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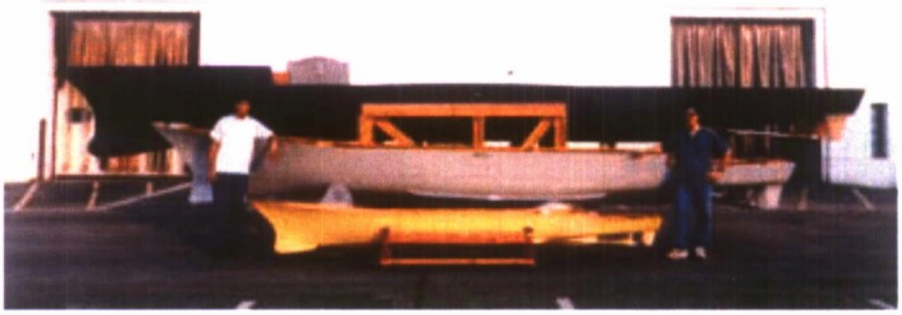
Scaling Effects on Stern Flap Performance
Progress Report

By
Dominic S. Cusanelli



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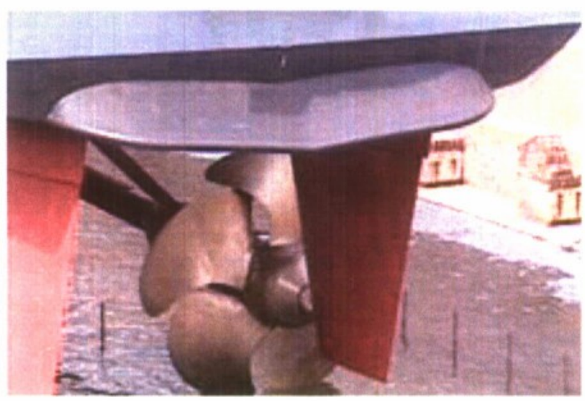

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14. ABSTRACT
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Comparison of stern flap trials results on *RAMAGE*, to that of a geosim model experiment series, was utilized for the refinement of techniques for extrapolation of model test data to full-scale performance. A practical technique, by which full-scale stern flap performance at sea could be projected from model-scale experimental data, is presented. An analysis tool for evaluating stern flap scaling effects, to be utilized with model-scale experimental results, to better project full-scale stern flap performance, was formulated. This formulation has several distinct advantages over its predecessor. Foremost, is the inclusion of the *RAMAGE* trials data in the updated version. In addition, the stern flap scale effects, as represented in this analysis tool, are dependant on not only the tested model scale ratio and speed range as before, but also on the magnitude of the model-scale performance relative to that of the study case.

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ABSTRACT

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ADMINISTRATIVE INFORMATION

This work was performed at the David Taylor Model Basin (DTMB), Carderock Division, Naval Surface Warfare Center (NSWCCD), Resistance and Powering Department, Code 5200. The DDG 61 Stern Flap Trials were funded by the Energy Plans and Policy Branch, OPNAV N420, through the Shipboard Energy R&D Office, NSWCCD Code 859, Sponsor R823. Continued stern flap scaling effects research was funded through the Stern Flap Dual Use Science & Technology initiative, sponsored by the Office of Naval Research, ONR 333.

INTRODUCTION

Through a great variety of model-scale and full-scale test programs, the U.S. Navy has shown that a small extension of the hull bottom surface aft of the transom, known as a stern flap, can improve the speed/power performance of many different types of ships; Karafiath, Cusanelli, and Lin [1]. While significant powering improvement is indicated through model-scale design experiments, the actual performance of full-scale prototype stern flaps have generally exceeded that of the model-scale predictions, especially at low speeds; Cusanelli [2]. This circumstance leads the designer to conclude, that as a consequence of the smaller scale, the flow conditions around the model stern flap are not truly representative of that on the ship.

The *ARLEIGH BURKE* (DDG 51) Class destroyer was chosen as the ship platform for the stern flap scaling investigation. The present study is a continuation of the investigation into the scaling effects involved in stern flap performance, with the intention of developing an appropriate method for extrapolating model test data to full-scale performance predictions.

Previously, model experiments were conducted on three different DDG 51 Class geometrically-similar models (referred to herein as "geosim" models), a 38 ft (11.6 m) scale ratio 12.866 model, a 24 ft (7.3 m) scale ratio 20.2609 model, and a 14 ft (4.3 m) scale ratio of 36.0 model. It was determined through these model experiments, and associated computational fluid dynamics (CFD) calculations, that stern flap performance did improve as model size increased, and an initial method of model-scale to full-scale extrapolation was developed; Cusanelli, Percival, and Lin [3]. A full-scale stern flap trial on a DDG 51 destroyer had yet to be conducted, and therefore, ship/model comparisons were made with available full-scale stern flap trials data on various other U.S. Navy classes.

Since the time of the initial stern flap scaling investigation, the U.S. Navy has installed stern flaps on a number of *ARLEIGH BURKE* Class destroyers, one of which is presented as Fig. 1. In December, 2000, pre- and post-stern flap performance evaluation trials were completed on the USS *RAMAGE* (DDG 61); Cusanelli, Brodie, and Chirichella [4]. Once again, the performance of the full-scale prototype stern flap exceeded that of the model-scale prediction. The *RAMAGE* full-scale stern flap trials provides invaluable information towards the continuation of the stern flap scale effects investigation.

Fig 1. Photograph of completed stern flap installation on USS *CURTIS WILBUR* (DDG 54)

Concept Background and Descriptions

The stern flap retrofit to *RAMAGE* was designed to be installed behind a stern wedge, which was inlayed into the transom plating of all *ARLEIGH BURKE* (DDG 51) Flight I/II hulls at the time of their initial construction. This particular stern flap design condition distinguishes it from all previous full-scale tested U.S. Navy combatant stern flaps. Stern wedges and stern flaps are very similar, and also operate along similar principles. While a stern flap is an extension of the hull bottom surface which effectively lengthens the ship aft of the transom, wedges are located completely under the hull beneath the transom (and generally inlayed into the transom plating). The DDG 51 Flight I/II stern flap design program, initiated in 1996, provided the first model-test confirmation that a stern flap, installed in addition to the hull's existing wedge, could further reduce the powering requirements; Cusanelli [5]. The combination of the two concepts, patented as the integrated wedge-flap [6], initiates forward of the transom under the hull (wedge portion) and extends aft of the transom (flap portion).

The stern flap portion alone of the integrated wedge-flap, as a retrofit, results in the stern flap performance benefits presented herein on *RAMAGE* (DDG 61), and extended to the *ARLEIGH BURKE* Flight I/II Class, as a whole. The *RAMAGE* stern flap performance, solely, will be utilized for the comparison to the model experiments, and for the continued evaluation of stern flap scaling effects.

The available DDG 51 Class full-scale trials and model-scale stern flap configurations, Table 1, provide for an invaluable, but not an entirely complete, data set for the stern flap scaling effects investigation. Each line entry of Table 1 represents both with and without flap comparative tests. The *RAMAGE* stern flap, 4.7 ft chord, 24 ft span, and 13° trailing edge down (TED) was installed behind the fleet 3.2 ft chord, 13° TED wedge. This stern flap configuration was tested on only the mid-sized Model 5513. The stern flap design tested on all three of the DDG 51 models during the geosim series had the similar chord length and span, but with an angle of 10° TED, and no stern wedge installed.

Table 1. DDG 51 Class full-scale trials and model-scale experiments available for the present stern flap scaling effects evaluation

Platform	Size	Displ. (tons)	Transom Configuration					Test(s) Conducted
			Wedge		Stern Flap			
			Chord	Angle	Chord	Span	Angle	
RAMAGE (DDG 61)	Full-Scale	8680	3.2'	13°	4.7'	24'	13°	Speed/Power Trials
Model 5513	1:20.261	8900	3.2'	13°	4.7'	24'	13°	Resistance & Power
Model 5488	1:12.866	8900	*(none)*		4.6'	24'	10°	Resistance
Model 5513	1:20.261	8900	*(none)*		4.6'	24'	10°	Resistance
Model 9141	1:36.0	8900	*(none)*		4.6'	24'	10°	Resistance

At the time of the initial stern flap scaling investigation [3], there was no assurance that full-scale stern flap evaluation trials would be conducted on a DDG 51 destroyer. Therefore, the geosim model hulls and model-scale stern flaps were configured so that the most accurate comparisons could be made to available trials data on U.S. Navy combatants, all of which had 10° TED flaps and no wedges. It was also felt that the removal of the DDG 51 transom wedge would better serve to isolate the performance of the stern flap at model-scale.

In order to determine meaningful stern flap scaling effects between the speed/power data of the *RAMAGE* stern flap trials (with wedge), and the geosim model test series stern flap configuration (no wedge) resistance data, several parallel comparisons must first be made through the Model 5513 resistance and powering data and configurations common to both sets.

RAMAGE FULL-SCALE TRIALS

The USS *RAMAGE* (DDG 61) was assigned by Surface Fleet Atlantic (SURFLANT) as a test ship for the stern flap evaluation. A baseline speed/power trial on *RAMAGE* was accomplished in June 2000. The stern flap was installed, at pier-side, using a cofferdam, during the period of 2-27 Oct. 2000, and the stern flap speed/power trial was completed in December 2000. Comparisons were made between the pre- and post-flap trials, and stern flap performance was determined. Complete descriptions of the pre- and post-flap trials conducted on *RAMAGE*, including performance comparisons and additional photographs, are presented in Reference 4. The reported trials data are reproduced in Appendix A, Tables A1 and A2. A summary of the full-scale stern flap performance on *RAMAGE* is presented in Table 2. Data presented in Table 2 are representative of ship trials conditions of 8680 tons displacement and clean hull, equivalent to that of the stern flap trial.

Table 2. Stern flap* performance from trials conducted on USS *RAMAGE* (DDG 61)

Ship Speed (knots)	**Baseline** Total Shaft Power (hP)	**Stern Flap** * Total Shaft Power (hp)	Stern Flap* Power Reduction (%)
12	2650	2500	-5.6
14	5189	4600	-11.3
16	7443	6300	-15.4
18	10,628	9,090	-14.5
20	14,844	12,850	-13.4
22	20,021	17,590	-12.1
24	26,584	23,650	-11.0
26	36,365	31,940	-12.2
28	52,311	47,750	-8.7
30	81,365	73,640	-9.5
30.9	100,000	85,950	-14.1
31.8	N/A	100,000	N/A

*Stern Flap 13° installed behind transom wedge

The stern flap evaluation trials on *RAMAGE* indicated that the stern flap reduced the ship power-at-speed by 5.6% to 15.4%. It appeared to have virtually no negative impact on ship operations on a speed/power basis. The stern flap also increased the top speed of the *RAMAGE* by 0.9 knots. However, in order to attain full propulsion plant power, and achieve the maximum 31.8 speed with flap installed, it was necessary to increase the propeller pitch by approximately 5% over design. The stern flap data also shows a substantial power reduction of more than 14,000 hP (14.1%), at the 30.9 knot maximum ship speed achieved by the baseline ship. Trials indicate that the installation of a stern flap, on a DDG 51 Class Flight I/II destroyer, will result in a net annual fuel savings of 4726 barrels (7.5% reduction) per ship. The annual fuel cost savings will be $195,000 per ship.

MODEL 5513 DESIGN EXPERIMENTS

Experiments were conducted on Model 5513 to evaluate the installation of a stern flap, in addition to the transom wedge, on the DDG 51 Class Flight I/II destroyers [5]. This model-scale stern flap design & optimization program was the initial assessment of the integrated wedge-flap design. Model 5513 was ballasted to the reported class representative ship displacement of 8900 tons, even keel, for the stern flap experiments. The *RAMAGE*, at the time of the stern flap trials, was 8680 tons displacement.

Several stern flap designs, varying in chord length from 0.5% to 1.0% of the ship LBP, and angles from 3° to 17° trailing edge down (TED) relative to the local centerline buttock slope (run), were evaluated behind the DDG 51 fleet transom wedge. The fleet wedge, designed to be an integral part of the hull, has a chord length of 0.68% LBP and a nominal centerline angle of 13°. A complete description of the Model 5513 test series, including details of tested flap geometry, additional photographs, and all experimental results, are presented in Reference 5.

The stern flap selected had the following full-scale dimensions: chord length of 4.7 ft (1.0% LBP), an angle of 13° TED (parallel to the 13° centerline angle of the fleet wedge), and a span of 24 ft across the transom. This stern flap configuration is the same as that installed on *RAMAGE*. The reported model-scale powering data, including still air drag (to be comparable to trials conditions), for the baseline and selected stern flap configurations, are reproduced in Appendix A, Tables A3 and A4, and are summarized in Table 3. The stern flap portion (alone) of the integrated wedge-flap results in the change in performance presented in Table 3.

Table 3. Model-scale stern flap* performance on DDG 51 Class

Ship Speed (knots)	**Baseline** Total Shaft Power (hP)	**Stern Flap** * Total Shaft Power (hp)	Stern Flap* Power Reduction (%)
10	1473	1494	+1.4
12	2629	2634	+0.2
14	4240	4212	-0.7
16	6391	6319	-1.1
18	9336	9086	-2.7
20	13,398	12,895	-3.8
22	19,236	18,353	-4.6
24	25,699	24,169	-6.0
26	34,482	32,541	-5.6
28	51,061	48,236	-5.5
30	74,689	70,034	-6.2
31.8^	100,000	93,597	-6.4
32.2^	N/A	100,000	N/A

*Stern Flap 13° installed behind transom wedge. Configuration nominally equivalent to *RAMAGE*.

^Maximum speeds are higher at model-scale, because propeller cavitation is not present.

The model-scale stern flap experiments indicated a maximum stern flap power-at-speed reduction of 6.4%, and an increase in the top speed of 0.4 knots. The model-scale experiments also indicated that at speeds of 12 knots and below, the stern flap would result in an increase in ship delivered power. This low speed powering penalty has not been measured in any of the full-scale stern flap applications, and is now believed to be a model-scale phenomena.

<u>PERFORMANCE COMPARISON, *RAMAGE* VS. MODEL 5513</u>

The *RAMAGE* and Model 5513 stern flap geometry is nominally equivalent, however, some small differences were present due to ship construction tolerances. The stern flap evaluation trials on *RAMAGE* indicated that the stern flap reduced the ship power, and increased the ship top speed, to a greater extent than that projected from the model experiments. A ship versus model comparison of the stern flap performance ratio is presented in Fig. 2. The performance ratio is defined by the delivered power (PD) for the ship with the stern flap installed divided by the PD for the baseline (no flap) ship. A value below 1.0 indicates a power reduction due to the stern flap. The magnitude of the model-to-ship stern flap scale effect is indicated by the yellow shaded region in Fig. 2. As has been indicated in all other stern flap programs to date, the greatest performance differences between model and full scale appear to be at low speed. In the case of the *RAMAGE*, the model-scale tests under-predicted the stern flap performance in the range of 12% at speeds of 14 to 18 knots, but only by approximately 2% when approaching top speed.

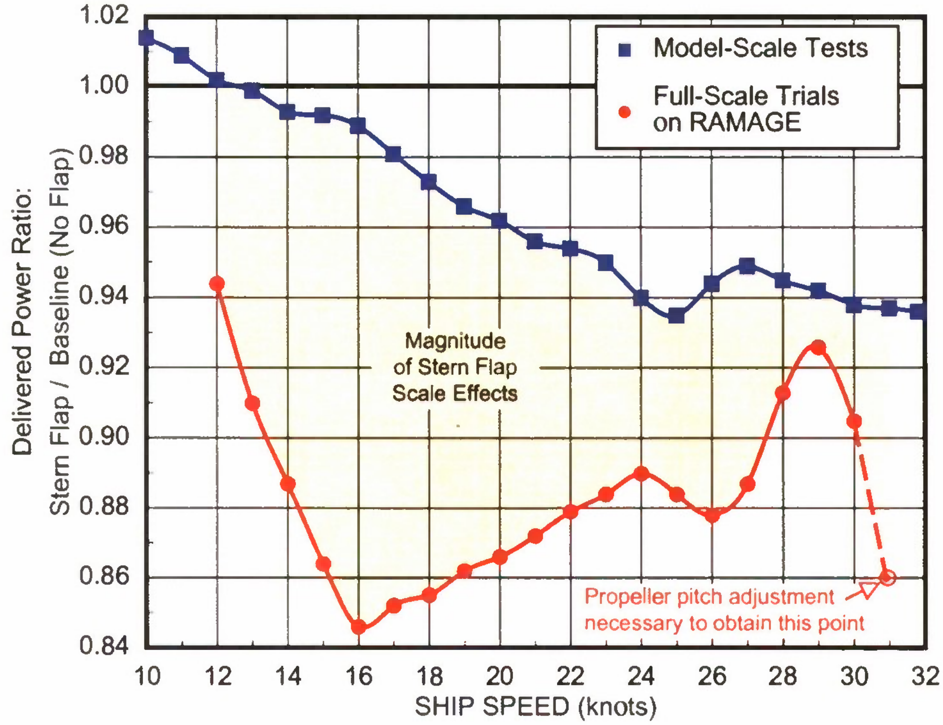
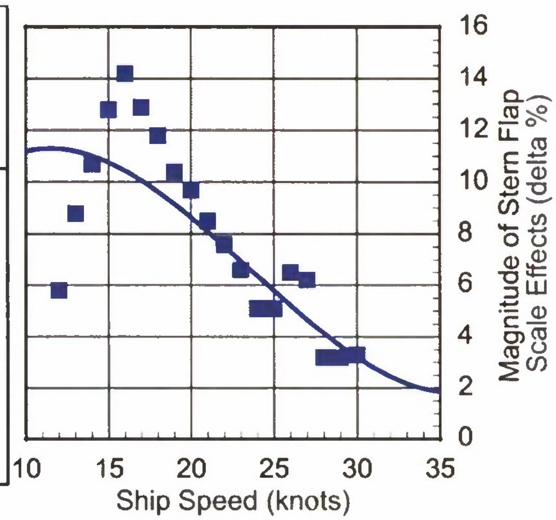


Fig. 2. Stern flap performance ratio on USS *RAMAGE* (DDG 61) compared to that of model-scale experiments

Table. 4. Differences in stern flap performance, full-scale trials versus model-scale experiments

Ship Speed (knots)	Stern Flap Effect on Power: USS RAMAGE **Full-Scale** Shaft Power (%)	Stern Flap Effect on Power: Model 5513 **Model-Scale** Shaft Power (%)	Magnitude of Stern Flap Scale Effects (Δ %)
12	-5.6	+0.2	5.8
14	-11.3	-0.7	10.7
16	-15.4	-1.1	14.2
18	-14.5	-2.7	11.8
20	-13.4	-3.8	9.7
22	-12.1	-4.6	7.6
24	-11.0	-6.0	5.1
26	-12.2	-5.6	6.5
28	-8.7	-5.5	3.2
30	-9.5	-6.2	3.3



The magnitude of the model-to-ship stern flap scale effect is summarized in Table 4 with an associated graphic representation. A very simplified 3rd order polynomial curve is shown through the scale effect values.

GEOSIM MODEL EXPERIMENTAL SERIES

The DDG 51 Class destroyer was chosen as the model test platform because three greatly different sized geosim models exist for this class, as shown in Fig. 3. The largest, Model 5488 (black), was built at DTMB to a scale ratio 12.866, with overall length of 38 ft. The mid-sized Model 5513 (gray), was built at DTMB, scale ratio 20.2609, and is 24 ft in length. The smallest, Model 9141 (yellow), has a scale ratio of 36.0, and length of 14 ft. Model 9141 was built by the U.S. Naval Academy, Annapolis. The models were similarly appended, with/without the model-scale stern flap, at the displacement of 8900 tons, even keel. Complete descriptions and comparisons of all three geosim models, additional photographs, and experimental results, are presented in Reference 3.

The geosim series stern flap had full-scale dimensions of 4.6 ft chord, 24 ft span, and angle of 10° TED. For both the baseline and stern flap configurations, the DDG 51 Flight I/II transom wedge was removed. At the time of the initial stern flap scaling investigation, there was no assurance that full-scale stern flap evaluation trials would be conducted on a DDG 51 destroyer. Therefore, the model hulls and model-scale stern flaps were configured so that the most accurate comparisons could be made to available trials data on U.S. Navy combatants. Previous stern flap trials had been conducted on the *A.W. RADFORD* (DD 968) and the *COPELAND* (FFG 25). Both of these prototype stern flaps had chord lengths of 1.0% LWL, angles of 10° TED, and did not include wedges in the associated hull designs. It was also felt that the removal of the DDG 51 transom wedge would better serve to isolate the performance of the stern flap at model-scale.

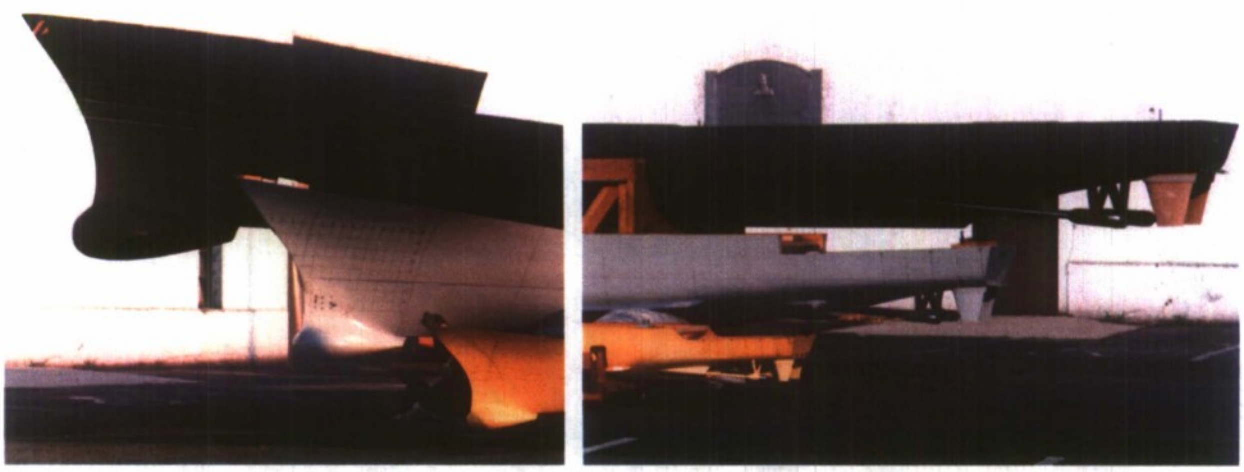


Fig 3. Bow and stern photographs of the three geosim DDG 51 Models, 5488 (black), 5513 (gray), and 9141 (yellow)

During the geosim model series, only resistance experiments (for predictions of effective power) were conducted. A summary of the effective powers for baseline and stern flap configurations, from the DDG 51 geosim model series, is presented in Table 5. The performance of the stern flap at model-scale, that is, the ability of the stern flap to reduce ship effective power, increased with increasing model size. Essentially the larger the model, the better the stern flap performance. The geosim models also indicated that the "cross-over" speed, i.e. the speed where the stern flap first begins to reduce ship resistance, decreased with increasing hull size, indicated by **bold-face** in Table 5. Again, the low speed powering penalty has not been measured in any of the full-scale applications, and is now believed to be a model-scale phenomena.

Table 5. Model-scale stern flap* performances from DDG 51 geosim model series

	Large Model 5488			Mid-Size Model 5513			Small Model 9141		
Speed (knots)	Baseline PE (hP)	Stern Flap* PE (hP)	Effect (%)	Baseline PE (hP)	Stern Flap* PE (hP)	Effect (%)	Baseline PE (hP)	Stern Flap* PE (hP)	Effect (%)
10	972	993	+2.1	979	1006	+2.7	1074	1133	+5.5
12	1725	1753	+1.6	1740	1777	+2.1	1868	1952	+4.5
14	2837	2837	0.0	2838	2867	+1.0	2991	3074	+2.8
16	4347	4289	**-1.3**	4321	4334	+0.3	4501	4557	+1.2
18	6438	6273	-2.6	6299	6229	**-1.1**	6500	6500	0.0
20	9549	9149	-4.2	9080	8848	-2.6	9319	9179	**-1.5**
22	13970	13245	-5.2	13011	12495	-4.0	13559	13172	-2.9
24	18936	17837	-5.8	17550	16576	-5.5	18774	18083	-3.7
26	25264	23781	-5.9	23598	22231	-5.8	25261	24194	-4.2
28	36390	34496	-5.2	34096	32338	-5.2	36192	34752	-4.0
30	53248	50615	-4.9	49743	47227	-5.1	52660	50284	-4.5
32	73923	70053	-5.2	68668	65048	-5.3	73084	69561	-4.8

*Stern Flap 10° with transom wedge removed.

PERFORMANCE COMPARISON, FULL-SCALE VS. GEOSIM MODELS

In order to determine meaningful stern flap scaling effects between the speed/power data of the *RAMAGE* stern flap trials (with wedge), and the geosim model test series stern flap configuration (no wedge) resistance data, several parallel comparisons must first be made through the Model 5513 resistance and powering data and configurations common to both sets.

Stern flap performance on *RAMAGE* was based on trials data of ship total delivered power (PD). From the DDG 51 geosim model series, only resistance (effective power) was determined. There is no technique for determining ship effective power from full-scale trials data. However, delivered power can be determined, fairly accurately, from model-scale effective power, if previous resistance and powering experiments have been conducted. Baseline and stern flap resistance and powering experiments were conducted on Model 5513 with 13° stern flap, Reference 5. The Model 5513 propeller-hull interaction coefficients were utilized, with the respective geosim model series effective powers, to generate geosim model powering data, with/without stern flap. The resultant powering data is presented in Appendix A, Tables A5-A11.

Full-scale performance for a DDG 51 with no wedge and 10° stern flap, based on the *RAMAGE* trials, was then estimated. The magnitude of the 13° stern flap *RAMAGE* - to - Model 5513 scaling effects, Table 3, was applied to the 10° stern flap delivered power performance determined on Model 5513, in order to estimate the full-scale 10° stern flap performance. Details of this analysis are presented in Appendix A, Table A12. Table 6 and Figure 4 present the comparison of stern flap powering performance, based on geosim model series and full-scale trials. The comparison is again in the form of the stern flap performance ratio, where a value below 1.0 indicates a power reduction.

Table 6. DDG 51 stern flap performances, geosim model series and full-scale trials, all representing an equivalent 10° stern flap configuration*

		Geosim Models		
Speed (knots)	**Full Scale** PD (%)	**Large** PD (%)	**Mid-Size** PD (%)	**Small** PD (%)
10	-9.0	+1.4	+2.0	+4.8
12	-9.7	+0.8	+1.3	+3.8
14	-10.7	-0.8	+0.3	+2.1
16	-11.0	-2.2	-0.5	+0.4
18	-11.8	-3.6	-2.1	-1.0
20	-12.3	-5.4	-3.7	-2.6
22	-12.9	-6.7	-5.4	-4.2
24	-13.6	-7.6	-7.2	-5.4
26	-12.9	-7.8	-7.7	-6.1
28	-11.4	-7.4	-7.3	-6.0
30	-10.7	-7.4	-7.5	-6.9
32	*-10.2*	-7.8	-7.8	-7.3

*Full-scale performance based on scale effect determined from *RAMAGE* 13° flap trials applied to 10° flap model-test data. Model-scale performance based on geosim model series resistance experiments with propeller-hull interaction coefficients determined from Model 5513 powering experiments.

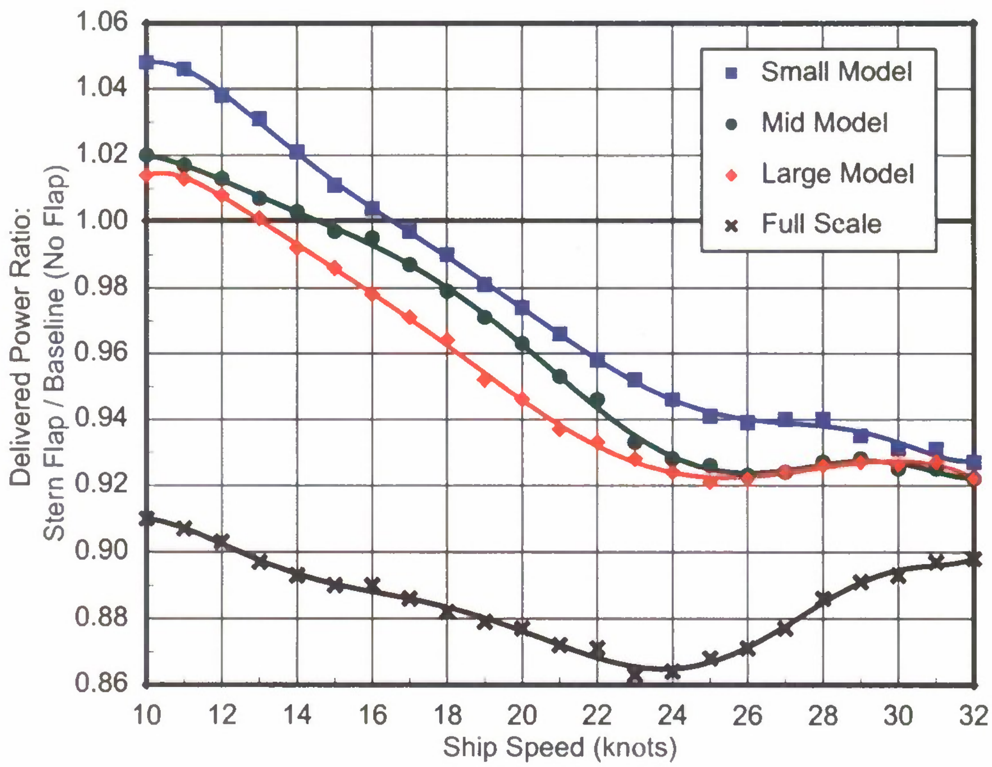


Fig 4. DDG 51, stern flap performance ratios, geosim model series and adjusted full-scale data, all representing an equivalent 10° stern flap configuration

A comparison of the stern flap performance, evaluated as percent change in delivered power due to the stern flap, based on platform scale, is presented in Fig. 5. The data has been separated into seven speed sequences, based on Froude Number (F_N) increments of 0.5, to make it more useful for a parametric evaluation. The data of Fig. 5 were then normalized by the full-scale performance at each of the seven speeds, and presented as the stern flap performance adjustment factor, in Fig. 6. This factor appraises the relative stern flap powering performance, model-scale versus full-scale. The data falls into a clear family of curves, showing that stern flap powering performance (i.e. the magnitude of the stern flap reduction in delivered power) improves significantly with increasing platform size. Also, the lower speed model-scale data exhibits considerably greater performance differences versus full-scale than at the higher speeds. For all speeds, as model scale ratio is increased (model size decreased), the stern flap powering rapidly attains a fixed performance level, which remains fairly constant between model scale ratios of 15 through 30. The data indicate that for model scale ratios greater than 30, the accuracy to which stern flap powering performance can be predicted diminishes rapidly.

Qualitative comparisons of the localized flow patterns around the transoms of the three DDG 51 models also indicate substantial variations across model scales, as depicted in Appendix B, Figure B1. As model size is increased, the model wake becomes visually more like that of a full-scale ship wake, it is more turbulent, depicts better eddy-making, and it contains a greater concentration of whitewater. As a generalization, the transom flow patterns exhibited on the larger model, are not reproduced until a speed 2 ~ 4 knots higher on the mid-size model, with an additional 3 ~ 5 knot higher speed increment necessary for the small model.

Visual evidence, as to the scaling differences between the model sizes, is best depicted at a speed of 22 knots, which exemplifies some of the characteristic differences between the local transom flows. The wake of the larger Models 5488 and 5513 appear to contain reasonable amounts of whitewater at 22 knots, and in fact, for speeds as low as 14 knots. To the contrary, the small Model 9141 wake seems to contain little whitewater until speeds above 22 knots.

The three models show significant differences in transom flow "breakaway" speed (speed for clean unattached transom flow). The transom breakaway speed for the baseline configuration (no stern flap), for large model was approximately 22 knots, for the mid-size model was approximately 30 knots, while for the small model breakaway was (unrealistically) never attained. With the stern flap installed, the transom breakaway speed for large and mid-size models were 20 and 24 knots respectively, while for the small model breakaway was again not achieved until above 32 knots. These differences in model scale transom flow breakaway speeds gain even greater significance when compared to the full scale breakaway speeds which were observed during the stern flap evaluation trials to be as low as 16 ~ 18 knots when the stern flap was installed, and 22 ~ 24 knots for the baseline configuration.

At 22 knots, with stern flap installed on large Model 5488, the flow has detached from the transom, and there is little evidence of any rotational vortices which were present at lower speeds. The mid-size Model 5513 still exhibits some attached flow rolling back over the center third of the flap, (flow in transition), and contains strong rotational vortices. For small Model 9141, the flow is fully attached across the entire transom, and the rotational vortices are just beginning to form.

The stern flap effects the transom flow as follows. The transverse width of the stern wave pattern was significantly reduced. For the baseline case, the stern waves widen rapidly as they move aft of the transom, whereas, the stern flap causes a considerable "neck down", or reduction in width, prior to the waves becoming wider moving aft. The total area of turbulence and whitewater is reduced. The flow patterns suggest that the stern flap's increase in the hydrodynamic length of the ship is greater than the chord length of the flap itself. Transom flow breakaway speeds were reduced 6 to 8 knots by the flap.

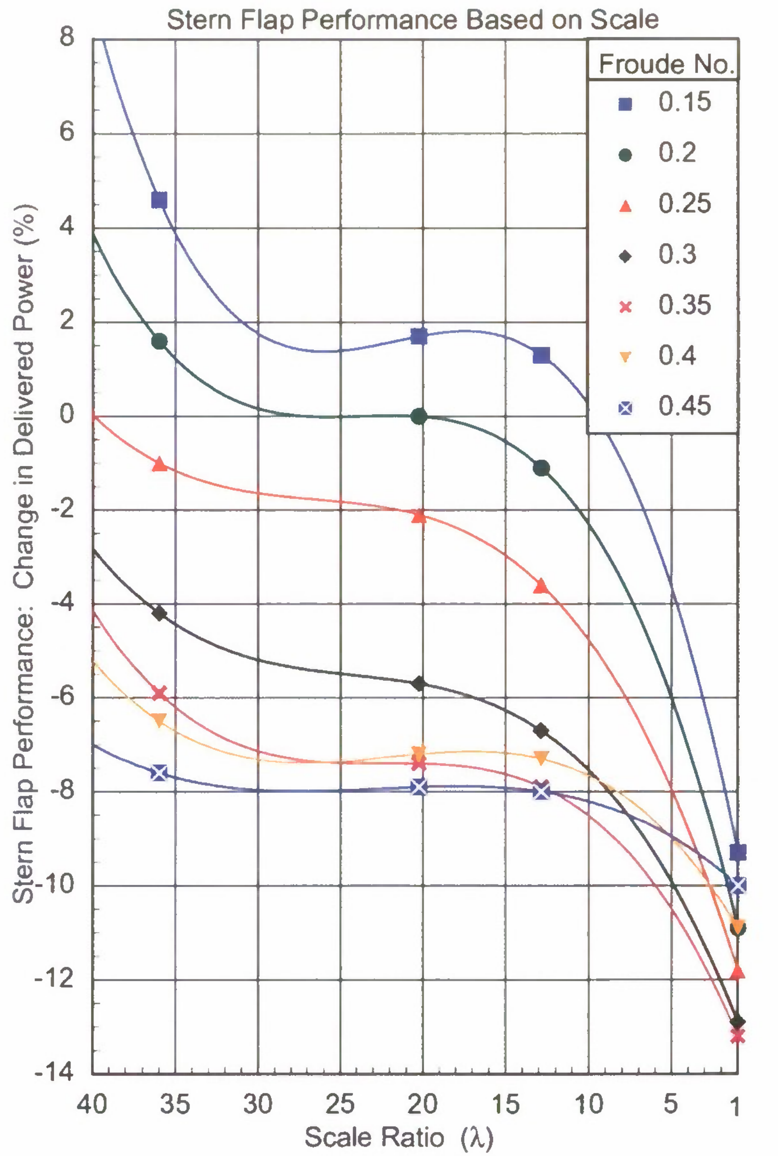


Fig. 5. Stern flap performance, evaluated as change in delivered power, based on platform scale, DDG 51, 10° stern flap

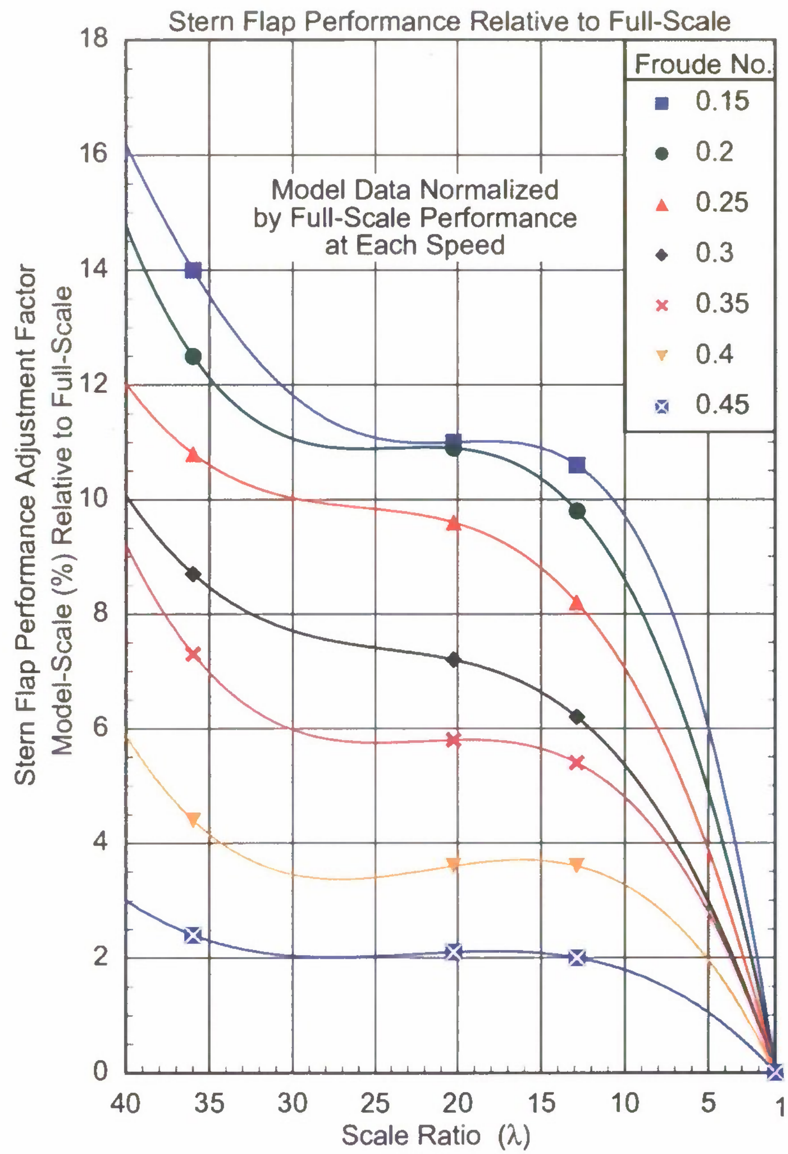


Fig. 6. Stern flap performance adjustment factor, model-scale relative to full-scale, DDG 51, 10° stern flap

GUIDANCE FOR PROJECTING FULL-SCALE STERN FLAP PERFORMANCE

The objective of this stern flap scale effects investigation has always been the formulation of a practical technique by which full-scale stern flap performance at sea could be projected from model-scale experimental data.

Many different extrapolation approaches and plotting methods were examined in the initial research [5]. The concept of a single graphic "analysis tool" was developed, which, when grouped by speed increments, could indicate the additional improvement necessary to be applied to stern flap model test data in order to project full scale performance. This technique still appears to be the best means of accounting for the scaling effects, however, through repeated uses on many subsequent model-scale stern flap test series, one disadvantage became apparent. This initial analysis tool proved reasonable for projecting full-scale stern flap performance on combatant vessels, such as the DDG 51 from which it was developed. However, the suggested model-scale to full-scale performance improvements appeared to be too large in magnitude to be practical for application to hulls where the overall stern flap performance was not as beneficial as that on combatants.

In the combatant applications, the model-scale stern flap delivered power reductions, over the targeted speeds, ranges from about 6% to as much as 10%. On smaller hulls such as planing or semi-planing craft, or on larger hulls such as amphibious, sea lift, and carriers, where the objective of the stern flap design could be greatly different from that of a combatant, the model-scale stern flap delivered power reductions were frequently in the range of only 2% to 4%. It was apparent that the application of the stern flap scaling effects developed for the combatant cases, to stern flap applications that had only a fraction of the comparable model-scale performance effect, was not justified.

It was necessary to develop a modified scale effect analysis tool, that accounted for the magnitude of the model-scale power reduction (model-scale stern flap performance). The applied stern flap scale effect should be dependant on not only on the tested model scale ratio and speed range, but also on the model-scale performance in comparison to that on the DDG 51 from which the scaling data was developed (the stern flap performance adjustment factor). In order to do this, the stern flap delivered power performance of each of the geosim models was normalized by its peak performance (defined as maximum power reduction) within the targeted speed range. For the DDG 51 large, mid-sized, and small geosim models, the peak performances were 7.9, 7.7, and 6.1 percent power reductions, respectively.

The stern flap powering data, re-analyzed by the aforementioned method, is presented as the "stern flap scaling multiplier" in Fig. 7. The model-scale and full-scale stern flap data, presented in this way, form a family of curves with, effectively, values on the Fig. 7 ordinate (y-axis) of stern flap scaling effects as multipliers of the peak recorded model-scale performance. Figure 7 represents the updated analysis tool for evaluating stern flap scaling effects.

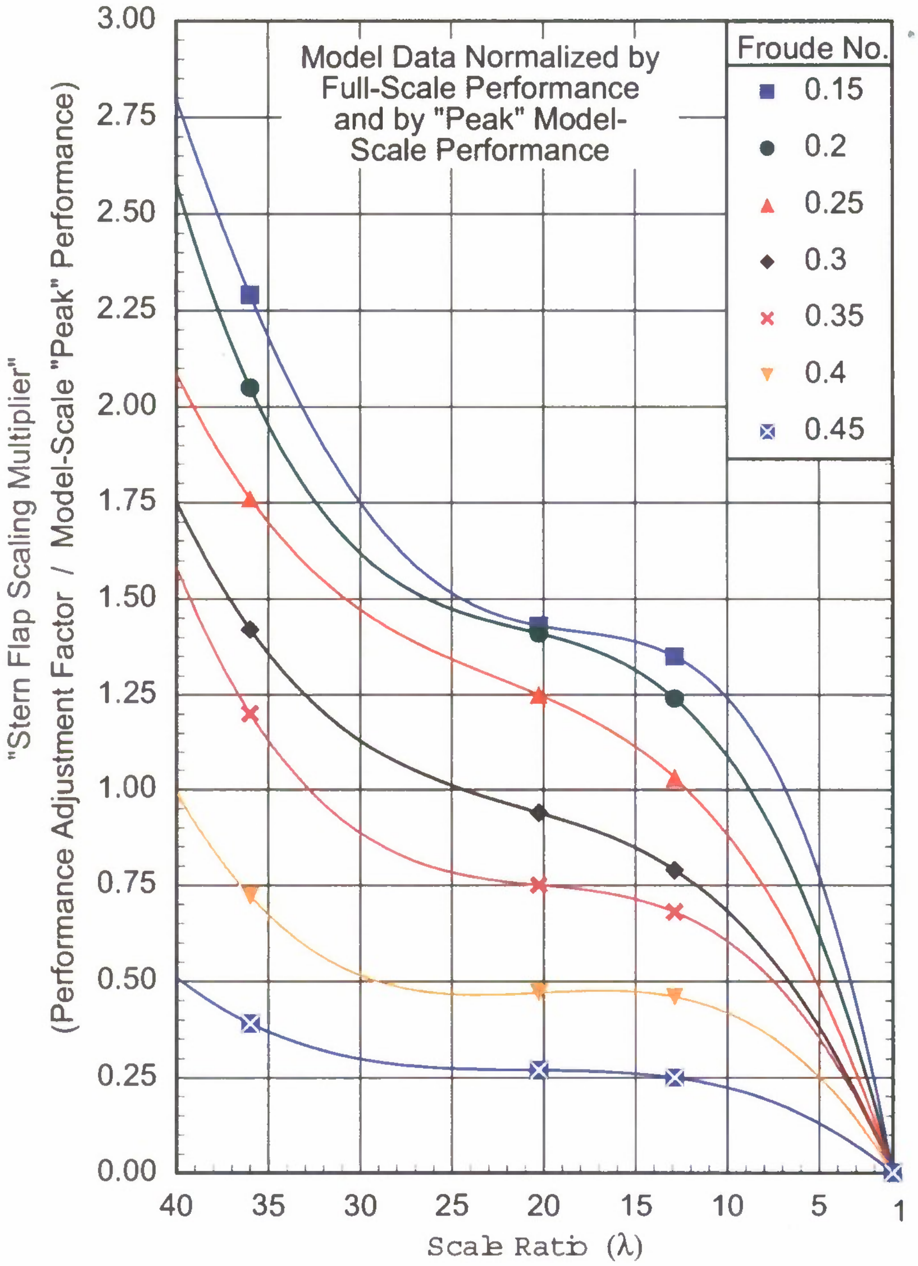


Fig 7. Stern Flap Scaling Multiplier: Analysis tool for evaluating stern flap scaling effects. (Based on DDG 51 scaling study with 10° stern flap.)

The proposed technique by which to utilize the stern flap scaling multiplier and analysis tool is presented in Table 7. The model-scale data presented in Table 2 of this report, for the Model 5513 DDG 51 Flight I/II stern flap (chord length 1.0% LBP, angle of 13° TED, installed behind the fleet wedge), will be utilized in the following example.

Proposed technique for scaling model stern flap data to full-scale, referring to Table 7:

- Model-scale speeds are converted to F_N, Column A. F_N in increments of 0.5 can be selected so that the stern flap scaling multipliers can be read directly off the curves of Fig. 7.
- Values of the stern flap scaling multipliers on the ordinate (y-axis) are determined for each F_N, at the scale ratio of Model 5513, $\lambda = 20.2609$ on the abscissa (x-axis), Column B.
- The model-scale experimental stern flap performance data is recorded in Column C.
- Model-scale stern flap performance "peak" (maximum delivered power reduction) is recorded in Column D. The peak performance was chosen at $F_N = 0.35$ (25 knots). It is recommended to utilize the stern flap peak performance within the target speed range for the stern flap design, rather than performance at either the high or low ends of the ship's speed range, where the stern flap may exhibit even greater power reduction.
- The estimate of the beneficial stern flap scaling effect, Column E, is determined by multiplying the model scale peak performance (Column D) by the scaling multipliers (Column B).
- The projected full-scale stern flap performance, Column F, is then determined by increasing the model-scale delivered power reduction (Column C) by the amount indicated for the scaling effect (Column E).

Table 7. DDG 51 model-scale stern flap performance adjusted for scaling effects by proposed technique, and resultant full-scale projected performance

Column A	Column B	Column C	Column D	Column E	Column F
	λ = 20.2609	Measured	25 knots		Projected
	Model 5513 Stern Flap Scaling Multiplier	Model-Scale Stern Flap Performance	Model-Scale Flap "Peak" Performance	Beneficial Stern Flap Scaling Effect	Full-Scale Stern Flap Performance
Fn	(Fig. 7)	(%)	(%)	(%)	(%)
0.15	1.43	+0.9	-6.5	-9.3	-8.4
0.20	1.41	-0.8	-6.5	-9.2	-9.9
0.25	1.25	-2.7	-6.5	-8.1	-10.8
0.30	0.94	-4.6	-6.5	-6.1	-10.7
0.35	0.75	-6.5	-6.5	-4.9	-11.3
0.40	0.47	-5.8	-6.5	-3.1	-8.9
0.45	0.27	-6.4	-6.5	-1.8	-8.1

- The full-scale stern flap delivered power would be estimated by reducing the baseline delivered power by the percentage amount indicated by the projected full-scale stern flap performance (Column F).

The scaling effects indicated by the proposed technique, Table 7, were then applied to the DDG 51 stern flap application, (1% chord at 13° TED installed behind the fleet wedge), for which there exists both Model 5513 data and full-scale data on *RAMAGE*. Figure 8 presents the stern flap performance in ship trials, as compared to original model-scale performance, and the new model projection accounting for scale effects. Of course, this represents an idealized case for the stern flap scaling effects correction, since the basis of its development was the 5513 model-scale versus *RAMAGE* data. The simplification of the ship/model flap performance comparison data, to the single 3rd order polynomial presented in the Table 3 graphic, smoothes out the determined "projected" full-scale performance with scale effect data of Table 7 and Fig. 8. The correlation between the full-scale *RAMAGE* trials data and that of the projected data (model plus scale effect), is far better than that of the original model-scale data. Even though the new model plus scaling projection does not precisely emulate the *RAMAGE* data, the time-averaged delivered power performances, when summed across the entire speed range, would now become more equivalent.

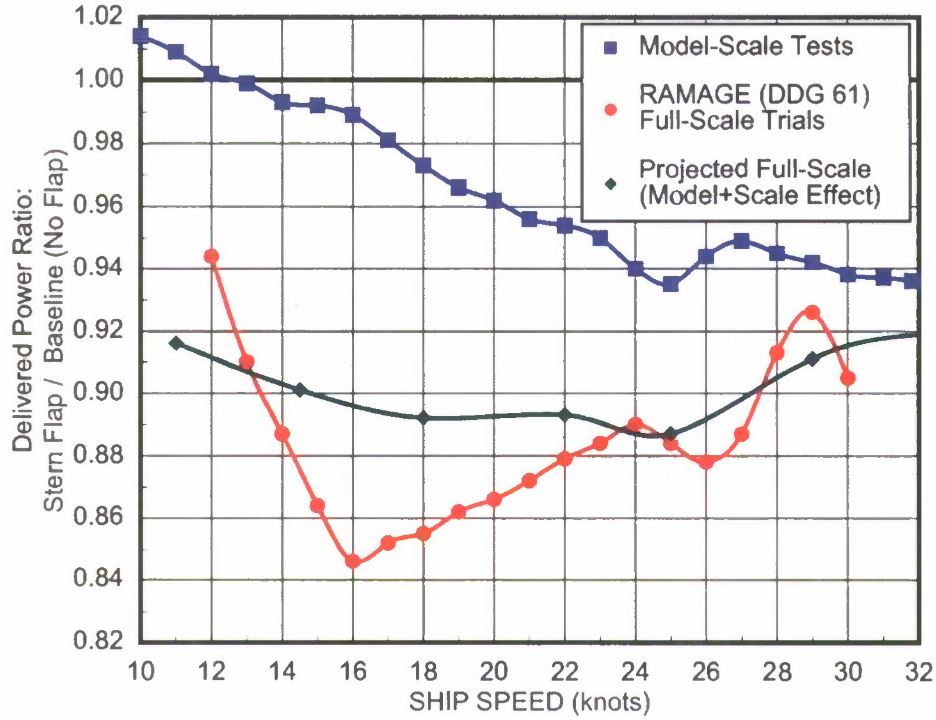


Fig 8. Stern flap performance trials on USS *RAMAGE* (DDG 61) comparison to model-scale performance and new adjusted projection with scaling effects accounted for by proposed technique

The "stern flap scaling multiplier" analysis tool and proposed technique was further exercised by application to the data of four additional stern flap applications for which there exists both model-scale and full-scale data. These four cases are: destroyer USS *A.W. RADFORD* (DD 968), frigate USS *COPELAND* (FFG 25), patrol coastal USS *SHAMAL* (PC 13), and U.S. Coast Guard patrol boat WPB1345 *STATEN ISLAND*. Figure 9 presents the stern flap performance during ship trials, as compared to original model-scale performance, compiled from References 7 through 15, and the new model plus scaling projections.

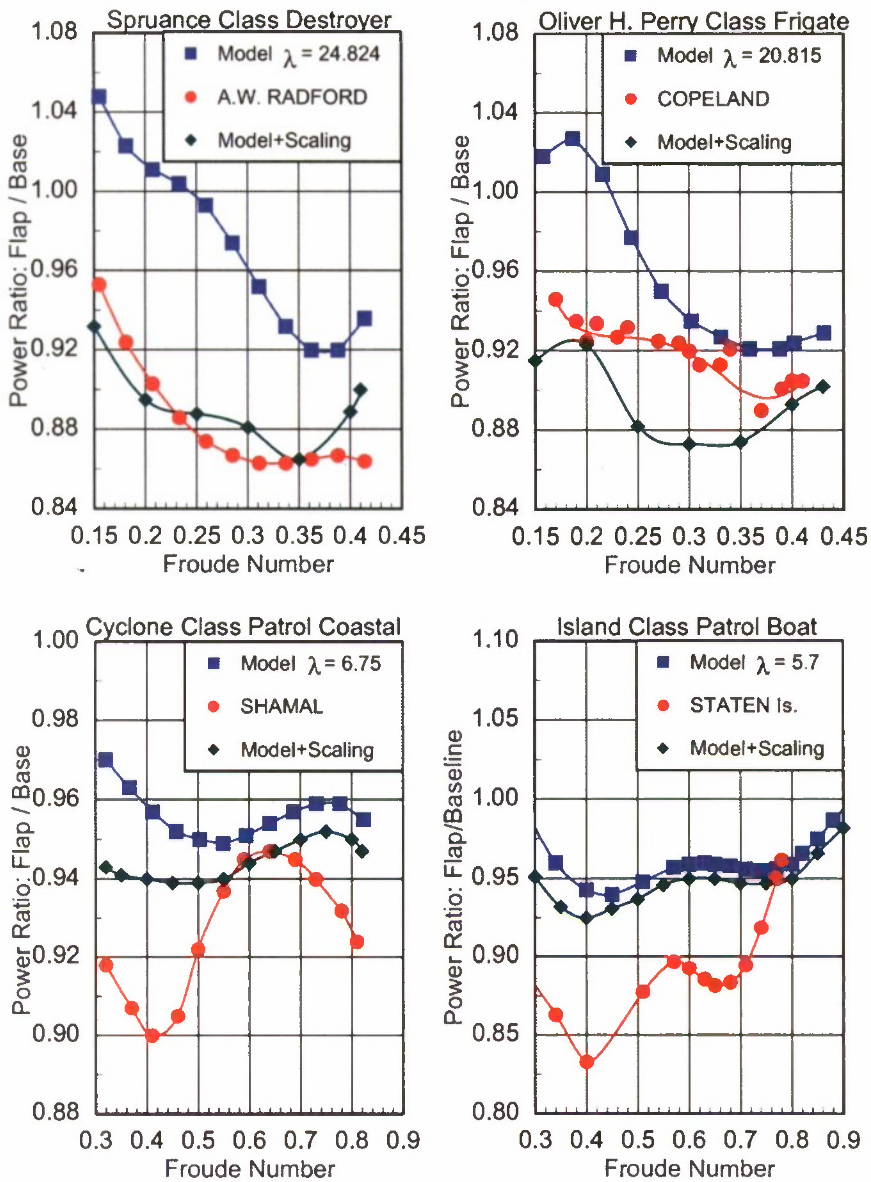


Fig 9. Stern flap performance trials on USS *A.W. RADFORD* (DD 968), USS *COPELAND* (FFG 25), USS *SHAMAL* (PC 13), and WPB1345 *STATEN ISLAND*, comparison to model-scale performance and new projections plus scaling effects

The destroyer *A.W. RADFORD*, exhibits remarkably similar performances between the trials and the new model plus scaling projection. This ship, by virtue of being a twin-screw destroyer hullform, is very similar to the DDG 51 hullform on which the stern flap scaling effects study was based. It appears that the proposed method for estimating stern flap scaling effects works exceptionally well when applied to this type of similar hullform. The new model plus scaling projection for the *COPELAND* lies within the range of the ship trials data, however, the proposed technique does appear to project stern flap scaling effects that are larger in value than measured.

The performances of the prototype stern flaps on both *SHAMAL* and *STATEN ISLAND* are significantly better than the original model-scale performance and the projection with scaling effects included. For this type of stern flap application, even the lowest speeds tested represent F_N in the range of the highest speeds for which the stern flap scaling effects were developed. The assumption that the scaling effects data, developed for a displacement hull in the speed range $0.15 \leq F_N \leq 0.45$, is applicable to a semi-planing or planing craft at higher speeds, is unsupported. In such cases, the designer must simply assume that the stern flap scaling multipliers remain unchanged for $F_N = 0.45$ and above. The *SHAMAL* and *STATEN ISLAND* trials appear to indicate that the technique for applying the current stern flap scaling effects developed for the DDG 51 destroyer hullform, is not appropriate for these smaller high speed craft.

CONTINUED RESEARCH

DDG 51 Stern Flap Scaling Effects Study

The available DDG 51 Class full-scale trials and model-scale stern flap configurations (Table 1), provide for an invaluable, but not an entirely complete, data set for the stern flap scaling effects investigation. The current work was prepared using a methodology best suited to, but also restricted by, the available DDG 51 stern flap data. In order to fully complete the DDG 51 full-scale / model-scale stern flap data set, the following model-scale experiments are recommended:

- Ship/Model correlation (resistance and power) between *RAMAGE* baseline and stern flap trials and Model 5513. Model displacements/drafts and configurations corresponding to baseline trials conditions with fleet wedge design installed, and stern flap trials conditions with flap design equivalent to that manufactured at full-scale on RAMAGE.
- New geosim models test series (resistance). Model displacement/draft to correspond to stern flap trials conditions. Stern flap design and fleet wedge equivalent to installation on RAMAGE.

Application to Other Types of Hullforms

Interest has been increasing in the area of stern flap applications to large military platforms such as carriers, larger monohulls (sea lift, auxiliaries), and amphibious ships, and commercial vessels such as passenger/car ferries and cruise ships. Recent programs have been successful in designing stern flaps for these large-sized vessels, where beneficial model-scale performance has been exhibited at high speed. However, even the top speed of some of these hullforms may be in a F_N range where large stern flap scaling effects have been shown on destroyers, and they may regularly operate at speeds substantially lower than those of the DDG 51 study. Due to the large size of these vessels, upwards of 800 ft in length, model-scale representations are frequently built to scale ratios of 30 or greater. The DDG 51 data indicates that for model scale ratios greater than 30, the accuracy to which stern flap powering performance can be predicted diminishes rapidly. The challenge is to determine the scaling effects and ultimately project the full-scale performance at these low F_N ranges, on these relatively high scale ratio models, in order to effectively design stern flaps for application to these types of hullforms.

Full-scale data on small, high speed, semi-planing craft, indicate that stern flaps may still perform better than the model data indicates, even with the current process of adjustment for stern flap scaling effects. Because these types of craft typically operate a speeds substantially above the $F_N = 0.45$ maximum for the DDG 51 scaling study, data does not yet exist for the evaluation of stern flap scale effects over much of their speed range. These models are typically built to scale ratios far lower (generally less that 8) than those studied on destroyers. The assumption that the scaling effects data, developed for a displacement hull, is applicable to these craft at higher speeds, and for lower scale ratios, is unsupported.

For a wider application of stern flaps to all ship types, and a better understanding of the beneficial stern flap scaling effects, stern flap research should be continued in these general topic areas:

- Model-scale tests at speeds both higher and lower than those studied thus far on destroyers.
- Additional model-scale design experience for a high-speed planing or semi-planing craft, and for larger displacement hulls and amphibious ships.
- Full-scale prototype stern flap installation and evaluation trials on a large displacement hull or amphibious ship.
- Ship/Model correlation to pre- and post-flap trials conditions and configurations, for all full-scale tested prototype stern flaps.

CFD Analysis

Model-scale tests and CFD analyses have supported the understanding of the hydrodynamics of a stern flap on a transom stern ship. The physics of the free surface generated behind a ship, whether with or without a flap, needs to be more fully understood in order to better quantify the scaling effects present in this highly turbulent flow region. More detailed free-surface flow computations around the stern flap, for a variety of Reynolds numbers, should be analyzed so that the controlling mechanisms for stern flap scaling effects can be better defined/understood.

CONCLUSIONS

Beneficial stern flap scaling effects have been confirmed through model testing with various-sized geosim models of the DDG 51 destroyer, computational fluid dynamics calculations, and the comparison to recent full-scale stern flap evaluation trials on the USS *RAMAGE* (DDG 61).

An appropriate technique, by which full-scale stern flap performance at sea could be projected from model-scale experimental data, is presented. A "stern flap scaling multiplier" analysis tool and proposed technique for evaluating stern flap scaling effects, in order to project full-scale stern flap performance from model-scale data, was formulated. This formulation has several distinct advantages over its predecessor. Foremost, is the inclusion of the *RAMAGE* trials data in the updated version. In addition, the stern flap scale effects, as represented in this analysis tool, are dependant on not only the tested model scale ratio and speed range as before, but also on the magnitude of the model-scale performance relative to that of the study case.

The stern flap scaling effects tool and proposed analysis technique was utilized for the DDG 51 case, by applying the indicated scaling effects to the model-scale data, and comparing the resultant new stern flap performance projection to that of the *RAMAGE* trials. The same procedure was undertaken for three previous U.S. Navy stern flap programs, on the destroyer *A.W. RADFORD* (DD 968), the frigate *COPELAND* (FFG 25), and the patrol coastal *SHAMAL* (PC 13), as well as U.S. Coast Guard patrol boat WPB1345 *STATEN ISLAND*. The destroyers exhibit remarkably similar performances between the trials and the model with the new scaling projection, while the frigate lies within the range of the ship trials data. It appears that the proposed method for estimating stern flap scaling effects works well when applied to combatant hullforms. It appears that the current scaling methods developed for displacement hulls are not appropriate for semi-planing or planing craft at higher speeds.

For wider application of stern flaps to all ship types, the beneficial stern flap scaling effects, at speeds both higher and lower than those studied thus far on destroyers, and for models with large scale ratios, still need to be better understood. For larger-sized vessels, the challenge is to determine the scaling effects and ultimately project the full-scale performance at low F_N ranges, on relatively high scale ratio models, in order to effectively design stern flaps for application to these types of hullforms. For small, high speed craft, the difficulty lies in projecting stern flap effects at speeds typically above the maximum speeds of the scaling study, where comparison data does not yet exist.

ACKNOWLEDGMENTS

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APPENDIX A

FULL-SCALE TRIALS DATA AND MODEL-TEST EVALUATIONS

TABLES OF APPENDIX A

Table A1. USS *RAMAGE* (DDG 61) baseline trials results, fleet configuration with wedge, 8780 tons

Run Number	Ship Speed Avg (knots)	Shaft Speed Port (rpm)	Shaft Speed Stbd (rpm)	Shaft Speed Avg (rpm)	Shaft Torque Port (lbf-ft/1000)	Shaft Torque Stbd (lbf-ft/1000)	Shaft Torque Total (lbf-ft/1000)	Shaft Power Port (hp/1000)	Shaft Power Stbd (hp/1000)	Shaft Power Total (hp/1000)	Propeller Pitch Port (%)	Propeller Pitch Stbd (%)	Propeller Pitch Avg (%)
1210E	14.15	55.5	56.0	55.8	150	140	290	1.6	1.5	3.1	97	98	98
1220W	10.45	54.8	55.2	55.0	160	145	305	1.7	1.5	3.2	98	98	98
1230E	14.10	55.6	56.0	55.8	155	140	295	1.6	1.5	3.1	98	98	98
Average	**12.30**			**55.4**			**300**			**3.1**			**98**
1180E	17.40	69.6	69.8	69.7	250	220	470	3.3	2.9	6.2	98	98	98
1190W	13.50	69.7	70.2	70.0	265	235	500	3.5	3.1	6.7	98	98	98
1200E	17.70	70.2	70.9	70.5	255	240	495	3.4	3.2	6.6	98	98	98
Average	**15.55**			**70.0**			**490**			**6.5**			**98**
1000E	17.45	83.8	84.6	84.2	390	330	720	6.2	5.3	11.5	97	98	97
1010W	18.45	83.6	84.6	84.1	390	330	720	6.2	5.3	11.5	97	98	97
Average	**17.95**			**84.2**			**720**			**11.5**			**97**
1030E	22.25	103.7	104.6	104.1	585	515	1100	11.6	10.3	21.8	97	98	97
1040W	21.60	104.6	105.5	105.1	610	510	1120	12.1	10.2	22.4	97	97	97
1050E	22.30	104.0	105.4	104.7	640	520	1160	12.7	10.4	23.1	97	98	97
Average	**21.95**			**104.7**			**1125**			**22.4**			**97**
1120W	23.40	114.5	116.3	115.4	635	585	1220	13.8	13.0	26.8	97	98	97
1130E	24.25	114.5	118.9	116.7	630	620	1250	13.7	14.0	27.8	97	97	97
1140W	23.80	114.6	118.8	116.7	625	620	1245	13.6	14.0	27.7	97	98	97
Average	**23.95**			**116.4**			**1240**			**27.5**			**97**
1060E	26.75	129.0	130.5	129.7	910	835	1745	22.3	20.7	43.1	97	97	97
1070W	26.55	129.2	131.8	130.5	870	830	1700	21.4	20.8	42.2	97	98	97
Average	**26.65**			**130.1**			**1725**			**42.7**			**97**
1062W	25.40	129.3	129.8	129.6	975	855	1830	24.0	21.1	45.1	99	98	98
1072E	28.45	128.9	129.9	129.4	965	820	1785	23.7	20.3	44.0	99	98	98
1082W	25.50	129.2	129.9	129.5	980	830	1810	24.1	20.5	44.6	99	98	98
Average	**26.95**			**129.5**			**1805**			**44.4**			**98**
1087W	28.95	151.0	154.7	152.8	1165	1145	2310	33.5	33.7	67.2	97	98	97
1088E	29.25	151.1	155.2	153.2	1170	1140	2310	33.7	33.7	67.4	97	98	97
Average	**29.10**			**153.0**			**2310**			**67.3**			**97**
1090E	31.15	174.1	170.9	172.5	1495	1325	2820	49.5	43.1	92.7	97	98	97
1100W	29.75	174.2	171.4	172.8	1480	1315	2795	49.1	42.9	92.0	97	98	97
Average	**30.45**			**172.6**			**2810**			**92.3**			**97**
1092W	30.55	166.2	170.0	168.1	1575	1495	3070	49.8	48.4	98.2	99	101	100
1103E	30.90	167.3	170.5	168.9	1575	1505	3080	50.2	48.9	99.1	99	101	100
1112W	30.50	167.0	170.7	168.8	1575	1500	3075	50.1	48.7	98.8	99	101	100
Average	**30.70**			**168.7**			**3075**			**98.8**			**100**

Table A2. USS *RAMAGE* (DDG 61) stern flap trials results, flap of 1% chord at 13° installed behind fleet wedge, 8680 tons

Run Number	Ship Speed Avg (knots)	Shaft Speed Port (rpm)	Shaft Speed Stbd (rpm)	Shaft Speed Avg (rpm)	Shaft Torque Port (lbf-ft/1000)	Shaft Torque Stbd (lbf-ft/1000)	Shaft Torque Total (lbf-ft/1000)	Shaft Power Port (hp/1000)	Shaft Power Stbd (hp/1000)	Shaft Power Total (hp/1000)	Propeller Pitch Port (%)	Propeller Pitch Stbd (%)
2090W	15.50	70.5	71.0	70.8	200	245	445	2.7	3.3	6.0	99	99
2100E	15.60	69.8	70.1	70.0	185	230	415	2.5	3.1	5.5	99	99
Average	**15.55**			**70.4**			430			**5.8**		
2180E	20.85	94.9	95.1	95.0	365	430	795	6.6	7.8	14.4	99	99
2190W	20.65	95.1	95.2	95.2	375	435	810	6.8	7.9	14.7	99	99
Average	**20.75**			**95.1**			**805**			**14.5**		
2000E	24.95	116.6	115.8	116.2	580	615	1195	12.9	13.6	26.4	99	99
2010W	24.50	116.0	115.3	115.7	580	610	1190	12.8	13.4	26.2	99	99
Average	**24.73**			**115.9**			**1195**			**26.3**		
2210W	27.35	133.4	131.5	132.5	830	870	1700	21.1	21.8	42.9	99	99
2220E	27.65	132.7	131.3	132.0	810	855	1665	20.5	21.4	41.8	99	99
2230W	27.15	133.1	131.8	132.5	815	855	1670	20.7	21.5	42.1	99	99
Average	**27.45**			**132.2**			**1675**			**42.2**		
2030W	30.70	156.6	155.3	156.0	1210	1245	2455	36.1	36.8	72.9	99	99
2040E	29.00	155.4	152.8	154.1	1175	1205	2380	34.8	35.1	69.8	99	99
2050W	30.45	155.6	152.8	154.2	1190	1215	2405	35.3	35.3	70.6	99	99
Average	**29.80**			**154.6**			**2405**			**70.8**		
2061S	29.45	170.0	168.8	169.4	1515	1515	3030	49.0	48.7	97.7	106	104
2070N	33.90	169.1	167.6	168.4	1570	1525	3095	50.5	48.7	99.2	106	104
Average	**31.70**			**168.9**			**3065**			**98.5**		

Table A3. DDG 51 powering prediction from Model 5513, fleet configuration with wedge, 8900 tons, still air drag included

```
DDG 5513 Exp12 @8900t Wedge w/SAD  10/1/96
        SHIP LENGTH               467.0 FEET   ( 142.3 METERS)
        SHIP DISPLACEMENT          8900. TONS   ( 9046. METRIC TONS)
        SHIP WETTED SURFACE      34809. SQFT   ( 3234. SQ METERS)
        CORRELATION ALLOWANCE .00015          ITTC FRICTION USED
        STILL AIR DRAG REF. AREA     4418.0 SQFT   (   410.43 SQ METERS)
        WIND DRAG COEF.    0.70          POWER MARGIN FACTOR    1.00
```

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	1.591	1020.0	760.6	1473.6	1098.9	44.5
11.0	5.66	1.671	1382.0	1030.6	1996.9	1489.1	49.0
12.0	6.17	1.736	1819.0	1356.4	2629.1	1960.6	53.4
13.0	6.69	1.785	2335.0	1741.2	3375.7	2517.3	57.9
14.0	7.20	1.820	2933.0	2187.1	4240.3	3162.0	62.5
15.0	7.72	1.847	3621.0	2700.2	5240.2	3907.6	67.1
16.0	8.23	1.876	4416.0	3293.0	6391.3	4766.0	71.7
17.0	8.75	1.921	5346.0	3986.5	7753.9	5782.1	76.4
18.0	9.26	1.981	6434.0	4797.8	9336.1	6961.9	81.1
19.0	9.77	2.051	7691.0	5735.2	11186.7	8341.9	86.0
20.0	10.29	2.156	9202.0	6861.9	13398.4	9991.2	90.9
21.0	10.80	2.316	11076.0	8259.4	16178.5	12064.3	95.8
22.0	11.32	2.451	13144.0	9801.5	19236.4	14344.6	100.8
23.0	11.83	2.511	15210.0	11342.1	22335.2	16655.3	105.9
24.0	12.35	2.561	17460.0	13019.9	25699.4	19164.1	110.8
25.0	12.86	2.631	20032.0	14937.9	29577.3	22055.8	116.1
26.0	13.38	2.776	23268.0	17350.9	34482.4	25713.5	121.6
27.0	13.89	3.086	27866.0	20779.7	41383.4	30859.6	127.6
28.0	14.40	3.566	34228.0	25523.8	51061.9	38076.9	134.4
29.0	14.92	4.026	41382.0	30858.6	61944.0	46191.6	142.0
30.0	15.43	4.506	49690.0	37053.8	74689.5	55695.9	150.3
31.0	15.95	4.986	59106.0	44075.3	89227.9	66537.3	158.7
32.0	16.46	5.306	68135.0	50808.3	103266.7	77006.0	165.6

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	0.690	0.760	0.980	0.930	0.710	0.985	1.005	0.980	1.345
11.0	0.690	0.760	0.980	0.930	0.710	0.975	1.000	0.975	1.335
12.0	0.690	0.760	0.980	0.930	0.710	0.970	0.995	0.965	1.330
13.0	0.690	0.760	0.975	0.930	0.710	0.965	0.990	0.965	1.325
14.0	0.690	0.760	0.970	0.935	0.710	0.965	0.990	0.965	1.325
15.0	0.690	0.760	0.965	0.940	0.715	0.960	0.990	0.970	1.320
16.0	0.690	0.760	0.965	0.945	0.720	0.955	0.990	0.970	1.320
17.0	0.690	0.760	0.960	0.945	0.720	0.955	0.995	0.975	1.320
18.0	0.690	0.760	0.955	0.950	0.720	0.950	0.995	0.970	1.315
19.0	0.690	0.760	0.955	0.950	0.720	0.950	0.995	0.975	1.310
20.0	0.685	0.760	0.955	0.950	0.720	0.945	0.995	0.970	1.300
21.0	0.685	0.755	0.955	0.945	0.715	0.945	0.990	0.965	1.290
22.0	0.685	0.755	0.960	0.945	0.715	0.945	0.985	0.960	1.280
23.0	0.680	0.755	0.955	0.945	0.715	0.945	0.990	0.960	1.280
24.0	0.680	0.755	0.955	0.945	0.710	0.945	0.990	0.965	1.275
25.0	0.675	0.755	0.950	0.945	0.715	0.945	0.995	0.970	1.275
26.0	0.675	0.755	0.950	0.940	0.710	0.945	0.995	0.970	1.270
27.0	0.675	0.750	0.955	0.940	0.705	0.945	0.990	0.960	1.250
28.0	0.670	0.745	0.965	0.935	0.695	0.950	0.980	0.945	1.220
29.0	0.670	0.740	0.965	0.935	0.690	0.950	0.985	0.945	1.195
30.0	0.665	0.735	0.960	0.945	0.690	0.955	0.995	0.955	1.180
31.0	0.660	0.730	0.955	0.950	0.690	0.960	1.000	0.970	1.165
32.0	0.660	0.725	0.960	0.950	0.685	0.960	1.000	0.965	1.150

Table A4. DDG 51 powering prediction from Model 5513, flap installed (1% chord, 13°) behind fleet wedge, 8900 tons, still air drag included

```
DDG 5513 Exp18 @8900t wedge & Flap w/SAD  10/1/96
         SHIP LENGTH              467.0 FEET    ( 142.3 METERS)
         SHIP DISPLACEMENT        8900. TONS    ( 9046. METRIC TONS)
         SHIP WETTED SURFACE     34809. SQFT    ( 3234. SQ METERS)
         CORRELATION ALLOWANCE .00015        ITTC FRICTION USED
         STILL AIR DRAG REF. AREA     4418.0 SQFT   (  410.43 SQ METERS)
         WIND DRAG COEF.    0.70           POWER MARGIN FACTOR    1.00
```

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	1.663	1042.0	777.0	1494.1	1114.2	44.7
11.0	5.66	1.723	1403.0	1046.2	2014.1	1501.9	49.2
12.0	6.17	1.770	1837.0	1369.9	2634.9	1964.9	53.6
13.0	6.69	1.806	2349.0	1751.6	3370.1	2513.1	58.1
14.0	7.20	1.824	2936.0	2189.4	4212.5	3141.3	62.6
15.0	7.72	1.847	3621.0	2700.2	5196.4	3875.0	67.0
16.0	8.23	1.866	4403.0	3283.3	6319.1	4712.2	71.6
17.0	8.75	1.889	5299.0	3951.5	7606.4	5672.1	76.1
18.0	9.26	1.921	6328.0	4718.8	9086.8	6776.0	80.6
19.0	9.77	1.965	7512.0	5601.7	10802.2	8055.2	85.2
20.0	10.29	2.056	8960.0	6681.5	12895.9	9616.5	89.9
21.0	10.80	2.201	10753.0	8018.5	15474.4	11539.3	94.7
22.0	11.32	2.320	12722.0	9486.8	18353.3	13686.0	99.8
23.0	11.83	2.370	14691.0	10955.1	21218.5	15822.7	104.7
24.0	12.35	2.382	16711.0	12461.4	24169.6	18023.3	109.7
25.0	12.86	2.433	19095.0	14239.1	27666.3	20630.8	114.9
26.0	13.38	2.610	22383.0	16691.0	32541.6	24266.3	120.2
27.0	13.89	2.935	26967.0	20109.3	39274.1	29286.7	126.0
28.0	14.40	3.385	33021.0	24623.8	48236.1	35969.7	132.5
29.0	14.92	3.817	39839.0	29707.9	58339.4	43503.7	139.7
30.0	15.43	4.267	47737.0	35597.5	70034.1	52224.5	147.9
31.0	15.95	4.722	56722.0	42297.6	83607.0	62345.7	156.3
32.0	16.46	5.036	65452.0	48807.5	96752.3	72148.2	163.0

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	0.695	0.760	0.980	0.935	0.715	0.985	1.005	0.980	1.340
11.0	0.695	0.760	0.975	0.940	0.715	0.975	1.000	0.980	1.335
12.0	0.695	0.760	0.975	0.940	0.715	0.970	0.995	0.975	1.330
13.0	0.695	0.760	0.975	0.940	0.715	0.965	0.995	0.970	1.325
14.0	0.695	0.760	0.970	0.945	0.720	0.965	0.995	0.970	1.325
15.0	0.695	0.760	0.970	0.945	0.720	0.960	0.990	0.970	1.320
16.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.970	1.320
17.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.970	1.320
18.0	0.695	0.760	0.960	0.955	0.725	0.950	0.990	0.970	1.315
19.0	0.695	0.760	0.960	0.955	0.725	0.950	0.985	0.970	1.310
20.0	0.695	0.760	0.960	0.955	0.725	0.945	0.985	0.965	1.305
21.0	0.695	0.760	0.965	0.950	0.720	0.945	0.980	0.960	1.295
22.0	0.695	0.755	0.965	0.950	0.720	0.945	0.980	0.955	1.285
23.0	0.690	0.755	0.960	0.950	0.720	0.945	0.980	0.960	1.285
24.0	0.690	0.755	0.955	0.955	0.725	0.945	0.985	0.965	1.285
25.0	0.690	0.755	0.950	0.960	0.725	0.945	0.995	0.975	1.285
26.0	0.690	0.755	0.955	0.955	0.720	0.945	0.990	0.970	1.275
27.0	0.685	0.750	0.965	0.945	0.710	0.945	0.980	0.955	1.250
28.0	0.685	0.745	0.975	0.940	0.700	0.950	0.970	0.940	1.220
29.0	0.685	0.740	0.980	0.945	0.695	0.950	0.970	0.935	1.200
30.0	0.680	0.735	0.975	0.955	0.700	0.955	0.980	0.950	1.185
31.0	0.680	0.730	0.970	0.960	0.700	0.960	0.990	0.965	1.170
32.0	0.675	0.725	0.970	0.960	0.695	0.960	0.990	0.960	1.155

Table A5. DDG 51 powering estimate from Model 5488, no wedge, no flap, 8900 tons

```
5488 Baseline PE with 5513 Baseline interactions  11/29/01
      SHIP LENGTH             467.0 FEET   ( 142.3 METERS)
      SHIP DISPLACEMENT       8900. TONS   ( 9046. METRIC TONS)
      SHIP WETTED SURFACE   34809. SQFT   ( 3234. SQ METERS)
      CORRELATION ALLOWANCE .00015        ITTC FRICTION USED
```

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	1.432	972.0	724.8	1404.9	1047.6	44.2
11.0	5.66	1.487	1308.0	975.4	1890.2	1409.5	48.5
12.0	6.17	1.556	1725.0	1286.3	2492.7	1858.8	52.9
13.0	6.69	1.634	2234.0	1665.9	3228.4	2407.4	57.5
14.0	7.20	1.704	2837.0	2115.6	4099.8	3057.2	62.1
15.0	7.72	1.766	3539.0	2639.0	5119.8	3817.9	66.8
16.0	8.23	1.821	4347.0	3241.6	6289.8	4690.3	71.5
17.0	8.75	1.889	5299.0	3951.5	7684.4	5730.2	76.3
18.0	9.26	1.984	6438.0	4800.8	9342.1	6966.4	81.1
19.0	9.77	2.117	7829.0	5838.1	11393.2	8495.9	86.3
20.0	10.29	2.299	9549.0	7120.7	13922.5	10382.0	91.5
21.0	10.80	2.516	11637.0	8677.7	17037.8	12705.1	96.7
22.0	11.32	2.707	13970.0	10417.4	20514.9	15298.0	102.1
23.0	11.83	2.844	16438.0	12257.8	24248.5	18082.1	107.5
24.0	12.35	2.914	18936.0	14120.6	28008.2	20885.7	112.7
25.0	12.86	2.989	21727.0	16201.8	32238.9	24040.5	118.1
26.0	13.38	3.151	25264.0	18839.4	37645.2	28072.0	123.7
27.0	13.89	3.469	30147.0	22480.6	45053.1	33596.1	129.8
28.0	14.40	3.891	36390.0	27136.0	54615.6	40726.9	136.3
29.0	14.92	4.381	44001.0	32811.5	66318.8	49453.9	144.0
30.0	15.43	4.941	53248.0	39707.0	80721.8	60194.2	152.9
31.0	15.95	5.431	63119.0	47067.8	96118.3	71675.4	161.4
32.0	16.46	5.889	73923.0	55124.4	113339.3	84517.1	169.0

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	0.690	0.760	0.980	0.930	0.705	0.985	1.005	0.980	1.355
11.0	0.690	0.760	0.980	0.930	0.710	0.975	1.000	0.975	1.350
12.0	0.690	0.760	0.980	0.930	0.710	0.970	0.995	0.970	1.340
13.0	0.690	0.760	0.975	0.930	0.710	0.965	0.990	0.965	1.335
14.0	0.690	0.760	0.970	0.935	0.710	0.965	0.990	0.965	1.330
15.0	0.690	0.760	0.965	0.940	0.715	0.960	0.990	0.970	1.325
16.0	0.690	0.760	0.965	0.945	0.720	0.955	0.990	0.970	1.325
17.0	0.690	0.760	0.960	0.945	0.720	0.955	0.995	0.975	1.320
18.0	0.690	0.760	0.955	0.950	0.720	0.950	0.995	0.970	1.315
19.0	0.685	0.760	0.955	0.950	0.720	0.950	0.995	0.975	1.305
20.0	0.685	0.760	0.955	0.950	0.720	0.945	0.995	0.970	1.295
21.0	0.685	0.755	0.955	0.945	0.715	0.945	0.990	0.965	1.275
22.0	0.680	0.755	0.960	0.945	0.710	0.945	0.985	0.960	1.265
23.0	0.680	0.750	0.955	0.945	0.710	0.945	0.990	0.960	1.260
24.0	0.675	0.750	0.955	0.945	0.710	0.945	0.990	0.960	1.255
25.0	0.675	0.750	0.950	0.945	0.710	0.945	0.995	0.965	1.255
26.0	0.670	0.750	0.950	0.940	0.705	0.945	0.995	0.965	1.245
27.0	0.670	0.745	0.955	0.940	0.700	0.945	0.990	0.955	1.230
28.0	0.665	0.740	0.965	0.935	0.690	0.950	0.980	0.940	1.200
29.0	0.665	0.735	0.965	0.935	0.685	0.950	0.985	0.945	1.180
30.0	0.660	0.725	0.960	0.945	0.685	0.955	0.995	0.955	1.160
31.0	0.655	0.720	0.955	0.950	0.685	0.960	1.000	0.965	1.145
32.0	0.650	0.715	0.960	0.950	0.680	0.960	1.000	0.960	1.130

Table A6. DDG 51 powering estimate from Model 5488, no wedge, flap installed (1% chord, 10°), 8900 tons

```
5488 w/Flap PE with 5513 w/Flap interactions  11/29/01
        SHIP LENGTH             467.0 FEET   ( 142.3 METERS)
        SHIP DISPLACEMENT       8900. TONS   ( 9046. METRIC TONS)
        SHIP WETTED SURFACE    34809. SQFT   ( 3234. SQ METERS)
        CORRELATION ALLOWANCE  .00015         ITTC FRICTION USED
```

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	1.502	993.0	740.5	1424.2	1062.0	44.3
11.0	5.66	1.552	1334.0	994.8	1915.0	1428.0	48.8
12.0	6.17	1.610	1753.0	1307.2	2513.8	1874.5	53.2
13.0	6.69	1.664	2254.0	1680.8	3232.5	2410.5	57.7
14.0	7.20	1.704	2837.0	2115.6	4068.8	3034.1	62.2
15.0	7.72	1.747	3519.0	2624.1	5048.0	3764.3	66.7
16.0	8.23	1.774	4289.0	3198.3	6152.9	4588.2	71.2
17.0	8.75	1.824	5202.0	3879.1	7464.7	5566.4	75.8
18.0	9.26	1.890	6273.0	4677.8	9006.1	6715.8	80.5
19.0	9.77	1.978	7540.0	5622.6	10843.5	8086.0	85.2
20.0	10.29	2.134	9149.0	6822.4	13177.0	9826.1	90.3
21.0	10.80	2.316	11076.0	8259.4	15959.7	11901.2	95.3
22.0	11.32	2.483	13245.0	9876.8	19146.6	14277.6	100.6
23.0	11.83	2.599	15536.0	11585.2	22505.3	16782.2	105.9
24.0	12.35	2.651	17837.0	13301.0	25885.0	19302.4	111.1
25.0	12.86	2.715	20427.0	15232.4	29698.8	22146.4	116.4
26.0	13.38	2.872	23781.0	17733.5	34698.6	25874.7	121.7
27.0	13.89	3.185	28457.0	21220.4	41612.4	31030.4	127.5
28.0	14.40	3.606	34496.0	25723.7	50599.4	37732.0	133.8
29.0	14.92	4.081	41785.0	31159.1	61507.5	45866.1	141.3
30.0	15.43	4.619	50615.0	37743.6	74779.0	55762.7	150.0
31.0	15.95	5.089	60032.0	44765.9	89132.4	66466.0	158.5
32.0	16.46	5.499	70053.0	52238.5	104523.9	77943.5	165.8

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	0.695	0.760	0.980	0.935	0.715	0.985	1.005	0.985	1.350
11.0	0.695	0.760	0.975	0.940	0.715	0.975	1.000	0.980	1.345
12.0	0.695	0.760	0.975	0.940	0.715	0.970	0.995	0.975	1.340
13.0	0.695	0.760	0.975	0.940	0.715	0.965	0.995	0.975	1.335
14.0	0.695	0.760	0.970	0.945	0.720	0.965	0.995	0.975	1.330
15.0	0.695	0.760	0.970	0.945	0.720	0.960	0.990	0.970	1.330
16.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.975	1.325
17.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.970	1.320
18.0	0.695	0.760	0.960	0.955	0.725	0.950	0.990	0.970	1.315
19.0	0.695	0.760	0.960	0.955	0.725	0.950	0.985	0.970	1.310
20.0	0.695	0.760	0.960	0.955	0.725	0.945	0.985	0.965	1.300
21.0	0.695	0.755	0.965	0.950	0.720	0.945	0.980	0.955	1.285
22.0	0.690	0.755	0.965	0.950	0.715	0.945	0.980	0.955	1.275
23.0	0.690	0.755	0.960	0.950	0.715	0.945	0.980	0.960	1.270
24.0	0.690	0.755	0.955	0.955	0.720	0.945	0.985	0.965	1.270
25.0	0.690	0.755	0.950	0.960	0.725	0.945	0.995	0.975	1.270
26.0	0.685	0.755	0.955	0.955	0.715	0.945	0.990	0.965	1.260
27.0	0.685	0.750	0.965	0.945	0.710	0.945	0.980	0.955	1.240
28.0	0.680	0.740	0.975	0.940	0.700	0.950	0.970	0.935	1.210
29.0	0.680	0.735	0.980	0.945	0.695	0.950	0.970	0.935	1.185
30.0	0.675	0.730	0.975	0.955	0.695	0.955	0.980	0.950	1.170
31.0	0.675	0.725	0.970	0.960	0.695	0.960	0.990	0.965	1.155
32.0	0.670	0.720	0.970	0.960	0.690	0.960	0.990	0.960	1.135

Table A7. DDG 51 powering estimate from Model 5513, no wedge, no flap, 8900 tons

5513 Baseline PE with 5513 Baseline interactions 11/29/01

SHIP LENGTH 467.0 FEET (142.3 METERS)
SHIP DISPLACEMENT 8900. TONS (9046. METRIC TONS)
SHIP WETTED SURFACE 34809. SQFT (3234. SQ METERS)
CORRELATION ALLOWANCE .00015 ITTC FRICTION USED

SHIP SPEED		RESIDUARY RES.COEF.	EFFECTIVE POWER- PE		DELIVERED POWER- PD		PROPELLER REV. PER MINUTE
(KTS)	(M/S)	(CR*1000)	(HP)	(kW)	(HP)	(kW)	
10.0	5.14	1.455	979.0	730.0	1414.9	1055.1	44.2
11.0	5.66	1.520	1321.0	985.1	1908.9	1423.4	48.6
12.0	6.17	1.585	1740.0	1297.5	2514.4	1875.0	53.0
13.0	6.69	1.655	2248.0	1676.3	3248.7	2422.6	57.5
14.0	7.20	1.706	2838.0	2116.3	4101.3	3058.3	62.1
15.0	7.72	1.761	3533.0	2634.6	5111.0	3811.3	66.8
16.0	8.23	1.800	4321.0	3222.2	6251.6	4661.8	71.4
17.0	8.75	1.845	5233.0	3902.2	7587.0	5657.7	76.1
18.0	9.26	1.905	6299.0	4697.2	9136.0	6812.7	80.8
19.0	9.77	1.990	7565.0	5641.2	10998.8	8201.8	85.7
20.0	10.29	2.106	9080.0	6771.0	13215.2	9854.6	90.6
21.0	10.80	2.268	10941.0	8158.7	15973.2	11911.2	95.6
22.0	11.32	2.410	13011.0	9702.3	19032.2	14192.3	100.6
23.0	11.83	2.520	15243.0	11366.7	22386.1	16693.3	105.9
24.0	12.35	2.583	17550.0	13087.0	25838.9	19268.1	111.0
25.0	12.86	2.667	20203.0	15065.4	29843.5	22254.3	116.3
26.0	13.38	2.838	23598.0	17597.0	35001.0	26100.2	121.9
27.0	13.89	3.145	28217.0	21041.4	41943.4	31277.2	128.0
28.0	14.40	3.546	34096.0	25425.4	50846.8	37916.4	134.3
29.0	14.92	4.000	41188.0	30713.9	61622.8	45952.1	141.8
30.0	15.43	4.513	49743.0	37093.3	74778.5	55762.3	150.4
31.0	15.95	4.967	58930.0	43944.1	88928.7	66314.1	158.6
32.0	16.46	5.360	68668.0	51205.7	104184.3	77690.2	165.9

SHIP SPEED	EFFICIENCIES (ETA)					THRUST DEDUCTION AND WAKE FACTORS			ADVANCE COEF.
(KTS)	ETAD	ETAO	ETAH	ETAR	ETAB	1-THDF	1-WFTT	1-WFTQ	ADVC
10.0	0.690	0.760	0.980	0.930	0.705	0.985	1.005	0.980	1.355
11.0	0.690	0.760	0.980	0.930	0.710	0.975	1.000	0.975	1.345
12.0	0.690	0.760	0.980	0.930	0.710	0.970	0.995	0.970	1.340
13.0	0.690	0.760	0.975	0.930	0.710	0.965	0.990	0.965	1.335
14.0	0.690	0.760	0.970	0.935	0.710	0.965	0.990	0.965	1.330
15.0	0.690	0.760	0.965	0.940	0.715	0.960	0.990	0.970	1.325
16.0	0.690	0.760	0.965	0.945	0.720	0.955	0.990	0.970	1.325
17.0	0.690	0.760	0.960	0.945	0.720	0.955	0.995	0.975	1.325
18.0	0.690	0.760	0.955	0.950	0.720	0.950	0.995	0.975	1.320
19.0	0.690	0.760	0.955	0.950	0.720	0.950	0.995	0.975	1.315
20.0	0.685	0.760	0.955	0.950	0.720	0.945	0.995	0.970	1.305
21.0	0.685	0.760	0.955	0.945	0.715	0.945	0.990	0.965	1.295
22.0	0.685	0.755	0.960	0.945	0.715	0.945	0.985	0.960	1.285
23.0	0.680	0.755	0.955	0.945	0.715	0.945	0.990	0.960	1.280
24.0	0.680	0.755	0.955	0.945	0.710	0.945	0.990	0.965	1.275
25.0	0.675	0.755	0.950	0.945	0.715	0.945	0.995	0.970	1.275
26.0	0.675	0.755	0.950	0.940	0.710	0.945	0.995	0.970	1.265
27.0	0.675	0.750	0.955	0.940	0.705	0.945	0.990	0.960	1.245
28.0	0.670	0.745	0.965	0.935	0.695	0.950	0.980	0.945	1.220
29.0	0.670	0.740	0.965	0.935	0.690	0.950	0.985	0.945	1.200
30.0	0.665	0.735	0.960	0.945	0.690	0.955	0.995	0.955	1.180
31.0	0.665	0.730	0.955	0.950	0.690	0.960	1.000	0.970	1.165
32.0	0.660	0.725	0.960	0.950	0.685	0.960	1.000	0.965	1.150

Table A8. DDG 51 powering estimate from Model 5513, no wedge, flap installed (1% chord, 10°), 8900 tons

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5513 w/Flap PE with 5513 w/Flap interactions  11/29/01
        SHIP LENGTH                467.0 FEET   ( 142.3 METERS)
        SHIP DISPLACEMENT          8900. TONS   ( 9046. METRIC TONS)
        SHIP WETTED SURFACE       34809. SQFT   ( 3234. SQ METERS)
        CORRELATION ALLOWANCE .00015            ITTC FRICTION USED
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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	1.544	1006.0	750.2	1442.7	1075.8	44.4
11.0	5.66	1.596	1352.0	1008.2	1940.7	1447.2	48.9
12.0	6.17	1.656	1777.0	1325.1	2548.3	1900.3	53.3
13.0	6.69	1.706	2282.0	1701.7	3272.9	2440.6	57.8
14.0	7.20	1.741	2867.0	2137.9	4112.3	3066.5	62.3
15.0	7.72	1.780	3553.0	2649.5	5097.3	3801.1	66.8
16.0	8.23	1.810	4334.0	3231.9	6218.4	4637.1	71.4
17.0	8.75	1.835	5218.0	3891.1	7488.0	5583.8	75.9
18.0	9.26	1.865	6229.0	4645.0	8941.6	6667.8	80.4
19.0	9.77	1.925	7429.0	5539.8	10680.0	7964.1	85.0
20.0	10.29	2.010	8848.0	6598.0	12730.0	9492.7	89.7
21.0	10.80	2.139	10581.0	7890.3	15217.3	11347.6	94.5
22.0	11.32	2.250	12495.0	9317.5	18011.2	13431.0	99.4
23.0	11.83	2.310	14469.0	10789.5	20883.3	15572.6	104.4
24.0	12.35	2.350	16576.0	12360.7	23965.7	17871.2	109.5
25.0	12.86	2.427	19066.0	14217.5	27622.5	20598.1	114.9
26.0	13.38	2.581	22231.0	16577.7	32308.9	24092.8	120.1
27.0	13.89	2.878	26628.0	19856.5	38746.4	28893.2	125.7
28.0	14.40	3.282	32338.0	24114.4	47150.8	35160.3	131.9
29.0	14.92	3.720	39118.0	29170.3	57175.7	42635.9	139.1
30.0	15.43	4.205	47227.0	35217.2	69201.3	51603.4	147.5
31.0	15.95	4.633	55922.0	41701.0	82284.8	61359.8	155.7
32.0	16.46	4.995	65048.0	48506.3	96077.1	71644.7	162.7

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	0.695	0.760	0.980	0.935	0.715	0.985	1.005	0.985	1.350
11.0	0.695	0.760	0.975	0.940	0.715	0.975	1.000	0.980	1.340
12.0	0.695	0.760	0.975	0.940	0.715	0.970	0.995	0.975	1.335
13.0	0.695	0.760	0.975	0.940	0.715	0.965	0.995	0.970	1.330
14.0	0.695	0.760	0.970	0.945	0.720	0.965	0.995	0.970	1.330
15.0	0.695	0.760	0.970	0.945	0.720	0.960	0.990	0.970	1.325
16.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.970	1.325
17.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.970	1.320
18.0	0.695	0.760	0.960	0.955	0.725	0.950	0.990	0.970	1.320
19.0	0.695	0.760	0.960	0.955	0.725	0.950	0.985	0.970	1.315
20.0	0.695	0.760	0.960	0.955	0.725	0.945	0.985	0.965	1.310
21.0	0.695	0.760	0.965	0.950	0.720	0.945	0.980	0.960	1.295
22.0	0.695	0.755	0.965	0.950	0.720	0.945	0.980	0.955	1.290
23.0	0.695	0.755	0.960	0.950	0.720	0.945	0.980	0.960	1.285
24.0	0.690	0.755	0.955	0.955	0.725	0.945	0.985	0.965	1.290
25.0	0.690	0.755	0.950	0.960	0.725	0.945	0.995	0.975	1.285
26.0	0.690	0.755	0.955	0.955	0.720	0.945	0.990	0.970	1.275
27.0	0.685	0.750	0.965	0.945	0.710	0.945	0.980	0.955	1.255
28.0	0.685	0.745	0.975	0.940	0.700	0.950	0.970	0.940	1.230
29.0	0.685	0.740	0.980	0.945	0.700	0.950	0.970	0.940	1.205
30.0	0.680	0.735	0.975	0.955	0.700	0.955	0.980	0.950	1.185
31.0	0.680	0.730	0.970	0.960	0.700	0.960	0.990	0.965	1.175
32.0	0.675	0.725	0.970	0.960	0.695	0.960	0.990	0.960	1.160

Table A9. DDG 51 powering estimate from Model 9141, no wedge, no flap, 8900 tons

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9141 Baseline PE with 5513 Baseline interactions  11/29/01
        SHIP LENGTH             467.0 FEET   ( 142.3 METERS)
        SHIP DISPLACEMENT       8900. TONS   ( 9046. METRIC TONS)
        SHIP WETTED SURFACE    34809. SQFT   ( 3234. SQ METERS)
        CORRELATION ALLOWANCE .00015          ITTC FRICTION USED
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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	1.769	1074.0	800.9	1551.8	1157.2	44.9
11.0	5.66	1.800	1434.0	1069.3	2072.6	1545.5	49.3
12.0	6.17	1.830	1868.0	1393.0	2700.8	2014.0	53.7
13.0	6.69	1.855	2381.0	1775.5	3443.3	2567.7	58.1
14.0	7.20	1.890	2991.0	2230.4	4325.7	3225.6	62.7
15.0	7.72	1.920	3696.0	2756.1	5350.8	3990.1	67.3
16.0	8.23	1.945	4501.0	3356.4	6516.9	4859.7	71.9
17.0	8.75	1.980	5434.0	4052.1	7884.3	5879.3	76.6
18.0	9.26	2.019	6500.0	4847.0	9434.3	7035.2	81.2
19.0	9.77	2.091	7774.0	5797.1	11310.8	8434.4	86.2
20.0	10.29	2.204	9319.0	6949.2	13574.7	10122.6	91.1
21.0	10.80	2.380	11256.0	8393.6	16453.1	12269.1	96.1
22.0	11.32	2.580	13559.0	10110.9	19876.5	14821.9	101.5
23.0	11.83	2.751	16094.0	12001.3	23709.0	17679.8	107.1
24.0	12.35	2.875	18774.0	13999.8	27752.7	20695.2	112.5
25.0	12.86	2.989	21727.0	16201.8	32238.9	24040.5	118.1
26.0	13.38	3.151	25261.0	18837.1	37640.4	28068.5	123.7
27.0	13.89	3.450	30037.0	22398.6	44874.6	33462.9	129.7
28.0	14.40	3.862	36192.0	26988.4	54287.8	40482.4	136.1
29.0	14.92	4.330	43626.0	32531.9	65688.0	48983.5	143.7
30.0	15.43	4.869	52660.0	39268.6	79716.9	59444.9	152.5
31.0	15.95	5.352	62408.0	46537.6	94888.2	70758.1	160.9
32.0	16.46	5.805	73084.0	54498.7	111864.5	83417.3	168.5

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	0.690	0.760	0.980	0.930	0.710	0.985	1.005	0.980	1.335
11.0	0.690	0.760	0.980	0.930	0.705	0.975	1.000	0.970	1.330
12.0	0.690	0.760	0.980	0.930	0.705	0.970	0.995	0.965	1.325
13.0	0.690	0.760	0.975	0.930	0.710	0.965	0.990	0.965	1.320
14.0	0.690	0.760	0.970	0.935	0.710	0.965	0.990	0.965	1.320
15.0	0.690	0.760	0.965	0.940	0.715	0.960	0.990	0.970	1.315
16.0	0.690	0.760	0.965	0.945	0.715	0.955	0.990	0.970	1.315
17.0	0.690	0.760	0.960	0.945	0.720	0.955	0.995	0.970	1.315
18.0	0.690	0.760	0.955	0.950	0.720	0.950	0.995	0.970	1.310
19.0	0.685	0.760	0.955	0.950	0.720	0.950	0.995	0.975	1.305
20.0	0.685	0.760	0.955	0.950	0.720	0.945	0.995	0.970	1.300
21.0	0.685	0.755	0.955	0.945	0.715	0.945	0.990	0.965	1.285
22.0	0.680	0.755	0.960	0.945	0.710	0.945	0.985	0.960	1.270
23.0	0.680	0.755	0.955	0.945	0.710	0.945	0.990	0.960	1.265
24.0	0.675	0.750	0.955	0.945	0.710	0.945	0.990	0.960	1.260
25.0	0.675	0.750	0.950	0.945	0.710	0.945	0.995	0.965	1.255
26.0	0.670	0.750	0.950	0.940	0.705	0.945	0.995	0.965	1.245
27.0	0.670	0.745	0.955	0.940	0.700	0.945	0.990	0.955	1.230
28.0	0.665	0.740	0.965	0.935	0.690	0.950	0.980	0.940	1.205
29.0	0.665	0.735	0.965	0.935	0.685	0.950	0.985	0.945	1.180
30.0	0.660	0.730	0.960	0.945	0.685	0.955	0.995	0.955	1.165
31.0	0.660	0.725	0.955	0.950	0.685	0.960	1.000	0.965	1.150
32.0	0.655	0.715	0.960	0.950	0.680	0.960	1.000	0.960	1.130

Table A10. DDG 51 powering estimate from Model 9141, no wedge, flap installed (1% chord, 10°), 8900 tons

9141 w/Flap PE with 5513 w/Flap interactions 11/29/01

SHIP LENGTH	467.0 FEET	(142.3 METERS)	
SHIP DISPLACEMENT	8900. TONS	(9046. METRIC TONS)	
SHIP WETTED SURFACE	34809. SQFT	(3234. SQ METERS)	
CORRELATION ALLOWANCE	.00015		ITTC FRICTION USED

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	1.964	1133.0	844.9	1625.9	1212.4	45.3
11.0	5.66	1.986	1509.0	1125.3	2168.4	1616.9	49.8
12.0	6.17	1.990	1952.0	1455.6	2802.7	2090.0	54.2
13.0	6.69	1.990	2471.0	1842.6	3548.5	2646.1	58.6
14.0	7.20	1.990	3074.0	2292.3	4414.5	3291.9	63.1
15.0	7.72	1.990	3768.0	2809.8	5412.0	4035.7	67.5
16.0	8.23	1.990	4557.0	3398.2	6545.1	4880.7	72.0
17.0	8.75	2.005	5471.0	4079.7	7859.1	5860.5	76.5
18.0	9.26	2.019	6500.0	4847.0	9340.1	6964.9	81.0
19.0	9.77	2.060	7710.0	5749.3	11095.0	8273.6	85.6
20.0	10.29	2.147	9179.0	6844.8	13221.8	9859.5	90.4
21.0	10.80	2.300	11031.0	8225.8	15891.9	11850.6	95.2
22.0	11.32	2.460	13172.0	9822.4	19035.4	14194.7	100.4
23.0	11.83	2.613	15585.0	11621.7	22580.4	16838.2	105.9
24.0	12.35	2.710	18083.0	13484.5	26263.2	19584.4	111.4
25.0	12.86	2.800	20833.0	15535.2	30324.6	22613.0	116.9
26.0	13.38	2.950	24194.0	18041.5	35341.7	26354.3	122.1
27.0	13.89	3.243	28803.0	21478.4	42159.8	31438.5	127.8
28.0	14.40	3.645	34752.0	25914.6	51012.3	38039.8	134.0
29.0	14.92	4.075	41742.0	31127.0	61437.0	45813.6	141.3
30.0	15.43	4.579	50284.0	37496.8	74229.4	55352.9	149.7
31.0	15.95	5.035	59547.0	44404.2	88317.3	65858.2	158.1
32.0	16.46	5.450	69561.0	51871.6	103685.7	77318.4	165.5

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	0.695	0.760	0.980	0.935	0.710	0.985	1.005	0.980	1.320
11.0	0.695	0.760	0.975	0.940	0.715	0.975	1.000	0.975	1.315
12.0	0.695	0.760	0.975	0.940	0.715	0.970	0.995	0.975	1.315
13.0	0.695	0.760	0.975	0.940	0.715	0.965	0.995	0.970	1.315
14.0	0.695	0.760	0.970	0.945	0.720	0.965	0.995	0.970	1.315
15.0	0.695	0.760	0.970	0.945	0.720	0.960	0.990	0.970	1.310
16.0	0.695	0.760	0.965	0.950	0.720	0.955	0.990	0.970	1.310
17.0	0.695	0.760	0.965	0.950	0.725	0.955	0.990	0.970	1.310
18.0	0.695	0.760	0.960	0.955	0.725	0.950	0.990	0.970	1.310
19.0	0.695	0.760	0.960	0.955	0.725	0.950	0.985	0.970	1.305
20.0	0.695	0.760	0.960	0.955	0.725	0.945	0.985	0.965	1.300
21.0	0.695	0.755	0.965	0.950	0.720	0.945	0.980	0.955	1.285
22.0	0.690	0.755	0.965	0.950	0.715	0.945	0.980	0.955	1.275
23.0	0.690	0.755	0.960	0.950	0.715	0.945	0.980	0.960	1.270
24.0	0.690	0.755	0.955	0.955	0.720	0.945	0.985	0.965	1.265
25.0	0.685	0.755	0.950	0.960	0.720	0.945	0.995	0.975	1.265
26.0	0.685	0.750	0.955	0.955	0.715	0.945	0.990	0.965	1.255
27.0	0.685	0.745	0.965	0.945	0.710	0.945	0.980	0.955	1.235
28.0	0.680	0.740	0.975	0.940	0.695	0.950	0.970	0.935	1.210
29.0	0.680	0.735	0.980	0.945	0.695	0.950	0.970	0.935	1.185
30.0	0.675	0.730	0.975	0.955	0.695	0.955	0.980	0.950	1.170
31.0	0.675	0.725	0.970	0.960	0.695	0.960	0.990	0.965	1.155
32.0	0.670	0.720	0.970	0.960	0.690	0.960	0.990	0.960	1.140

Table A11. DDG 51, change in delivered power due to stern flap, data based on three geosim model experiments

	Large Model		Mid-Size Model		Small Model		Stern Flap Power Reductions		
Ship Speed (knots)	5488 Stern Flap PD (hP)	Baseline PD (hP)	5513 Stern Flap PD (hP)	Baseline PD (hP)	9141 Stern Flap PD (hP)	Baseline PD (hP)	Large 5488 (%)	Mid-Size 5513 (%)	Small 9141 (%)
10	1424	1405	1443	1415	1626	1552	+1.4	+2.0	+4.8
11	1915	1890	1941	1909	2168	2073	+1.3	+1.7	+4.6
12	2514	2493	2548	2514	2803	2701	+0.8	+1.3	+3.8
13	3233	3228	3273	3249	3549	3443	+0.1	+0.7	+3.1
14	4069	4100	4112	4101	4415	4326	-0.8	+0.3	+2.1
15	5048	5120	5097	5111	5412	5351	-1.4	-0.3	+1.1
16	6153	6290	6218	6252	6545	6517	-2.2	-0.5	+0.4
17	7465	7684	7488	7587	7859	7884	-2.9	-1.3	-0.3
18	9006	9342	8942	9136	9340	9434	-3.6	-2.1	-1.0
19	10844	11393	10680	10999	11095	11311	-4.8	-2.9	-1.9
20	13177	13923	12730	13215	13222	13575	-5.4	-3.7	-2.6
21	15960	17038	15217	15973	15892	16453	-6.3	-4.7	-3.4
22	19147	20515	18011	19032	19035	19877	-6.7	-5.4	-4.2
23	22505	24249	20883	22386	22580	23709	-7.2	-6.7	-4.8
24	25885	28008	23966	25839	26263	27753	-7.6	-7.2	-5.4
25	29699	32239	27623	29844	30325	32239	-7.9	-7.4	-5.9
26	34699	37645	32309	35001	35342	37640	-7.8	-7.7	-6.1
27	41612	45053	38746	41943	42160	44875	-7.6	-7.6	-6.0
28	50599	54616	47151	50847	51012	54288	-7.4	-7.3	-6.0
29	61508	66319	57176	61623	61437	65688	-7.3	-7.2	-6.5
30	74779	80722	69201	74779	74229	79717	-7.4	-7.5	-6.9
31	89132	96118	82285	88929	88317	94888	-7.3	-7.5	-6.9
32	104524	113339	96077	104184	103686	111865	-7.8	-7.8	-7.3

Table A12. DDG 51 stern flap trials data estimate, no wedge, 1% flap installed at 10°

	Stern Flap 1% @ 13° Installed Behind Wedge				Stern Flap 1% @ 10°, No Wedge		
	USS RAMAGE Trials			3rd Order	Model 5513	Full-Scale	Full-Scale
Ship Speed (knots)	Baseline Total Shaft Power PD (hP)	Stern Flap Total Shaft Power PD (hP)	Stern Flap Power Reduction (%)	Curve-Fit Magnitude* Scale Effects (Δ %) PD	Stern Flap Power Reduction (%) PD	Estimated^ Stern Flap PD Reduction (%) PD	Estimated Stern Flap Shaft Power PD (hP)
10	-	-	-	11.0	+2.0	-9.0	-
11	-	-	-	11.0	+1.7	-9.3	-
12	2650	2500	-5.6	11.0	+1.3	-9.7	2394
13	4065	3700	-9.0	11.0	+0.7	-10.3	3649
14	5189	4600	-11.3	11.0	+0.3	-10.7	4632
15	6250	5400	-13.6	10.8	-0.3	-11.0	5560
16	7443	6300	-15.4	10.5	-0.5	-11.0	6626
17	8893	7580	-14.8	10.1	-1.3	-11.4	7881
18	10628	9090	-14.5	9.6	-2.1	-11.8	9377
19	12594	10850	-13.8	9.2	-2.9	-12.1	11076
20	14844	12850	-13.4	8.6	-3.7	-12.3	13016
21	17302	15080	-12.8	8.1	-4.7	-12.8	15082
22	20021	17590	-12.1	7.5	-5.4	-12.9	17439
23	23101	20420	-11.6	7.0	-6.7	-13.7	19944
24	26584	23650	-11.0	6.4	-7.2	-13.6	22964
25	30937	27360	-11.6	5.8	-7.4	-13.2	26844
26	36365	31940	-12.2	5.2	-7.7	-12.9	31671
27	43291	38400	-11.3	4.7	-7.6	-12.3	37972
28	52311	47750	-8.7	4.1	-7.3	-11.4	46343
29	64639	59860	-7.4	3.6	-7.2	-10.9	57618
30	81365	73640	-9.5	3.2	-7.5	-10.7	72695
30.9	100000	85950	-14.1	2.8	-7.5	-10.3	89746
31	-	88150		2.8	-7.5	-10.3	92322
31.8	-	100000		2.5	-7.7	-10.2	113175
32	-	-		2.5	-7.8	-10.2	-

*Determined RAMAGE vs. Model 5513

^Including Scale Effects

APPENDIX B

MODEL-SCALE TRANSOM FLOW OBSERVATIONS

FIGURES OF APPENDIX B

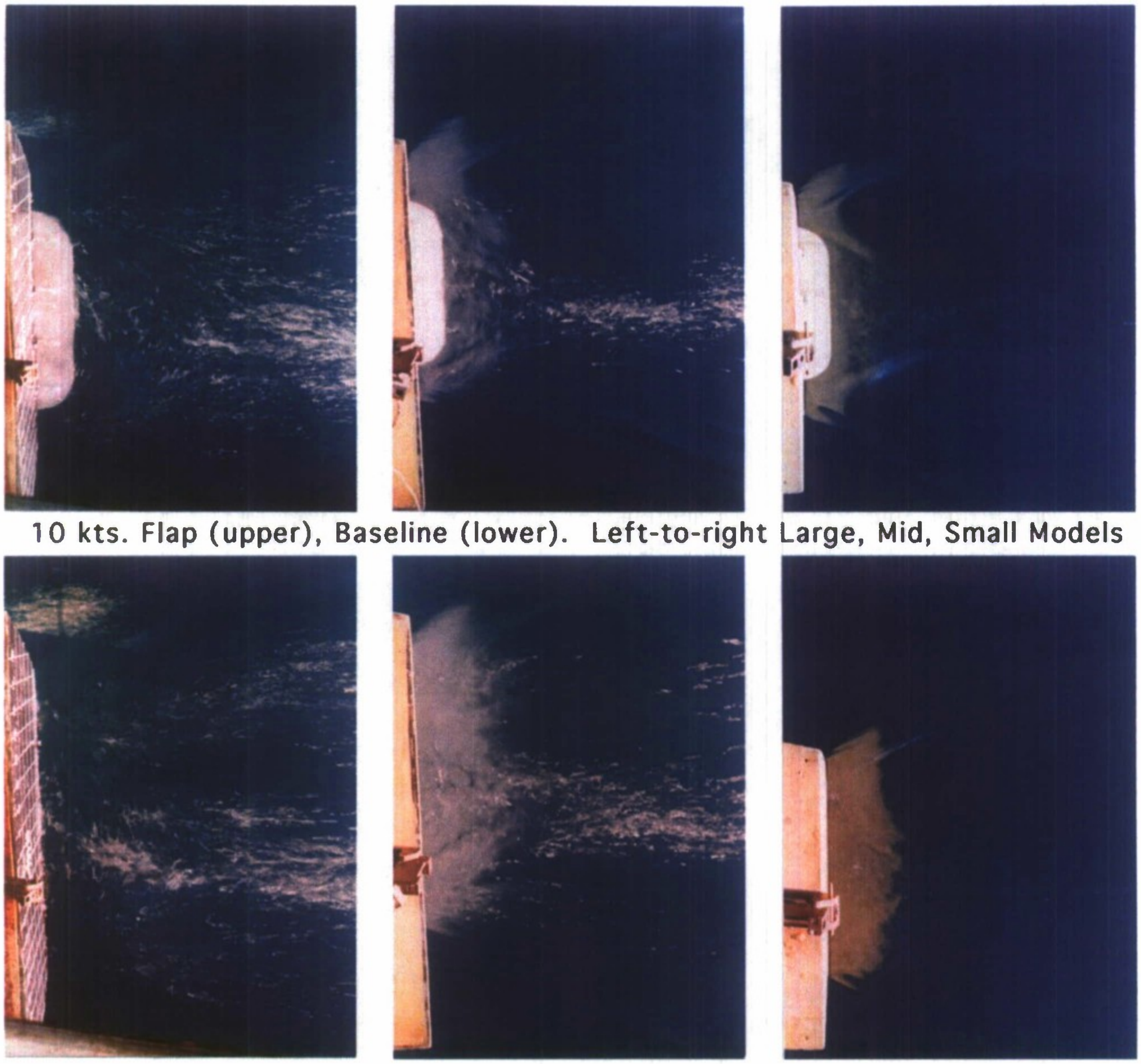


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap

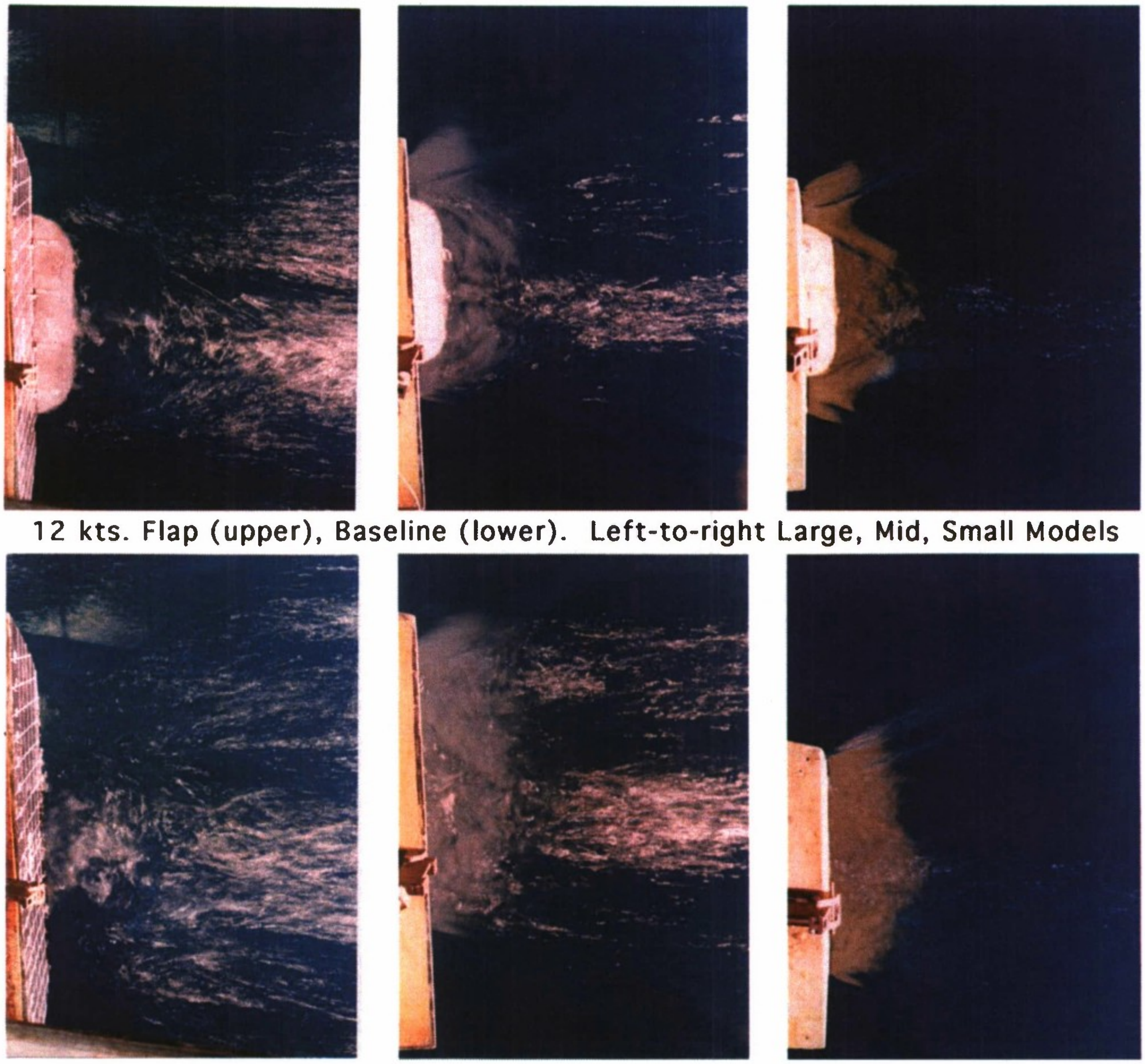
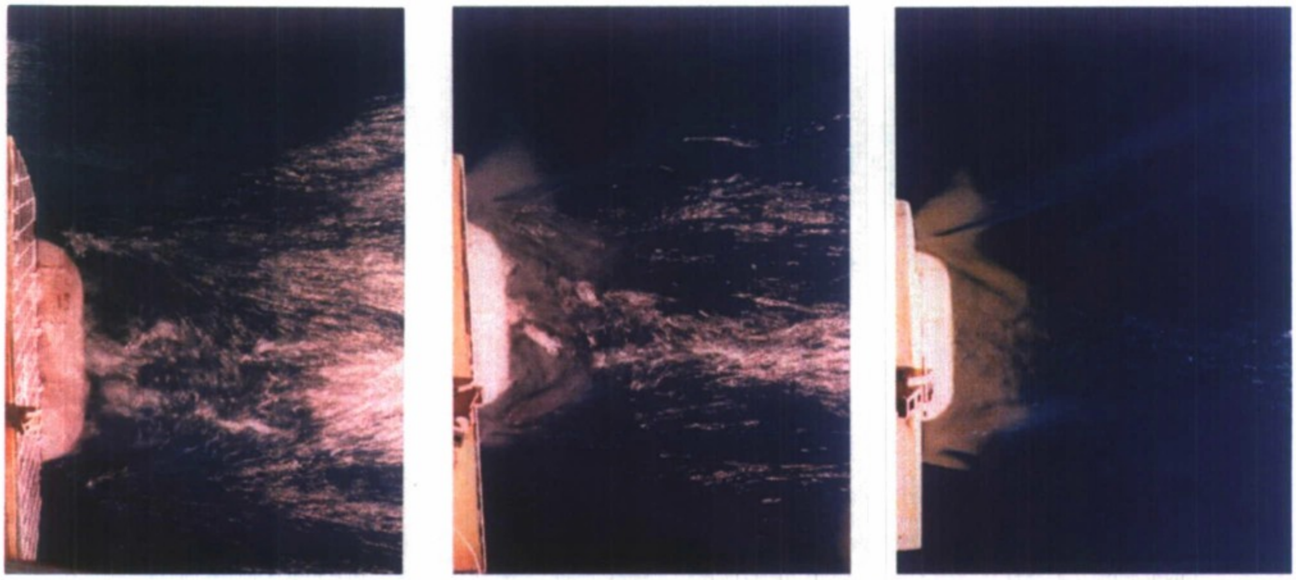


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued



14 kts. Flap (upper), Baseline (lower). Left-to-right Large, Mid, Small Models

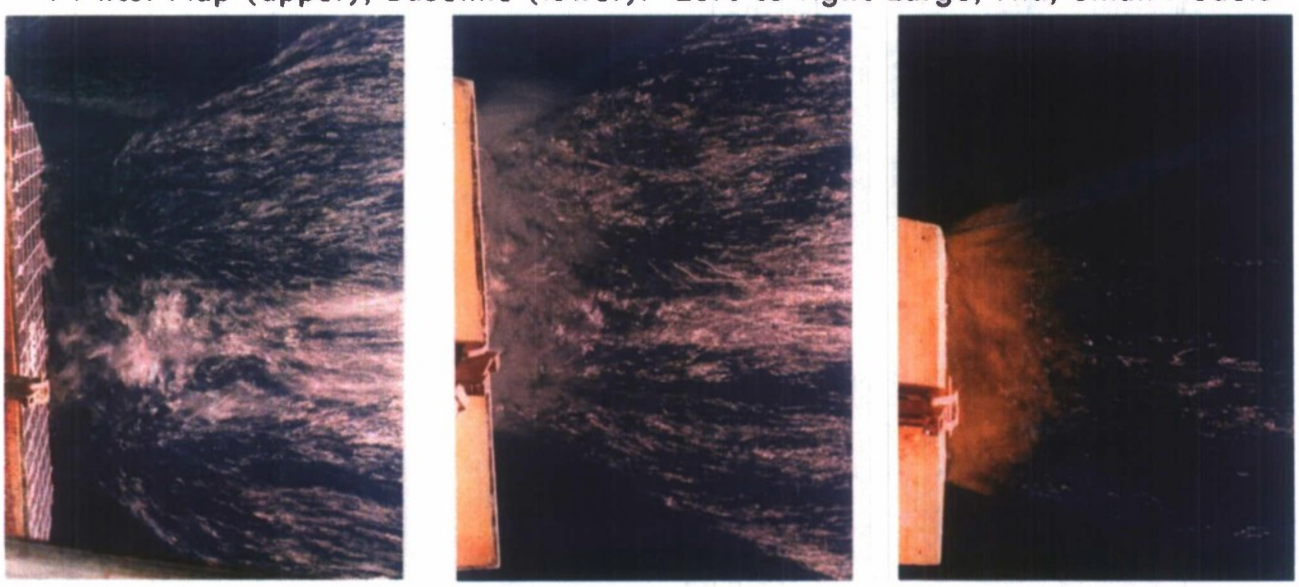


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued

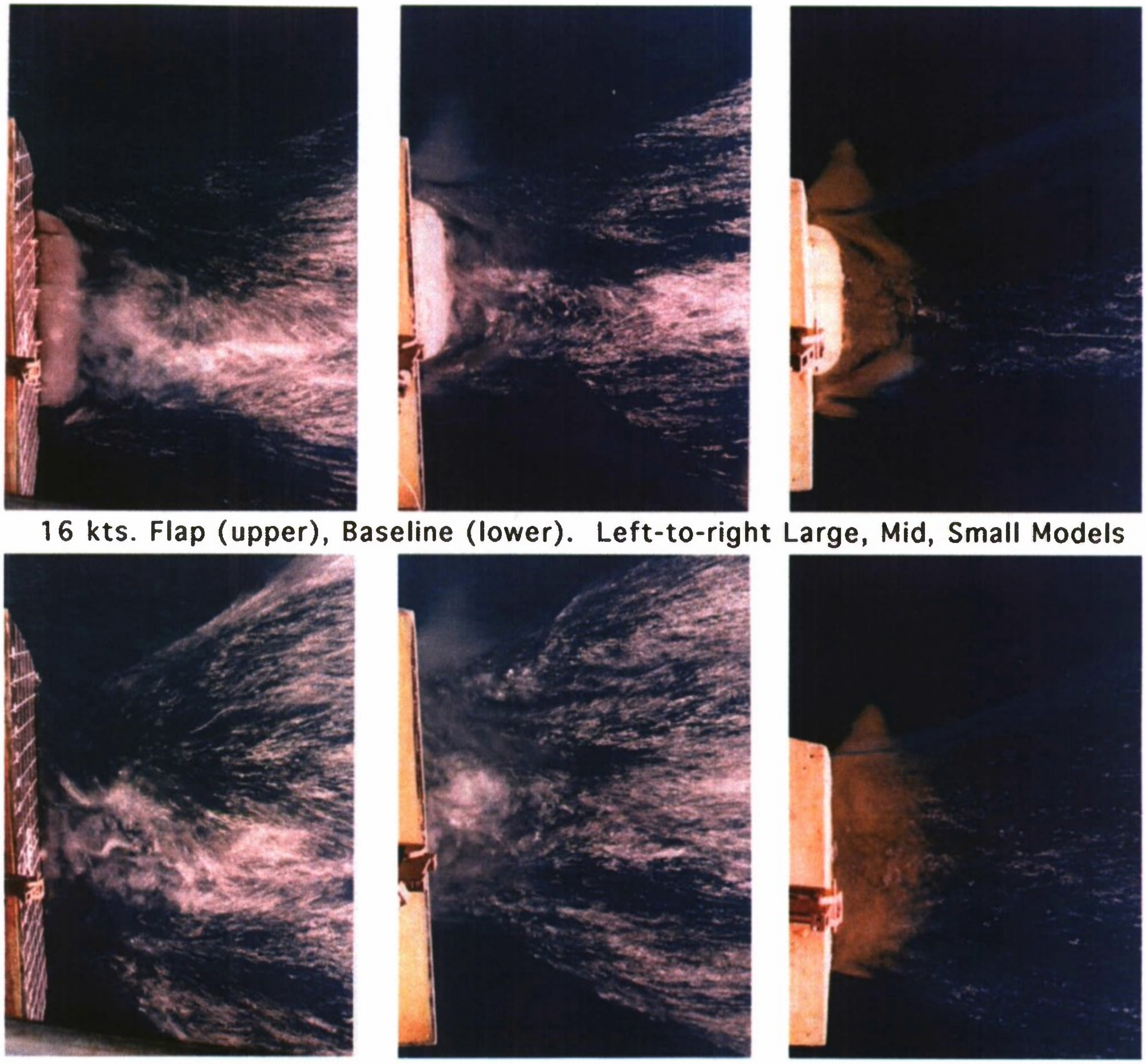
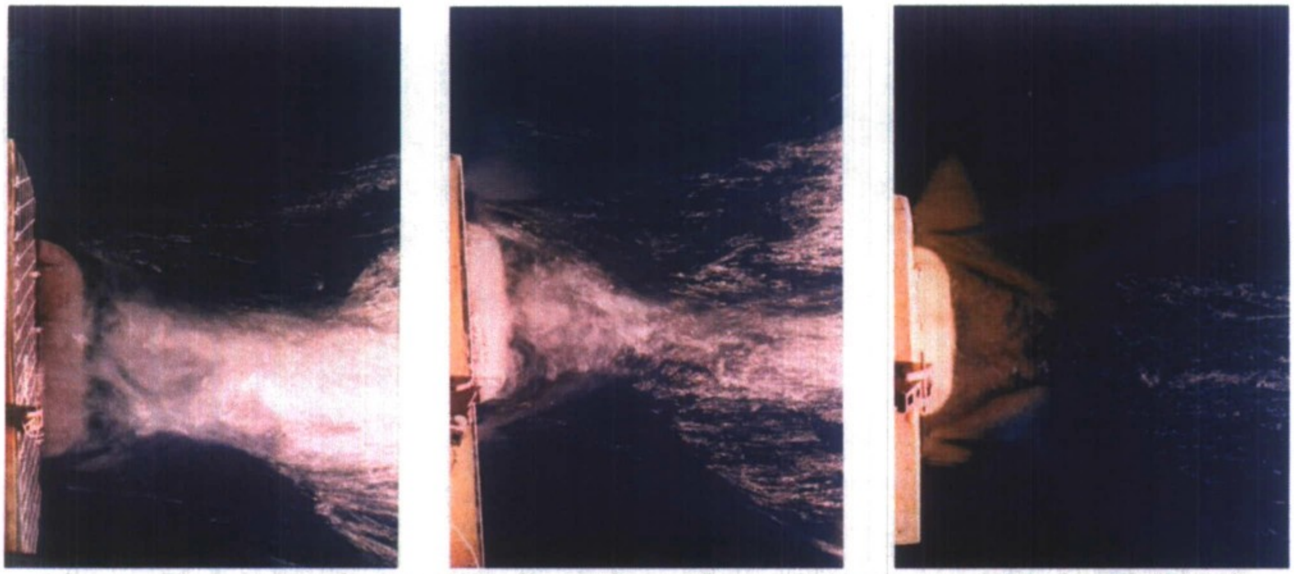


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued



18 kts. Flap (upper), Baseline (lower). Left-to-right Large, Mid, Small Models

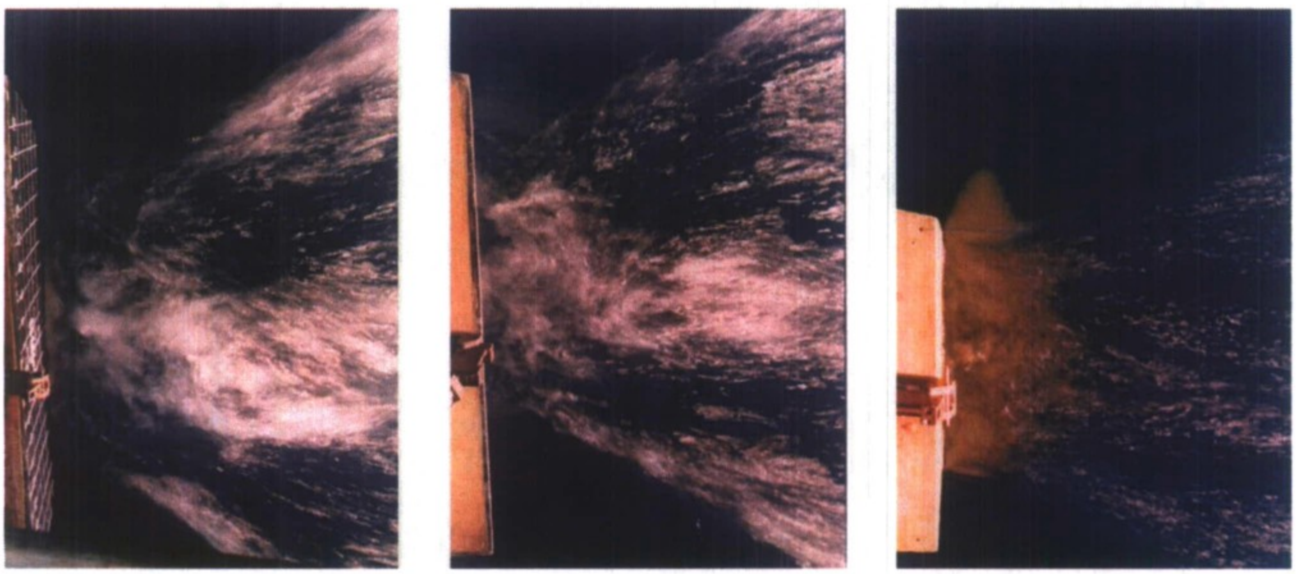
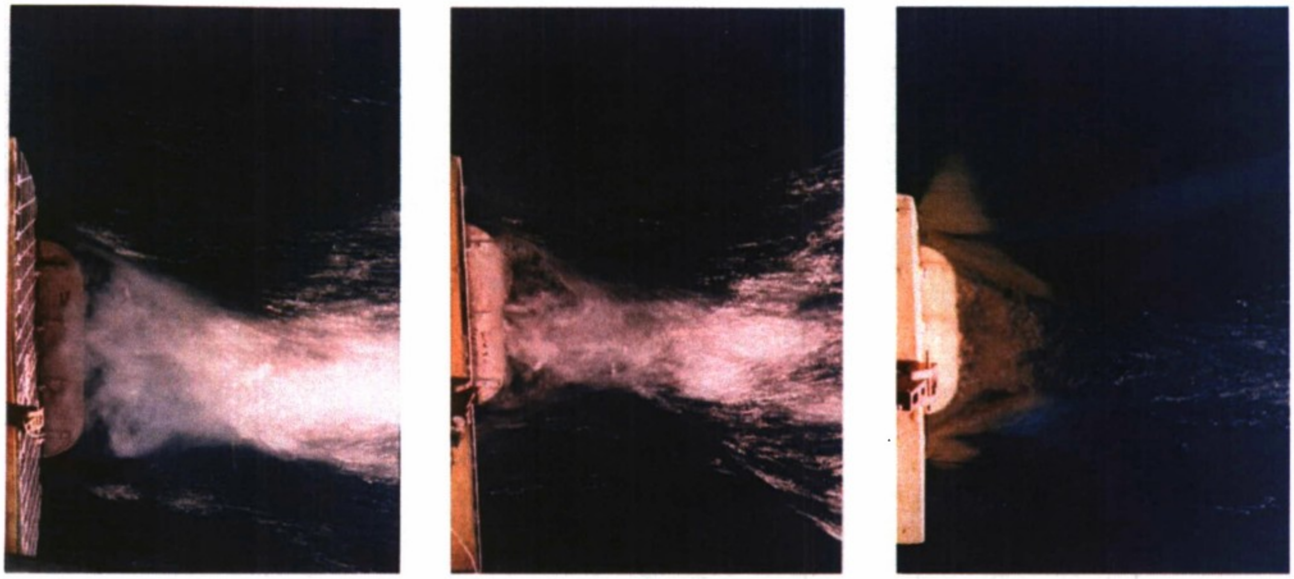


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued



20 kts. Flap (upper), Baseline (lower). Left-to-right Large, Mid, Small Models

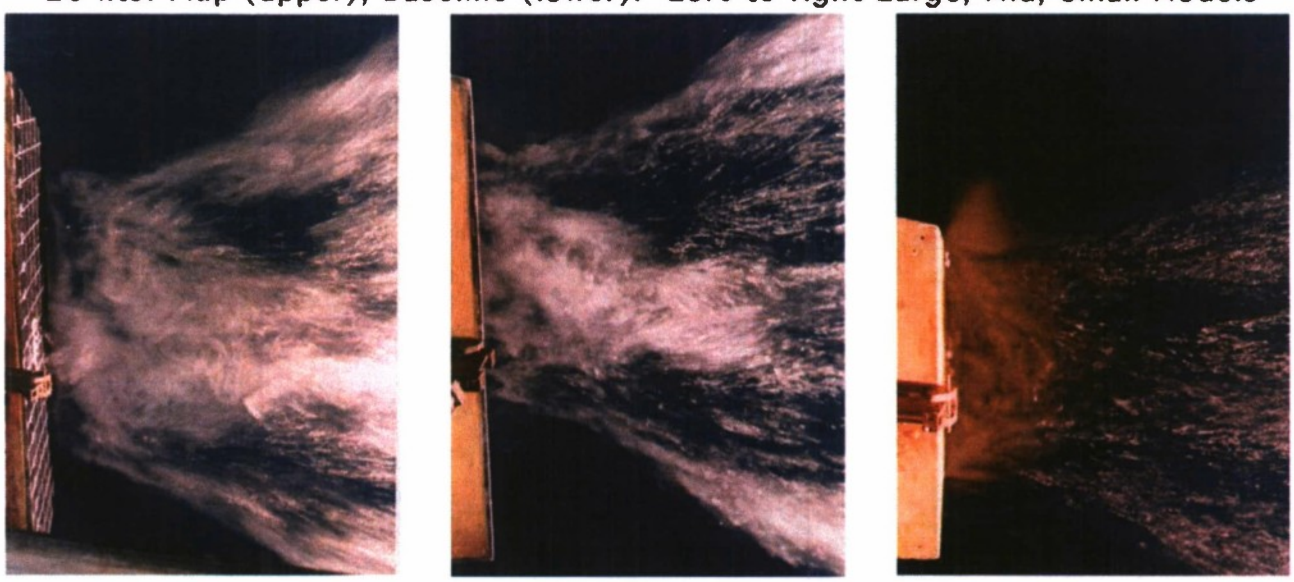
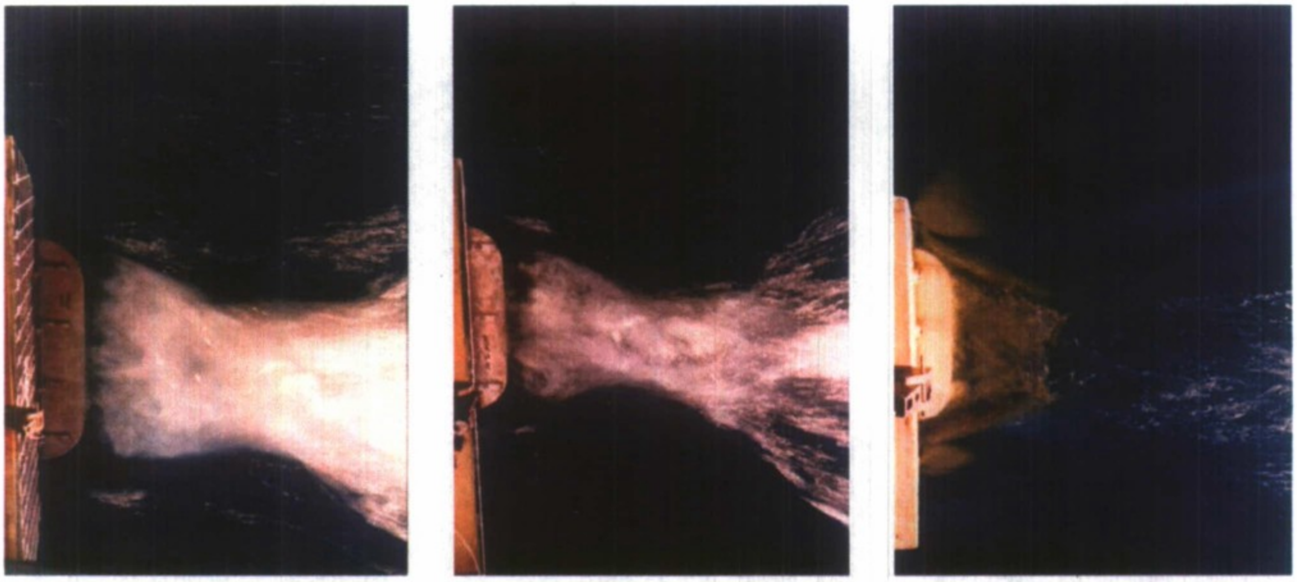


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued



22 kts. Flap (upper), Baseline (lower). Left-to-right Large, Mid, Small Models

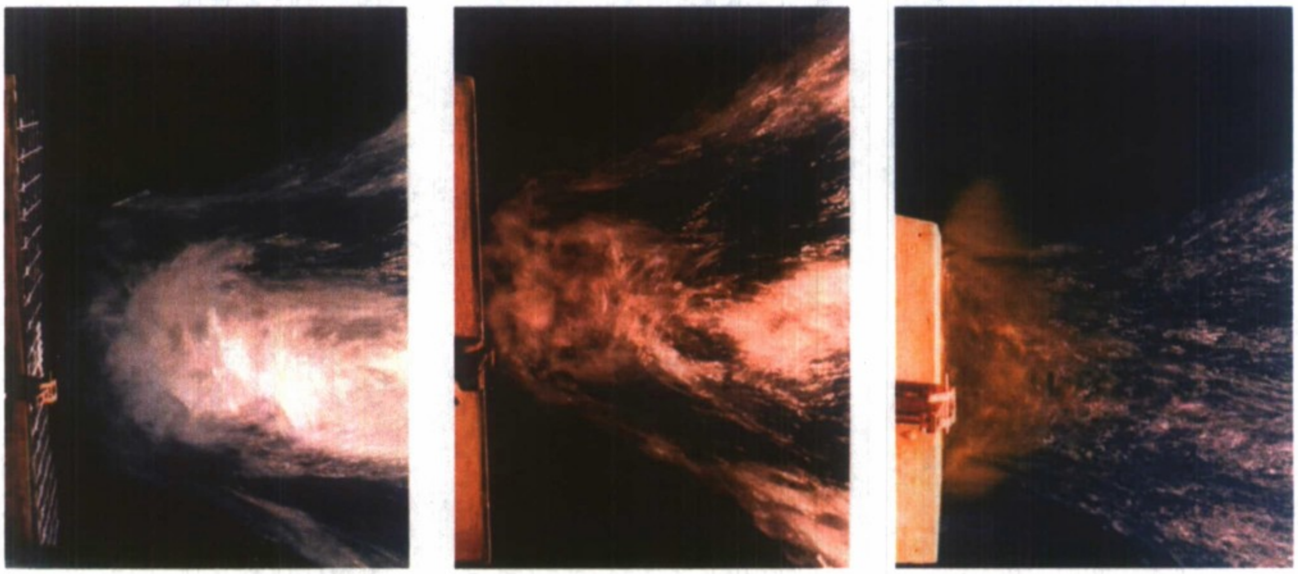


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued

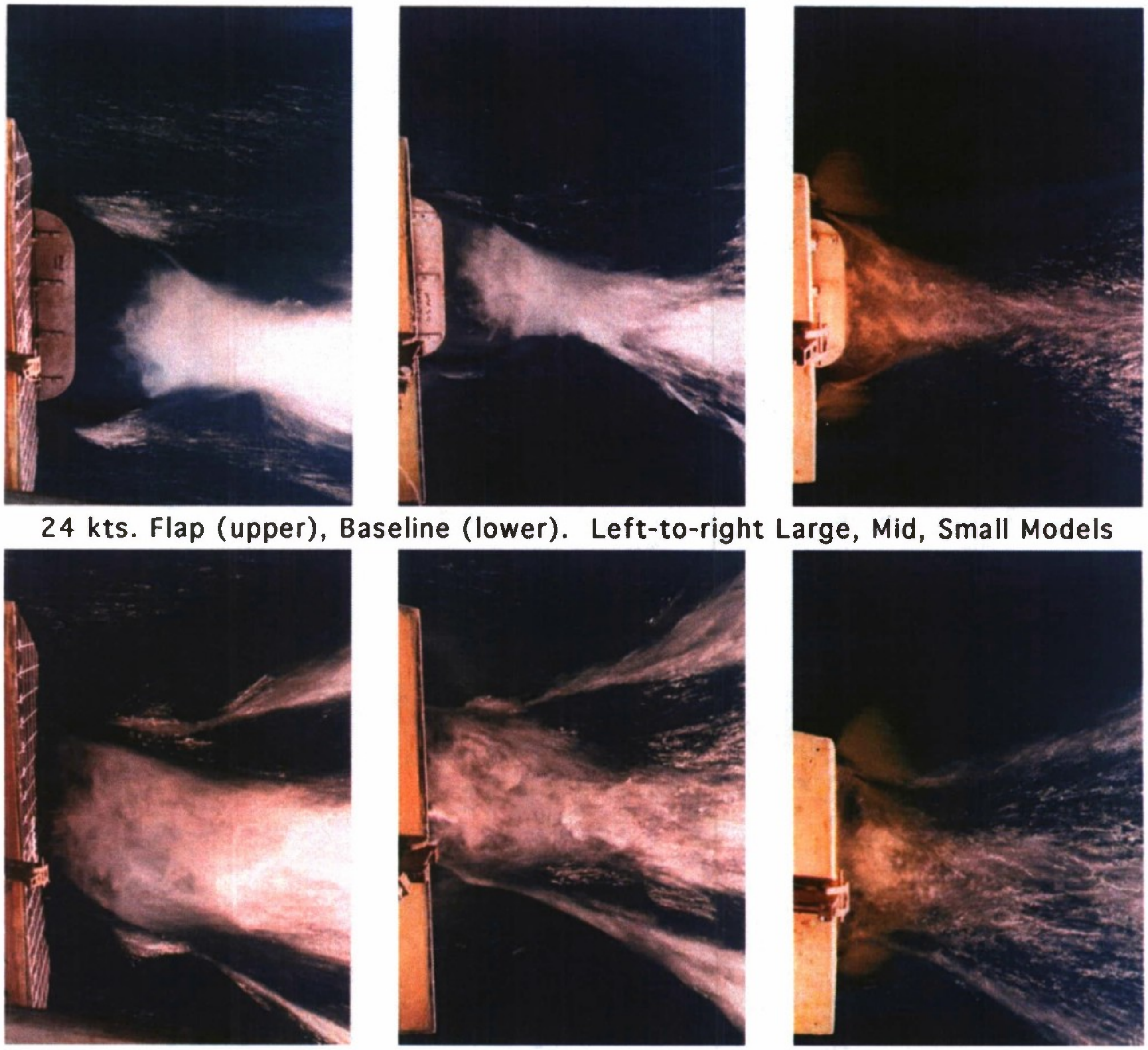


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued

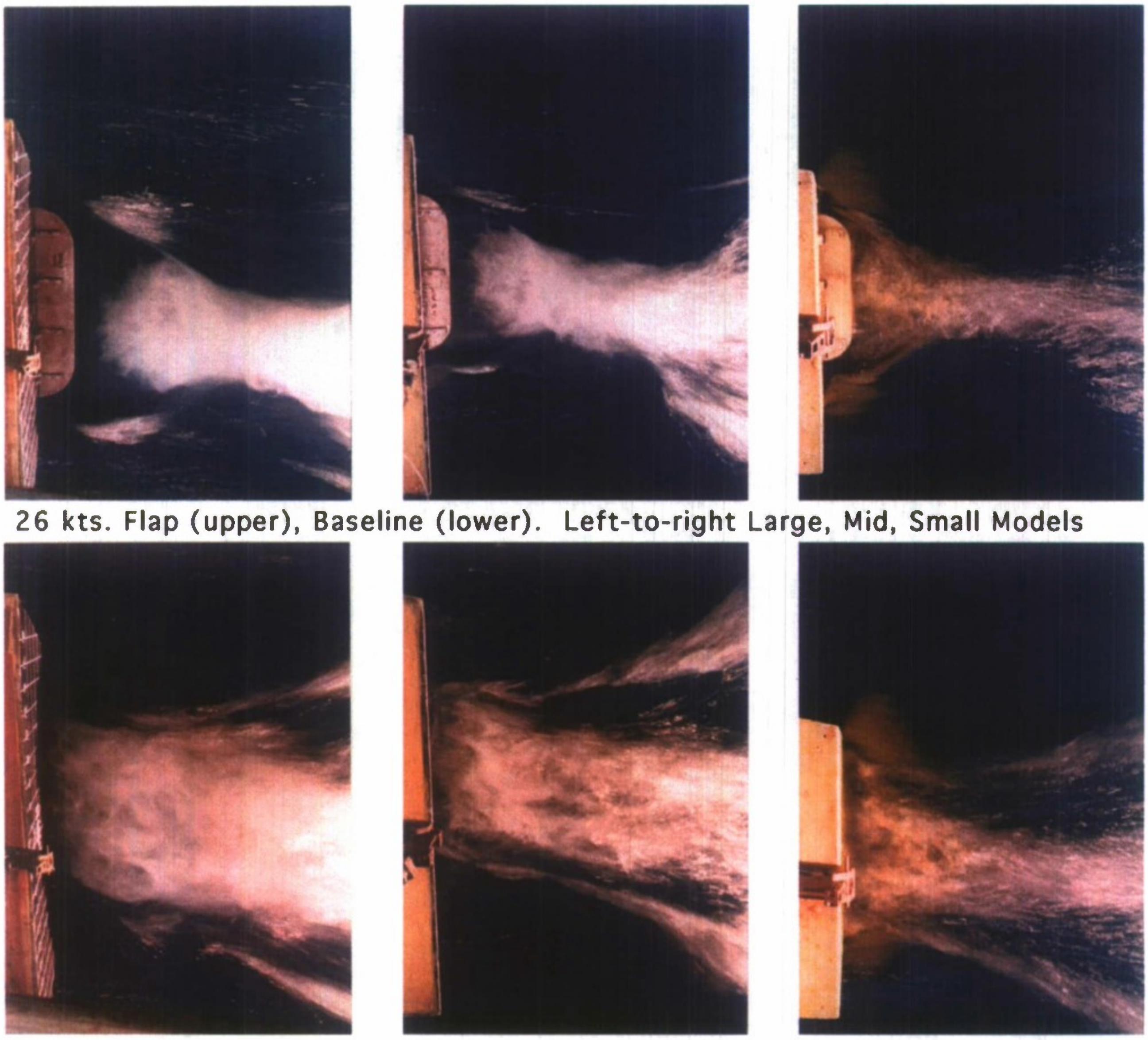
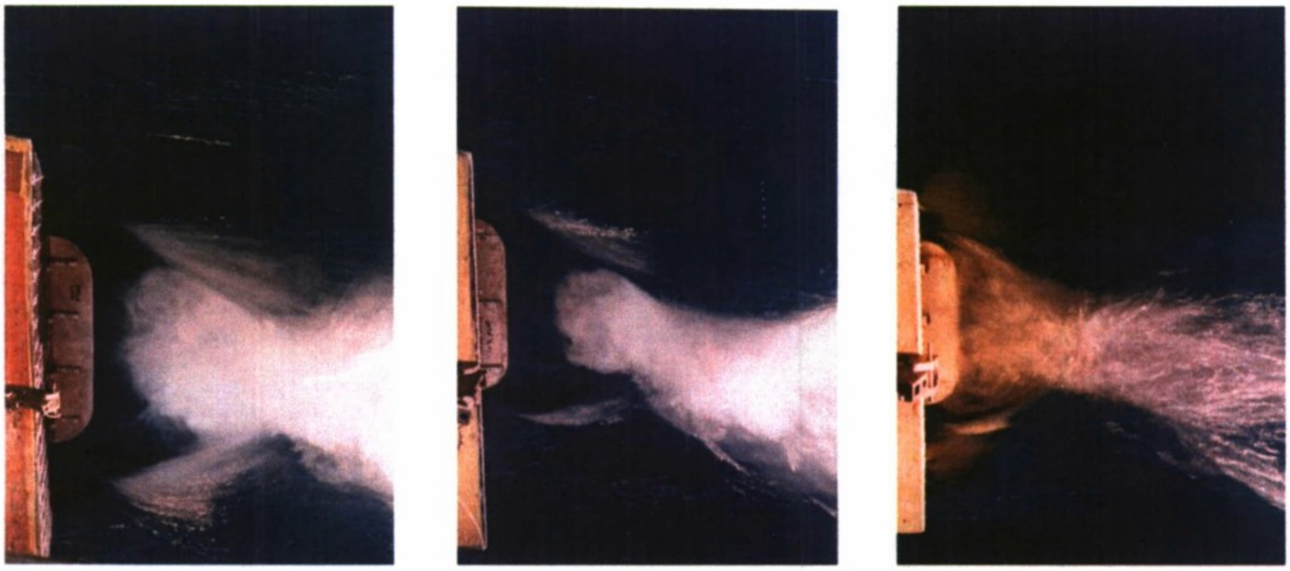


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued



28 kts. Flap (upper), Baseline (lower). Left-to-right Large, Mid, Small Models

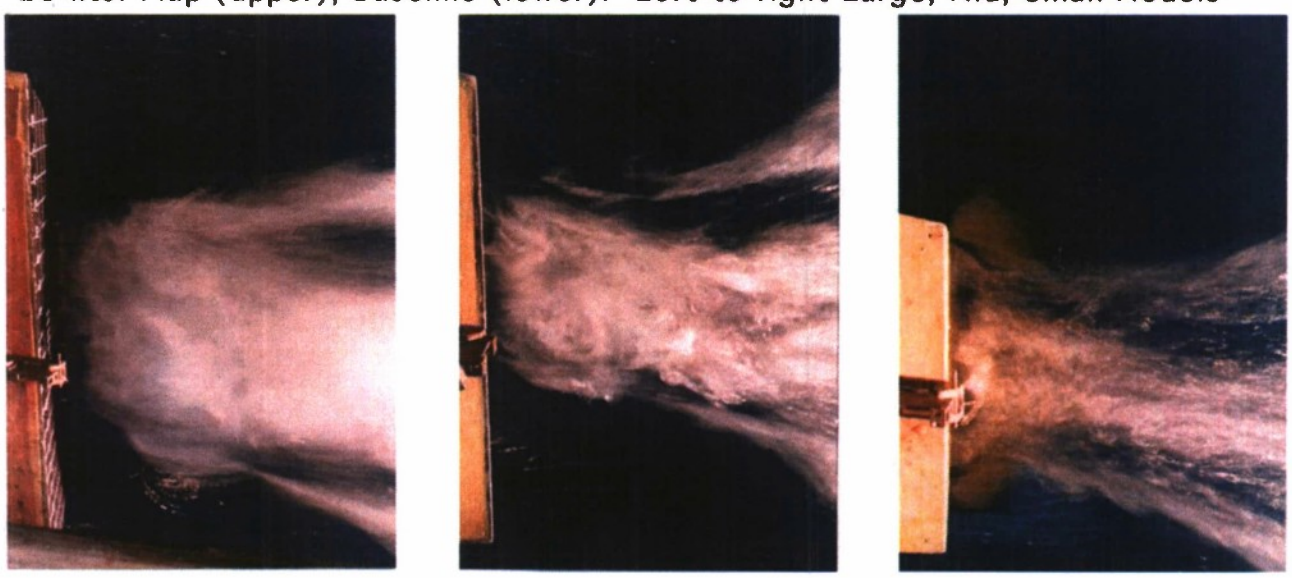


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued

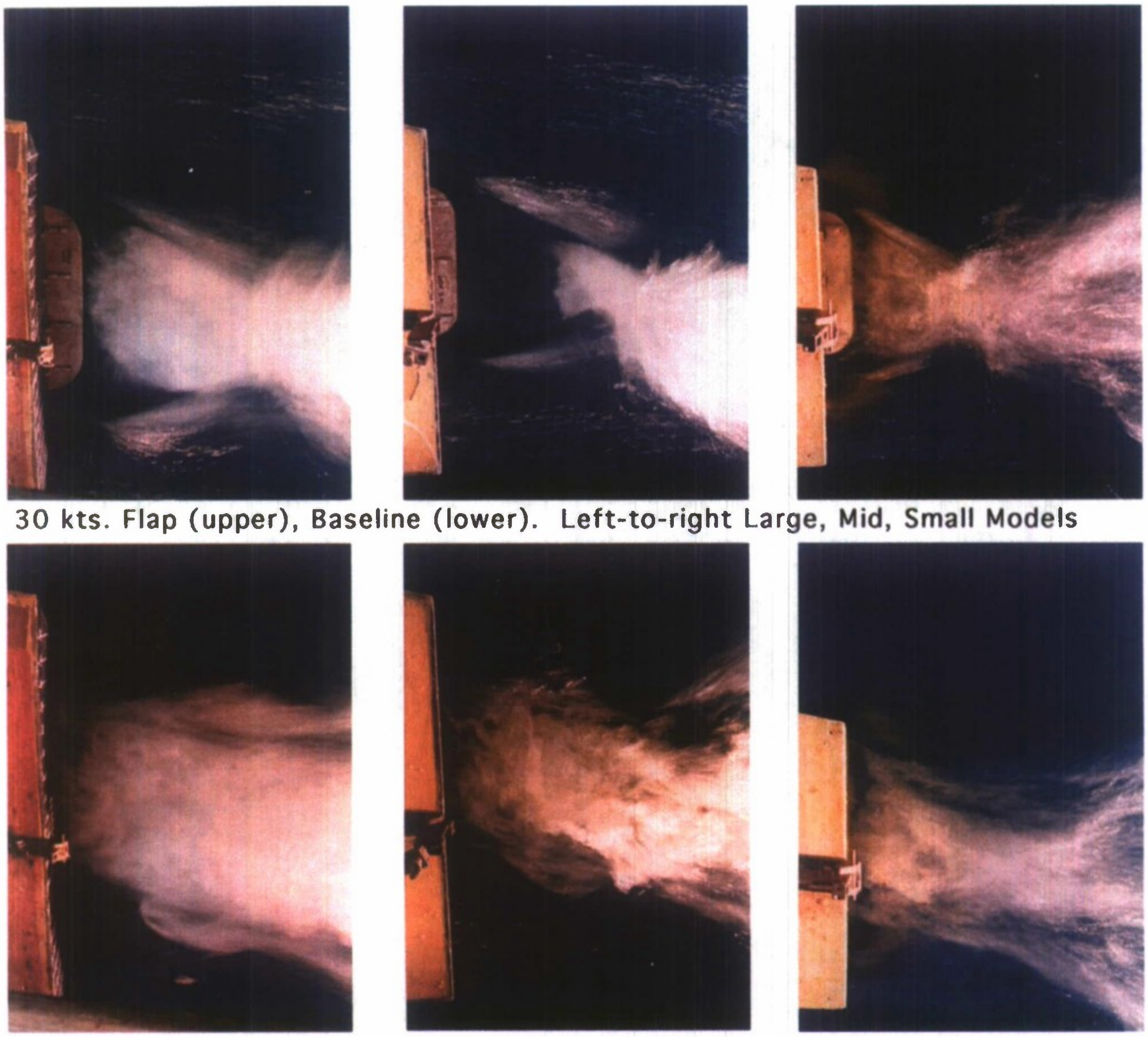


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued

32 kts. Flap (upper), Baseline (lower). Left-to-right Large, Mid, Small Models

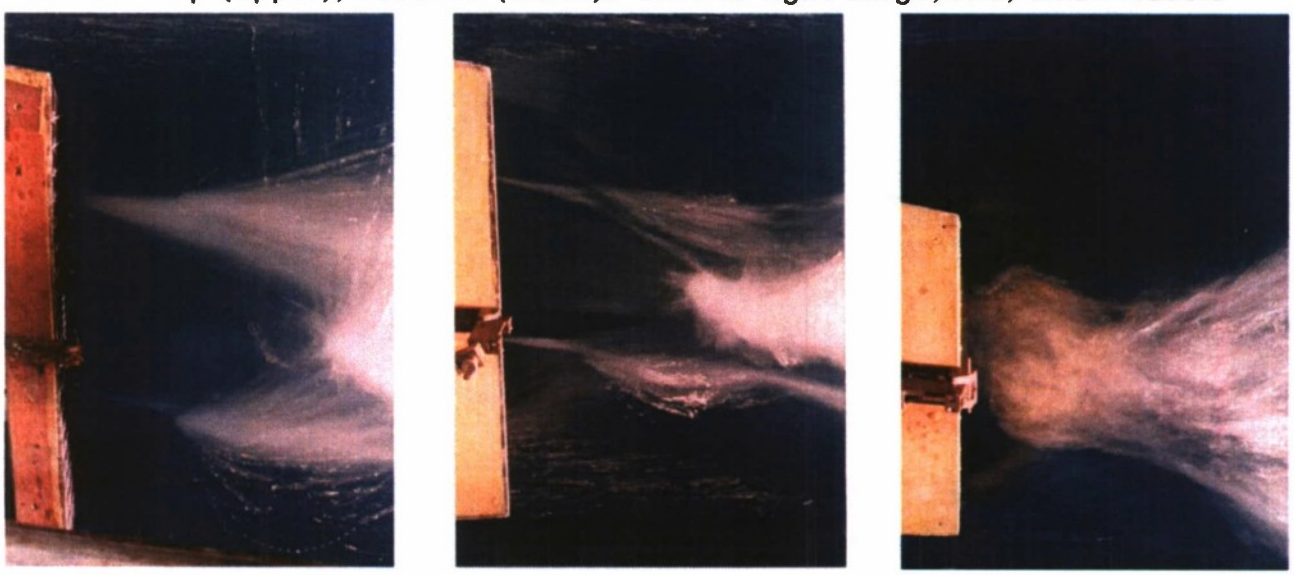


Fig. B1. DDG 51 Models 5488 (large), 5513 (medium), and 9141 (small), comparisons of localized flow patterns around transoms, equivalent speeds, with and without stern flap - continued

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