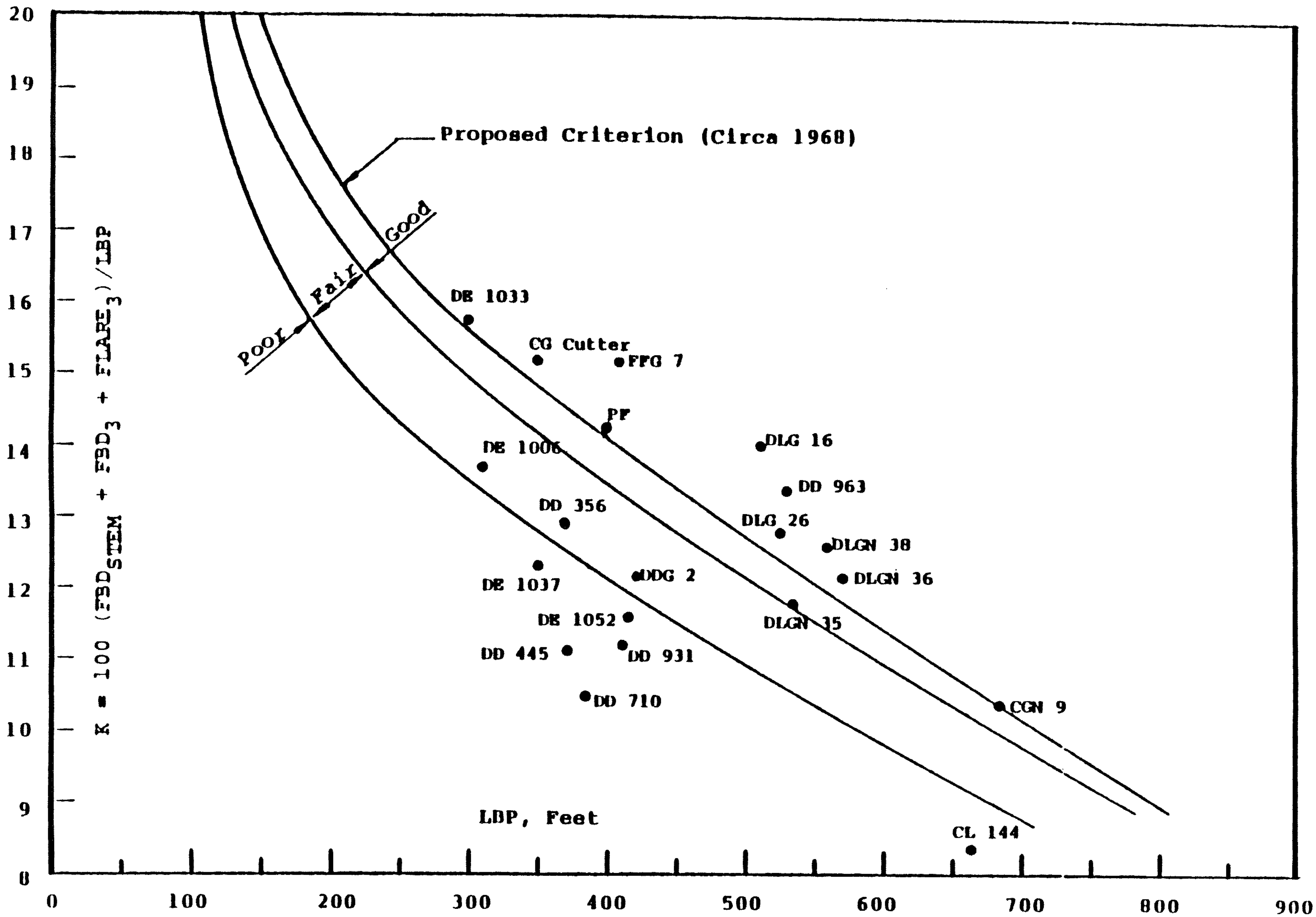


FIGURE 2 - Freeboard and Flare Definitions



<u>FIGURE 3</u> - Combined Freeboard and Flare for Destroyer Type Ships

This method is only applicable to destroyer type ships and is expressed as:

$$K = 100\ (FBD_{STEM} + FBD_3 + FLARE_3)/LBP$$

"Poor", "fair", and "good" ranges for K are presented in Figure 3.

079-2-c(3). Auxiliary Ships

For all U.S. Navy auxiliary ships the minimum freeboard calculation methods presented in Sections c(1) and c(2) should be applied first. The following methods which are related to the ship speed should be used for checking purposes depending on the hull form type.

1. Merchant Ship Hull Forms

The following method, which is presented in Reference 5, pertains to merchant ship hull forms with moderate speed/length ratios. This method relates required freeboard to ship speed and results in increased freeboard for increased ship speed. Freeboard is obtained from a plot of $V/\sqrt{LWL}$ vs. FBD/LWL (See Figure 5) which represents the relation of ship speed to freeboard. This method can be used for T-ships since they are generally merchant ships which have been adapted for use as auxiliary ships by the Military Sealift Command.

2. Tug, Trawler and Research Ship Hull Forms

The freeboard forward for research ships (Reference 6) can be calculated using the following equation:

$$\min FBD_{STEM} = .01\ LWL \times [7+25\ (V/\sqrt{LWL}-.85)]$$

This equation was used along with those of Section c(2) for the salvage ship ARS 50 (Reference 7).

079-2-c(4). Aircraft Carriers

The design of aircraft carrier freeboard to the flight deck forward should use the method described in Sections c(1) and c(2). The design of aircraft carrier freeboard to the hangar deck is dependant upon the position of the aircraft elevators along the length of the ship. Reference 8 presents a method for the development of aircraft carrier freeboard. The method makes use of Figure 6 to determine elevator clearance as a function of ship length and ship station. Once the elevator clearance is obtained, for a particular station, it is added to the elevator depth. This sum represents the minimum design freeboard required at the hangar deck, which is usually the main deck. This same graph can be used to determine the minimum required height of the underside of sponsons above the waterline at any location along the ship.

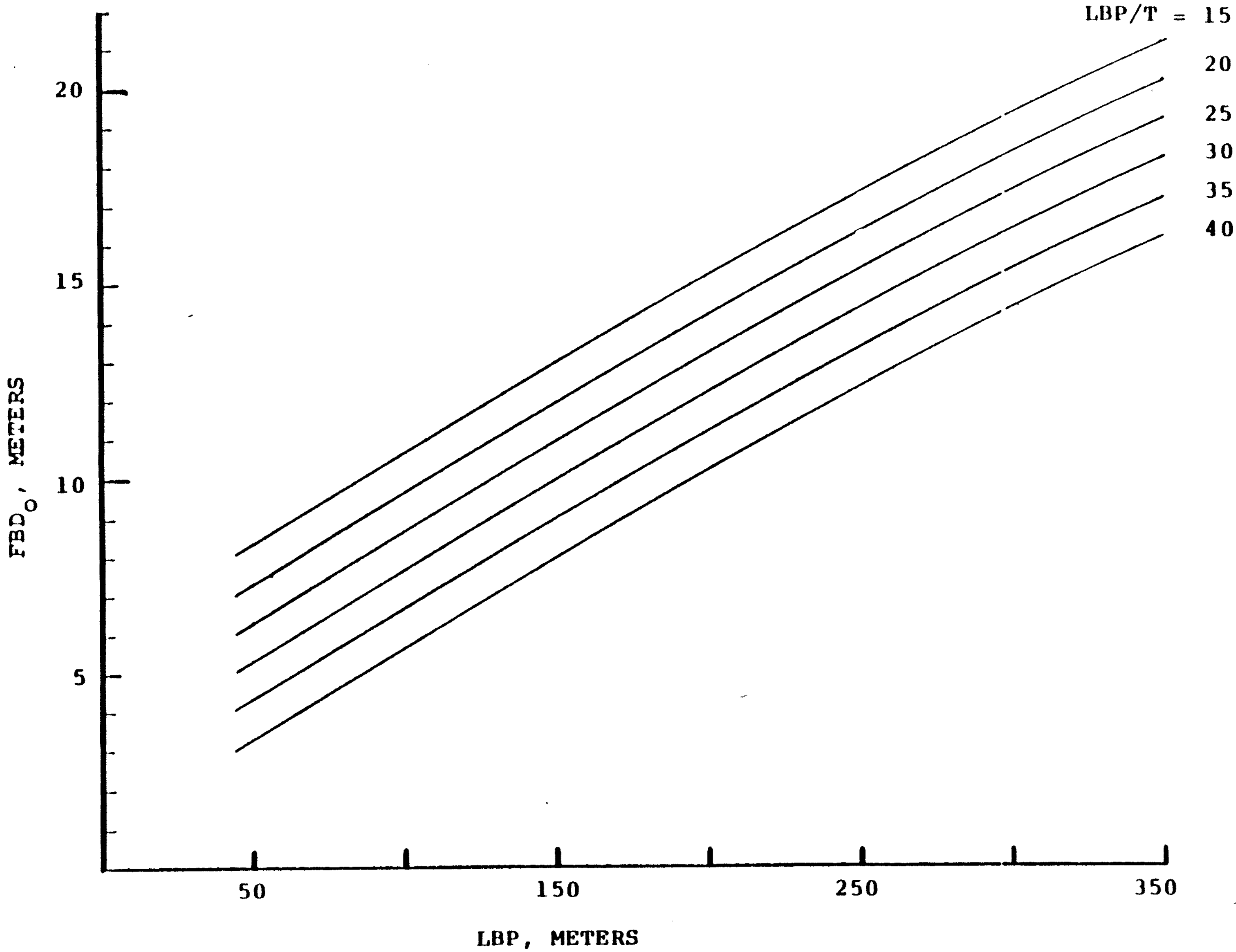


FIGURE 4 - Required Freeboard As a Function of Ships Length and Draft for Surface Combatants Based on Bales Advanced Technique (Reference 1)

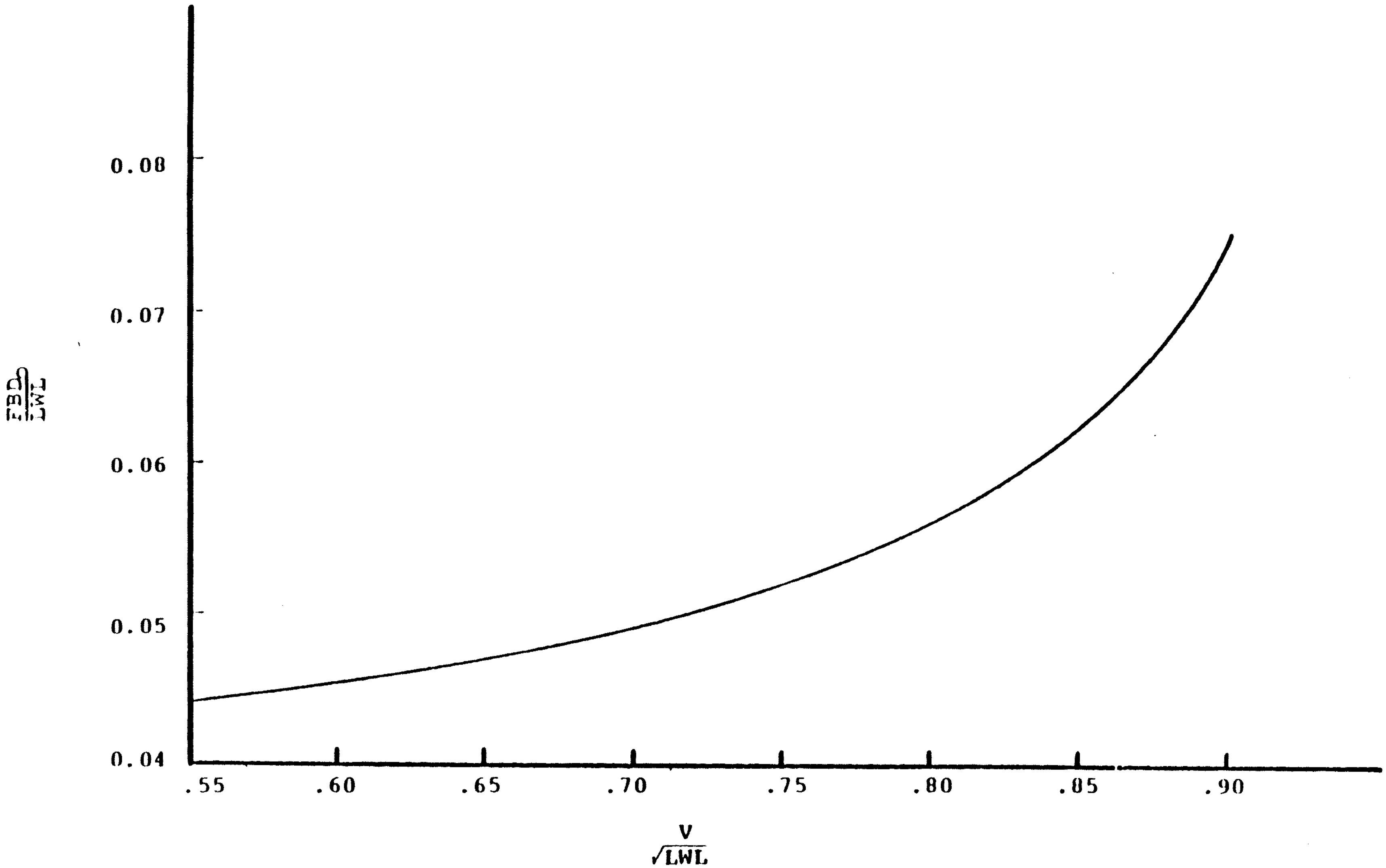


FIGURE 5 - Freeboard-Length Ratio as a Function of Speed-Length Ratio

079-2-c(5). Amphibious Warfare Ships

For most amphibious warfare ships the minimum freeboard calculation methods mentioned in Sections c(1) and c(2) are applied for forward freeboard calculation. For amphibious warfare ships with deck edge aircraft elevators or sponsons the method described in Section c(4) should be applied.

079-2-d. Minimum Required Freeboard Calculation During Contract Design

During Contract Design, the method presented by Bales in References 1 and 9 can be used to check the designed freeboard of earlier design stages. The methodology of Bales can be used for all ship classes. Since some correction factors developed in this method are based on combatant ship data, the method presented in this section is strictly valid for combatant ships only.

Bales' method, developed at DTNSRDC, incorporates ship motion studies, sea-state frequency of occurrence and dynamic effects such as ship sinkage and trim and above-water hull form characteristics into the freeboard calculation technique. This process is lengthy and the Ship Motion Program, SMP-80, (Reference 2) or equivalent computer program must be used to obtain values of kinematic relative motion, kinematic relative velocity, and absolute vertical acceleration.

The required freeboard computation assumes that the design freeboard (geometric freeboard) (See Figure 7), F_G, can be expressed as:

$$F_G = F_r + \delta_1 F + \delta_2 F = \delta_3 F$$

F_r, $\delta_1 F$, $\delta_2 F$ and $\delta_3 F$ are as defined in Section b.

This computation also assumes that ship-to-wave relative vertical motion, r, can be expressed as:

$$r = r_k + \delta_1 r + \delta_2 r$$

r_k, $\delta_1 r$ and $\delta_2 r$ are also as defined in Section b.

For a specified acceptable probability of deck wetness ($\lim(P_w)_n$, where the subscript "n" indicates Ship Station) and a required operating significant wave height ($\lim(\tilde{\zeta}_w)_{1/3}$, based on operational limits), the freeboard required due to relative motion at ship station, n, for an assigned modal wave period $(T_w)_o$ is:

$$\text{req } (F_r)_n = \lim(\tilde{\zeta}_w)_{1/3} \times [r_{1/3}/(\tilde{\zeta}_w)_{1/3}]_n \times \left\{-.5\ln[\lim(P_w)_n]\right\}^{1/2}$$

Now, $\delta_1 F_n$ and $\delta_2 F_n$ can be added directly to req $(F_r)_n$ independent of the wave environment based on model test results presented in Reference 9. Since there is no good way to quantify $\delta_3 F$ yet, it is ignored at this time. The

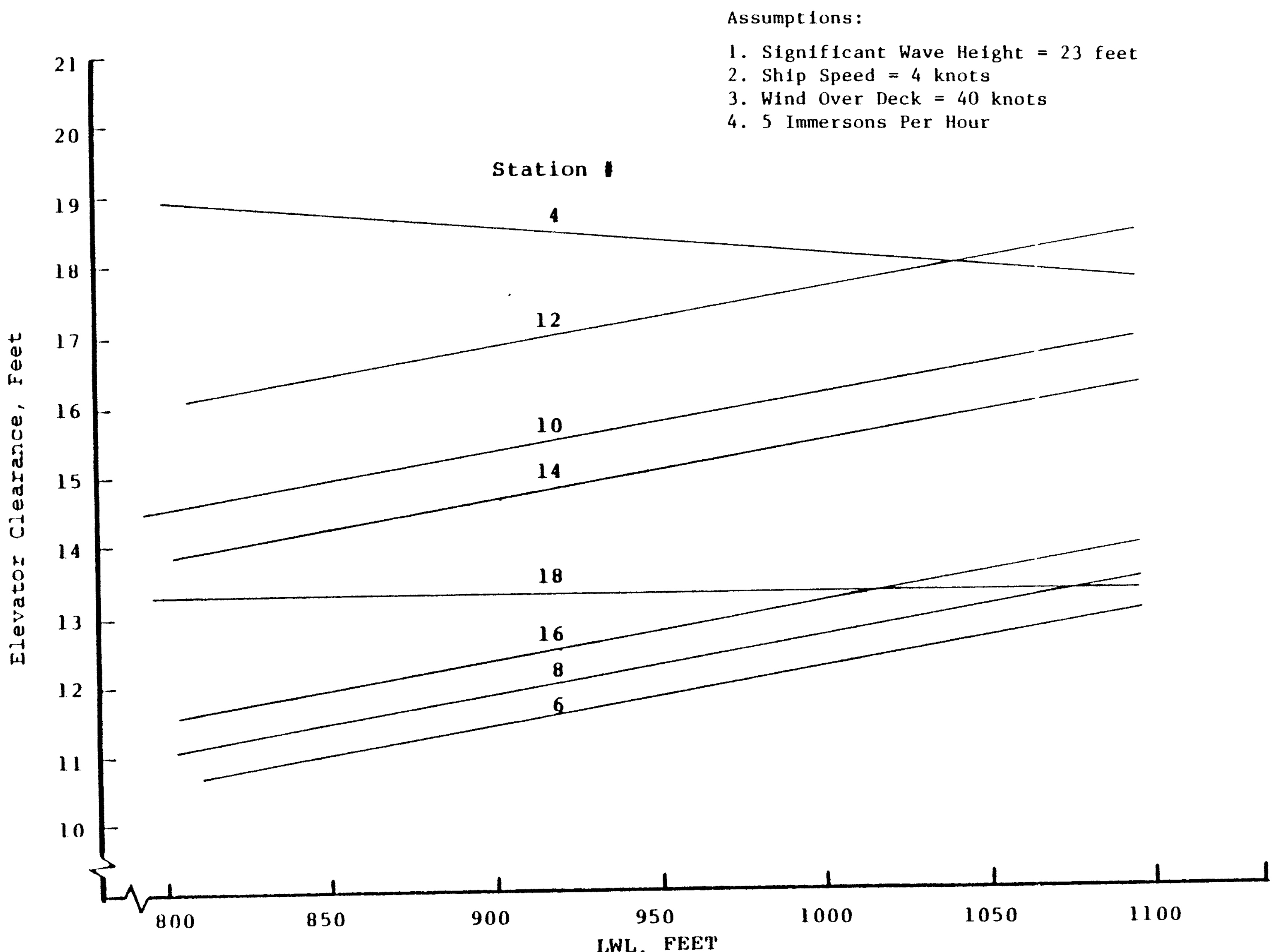


FIGURE 6 - Elevator Clearance Criterion Versus Ship Length for Various Ship Station Locations

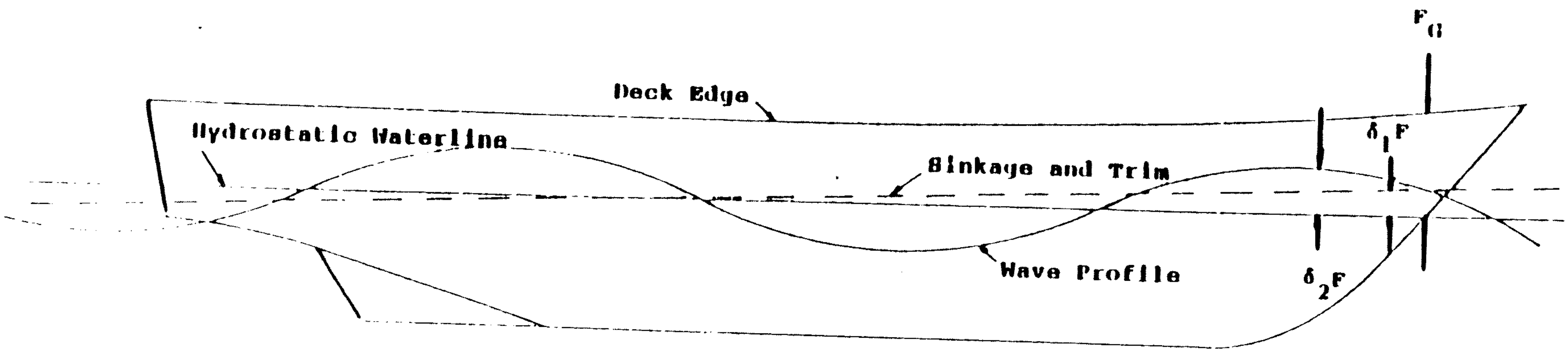


FIGURE 7 Freeboard Definition for Bales Advance Technique

required geometric freeboard at any station is taken as the maximum of req $(F_r)_n$ above for a range of modal wave periods (say 5 to 17 seconds) and then corrected for sinkage/trim and bow wave profile using $(\delta_1 F)_n$ and $(\delta_2 F)_n$:

$$(F_G)_n = \max \text{ req } (F_r)_n + \delta_1 F_n + \delta_2 F_n$$

The complete derivation of the right hand side terms of the equation for req $(F_r)_n$, $\delta_1 F$, and $\delta_2 F$ is presented in Reference 10 along with a complete example illustrating the use of this method.

079-2-e. Above Water Hull Design Impacts On Freeboard And Wetness

Of the above-water hull design parameters, a sufficient amount of flare is helpful in deflecting water outward as the bow moves downward into a wave to decrease the occurrences of deck wetness and to increase effective freeboard. However, an extreme flare may intensify the slamming impact and may also cause a greater speed loss than would be necessary to limit wetness. As shown in Figure 8, ships with superior wetness (see Figure 3) have flare angles of between 20 and 25 degrees.

A knuckle is often used in combination with flare on ships in which there is a requirement to maintain arrangeable deck area forward and which would result in excessive flare if the flare were carried to the weather deck. Combined knuckle and flare is illustrated in Figure 8.

Bulkwarks provide a relatively simple way to increase freeboard without increasing internal volume. They provide a good means of correcting wetness problems on existing ships such as was done on the FF 1052 class or in designs where increased sheer forward or increased deck height is undesireable. Bulwarks may reduce the effective range of gun arcs of fire which must be examined for each case. The bulwark should extend aft to at least Station 3.

Spray rails provide a simple way of reducing deck wetness on designs in which wind driven spray is brought on deck or whipped into the bridge. Spray rails are fitted forward below the edge of the weather deck illustrated in Figure 9. It should be pointed out that once the ship's motions become so severe that the rails are submerged, the increase in effective freeboard is lost.

Sheer is increased forward in order to provide the required freeboard. If excessive sheer is required, then a bulwark may be indicated or a raised fo'c'sle added. Bales, in Reference 2, suggests that the initial slope of the sheer at Station 0 be half meter per ship station and decrease aft. Reverse sheet forward of Station 1-1/2 can help to eliminate gun arc of fire problems created by bulwarks.

Breakwaters are important to above-water hull design because they protect deck equipment once green water has been shipped on deck. The breakwater is vee shaped and is located forward of the forward most gun or missile launcher on the weather deck. A typical breakwater installation is illustrated in Figure 10.

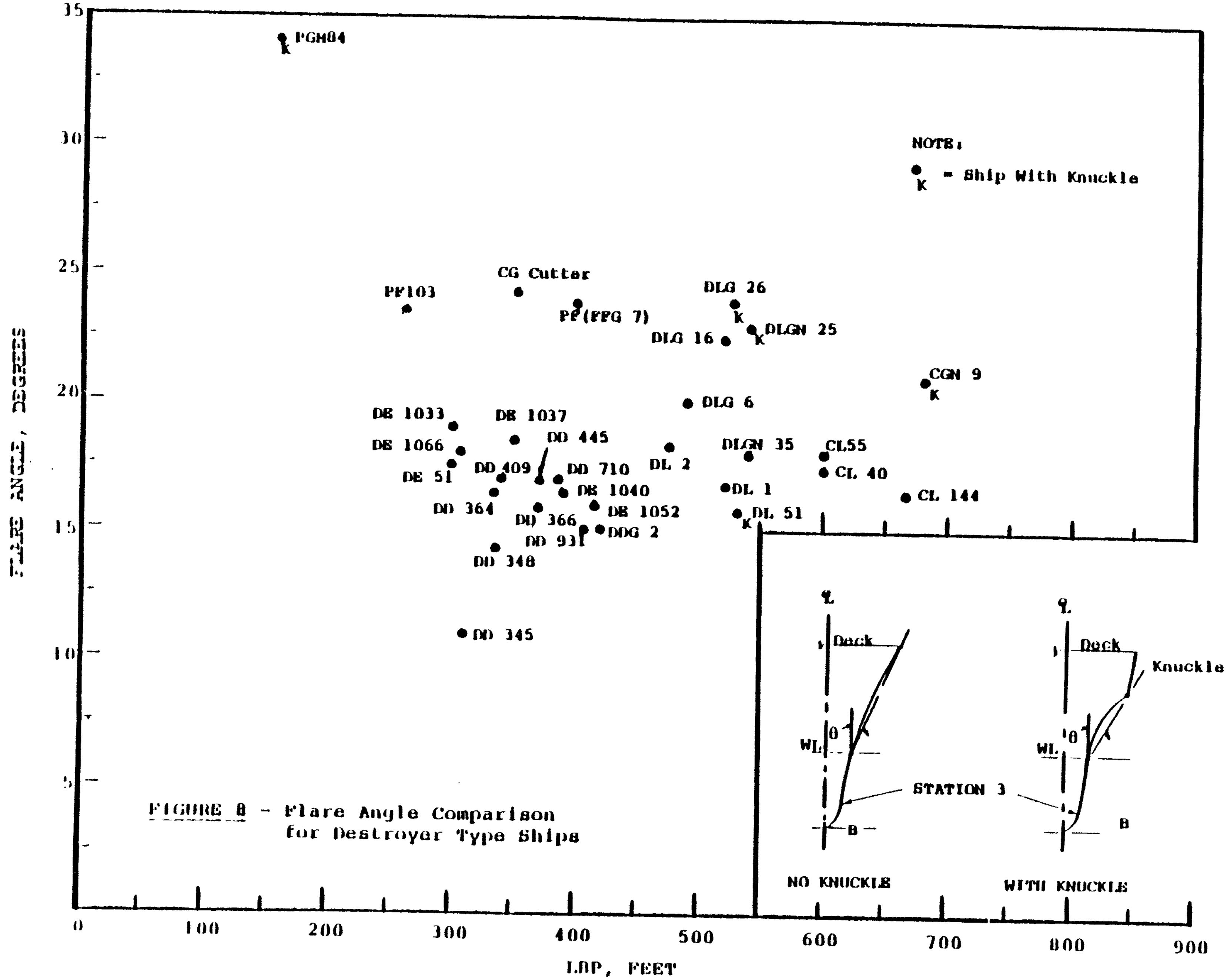


FIGURE 8 - Flare Angle Comparison for Destroyer Type Ships

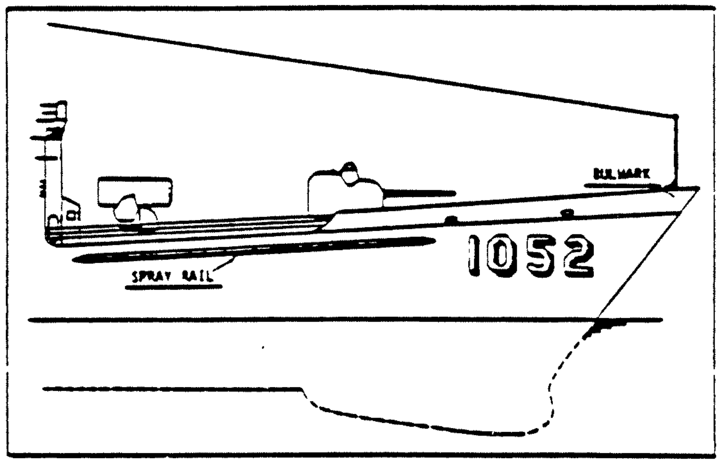


FIGURE 9 - Bulwark and Spray Rails on FF 1052 Class Ships.

079-2-f. Stability and Regulatory Agency Impacts on Required Freeboard

Freeboard has a great influence on reserve buoyancy. It is necessary to provide adequate freeboard along the length of the ship which provides adequate reserve buoyancy in both the intact and damaged conditions. Stability criteria which establish minimum freeboard at locations other than the bow based on reserve buoyancy requirements for U.S. Navy ships in the intact and damaged condition are presented in Reference 11.

The wetness criteria will generally govern in the determination of freeboard forward over the criteria used in the design for reserve buoyancy. However, Reference 11 must be checked to ensure that adequate freeboard is provided along the rest of the ship.

Because many U.S. Navy Auxiliary ships (T-ships) must meet ABS and U.S. Coast Guard regulations, the load line calculation method presented in Reference 12 must be used to check the designed freeboard at midships. The ships block coefficient and depth have the greatest impact on the determination of minimum freeboard in the load line calculation method. The freeboard obtained from this method is the minimum design freeboard required for ABS and USCG classification. The greatest freeboard obtained from either this method or the method presented herein should be used as the driving design freeboard.

079-2-g. Example Calculations

Example calculations for the methods presented herein are given below. For destroyers or combatant type ships the FFG 7 ship characteristics are used. T-ARC 7 and ARS 50 ship characteristics are used for auxiliary ship freeboard calculations. For the aircraft carrier freeboard design method the CVV ship characteristics are used.

079-2-g(1). Destroyer Type Ships

This example illustrates the two required freeboard calculation techniques presented in 079-2-c(2) for destroyer hull forms.

For the first method the required freeboard is calculated using the following equation:

$$100\ FBD_0/LBP = 1.011827(100T/LBP) - .000636215(LBP) + 2.780649$$

subject to the following conditions

$150 < LBP < 1300$
$2.5 < 100T/LBP < 5.2$
$30 < \Delta/(.01\ LBP)^3 < 120$

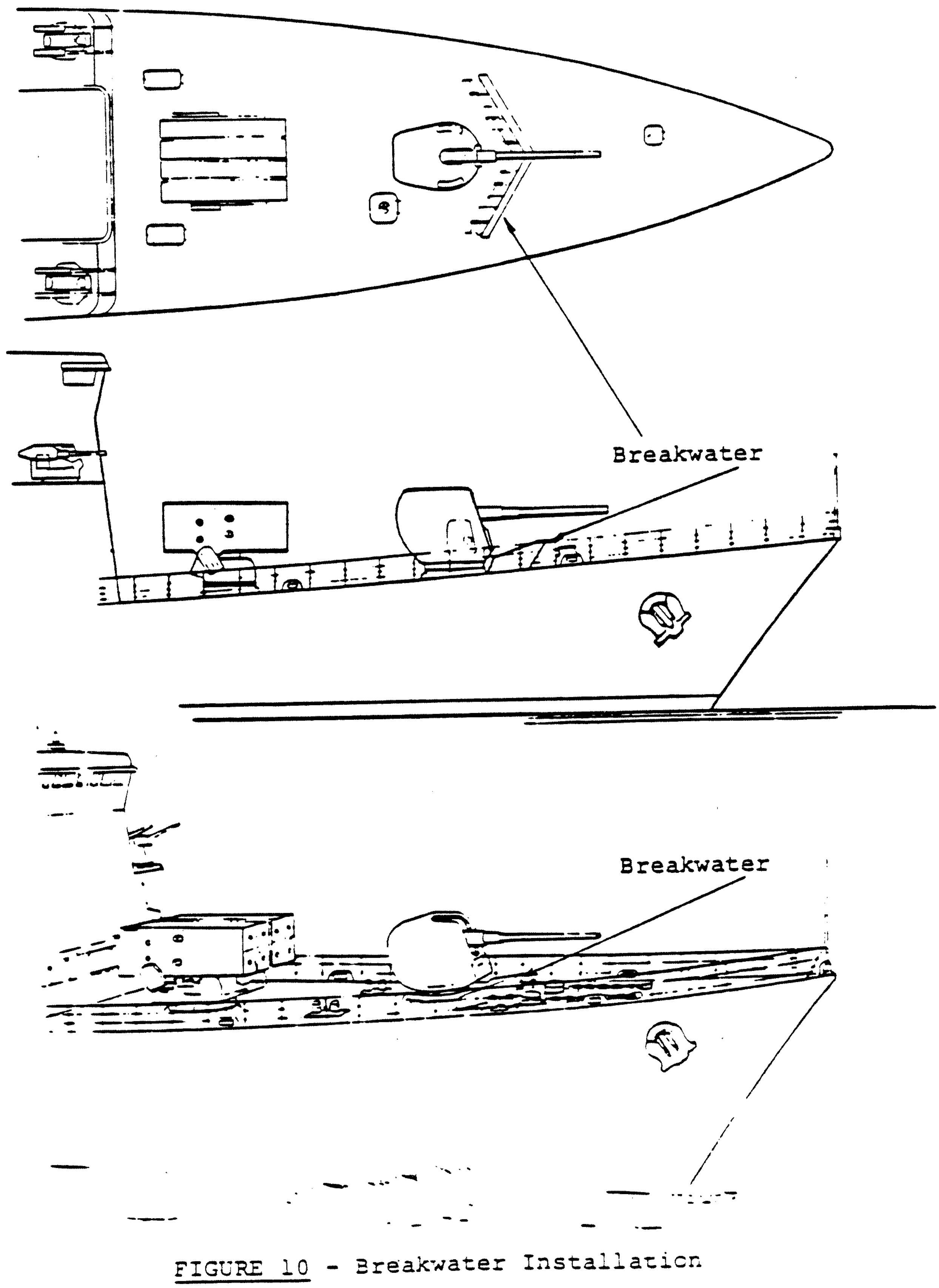


FIGURE 10 - Breakwater Installation

For the FFG 7

LBP	=	408. feet (124.35 meters)
T	=	14.35 feet (4.37 meters)
Δ	=	3605 L. tons
100T/LBP	=	3.52
$\Delta/(.01LBP)^3$	=	53.1

The FFG 7 satisfies the conditions resulting in

$$100FBD_o/LBP = 1.011827(3.52)-0.000636215(408) + 2.780649 = 6.08$$

or,

$$FBD_o = 24.82 \text{ feet}$$

The actual freeboard for the FFG 7 at Station 0 without its bulwark is 25.15 feet and with its bulwark is 29.15 feet.

The second method for destroyer type ships makes use of flare at Station 3 and the freeboards at the stem and Station 3.

For the FFG 7:

FBD_o	=	27.48 feet (without bulwark)
	=	31.48 feet (with bulwark)
FBD_3	=	21.15 feet (with or without bulwark)
$FLARE_3$	=	9.00 feet

For LBP = 408 feet the K values without and with the bulwark are calculated as:

$$K = 100\ (FBD_o + FBD_3 + FLARE_3)/LBP$$

$$K \text{ without} = 100(27.48 + 21.15 + 9.00)/408 = 14.13$$

$$K \text{ with} = 100(31.48 + 21.15 + 9.00)/408 = 15.11$$

It can be seen from Figure 11 that the freeboard without bulwark and the freeboard with the bulwark is "good".

079-2-g(2). <u>Combatant Ships</u>

Bales' method for combatant ships makes use of ship length and draft in the following equation:

$$FBD_o = 10.5 + 0.045\ (LBP-150) - 0.00002(LBP-150)^2 - 0.20\ (LBP/T-27.5)$$

For the FFG 7:

$$FBD_o = 10.5 + 0.045\ (124.35 - 150) - .00002\ (124.35 - 150)^2$$
$$- 0.20\ (124.35/4.37 - 27.5)$$
$$= 9.14 \text{ meters}$$
$$= 30.00 \text{ feet}$$

For this method the actual freeboard is only acceptable with a bulwark.

079-2-g(3). Auxiliary Ships

1. Merchant Ship Hull Form

The T-ARC 7 is chosen for this example. The freeboard calculation method presented in Sections c(1) and c(2) should be applied first. Because the above examples already show how to use those methods only the use of Figure 5 as presented in Section c(3) will be illustrated here.

Figure 5 yields a freeboard/length ratio as a function of speed/length ratio.

For T-ARC 7:

$$LWL = 400$$
$$V = 16.9 \text{ knots}$$
$$V/\sqrt{LWL} = .85$$

From Figure 5 for a speed/length ratio of .85 the required freeboard/length ratio is:

$$FBD/LWL = .0625$$
$$\text{or, } FBD = 25 \text{ feet}$$

The actual freeboard for the T-ARC 7 is 42.75 feet which is greater than that required by the above calculation.

2. Tug, Trawler and Research Ship Hull Form

ARS 50 salvage ship is used for this example.

The method for tug hull forms presented in section c(3) is used for checking the freeboard at the stem:

$$FBD_{STEM} = .01LBP[7.0 + 25\ (V/\sqrt{LBP} - .85)]$$

For the ARS 50:

$$LBP = 240 \text{ feet}$$
$$V = 14 \text{ knots}$$
$$FBD_{STEM} = .01 \times 240\ [7.09 + 25.\ (14/\sqrt{240} - .85)]$$
$$= 20.0 \text{ feet}$$

where V = nominal service speed, knots

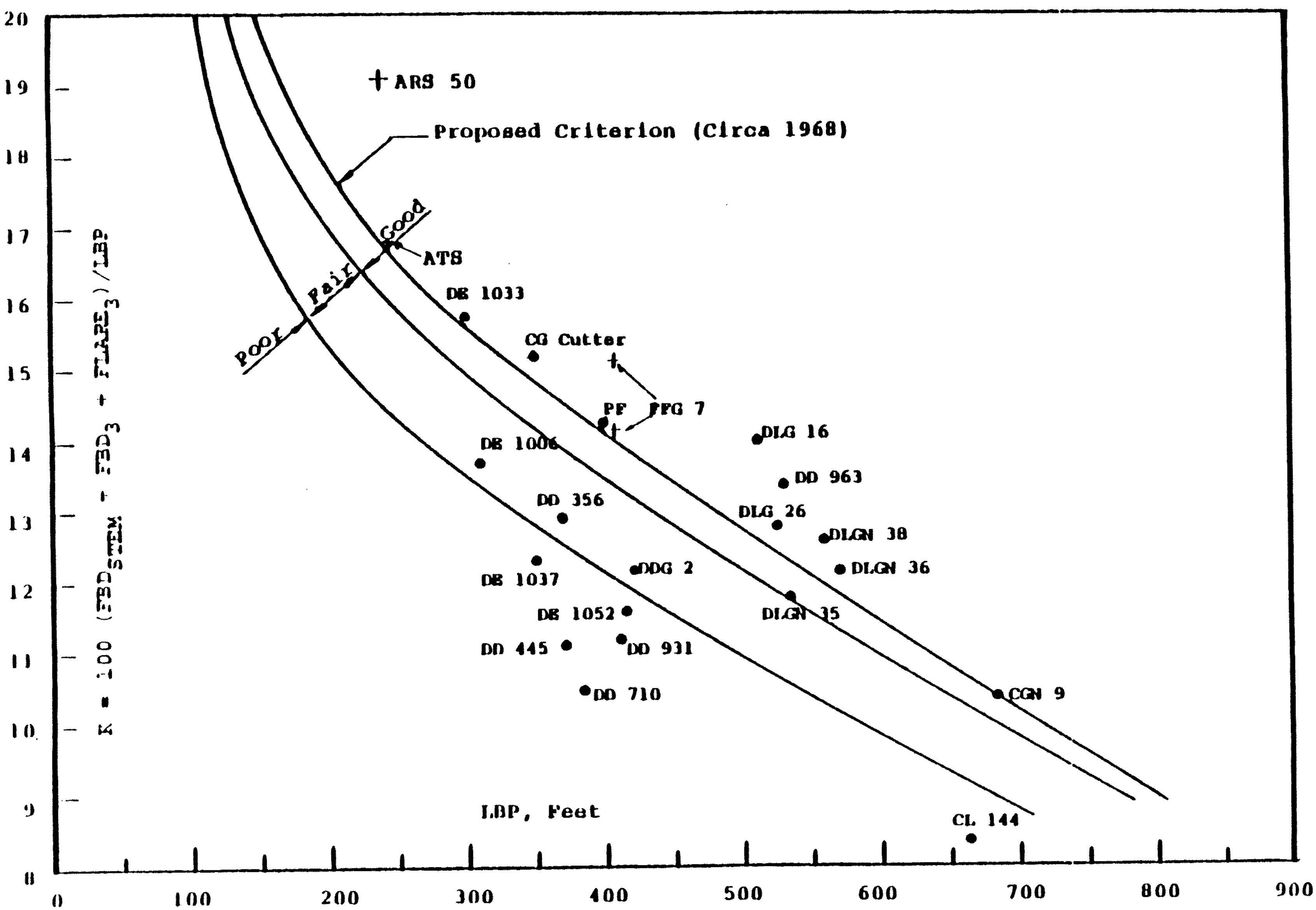


FIGURE 11 - ARS 50, Comparison of "Freeboard Plus Flare" with other U.S. Navy Ships

The actual freeboard forward of 18.5 feet is reasonably close to this requirement. This method does not account for the effects of bow flare as does the three parameter technique of section c(2) with which a comparison calculation is made below and plotted in Figure 11 for the ARS 50:

FBD_{STEM} = 18.5 feet (without bulwark)
FBD_3 = 17.2 feet
$FLARE_3$ = 10.0 feet
K = 100 (FBD_{STEM} + FBD_3 + $FLARE_3$)/LBP
= 100(18.5 + 17.2 + 10.0)/240
= 19.04

As shown in Figure 11, the freeboard is adequate using this technique.

079-2-g(4). Aircraft Carriers

The position of the aircraft elevator along the length of the ship is important in this method. It is the elevator clearance which determines freeboard requirements to the hangar deck for aircraft carriers having deck edge elevators. The required freeboard is the maximum determined from an analysis of each elevator. The method is illustrated in the following example for the CVV.

For CVV the elevators are located at Stations 10 and Station 16.

From Figure 6, the required clearances are:

Station 10 = 15.0 feet
Station 16 = 12.1 feet

The depth of the elevator is 8 feet, the required freeboards are:

Station 10 = 23.0 feet
Station 16 = 20.1 feet

The actual CVV freeboard of 21.0 feet is nominally adequate because it meets the 20.1 feet requirement at station 16 which has been shown to be the determining location (reference (8)).

The freeboard to the flight deck (57.0 feet) is adequate as shown by the following calculations using methods presented in Sections c(1) and c(2):

For CVV

LBP = 860 feet (262.12 meters)
T = 34 feet (10.36 meters)
Δ = 61426 LT
100T/LBP = 3.95
$\Delta/(.01LBP)^3$ = 96.57

For the method of Section c(2) the CVV satisfies the limits on 100T/LBP and $\Delta/(.01LBP)^3$. The minimum required freeboard is calculated below:

$$100FBD_o/LBP = 1.011827(3.95)-.000636215(860) + 2.780649$$
$$= 6.23$$
$$\text{or, } FBD_o = 53.58 \text{ feet}$$

Using Bales simplified formula presented in Section c(1):

$$FBD_o = 10.5 + 0.045\ (LBP-150) - .0002(LBP-150)^2 - 0.20(LBP/T-27.5)$$
$$= 10.5 + 0.045\ (262.12-150)-.00002\ (262.12-150)^2 - 0.20\ (262.12/10.36-27.5)$$
$$= 15.73 \text{ meters}$$
$$= 51.62 \text{ feet}$$