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Hydrodynamic Efficiency Improvements to the USCG 110 Ft WPB *ISLAND* Class Patrol Boats

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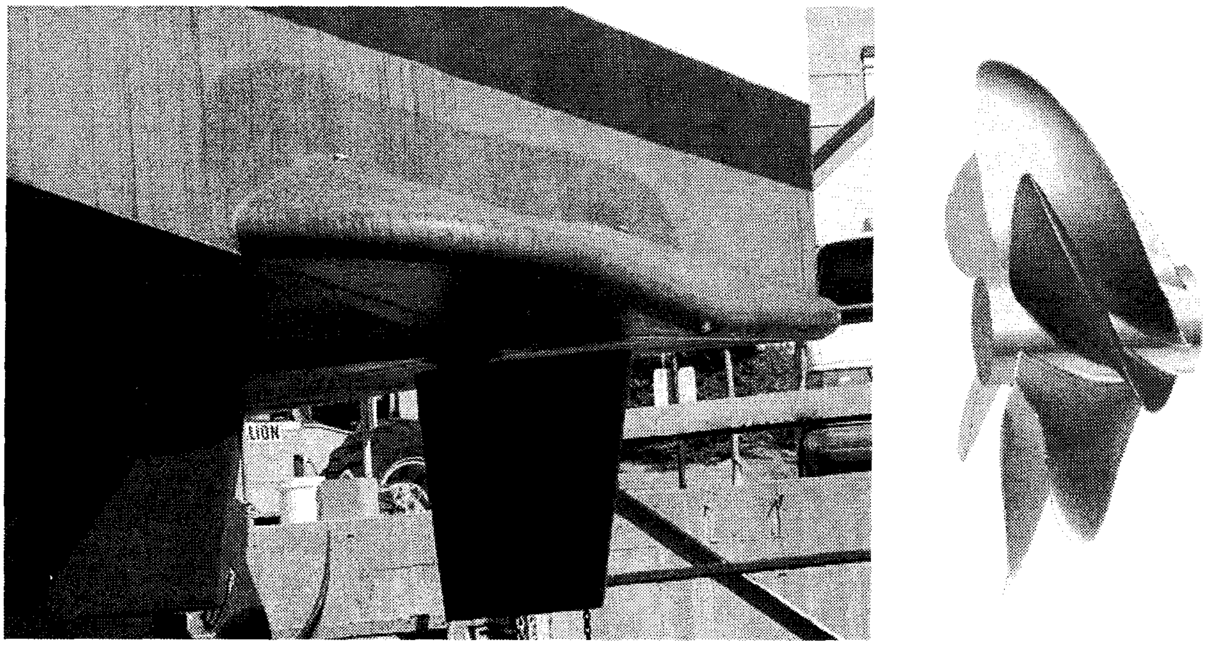


Stern flap installed on USCG *JEFFERSON ISLAND* (WPB 1340); computer rendering of new 6-bladed propeller design

Hydrodynamic improvements consisting of the design of a stern flap, spray rails, and new 6-bladed propellers, were undertaken for application to the forty nine ISLAND Class patrol boats operated by the USCG. A large, 18 ft (5.5 m) hydrodynamic hull model was constructed for use with stern flap optimization resistance tests, spray rail evaluation, and the prediction of resistance and estimated thrust needed for a new propeller design. Eight different stern flap designs were model tested as part of a systematic investigation regarding the effects of varying the chord length, span, angle and plan form area distribution. The final flap design minimized the estimated fuel usage over a range of operating conditions that included two displacements, and a varying speed-time profile from 12 to 30 knots.

The stern flap was predicted to increase the full load maximum speed by 0.8 knots to 27.85 knots. At the 24 knot cruise speed a 3.7 percent reduction in delivered power was predicted. The annual fuel savings for the prescribed displacements and operational speeds was estimated to be 13,000 gallons per boat.

A new 6-bladed propeller design was undertaken with the goal of increasing fuel economy, reducing air borne noise, and improving engine reliability by providing proper engine loading. Special attention was paid to suppressing root cavitation. The relatively simple wake field permitted accurate quasi-steady panel method calculations of blade pressure distributions. Iterative panel calculations modeling the blade and the hub were used to alter blade shape to achieve satisfactory performance. Model-scale open water and cavitation tests were not conducted. The confidence in this propeller design is based on the Naval Surface Warfare Center, Carderock Division (NSWCCD) experience gained from design, model tests, and full scale trials data on the PC 1 Cyclone Class propeller, which has operating conditions similar to those of the ISLAND Class propeller.

On average throughout the speed range, the new 6-bladed propeller design is predicted to be almost 8 percent more efficient than the existing fleet propeller. In addition, it will be free of thrust breakdown. With the stern flap, spray rails, and new propeller, the maximum speed is predicted to increase by 2.5 knots to 29.6 knots in the full load condition. The speed increase is due to reduced resistance, greater propeller efficiency, and increased available engine power due to a better fit between the propeller power curve and the envelope of available engine power.

Observations of the flow patterns and model trim during the resistance testing indicated the need for a supplementary spray rail. Discussions with the USCG boat operators substantiated the need for additional spray suppression. An enlargement and extension of the existing spray rail was designed and it proved to be very effective in suppressing the model spray.

The stern flap and spray rails have been fitted to the USCG JEFFERSON ISLAND (WPB 1340). Initial operations show that the patrol boat gets up on a plane more readily than before. The USCG is in the process of ordering retrofit kits fleet wide for installation at haul out opportunities.

NOMENCLATURE

AP	aft perpendicular
BHP	engine brake horsepower
B_X	beam, maximum
C, c	blade chord
CA, C_A	correlation allowance
Cb	block coefficient
CFD	computational fluid dynamics
C_L	blade lift coefficient
Cn, C_N	ship/model RPM correlation coefficient
Cpd, C_{PD}	ship/model power correlation coefficient
Cp	prismatic coefficient
CP	pressure coefficient
CR, C_R	residuary resistance coefficient
Cwp	waterplane coefficient
D	diameter
EAR	expanded area ratio
F	local camber
Fn	Froude number
FP	forward perpendicular
g	gravitational constant
H	static pressure head
I_T	blade rake
J	advance coefficient
JA	propeller advance coefficient
K_T	thrust coefficient
K_Q	torque coefficient
LBP	length between perpendiculars
LCG	longitudinal center of gravity
LWL	length waterline
max, min	maximum, minimum
n	revolutions per second
p	local pressure
P	blade pitch
PD, P_D	delivered power
PE, P_E	effective power
r	radial distance
R	radius
RPM, rpm	revolutions per minute
STP	speed-time profile
1-t	thrust deduction factor
T	local or sectional thickness
TED	trailing edge down
Vs	ship speed
VT	tangential velocity
W_T	Taylor wake fraction
X (x)	distance along chord
Y	blade section offset
η	efficiency
λ	model scale factor
θs	blade skew
σ_i	cavitation inception number

INTRODUCTION

The first of the U.S. Coat Guard *ISLAND* Class 110 ft. WPB patrol boats was commissioned in 1986. Today there are 49 units of the class engaged in offshore surveillance, law enforcement, and search and rescue missions. The hull is a modified Vosper-Thornycroft (British) patrol boat design, 110 ft (33.5 m) overall length, with twin shafts, and 49.6 inch (126 cm) diameter fixed-pitch propellers. Principal ship characteristics (full load) are shown in Table 1 (with body plan). There are three sub-classes of *ISLAND* cutters. The sixteen "A" class cutters have slightly different arrangement and structure, especially forward, which principally results in more fuel tankage than the twenty "B" class or eleven "C" class cutters. (The latter two are substantially identical with respect to arrangement and structure.) The "A" and "B" class cutters have Paxman Valenta main engines, whereas, the "C" class cutters have slightly smaller Caterpillar 3516 main engines.

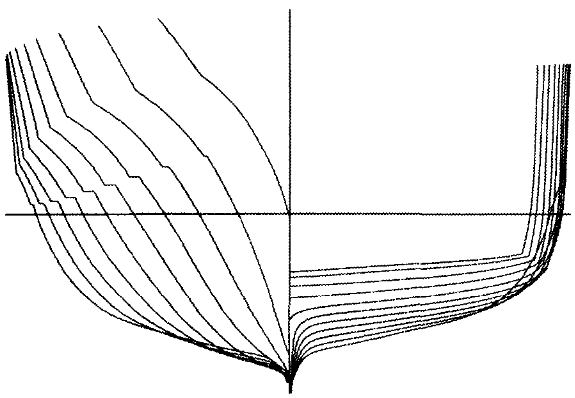
Ship trials on the *ISLAND* Class 110 WPB series C, have indicated that the Caterpillar 3516 engines operate above the recommended engine torque curve. This has resulted in the inability of this particular engine design to reach full engine RPM and power. In addition, long term operational experience shows that there is propeller blade root erosion caused by cavitation. Therefore, the USCG has initiated a program to improve the hydrodynamic performance of the *ISLAND* Class 110 ft. WPB patrol boats, with specific emphasis on the following characteristics:

- Increase the maximum attainable speed at full power.
- Reduce the propeller cavitation and cavitation erosion damage to the propeller's blades.
- Reduce the propulsion generated onboard radiated noise and vibration levels.
- Reduce the propulsion fuel usage.
- Bring into better balance the ship's speed/power characteristics with the engine operating envelope.

Table. 1. *ISLAND* Class ship/model characteristics

	SHIP		MODEL (λ = 5.706)	
Length (LWL)	104.3 ft	31.8 m	18.28 ft	5.57 m
Beam (Bx)	21.1 ft	6.4 m	3.69 ft	1.13 m
Displacement	163.4 Lton	166.0 MT	0.88 Lton	0.89 MT
Draft FP	7.66 ft	2.33 m	1.34 ft	0.41 m
Draft AP	6.85 ft	2.09 m	1.20 ft	0.37 m
Wetted Surface	2242 sqft	208.3 sqm	68.86 sqft	6.40 sqm

Coefficients: Cp = 0.691 Cb = 0.402 Cwp = 0.783



The retrofit of a stern flap and a new propeller were envisioned to accomplish the above objectives. U.S. Navy experience with stern flaps has shown the potential of stern flaps to improve the speed and power characteristics; Karafiath, et. al, [1999]. The specific experience with the design, manufacture, and full scale testing of the *USS CYCLONE* Class flap and new propeller design, Cusanelli [1996], indicated a significant improvement in the powering and cavitation characteristics. The same design methods for stern flap design and for propeller design that were used for the *USS CYCLONE* patrol boat were applied to the *ISLAND* Class and are described herein.

MODEL CONSTRUCTION

A new geosim Model 5526 (linear scale ratio = 5.706), representing the *ISLAND* Class 110 WPB patrol boats, was constructed for this project, Figure 1. A model length of 18.28 ft (5.57 m) LWL was selected to minimize stern flap scaling effects and still remain within the normal instrumentation and tow carriage capabilities at NSWCCD. This model size is relatively large in comparison to the typical models of high speed patrol boats. The model was constructed of sugar pine and was cut on a 5-axis numerically controlled milling machine, based on a non-uniform rational B-spline (NURBS) FastShip file.

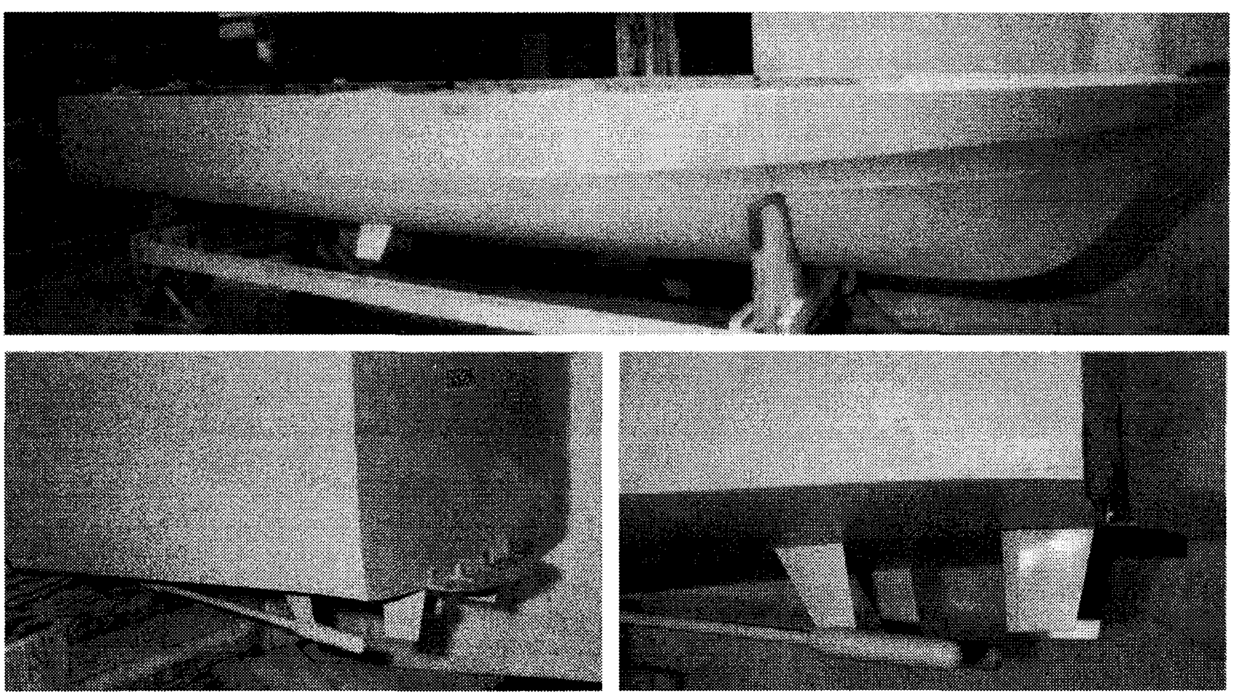


Fig. 1. Model 5526 representing the USCG *ISLAND* Class 110 WPB (shown with stern flap installed)

Appendages installed on the model were: twin roll stabilizer fins, twin rudders, and twin shaft and strut propulsion appendages. The model also included a 5° wedge inlayed into the hull surface at the transom that is already a feature on the existing *ISLAND* Class boats. Referring to Figure 1 note the single arm strut shaft support that is similar to the arrangement on the *CYCLONE* Class ships. There are no rotating shafts installed on Model 5526, since all experiments were to be resistance experiments. The shafting was installed for an accurate measurement of resistance, not powering. Also note that there is a stern flap fitted on the model in these photographs.

An inspection of model 5526 was performed using NSWCCD's laser scanner, and the results were compared to the original FastShip surface. The comparison indicates that the majority of the model is within 0.03 inches (0.76 mm) of the FastShip surface, and all points on the surface are within 0.05 inches (1.27 mm), which is considered the acceptable surface tolerance

SHIP/MODEL COMPARISON – CORRELATION ALLOWANCE ESTIMATE

Prior to the stern flap evaluation and selection, it was necessary to perform a ship/model powering comparison between Model 5526 and standardization trials results of the *BAINBRIDGE ISLAND* (WPB 1343). This comparison was made in order to estimate the ship/model correlation allowance for the new Model 5526. A ship/model comparison insures that the most accurate assessment of ship performance will be achieved. Powering performance trials had been conducted on the *BAINBRIDGE ISLAND* (WPB 1343), off the coast of Cape Henry, Virginia, in 1991; Haupt and Puckette [1991]. These trials determined the propulsion performance at a loading condition of 151 tons (153.4 metric tonnes), LCG of 5.09 ft. (1.55 m) aft of mid-ships, and a static trim of -1.0°. A model-scale resistance test was conducted at this loading condition.

Model scale powering experiments, which are necessary for a formal and precise determination of correlation allowance, were not performed on Model 5526. Instead, model resistance predictions, representative class propeller open water performance data, and assumed propeller-hull interaction coefficients, were utilized to estimate *ISLAND* Class powering performance for comparison to the ship trials results. Since powering experiments were not conducted on Model 5526, the standard methods by which ship/model correlation coefficients are determined could not be utilized. A method relating model resistance predictions to ship trials powering data had to be used. A powering estimate for the *ISLAND* Class, at the trials loading condition, was prepared by NSWCCD. It was desired that this powering estimate reflect the speeds and delivered powers measured during the WPB-1343 standardization trials. Initial estimates of propeller-hull interaction coefficients of 1-t, $1\text{-}W_T$, and η_R, representative of similar patrol craft, were then assumed, and propeller efficiency was calculated from the trials RPM and the open water characteristics of model propeller 5128 (which represents the current propeller on the *ISLAND* Class boats). An iterative process of "fairing", or smoothing, of the assumed propeller-hull interaction coefficients was necessary in order to retain all values within reasonable bounds for similar craft and to simultaneously match the trials speed and power.

Ultimately, ship resistance predicted from the Model 5526 experiments was utilized with the faired propeller-hull interaction coefficients to estimate the full scale powering. The ship/model powering correlation allowance was estimated by solving for the value of C_A which, when used with the standard NSWCCD powering prediction method, Grant and Wilson [1976], results in the best agreement between the ship trial measured delivered power (at speed) and the estimated delivered power from model experiments; Hadler, et al. [1962]. Due to variations of C_A correlation with speed, some engineering judgment is used to select the best value. Though the full scale trial data often includes slow speed measurements, in practice, the correlation is done for the speeds where sufficient power is developed for accurate measurements. The highest speeds are generally of the most interest, because the high speed data for both model and ship is considered more accurate, and because the prediction of maximum speed and power is a primary concern. However, for the *ISLAND* Class at full power, the current ship propellers are believed to cavitate excessively. Comparison of full scale data at speeds where the ship propeller exhibits cavitation to that of the non-cavitation corrected model predictions, would result in an erroneous correlation allowance. Thus only five trial speeds data spots between 15.1 and 25 knots were used for the estimate of correlation allowance.

Table 2 presents the powering prediction for *BAINBRIDGE ISLAND* (WPB 1343) derived from Model 5526, at 151 tons (153.4 metric tonnes), with a correlation allowance of 0.0003. The comparisons between ship trials measured delivered power and estimated model delivered power, are presented in NSWCCD standard form utilized for a formal ship/model correlation, in Table 3 and in Figure 2 as power correlation C_{PD}, and RPM correlation, C_N, which are defined as non-dimensional coefficients of ship trial measurement / model prediction.

A value of C_A = 0.0003 was considered the appropriate correlation allowance for the *BAINBRIDGE ISLAND*. It should be viewed only as a model testing adjustment factor which brings the present model resistance predictions, utilized to estimate ship powering, in line with the measured ship trials data.

Table 2. Model 5526 powering prediction for *BAINBRIDGE ISLAND* (WPB 1343), 151 L. tons, correlation allowance of 0.0003

SHIP SPEED (KTS)	SHIP SPEED (M/S)	RESIDUARY RES.COEF. (CR*1000)	EFFECTIVE POWER- PE (HP)	EFFECTIVE POWER- PE (kW)	DELIVERED POWER- PD (HP)	DELIVERED POWER- PD (kW)	PROPELLER REV. PER MINUTE
10.0	5.14	4.945	144.8	108.0	275.4	205.3	288.8
11.8	6.07	5.428	252.3	188.1	465.7	347.2	345.5
15.1	7.77	7.872	692.4	516.4	1278.0	953.0	473.1
17.5	9.00	8.536	1145.0	853.8	2105.4	1570.0	556.4
21.1	10.85	7.289	1764.0	1315.4	3159.9	2356.3	647.3
22.9	11.78	6.487	2057.7	1534.4	3625.5	2703.5	684.9
25.0	12.86	5.67	2415.5	1801.3	4159.0	3101.3	725.9
29.2	15.02	4.532	3264.5	2434.3	5167.2	3853.2	797.9

SHIP SPEED (KTS)	EFFICIENCIES (ETA) ETAD	ETAO	ETAH	ETAR	ETAB	THRUST DEDUCTION AND WAKE FACTORS 1-THDF	1-WFTT	1-WFTQ	ADVANCE COEF. ADVC
10.0	0.525	0.635	0.810	1.025	0.650	0.825	1.015	1.030	0.860
11.8	0.540	0.630	0.820	1.050	0.660	0.835	1.020	1.050	0.855
15.1	0.540	0.615	0.830	1.065	0.655	0.860	1.040	1.080	0.810
17.5	0.545	0.610	0.840	1.060	0.650	0.880	1.050	1.090	0.810
21.1	0.560	0.625	0.855	1.040	0.650	0.905	1.055	1.080	0.845
22.9	0.570	0.635	0.870	1.030	0.650	0.920	1.055	1.075	0.865
25.0	0.580	0.640	0.890	1.020	0.655	0.935	1.050	1.065	0.890
29.2	0.630	0.645	0.945	1.040	0.670	0.960	1.015	1.035	0.910

Table 3. Ship/Model comparison: *BAINBRIDGE ISLAND* (WPB 1343) versus Model 5526, 151 L. tons, correlation allowance 0.0003

BAINBRIDGE DATA			MODEL DATA CA = 0.0003			
Speed (knots)	Shaft RPM	Power (hP)	Shaft RPM	Power (hP)	ship/ model Cn	ship/ model Cpd
10.0	275.0	217	288.8	275	0.952	0.787
11.8	344.5	436	345.5	466	0.997	0.936
15.1	470.5	1250	473.1	1278	0.995	0.978
17.5	554.5	2065	556.4	2105	0.997	0.981
21.1	647.0	3187	647.3	3160	1.000	1.009
22.9	685.5	3627	684.9	3626	1.001	1.000
25.0	728.5	4213	725.9	4159	1.004	1.012
29.2	795.5	5092	797.9	5167	0.997	0.985
Cn, Cpd average (15-25 kts) =>					**0.999**	**0.998**

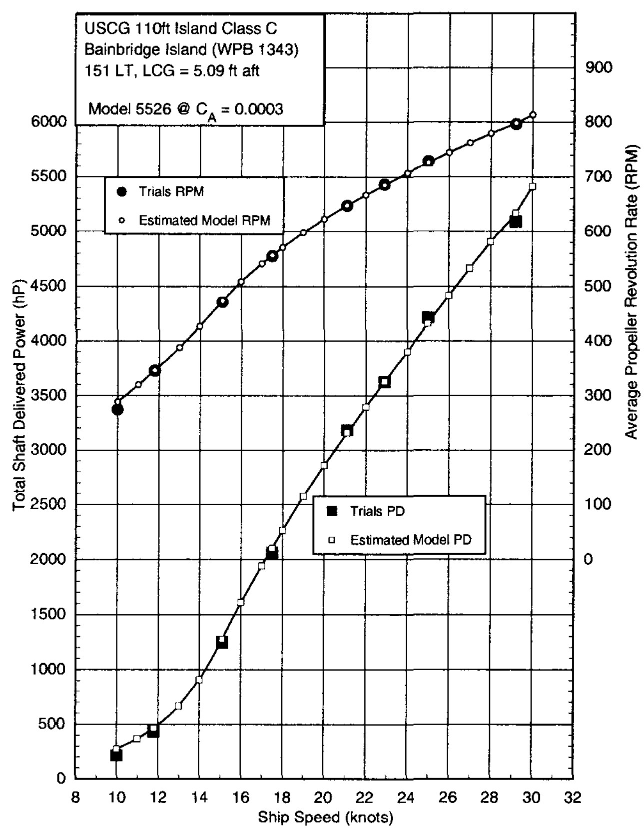


Fig. 2. Ship/Model comparison: *BAINBRIDGE ISLAND* (WPB 1343) versus Model 5526, 151 L. tons, correlation allowance 0.0003

At this time, any comparison of the *ISLAND* Class C_A to the NAVSEA [1982] correlation data base of U.S. Navy ships, should be done with great caution. The NAVSEA correlation data base is generally populated by much larger ships, but there are two small vessels with correlation allowance of 0.0006 and 0.00065 respectively. Recent correlation work, Karafiath [1997] indicates that effective anti-fouling paints may reduce the Correlation Allowance by 0.0001 to 0.0002. The general practice applicable to planing craft is to use a correlation allowance of 0.000. Thus the 0.0003 value is considered reasonable for the *ISLAND* class ships. It should not be added to the NAVSEA data base until it is confirmed through traditional model powering tests.

STERN FLAP SELECTION

The general practice with regard to stern flap design is to conduct model experiments that optimize the selected stern flap geometry with regard to the selected span, chord and flap angle. Past experience with model testing of various span stern flaps has indicated that the maximum span of the flap should be one that avoids the region of turbulent flow which typically originates from the transom corner. Computational fluid dynamics (CFD) efforts have been invaluable with regard to understanding the hydrodynamic mechanisms responsible for the improved performance with a stern flap. However, these calculations are still costly and difficult to perform. The limited level of experience with these calculations precluded their use as the sole design tool without the benefit of model tests. Thus, the decision was made to conduct model tests and rely on engineering experience to generate several stern flap designs for testing. Tests were conducted at the full load condition of 163.39 tons (166.04 metric tonnes), LCG = 4.65 ft (1.42 m) aft of mid-ship.

Eight model stern flaps were designed and manufactured. The geometry of these stern flaps are presented in Table 4 and depicted in the small-scale sketches of Figure 3. These stern flaps were designed as several different series to systematically investigate variations in flap chord length, span, angle, and plan form area distribution.

The first series, comprised of flaps #1, #2, #3, and #4, was designed to investigate variations in flap chord length, while holding span constant at 16 ft (4.88 m). This span was judged the maximum reasonable width possible, without impinging on the high-speed wake off the transom corners. The wetted transom width, at the full load condition, is 18.5 ft (5.64 m). A second series, comprised of flaps #3, #5, and #6, was designed to investigate variations in span, while holding chord length constant at 2 ft (0.61 m). A third series, comprised of flaps #1, #7, and #8, was designed to investigate variations in span, while holding chord length constant at only 1 ft (0.31 m). Additionally, comparisons of flaps #1 versus #6, and #2 versus #5, were designed to depict variations in plan form area distribution, while holding the respective values of total plan form area constant.

Table. 4. Geometry of model-scale stern flaps

	Ship Scale Dimensions			
Flap#	Chord Length (ft)	Span (ft)	Planform Area (sq. ft)	Angles Tested (trail edge down)
1	1	16	15.6	0°, 5°, 7.5°, 10°
2	1.5	16	23.0	0°, 5°, 10°
3	2	16	30.3	0°, 5°, 7.5°, 10°
4	2.5	16	37.3	0°, 5°, 10°
5	2	12.4	23.0	0°, 5°, 7.5°, 10°
6	2	8.7	15.6	0°, 5°, 7.5°, 10°
7	1	12.4	11.9	0°, 5°, 7.5°, 10°
8	1	8.7	8.2	7.5°, 10°

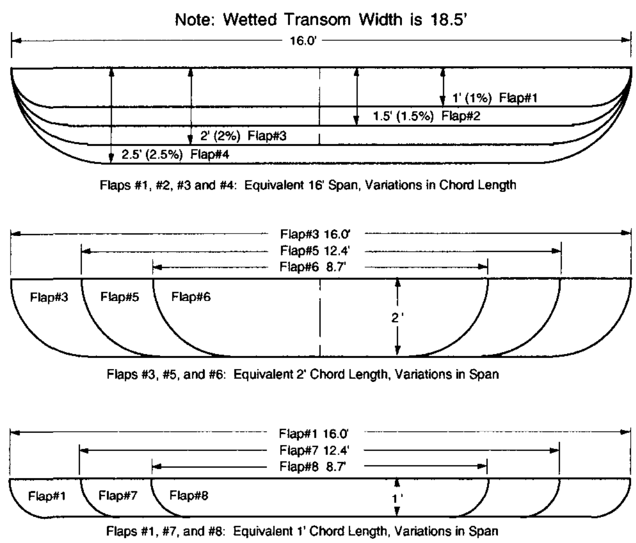


Fig. 3. Sketch of model-scale stern flaps

A simple radius corner treatment (in plan view) equal to the flap chord length, was chosen for all flap designs, to simplify construction and reduce full scale flap manufacturing costs. [The corner of the full-scale installed flap is made of 4 inch (10.2 cm) nominal OD pipe. Since the standard bender radius is five times nominal OD, the corner radius is 20 inches (50.8 cm) on the pipe centerline.] Flaps were evaluated (nominally) over a range of angles, from 0 to 10 degrees trailing edge down (TED), in 2.5 degree increments. The coordinate system used for flap angle is defined with zero degrees parallel to the slope of the local buttock angle (run) at the 4 ft (1.22 m) buttock. The gap between the transom and the flap was bridged by a small fairing strip fastened to the model to prevent cross-flow and pressure loss at the intersection between the forward edge of the flap and the transom.

STERN FLAP SELECTION CRITERIA

The selection criteria for the *ISLAND* Class stern flap design evolved during the testing into the following:

- Maximize reduction in ship powering over high speed range of 28 to 32 knots.
- Maximize the total fuel saved by emphasizing performance at cruise speeds (20 to 24 knots) without top speed loss. [Original criteria was stated as: Disallow any increase in ship powering at cruising speed, as indicated by performance at 24 knots.]
- Limit ship running trim modification (bow down) to 1.0 degrees, at all speeds.

An estimated speed-time profile based on 3000 annual operational hours, was specified for estimating total fuel savings as shown in Table 5. A split of 2/3 time (2000 hr.) at full load, and 1/3 time (1000 hr.) at min-ops, was assumed.

Table 5. *ISLAND* Class estimated speed-time profile

Speeds (kts)	12	15	18	21	23	25	27
Time Profile (%)	40	25	10	5	5	5	10

RESISTANCE TESTS FOR FLAP SELECTION

Model results, from the stern flap optimization series at full load, are shown in Figure 4. Depicted are examples of variations in flap angle, span, and chord. The performance is depicted as a reduction ratio, defined as PE Flap / PE Baseline. A value below 1.0 denotes a PE reduction with the flap installed. The reduction in resistance, on a percentage basis, is somewhat small as compared with test results on other models, Karafiath et al. [1999]. This is believed to be due to the influence of the five degree wedge that is already on the ship (and model). Therefore, the performance of these flaps represent an increase in performance over a configuration that already has a wedge. The combination of a stern wedge and stern flap, patented as the integrated wedge-flap, Cusanelli and Karafiath [2000], has also been shown to reduce powering; Cusanelli and Karafiath [1997].

The shaded areas of Figure 4 represent undesirable areas of operation. A change in trim is limited to 1 degree. A resistance increase at speeds greater than 24 knots is unacceptable. The shading between 12 and 24 knots is somewhat arbitrary and reflects an allowance for configurations with poor low speed performance, that might be offset by good high speed performance.

A summary of the stern flap optimization tests is shown in Table 6. The selected flap was #6, at 7.5 degrees. Within the accuracy of the experiments, flap #1 at 7.5 degrees had very similar resistance, but flap #6 was just slightly better in terms of resistance and trim change. Flaps #1 and #6 have the same plan form area. Flap #6 represents a full scale stern flap with chord length 2 ft, span of 8.7 ft. and an angle of 7.5° trailing edge down relative to the local slope (run) at the 4 ft buttock.

Flap #5, with slightly better resistance at 12 knots than #6, had a much larger trim change which was undesirable. Therefore flap #5 was not selected The resistance and or trim characteristics of the remaining flaps, number 2, 3, 4, 7, and 8, were worse than that of flap #6 and therefore they were not selected.

PERFORMANCE WITH SELECTED FLAP (#6)

The resistance of the *ISLAND* Class with the selected stern flap #6, full speed range, was predicted directly from experimental data on Model 5526. Resistance predictions were made at both the full load condition, and at a minimum operations load (min-ops) of 143.6 tons (145.9 metric tonnes), LCG = 5.25 ft (1.6 m) aft of mid-ship. The flap was "custom" installed, at the 7.5° angle, to insure a more precise fit along the model transom.

The model resistance test results were used to estimate powering with and without the stern flap. Model resistance, representative class propeller open water performance data, and the faired estimated propeller-hull interaction coefficients, were utilized to predict the *ISLAND* Class powering performance. The propeller hull interaction coefficients were the same values that were developed for the ship-model comparison of power using the *BAINBRIDGE ISLAND* trials data, and the model resistance tests at 151 tons (153.4 metric tonnes).

Table 6. Summary of model-scale stern flap optimization experiments

Flap#	Angle TED (degrees)	Economic Speed: 12 knots (PE flap/base)	Cruising Speed: 24 knots (PE flap/base)	High Speed: 30 knots (PE flap/base)	Maximum Trim Modification (Δ degrees)
1	7.5	0.979	0.982	0.999	-0.65
2	5.0	0.976	0.993	1.003	-0.26
3	5.0	0.962	0.992	1.003	-0.32
4	5.0	0.969	0.995	1.009	-0.31
5	7.5	0.969	0.976	1.007	-1.00
6	**7.5**	**0.979**	**0.979**	**0.997**	**-0.63**
7	10.0	0.986	0.974	0.999	-0.96
8	10.0	0.993	0.983	1.002	-0.72

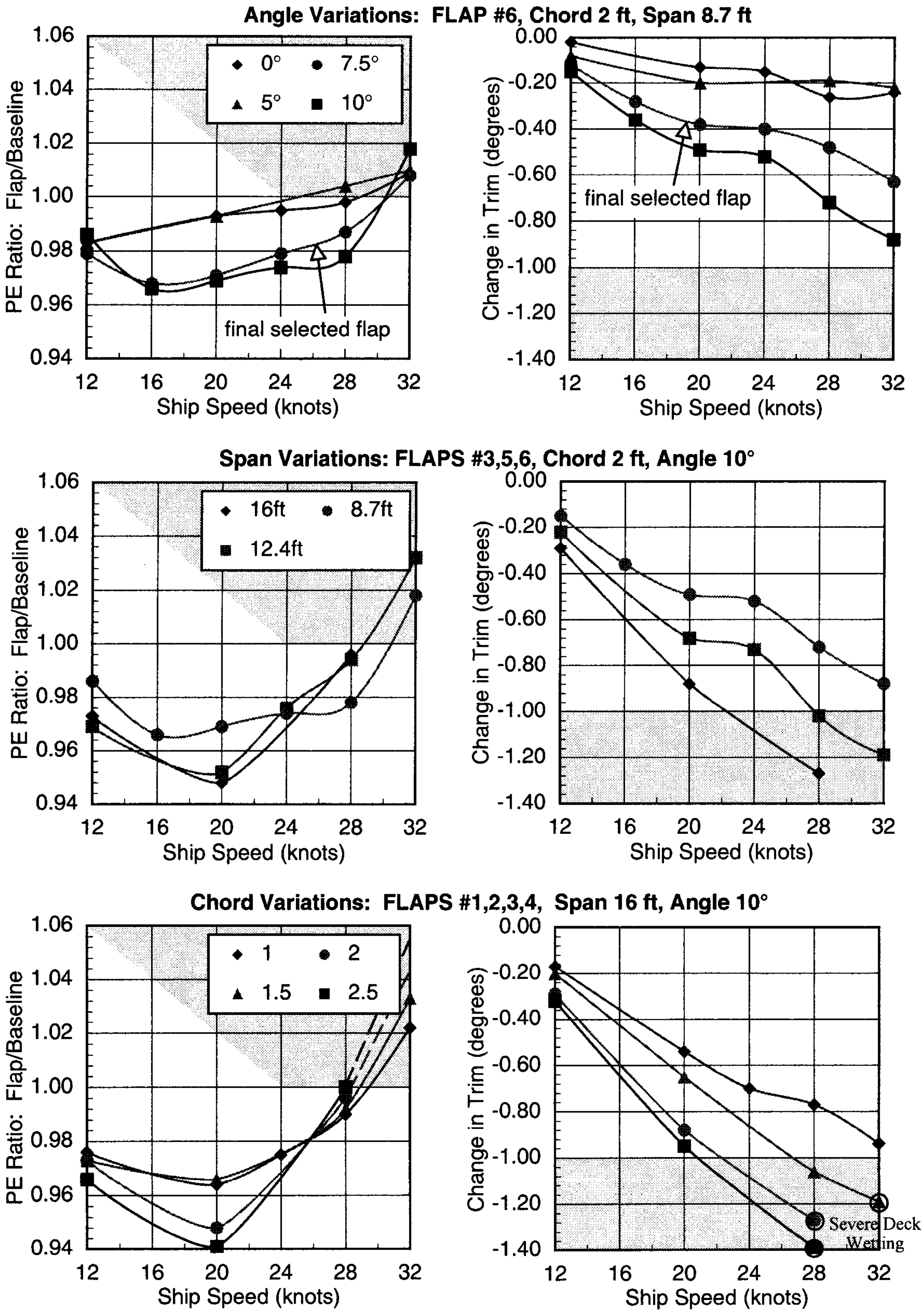


Fig. 4. Examples of results of model-scale stern flap optimization experiments (Stern flap scale effects are not included)

Referring to the selected stern flap results shown in Figure 5, for full load, the model resistance predictions indicate a decrease in effective power (P_E) due to the selected stern flap for speeds of 10 to 32 knots. The maximum stern flap P_E reduction is predicted to be 3.76 percent at a speed of 16 knots. The average decrease in P_E, over the high speed range (as indicated by 28 through 32 knots), is approximately 0.8 percent.

At the min-ops loading, Figure 6, a decrease in ship P_E with the stern flap is again shown for all speeds tested. The maximum flap P_E reduction due to the stern flap is predicted to be 3.74 percent at a speed of 15 knots. The average high speed decrease in P_E is approximately 0.9 percent.

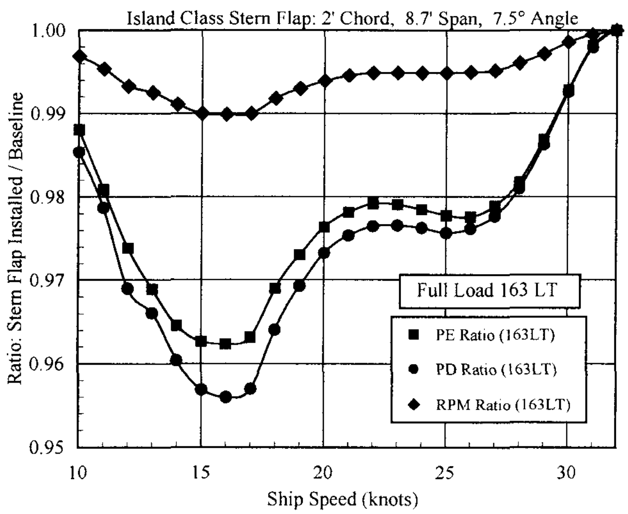


Fig. 5. Model-scale performance of selected stern flap #6, Full Load condition of 163.39 L. tons

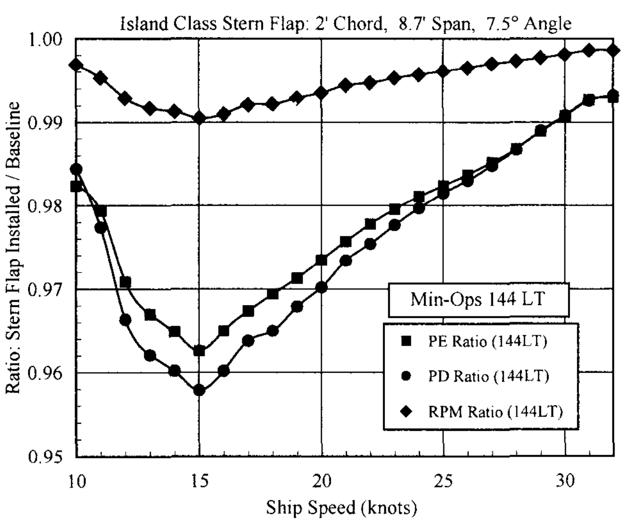


Fig. 6. Model-scale performance of selected stern flap #6, Min-Ops condition of 143.61 L. tons

The powering predictions, also depicted in Figures 5 and 6, show that the stern flap causes a slightly greater decrease in delivered power than in effective power (resistance), for both loading conditions. One reason for this is that resistance decrease unloads the propeller and increases the propeller efficiency slightly. The results of previous model tests for other ships have shown a general trend indicating that the flap causes a slightly greater reduction in delivered power than in resistance; Karafiath et al. [1999].

Ship Running Trim Effects

Comparisons were made between the ship running trim, for the *ISLAND* Class with and without the stern flap installed, for both the full load and min-ops conditions. As shown in Figure 7, the *ISLAND* Class ship running trim, at both full load and min-ops, was affected very similarly by the stern flap. The net change in bow down trim angle, resulting from the stern flap, increased as ship speed increased. The change in trim angle remained within 0.6 degrees over the range of ship operational speeds (12 to 30 knots). Therefore, the selected stern flap satisfied the design criteria for ship running trim modification (bow down) not to exceed 1.0 degrees, at any speed.

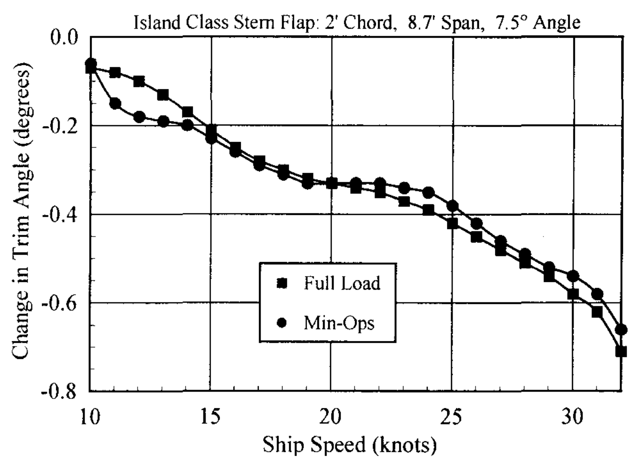


Fig. 7. Selected stern flap #6, effect on ship running trim

Stern Flap Scale Effect

While powering improvements are indicated by these Model 5526 stern flap experiments, the actual full-scale stern flap on the *ISLAND* Class would generally be expected to exceed the performance indicated on the model. Based on past experience, the actual performance of full-scale prototype stern flaps have been found to exceed that of their model-scale predictions; Cusanelli [1998]. Ship trials indicate that the model experiments generally tend to under-predict the stern flap performance in the range of roughly 2 percent to as much as 12 percent with the greatest performance discrepancies at the lower end of the speed range.

Indications are that the stern flap scale effect might have a strong Reynolds Number dependency. Three sets of ship trials, and recent testing on various size models, have been conducted with and without the stern flaps, in an effort to better understand stern flap scale effects. Computational efforts for studying these scale effects have been made possible by the recent emergence of improved computers and flow codes that can perform calculations at full scale Reynolds numbers. Great strides have been made towards verification and explanation of performance and flow observations of stern flaps, through the combination of these full-scale, model-scale, and computational efforts.

This unique data set has been used to develop a simple quantitative empirical stern flap performance adjustment method for estimating the magnitude of the stern flap scale effect. This performance adjustment loosely simulates the full scale experience, i.e., indicating greater model data adjustments at lower speeds and at increasing model scale ratio. Performance projections, adjusting model data for scale effects by the performance adjustment , were compared to the stern flap ship trials performance. This stern flap performance adjustment tends to bring the prediction from the model data more in line with the full-scale results. However, the adjustment needs to be used with great caution, bearing in mind that it was developed from the specific geometry of a stern flap on a destroyer hull form.

Full-Scale Projected Delivered Power

The performance adjustment was utilized to modify the model-scale powering prediction. However, the maximum speed on the performance adjustment method is represented by Froude number equal to 0.45. At higher speeds, guidance from the *USS CYCLONE* (PC 13) model to full-scale comparison of stern flap performance was utilized. The *CYCLONE* data shows that between Froude Numbers of 0.55 and 0.8 the stern flap performance demonstrated by ship trials was an average of 1.5 percent better than the performance indicated by the model self propulsion prediction. Thus, for the high speed portion of the *ISLAND* Class stern flap powering projection, this 1.5 percent performance improvement was assumed. These new stern flap performance projections for the *ISLAND* Class, adjusted for stern flap scale effects, are presented in Figures 8 and 9, for full load and min-ops loading conditions, respectively.

Thrust breakdown due to propeller cavitation is not accounted for within these powering projections. However, some cavitation effects, inherent in the full scale *BAINBRIDGE ISLAND* trials data, would have influenced the fairing of interaction coefficients. The ship/model comparison, therefore, has some of the high speed cavitation effects included.

A photograph of the stern flap prototype, as installed on the *JEFFERSON ISLAND* (WPB 1340), is presented in the frontispiece.

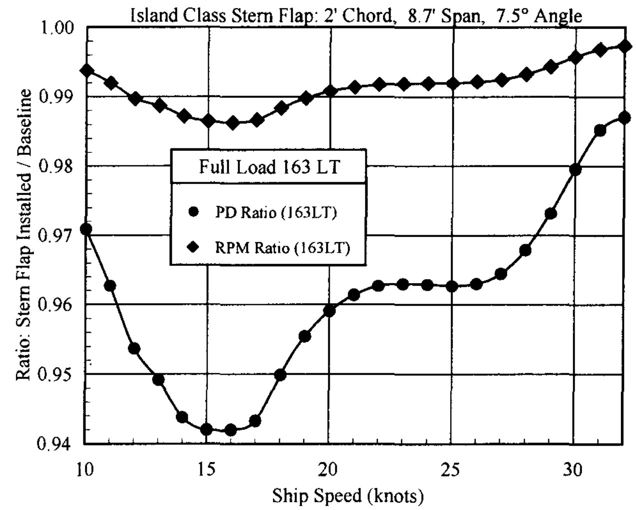


Fig. 8. Projected full-scale stern flap performance on *ISLAND* Class, full load condition of 163.39 tons

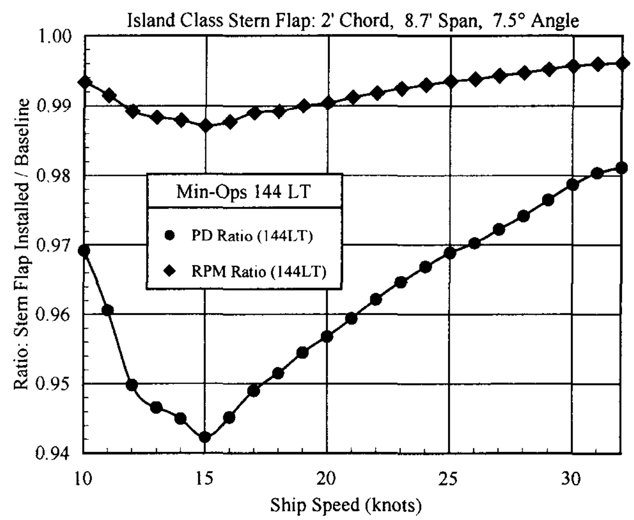


Fig. 9. Projected full-scale stern flap performance on *ISLAND* Class, min-ops condition of 143.6 tons

ENGINE OPERATING ENVELOPE

Projected shaft powering comparisons were made to the *ISLAND* Class main propulsion engine operating envelope, for those boats with the Caterpillar 3516 engine. An enlargement of the main engine operating envelope, near full power, is depicted in Figure 10. The engine envelope represents the "upper curve" on engine brake horsepower, BHP, defined by the equation: BHP = (engine RPM / 1910)$^{2.7}$ * 2730. This curve of engine brake horsepower versus engine speed has typically been referred to as the engine performance curve. Also depicted on this figure is the engine maximum power, with bands representing a power tolerance of $\pm$3 percent A transmission gear loss of 3 percent was utilized for the conversion between BHP and delivered shaft power. The transmission gear ratio between engine RPM and shaft (propeller) RPM is 2.33:1

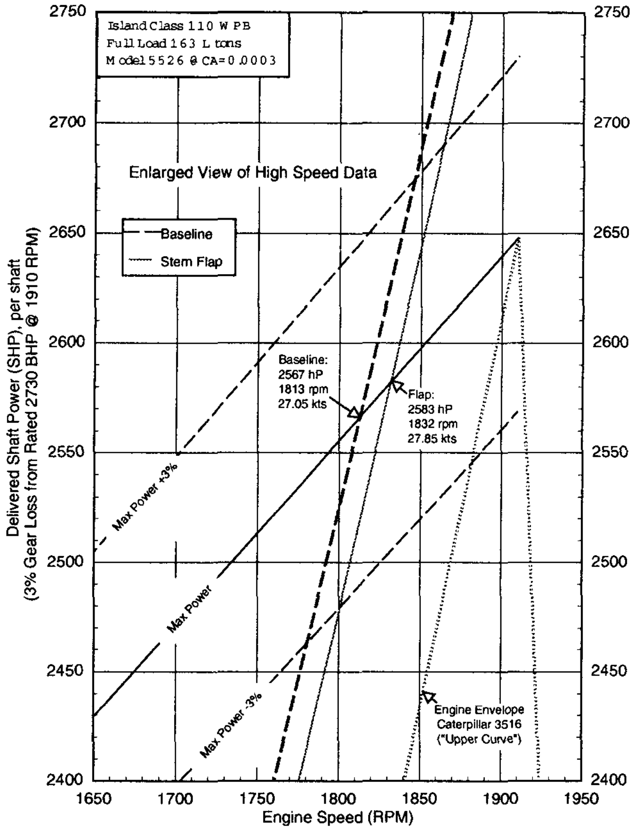


Fig. 10. *ISLAND* Class main engine operating envelope (Caterpillar 3516), with projected shaft powers baseline vs. stern flap, full load

The installation of the stern flap shifts the projected powering curve closer to the recommended engine operating envelope. At the full load condition, the maximum available delivered power at the propeller increases from 2567 hP (1914 kW) to 2583 hP (1926 kW). However, an even greater change in the ship's power versus speed relationship would be necessary for the ship performance to shift into the confines of the recommended engine operation envelope. A propeller redesign would be necessary in order to achieve a change of this magnitude. Similarly, in the min-op load condition, the flap shifts the operating curve closer to the recommended engine performance envelope, but it still falls outside the recommended engine operation envelope.

Maximum Ship Speed

Maximum available shaft power and engine RPM were determined from the intersection of the projected powering curve and the line defining the engine maximum power. Maximum ship speed was then determined for this powering point. For the full load condition, the maximum attainable speed, for the *ISLAND* Class 110 WPB patrol boats, with the stern flap installed, is projected to be 27.85 knots, at a total shaft power of 2583 hP (1926 kW), and with a propeller speed of 786.3 RPM (engine speed 1832 RPM). This represents an increase in top speed of 0.80 knots over the existing boats. At min-ops, the maximum attainable speed, with the stern flap installed, is projected to be 30.38 knots, at a total shaft power of 2635 hP (1965 kW), and with a propeller speed of 812.9 RPM (engine speed 1894 RPM). This represents an increase in top speed of 0.38 knots.

A summary of the projected benefits due to the installation of a stern flap, on the *ISLAND* Class 110 WPB patrol boats, is presented in Table 7.

Table 7. *ISLAND* Class with stern flap, projected full-scale performance characteristics

Criteria	Full Load	Min-Ops
PD @ High Speed: 28~32 kts	-0.82%	-0.96%
Projected Maximum Speed	27.85 kts	30.38 kts
Increase in Maximum Speed	+0.80 kts	+0.38 kts
PD @ Cruising Speed: 24 kts	-3.7%	-3.3%
PD @ Engine Idle Speed: 12 kts	-4.6%	-5.0%
Maximum Powering Reduction	-5.8% @ 16kts	-5.8% @ 15kts
Incipient Effective Speed	< 12 (@idle)	< 12 (@idle)
Annual Fuel Consumption	-4.5%	-3.9%
Trim Modification (Bow Down)	0.6°	0.6°

MEASUREMENT UNCERTAINTY

Resistance measurement uncertainties (precision errors) were examined on Model 5526 at two ship speeds, 16 and 24 knots. The precision error, also known as random or repeatability error, is an indicator of the "scatter" in the data, or the unsteadiness of the phenomenon being measured and the instability of test equipment. For Model 5526, the total uncertainty of the resistance measurement was ± 0.5 percent at 16 knots and ± 1.0 percent at 24 knots. The levels of these measurement uncertainties are less than the measured flap performance improvements.

TRANSOM FLOW OBSERVATIONS

Excessive wave height, eddy-making, and turbulence, represent lost energy in the local transom flow of a vessel. A great deal of qualitative information can be obtained about the performance of a stern flap by careful observations of its effects on the flow past the transom and the localized waves generated at the transom. Transom flow can be categorized by three simplified descriptions. At slow speeds, the transom and flap are fully wetted and the flow is said to be "attached". Resistance is increased by the "base drag" of the immersed transom and by significant eddy-making. As speed increases, the transom becomes less submerged and less water tends to flow back over the flap. Over a small speed range the stern flow becomes "transitional", periodically breaking free of the transom and flap then rolling forward to wet them again. At a yet higher speed, the flow detaches cleanly or "breaks-away" from the bottom edge of the transom or flap. The speed at which this detachment occurs is affected by factors which include ship displacement, ship trim, transom design and depth of submergence, and the specific design of the transom and stern flap.

The effect of the stern flap on the localized flow around the transom, and its effects on the ship speed at which the stern flow breaks away from the transom, were carefully observed. Photographs comparing the transom flow, with and without the stern flap installed, were taken at the full load condition, for 2 knot increments of ship speed. Depicted in Figure 11 is one such comparison, at 16 knots. The character of the transom flow was considerably altered by the stern flap over speeds from 12 to 20 knots. Within this speed range, the transom wave appears to be decreased in both height and overall width by the stern flap.

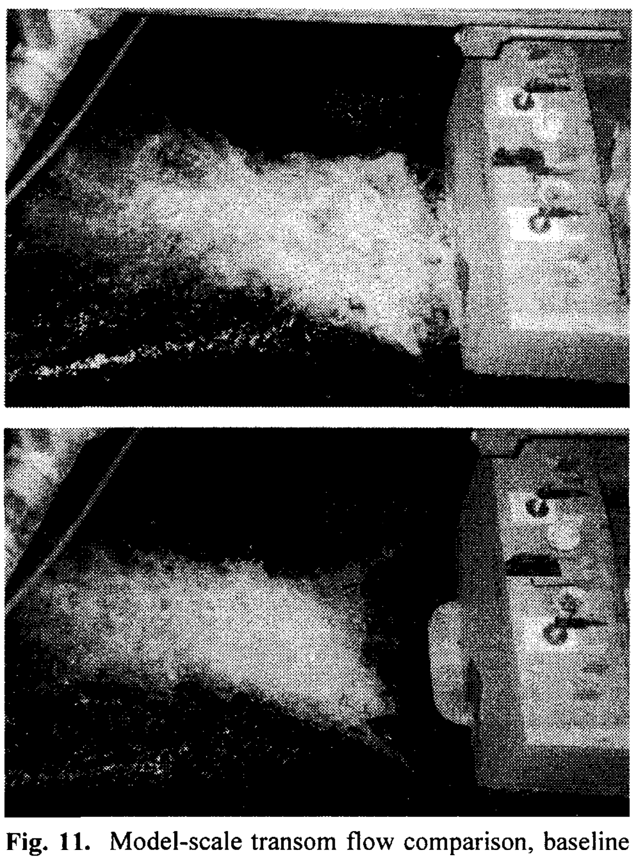


Fig. 11. Model-scale transom flow comparison, baseline (upper) and with stern flap (lower), full load, 16 knots

The ship speed at which the transom flow detaches (break-away) was reduced from approximately 17 knots for the baseline hull to 15 knots when the stern flap was installed. Referring to the comparison photographs at 16 knots, the baseline hull still exhibits attached flow, while the stern flap exhibits fully detached flow. At this speed, the stern flap caused the greatest improvement in the transom flow. The stern flap exhibited its maximum powering reduction at 16 knots. Of particular interest is that the reduced span flap also caused the flow, outboard of its span, to break away cleanly from the transom.

For speeds in excess of 22 knots, there appears to be little visual difference in the local transom flow with or without the stern flap installed. However, at these higher speeds, the stern flap does appear to reduce the visual wake deficit behind the twin rudders. This effect of stern flap on the rudder wake deficit had not been previously been observed.

SPRAY RAILS

During the model-scale stern flap evaluation, a significant amount of spray was observed in the bow region, for ship speeds in excess of 24 knots. This spray resulted in model deck-wetting. Representatives from USCG, present at the model testing, reported that similar spray patterns leading to deck-wetting have been observed at full scale. This spray originates in the region of the bow between the stem and the ship's lower chine. At this forward location the lower chine tapers to zero thickness. Since there is nothing on the hull to deflect these flow streamlines (either at ship or model-scale), the water tends to cling to the hull and project upwards. At speeds of 24 to 28 knots, the flow appears to separate off the upper chine. At speeds above 28 knots, the flow progresses upward all the way to the deck line before separating. Once at the upper chine or deck level, the flow separates in a spray sheet which increases in size with increasing speed.

Bow spray rails were installed on the model after the completion of the flap optimization experiments. At ship scale, the bow spray rails would extend 7.25 ft (2.2 m) aft from the stem, following the contour indicated by the existing lower chine line, and extend off the hull surface (thickness) approximately 1.5 inches (3.8 cm). Model-scale experiments were conducted, at full load, with and without the spray rails installed. Effective power predictions showed a relatively small increase due to the spray rail; 0.2 to 1.3 percent over the speed range of 14 to 19 knots. Prior to, and above this speed range, the spray rails did not affect resistance.

With the bow spray rails installed there was no deck-wetting and the spray was deflected to the side as shown in Figure 12. The spray rails remained on the model for the balance of the testing, with and without the flap, at both loading conditions.

A photograph of the port bow spray rail as installed on the *JEFFERSON ISLAND* (WPB 1340), is presented in Figure 13.

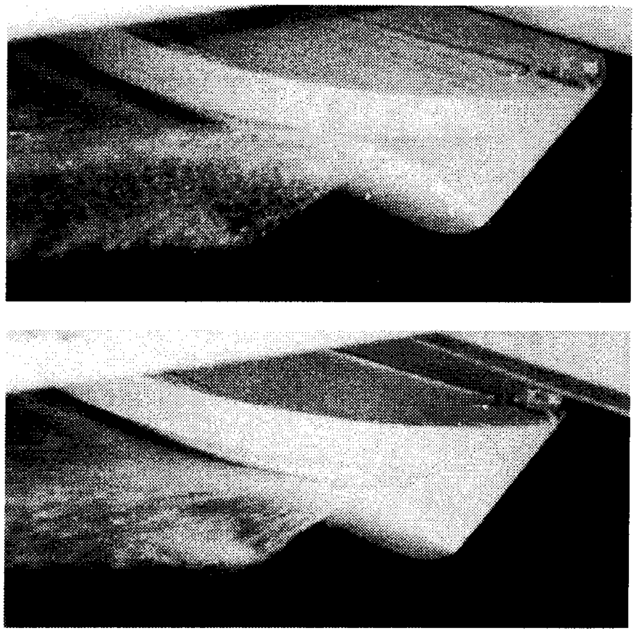


Fig. 12. Model-scale bow spray comparison, baseline (upper) and with bow spray rails installed (lower), full load, 28 knots

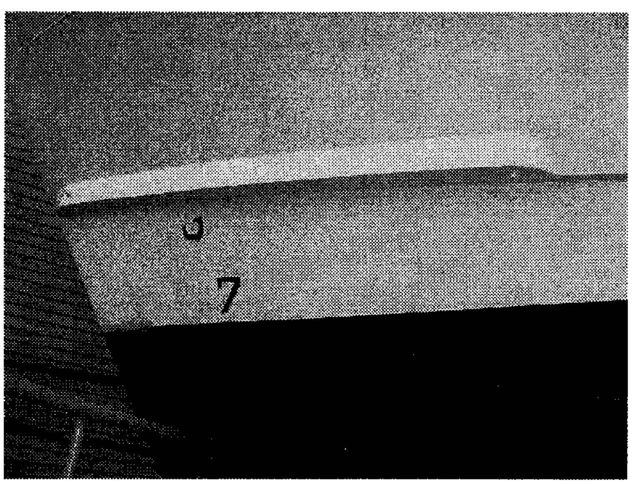


Fig. 13. Bow spray rail (port side) as installed on the *JEFFERSON ISLAND* (WPB 1340)

FULL SCALE OBSERVATIONS

As previously mentioned, both the stern flap (frontispiece), and the bow spray rails (Figure 13), were installed on the *JEFFERSON ISLAND* (WPB 1340). The following are informal observations of their performance full scale. Winter weather and operational considerations have delayed formal ship trials until a later date.

With the stern flap installed, the *JEFFERSON ISLAND* was noted to get up on a plane easier, and the engine was noted to be running easier (somewhat unloaded). These observations indicate that the stern flap is performing effectively. The observation regarding the ease of transition to planing is consistent with the transom flow observations on the model at 16 knots. Due to the flap, the flow detaches from the transom at a lower speed, and the vessel appears to plane earlier. Stern flap installations on other ships have produced visual modifications in the wake as well, with the principal features being a reduction in height of the transom convergence wave and "rooster tail", and a shift in the convergence position further aft (away from the transom).

It was also reported, that with the vessel operating in 1 to 2 ft (0.3 to 0.6 m) seas, the spray rails were working as designed.

COMPARISON WITH OTHER WORK

Unknown to those performing this model test effort, work was done at the University of Michigan to analytically design stern flaps for the *ISLAND* Class patrol boats; Cocklin et. al. [2000]. Two different analytical methods were exercised. The first method used the model test work of Brown [1971] to empirically define stern flap lift and drag. The hull trim and heave was then adjusted for these forces and total resistance was calculated using the Michigan Power Prediction Program. Method two involved the POWERSEA [1999] program, using low aspect ratio strip theory, to predict the forces on a planing hull. Again, flap forces were estimated using Brown's equations. Acknowledgement was made of the fact that these prediction methods are for planing craft and that neither method was capable of taking into account the effect of the flap on altering the pressure distribution and the forces on the hull. The stern flap configurations analyzed by Cocklin were somewhat different than the ones which were model tested at NSWCCD. Thus, a direct comparison to the model test data is difficult. Nevertheless, the trend appears to be that these analytical methods were unable to predict the relatively low speed (16 knot) powering improvements shown by the model tests, and they tended to show greater improvement at the high speed than indicated by the model tests. Again, the limitations of trying to apply predictions meant for planing craft to the semi-planing speed regime were acknowledged.

There is very little data on the effect of the flap on seakeeping, however, Cocklin did provide some calculated results for a 3 ft (0.91 m) high and 52 ft (15.9 m) long regular wave. The conclusions were "The flap slightly reduces the maximum positive acceleration that the person feels at the bow", and also that " it is likely that the vessel will require less power in waves with a stern flap than without a stern flap".

PRESENT *ISLAND* CLASS PROPELLER DESIGN

The present *ISLAND* Class "fleet" propellers generate ongoing problems with erosion damage due to excessive blade cavitation at high speed, excessive engine loading, and excessive noise affecting habitability in the aft stateroom. The root cavitation problems were evident after completion of the original builder's trials; Latas et al. [1986]. Latas reported that cavitation erosion was evident at the root of each blade about 75 percent of the chord length aft. Cavitation tunnel tests conducted overseas duplicated the cavitation patterns and showed that the cavitation began at the leading edge of the root at about 25 knots. Leading edge modifications were tried but did not reduce the cavitation to an acceptable level. Finally, cavitation relief holes were installed in the blades. The holes were demonstrated to be effective at model-scale, however, long term full scale experience has shown that the holes are only partially effective in reducing cavitation damage.

Later, Neely et al [1993] designed fixed pre-swirl stator vanes, in an attempt to solve the fleet propeller blade root cavitation problem through improved inflow conditions and through a reduction in the root leading edge angle of attack. These vanes were to replace the existing rope guards, thus putting a limitation on the available hub length for the pre-swirl vanes. Cavitation tests showed a significant improvement in efficiency and a greatly reduced tendency for root cavitation erosion. However, the root erosion was not totally eliminated.

NEW 6-BLADED PROPELLER DESIGN

The traditional propeller design process uses technical input, from model self propulsion experiments with a stock propeller, to determine the required thrust for the propeller. Model wake survey experiments are used to determine the inflow to the propeller. After the propeller is designed, model self propulsion experiments, and propeller open water tests and cavitation tests, are performed to verify the predicted powering and cavitation aspects of the propeller design. However, for the *ISLAND* Class propeller design a different approach was adopted in order to provide the technical input to the propeller design process. The *ISLAND* Class propeller was modeled after the Navy's 6 bladed propeller designed for the PC1 *CYCLONE* Class, Jessup [1997].

- Thrust was estimated from resistance experiments, which were calibrated with full-scale trials data, and from thrust deduction estimates for similar craft. The propeller was designed for the stern flap condition.
- The wake field was estimated from the data on the PC 1 *CYCLONE* Class model, with an adjustment for the difference in shaft angles.
- The same propeller design procedure was used for both the PC 1 Class and the *ISLAND* Class. The computed open water prediction for the *ISLAND* Class was slightly adjusted using guidance from the comparison of the PC 1 computed predictions, and the PC 1 propeller open water data .
- The cavitation prediction was made through comparison to the PC 1. (The propeller blade section design shared similarities with that of the PC 1.)

Thus, it can be seen that the PC 1 experience was very important to the *ISLAND* Class propeller design. The new propeller design is expected to reduce airborne noise, increase fuel economy, and improve engine reliability by providing proper engine loading.

The state of the art of propeller design, at the time-frames of the fleet propeller and the stator vane designs, was such that only the blades of the propeller and stator were simulated in the design process. In contrast, the current design methodology geometrically models and represents the propeller blade, root, and hub. These advances in propeller design instill a high level of confidence with regard to the analytical evaluation of the flow at the root.

Design Philosophy and Requirements

The current fleet propeller was analyzed using the PSF10, performance panel code, Lee [1987]. For the estimated flow inclination, analysis shows that the fleet propeller blade sections operated at relatively high angle of attack throughout its speed range. The fleet propeller was designed to produce leading edge cavitation that incepted at relatively low speed. The new 6-bladed propeller was designed to avoid leading edge and root cavitation.

This new design philosophy is carried out by applying new blade sections similar to those used in the recent PC 1 design. Table 8 compares propeller blade geometry and design criteria between *ISLAND* Class and PC 1 Class propellers. Highlights of the design requirements were;

- Optimized for 110 WPB *ISLAND* "C" Class.
- Designed for the maximum continuous speed at the full load 164 L tons without exceeding the rating of the Caterpillar engine, 2730 BHP at 1910 RPM.
- Propeller clearance to be a minimum 0.15 D from the tip to the hull. The propeller diameter was kept the same as that of the original design.
- The engine is to achieve wide open throttle RPM of 1% to 3% over the rated RPM in the trial condition.
- The material is to be nickel aluminum bronze, MIL-B-24480A UNSC95800.

Table 8. Design parameters and blade geometry for *ISLAND* Class and *CYCLONE* Class propellers

Class Design	No. of Blades	EAR	Propeller Wt. lbs	Blade Wt. lbs	Static Head ft	Design JA
Fleet ISLAND	5	1.171	775	380	37.5	0.9
6-Bladed ISLAND	6	1.169	928	533	37.5	0.876
PC 1 CYCLONE	6	1.175	1238	563	36.4	1.153

Propeller Wake

The propeller inflow for *ISLAND* Class has not been measured, and therefore, was estimated. The axial inflow to the propeller was assumed to be uniform. The wake in the analysis is primarily a result of the shaft inclined to the flow. The flow angle was approximated as 10.1 degrees. The flow angle was 6.1 degrees for PC 1. A simplified wake model was assumed to estimate the maximum and minimum loading conditions as input to PSF10. The design points for the maximum and minimum loading condition are explained in Jessup and Wang [1997]. The wake indicates that the *ISLAND* Class propeller will be under higher loading variation than the PC 1 Class propeller. The propeller design is based only on the tangential wake variation, producing a sinusoidal angle of attack change with blade angular position. The resulting tangential velocity is shown in Fig. 14 with a first harmonic value of 0.176Vs at the blade tip.

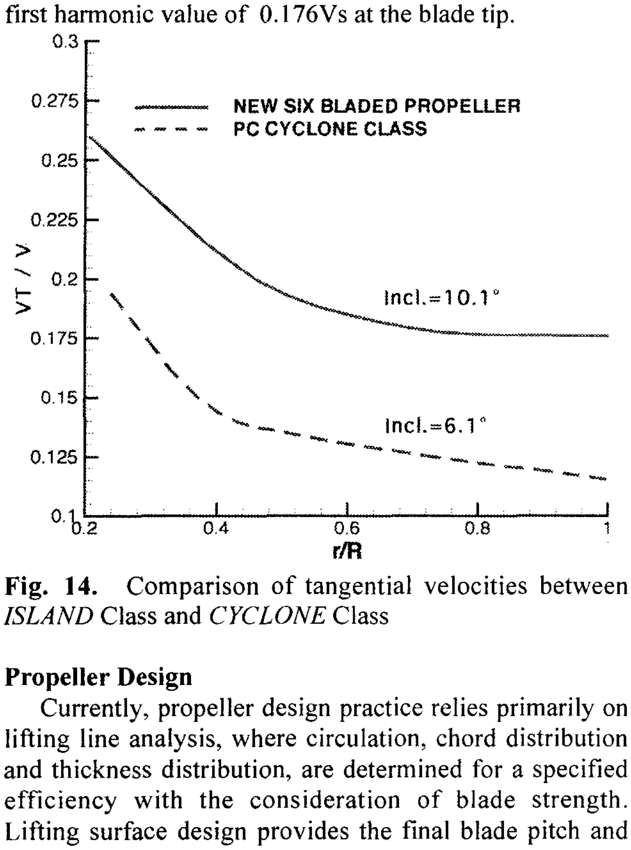


Fig. 14. Comparison of tangential velocities between *ISLAND* Class and *CYCLONE* Class

Propeller Design

Currently, propeller design practice relies primarily on lifting line analysis, where circulation, chord distribution and thickness distribution, are determined for a specified efficiency with the consideration of blade strength. Lifting surface design provides the final blade pitch and camber with the additional input of rake and skew.

In this *ISLAND* Class design, the approach was different, with the PC 1 design providing an initial starting point. The *ISLAND* Class design was refined by iterating geometrical parameters to improve performance and to match the Class requirements on powering and cavitation, using PSF10.

Circulation Distribution

The span wise circulation distribution originated from a PC 1 design with a different design advance ratio, J=1.155. By adjusting geometrical parameters and changing to a new design point at J=0.876, a new circulation, resulting in better cavitation performance relative to the current fleet propeller, was achieved. The final circulation distribution, and lift coefficient, C_L, for the new 6-bladed *ISLAND* Class propeller design, are compared with those of the fleet *ISLAND* Class and the PC 1 *CYCLONE* Class propeller designs, in Figure 15.

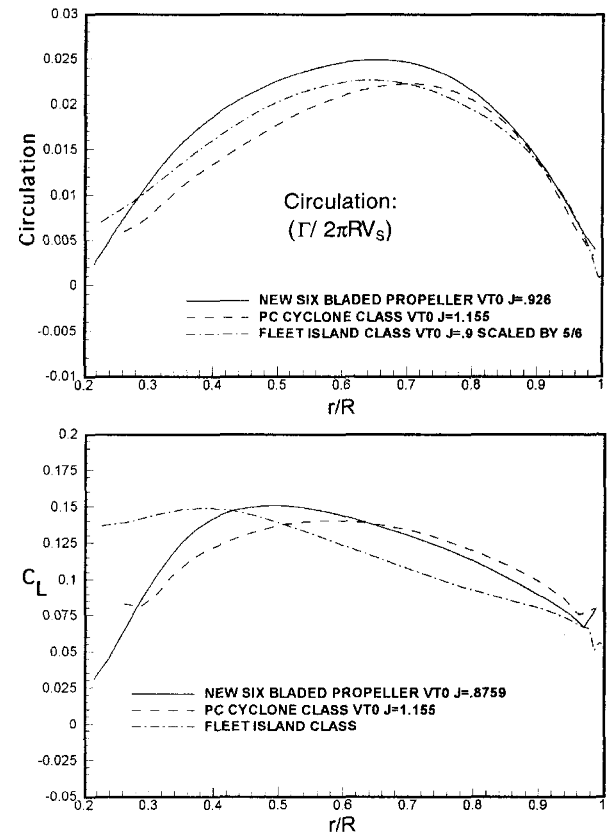


Fig. 15. Comparison of circulation and lift coefficient between *ISLAND* Class and *CYCLONE* Class propellers

Blade Stress Analysis

The program BSTRESS, Schott et al. [1989], based on beam theory, was used to check blade structural stress. The maximum blade stress calculated for the new design was 12,256 psi, occurring at 0.206 r/R, full power. This was below the accepted Navy stress limit of 12,500 psi.

Lifting Surface design

Lifting surface design code, PBD-10, Kerwin [1984], was used early in the design to calculate the blade pitch and camber distribution from the specified blade chord, skew, rake, thickness, and the specified span-wise circulation distribution assuming no hub. The chord-wise loading representing upper and lower surface pressure difference was also included in the design with the specified span-wise and chord-wise thickness distributions. The resulting span-wise distribution of blade pitch, and a fully three dimensional blade camber distribution, were computed. The final geometry, which is significantly different from the initial PBD-10 design, is a result of geometry adjustments using iterative panel method calculations to achieve final powering performance and optimized cavitation performance. The geometry differences relative to the PC 1 propeller are discussed below:

Chord length: The overall chord length had been reduced to achieve better efficiency. Subsequently the chord length was increased in some areas to improve cavitation.

Pitch: Variations in blade pitch were used to meet powering requirements and to adjust leading edge cavitation inception resulting from high angle of attack. Increasing pitch increased propeller loading, improved pressure side cavitation and degraded suction side cavitation.

Camber: Section camber, F/C, was adjusted independently or in conjunction with a change in P/D. Increased camber decreases suction side leading edge cavitation, but increases pressure side leading edge cavitation. Attempts were also made to modify the leading edge camber. Successive adjustments gradually resulted in the final design.

Thickness: Thickness was selected based on strength considerations, cavitation considerations, and restrictions on the blade weight. Increasing T/C provides increased tolerance to leading edge cavitation due to change in the angle of attack, while increasing the potential for back bubble cavitation. Increasing T/C also increases blade weight. Sufficient blade thickness at the root is required for structural consideration at the expense of degraded cavitation performance.

Rake: Adjusted parametrically during the design process to seek better cavitation performance. Final rake distribution was very similar to that of the PC 1 propeller.

Diameter: Remained equivalent to that of the fleet propeller.

Panel Method Prediction of Cavitation Inception

The typical panel grid distribution had 40 span-wise constant spaced panels and 30 chord-wise cosine spaced panels. Three panel code calculations were performed for each iteration. The circumferential average design case assumed uniform flow and was used to make powering predictions with the tangential and radial inflow assumed zero. The maximum and minimum loading cases were calculated assuming positive and negative tangential flow assigned as VT+ and VT-, respectively. Pressure distributions for the three calculated cases were analyzed leading to further geometric adjustments for the next iteration. Predicted cavitation inception speed was calculated from CP_{min} from the maximum and minimum loading conditions by $\sigma_i = -CP_{min} = 2gH/V_{i,s}{}^2$.

Final blade pressure distributions for the 81 percent radius are presented in Figure 16, for uniform flow at J_A=0.876. Blade pressure distributions for maximum and minimum loading conditions, at the 81 percent radius, is presented in Figure 17. These pressure peaks occur on the blade suction side at maximum loading and on the blade pressure side at minimum loading. A view of the blade grid distribution is shown in Figure 18.

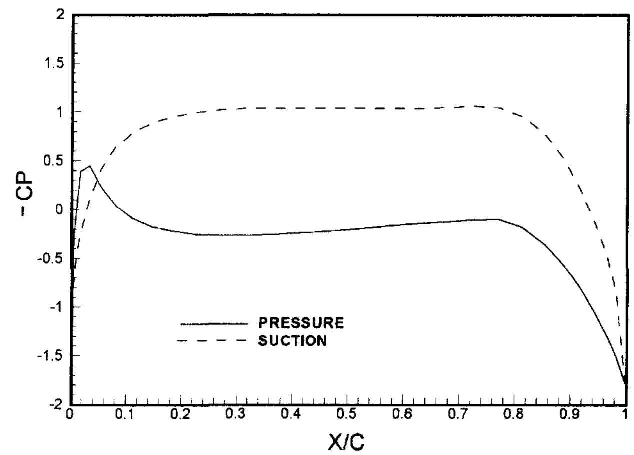


Fig. 16. Circumferential average blade pressure distribution, r/R = 0.811, J_A = 0.876

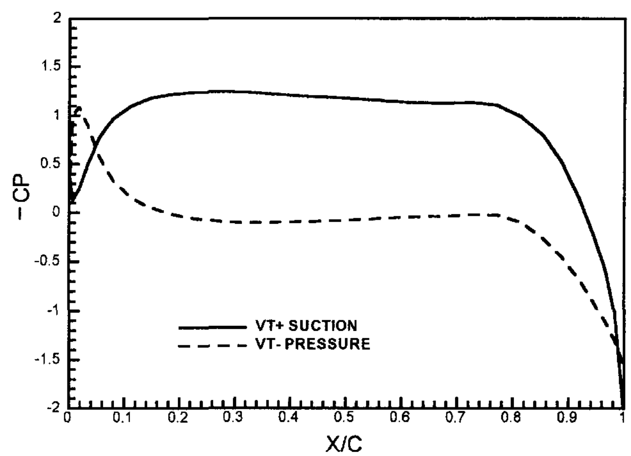


Fig. 17. Maximum and minimum blade pressure distribution, r/R = 0.811, J_A = 0.876

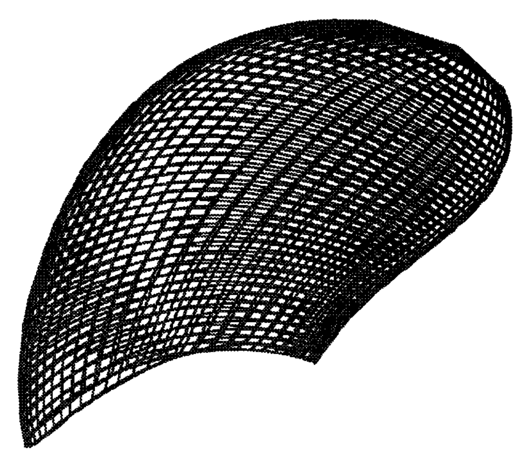


Fig. 18. Propeller blade grid distribution

FINAL DESIGN GEOMETRY

The parameters of pitch and chord selected for the final 4.134 ft (1.26 m) diameter, 6-bladed propeller, are presented in Figure 19. Detailed geometry was created using the code NCBLADE, Kerwin [1984]. An anti-singing trailing edge was added over most of the span. The trailing edge radius was increased near the root to provide a smooth transition between the squared off trailing edge at the root and the anti-singing trailing edge over most of the blade. For the 79 percent radius the resulting trailing edge section is compared with PSF10 section in Figure 20.

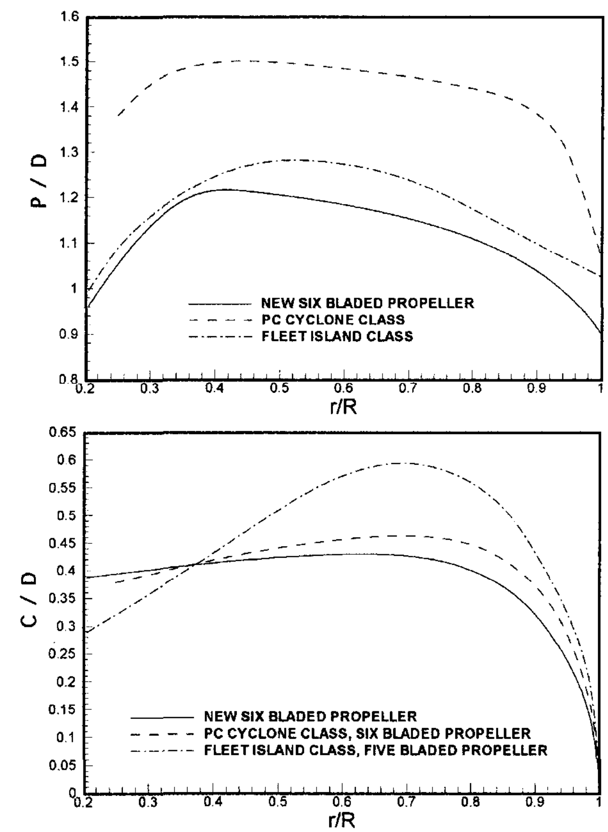


Fig. 19. Propeller geometry parameters, pitch and chord

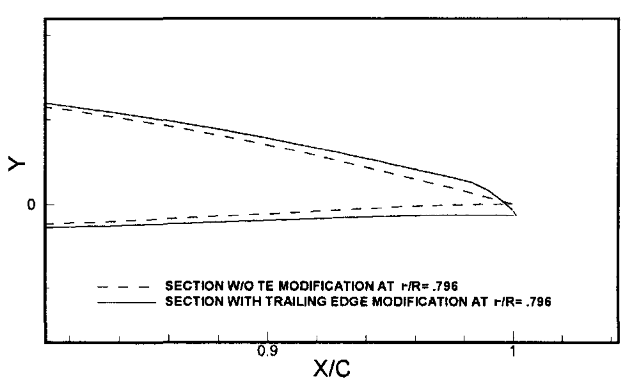


Fig. 20. Propeller blade sections, with and without trailing edge modification, r/R = 0.796

NCBLADE was used to create two B-spline surfaces, one for the majority of the blade and one for the trailing edge details. The B-spline surfaces have the advantage of being completely defined at all points, eliminating possible errors in interpolation or interpretation by manufacturers. The code FILLET was used to add a 1/3 fillet between the root of the blade and the hub. The 1/3 fillet has a radius equal to one-third of the blade thickness at that point, with a minimum full scale radius of 1 inch.

Propeller geometric characteristics of the completed *ISLAND* Class 6-bladed propeller design are presented in Table 9. Computer renderings with blade trailing edge modification and fillets, are presented in Figure 21, and on the frontispiece.

Fig. 21. Computer renderings of *ISLAND* Class 6-bladed propeller

Open Water Performance

Performance predictions were made for the 6-bladed propeller design using panel code PSF10, with constant and half cosine span-wise spacing, to predict the propeller

Table 9. *ISLAND* Class 6-bladed propeller geometric characteristics

r / R	P/D	lT/ D	θs (deg)	C/D	F/C	T/C
0.206	0.962	-0.014	-6.000	0.387	-0.0287	0.0962
0.30	1.135	0.010	3.497	0.401	0.0197	0.0876
0.40	1.214	0.032	11.705	0.413	0.0212	0.0732
0.50	1.204	0.051	18.553	0.423	0.0185	0.0610
0.60	1.183	0.068	24.571	0.429	0.0181	0.0529
0.70	1.152	0.083	29.717	0.426	0.0180	0.0464
0.80	1.108	0.101	34.266	0.400	0.0164	0.0401
0.90	1.037	0.125	39.043	0.321	0.0123	0.0377
0.95	0.983	0.144	41.950	0.240	0.0095	0.0409
0.99	0.920	0.163	44.528	0.118	0.0070	0.0453
1.00	0.899	0.168	45.180	0.000	0.0063	0.0380
No. of Blades: 6		D: 4.134 feet		EAR: 1.168		

Table 10. Open water characteristics

JA	KT	10xKQ	ηo
0.500	0.420	0.7007	0.477
0.600	0.358	0.6254	0.546
0.700	0.298	0.5478	0.605
0.800	0.243	0.4692	0.661
0.876	0.202	0.4073	0.691
0.900	0.188	0.3867	0.696
0.926	0.173	0.3641	0.700
0.950	0.158	0.3429	0.699
1.000	0.128	0.2966	0.689
1.100	0.067	0.1982	0.594

open water characteristics. Since model testing of the new propeller design was not planned the open water characteristics were scaled empirically by using the ratio between experiments and PSF10 predictions from the PC 1 propeller. The resulting open water data were used to predict the delivered power and rpm. The results with empirical corrections are given in Table 10, for the constant spacing computation, which is more fair over the range of J.

Cavitation Performance

The predicted cavitation inception speeds, for both the *ISLAND* Class fleet and new 6-bladed propeller designs, at the design point, for both pressure side and suction side cavitation, are presented in Figure 22. For suction side cavitation, the new 6-bladed propeller is far superior in comparison to the current fleet design, i.e. has a much higher cavitation inception speed, over the entire blade surface. In terms of pressure side cavitation inception, the new design is better over most of the blade surface area, except at X/C of 0.4, but there, inception is predicted beyond the operating speed of 30 knots..

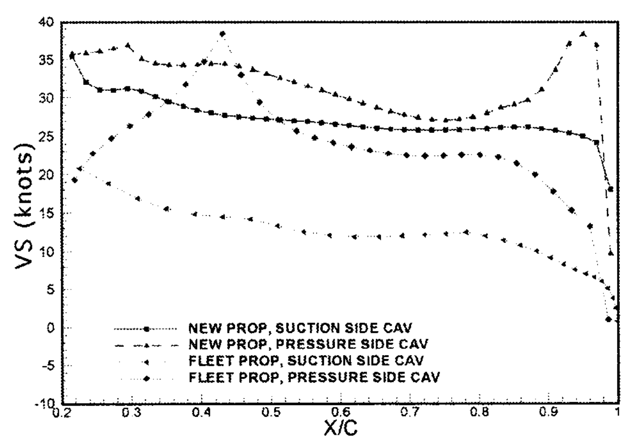


Fig. 22. Predicted cavitation inception speeds, at the design point, for both pressure and suction sides

The low cavitation inception speeds predicted at the trailing edge of the propeller (X/C of 0.98 and above) are not expected to have any significant impact on the practical operation of the propeller. The cavitation inception for the *ISLAND* Class propeller will occur around 25 knots. Thrust breakdown is estimated to start at 5 knots above inceptions or around 30 knots, which is generally beyond the maximum expected ship speed.

PERFORMANCE WITH STERN FLAP AND NEW 6-BLADED PROPELLER

Full-scale performance projections were made for the *ISLAND* Class 110 WPB with both the stern flap and new 6-bladed propellers installed. The predicted shaft power and RPM, as a function of ship speed, at the full load condition, is presented in Table 11. These predictions are based on the resistance tests, powering projection, and estimated propeller-hull interaction coefficients summarized previously, and on the predicted open-water performance for the new 6-bladed propellers. Comparisons are also drawn to the baseline *ISLAND* Class cutter (no stern flap, fleet propellers).

Powering comparisons to the *ISLAND* Class main propulsion engine operating envelope, near full power, are depicted in Figure 23. The new 6-bladed propeller design, when installed along with the stern flap, causes the power demand curve to shift toward the recommended engine operating envelope, as shown in Figure 23. Near the maximum speed, and at very low speeds, the demand curve falls within the recommended engine operating curve. At the maximum power condition, the new propeller enables the engines to develop additional power. A new full power point, of 2622 hP (1955 kW) per shaft, can be attained with the installation of both the stern flap and the new 6-bladed propeller design. At this engine power for the full load condition, the estimated ship speed is 29.60 knots, at a propeller speed of 821 RPM.

Table 11. *ISLAND* Class 110 WPB, with both the stern flap and new 6-bladed propellers installed vs. baseline, full load condition

	BASELINE		FLAP & NEW PROP			
VS (kts)	PD (hP)	Prop RPM	PD (hP)	Prop RPM	Effect PD %	Effect RPM
10	288	291.7	258	290.7	-10.4	-1.0
12	542	359.4	477	356.8	-12.1	-2.6
14	1023	438.1	891	433.9	-13.0	-4.2
15	1405	482.1	1221	477.5	-13.1	-4.6
16	1839	524.0	1602	519.1	-12.9	-4.9
18	2582	587.9	2265	583.5	-12.3	-4.4
20	3240	639.9	2866	636.1	-11.5	-3.8
21	3533	662.2	3131	658.5	-11.4	-3.7
22	3810	683.4	3382	679.8	-11.2	-3.6
23	4075	703.3	3619	699.7	-11.2	-3.6
24	4328	722.3	3846	718.6	-11.1	-3.7
25	4593	741.1	4082	737.5	-11.1	-3.6
26	4858	759.5	4320	756.0	-11.1	-3.5
27	5120	777.2	4560	773.9	-10.9	-3.3
28	5379	794.2	4808	791.6	-10.6	-2.6
29	5628	810.4	5057	808.7	-10.1	-1.7
30	5935	828.8	5369	828.2	-9.5	-0.6

Maximum Attainable:	VS (kts)	PD (hP)	Prop RPM
Baseline	27.05	5134	778.1
Flap & New Prop	29.60	5244	820.4

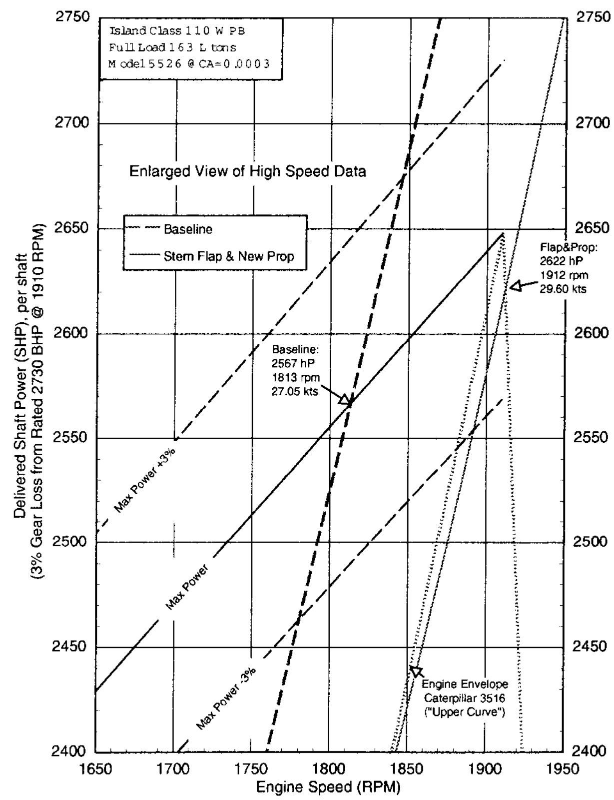


Fig. 23. *ISLAND* Class main engine operating envelope (Caterpillar 3516), with projected shaft powers baseline vs. stern flap and new 6-bladed propeller, full load condition

The improved *ISLAND* Class performance represents approximately a 2.6 knot maximum speed increase over the current baseline. Much of this performance improvement is due to the new 6-bladed propeller design, which is a nearly constant 7.7 percent more efficient than the fleet propeller throughout the speed range.

Reduction In Annual Fuel Consumption

The installation of a stern flap and the new 6-bladed propeller design on the *ISLAND* Class 110 WPB results in the capability to maintain ship speed with less delivered power, and lower propeller speed, and therefore, represents a potential for propulsion fuel reduction. Data pertaining to the fuel consumption rates of the *ISLAND* Class C series Caterpillar 3516 main propulsion engines was collected during the standardization trials on the *BAINBRIDGE ISLAND*; Haupt and Puckette [1991]. Fuel consumption rates were recorded for ship speeds in the range of 15 through 29 knots, at a loading condition of 151 ltons, with an LCG of 5.09 ft. aft of mid-ship, and static trim of -1.0°. These fuel rates, with adjustment for changes in powering performance, were utilized to estimate fuel consumption (gal/hr), at the full load and min-ops conditions.

Fuel calculations were made for the following configurations;

- Baseline (current *ISLAND* Class)
- Stern flap installed
- Stern flap & new 6-bladed propeller design installed

The predicted powering performances, the estimated speed-time profiles, and the estimated annual fuel consumption, for the *ISLAND* Class, in the three aforementioned configurations, are presented in Table 12. The annual operational hours are shown as a percentage of time for the baseline condition, 2000 hrs at full load and 1000 hours at min ops. Note that the preponderance of operations are at the low end of the speed range with 10 percent of the time at maximum speed. For the configuration with just the stern flap, and for the combined stern flap and new 6-bladed propeller configuration, the maximum speed was increased to reflect the increased speed capability with these hydrodynamic enhancements. It is felt that when maximum speed is needed the operators will push to utilize the full speed capability of the boat. At the higher speed the vessel will cover the same distance in less time and this is reflected as reduced operational hours at high speed for the configurations with the hydrodynamic enhancements.

Table 12. Estimate of *ISLAND* Class 110 WPB annual propulsion fuel consumptions

BASELINE (No Flap), Full Load — 2000 Annual Operational hours

Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission STP (hours)	Annual Fuel Consumption (gal/yr)
12	542	33.4	800	26747
15	1405	79.9	500	39935
18	2582	135.5	200	27095
21	3533	181.2	100	18117
23	4075	210.2	100	21015
25	4593	241.2	100	24117
27.05	5134	278.2	200	55636
	Total Annual Fuel (gal/yr):			212662

STERN FLAP, Full Load — 1994 Annual Operational hours

Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission STP (hours)	Annual Fuel Consumption (gal/yr)
12	517	32.0	800	25564
15	1323	75.8	500	37881
18	2453	129.5	200	25898
21	3396	174.3	100	17430
23	3924	201.8	100	20178
25	4421	230.5	100	23049
27.85	5166	280.5	194	54480
	Total Annual Fuel (gal/yr):			204479
	Annual Fuel Savings (gal/yr):			8182
				3.8%

FLAP & NEW PROPS, Full Load — 1983 Annual Operational hours

Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission STP (hours)	Annual Fuel Consumption (gal/yr)
12	481	29.8	800	23856
15	1220	70.5	500	35265
18	2261	120.6	200	24125
21	3133	161.4	100	16144
23	3617	185.5	100	18550
25	4089	211.0	100	21098
29.6	5244	286.4	183	52348
	Total Annual Fuel (gal/yr):			191386
	Annual Fuel Savings (gal/yr):			21275
				10.0%

BASELINE (No Flap), Min-Ops — 1000 Annual Operational hours

Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission STP (hours)	Annual Fuel Consumption (gal/yr)
12	482	29.9	400	11952
15	1191	69.1	250	17265
18	2134	114.7	100	11472
21	2965	153.4	50	7670
23	3476	178.3	50	8916
25	3971	204.4	50	10218
30	5252	287.0	100	28697
	Total Annual Fuel (gal/yr):			96191

STERN FLAP, Min-Ops — 999 Annual Operational hours

Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission STP (hours)	Annual Fuel Consumption (gal/yr)
12	458	28.4	400	11374
15	1123	65.5	250	16375
18	2030	109.9	100	10990
21	2845	147.7	50	7387
23	3353	172.2	50	8609
25	3847	197.6	50	9881
30.38	5270	288.3	99	28459
	Total Annual Fuel (gal/yr):			93076
	Annual Fuel Savings (gal/yr):			3115
				3.2%

FLAP & NEW PROPS, Min-Ops — 997 Annual Operational hours

Speed (kts)	Total Power PD (hP)	Fuel Consumed (gal/hr)	Mission STP (hours)	Annual Fuel Consumption (gal/yr)
12	425	26.5	400	10581
15	1032	60.7	250	15187
18	1866	102.2	100	10220
21	2618	137.2	50	6858
23	3086	159.2	50	7958
25	3552	182.2	50	9109
30.8	4986	267.5	97	26058
	Total Annual Fuel (gal/yr):			85971
	Annual Fuel Savings (gal/yr):			10220
				10.6%

Fuel usage (Baseline) for 3000 Operating hours
2/3 time at full load (163 L tons)
1/3 time at Min-Ops (144 L tons)

	SAVINGS due to STERN FLAP	SAVINGS due to FLAP & NEW PROPELLER
Annual Fuel Savings (gal/yr):	11297	31495
Fuel Reduction (%):	3.7%	10.2%
Fuel Cost Savings ($1.5/gal):	$16,946	$47,243

The estimated average reduction in annual fuel consumption, provided for by the installation of the stern flap, is 3.7 percent, 11,297 gallons, with a cost savings of $16,946 ($1.50 per gallon at commercial dock). For the combined stern flap and new 6-bladed propeller configuration, the savings are 10.2 percent on fuel, 31,495 gallons, with a cost savings of $47,243. If the new propellers were to be installed without the flap, the attributable fuel cost savings would be $30,297, ($47,243 combined minus $16,946 attributable to stern flap).

Additional estimates of fuel savings were prepared assuming that for all configurations the maximum boat speeds and operating hours are the same as that of the baseline configuration. In that case, the estimated yearly fuel savings for the stern flap increased to $19,993, and to $55,419 for the combined stern flap and new 6-bladed propeller configuration.

ECONOMIC ANALYSES

The Coast guard is proceeding with plans to retrofit all *ISLAND* Class patrol boats with the stern flaps. The prototype "first of series" stern flap had associated costs of $6,100 for "kit" manufacture, and about $7,500 for installation at a routine haul out availability. The total procurement cost for the first batch of thirty-three *ISLAND* Class stern flap kits was $64,839, ($54,160 for manufacture and $10,679 for packaging). This corresponds to a stern flap kit per unit cost of $1,965. With shipping, the total marginal stern flap retrofit cost at a routine availability is estimated to be on the order of $10,000. (Haul out fees are not included in the marginal costs as hauling is required for other routine purposes.) The non-recurring model test and stern flap design costs are less than $2,000 per boat.

The stern flap is estimated to have a yearly fuel savings of $16,946. The fuel savings will recover the investment cost within the first year. While the stern flap increases maximum speed, maximum range, it may also reduce engine maintenance due to a better match between the power demand curve and the engine operating envelope.

The new propeller will offer even greater improvements. The yearly fuel savings attributable to just the new 6-bladed propellers is $30,297. However, there are again additional savings due to reduced engine maintenance, reduced propeller maintenance, and improved habitability due to reduced propeller noise. These savings are difficult to quantify, but they may be very significant.

The cost of a pair of the new 6-bladed propellers is expected to be between $70,000 and $100,000. However, the existing propellers on many of the vessels are very old and may need replacement soon. In addition, there is only one (new) pair of spare fleet propellers left for the entire

Class. Thus, some replacement propellers will need to be purchased soon. Due to their increased weight and increased number of blades, the new 6-bladed propellers are expected to cost somewhat more than the old 5-bladed propellers, perhaps as much as 10 percent more. The non recurring cost for the new 6-bladed propellers is less than $1000 per boat. The payback period associated with just the propeller costs and benefits is dependent upon many assumptions of costs and savings. In the most conservative scenario, which assumes the full purchase cost of the propeller and assumes savings that accrue only through reduced fuel usage, the payback period will be on the order of three years.

With all 49 boats retrofitted with a stern flap and new propellers, the annual fuel saving is estimated to be about $2.3 Million per year. The engine maintenance benefits are not easily quantified, but can be substantial. Stern flap maintenance costs are negligible.

SUMMARY

The retrofit of the stern flap and new 6-bladed propellers will allow the *ISLAND* Class 110 WPB cutters to significantly reduce fuel usage, increase maximum speed, and allow the engines to operate much closer to, or within, their recommended design parameters. The reduced levels of cavitation with the new 6-bladed propellers is expected to reduce the noise in the aft state room, and reduce the propeller maintenance costs. The fuel used for propulsion will be reduced by about 10 percent. Details of these benefits are shown in Table 13.

Table 13. *ISLAND* Class 110 WPB performance summary

Configuration	Min-Op 144 L tons	Full Load 163 L tons
Baseline Ship		
Delivered Power (hP), available	5252	5134
Propeller RPM	809	778
Maximum Speed (knots)	30.0	27.1
Stern Flap		
Delivered Power (hP), available	5270	5166
Propeller RPM	813	786
Maximum Speed (knots)	30.4 (+0.4)	27.9 (+0.8)
Range Increase @18 Knots	4.4%	4.6%
Annual Fuel savings (gallons)	3115	8182
Stern Flap & New 6-Bladed Propeller		
Delivered Power (hP), available	4986	5244
Propeller RPM	824	820
Maximum Speed (knots)	30.8 (+0.8)	29.6 (+2.5)
Range Increase @18 Knots	12.2%	12.3%
Annual Fuel savings (gallons)	10220	21275

ACKNOWLEDGMENTS

The authors wish to thank all the professional, technical, and industrial staff at the David Taylor Model Basin, NSWCCD, who were involved in the execution of this program, and in particular; Scott Percival, who prepared the surface geometry prior to model manufacture; Jim Harshaw, who conducted the model hull surface inspection; Liam O'Connell, who was of great assistance in the model testing and data analysis; Jim Bailar and Han-ch'ing Wang, for their assistance with the propeller design; and Thad J. Michael, who detailed the final propeller geometry for manufacturing.

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Discussion

Ryan R. Young, Member

The views expressed here are those of the discusser, and not necessarily those of the U.S. Coast Guard or the Department of Transportation.

The authors have produced excellent results, and an excellent paper, with a good overall design approach. In my view, they have been judicious, economical, and conservative (a rare mix), in the choice of tools to apply to this problem.

I was deeply involved in the initial evaluation of the 110 ft WPB ("Engineering and Operational Characteristics of a 110 Ft Island Class Patrol Boat (WPB)," Ryan R. Young, USCG Research and Development Center, January 1987), and I recall vividly the spray characteristics. The USCGC *Farallon*, first of class, covered herself with spray from the foredeck all the way to the transom. I'm glad to see effective spray rails fitted forward. The lines plan just below Table 1 clearly shows the original spray rail starting further aft; my recollection is that it mostly just chopped the sheet flow and solid spray into smaller chunks, more easily carried aft by air flow! Is this also happening with the new forward spray rail on the USCGC *Jefferson Island*, or is the new rail effectively directing the spray away from the hull?

Spray rails are crucial to the design of effective hulls of this size and speed range, but there is very little helpful and useful information available to the designer. Joseph Koelbel's article on performance prediction in "Small Craft Engineering—Resistance, Propulsion, and Seakeeping," University of Michigan, College of Engineering, Department of Naval Architecture and Marine Engineering, Report #120, October 1971 is a good, if dated, starting point. Are the authors aware of more recent guidance on the design of spray rails?

A historical note: The first props for this class came straight from England, and were fitted with the root holes right from the start. Later U.S. cast props came without holes, but rapidly got them, either as a conscious modification (preferred!), or from severe cavitation damage.

I want to draw attention to an area your paper addresses that is so important I don't want readers to miss it. Patrol boats spend most of their time at cruise speed, and most of their fuel. Your new flaps and props produce substantial reductions in resistance and fuel consumption at the speeds where patrol boats actually patrol. Focusing on top speed only is easy to do, but does not increase either the effectiveness or economy of a patrol platform.

One of the reasons the hull form of the 110 ft WPBs, a linear descendent of the Rum Runners of the 1930s and the E-Boats of WWII, has persisted is that is has very good mid-range resistance, better than the first generation of Deep-Vee forms, while having excellent sea keeping in all but roll axis—which active stabilizers fix (at least if you're moving!).Further, in this crucial mid-range of speeds, the "semi-planing" condition, the analytical tools for resistance and appendage performance are not yet up to the task of gaining the incremental resistance improvements you've achieved. I suspect the shortcomings of the analytical tools (such as the Brown equations) apply equally to Deep-Vee forms as they do to the Round Bilge form of this now venerable (the first 110s were delivered around 1982, the prototypes were at least 20 years older!) Vosper design.

Allen Engle, Member

Approximately 12 years ago the U. S. Navy first investigated the concept of a stern flap as a means to improve ship efficiency. The prototype concept, as applied to the FFG 25, was shown to provide far greater efficiency gains full scale then what was indicated by model tests. Based on this success, plans were made to install the prototype design on all ships of the FFG 7 class. However, at the time, efforts to examine the feasibility of a stern flap to other ship classes was very limited. It is with this last point in mind that I would like to congratulate Messrs Karafiath and Cusanelli for the persistence in pursuing the application of stern flaps to a wide range of hull form concepts.

In addition, it is good to see that advanced CFD methods, unavailable to us when the stern flap concept was first proposed, can now be applied to help one understand the underlying hydrodynamics that are at work. It is with this in mind that I have some comments relating to scaling and stern flap selection.

Within the paper it is stated that there may be a strong Reynolds scaling effect present. As I recall when we were involved with the initial FFG 7 prototype investigations it was thought that surface tension, and by extension, Weber number effects might also come into play. The paper today, however, suggests that Reynolds scaling is the overriding factor. I would be curious to know, is Weber scaling still considered a contributor or have studies performed over the past decade eliminated this possibility? A related question that comes to mind is model size. The model that was tested was approximately 5.5m in length. Due to the significant differences between model and full scale results, can the authors comment on what would be a minimally acceptable scale ratio for testing stern flaps in a towing tank?

A final thought concerning scaling effects; in order to address the incompatibility of simultaneously accounting for both Froude and Reynolds scaling there has been some recent efforts to perform what is know as hybrid model testing (reference 1). The idea behind this concept is to scale a model using Froude scaling laws but to apply an external force to compensate for the forces present at model scale, during the actual test. Would the authors see any benefit to utilizing such model testing technique within this application or are the empirical adjustments alluded to in the paper considered adequate?

With regard to flap selection, the authors indicate that the selected flap must be optimized over the ship's entire operating speed range. Could the authors discuss what additional gains, if any, may be obtained if the stern flap could be made an adjustable flap, and hence have the angle of attack optimized for each speed.

A final question I have is related to measurement uncertainty. It is my understanding that experimental uncertainty is the result of both bias and precision errors. However, the text only addresses precision errors. Will future studies address bias as well?

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Authors' Closure

We thank all of the discussers for their comments and kind words with regard to our successful efforts to retrofit stern flaps on many USN and USCG ships, and to raise the design community's awareness of their benefits.

The following comments reply to some common themes raised by the discussers.

Model Testing: The history of the Island Class design is summarized in the Latas and McCarthey [1986] reference in our paper. We have not seen any public release model test data, but we have seen model test data on similar hull forms from the time period when the Island Class was designed. Many of these tests are with a model too small for accurate propulsion testing. With respect to the stern flap, we made a special effort to construct a large 5.5 m hull model in order to get good stern flap model test resistance data. Our previous studies reported in SNAME *Transactions*, Karafiath et al [1999] with three different size DDG 51 models indicated that such a large model is needed for defining stern flap performance. We suspect that for this case, the traditional 2 to 3 m model, normally tested for planing boats, would have led to an erroneous conclusion that the stern flap is not effective for saving fuel.

Installation Tolerance: Our experience with the stern flap installation on five different ship classes is that, with current shipyard practices, the flap can be installed within ±2 deg of the design angle. The performance of a uniform deviation from the design angle can be estimated from model test data that is usually collected at the time of the stern flap design. We have a proposal to evaluate the performance of a twist variation during a special model test series, where a stereolithographic rapid prototyping method will be used to manufacture a model of the 4.2 deg of twist on the flap, as-built, on the DDG 61. For comparison, while the average angle of the as-built stern flap on the USCG *Staten Island* (WPB 1345) was 1.5 deg greater trailing edge down than designed, the measured twist over the span was only 0.3 deg.

Hydrodynamic Computations: CFD computations have played an important role in understanding the various hydrodynamic flow features that contribute to stern flap performance. We have used some basic flow calculations to quantify the stern flap's contribution to wave resistance reduction and to afterbody resistance reduction. These calculations were for destroyer-sized vessels, where the stern flap caused only a minor trim change. The calculations are most useful when they are combined with experimental results that calibrate the calculation. For a planing hull, such as the Island Class, one would need a special flow code to handle the dynamic effects and the spray effects.

Surface Wake: Although the appearance of the flap effect on the surface wake of the Island Class is somewhat different than on the PC 13, there is a common characteristic, in that the rooster tail is moved further aft. Also, in both cases, the flap allows the flow to cleanly separate from the transom leaving a dry transom. The burbles and turbulent flow just behind the transom is eliminated or reduced, especially near hump speed. There were no wake wash measurements taken on this model and the impact of the stern flap on the farfield wave heights has not been measured. The flow observations on the model, and on the full scale, suggest that the biggest beneficial impact of the stern flap on the downstream wave size will be during the transit of the hump speed region. A with and without flap comparison of the measured model surface wake, behind a destroyer hull, is presented in our SNAME *Transactions* 1999 paper.

Design Issues: In order to achieve the full potential of the flap, it should be taken into account during the ship's initial design. The flap could affect the choice of engine if the flap performance allows a smaller size engine to be used. The flap will have a small effect on the design of the propeller, most probably the pitch would be adjusted slightly due to the lower resistance. In addition, the propeller inflow could change, especially on a planing hull, because of the decreased trim. In the case of a retrofit flap, where the vessel size and engine are fixed, it is critical to review the desired objectives of the flap retrofit. A flap designed for maximum speed improvement will have a different geometry from one designed to minimize fuel consumption. For the greatest decrease in fuel usage, one must tailor the design of the flap to the ship's speeds where the greatest amount of fuel is being used. Thus, the ship's expected usage pattern in terms of operating hours at various speeds and displacements is a necessary input to the design.

Propeller Design: The existing propeller experienced erosion damage on delivery as documented by Latas and McCarthey [1986]. The USCG approached NSWC for fixes to the problem that did not involve propeller replacement. An early perceived fix was the drilling of pressure relief holes in the root; however, in the long term these holes did not solve the problem. The original propeller could have been expected to perform better, but not as good as the performance achieved with our new propeller design, which was prepared with far superior propeller design methods than the commercial propeller design methods of the 1980s.

An Adjustable Flap: One can determine a schedule of optimum flap angles as a function of speed from the model tests, or for that matter, the angles could be determined during full-scale trials. The critical consideration with an adjustable flap is to ensure that there is no pressure leakage at the flap hinge line. Traditional technologies for achieving an adjustable flap involve hinges, seals, and powered actuators, all of which increase installation and maintenance costs. On the FFG 25 stern flap retrofit, the fixed flap reduced fuel usage by 4%, and an adjustable flap was estimated to provide an additional 1/2% reduction in fuel. An idea that is currently being explored is to have an adjustable flap, split at the ship's centerline, to enable independent actuation for assisting with ship roll control. Magneto-restructuring and other new technologies for changing the shape of metal are seen as an ideal application to adjustable stern flaps because of the elimination of the hinge sealing issue.

WPB Full-Scale Experience: The initial plan for fitting the stern flap on the WPB included pre- and post-flap ship powering standardization trials, with fully instrumented shafting for measuring torque. Budget and operational constraints allowed for the conduction of trials of limited scope only, without shaft torque instrumentation. GPS speed and RPM, for reciprocal runs, were measured for both the with and without flap cases, on the *Staten Island* (WPB 1345).However, during the post-flap trials, the WPB 1345 was 19 tons heavier than during the pre-flap trials, due to a full load of fuel. In both cases, the vessel had the current fleet propellers, not the new 6-bladed design. During the trials with the stern flap, the engines were able to develop an additional 70 RPM, and the combination of reduced resistance and increased engine power resulted in an increase in top speed. Using model test information as a guide, the ship data were adjusted to a common displacement, resulting in an approximately 2 knot increase in top speed. With the engine RPM restricted to that of the pre-flap case the speed increase is 1 knot. With the flap installed, the ship trim decrease is about 1 deg. The spray rail was observed to be working well, and the operators said that the vessel got up on a plane much more readily.

Hybrid Model Testing: *Mr. Engle*'s reference on the subject implies that the model test should be adjusted by a controlled external force to account for scale effects. In a limited sense, we already do this in self-propulsion testing, through the tow force which is applied to keep the trust loading on model and ship propeller the same. However, the tow force does not change the relatively thicker boundary layer on the model. We would like to do further research relating to stern flap performance scaling issues. In the meantime, we rely on our empirical full-scale and model-scale database of stern flap performance to adjust model test data for a more realistic assessment of stern flap performance. In addition to the ship-model database, our adjustment is guided by model tests with various sized geosym models, and by CFD computations that enhance our understanding of stern flap hydrodynamics.

We thank SNAME for the opportunity to present our stern flap results, and urge the ship design community to consider a stern flap as part of the initial design for many types of vessels.