APPENDIX E-a

Naval Architecture Technical Memorandum
Plan Formulation

ART ANDERSON ASSOCIATES

RICH PASSAGE RESEARCH
PASSENGER ONLY FAST FERRY PROJECT

PHASE 1

Task 1 – Plan Formulation Technical Memorandum

TASK 1 – PLAN FORMULATION TECHNICAL MEMORANDUM

1 Executive Summary

This Technical Memorandum reports on the results of Task 1 – Plan Formulation for the Rich Passage Research Project. In this task, two subtasks were executed. The Search For State Of The Art Tools subtask involved a review of available software applications, which would enable Art Anderson Associates, Inc (AAA) to predict the near-field wake wash of certain high-speed passenger only fast ferry (POFF) vessels. This review, described herein, resulted in the AAA selection of FloSim computational fluid dynamics (CFD) software for the planned analyses. The near-field output from this CFD software will be provided for input to the Pacific International Engineering, LTD (PIE) Wake Propagation Model. To date, PIE has not provided their concurrence regarding the CFD selection, as planned.

In the Methodology Development subtask, the detailed process steps are documented here describing the establishment of low-wake wash hull candidates, eliminating criteria for down-selecting to the preferred hull types, and the final analysis required to determine the best hull type for Rich Passage POFF operations. As is the nature of research, this process is likely to evolve further as task 2 unfolds.

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TASK 1 – PLAN FORMULATION TECHNICAL MEMORANDUM

3 Introduction

Rich Passage is a narrow curving channel between the southern shoreline of Bainbridge Island and northern shoreline of the Kitsap Peninsula in Washington state. In an effort to reduce the vessel wake impact to the shoreline, a speed limit of 12 knots is imposed on ferries transiting through Rich Passage. This project is intended to derive the fast passenger ferry hull type and/or shoreline protection method that will enable fast passenger ferry operations in Rich Passage and provide 25 to 30 minute transits between Bremerton and Seattle.

This Technical Memorandum documents the AAA work completed in collaboration with PIE under Task 1 of the Rich Passage Research subcontract between AAA and PIE. Under this subcontract, AAA will conduct the low-wake wash fast passenger ferry down-selection process and near-field wake wash prediction needed for PIE to ultimately predict the shoreline effects of preferred hull forms. The subcontract provides that PIE will fund Task 2.3 Naval Architecture, based on the findings of Task 1.

A Kickoff Meeting was held on June 18th, 2004 where the contractors establish definitions and assumptions for the project. These were documented through iterative revisions to the Kickoff Meeting Notes. Most germane to these Notes is the nomenclature provided below.

Freeboard – *Coastal Engineering*: the vertical distance between the crest of a breakwater, revetment, or structure and the water level including the effects of wave action and run-up.

Freeboard – *Naval Architecture*: The distance between the water line and the lowest weather deck of a ship.

Near-field – region near the vessel characterized by impulsive impact from the vessel on the water, a region of high shear (velocity gradients) and chaotic turbulence. The near field region outer boundary is the distance to where the flow disturbance generated by the vessel has coalesced into gravity waves, approximately 2 ship lengths wide and several ship lengths aft of the vessel.

Far-field – region at some distance at which the wake-wash is characterized by surface gravity wave propagation, usually at least 2 ship lengths away on either side of the vessel track and several ship lengths astern of the vessel.

Drawdown – a lowering of the water level surrounding a vessel caused by the vessel's pressure field

Hydrodynamics – the study of fluids in motion

Run-up – the maximum elevation of the water level (or vertical position of the shoreline) above the still water level - consists of both the wave set-up (mean) and the maximum extent of swash excursion (oscillation about mean).

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Overtopping – Water carried over the top of a coastal structure due to run-up or surge action exceeding the crest height; typically expressed as a flow rate (discharge)

Directional spectrum – $S(f,\theta)$ – the variance of the water surface elevation as a function of frequency (f) and direction (θ). A complementary phase spectrum, $\phi(f,\theta)$ can be used to describe the phase of the spectrum. The phase is required to allow the surface elevation time series to be reproduced.

Variance spectral density – $S(f)$ – the distribution of surface elevation variance with frequency (f) (independent of direction).

Wake – classical naval architecture term defined as the fluid layer near the vessel's hull that possesses vorticity. Also a classical naval architecture term defined as the velocity profile in the plane of the propeller. From a lay person's perspective wake is generally surface waves generated by a moving vessel

Wash – may be a better term (Naval Architecture) for describing surface elevation and disturbance caused by a moving vessel

Wake wash – a composite term that refers to craft generated hydrodynamics including near-field and far-field effects; a general term for the wave field created by a ship and usually refers to the pattern as it spreads outward with gravity wave characteristics

Froude Number – a non-dimensional number named after William Froude. The two forms of Froude Number of concern here are the Length Froude Number (F_{nL}) and the Depth Froude Number (F_{nh}). Froude Numbers are calculated from the equation $F_n = \frac{V}{\sqrt{g_c L}}$, where L is either the length on the waterline for F_{nL} or the depth of the water for F_{nh}; and g_c is the gravitational constant.

Divergent waves – that portion of the ship's generated wave field that moves generally away from the sailing line. Above depth Froude number = 1, these waves dominate. Diverging waves are generated most notably at the bow, but are generated by other parts of the hull as well.

Transverse waves – that portion of the ship's generated wave field that runs generally perpendicular to the sailing line. Above $F_{nh} = 1$, these waves tend to disappear. Transverse waves are generated most notably at the stern, but are generated by other parts of the hull as well.

Super-critical waves – Depth Froude number $F_{nh} > 1$. The angle between the sailing line and the Cusp Locus line decreases as the vessel goes faster. There is typically no transverse wave pattern.

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Sub-critical wave patterns – $F_{nh} < 1$. The angle between the sailing line and the Cusp Locus line increases as F_{nh} increases (for a constant F_{nh} increases as the vessel goes faster). There typically are transverse waves merging with diverging waves.

Deep water – $F_{nh} < 0.57$. The angle between the sailing line and the Cusp Locus line is the classic Kelvin wave angle, 19° 28'.

Mapping parameters/data – Parameters and data that will be outputted from the AAA CFD ferry wake prediction model and input into the PIE wake propagation model.

4 Search State Of The Art Tools:

AAA in collaboration with PIE conducted an international search of the latest tools and methods for analyzing and predicting near-field wakes produced by high-speed hull forms. This took the form of a literature search as well as correspondence with leading marine researchers and CFD organizations.

Several CFD software packages were investigated, including both volumetric method and panel method types. This included discussions and demonstrations with the software companies, naval hydrodynamicists, and towing tank facilities users. A multitude of discussions were held with PIE on this subject as well. The information gathered has been compiled in a document, which includes discussions regarding various aspects of this technology, as well as a comparative table of the software packages reviewed. This document has been used as a basis for discussions with PIE and was continuously updated as the search moved forward. Volumetric method types were eliminated since they require a much greater run time than panel method and were more appropriate for very detailed analyses. Within the panel method types, a more difficult trade-off selection has been between the time domain types (TD) and quasi-static (QS) types. The quasi-static types run 4 – 5 times faster, but cannot analyze some relevant conditions as well as time domain types, such as turns, degrees of freedom, accelerations and decelerations. The three finalists reviewed are VSAero (QS), USAero (TD) and FloSim (TD).

In the science of Computational Fluid Dynamics (CFD) the usual method is to discretize the fluid domain into small cells to form a grid, and then apply iterative methods to solve the Navier-Stokes equations or simpler formulations (e.g. Euler equations for potential flow) for them.

The solution of the Navier-Stokes equation alone is sufficiently accurate for cases where there is laminar fluid flow. For turbulent flows special turbulence models must be used that introduce new terms into the equations. For many problems, the solutions for the fluid equations are obtained at the same time as are the equations describing other properties of the system. These other equations can include those describing heat transfer, chemical reactions and radiative heat transfer. More advanced codes allow the simulation of more complex cases involving multiple fluids ('multi-phase') or non-Newtonian fluids.

4.1 Finite element method:

The finite element method is used more often in analysis of structures. While applicable to fluids, the finite element method is not normally used.

4.2 Finite volume method:

The "classical" approach, most often used in commercial software. The conserving equations are solved on discrete control volumes by integration. "Finite volume" refers to the small volume surrounding each node point on a mesh. In the finite volume method, volume integrals in a partial differential equation that contain a divergence term are converted to surface integrals, using the divergence theorem. These terms are then evaluated as fluxes at the surfaces of each finite volume. The advantage of the finite volume method is that it is easily adaptable to unstructured meshes, however, requires a lot of computational time.

The following ‘finite volume” commercial software CFD products were reviewed:

- CFX (Ansys)
- Star/Comet (Adaptco)
- Fluent (Fluent Inc.)
- Phoenics (CHAM Ltd.)
- Flow-3D (Flow Science Inc.)

4.3 Panel Method.

In the panel method, one mesh is generated that represents the hull and another mesh that represents the free-surface. It requires much less computational time and is easier to learn than volumetric methods. The general consensus among the CFD community is that volumetric methods are better for analyzing the flow around the hull in fine detail e.g. the flow interaction between hydrofoil and side walls, the effect of various bulbous bows on the flow, the modeling of the flow directly behind the propeller etc. However, panel methods are sufficient for analyzing the wash generated by a vessel.

Although this method has some disadvantages, e.g. it neglects viscosity, it is relatively simple to write and is therefore often used in CFD codes by universities, institutions and smaller companies.

Commercial software utilizing the panel method include the following:

- VSAero & USAero (Analytical Methods, Inc.)
- FloSim
- ShipFlow (FlowTech)

SPLASH (South Bay Simulations, Inc.)

Of the four CFD programs that employ panel methods, ShipFlow was eliminated not due to the software itself (though a demonstration of the software was never organized) but due to difficulty in obtaining support and training. Training would be significantly more expensive for the program since it would involve bringing the trainers to the U.S. from Sweden.

4.3.1 Analytical Methods, Inc. (AMI) Software

AMI has been a company since 1971. They have two offices. One office is in Virginia that deals mostly with marine and other hydrodynamic analyses, and one office is in Redmond, WA that deals mostly with aircraft and other aerodynamic analyses. AMI offers two software packages which are applicable to our problem. The packages are: VSAero with FSWAVE and USAero with FSP.

4.3.2 VSAero and FSWave

VSAero solves three-dimensional potential flow equations using the boundary integral panel method based on Morino’s formulation for quasi-steady state conditions.

FSWave is a plug-in module for VSAero and calculates the non-linear characteristics of a free-surface disturbed by an arbitrary hull configuration. VSAero patches on the ship hull provide the pressure and skin friction distributions and hydrodynamic forces. Used together, VSAero and FSWave predict the wave forms produced by and the wave resistance of floating or submerged bodies traveling through calm water with a constant forward speed.

4.3.3 USAero and FSP

USAero solves the fluid flow equations over a specified time domain. This is particularly useful for handling accelerating/decelerating motion and turns. It can also perform calculations in six degrees of freedom (DOF). Input, output and other capability are very similar to VSAero described above.

Because VSAero uses the steady-state form of the general transport equation, and USAero uses the time dependent form of this equation, USAero takes approximately four to five times longer to do a steady-state calculation

FSP is a plug-in module for USAero designed to calculate the non-linear characteristics of a free-surface, much like the FSWave module does for VSAero.

For one to become proficient, the USAero developers recommend their five day intensive course followed by at least two months of full-time use.

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4.3.4 FloSim

FloSim is a non-linear time domain type CFD program written specifically for analysis of vessels. It is written by Brian Maskew who retired from AMI to write his own program for the Windows platform. Mr. Maskew wrote most of USAero and has incorporated the theory into FloSim as well as new algorithms and features, which are more accurate for vessel hydrodynamic analyses.

FloSim solves the fluid equations for dynamic equilibrium conditions and includes pitch (My) and sinkage (Fz), but does not currently include slip (Fx), surge (Fy), roll (Mx) and yaw (Mz). Both Mx and Mz equilibrium calculation are required for analysis of a model during a turn. The FloSim developer would be required to make program modifications by an agreed on date early next year that would include all of the necessary calculations for dynamic equilibrium solution.

4.4 Selection of The CFD Tool

The team has determined that finite volume methods are not a good choice for our CFD tool because:

- The volumetric method is very hard to learn and training would be a long process.
- There is only limited marine validation. Most uses of the volumetric method are for analysis of appendage interfaces and other small details. The method is not normally used for analysis of entire hulls.
- The volumetric method is very computer intensive, to the point where it would probably delay completion of the project.

In comparing USAero and VSAero from AMI, USAero is preferred. The team's rationale for this is:

- USAero at the same price is mathematically more rigorous
- USAero handles speeds where F_{nL} >1 better than VSAero
- USAero uses a time stepping domain so it handles unsteady states (e.g. acceleration/deceleration and variable bathymetry w/ respect to time).
- USAero handles 6 degrees of freedom, so sinkage, roll, pitch and yaw inputs can be used for analysis of wash performance in turns.

The choice of CFD tools has been reduced by the logic above to a choice between USAero with FSP and FloSim. The main author of both USAero and FloSim is Brian Maskew. AAA chooses to use FloSim because:

- FloSim has been specifically developed for analyzing vessel hydrodynamics.
- Run time efficiencies favor FloSim
- The methodology of wake attachment to the stern has been improved over USAero providing better information on near-field wave profile and better resistance prediction.

- Wave dampening methodology has been improved over USAero for near field wave predictions.
- FloSim has an improved separated transom flow model over USAero.
- FloSim input is more intuitive than USAero and thus easier to use.
- FloSim has automatic regridding options which improve consistency and efficiency while modifying vessel trim or making minor changes to model geometry.

5 Methodology Development:

AAA will collaborate with PIE to detail the analytical steps required to accomplish all of the Phase 1 tasks. This will also include defining nomenclature, data formats and parameters that are to be generated by the Wake Predictor for input to the PIE Shoreline Affects Model, data normalization parameters for conducting analyses, as well as identifying the CFD strategy that is the most appropriate for this analysis. Where the predictive objectives are outside existing commercial CFD analytical capability, other analytical methods will be identified to execute the analysis to the greatest degree of accuracy possible.

5.1 Search State Of The Art Hulls

5.1.1 Define low wake wash hull type criteria. These will include hull features that minimize the amount of hull wetted surface area and submerged volume (i.e. foils, forced air induction, passive air induction, etc.) and/or features that cause wake cancellation to some degree (i.e. multi-hulls, interceptors, trim tabs etc.).

5.1.2 Identify all possible low wake wash hull types based on the low wake wash hull criteria.

5.1.3 Document the low wake wash hull types and criteria in a table similar to that shown in the following table.

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		Low Wake Criteria	
Hull	**Feature**	Minimize Wetted Surface Area	Wake Cancellation
Catamaran	Semi or Planing	X	X
Catamaran	w/Foils	X	X
Stolkraft	Planing	X	X

5.2 Selection of preferred Hull Alternatives

5.2.1 Define wake wash hull type elimination criteria to specifically screen out all hull forms except the few best hull types. The project scope plans for no more than three preferred hull alternatives to be analyzed further in subtask 3 to determine the single best low wake hull.

5.2.2 Gather existing information that substantiates the elimination criteria.

5.2.2.1 Obtain available wake wash measurements data, and associated parameters such as speed, distance from track, displacement, water depth, etc. Also, obtain hull form particulars such as length, beam overall, passenger capacity, displacement, etc.

5.2.2.2 Obtain available literature wherein assessments have been made regarding the relative superiority/inferiority of various low wake hull types and features.

5.2.3 Apply the elimination criteria, substantiated by the referenced evidence and engineering judgment, to down-select the preferred hull alternatives.

5.3 Best Low Wake Hull Selection

5.3.1 Develop the operational requirements for passenger only ferries in Rich Passage to establish the normalized designs of the preferred hull alternatives.

Operational requirements could include:

- 150 passenger capacity
- Cruising speed 37 knots in full load condition (displacement and trim)
- Low wake wash at cruising speed in full load condition
- Low engine exhaust emissions
- Low noise emissions

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5.3.2 Define the "cases" of fast passenger ferry operation in Rich Passage to be analyzed and studied. Each case will be a unique combination of the following variables: tracks in each direction through Rich Passage (including turns), water depths (accounting bottom topography along each track and various tide levels), and speed at tidal current conditions of maximum ebb, maximum flood and slack water.

5.3.3 Prepare a preliminary design for each of the preferred hull alternatives identified in subtask 2 in that satisfies the operational requirements. Each preliminary design would include a lines drawing, weight estimate, center of gravity location, and speed-power estimate. CFD could be used as a design analysis tool in preparing the preliminary designs.

5.3.4 Using a CFD tool, run each of the preferred hull forms through all of the cases selected for analysis.

5.3.4.1 The CFD output data will include the parameter required as input to PIE's wake propagation model.

5.3.4.2 A consultant with expertise in the CFD tool and experience in modeling ships will be used to set up the models for each of the preferred hull types. AAA will provide the consultant with the preliminary designs of the preferred hull types to set up the models.

5.3.4.3 AAA engineers will receive training on the CFD tool and how the consultants set up the preferred hull models.

5.3.4.4 The CFD tool has been validated as accurate for wake wash prediction when analyzing most hull forms and features, with the exception of air inducted hull types and foil supported catamaran types. Physical model testing may be required if one of these hull types are derived to be a preferred hull type.

5.3.5 AAA will receive the models set up by the CFD consultant and use the CFD tool to run all cases on each of the preferred hull alternatives.

5.3.6 The results of each case will be transferred to PIE, who will use the data to analyze the wake propagation and shoreline impact and determine which preferred hull type and cases cause the least damage to the shoreline.

APPENDIX E-b

Naval Architecture Technical Memorandum
State of the Art Hulls

ART ANDERSON ASSOCIATES

Rich Passage Research
Passenger Only Fast Ferry Project

October 2004

Phase 1
Task 2.1 – Naval Architecture—Search State of the Art Hulls
Technical Memorandum

TASK 2.1—NAVAL ARCHITECTURE—SEARCH STATE OF THE ART HULLS TECHNICAL MEMORANDUM

Executive Summary

The objective of this subtask has been to assemble and organize wake and wake impact/erosion data from Rich Passage based on an intensive literature search. The result is a listing of nineteen candidate hull forms that could allow an environmentally acceptable fast ferry operation through Rich Passage. In accomplishing the subtask, an international search was conducted to identify high-speed vessel hull form technologies relevant to the design of a passenger only fast ferry (POFF).

In the follow-on task, 2.2, the objective will be to present the data in a non-dimensional for all of the candidate hulls (where data is complete) so that a fair comparison of the individual hullforms can be made.

The literature search was limited to information in the public domain including peer-reviewed papers, published magazine articles, reports and the Internet. Other forms of research such as personal correspondence, visits to researchers, CFD analysis, model tests, and full-scale trials were not employed. Further, to keep within the scope of strictly evaluating hull forms, “add-on” devices to alter vessel performance such as trim tabs or interceptors were not considered. This was an intensive effort and included as much of the international literature as possible was considered.

TASK 2.1—NAVAL ARCHITECTURE—SEARCH STATE OF THE ART HULLS TECHNICAL MEMORANDUM

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TASK 2.1—NAVAL ARCHITECTURE—SEARCH STATE OF THE ART HULLS TECHNICAL MEMORANDUM

1 Introduction

The objective of this subtask has been to assemble and organize wake and wake impact/erosion data from Rich Passage. The result is a listing of candidate hull forms that could allow an environmentally acceptable fast ferry operation through Rich Passage. These results will be available to any organizations interested in providing fast ferry service through Rich Passage, and to other organizations in the state and country interested in providing environmentally benign fast ferry service. In accomplishing the subtask, an international search was conducted to identify high-speed vessel hull form technologies relevant to the design of a passenger only fast ferry (POFF).

The search is intended to accomplish three purposes:

Identify possible fast ferry hull types,

Identify hull form characteristics that contribute to low wake wash, and

Compile hull form performance and wake wash data.

In this memorandum the term **hull type** is used to classify in a conceptual, qualitative way the means by which lift is generated to support the vessel's weight and carried it through the water. The term **hull form** is used to identify a particular implementation of a hull type. For example, as discussed more fully below, a catamaran is one **hull form** of the displacement **hull type.**

Subsequently in Subtask 2.2, "Preferred Hull Alternatives," the information gathered here will be used to select two, or at most three, low wake wash hull forms for analytical evaluation in Subtask 2.3, "Best Low Wake Hull Selection."

2 Approach

2.1 General

The literature search was limited to information in the public domain including peer-reviewed papers, published magazine articles, reports and the Internet. Other forms of research such as personal correspondence, visits to researchers, CFD analysis, model tests, and full scale trials specific to this project were not employed. Further, to keep within the scope of strictly evaluating hull forms, "add-on" devices to alter vessel performance such as trim tabs or interceptors were not considered. This was an intensive effort and included as much of the international literature as possible was considered.

The steps used in selecting the preferred hull form alternatives are summarized below.

1st—identify all possible fast ferry hull types

2nd—screen out hull types unsuited for environmentally benign fast ferry in Rich Passage

3rd—for remaining hull types analyze the available literature to 1) identify hull form characteristics that contribute to low wake wash, and 2) retrieve wake wash measurement data.

Hull form characteristics that contribute to low wake wash may not be mutually exclusive. However, to be considered a low wake wash hull type it must possess at least one of the identified characteristics.

Both experimental (model test) and full scale wake wash measurements were sought. But, associated hull form particulars must also have been available so that a fair (non-dimensional) comparison could be made.

4th—screen the list of all possible ferry hull types to eliminate those that do not possess at least one low wake wash characteristic identified by the literature search (provide citation).

2.2. Search State Of The Art Hulls

First, low wake wash hull type criteria was established. These included hull features that minimize the amount of hull wetted surface area and submerged volume (i.e. foils, forced air induction, passive air induction, etc.) and/or features that cause wake cancellation to some degree (i.e. multi-hulls, interceptors, trim tabs etc.)

Second, all possible low wake wash hull types based on the low wake wash hull criteria were identified.

Third, the low wake wash hull types and criteria documented in tabular form.

2.3 Identify preferred Hull Alternatives

Define wake wash hull type elimination criteria to rationalize why all hulls that meet the low wake wash hull type criteria are inferior to the few best hull types. This will include issues such as wake reduction evidence, operational feasibility, etc. The project scope plans for no more than three preferred hull alternatives to be analyzed further in subtask 2.3 to determine the single best low wake hull.

Gather existing information that substantiates the elimination criteria.

Obtain available wake wash measurements data, and associated parameters (to the greatest extent practicable) of the measurements such as speed, distance from track, displacement, water depth, etc. Also, obtain hull form particulars (to the greatest extent practicable) such as length, beam overall, passenger capacity, displacement, etc.

TASK 2.1—NAVAL ARCHITECTURE—SEARCH STATE OF THE ART HULLS TECHNICAL MEMORANDUM

Obtain available literature wherein assessments have been made regarding the relative superiority/inferiority of various low wake hull types and features.

Apply the elimination criteria, substantiated by the referenced evidence and engineering judgment, to down-select the preferred hull alternatives.

3 Hull Types

3.1 General

One common scheme used in the advanced marine vehicle field to classify hull types is the "lift triangle" or "sustention triangle" [1], [2][1] as illustrated in Figure 1. The three corners of the triangle define primary means—buoyant lift, dynamic lift, and powered lift— by which lift is generated to support the vessel's weight. Hull types employing a combination of primary means are located along the edge connecting the corners to indicate, relatively, how much lift is generated by each means.

Another scheme used to classify hull types is the "lift pyramid" [3] as illustrated in Figure 2. The pyramid is a tetrahedron with four vertices each of which represents a "pure" hull type—hydrostatic lift, hydrodynamic lift, aerostatic lift, and aerodynamic lift. Hull types employing combinations of pure types are located along the edges connecting the vertices to indicate, relatively, how much lift is generated by each pure type.

Hull type classification schemes are introduced here to ensure that all hull types are considered. All hull types have been used at one time or another for fast ferries [3], although not all of these implementations are suitable for Rich Passage. This report provides a description of hull types with a brief discussion of their advantages and disadvantages for fast ferry service is given below.

3.2 Displacement Hulls

3.2.1 General

Displacement hulls (buoyant lift vessels in the lift triangle) support the vessel's weight through hydrostatic buoyant force. Forward motion is not required to maintain lift. On the lift pyramid displacement hulls are the "pure" hydrostatic lift hull type. Displacement hulls can consist of one (monohull), two (catamaran), three (trimaran), four (quadramaran), or even more separate immersed buoyant bodies connected together structurally above the waterline. For this project displacement hulls of three or more separate immersed bodies are grouped together as "multi-hulls". Displacement hulls are by far the most common hull type.

[1] Numbers in brackets refer to references in Section 9

Advantages: Displacement hulls are efficient at carrying high payloads with small installed propulsion power. One reason for this efficiency is that displacement hulls tend to have relatively low design speed. Relatively large changes in payload can be accommodated without degrading performance, although lower payloads generally lead to lower wake wash. Similarly, moderate shifts in LCG do not significantly alter operating trim or degrade performance.

Disadvantages: Due to the nature of wave making, installed power requirements increase rapidly with increased design speed for a given length of vessel. Also, with increased design speed the surface waves become larger, therefore wake wash is increased. Displacement hulls suffer from speed degradation with increasing rough water.

3.2.2 Displacement Multi-Hulls

Displacement multihulls have similar advantages and disadvantages as a monohull. However each individual immersed body of displacement multi-hulls tends to be more slender than that of a monohull.

Advantages: Displacement multi-hulls generally have higher hull speeds largely due to their more slender immersed bodies. This higher speed can be maintained in rough water. The spacing of the individual immersed bodies also results in greater useable deck area than monohulls. Wave cancellation can result from judicious multihull configuration thus, resulting in lower wake wash.

Disadvantages: Bending and dynamic pressure loading of the cross structure connecting individual immersed bodies can severe. A more complicated structural may be needed to react to these loads, which can increase construction costs. Depending upon route and terminal facilities the greater beam of displacement multi-hull could result in unwanted operating restrictions.

3.2.3 Small Waterplane Area Twin Hull (SWATH) Vessels

SWATH's consists of two submerged parallel torpedo-like hulls attached to two or more streamlined struts that pierce the water surface and support a platform carried above the water. The small waterplane area, which is the principal feature of SWATH's, greatly reduces the vessel's wave induced motions. However, the small waterplane area makes SWATH's sensitive to changes in weight and LCG. To compensate an active ballast system is installed for maintaining desired draft and trim.

Advantages: SWATH's provide a very stable platform in rough water. The surface piercing struts, which are usually thin, contribute to reduced wave-making and hence may also contribute to low wake wash.

Disadvantages: Construction costs of SWATH's are higher than conventional twin hulled vessels due to their more complicated cross deck structure and the installation of active ballast systems and increased labor costs to construct the hulls.. In addition, many SWATH designs incorporate an active ride control system that further increases construction cost. SWATH's have deep draft often resulting in severe operating limitations.

3.3 Planing Hulls

Planing hulls derive the majority of their lift from dynamic lift created by pressure on the bottom due to high speed, and the small remainder from hydrostatic lift. At full planning speed the vessel is essentially traveling along the surface of the water. Forward motion is required for a planning hull to generate lift, and attainment of a certain speed (which depends on the design of the vessel) is necessary to generate the full dynamic lift. Below this speed the vessel's resistance is generally greater than when fully planning. Sufficient power must be installed to overcome the increased resistance and reach full planing. Planing hulls are most often monohulls, but planning catamarans have been used successfully as high speed ferries.

The vessel's bottom, or planning surface, is usually sloped upward from the centerline. The angle of the slope is the deadrise angle, and an important variable in the design. The chine, or transition from bottom surface to the vessel's side can be either a sharp angle (hard chine) or rounded (soft chine). The choice of hard chine or soft chine influences both planning qualities and seakeeping.

Advantages: At fully planing speeds, wavemaking resistance and wake wash decrease with speed. Because they ride on the surface of the water planing vessels usually do not have draft limitations. A hard chine planing vessel inherently has better seakeeping, in particular roll damping, than a soft chine vessel.

Disadvantages: Planing vessels need to be relatively light with relatively large bottom area in order to keep required installed power to reasonable levels. Constructing vessels with such large power to weight ratios, and planing surface area to weight ratios may require expensive "exotic" materials and/or specialized processes.. They are inefficient when not at planing speeds and are uneconomical when run at lower speeds. Proper performance is very sensitive to the attitude, or angle of attack, of the planning surface. Thus planing vessels are very sensitive to shifts in LCG that alter operating trim, which can degrade performance and increase wake wash.

3.4 Hydrofoils

Hydrofoils (dynamic lift vessels in the lift triangle) lift their hulls out of the water at operating speed by the upward hydrodynamic force generated by an immersed foil system. When the hull is completely lifted out of the water the vessel is said to be foilborne. The foils are attached to the hull by struts. The foils themselves generate lift similar to airplane wings. Forward motion is required for the foils to generate lift, and attainment of a certain speed (which depends on the design of the vessel) is needed to lift the hulls out of the water.

Two types of foils systems are used. Surface piercing foils are generally u-shaped or v-shaped with the upper ends above the water surface. This configuration is self-stabilizing, but as the upward hydrodynamic force increases with increased speed the vessel lifts more and a smaller amount of the foil remains immersed. Fully submerged foils are generally straight with both ends immersed. This configuration is not self-stabilizing so a more complicated active control system is required. Upward hydrodynamic force can be controlled by varying the foil's angle of attack to maintain the vessel at a constant height above the water as speed is increased.

Advantages: Because the hull is lifted completely out of the water when hydrofoils are at operating speed no waves are generated except by the struts. Hydrofoils are therefore inherently low wake wash hull. Properly designed the vessel motions when foilborne are uncoupled from the motions of ambient waves. Hydrofoils can maintain speed in rough water better than more conventional vessels, and with considerably lower vertical accelerations.

Disadvantages: Hydrofoils are weight sensitive. This often results in the selection gas turbines for propulsion prime movers because of their high power to weight ratio. Gas turbines, however, produce high levels of airborne noise. Although hydrofoils do show promise with regard to wake reduction, the development of these vessels has been plagued with high cost of maintenance and construction costs. When foilborne a series of shafts and right-angle gears are needed to transmit propulsive power to submerged propulsors. For fully submerged foil systems the active control system can be relatively complex. Expensive gas turbines combined with a right-angle drive train and installation of a complicated active control system make current hydrofoils more expensive to construct, operate, and maintain.

3.5 Foil-Assisted Hulls

A foil-assisted hull combines the dynamic lift of a hydrofoil with the buoyant lift of a displacement hull. The lift provided by the foil system specifically designed to lift the vessel only partially out of the water. Forward motion is required for the foils to provide their lift. The foil system is normally designed for optimum performance at a pre-selected speed with fixed foils. Foil-assisted hulls are usually catamarans or multi-hulls.

Advantages: With the vessel partially lifted out of the water, wave making resistance is decreased which results in a reduction of installed propulsive power and lower wake wash. Since a portion of the hull remains immersed conventional propulsion system arrangements (i.e. in-line shafts and propellers, waterjets) can be accommodated. Moveable foils that can alter their angle of attack can be used, which provides a measure of ride control and active trim control further lowering wake wash.

Disadvantages: The foil system increases construction cost, especially if the foils are moveable. Foil-assisted hulls are weight sensitive. Performance is degraded when operated at speeds below the optimized design speed.

3.6 Air Cushioned Vehicle (ACV)

ACV's (powered lift vessels in the lift triangle), also called hovercraft, provide lift to support the vessel's weight by a cushion of pressurized air that is pumped under the vessel by large blowers. Skirts, usually flexible, extend down into the water to keep the air cushion intact. Forward motion is not required to maintain the air cushion. At speed the small portion of the skirts that are immersed virtually eliminates wave-waking resistance and frictional resistance is very small. As a consequence high over-water speeds can be attained with relatively small propulsive power. The air cushion provides a soft suspension for going over rough seas. An ACV is also capable of "flying" over smooth ground [4].

Advantages: Largely due to having so little volume immersed ACV's have low wake wash. Payload capacity can be high, however the higher air cushion pressure needed to support a high payload usually increases power requirements for lift fans. ACV's can operate over virtually any type of surface (including deep water, shallow water, the surf zone, mud, marsh land, solid ice, and broken ice) so long as the slope is not too great. Because of this terminal requirements are minimal, although ACV's are generally "moored" on a solid surface instead of waterborne.

Disadvantages: Construction and operating costs are generally higher than more conventional vessels. High wear rate of the flexible skirt contribute to increased maintenance costs. In operation ACV's have high levels of airborne noise caused by high tip speeds of propulsion airscrews and lift fans. The air cushion can throw up considerable quantities of sand or saltwater spray that can impair the vision of the operator and/or interfere with the vessel's surroundings. Because so little volume is immersed ACV' can be difficult to maneuver and control. To compensate for poor maneuvering bow thrusters are sometimes used.

3.7 Surface Effect Ship (SES)

A SES combines the powered lift of an ACV with twin rigid sidewalls of a catamaran. Flexible seals fore and aft contain a cushion of pressurized air between the sidewalls. Forward motion is not required to maintain the air cushion. Full displacement side hulls allow the vessel to operate as a displacement catamaran at low speeds when off cushion.

Advantages: The SES' capability of operating hullborne at low speeds and on cushion at higher speeds allows efficient operation where low speed maneuvering or patrolling is required. Even though because of the rigid side walls a SES must be operated and moored waterborne, freeboard is adjustable by varying the pressure within the air cushion. An adjustable freeboard can be advantageous when loading and unloading passengers. At operating speed only a relatively small portion of the sidewalls is immersed, which leads to low wake wash.

Disadvantages: Construction and operating costs are generally higher than more conventional vessels. High wear rate of the flexible seals contribute to increased maintenance costs. SES' are weight sensitive. On cushion lift fans have a maximum pressure they can generate so an increase in vessel weight increases the draft of the fixed sidewalls, which increases wave and wake wash. Similarly, shifts in LCG will alter operating trim, which can increase wake wash. SES motions have been reported to like riding over cobblestones.

3.8 Wing in Ground Effect (WIG) Vessels

A WIG (also called wingship or ekranoplan) is an airplane operating close to the ground or water surface to take advantage of the "ground effect", which results in a reduction of lift-induced drag. Properly designed a wing will have higher lift-to-drag when near the ground. Existing WIG's are demonstrators; none have been used in commercial passenger operations.

Advantages: Once airborne WIG's have no contact with the water, allowing them to operate at aircraft-like speeds significantly greater than high-speed waterborne craft.

Disadvantages: Construction costs are high because the sophisticated structure and control systems of WIG's are more aircraft-like than marine vessels. WIG's must have take-off and landing areas near their terminals, and the terminals must be specifically design to accommodate the WIG's airplane-like configuration. WIG's have operational limits of sea state and wind speed that could affect scheduling of regular service. It is unclear which regulatory agencies would have jurisdiction over the construction and operation of WIG's, or how passenger vessel regulations might affect design. Historically, the development of WIG vehicles have been plagued with accidents and controllability issues.

3.9 Air-Lubricated Hulls

Air-lubrication attempts to reduce hull frictional resistance by creating a layer of mixed air and water at the surface of chambers or tunnels incorporated into the hull form. This is accomplished by careful shaping of the hull, especially the forward portions, so as to funnel the air to mix with the water. Forward motion is required to develop sufficient pressure via a ram-air effect to drive the mixing. Some air-lubricated hulls [5] incorporate features such as steps and sharp transitions of cross-sectional area to utilize the ram-air to create an air cushion toward the rear of the vessel for additional reduction in resistance. Bottom surfaces outside of those that are designed to be air-lubricated are usually planning surfaces.

Advantages: The lower resistance of air-lubricated hulls means less installed propulsive power. Air-lubricated hulls tend to be low wake wash vessels.

Disadvantages: Hull construction to fabricate the shapes necessary to funnel the air is generally more complicated than conventional hull forms, which increases cost. Air-lubricated hulls are weight sensitive. Shifts in LCG will alter operating trim, which can increase wake wash.

4 Low Wash Criteria

4.1 General

Any moving vessel at or near the free surface will generate a pressure gradient as the water is pushed out of the way. This pressure gradient causes a wave system to develop that extends behind and outward of the vessel's path. Near the moving vessel, in the near field, the fluid flow in the wave system is turbulent and non-linear. Further away from the moving vessel, in the far field, the flow becomes more regular and indistinguishable from classic gravity waves. These far field, gravity waves are the wake wash.

Both speed, V, and water depth, h, influence the wave system developed by a vessel of a given length, L, and thus the wake wash. Two vessels of different lengths traveling at the same speed generate different wave systems. A given vessel traveling at a given speed will generate completely different wave systems in deep water and in shallow water. The explanation of this phenomena is not presented here. However, two non-dimensional numbers accounting for the effects of shallow water (length Froude number, $Fn = V / \sqrt{(g L)}$) and depth Froude number, $Fnh = V / \sqrt{(g h)}$) are used to evaluate the effects of differing lengths, speeds, and water depths when comparing hull forms.

Recording the wake wash (water surface elevation) as a function of time at a single point as the vessel moves past provides a trace, or time series, that is analyzed to obtain a measure of the wake wash Common among some investigators, [6], the measure of the wake wash is the maximum wake wash height, H, and/or wake wash energy, $E = 1961\ H^2\ T^2$ in metric units. T is the wave period, or time between the two successive zero up-crossings, associated with H. Since wake wash height diminishes as it travels away from the moving vessel the distance from the vessel's track must also be recorded so that the wake wash heights in the wave trace can be corrected to a standard distance from the vessel's track, thus permitting comparisons between different vessels.

Given the physics that governs naval hydrodynamics there are three practical ways to reduce wake wash:

Varying speed,

Reduce pressure gradient in way of the hull, and

Increase wave cancellation.

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All candidate low-wash hull forms must possess some characteristic(s) that enhances at least one of the above ways to reduce wake wash. Further, to be fair the comparison of wake wash of two hull forms must be done at the same length Froude number and the same depth Froude number.

4.2 Reduce Speed

Operating at lower length Froude number and/or lower depth Froude number will reduce wake wash. However, speed is often dictated by the needs of the ferry service and the route fixes water depth so depth Froude number cannot be reduced. This is certainly true for fast ferry service in Rich Passage. Thus the only effective way to reduce speed is to increase vessel length to lower length Froude number. A longer, larger vessel will be more costly to build and may not be economically viable. Reducing speed to lower wake wash is not considered an effective way to reduce wake wash except for the purposes of this study and, except in very specialize cases, it is not compatible with the transportation requirements. Therefore, reducing speed was not used as a criterion in identifying candidate low wash hull forms.

4.3 Reduce Pressure Gradient

Reducing the pressure gradient caused by a moving vessel in the vicinity of the free surface will reduce wake wash. This can be achieved by reducing waterplane area, reducing submerged volume, and/or by reducing slenderness ratio ($\nabla / (0.1L)^3$). Small waterplane area is a dominant feature of SWATH’s but can also be achieved by complete or partial dynamic support (e.g. planning hulls, hydrofoils, and/or foil-assisted hulls). Air-lubricated hulls can be included since they usually feature some planning surfaces. Reduced submerged volume can be achieved by lightweight design. Complete or partial powered lift hull types (e.g. ACV and SES) by their nature have small submerged volume. Reduced slenderness ratio is usually achieved by increasing a hull’s length relative to beam and depth while maintaining static submerged volume. For displacement monohulls stability considerations limit the extent to which slenderness ratio can be reduced. Thus slender hulls are normally utilized on catamarans and multi-hulls. Therefore, reduced pressure gradient can be used as a criterion for identifying SWATH’s, planning hulls, hydrofoils, foil-assist hulls, ACV’s, SES’, slender catamarans, and slender multi-hulls as low wash hull forms.

4.4 Increase Wave Cancellation

Wave cancellation occurs when the waves produced by two or more immersed bodies of the vessel interact at a given speed to cancel each other out thus lowering wake wash. For a given configuration wave cancellation is strongly dependent on speed; vessels with low wake wash at the optimal speed can produce high wake wash at some other speed. The usual wave cancellation interaction is between the submerged portions of catamarans and multi-hulls. However, the interaction between forward and aft foil systems of a hydrofoil, and between the foil and hull(s) of a foil-assisted hull can also create wave cancellation

Therefore, wave cancellation can be used as a criterion for identifying catamarans, multi-hulls, hydrofoils, and foil-assist hulls as low wash hull forms.

5 Suitability of Hull Types to Rich Passage Fast Ferry Service

Although nearly all hull types have been used for fast ferries in commercial service not every hull type is suitable for use in Rich Passage. Those hull types that are not suitable for used in Rich Passage are identified in this section, and will, in general, not be considered further. Results of this evaluation are summarized in Table 1.

A complete set of operational requirements for fast ferry service through Rich Passage has yet to be developed. However, two minimum requirements are 1) 35 knot service speed, and 2) carry 150 passengers. These requirements are considered when evaluating hull types for suitability for Rich Passage service. The passenger capacity requirement implies a relatively small vessel with an anticipated length of 24 m to 30 m. The anticipated length combined with the required service speed yields length Froude numbers from 1.05 to 1.17. This speed regime is in the semi-planing range.

Displacement Monohull: Displacement monohulls usually operated at a length Froude numbers below that needed. Operating beyond their usual speed regime (i.e. at higher speeds) will significantly increase wave making resistance and wake wash, thus making them unsuited for Rich Passage service.

SWATH: The economic feasibility of SWATH's is doubtful because the structural complexity of the cross deck structure makes construction costs higher compared to other hull types. In addition, SWATH's have deep drafts for their length that might limit future operational flexibility. Uncertain economic feasibility make SWATH's unsuited for Rich Passage service.

Hydrofoils: High construction and maintenance cost associated with the complicated "right angle" propulsion drive train, and perhaps with installing gas turbine engines make current hydrofoils unsuited for Rich Passage service.

Air Cushion Vehicles: The economic feasibility of air cushion vehicles is doubtful because the lift fan installation makes construction costs higher compared to more conventional hull types. In addition, skirt wear results in higher maintenance costs. Propulsion airscrews and lift fans are noisy. Uncertain economic feasibility, airborne noise, and poor maneuverability make air cushion vehicles unsuited for Rich Passage service.

Surface Effect Ships: The economic feasibility of surface effect ships is doubtful because the lift fan installation makes construction costs higher compared to more conventional hull types. Skirt wear results can result in higher maintenance costs. Cobblestone-like motions are likely to result in passenger dissatisfaction. Uncertain economic feasibility and cobblestone-like ride qualities make surface effect ships unsuited for Rich Passage service.

Wing in Ground Effect Craft: Currently WIG's are experimental craft. Although limited development efforts have been made there WIG's have yet to be placed into commercial service. Such uncertainties make WIG's unsuited for Rich Passage service.

6 Results and Comments

Candidate low wake wash fast ferry hull forms from the literature search are identified in Table 2. Document identifiers in the "Reference" column of Table 2 refer to entries in Appendix A, Bibliography. In some cases the same wake wash information for the same ship is presented in more than one document, all of which are identified in Table 2.

Table 2 does not include any hull forms for hull types considered not suitable for Rich Passage service as identified in Table 1, except for surface effect ships (SES). Surface effect ships are included because a hybrid of surface effects ships' and other technologies, the air-cavity ship, may be suitable for Rich Passage service.

The literature search has revealed four gaps or inconsistencies in the empirical data.

First, a large amount of empirical wake wash data is proprietary. This applies to wake wash measurements themselves as well as particulars of the trial and vessel loading conditions.

Second, usually only analyzed wake wash data is presented, often as a numeric value of wash height or wash energy. Raw data in the form of time history traces of water surface elevation is rarely presented. Without more complete datasets than are found in the literature it is difficult to make independent analyses or comparisons of different hull forms.

Third, some recently emerging technologies (e.g. air-lubricated hulls [5] and air-cavity ships [7]) show promise as low wake wash hull forms, but few details of their performance characteristics, including wake wash measurements, are presented in the literature. This lack of disclosure is due largely to the proprietary nature of the hull form. Some of these hull forms are patented, [5].

Fourth, occasionally two papers with directly contradict each other. For example, Macfarlane and Renilson, [8], observe "although multihulls appear to generate lower wave heights than monohulls, they generate higher wave periods, therefore the energy in the wave generated by the monohull is similar to that generated by the multihull" MCA, [9], concludes "It was observed that catamarans operating in the supercritical regime produce less energetic waves than monohulls of similar length and displacement." Such contradictions are most likely due to the particulars of the data sets examined, or the particulars of trials and loading conditions represented.

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7 Notation

E	wake wash energy; $E = 1961\ H^2\ T^2$ in metric units
Fn	length Froude number; $Fn = V / \sqrt{(g\ L)}$
Fnh	depth Froude number; $Fnh = V / \sqrt{(g\ h)}$
g	gravitational acceleration (9.80665 m/s^2 ; 32.174 ft/s^2)
h	water depth
H	maximum wake wash (wave) height in the recorded wave trace
L	length of hull (at waterline)
T	wave period, time between successive zero up-crossings, associated with *H*
V	vessel speed
∇	static submerged volume of vessel

8 Abbreviations and Acronyms

AAA	Art Anderson Associates
ACV	Air Cushion Vehicle
CFD	Computational Fluid Dynamics
LCG	Longitudinal Center of Gravity
MCA	Maritime and Coastguard Agency (UK)
PIE	Pacific International Engineering Inc
POFF	Passenger Only Fast Ferry
SES	Surface Effects Vessel
SWATH	Small Waterplane Area Twin Hull
WIG	Wing in Ground Effect

9 References

[1] Hahn, A B. “High Speed Sealift : A Look into the 21st Century.” Power Point Presentation, International Workboat Show and Conference. Nov 1997

[2] McKesson, C B., ed., “Hull forms and propulsor technology for high speed sealift.” Technical report, John J McMullen Associates Inc, Rev Feb 1998. Report from the High Speed Sealift Technology Workshop, 21-23 Oct 1997.

[3] Goubault, P and Hicks, J. “Alternative hullforms for high-performance ferries.” Technical and Research Report R-51, SNAME, 2000.

[4] http://www.sneadsferry.org/boating/history_pg3.htm

[5] Art Anderson Associates. “Stolkraft technical Paper.” <http://www.artanderson.com/Stolkraft%20Technical%20Paper.pdf>

[6] Stumbo, S, Fox, K, Dvorak, F, and Elliott, L. “The prediction, measurement and analysis of wake wash from marine vessels,” *Marine Technology*, 36(4):248-260, Winter 1999.

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[7] Matveev, K. "Air-cavity ships are ready for a wider market." *Speed at Sea*, 9(1):13-16, Feb 2003.

[8] Macfarlane, G J and Renilson, M R. "When is low wash low wash? - an investigation using a wave wake database." Hydrodynamics of High Speed Craft - Wake Wash and Motions Control, RINA, London, Nov 2000.

[9] Maritime and Coast Guard Agency. "A Physical Study of Fast Ferry Wash Characteristics in Shallow Water." Research Project 457. Nov 2001.

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Table 1 Suitability of Hull Types to Rich Passage Service

Hull Type	Suitable for Rich Passage	Remarks
Displacement hulls:		
Monohull	no	Not suited to required speed regime
Catamaran	YES	
Multi-hull	YES	
SWATH	no	High construction cost; draft limitations
Planing hulls		
Catamaran	YES	
Multi-hull	YES	
Hydrofoils	no+	High construction and maintenance costs
Foil-assisted multi-hulls	YES	
Air cushion vehicles (ACV)	no	Expensive; noisy; poor maneuverability
Surface effects ship (SES)	no *	Expensive; poor ride quality
Wing in Ground Effect (WIG)	no	Experimental; none in commercial service
Air lubricated hulls	YES	

* Air-cavity ships, [7], may overcome SES disadvantages and be suitable for Rich Passage service.

+ Although data is not available new foil developments may eliminate the high costs previously associated with hydrofoil production.

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Table 2 Candidate Low Wake Wash Hull Forms from Literature Search

Hull type	Ship / Hull form	Length	Low wash criteria: Reduce pressure gradient	Low wash criteria: Wave cancella-tion	Reference
Catamaran	PacifiCat	96 m		X	Doc0021
Catamaran	*Sassacus*	42.01 m		X	Doc0021
Catamaran	E-Cat	38.6 m	X	X	Doc0021
Catamaran	*Chinook*	38.5 m		X	Doc0021
Planing catamaran	*Bravest*	38.0 m	X	X	Doc0021
Catamaran	*Sassacus*	42.01 m		X	Doc0027
Catamaran	*Chinook*	38.6 m		X	Doc0027
Planing catamaran	*Bravest*	38.0 m	X	X	Doc0027
Catamaran	*Sassacus*	42.01 m	X	X	Doc0030
Catamaran	*Victoria Clipper*	127 ft		X	Doc0038
Surface effects ship	*Commencement*	21 m	X		Doc0038
Catamaran	*Tyee*	26.15 m		X	Doc0038
Catamaran	*Victoria Clipper*	127 ft		X	Doc0040
Surface effects ship	*Commencement*	21 m	X		Doc0040
Catamaran	*Tyee*	26.15 m		X	Doc0040
Planing monohull	Westport 95	95 ft	X		Doc0040
Catamaran	1:12 scale model	71.2 ft		X	Doc0066
Catamaran	1:16 scale model	90 ft		X	Doc0066
Catamaran	1:20 scale model	105 ft		X	Doc0066
Catamaran	E-Cat	36.8 m	X	X	Doc0068
Catamaran	AMHS FVF (NGA70)	70 m	X	X	Doc0070
Catamaran	PacifiCat	96 m		X	Doc0070
Foil-assist cat	*Condor Express*	21.95 m	X	X	Doc0077
Catamaran	*Tyee*	26.15 m			Doc0077
Catamaran	*Chinook*	38.6 m			Doc0077
Catamaran	*St Nicholas*	23.77 m		X	Doc0077
Catamaran	*St Nicholas*	23.77 m		X	Doc0079
Catamaran	(unnamed)	30 m		X	Doc0080
Wave-piercing cat	(unnamed)	81 m		X	Doc0080
Air-lubricated	Stolkraft	7.5 m	X		Doc0085
Air-lubricated	Stolkraft *Green Flash*	9.1 m	X		Doc0091
Air-cavity ship	H-SES 2910-A	40 m	X	X	Doc0093
Air-cavity ship	H-SES 2932-A	40 m	X	X	Doc0093

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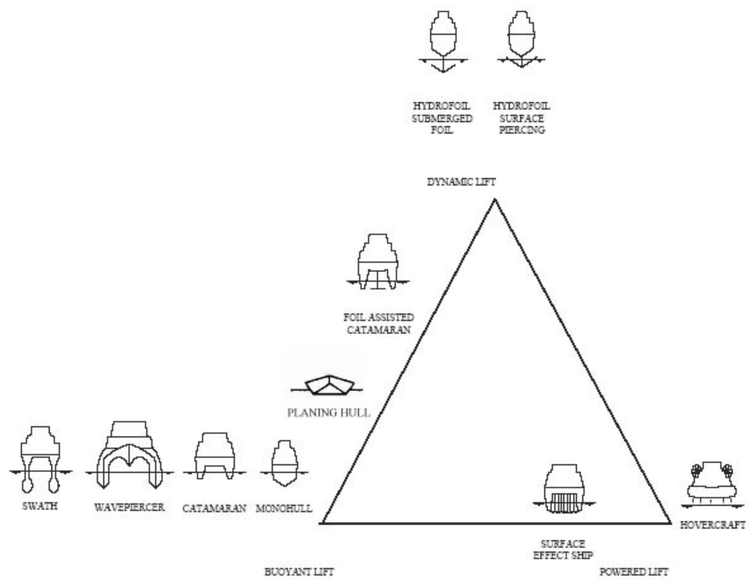

Figure 1 Lift Triangle

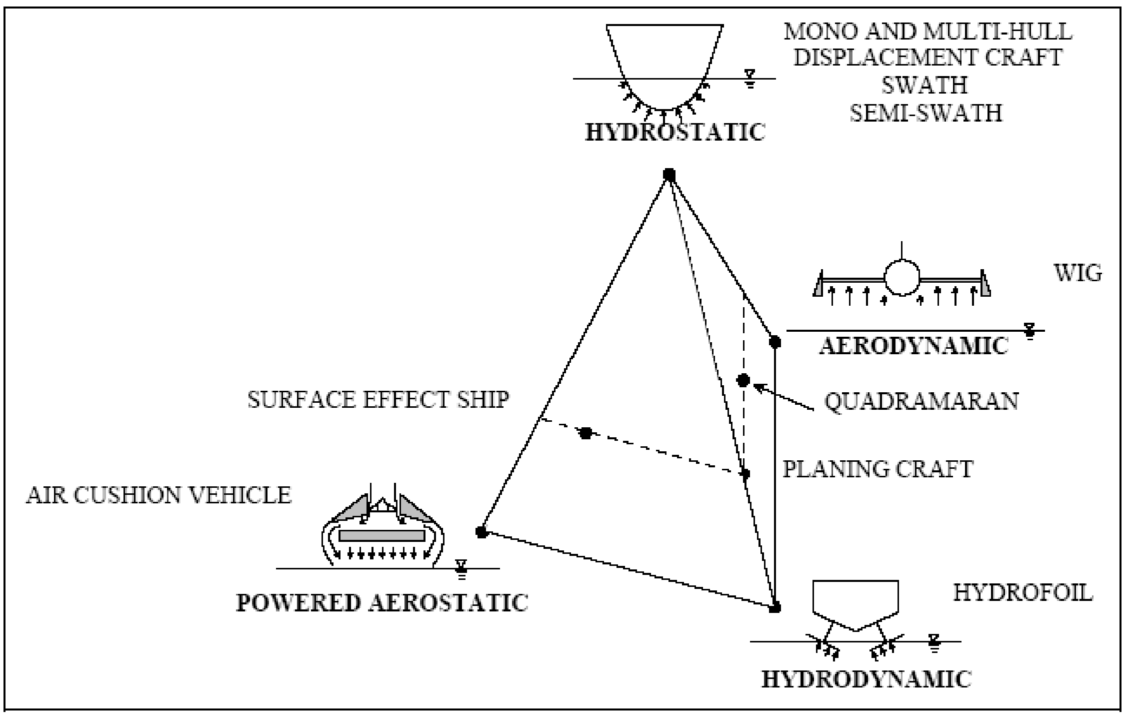

Figure 2 Lift Pyramid

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Appendix A Bibliography

All documents collected from the literature are cited in this bibliography. The document number (e.g. Doc0001) is assigned to continue the numbering scheme of a previous Art Anderson Associates in-house document collection. Therefore, document numbers shown here are not necessarily consecutive. URL's included were verified to be active at the time this report is issued.

[Doc0001] Weinblum, G, Kendrick, J, and Todd, M A. "Investigation of Wave Effects Produced by a Thin Body - TMB Model 4125." Report 840, David Taylor Model Basin, Washington DC, Nov 1952.

Detailed numeric formulae for predicting wake heights and compares numeric predictions to actual test results on a very simple slender body. May be applicable to prediction of wake heights but differences between the tested body and modern fast ferries will make extrapolation very difficult.

[Doc0011] Nece, R E, McCaslin, M R, and Christensen, D R (1985). "Ferry Wake Study." Final Report WA-RD-70.1, Washington State Department of Transportation, June 1985. (Research Project Y-2811 Task 16).

Wakes from ISSAQUAH, SUPER and EVERGREEN STATE class ferries compared. SUPER class best, ISSAQUAH next best and EVERGREEN STATE is worst. Report recommends results be used to guide ferry operations on specific routes where wake generation is a concern. The maximum speed tested is 18 knots. This paper illustrates that wakes have been a concern since the mid-80's but the vessels and speed addressed limit its applicability to fast passenger ferry wake analysis.

[Doc0015] "High speed low wash catamarans." *Ship & Boat International*. vol 91, no 3, pp 31-32, Apr 1991.

The concept is to take a catamaran of considerable length for its capacity, of modest beam but with extremely fine hulls of carefully chosen form. B/L approximately 12, with a vey low displacement to length ratio. Catamarans were chosen to replace hydrofoils because cats have more operational flexibility.

[Doc0016] Warren N. "Wash from fast ferries." *Ship & Boat International*. vol 91, no 3, pp 11-13, Apr 1991.

The direct and effective way to reduce wash is to reduce the displacement-length ratio. Good discussion of general principles of wake wash minimization, along with recognition that reducing wake generally means increasing cost.

[Doc0018] Pike, D. "Washout : The advantages of low-wash ferries." *Workboat Magazine.* vol *50*, no 3, pp 38-40, Jan/Feb 1993.

Rudimentary description of low-wash design requirements and brief discussions of low wash vessels. Not very technical.

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[Doc0019] "Low wash catamarans." *Ship & Boat International.* vol 93, no 6, pp 34, Jul/Aug 1993.

Brief description of two FBM designs based on the Riverbus design. A little data on wash height is included.

[Doc0021] Stumbo, S, Fox, K, and Elliott, L. "Hull form considerations in the design of low wake wash catamarans." 5th International Conference on Fast Sea Transportation (FAST '99), SNAME, Seattle, Sep 1999. <http://www.wakewash.com/Index_Files/HullFormForLowWash.pdf>

Recommends shorter, narrower, deeper hulls to get through the wave hump sooner and have lower wake heights at higher speeds. This is not useful guidance as far as modifying existing ferries but will be useful for future designs. Data from a number of different hull forms is presented.

[Doc0025] Hughes, M J. "VSAERO/FSWAVE Analysis of the AMD-360 with HYSUWaC Part 2." FAX, Apr 1999. FAX to Stan Stumbo dtd April 27, 1999.

Discussion of results of AMI's analysis of the AMD-360 with and without foils designed by Unistel Technologies. Results indicate the wake height would be approximately 1.5 cm lower and wave energy would be 238% higher with the foils at 40 knots. At lower speeds, the configuration with the hydrofoils generates higher wakes and more wave energy.

[Doc0027] Stumbo, S, Fox, K, Dvorak, F, and Elliott, L. "The prediction, measurement and analysis of wake wash from marine vessels." *Marine Technology*. vol, 36, no 4, pp 248-260, Winter 1999.

Includes discussions of wave dynamics, energy calculations, and vessel generated waves. A good part of the paper is devoted to a discussion of CFD methods and the results should be questioned as the ferry produced using this approach as a guideline has been required to slow down to avoid damage to beaches. It recommends the use of CFD to predict the wake height and energy of new designs.

[Doc0028] Doctors, L. "Development of low-wash vessels." page 14. International Conference and Exhibition for the Commercial Marine Industry (AusMarine '98), Nov 1998.

This is a comparison of 12 generic hull forms to see what characteristics have the most effect on wake height. Most of the focus is on speeds less than 30 knots. Low Cp, high L/B catamarans performed the best for both the 30 m and 60 m hull forms. All predictions were made using a computer program; no formulas are given in the paper

[Doc0029] Maritime and Coastguard Agency. "Investigation of High Speed Craft on Routes Near to Land or Enclosed Estuaries." Research Project 420. Oct 1998.

This report includes a significant discussion of the "soliton" wave and the associated critical depth and speed. This information will be useful in determining if the creation of a "soliton" is possible in Rich Passage as well as developing an approach to recommending route changes.

[Doc0030] Stumbo, S, Fox, K, and Elliott, L (1998a). "Wake Wash Measurement Trials, M/V SASSACUS." Wash measurement trial report, Mar 1998.

Detailed observations of the wake and energy generated by the M/V SASSACUS. The results of the test indicate that the wave energy generated is below the threshold limit calculated by WSF for waves in Rich Passage. Additional analysis is recommended to more precisely locate the maximum "no-harm" wake speed, which could be as high as 38 or 39 knots. Also identified is a "sweet spot" at which wake is minimized between 30 and 36-38 knots. The report also recommends that when transiting wake sensitive areas, the speed either be below 16 knots or at the "sweet spot".

[Doc0038] Stumbo, S (1990). Wake tests conducted in rich passage on 11/28/90. Letter, Washington State Ferries, Nov 1990.

Summary of vessel tests conducted by consultants for WSF. The discussion focuses on concerns other than wake height, which is only addressed in a single chart at the end of the paper.

[Doc0040] Rich passage wake study. Technical report, Washington State Ferries, Feb 1990.

Summary of tests conducted on a number of different hull forms. Recommends new ferry construction contracts include a performance requirement for low wake.

[Doc0044] Hay, D. "Ship waves in navigable waterways." page 16. American Society of Civil Engineers, Proceeding of the 11th Conference on Coastal Engineering, Sep 1968. Chapter 95.

Intended to provide guidance to coastal engineers for the design of shore protection structures or to determine speed limits in wake sensitive areas. Low to medium speeds tested. Limited applicability to Rich Passage study.

[Doc0045] Johnson, J W. "Ship waves in shoaling waters." page 11. American Society of Civil Engineers, Proceeding of the 11th Conference on Coastal Engineering, /seo 1968. Chapter 96.

[Doc0055] Whittaker, T J T and Elsaesser, B. "Coping with the wash : The nature of wash waves produced by fast ferries." *Ingenia*. No 11, pp 40-42, Feb 2002. <http://www.raeng.co.uk/news/publications/ingenia/issue11/ Ingenia%2011%20Whittaker.pdf>

Follow-on to Doc0044, addressing wake generation in shallower water. Maximum heights for two different models are provided. The author notes that the waves are of a magnitude that is of concern for people on the shoreline and small vessels moored near the shore.

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APPENDIX E-c

Naval Architecture Technical Memorandum
Preferred Hull Alternatives

ART ANDERSON ASSOCIATES

RICH PASSAGE RESEARCH
PASSENGER ONLY FAST FERRY PROJECT

October 2004

Phase 1
Task 2.2 – Naval Architecture—Preferred Hull Alternatives
Technical Memorandum

TASK 2.2—NAVAL ARCHITECTURE—PREFERRED HULL ALTERNATIVES TECHNICAL MEMORANDUM

Executive Summary

The objective of this subtask is to select two, or at most three, preferred low wake wash hull form alternatives from a list of candidate hull forms that could allow an environmentally acceptable fast ferry operation through Rich Passage. The candidate hull forms are from a list developed previously (subtask 2.1) during an intensive international literature search. The literature search also compiled wake wash data for the candidate hull forms.

Wake wash data compiled consisted of wash height and wash energy, measured at a known distance from the vessel's track for one or more speeds. The wash height and wash energy data were corrected to a standard measurement distance (300 m) from the vessel's track. To remove bias due to physical size and weight of the candidate hull forms, wake wash data was non-dimensionalized.

This study has provided a comparison of wake wash for different hull forms in a manner not shown in any previously published works on wake wash. However, this is only a necessary step in achieving the ultimate goal—to provide the naval architect with a tool to develop a hull form optimized for the Rich Passage, Washington environment.

In subtask 2.3 Art Anderson Associates will develop a separate preliminary design for each of the three preferred hull alternatives. Each design will be optimized specifically for the operational requirements of vessel speed, route, and water depth (including variations due to tidal range) for fast ferry service through Rich Passage. CFD modelling will be used to determine wake wash height and wash energy for each design over a range of water depths, hence over a range of depth Froude numbers. These CFD results will enable a non-dimensionlized comparison of wake wash height and wash energy versus depth Froude number.

Analysis of graphs of non-dimensional wash height versus length Froude number, and non-dimensional wash energy versus length Froude number near the likely length Froude number of an environmentally acceptable fast ferry in Rich Passage resulted in the following preferred hull alternatives for further study.

Air-Cavity Hull Catamaran

Air-Lubricated Hull

Foil-Assisted Catamaran

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1 Introduction

The objective of this subtask is to select two, or at most three, preferred low wake wash hull form alternatives from a list of candidate hull forms that could allow an environmentally acceptable fast ferry operation through Rich Passage. The list of candidate hull forms was developed in a previous subtask, [1][1], from an intensive international literature search. The literature search also compiled wake wash data (wake wash height and wake wash energy) for the candidate hull forms.

The selection of preferred alternative hulls is based on a non-dimensional presentation of available wake wash data for the candidate hull forms.

In the follow-on subtask, 2.3, a design specific to operational requirements for Rich Passage service will be developed for each preferred alternative hull. Each design will be developed to sufficient detail to show that the design is achievable, and to provide necessary input information for evaluation using advanced analytical tools such as computational fluid dynamics (CFD).

2 Wake Wash Data

2.1 Measurements and Raw Data Analysis

Wake wash data is gathered by a wave measuring and data logging device deployed adjacent to the test vessel's track. As the test vessel passes at constant speed the device records changes in water surface elevation as a function of time, usually as a time series of discrete sampled values. Commonly, an on board Global Positioning System (GPS) receiver measures the test vessel speed, and the average value over the duration of the run is recorded. Additionally, for each run the actual distance from the measuring device and the test vessel's track is measured and recorded. This process is repeated for each planned run.

After all planned runs are completed the wave measuring and data logging device is received and the data downloaded for analysis. The analysis examines the wave trace for each run to 1) identify each wave (measured surface elevation change between two successive zero up-crossings), 2) compute the period of each wave (time between two zero-up-crossings), and 3) compute the height of each wave (difference between the largest surface elevation and smallest surface elevation). The largest wave height is the wash height, H_0, for the run; and the associated period is the wave period, T, for the run.

Wake wash data for each run consists of the following values.

Vk vessel speed,
y_0 distance from measurement to vessel's track

[1] Numbers in brackets refer to references listed in Section 7

H_0 wash height
T wave period
E_0 computed wash energy, = 1961 H_0^2 T^2

2.2. Correction to Standard Distance from Vessel's Track

Wash height decreases with distance from the vessel's track. Therefore, some correction to a standard distance is needed in order to fairly compare wake wash data taken at different distances from the vessel's track. There is no universally accepted appropriate standard distance and proper means of correcting wake wash data by investigators in the field. Fortunately, universal acceptance is not needed to satisfy the objective of this subtask—selecting two or three preferred low wake wash hull form alternatives for further study. For this subtask applying a consistent correction is all that is needed.

The largest portion of compiled wake wash data is obtained from the reports of Stumbo, et al, e.g. [2]. In their reports measured wake wash heights are corrected to a distance of 300 m off the vessel's track by the cube root of the ratio of the distances, i.e. $(y_0 / 300)^{1/3}$, which for this report we represent with the symbol κ. The corrected wake wash height at 300 m distance from the vessel's track is equal to $\kappa * H_0$.

Wave period, T, does not change appreciably as wash height diminishes with distance from the vessel's track. Therefore wash energy, E_0, measured at y_0 can be corrected to a distance of 300 m from the vessel's track by the equation $E = \kappa^2 * E_0$.

Because the largest portion of compiled wake wash data corrects wash height and/or wash energy to 300 m off the vessel's track this value is selected as the standard distance for this memorandum. Wake wash data at other distances off the vessel's track are corrected to 300 m using the correction factor κ as explained above.

3 Non-Dimensionalization

As seen in Table 1 and reported in [1], wake wash data has been measured and documented for vessels of widely differing sizes. Also vessel speeds for wake wash trials vary appreciably. Not surprisingly, as a broad generalization, big vessels generate large wash heights and large wash energies, while little vessels generate small wash heights and small wash energies. Clearly selection of preferred low wash hull alternatives cannot be made by direct comparison of reported wake wash data. The compiled wake wash data must be non-dimensionalized to remove the aspect of vessel size so that they can be fairly compared.

Vessel size can be characterized by length or weight. Either characterization can be used to non-dimensionalize wake wash data. In this memorandum all length units are expressed in meters [m], and weight is expressed in kilo-Newtons [kN]. To non-dimensionalize a parameter it must be divided by some arithmetical combination of vessel characteristics that has the same dimension. The length dimension associated with vessel weight is the cube root of static submerged volume, i.e. $\nabla^{1/3}$. For wake wash data vessel speed, wash height, and wash energy must be non-dimensionalized. Each is discussed below.

Vessel speed: Length Froude number, $Fn = v / \sqrt{(g\ L)}$, is used as the non-dimensional parameter of vessel speed. *Fn* is chosen because length is, but weight is not reported for some candidate hull forms.

Wash height: The ratio of wash height to vessel length, H / L, is used as the non-dimensional parameter of wash height. *L* is chosen as the non-dimensionalizing characteristic (instead of $\nabla^{1/3}$) to be consistent with the non-dimensionalizing characteristic used for vessel speed, and because *L* is reported in the literature for each candidate hull form.

Wash energy: The ratio of wash energy to vessel weight, E / Δ; is used as the non-dimensional parameter of wash energy. Δ is chosen as the non-dimensionalizing characteristic (instead of $\rho\ g\ L^3$) because it is felt that energy is, in some sense, more related to vessel mass, hence weight, than to physical size as represented by length. Recall that wash energy, *E*, has units of Joules (an energy unit) per meter of wave front (a length unit). One Joule is one Newton-meter (force times distance). Therefore, *E* can be expressed as Newton-meters per meter, or simply as Newtons (a force unit), and the proper non-dimensionalizing characteristic has dimensions of force.

4 Application to Compiled Wake Wash Data

Candidate low wake wash hull forms as found from an intensive literature search, [1], are listed in Table 1. Characteristics of length (converted to meters as necessary) and weight (converted to kilo-Newtons as necessary) are also given. Numbers in brackets in the "Data source" column refer to references in Section 7 form which vessel characteristics and wake wash data are obtained.

All available wake wash data (Vk, y_0, H_0, T, and E_0) for candidate hull forms is presented in Appendix A. A blank entry in the table of Appendix A under one of these parameters means that data is not reported in the literature. The calculation to correct wake wash data to the standard 300 m off the vessel's track is shown in Appendix A, as is the calculation of non-dimensional parameters. The characters "n/a" in the E / Δ column indicates that vessel weight and/or wash energy were not reported in the literature, and that non-dimensional wash energy cannot be calculated.

Wherever possible wake wash data was taken from tabular values reported in the literature. Where wash height and/or wash energy were reported only as graphs (usually versus speed) values were read off of the graphs for use in Appendix A.

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Stevens Institute of Technology's Davidson Laboratory conducted a series of towing tank tests of three catamaran hull forms, [5]. The three hull forms are given ship numbers S10, S11, and S12 in Table 1 and Appendix A. Each model was tested over a range of displacements and longitudinal centers of gravity (LCG). The displacements are given in Table 1, but wake wash data for the "middle" of the test matrix is given in Appendix A. However, the wake wash data not presented here is useful in determining the effect of loading (displacement) and trim (LCG) on wash height, but does not affect selection of preferred hull alternatives from the candidate hull forms.

Wash height data at two or more distances from the vessel's track, y_0, are given in the literature for ship numbers S10, S12, and S18 of Table 1. Only the data that yields the largest values of H / L are presented in Appendix A.

5 Discussion and Recommendations

A graph of non-dimensional wash height (H / L) versus length Froude number (Fn) for all candidate low wake wash hull forms is presented as Figure 1. A graph of available non-dimensional wash energy (E / Δ) versus length Froude number (Fn) for all candidate low wake wash hull forms is presented as Figure 2.

Both Figure 1 and Figure 2 features a vertical dashed line at length Froude number of 1.17. This is the length Froude number of a 24 m vessel traveling at a speed of 35 knots. This represents the likely length Froude number for an environmentally acceptable fast ferry operation through Rich Passage

Both graphs show wide variation among ships of the same hull type, and between different hull types. This variation is most likely due to particulars of the wake wash measurements that were not identified or discussed in the literature. Some of these particulars could include the effects of water depth, differences in trim of the trials load condition, and precision of measuring instruments. However, close examination of the graphs reveals that these variations do not obscure differences between hull types. Clear preferences of hull alternatives still emerge, especially at the length Froude number of interest.

Some variation shown on the graphs could also be caused by "shifts" in length Froude number arising from using different lengths. The literature did not always distinguish between length overall and length on waterline. The calculation of length Froude number in Appendix A used whatever length was reported; if both length overall and length on waterline were reported length overall was used since this is the most commonly reported length. Length Froude number "shifts" will be proportional to the square root of the ratio of length on waterline to length overall. For hull forms of interest this ratio is close to one, thus length Froude number "shifts" will be small.

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Both wash height and wash energy are important in assessing environmental impact from high-speed vessels' wake wash. Unfortunately, both wash height and wash energy data are not available for all candidate hull forms of interest; e.g. air-lubricated hull ship number S18 and catamaran ship number S11b are missing wash energy data, air-cavity hull ship numbers S20 and S21 are missing wash height data. Nevertheless, candidate hull forms that have both wash height and wash energy data show generally the same relation between individual hull forms in both figures. Based on this, it is expected that the relation, or ranking, of candidate hull forms with missing wash data would not change were that data available.

Therefore, the preferred hull alternatives are those with the lowest non-dimensional wash height and non-dimensional wash energy near the length Froude number of interest. It is recommended that the following hull forms be selected for further analysis in subtask 2.3.

Air-cavity hull (as example, ship numbers S20 and S21)

Air-lubricated hull (as example, ship number S19)

Foil-assisted catamaran (as example, ship numbers S03a and S14)

Wash data presented here was measured in deep water (none of the references identifies the reported wake wash data as being in shallow water) so that the depth Froude number, *Fnh*, is sub-critical and the wake wash characterized by the classic Kelvin wave pattern. When operating in the Rich Passage at 35 knots, depth Froude number will be near critical or super-critical. In this speed regime the wake wash is characterized by an entirely different wave pattern. Since selection of preferred hull alternatives in this subtask is limited to candidate hull forms from an intensive international literature search, and that literature search did not reveal wake wash data for critical or super-critical depth Froude numbers, it must be assumed that the ranking of candidate hull forms is the same at all depth Froude numbers.

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6 Notation

All dimensional values are expressed in SI units.

E_0	$= 1961\ H_0^2\ T^2$, wake wash energy at distance y_0 from vessel's track, [J/m]
E	$= 1961\ H^2\ T^2$, wake wash energy at 300 m from vessel's track, [J/m]
Fn	$= v / \sqrt{(g\ L)}$, length Froude number
Fnh	$= v / \sqrt{(g\ h)}$, depth Froude number
g	$= 9.80665\ m/s^2$, gravitational acceleration
h	water depth, [m]
H_0	maximum wake wash (wave) height in the recorded wave trace, [m]
H	$= \kappa\ H_0$, maximum wake wash height corrected to 300 m from vessel's track, [m]
L	vessel length, [m]
T	wave period, time between successive zero up-crossings, associated with H_0, [s]
Vk	vessel speed, [kt]
v	$= (1852/3600)\ Vk$, vessel speed, [m/s]
yo	wake wash measurement distance from vessel's track, [m]
Δ	vessel displacement (weight), [kN]
	$\Delta = \rho\ g\ \nabla / 1000$
	$\Delta = 9.80665\ \Delta_1$; Δ_1 = vessel displacement in tones (1 tonne = 1000 kg)
	$\Delta = 9.96402\ \Delta_2$; Δ_2 = vessel displacement in LT (1LT = 2240 lb)
	$\Delta = 4.448222\ \Delta_3 / 1000$; Δ_3 = vessel displacement in pounds
κ	$= (y_0 / 300)^{1/3}$, wake wash height correction factor
ρ	$= 1025.6\ kg/m^3$, mass density of sea water at 15 °C
∇	$= 1000\ (\Delta / \rho\ g)$, vessel's static submerged volume, $[m^3]$

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Table 1 Candidate Low Wake Wash Hull Forms, [1]

No	Hull type	Ship / Hull form	*L* [m]	Δ [kN]	Data source
S01	Catamaran	PacifiCat	96	18931.64	[6]
S02	Catamaran	*Sassacus*	42.01	n/a	[2]
S03	Catamaran	E-Cat	38.6	1743.76	[3]
S04	Catamaran	*Chinook*	38.5	1845.31	[3]
S05	Planing catamaran	*Bravest*	38.0	544.27	[3]
S06	Catamaran	*Victoria Clipper*	38.71	n/a	[4]
S07	Surface effects ship	*Commencement*	21	n/a	[4]
S08	Catamaran	*Tyee*	26.15	n/a	[4]
S09	Planing monohull	Westport 95	28.96	n/a	[4]
S10a	Catamaran	1:12 scale model	21.70	498.20	[5]
S10b	Catamaran	1:12 scale model	21.70	498.20	
S10c	Catamaran	1:12 scale model	21.70	498.20	
S10d	Catamaran	1:12 scale model	21.70	498.20	
S11a	Catamaran	1:16 scale model	27.43	896.76	[5]
S11b	Catamaran	1:16 scale model	27.43	996.40	
S11c	Catamaran	1:16 scale model	27.43	1096.04	
S12a	Catamaran	1:20 scale model	32.00	671.01	[5]
S12b	Catamaran	1:20 scale model	32.00	870.12	
S12c	Catamaran	1:20 scale model	32.00	1000.85	
S13	Catamaran	AMHS FVF (NGA70)	70	7392.11	[6]
S14	Foil-assist cat	*Condor Express*	21.95	455.03	[7]
S15	Catamaran	*St Nicholas*	23.77	673.57	[8]
S16	Catamaran	(unnamed)	30	n/a	[9]
S17	Wave-piercing cat	(unnamed)	81	n/a	[9]
S18	Air-lubricated	Stolkraft	7.5	n/a	[10]
S19	Air-lubricated	Stolkraft *Green Flash*	9.1	56.00	[11]
S20	Air-cavity ship	H-SES 2910-A	40	1508.66	[12]
S21	Air-cavity ship	H-SES 2932-A	40	1508.66	[12]

TASK 2.2—NAVAL ARCHITECTURE—PREFERRED HULL ALTERNATIVES TECHNICAL MEMORANDUM

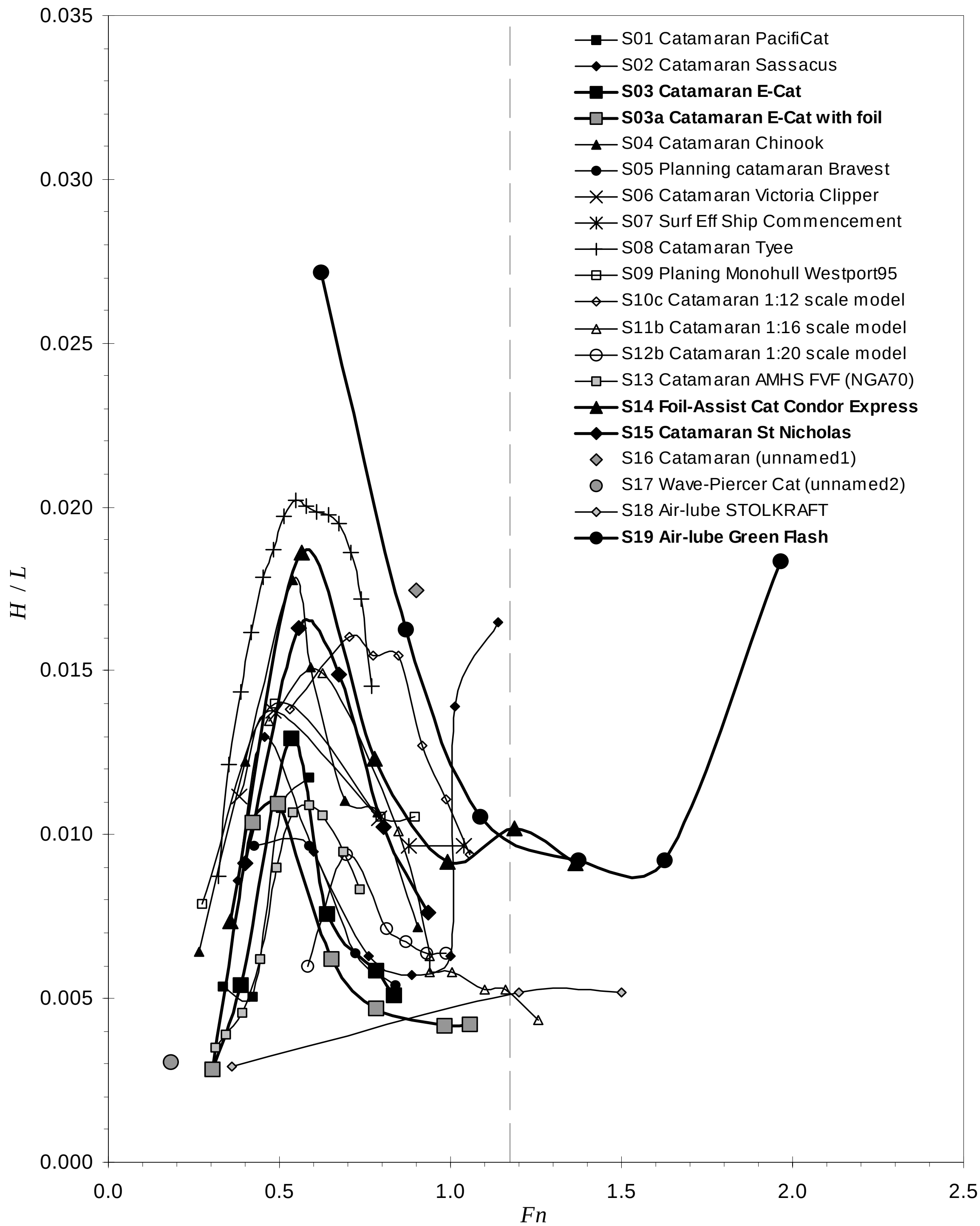

Figure 1 Non-Dimensional Wash Height vs Length Froude Number

TASK 2.2—NAVAL ARCHITECTURE—PREFERRED HULL ALTERNATIVES TECHNICAL MEMORANDUM

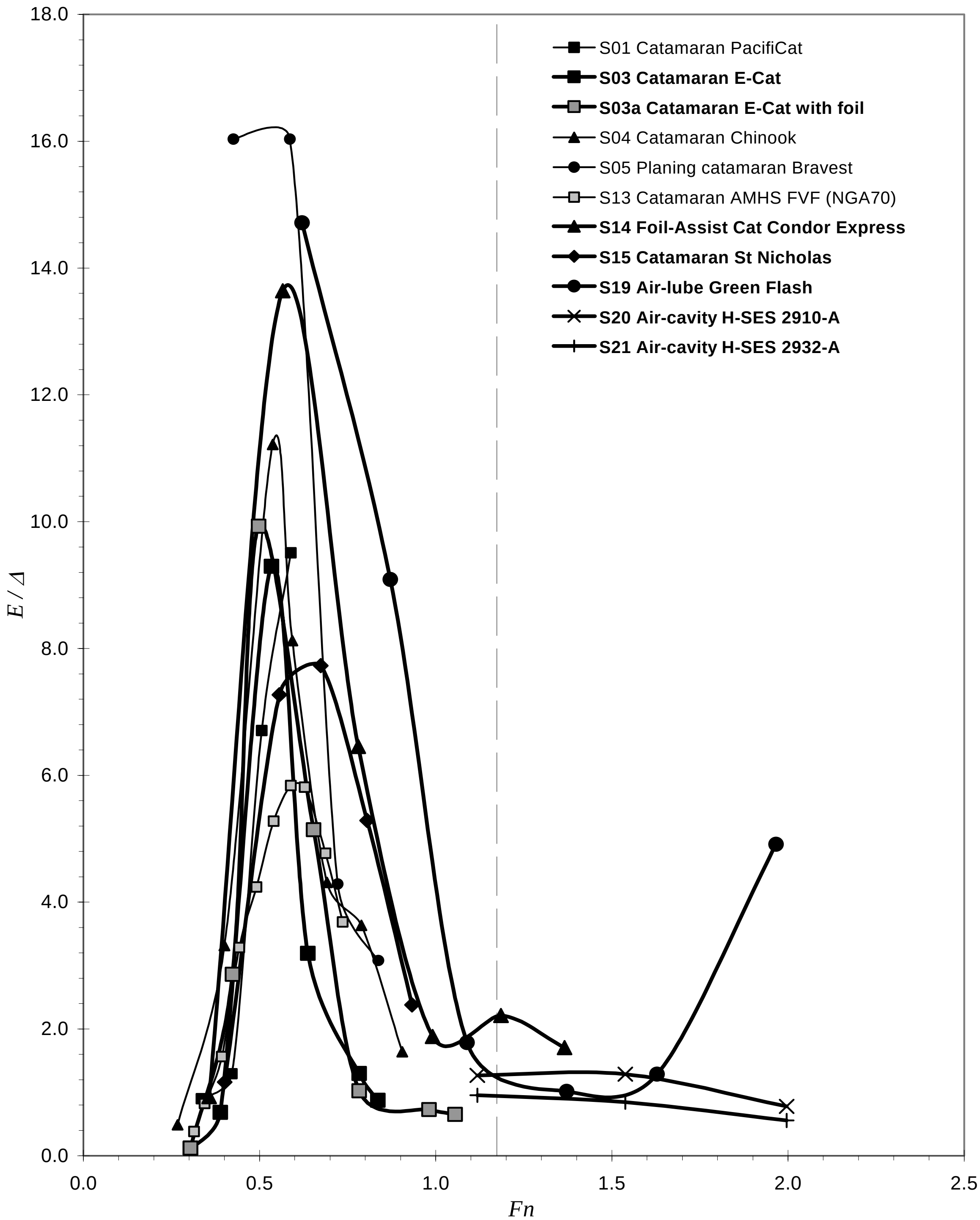

Figure 2 Non-Dimensional Wash Energy vs Length Froude Number

TASK 2.2—NAVAL ARCHITECTURE—PREFERRED HULL ALTERNATIVES TECHNICAL MEMORANDUM

Appendix A Compiled Wake Wash Data

No	Ship / Hull form	*Vk* [kt]	y_0 [m]	H_0 [m]	*T* [s]	E_0 [J / m]	κ [-]	*H* [m]	*E* [J / m]	*Fn* [-]	*H / L* [-]	*E* / Δ [-]	Remarks
S01	PacifiCat	20	300	0.513	5.75	17079	1.00000	0.513	17079	0.335	0.00534	0.902	
S01	PacifiCat	25.1	300	0.487	7.25	24485	1.00000	0.487	24485	0.421	0.00507	1.293	
S01	PacifiCat	30.2	300	1.038	7.75	126937	1.00000	1.038	126937	0.506	0.01081	6.705	
S01	PacifiCat	35.1	300	1.127	8.50	180016	1.00000	1.127	180016	0.589	0.01174	9.509	
S02	*Sassacus*	15	300	0.362	4.50	5204	1.00000	0.362	5204	0.380	0.00862	n/a	
S02	*Sassacus*	18	300	0.546	5.25	16113	1.00000	0.546	16113	0.456	0.01300	n/a	
S02	*Sassacus*	23.7	300	0.398	4.75	7016	1.00000	0.398	7016	0.601	0.00947	n/a	
S02	*Sassacus*	30	300	0.265	4.75	3107	1.00000	0.265	3107	0.760	0.00631	n/a	
S02	*Sassacus*	35	300	0.240	4.75	2549	1.00000	0.240	2549	0.887	0.00571	n/a	
S02	*Sassacus*	39.5	300	0.265	4.75	3107	1.00000	0.265	3107	1.001	0.00631	n/a	
S02	*Sassacus*	40	300	0.585	2.50	4194	1.00000	0.585	4194	1.014	0.01393	n/a	
S02	*Sassacus*	45	300	0.692	2.50	5869	1.00000	0.692	5869	1.141	0.01647	n/a	
S03	E-Cat	11.5	300	0.109	3.00	210	1.00000	0.109	210	0.304	0.00282	0.120	
S03	E-Cat	14.7	300	0.208	3.75	1193	1.00000	0.208	1193	0.389	0.00539	0.684	
S03	E-Cat	20.2	300	0.500	5.75	16209	1.00000	0.500	16209	0.534	0.01295	9.296	
S03	E-Cat	24.1	300	0.293	5.75	5566	1.00000	0.293	5566	0.637	0.00759	3.192	
S03	E-Cat	29.6	300	0.226	4.75	2260	1.00000	0.226	2260	0.783	0.00585	1.296	
S03	E-Cat	31.6	300	0.196	4.50	1526	1.00000	0.196	1526	0.836	0.00508	0.875	
S03a	E-Cat	11.5	300	0.109	3.00	210	1.00000	0.109	210	0.304	0.00282	0.120	with foil
S03a	E-Cat	16	300	0.401	3.98	4991	1.00000	0.401	4991	0.423	0.01039	2.862	with foil
S03a	E-Cat	18.8	300	0.422	7.05	17310	1.00000	0.422	17310	0.497	0.01093	9.927	with foil
S03a	E-Cat	24.7	300	0.240	8.93	8969	1.00000	0.240	8969	0.653	0.00622	5.144	with foil

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No	Ship / Hull form	Vk [kt]	y_0 [m]	H_0 [m]	T [s]	E_0 [J / m]	κ [-]	H [m]	E [J / m]	Fn [-]	H / L [-]	E / Δ [-]	Remarks
S03a	E-Cat	29.6	300	0.181	5.28	1786	1.00000	0.181	1786	0.783	0.00469	1.024	with foil
S03a	E-Cat	37.1	300	0.160	5.02	1270	1.00000	0.160	1270	0.981	0.00415	0.728	with foil
S03a	E-Cat	39.9	300	0.163	4.69	1140	1.00000	0.163	1140	1.055	0.00422	0.654	with foil
S04	*Chinook*	10.1	300	0.247	2.75	905	1.00000	0.247	905	0.267	0.00642	0.490	
S04	*Chinook*	15.1	300	0.471	3.75	6118	1.00000	0.471	6118	0.400	0.01223	3.315	
S04	*Chinook*	20.3	300	0.684	4.75	20700	1.00000	0.684	20700	0.537	0.01777	11.217	
S04	*Chinook*	22.4	300	0.582	4.75	14987	1.00000	0.582	14987	0.593	0.01512	8.122	
S04	*Chinook*	26.1	300	0.424	4.75	7954	1.00000	0.424	7954	0.691	0.01101	4.310	
S04	*Chinook*	29.8	300	0.411	4.50	6708	1.00000	0.411	6708	0.789	0.01068	3.635	
S04	*Chinook*	34.2	300	0.276	4.50	3025	1.00000	0.276	3025	0.905	0.00717	1.639	
S05	*Bravest*	16	300	0.367	5.75	8725	1.00000	0.367	8725	0.426	0.00966	16.031	
S05	*Bravest*	22	300	0.367	5.75	8725	1.00000	0.367	8725	0.586	0.00966	16.031	
S05	*Bravest*	27.1	300	0.242	4.50	2333	1.00000	0.242	2333	0.722	0.00637	4.286	
S05	*Bravest*	31.4	300	0.206	4.50	1677	1.00000	0.206	1677	0.837	0.00542	3.081	
S06	*Victoria Clipper*	30	300	0.406	3.90	4926	1.00000	0.406	4926	0.792	0.01049	n/a	
S06	*Victoria Clipper*	18.3	300	0.533	3.60	7231	1.00000	0.533	7231	0.483	0.01377	n/a	
S06	*Victoria Clipper*	14.5	300	0.432	3.30	3982	1.00000	0.432	3982	0.383	0.01116	n/a	
S07	*Commencement*	29	300	0.203	3.00	729	1.00000	0.203	729	1.040	0.00967	n/a	
S07	*Commencement*	24.5	300	0.203	3.00	729	1.00000	0.203	729	0.878	0.00967	n/a	
S08	*Tyee*	10	300	0.228			1.00000	0.228		0.321	0.00872	n/a	
S08	*Tyee*	11	300	0.318			1.00000	0.318		0.353	0.01216	n/a	

No	Ship / Hull form	*Vk* [kt]	y_0 [m]	H_0 [m]	*T* [s]	E_0 [J / m]	κ [-]	*H* [m]	*E* [J / m]	*Fn* [-]	*H* / *L* [-]	*E* / Δ [-]	Remarks
S08	*Tyee*	12	300	0.375			1.00000	0.375		0.385	0.01434	n/a	
S08	*Tyee*	13	300	0.423			1.00000	0.423		0.418	0.01618	n/a	
S08	*Tyee*	14	300	0.467			1.00000	0.467		0.450	0.01786	n/a	
S08	*Tyee*	15	300	0.489			1.00000	0.489		0.482	0.01870	n/a	
S08	*Tyee*	16	300	0.515			1.00000	0.515		0.514	0.01969	n/a	
S08	*Tyee*	17	300	0.528			1.00000	0.528		0.546	0.02019	n/a	
S08	*Tyee*	18	300	0.524			1.00000	0.524		0.578	0.02004	n/a	
S08	*Tyee*	19	300	0.519			1.00000	0.519		0.610	0.01985	n/a	
S08	*Tyee*	20	300	0.517			1.00000	0.517		0.642	0.01977	n/a	
S08	*Tyee*	21	300	0.510			1.00000	0.510		0.675	0.01950	n/a	
S08	*Tyee*	22	300	0.487			1.00000	0.487		0.707	0.01862	n/a	
S08	*Tyee*	23	300	0.450			1.00000	0.450		0.739	0.01721	n/a	
S08	*Tyee*	24	300	0.380			1.00000	0.380		0.771	0.01453	n/a	
S09	Westport 95	29.3	300	0.305	2.94	1575	1.00000	0.305	1575	0.894	0.01053	n/a	
S09	Westport 95	26	300	0.305	3.45	2168	1.00000	0.305	2168	0.794	0.01053	n/a	
S09	Westport 95	16	300	0.406	3.87	4851	1.00000	0.406	4851	0.488	0.01402	n/a	
S09	Westport 95	9	300	0.229	2.46	620	1.00000	0.229	620	0.275	0.00791	n/a	
S10c	1:12 scale model	15	18.288	0.762			0.39356	0.300		0.529	0.01382	n/a	Y060-Run49
S10c	1:12 scale model	20	18.288	0.884			0.39356	0.348		0.705	0.01604	n/a	Y060-Run50
S10c	1:12 scale model	22	18.288	0.853			0.39356	0.336		0.776	0.01548	n/a	Y060-Run51
S10c	1:12 scale model	24	18.288	0.853			0.39356	0.336		0.846	0.01548	n/a	Y060-Run52
S10c	1:12 scale model	26	18.288	0.701			0.39356	0.276		0.917	0.01272	n/a	Y060-Run53
S10c	1:12 scale model	28	18.288	0.610			0.39356	0.240		0.987	0.01106	n/a	Y060-Run54
S10c	1:12 scale model	30	18.288	0.518			0.39356	0.204		1.058	0.00940	n/a	Y060-Run55

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No	Ship / Hull form	*Vk* [kt]	y_0 [m]	H_0 [m]	*T* [s]	E_0 [J / m]	κ [-]	*H* [m]	*E* [J / m]	*Fn* [-]	*H / L* [-]	*E / Δ* [-]	Remarks
S11b	1:16 scale model	15	24.384	0.853			0.43317	0.369		0.470	0.01345	n/a	Y080-Run03
S11b	1:16 scale model	20	24.384	0.945			0.43317	0.409		0.627	0.01491	n/a	Y080-Run04
S11b	1:16 scale model	27	24.384	0.640			0.43317	0.277		0.847	0.01010	n/a	Y080-Run06
S11b	1:16 scale model	30	24.384	0.396			0.43317	0.172		0.941	0.00627	n/a	Y080-Run07
S11b	1:16 scale model	30	24.384	0.366			0.43317	0.159		0.941	0.00580	n/a	Y080-Run12
S11b	1:16 scale model	32	24.384	0.366			0.43317	0.159		1.004	0.00580	n/a	Y080-Run08
S11b	1:16 scale model	35	24.384	0.335			0.43317	0.145		1.098	0.00529	n/a	Y080-Run09
S11b	1:16 scale model	37	24.384	0.335			0.43317	0.145		1.161	0.00529	n/a	Y080-Run10
S11b	1:16 scale model	40	24.384	0.274			0.43317	0.119		1.255	0.00434	n/a	Y080-Run11
S12b	1:20 scale model	20	18.288	0.488			0.39356	0.192		0.581	0.00600	n/a	Y060-Run32
S12b	1:20 scale model	24	18.288	0.762			0.39356	0.300		0.697	0.00938	n/a	Y060-Run33
S12b	1:20 scale model	28	18.288	0.579			0.39356	0.228		0.813	0.00713	n/a	Y060-Run34
S12b	1:20 scale model	30	18.288	0.549			0.39356	0.216		0.871	0.00675	n/a	Y060-Run35
S12b	1:20 scale model	32	18.288	0.518			0.39356	0.204		0.929	0.00638	n/a	Y060-Run37
S12b	1:20 scale model	34	18.288	0.518			0.39356	0.204		0.987	0.00638	n/a	Y060-Run38
S13	AMHS FVF (NGA70)	16	300	0.244		2830	1.00000	0.244	2830	0.314	0.00349	0.383	
S13	AMHS FVF (NGA70)	17.5	300	0.273		6080	1.00000	0.273	6080	0.344	0.00390	0.822	
S13	AMHS FVF (NGA70)	20	300	0.320		11560	1.00000	0.320	11560	0.393	0.00457	1.564	
S13	AMHS FVF (NGA70)	22.5	300	0.435		24270	1.00000	0.435	24270	0.442	0.00621	3.283	
S13	AMHS FVF (NGA70)	25	300	0.629		31330	1.00000	0.629	31330	0.491	0.00899	4.238	
S13	AMHS FVF (NGA70)	27.5	300	0.746		39020	1.00000	0.746	39020	0.540	0.01066	5.279	
S13	AMHS FVF (NGA70)	30	300	0.763		43160	1.00000	0.763	43160	0.589	0.01090	5.839	
S13	AMHS FVF (NGA70)	32	300	0.740		42960	1.00000	0.740	42960	0.628	0.01057	5.812	

TASK 2.2—NAVAL ARCHITECTURE—PREFERRED HULL ALTERNATIVES TECHNICAL MEMORANDUM

No	Ship / Hull form	*Vk* [kt]	y_0 [m]	H_0 [m]	*T* [s]	E_0 [J / m]	κ [-]	*H* [m]	*E* [J / m]	*Fn* [-]	*H / L* [-]	*E* / Δ [-]	Remarks
S13	AMHS FVF (NGA70)	35	300	0.663		35250	1.00000	0.663	35250	0.687	0.00947	4.769	
S13	AMHS FVF (NGA70)	37.5	300	0.584		27260	1.00000	0.584	27260	0.736	0.00834	3.688	
S14	*Condor Express*	10.18	300	0.161	2.84	425	1.00000	0.161	425	0.357	0.00733	0.934	
S14	*Condor Express*	16.13	300	0.408	4.15	6208	1.00000	0.408	6208	0.566	0.01859	13.643	
S14	*Condor Express*	22.24	300	0.270	4.02	2937	1.00000	0.270	2937	0.780	0.01230	6.455	
S14	*Condor Express*	28.27	300	0.201	3.27	855	1.00000	0.201	855	0.991	0.00916	1.879	
S14	*Condor Express*	33.8	300	0.224	3.20	1007	1.00000	0.224	1007	1.185	0.01021	2.213	
S14	*Condor Express*	38.96	300	0.200	3.18	776	1.00000	0.200	776	1.366	0.00911	1.705	
S15	*St Nicholas*	11.9	300	0.217	2.91	784	1.00000	0.217	784	0.401	0.00913	1.164	
S15	*St Nicholas*	16.5	300	0.388	4.07	4897	1.00000	0.388	4897	0.556	0.01632	7.270	
S15	*St Nicholas*	20	300	0.354	4.61	5207	1.00000	0.354	5207	0.674	0.01489	7.730	
S15	*St Nicholas*	23.9	300	0.243	5.63	3562	1.00000	0.243	3562	0.805	0.01022	5.288	
S15	*St Nicholas*	27.7	300	0.181	5.63	1603	1.00000	0.181	1603	0.933	0.00761	2.380	
S16	(unnamed1)	30	200	0.600	2.40		0.87358	0.524		0.900	0.01747	n/a	
S17	(unnamed2)	10	50	0.450	3.50		0.55032	0.248		0.183	0.00306	n/a	
S18	Stolkraft	6	25	0.050			0.43679	0.022		0.360	0.00293	n/a	
S18	Stolkraft	20	25	0.090			0.43679	0.039		1.200	0.00520	n/a	
S18	Stolkraft	25	25	0.090			0.43679	0.039		1.500	0.00520	n/a	
S19	*Green Flash*	11.4	300	0.247	2.62	824	1.00000	0.247	824	0.621	0.02714	14.714	
S19	*Green Flash*	16	300	0.148	3.45	509	1.00000	0.148	509	0.871	0.01626	9.089	

TASK 2.2—NAVAL ARCHITECTURE—PREFERRED HULL ALTERNATIVES TECHNICAL MEMORANDUM

No	Ship / Hull form	*Vk* [kt]	y_0 [m]	H_0 [m]	*T* [s]	E_0 [J / m]	κ [-]	*H* [m]	*E* [J / m]	*Fn* [-]	*H / L* [-]	*E* / Δ [-]	Remarks
S19	*Green Flash*	20	300	0.096	2.35	100	1.00000	0.096	100	1.089	0.01055	1.786	
S19	*Green Flash*	25.2	300	0.084	2.02	57	1.00000	0.084	57	1.372	0.00923	1.018	
S19	*Green Flash*	29.9	300	0.084	2.29	72	1.00000	0.084	72	1.628	0.00923	1.286	
S19	*Green Flash*	36.1	300	0.167	2.25	275	1.00000	0.167	275	1.966	0.01835	4.911	
S20	H-SES 2910-A		50			6328	0.55032		1916	1.118		1.270	
S20	H-SES 2910-A		50			6406	0.55032		1940	1.538		1.286	
S20	H-SES 2910-A		50			3889	0.55032		1178	1.996		0.781	
S21	H-SES 2932-A		50			4762	0.55032		1442	1.118		0.956	
S21	H-SES 2932-A		50			4206	0.55032		1274	1.538		0.844	
S21	H-SES 2932-A		50			2778	0.55032		841	1.996		0.557	

APPENDIX E-d

Review of Technical Memoranda by Art Anderson Associates, Inc.

DRAFT Technical Memorandum

Subject: Project: 2002A. Seattle-Bremerton Passenger Only Fast Ferry Study Review of Technical Memoranda by Art Anderson Associates, Inc

This technical memorandum provides a critical review of the technical memoranda prepared by Art Anderson Associates, Inc. as deliverables for Naval Engineering tasks of the Seattle-Bremerton Passenger Only Fast Ferry Study (Contract Y-8977 WSDOT). The technical memoranda prepared by Art Anderson Associates, Inc. include the following documents:

- Task 1 – Plan Formulation Technical Memorandum (Version 2004-09-05E)
- Task 2.1 – Search of State of the Art Hulls, and
- Task 2.2 – Preferred Hull Alternatives

Task 1 – Plan Formulation Technical Memorandum (Version 2004-09-05E)
Task cost: $36K
Report: 9 pages (plus cover, exec summary and table of contents = 12)
Synopsis:
Task scope is to survey state-of-the-art analysis tools for near-vessel wake modeling, select a preferred CFD alternative and develop a methodology for applying this CFD tool to evaluate low-wake hulls.

The survey of state-of-the-art tools is an $18K task, in general this review provides only a superficial / cursory overview of the computational techniques available. The work needs to be more technically complete and precise: For example, at the bottom of page 6, the two paragraph description of CFD techniques is overly simplistic. A proper discussion of the use of Reynolds-averaged Navier-Stokes equations and the selection of turbulence closure models along with a discussion of computational efficiency, convergence problems and accuracy would be appropriate here. Or perhaps a discussion of the development of hybrid techniques which integrate panel, RANS and other techniques for efficient CFD modeling would be appropriate here. For example, the RINA summary of the 2003 CFD conference describing the current state of the art in CFD for naval architecture provides a picture of some of the leading edge techniques and challenges in CFD[1]. Discussion of European initiatives such as the MARNET-CFD program and the development of standards of 'best-practice' for marine applications of CFD might also be useful here – particularly with reference to application of the 'state-of-the-art' and the development of an appropriate methodology.

[1] http://www.rina.org.uk/rfiles/navalarchitect/cfd_april03.pdf

In the Executive Summary and in the Introduction there are comments on PI Engineering regarding CFD selection and future funding of AAA efforts in Task 2.3 that are irrelevant to this report and must be deleted.

Regarding the Introduction – "…a speed limit of 12 knots is imposed on ferries transiting through Rich Passage…" This is perhaps not correct, we believe that WSF imposed this restriction on the Chinook and Snohomish based on performance in Rich Passage. Subsequently private ferry operators have voluntarily adopted this speed limit in coordination with property owners and transit stakeholders. In any case, a reference is needed to substantiate the statement.

The project is not "intended to derive the fast passenger ferry hull type and/or shoreline protection method that will enable fast ferry operation in Rich Passage…" as stated on p.4. The project is to assess the potential shoreline impacts of potential POFF candidates and recommend those candidates and mitigation that could potentially provide an environmentally acceptable fast ferry service.

"The sub contract provides that PIE will fund Task 2.3 Naval Architecture based on the findings of Task 1." The statement is not a correct reflection of the SOW and contract. PIE is under no obligation to fund Task 2.3.

The literature search and review should be accompanied by references and communications from CFD developers.

In the first paragraph of Section 4, reference is made to a document containing information on software packages, discussions and a comparative review table – perhaps this should be the core of the Task 1 report.

Section 4.1 dismisses finite element techniques in two sentences. Finite element analysis is actually used extensively in CFD[2]. In fact, the finite volume technique is a subset of finite element analysis and finite element CFD techniques.

The finite volume method has been used extensively for wake modeling and naval architecture applications. Section 4.2 should describe some illustrative applications, provide examples, discuss the pro's and con's of this technique.

The panel method is in a sense a boundary element technique. The panel methods under consideration here do not neglect viscosity (see AMI's documentation of USAero for details). Potential flow methods neglect viscosity, but potential flow analysis is just one component of these panel method techniques. Typically these models use a higher order panel method to solve for the potential flow field (inviscid) around the hull. This is then coupled to a boundary layer model for flow near the hull and a Navier-Stokes solution for the

[2] For example, J. Garcia and E. Oñate. 2003. An Unstructured Finite Element Solver for Ship Hydrodynamics Problems. Journal of Applied Mechanics. Volume 70, Issue 1, pp. 18-26.

wake zone behind the vessel – the turbulence closure method most commonly employed within the N-S model is a k-ε model – see figure from the SHIPFLOW website:

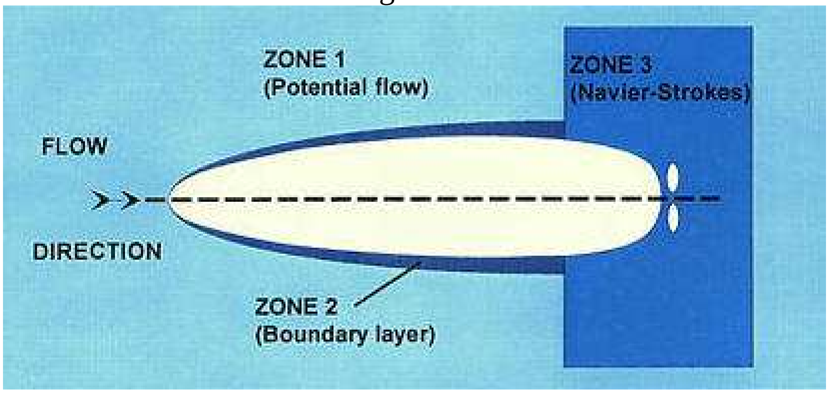

Figure 1 Computational zones employed in panel method (source: Shipflow at www.flowtech.se)

In general, the description of CFD methods and their capabilities is not sufficient. Common CFD websites such as:

http://www.bodrum-bodrum.com/vorteks/arsenal/cfdcodes.htm
http://www.cfd-online.com/

and the websites of CFD developers such as AMI, Fluent, Flowtech, etc. provide access to much more detailed and informative descriptions of these methods.

Section 4.3: ShipFlow has been extensively used for wake modeling both in the US and internationally (e.g. INCAT in Australia uses ShipFlow). Section 4.3 should mention this fact and perhaps provide some examples. The decision not to pursue ShipFlow based on training costs is not well-defended – other costs, accuracy and efficiency need to be discussed and compared.

Section 4.3.1 on AMI is very poorly written.

Section 4.3.3 Define the acronym FSP.

Section 4.3.4 Discuss the status of the FloSim software, number of users, level of development of the code. The fact that the code is just completing development and has undergone less testing and application than either AMI or ShipFlow's models is important and should be clearly noted.

The discussion of panel techniques should include some illustration of applications of the models to wake problems and a discussion of the boundary conditions required, the calibration process, computer and computation time requirements, etc.

p. 6 Search state of the art hulls
"Volumetric methods (VM) eliminated since they require much greater run time…"
This is a rather cursory evaluation and dismissal of VM. Seems no in-depth investigation of VM was undertaken. There may be advantages to have access to certain VM models or consultants to address specific technical applications or questions in the study.

p. 7 Panel Methods (PM) “…requires much less computational time and is easier to learn than volumetric methods…” – see also p. 9 “…The volumetric method is very hard to learn and training would be a long process…” “…the volumetric method is very computer intensive to the point where it could probably delay completion of the project…” Once again, training requirements are not considered an adequate basis for selection of panel methods over volumetric methods**.**

In the same paragraph on P. 7. “…general consensus among the CFD community…” References should be provided to substantiate this “consensus”.

“However, panel methods are sufficient for analyzing wash generated by a vessel…” The meaning of this statement is not entirely clear. One implication is that possibly VM are better than PM for analyzing wakes.

p. 8 Analytical Methods, Inc. (AMI) – AMI’s office locations are irrelevant to the study. As with Shipflow, both AMI’s packages (USAERO and VSAERO) have been applied to analysis of high-speed craft including fast ferry hulls. The section should document some illustrative examples of applications of the software, communications with the software developer (e.g. Hughes et al) concerning recent developments or plans for enhancement of the FSWAVE module, and discuss the pros and cons of the software in the context of the present study.

The point is made that VSAERO has several shortcomings in relation to USAERO thereby making USAERO the preferred option over VSAERO. However, this overlooks the possibility that the most efficient approach might be to use a combination of different softwares to address specific issues or questions. In numerical modeling, it is rare for any single model to be capable of providing all the features and functions required for analysis of a problem.

p. 9 FloSim
AAA readily adopts the FloSim model over AMI’s software with the argument that the major shortcoming of current AMI software is a lack of an adequate separated transom flow model (wake attachment to stern) and a few additional features that have been addressed in the FloSim development. However, they also indicate that FloSIm is still under development and would require several features to be added to make FloSim equivalent to some aspects of USAERO. In other words, as with any model, there are shortcomings. It seems reasonable that if Brian Maskew could add features to FloSim, Michael Hughes, a well-known and highly capable CFD expert and model developer who actually developed the FSWAVE module for USAERO, could add to and enhance the AMI tools. It should be noted that there are technical difficulties (testing and verification) associated with adding features and enhancements to a complicated numerical model. No evidence is provided that FloSim (in contrast with several other packages) has been applied or verified for analysis of high speed craft or fast ferry hulls.

This report includes 2 pages of definitions in the introduction which should be removed to an appendix, perhaps entitled “Glossary”. This glossary should be sorted so that entries are in alphabetical order. Definition of the term “Froude Number” would be improved if it described the dimensionless number as a ratio of inertial to gravitational forces in a flow field. The term g in the Froude number is not the ‘gravitational constant’ as stated, but is the acceleration due to gravity. In referring to the Froude number the subscripts *h* and *L* should be used consistently, the subscript *n* is superfluous (i.e. F_h and F_L).

Although it is mentioned, no evaluation is made of SPLASH in section 4.3.

The ‘methodology’ section of the Task 1 report is exceedingly brief (value $18K, length 3 ½ pages) – it outlines in point form the steps that could be taken to implement a CFD model for ship wakes. It makes no mention of calibration or validation procedures. It is stated in section 5.3.4.4 that “the CFD tool has been validated as accurate for wake wash prediction…” this is an important issue that requires substantial analysis and discussion. This is key to the selection and use of any CFD techniques in this study.

Task 2.1 – Search of State of the Art Hulls, and

Task cost: $16.6K
Report: 24 pages (plus cover etc.)
This task was intended to include documentation and compilation of wake data, however, there is none.

Propulsion systems were also to be included in this review. The SOW states “… identify the latest developments in high-speed vessel technology in terms of hull forms and propulsion systems that are relevant to the design…”

In the Executive Summary, reference is made to wake impact/erosion data. This is not part of the scope of work.

The phrase ‘this was an intensive effort’ is qualitative and unjustified, please omit.

In general, this document contains an insufficient number of diagrams, examples, illustrations and technical references.

It provides a rudimentary summary of vessel types but provides virtually no substantive findings with respect to wake generation by these vessels.

The term “planing hulls” is repeatedly mis-typed as ‘planning hulls’.

Section 3.8: The ‘Wing-in-ground-effect’ vessels such as the ekranoplan are, in our opinion, somewhat outside the scope of this study and should be deleted or only referred to anecdotally in passing.

There should be examples, illustrations and technical discussions of foil-supported and other vessels.

Terminology with respect to Froude numbers F_h and F_L is confusing and needs consistent nomenclature.

In Section 4.2, the discussion is not clear as to whether relative speed, F_L, or absolute speed, V, is being discussed. The statement that speed reduction will reduce wake height is erroneous and a mis-statement of fact.

Section 4.3: The term 'pressure gradient' needs definition and illustration – it is not readily apparent to the reader specifically which gradient is being referred to.

The concept of 'slenderness ratio' needs to be properly introduced, defined and illustrated. If slenderness ratio is defined as $SR = \nabla / (0.1L)^3$ then it would appear that as the length of a vessel increases for a given vessel displacement, the slenderness ratio decreases. Therefore slenderness of a vessel INCREASES as *SR* DECREASES. So it is actually the inverse of slenderness. Is this common usage in naval architecture? If so this should be stated and referenced.

Section 4.4: No evidence or technical discussion is provided for how wake cancellation works in practice. Does wake cancellation work over a wide spatial extent? How sensitive is wake cancellation to operating speed? The statement "therefore wave cancellation can be used as a criterion…" is unjustified so it is unclear how one would quantify or evaluate wake cancellation.

Section 5: The "minimum requirements" for Rich Passage are unsubstantiated. A reference or justification for the chosen speed and passenger capacity should be provided.

Section 6: The discussion of 'gaps and inconsistencies' is insufficient. The fact that wake data is often proprietary is acknowledged but none of the publicly available wake data is either described or presented here. There is time series data available in the literature and it should be reviewed and critically discussed in this report. The advantages and disadvantages of using summary statistics to characterize wakes should be discussed. The concept of hybrid hull forms or hull types should be discussed prior to Section 6. The fact that some technical papers contradict each other is hardly surprising and is not worthy of the trivial discussion presented in Section 6.

Task 2.2 – Preferred Hull Alternatives
Task cost : $33K
Report : 16 pages (plus cover etc.)

This report actually contains the summary statistical data which should have been presented in Task 2.1.

In the Executive Summary of this report, the following reference is made: "…The literature search also compiled wake wash data for the candidate hull forms." Is this referring to the Task 2.1 report – there is no compiled wake wash data in that report.
Paragraph 3 of the Executive Summary starts "In subtask 2.3 Art Anderson Associates…". This is to be omitted. The statement is not a correct reflection of the SOW and contract. PIE is under no obligation to fund Task 2.3.

Similarly, the 3rd paragraph of the introduction needs to be omitted.

Section 2.1 on wake wash measurement describes only the technique employed by Fox and Stumbo. There are many other sources of data and methods of data collection and analysis.

Section 2.2 should critically discuss the implications of assuming a 1/3 power law decay of wake height, particularly vis-a-vis the results from CFD simulations.

In Section 3 the nomenclature for Froude number is again inconsistent and needs to be corrected. Also the implications of using length Froude number exclusively instead of a combination of both depth and length Froude numbers should be discussed.

Also in Section 3 the logic of using H/L for wake and E/Δ is contradictory.

Section 4, 1st para: The phrase 'intensive literature search' is qualitative and unjustified – delete.

In Section 5: The discussion needs more detail. There is no presentation of wake performance curves for individual vessel types/classes. There is no discussion of actual wake heights generated, time series characteristics, etc. Certain datasets such as S20 and S21 actually exist over a wider range of Froude numbers than is shown in Figure 2 – is there justification for leaving out the other data?

The 'critical' Froude number of 1.17 in Figures 1 and 2 is only significant for *a priori* determination that the critical conditions in Rich Passage are a speed of 35 knots and a length of 24m. This presentation of the normalized data is of interest but needs to be discussed in more detail: For example, are there any commonalities in the curves for vessels of a common hull form? Section 5 states "Clear preferences of hull alternatives still emerge…" this statement is not self-evident and needs graphical and statistical support.

The preferential use of 'overall length' when length on waterline is available seems incorrect.

Most importantly, the data and figures provided do not support the conclusions that the air-cavity, air-lubricated and foil-assisted catamaran hulls offer the best performance. This is a key statement and needs to be clearly defended by the data compiled and analysed in this report.

Discussion of dimensionless performance such as H/L and E/Δ is interesting but should also be reduced to discussion of key parameters of wake height and energy.

The selection of air-assisted crafts has direct implications for the CFD methodology – this needs to be discussed either here or in Task 1.

Very little of the compiled data covers the range of depth and length Froude numbers that concern us in Rich Passage – a scatter diagram showing the data in F_h-F_L space should be included in this analysis.