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"Development of an Interface System
for the Design of
Submersible Internal Arrangements and Hull Forms"

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"Development of an Interface System for the Design of Submersible Internal Arrangements and Hull Forms"

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This report presents the results of an investigation into the development of an interface system for the design of submersible internal arrangements and hull forms. The research and development were conducted as a Trident Scholar project at the United States Naval Academy. The design process was founded on what is being called concurrent design methodology. The development of the process involved the interfacing of commercially available geometric modeling and CAD tools with analytical parametric methods of marine vehicle drag analysis. The interfaced design tools were then employed to design a human powered submersible in order to validate the efficiency of the particular concurrent design processes used in this project. The submersible vehicle's design requirement were established by the Biannual Human Powered Submarine Race committee. To provide a basis for relative performance comparisons, previously constructed and raced submersibles were remodeled using the system's CAD tools in order to be evaluated and compared to the new design generated by this project. The methods of design and analyisis are detailed in this report. The report also contains a new program that was created to extract vehicle hull form characteristics from geometric data. The results of this project have shown probable reductions in vehicle drag over existing human powered submersibles.

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1.0 Nomenclature

.3ds	-3D Studio CAD file format
A	-area
APM	-analytical parametric methods
A_X	-maximum section area
C_A	-model-ship correlation allowance
CAD	-computer aided design
CAM	-computer aided manufacturing
C_F	-frictional drag coefficient
CFD	-computational fluid dynamics
C_P	-prismatic coefficient
C_R	-residual drag or form drag coefficient
C_T	-total drag coefficient or CDwet
D	-diameter
D_h	-hydraulic diameter
.dxf	-data exchange file
D/L	-thickness ratio
EHP	-effective horsepower
EPDA	-equivalent parasite drag area
L	-length
L/D	-fineness ratio
l^*_t/D	-tail-cone fineness ratio
ρ	-mass density of operating fluid
P.C.	-propulsive coefficient
R_T	-total resistance
R_{BH}	-bare hull resistence
R_{APP}	-appendage resistence
R_N	-Reynold's number
SHP	-shaft horsepower
S_{wet}	-wetted surface area
V	-velocity
∇	-volume
ν	-kinematic viscosity

2.0 Introduction

The interfaced computer aided design (CAD) system concept stems from the need, in concurrent design methodology, for prompt and accurate three dimensional modeling of objects, to provide geometric data for later analysis and a visual medium of communication among clients, inventors, designers and engineers. The efforts of this Trident Scholar project were to interface commercially available CAD capabilities with parametric hydrodynamic hull performance calculations in order to provide a more effective method of submersible vehicle design, where internal arrangements are the crucial factors. The internal arrangements are critical because they impact directly on the efficiency and degree of mission satisfaction achieved by the vehicle. To estimate vehicle performance, analytical parametric methods (APM) of hull form hydrodynamic analysis were used in the interfaced system, where APM offers the capability to rapidly predict relative hydrodynamic performance based on hull shape parameters.

A major problem faced with any interfacing or integration among design phases is the difficulty of data exchange [Johnson 1990a, Gillman 1991]. Integrated systems require the same operating system, dynamic exchange of data, and, most importantly, a common data format. Many attempts have been made to establish a standard form for the storage and retrieval of geometric data [Gillman 1991, Johnson 1990, Hays 1990]. Even though some of these efforts have produced effective storage methods, the CAD industry is too diverse to adopt any single form, and therefore large integrated design systems have eluded the engineer. As an alternative, designers have turned to interfaced systems. Chris Borland of Boeing states that "Interfaced systems generally make it easier to perform tasks not originally conceived by developers of integrated systems with similar objectives." Another step toward CAD hull form and APM interfacing, once data forms have been normalized, involves manipulating the geometric data into relevant information. For this project, a data translation program was used to manipulate the geometric data. It served to read in geometric data, in a pre-specified form, and output that data as required to provide useful information, which, in this case, was input for the APM analysis.

The design of a human powered submersible is used as an example to demonstrate the logical and efficient design process an interfaced CAD and APM system makes possible. The submersible design may be considered for possible future construction and entry into the Bi-annual Human Powered Submarine Race by the United States Naval Academy. It is believed that enhancement of the submersible design process using concurrent methodology will in turn boost the performance of the vehicle.

3.0 OBJECTIVES

The objectives of the Trident research project were as follows:

1. Assemble a PC based, interfaced CAD and APM design system that will assist the user in optimizing the hull form that is constrained by the arrangement of the internal components. The optimization includes estimating the hydrodynamic consequences of the external shape necessary for a given set of internal arrangements and associated operator movements in order to design a hull form for a human powered submersible.

2. Show validity and effectiveness of an interfaced CAD/APM design process and its relation to concurrent engineering.

3. Present a proposed human powered submersible design to the U.S. Naval Academy's department of Naval Architecture, Ocean and Marine Engineering (NAOME), for consideration of future model testing and construction.

4 BACKGROUND

4.1 Concurrent Engineering

In today's engineering world the computer has become an integral part of design and analysis. However, there is a lack of adequate interfacing and integration among software components necessary for "concurrent engineering." The phrase "concurrent engineering" refers to a design methodology with the aim to engineer, design, manufacture and evaluate a project throughout its life cycle within an interfaced "design system." The concurrent design system provides the necessary support tools to examine all facets of design, manufacture, and product performance from commencement of the project [Jebb 1992]. Concurrent design contrasts the traditional series or sequential approach by allowing the users to examine the product at any point along the conventional design spiral (Figure 1) during any phase of the project. Concurrent methodology seeks to convert the serial nature of the design spiral into a parallel effort, reducing development time, design costs, and design-to- manufacture interface obstacles [Keys 1992, Jebb 1992].

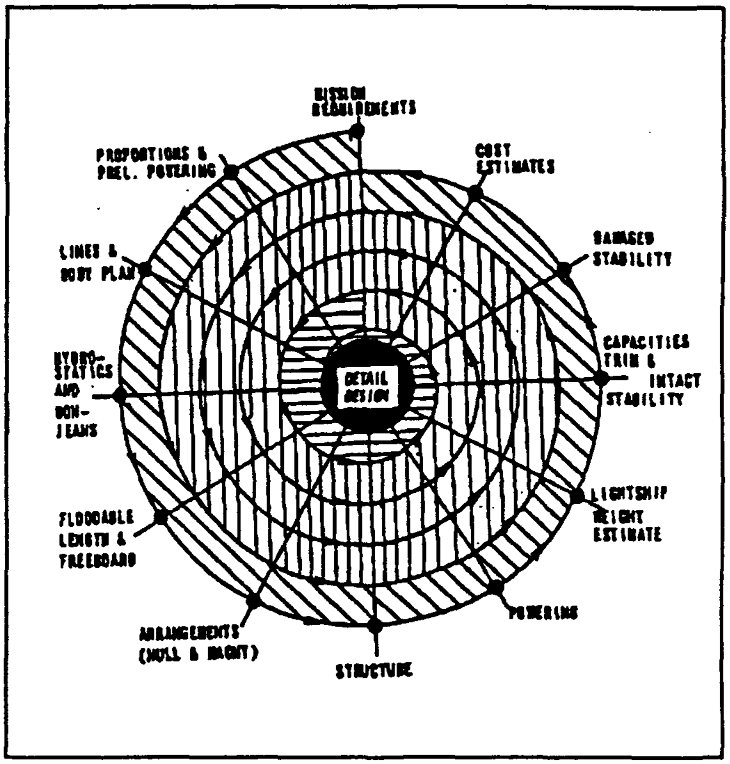


Figure 1 Traditional ship design spiral. [Taggart 1980]

The major "bottleneck" concurrent engineering faces today is the rapid exchange of data. The multitude of computer based tools that must be interfaced to accomplish concurrent design generates a wealth of information that must be stored in a neutral format to enable all applications to make use of it. A Standard for the Exchange of

Product (STEP) model data is a proposed system for the storage and standardization of product data. "STEP will allow a single logical database to support the data storage and retrieval requirements of all the computer-based design and analysis applications used throughout the product's life cycle" [Gillman 1991]. Also, The International Towing Tank Conference (ITTC) Symbols and Terminology Group has been developing a standard neutral format for the exchange of hydrodynamic performance data using the format specifications being developed by ISO/STEP for hull form, propeller and appendage geometry data [Johnson 1990a]. With advances in technology and industry cooperation as seen in these examples, the future of concurrent engineering is encouraging. It has been attempted to apply concurrent engineering ideas in a limited manner by the interfacing of CAD and APM, for the purpose of developing an efficient submersible design tool.

4.2 3-D CAD-Hull Forms/Internal Arrangements

> "Computer aided geometric modeling or computer aided design (CAD) is the ability to represent physical objects to allow design (synthesis) and evaluation (analysis and simulation) in a unified computer environment." [Chryssostomidis 1990]

CAD has been under development for over thirty years. Many techniques have evolved for the synthesis of objects in a computer environment. Wireframe and surface modeling are the most common; but recently, research has led to solids modeling which allows representation of physical objects as solids by the computer. This avoids many of the ambiguities associated with wireframe and surface models [Chryssostomidis 1990]. However, because of the solid modeling CAD system's complexity, a user-friendly interface is still in development [Cugini 1991]. In order to maintain a tolerant user interface, this project involved the use of commercially available wireframe and surface modeling CAD systems.

Both wireframe and surface modeling have specific advantages for the designer. Wireframe models use edge curves and object end points for object synthesis. Because of their relative simplicity, they are useful in representing complex models, such as submersible vehicle internal arrangements, for basic computer analysis [Chryssostomidis 1990]. Although the wireframe method represents the objects accurately to the eye, this method presents the problem of fairing hull forms. Fairing refers to the systems' ability to fit a "fair" or smooth surface to the established vertices of the wiremesh. This dilemma is mostly of concern when the design reaches the modeling phase of development. This is because computer aided manufacturing (CAM) of models has become so efficient that any disparities in the hull's geometric data are reproduced in the model.

To overcome this, surface modeling techniques were developed in the 1960's. Surface modeling systems typically employ piecewise continuous polynomial parametric surfaces [Rogers 1990]. Numerous systems based on Coons patches, Ferguson, Bezier and B-spline tensor product and rational surfaces have evolved [Rogers 1990, Faux 1981]. Surface methods of object synthesis are very practical in hull form design because of the inherent fairing that results from the mathematical construction of these surfaces. A common example of a surface modeling system used at the Naval Academy is the hull design system *Fastship* which employs B-spline surface construction. Despite the efficiency in hull synthesis, surface modeling methods are not practical for representation of objects with complex faceted geometric shapes. These complex shapes include most of the internal arrangements found in vehicle design. Because explicit connectivity information of the surfaces is not provided, the attempted synthesis of complex shapes may lead to surfaces that bound a physically unrealizable object. This weakness of surface modeling systems also complicates design analysis. [Chryssostomidis 1990, Miller 1986].

As indicated by Chryssostomidis, computer aided geometric modeling not only involves synthesis, but should also include analysis and simulation. The various aspects of marine vehicle analysis are discussed in the following section (4.3). The topic of simulation, however, is addressed with regard to 3D CAD because, for the design of human powered submersibles, simulation requires the ability to examine the motions of the submersible operators through animation of the human propulsor and driver. This subject is further detailed in Sections 5.1b, 5.1c and 5.2a.

4.3 Fluid Dynamics of Vehicle Design

The field of vehicle fluid dynamics encompasses many specialty areas which includes performance predictions based on empirical geometric parameter analysis, computational fluid dynamic modeling, and model testing of the vehicle alternatives. This section briefly introduces the latter two subjects, but focuses on geometric parameter analysis which is referred to in this report as analytical parametric methods (APM) and is the method of analysis used in this project.

Computational fluid dynamics (CFD) is most commonly applied to fluid flow situations where lifting forces dominate the design. The solution can then be derived from linear theories where viscosity is neglected [Morgan and Lin 1987]. Currently, the major unresolved problem for CFD has been solving for the viscous flow drag associated with ship hydrodynamics through application of the Navier-Stokes equations [Johnson 1990b]. This problem is being addressed by the application of turbulence models, but to date, there exists no accurate model for 3D flows. Therefore, CFD calculations for hull resistance are currently not a viable option. The advances and limitations of CFD methods are discussed in detail by Johnson ,1990b, "On the Integration of CFD and CAD Ship Design".

Marine vehicle model testing in towing tanks and wind tunnels is the basis of vehicle hydrodynamics. With W. Froude's advent of the method for extrapolating model-test data to full-scale application by correcting for the differences in skin friction drag, the use of model tests for performance predictions became the standard. The International Towing Tank Conference (ITTC), established in 1932, is accepted as the coordinating body for this field of work. The conference serves to review attempts to improve model testing methods and publish them as standards. Model testing, however, is still a costly and time consuming process to use at the beginning stages of development. Therefore, the data from decades of model tests have been used to develop analytical expressions that estimate hull performance. These expressions range from drag and propulsive relationships to equations for seakeeping and stability.

Any discussion of analytical predictions of hull powering performance begins with the total hull resistance (R_T) which is comprised of the bare hull resistance and the appendage resistance. Therefore,

$$R_T = R_{BH} + R_{APP} \tag{4-1}$$

The bare hull resistance comprises approximately 60-70% of the total resistance for large fully submerged submarines and is therefore the principal factor [Gillmer 1982]. To analyze and predict the bare hull resistance, Equation 4-2 is most commonly used.

$$R_{BH} = 1/2\rho A V^2 C_T \tag{4-2}$$

where, ρ = mass density of the operating fluid (slugs/ft^3),
A = reference area (generally wetted surface) (ft^2),
V= velocity (ft/s),
$C_T = C_{Dwet}$ = non-dimensional drag (or total resistance) coefficient.

The drag coefficient, C_T is associated with a particular reference area which must be accurately determined as a function of speed. This is done by measuring the model's resistance as it is towed through the model tank and then solving equation 4-2 for the total resistance coefficient at that speed.

In an attempt to analytically predict C_T of the prototype, the total resistance coefficient is generally broken down into components.

$$C_T = C_F + C_R + C_A \tag{4-3}$$

The drag coefficient consists of a friction drag coefficient, C_F, and a residuary (or form) drag coefficient, C_R [Allmendinger 1990, Gillmer 1982, Hoerner 1965]. C_T also may include other small factors. Typically, a model-ship correlation allowance C_A (.0002 to .0015) may be added to account for submersible surface roughness [Allmendinger 1990]. However, this allowance is ignored within this project as it is assumed that all hull forms will have a similarly smooth surface. Also, an adjustment for wave-making resistance, C_W, should be added if operating at a depth of less than five times the hull diameter [Allmendinger 1990]. This coefficient is also neglected as the human powered submarine race is typically held at depths greater than 20 feet and the hulls being considered here are generally three feet in diameter.

The frictional drag coefficient has been the focus of many experiments to determine an equation to predict this coefficient empirically. In 1932 K. Schoenherr developed a formula, Equation (4-4), to fit data for turbulent friction along a smooth plate [Gillmer 1982].

$$0.242/(C_F)^{0.5} = \log_{10}(R_nC_F) \qquad 4\text{-}4$$

The Schoenherr formula underestimates the frictional resistance of models where turbulence stimulators are used to trip the laminar boundary layer flow at low Reynolds numbers. It also does not allow C_F to be explicitly solved for as a function of Reynolds number [Gillmer 1982]. Therefore, in 1957 the ITTC adopted Equation (4-5) as an interim model-ship correlation line solution, accounting for the artificially turbulent model flow, in order to predict full scale ship resistance.

$$C_F = .075/(\log_{10}R_n - 2)^2 \qquad 4\text{-}5$$

In order to eliminate the problem of iteratively solving for C_F as a function of Reynolds number in Equation (4-4), Hoerner[1] developed the following formula which fits the Schoenherr line reasonably well between Reynolds number ranges of 10^6 to 10^8.

$$C_F = K/R_n^{1/m}$$

where, K=.044

m= 6 4-6

Figure 2, on the following page, shows the relationship of C_F versus Reynolds number for Equations (4-4), (4-5) and (4-6).

The residuary resistance, C_R, accounts for the resistance component caused by flow separation associated with adverse pressure gradients on the rear half of the vehicle. (This resistance component is known as form drag in aerodynamics.) "The analytical prediction of C_R is very difficult due to the complexities of the physics of fluid separation" [Allmendinger 90]. To examine residuary resistance, thousands of model tests have been conducted to measure the total drag, and then subtraction of the frictional resistance using the Schoenherr line (4-4) or the ITTC line (4-5) produces the residuary resistance. Figure 3 illustrates the effects of hull shape on C_R by plotting it against the length to diameter ratio. The two lines on this plot bound the expected operating regions

[1]In Hoerner's book *Fluid Dynamic Drag*, it states that K=.44 for the given Reynolds number range. However, this values does not produce the expected values of C_F. Based on the other values of K (0.030, .036) it has been assumed that the value of .44 is a misprint and should read 0.044.

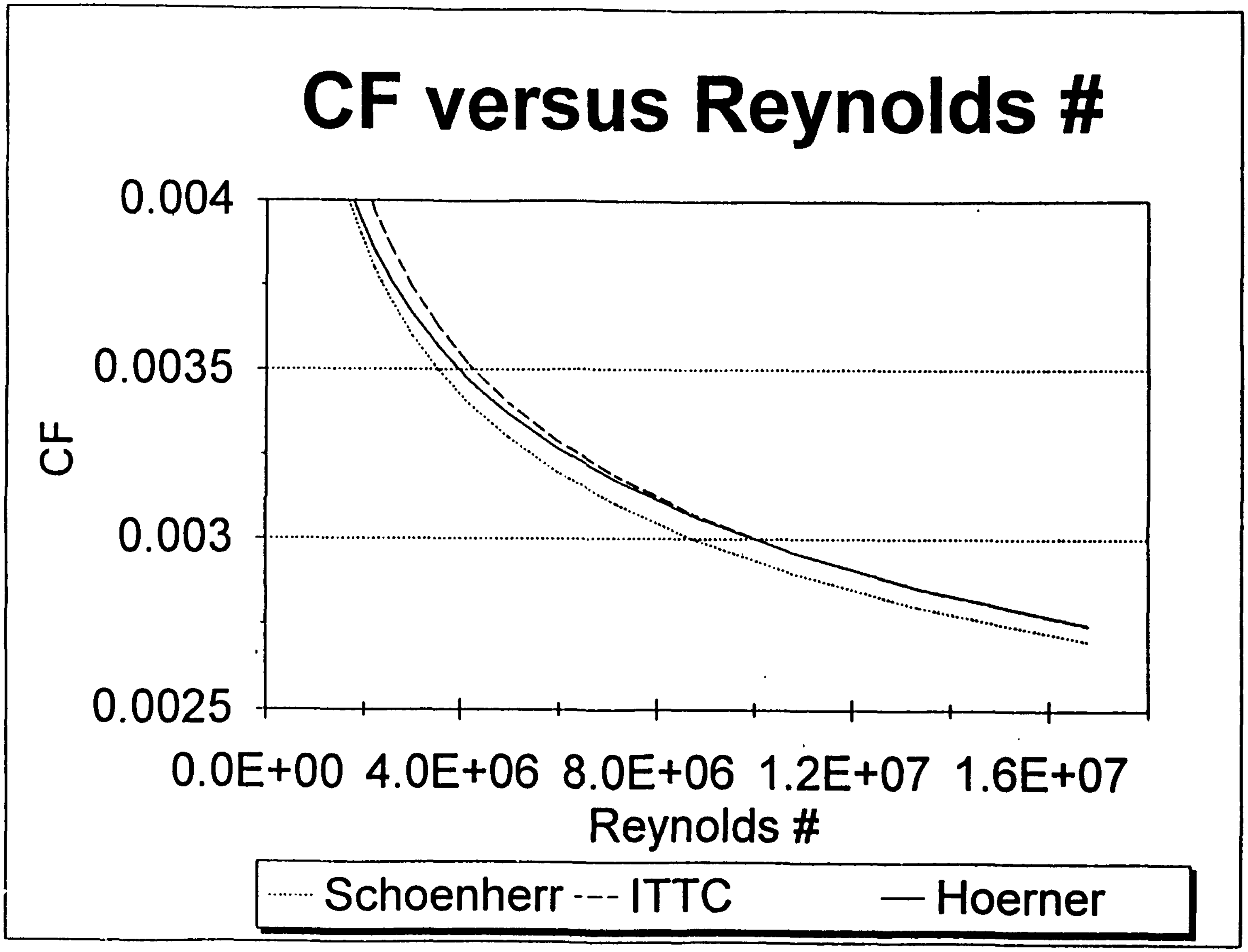


Figure 2 C_f calculations for equations 4-4,4-5 and 4-6.

of the human powered submersibles. The transition from laminar to turbulent flow within the range, $R_n = 10^6\text{-}10^7$, further complicates attempts to predict C_R and C_F values. It is within this Reynolds number region that operation of human powered submersibles occurs.

However, for the purely laminar and turbulent regions of the Reynolds number ranges, various analytical expressions have been developed and may be applied on a comparative basis in the transition realm. Hoerner approximates the total resistance coefficient, C_T, as C_F multiplied by an empirically determined factor to account for form drag as a function of diameter to length ratio [Hoerner 65].

$$C_T = C_F * [1 + 1.5(D/L)^{3/2} + 7(D/L)^3] \qquad 4\text{-}7$$

Figure 4 plots the relation of C_T versus Reynolds number while varying D/L. Note the large amount of scatter in the transition region, $R_n = 2x10^6\text{-}2x10^7$ [Brooks 1967]. The expression D/L is a ratio of the maximum diameter to the hull length and is referred to as the thickness ratio. Conversely, the expression L/D is used as the fineness ratio. For purposes of examining non-axisymmetric hull forms a hydraulic diameter was used and is defined as: $D = D_h = (4A_X/\pi)^{0.5}$ where A_X=max section area 4-8

With this approximation of C_T, Equation (4-2) can be used to predict the total drag which in turn allows relative hull performance analysis.

The fineness(L/D) or thickness(D/L) ratio as seen in Figures 4 and 5 [Hoerner 1965] is an extremely vital design characteristics that influences the total drag through the residuary drag term as well as affecting the separation point of a hull. From model tests done at the David Taylor Model Basin, it was determined that a fineness ratio (L/D) of about 7.0 is optimum for streamlined, appended submersibles. Within the L/D range of 6.5 to 8.0 performance dropoff is not appreciable [Gertler 1950, Brooks 1967, Ballard 1989].

However, many other hull form characteristics also play a key role in examining and optimizing a submersible's hull powering performance. Wetted Surface area (S_{wet}) is certainly a major factor in drag minimization which is apparent from Equation (4-2). Another geometric property that is examined is the section area curve of the hull form, which is a plot of the section areas as a function of the longitudinal position along the

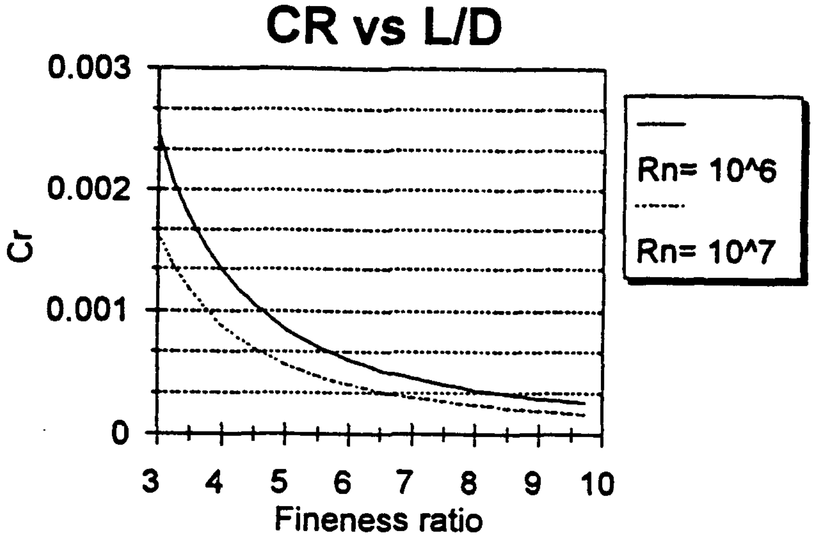
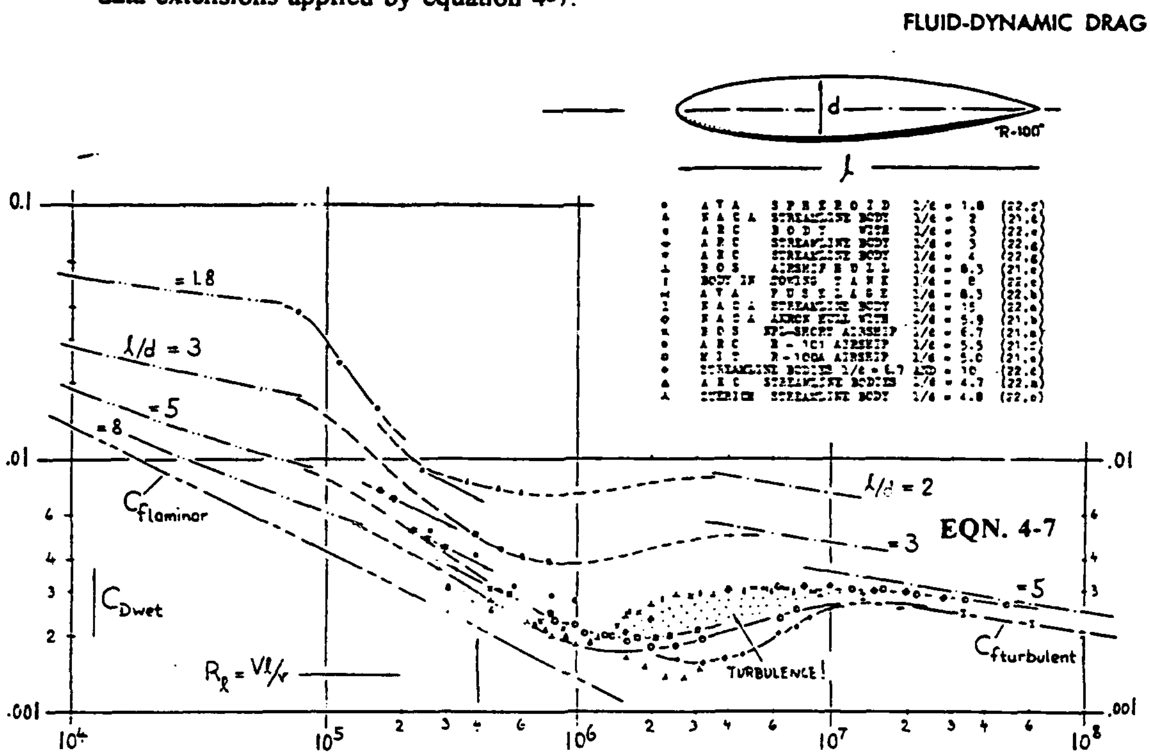


Figure 3 Form drag coefficient C_R for streamline bodies versus fineness ratio l/d.

Figure 4 Results of drag tests on streamlined bodies. data extensions applied by equation 4-7.



(a) AT R_v = 10^6 - WITH TURBULENT BOUNDARY LAYER

(b) AT R_v = $3x10^6$ - WITH TURBULENT BOUNDARY LAYER

(c) AT R_v = 10^7 - WITH TURBULENT BOUNDARY LAYER

(d) AT R_v = 10^6 - WITH NATURAL TRANSITION

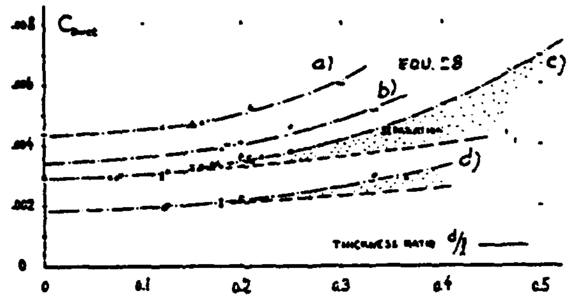


Figure 5 Variation of drag coefficient as a function of d/l.

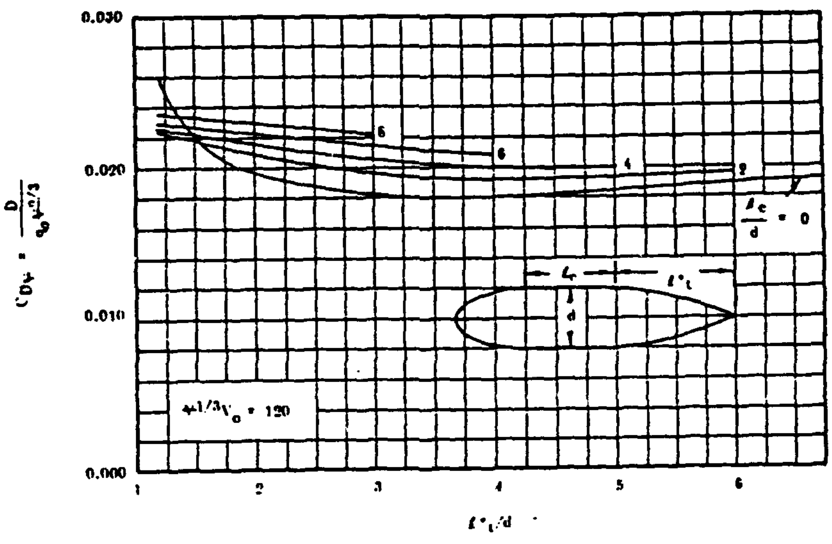


Figure 6 Variation of drag coefficient as a function of tail-cone fineness ratio (l^*_t/d).

hull. Although difficult to prove analytically, it is obvious from model tests that the section area curve of the body has a significant effect on flow separation and the resulting form drag of the hull. Unfairness in the section area curve will most likely contribute to flow separation and a resulting increase in form drag. A final key property is that of tail-cone fineness ratio which is defined as: l^{*}_{t}/D. This property is further defined and illustrated in Figure 6 [Brooks 1967]. For the optimum L/D ratio of 6.5, a tail-cone fineness (TCF) ratio of 3.9 is recommended [Brooks 1967]. Also, [Ballard 1989] suggests that the tail cone taper not exceed 20 degrees. This statement supports Brooks' recommendation of a TCF ratio equal to 3.9 which corresponds to an angle of approximately 15 degrees. Finally, two other properties of lesser importance are the prismatic coefficient (C_p) and logitudinal

$$C_p = \nabla / LA_x \tag{4-9}$$

position of maximum section area (A_x) [Brooks 1967]. Figures 7 and 8 [Gertler 1950] illustrate their effect on performance for small changes at relatively low operating speeds. A C_p of .6 for hulls experiencing turbulent flow is seen as optimum. The position of A_x should be approximately 40% of the hull length from the nose. However, [Hoerner 1965] states that by moving A_x further aft, laminarization may be continued to higher Reynolds numbers. Laminarization refers the partial laminar flow over the length of the body.

For the purposes of this project, the hull appendages were limited to control and stability surfaces. Also, a standard size was assumed for each hull in order to focus the comparative analysis on the hull shape. The process for approximation of appendage drag is very similar to that of the hull. The major difference is the local Reynolds numbers at which the control surfaces operate at because of their length.

To summarize the process of hydrodynamic drag estimation is difficult because of the multitude of parameters involved. The key principle is the estimation of C_F and its subsequent adjustment to account for form drag, C_R. Once this has been accomplished, the bare hull drag can be estimated by Equation 4-2 and can be combined with the appendage drag to produce an estimate of the total drag. Finally, it should be noted that although APM drag estimations can only yield ball park figures, it provides an efficient means for comparing relative performance which leads to less spent time and money.

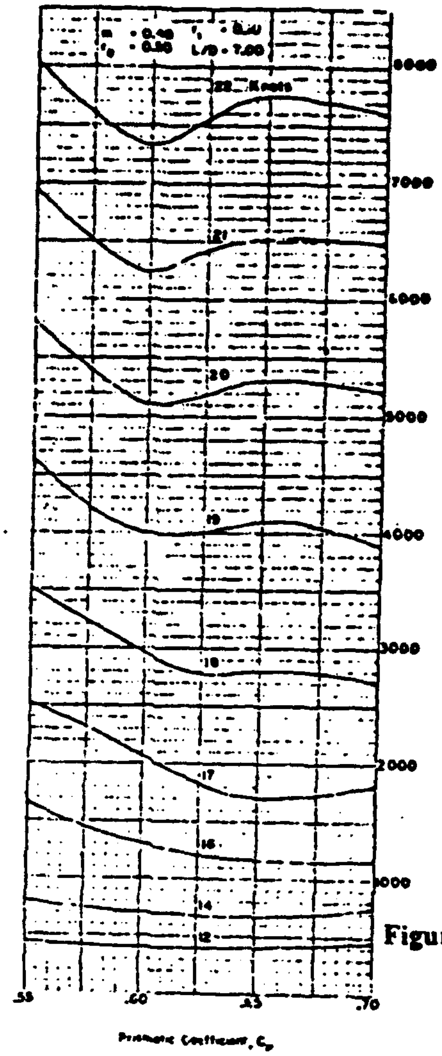


Figure 7 Variation of effective horsepower (EHP) as a function of speed (kts) and prismatic coefficient (C_p).

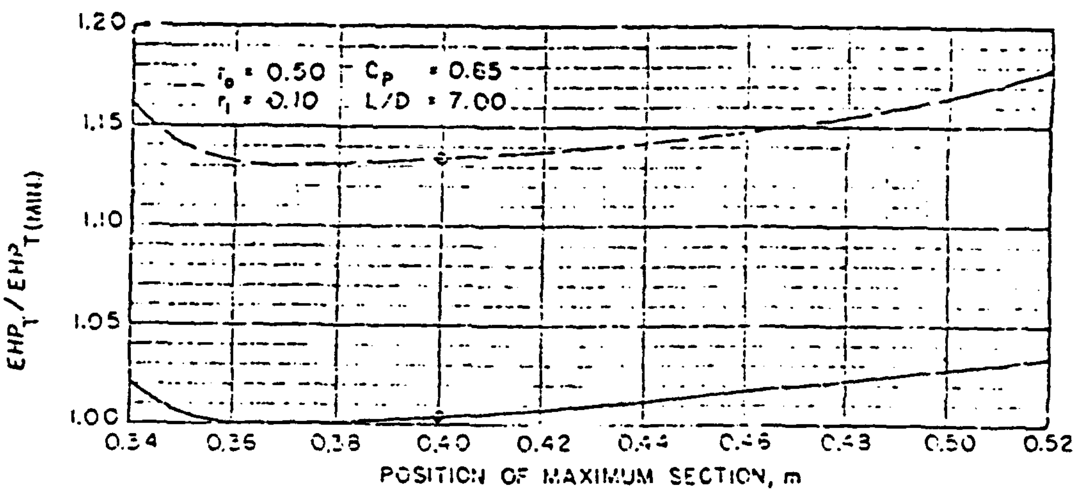


Figure 8 Variation of EHP as a function of position of maximum section area (m=A_x).

5.0 Methodology

5.1 Design system Criteria

In the past, the arrangement design process of the Naval Academy human powered submarines generally involved hand-drawn concept sketches and extensive cut-and-try fabrication activity. It lacked the tools to model the internal arrangements accurately or manipulate them efficiently. Once a drawing had been made, there existed no convenient way to examine in detail the relationship between man and machine's motions which is of paramount importance for a human powered vehicle. Finally, a hull shape concept was sketched and then modeled in *Fastship*. From *Fastship*, the hull characteristics (volume, wetted surface area) were output for subsequent off-line estimation of the vehicle's performance.

This design process exhibits many deficiencies that often lead to increased design and development time and possibly, decreased vehicle performance. The foremost problem is that hull design iterations did not include any means of performance comparison. The performance calculations were done on the final hull form. Second, without any means of examining the human power sources' motions, only a guess/estimate of the required space could be made. This consequently led to the human power source hitting his knees on the hull and air tanks of previous vehicles. This problem may have also developed due to the inability to model the internal arrangements of the vehicle accurately. Regardless, manipulation, by hand, of the internal arrangements which includes the human motions is very time consuming.

In order to overcome these deficiencies, criteria were established for the design process and thus was laid the framework for an interfaced system to accomplish the process. The following section offers a summary of the suggested features needed to produce an interfaced CAD/APM design system. The necessity and relevancy of each feature is briefly discussed in this section. Each feature is discussed in more detail as the software component that enables the interfaced system to accomplish each specific ability is introduced into the system.

5.1a Comprehensive CAD

It is estimated "...that the cost of design changes increase by an order of magnitude at each major stage of design and production." [Johnson 1990b]. A principal area in vehicle design where changes continually occur is in the internal arrangements. It is for this reason that an interfaced design system must include comprehensive CAD capabilities. The previously mentioned CAD system *Fastship*, used to model SUBDUE and SQUID[2], only allow the user to define the external hull form. Without the ability to model the internal components essential to the vehicle mission, it is a tedious process to predict the hydrodynamic consequences on the hull shape when changing internal arrangements. Therefore, the ability to synthesize all internal arrangements, as well as the hull form, is key to efficient design. It will increase the efficiency of communication between the client and designer, and thus reduce the design iterations necessary to meet the client specifications and simultaneously reduce initial production costs. Also, great flexibility is afforded the engineer during the design process because any changes can be simply made within the CAD system which will in turn allow for the most efficient design.

5.1b Animation

Animation capabilities are included in the system to afford the designer the ability to view the interaction with respect to ranges of motion of the principal components of the design. This enables the engineer to avoid possible conflict between mechanical moving parts and those who operate the system. In the case of marine vehicle design, the human interaction among the vehicle components is typically limited by internal component and hull design considerations. Human interaction refers to the space provided to accomplish a task, such as steering the vehicle which requires some space for human movement. Because a marine vehicle's cost is largely based on its size, this space must be minimized. Therefore, the ability to animate the human movements to determine the necessary motions envelope is a key to successful design. This component of the design

[2]SUBDUE and SQUID are previous entries in the annual human powered submarine race from the U.S. Naval Academy. SQUID won the first overall competition held in June 1989 and is now retired. However, Subdue is being remodelled and will be entered in the upcoming race in June 1993.

system is one that can only be practically accomplished with the use of computers.

5.1c Preliminary Hydrodynamic Analysis

Preliminary hydrodynamic analysis within the design process is essential to providing vehicle performance estimates to the designer so that he or she will have an objective analytical basis for arrangement comparisons. Such an analysis capability enables the designer to estimate the hydrodynamic consequences of the external shape necessary to contain the various internal arrangement models that have been generated. With this capability the designer can interactively optimize the internal arrangements and the external hull form.

5.1d Zero Waste Space

Wasted or void space should generally be minimized in vehicle design unless needed for buoyancy. The elimination of such space can decrease weight, surface area, and frontal area and thus increase performance. In this respect, the interfaced CAD/APM design system offers many advantages to the engineer. With the ability to predict the motions of both machine and man within his design, void space is almost automatically minimized. The idea of "zero waste space" is of special interest to this project because the design of a human powered submersible presupposes that the vehicle performance will be enhanced by balancing the optimum use of space with efficient hydrodynamic shapes. This subject is also discussed in the project results of this report which details the design of the Trident submersible.

5.2 CAD Tools

This section is a detailed discussion of the components assembled to provide a comprehensive CAD environment. The discussion includes the reasons for choosing the particular software from the many that are available. It also includes the capabilities and limitations of each component and how they contribute to the design process as a whole. It is important to note that all of the chosen software is IBM DOS 5.0 or Windows based and run on a personal computer with a 486DX/33 motherboard.

The IBM compatible PC was chosen as the base for the system for many reasons, the most obvious being the ready availability of such hardware. With the wide availability also comes the familiarity with the DOS system that makes learning to use the design system easier.

In order to develop a more efficient system in terms of speed and processing, the 386-20 PC that was provided to the project by the US Naval Academy Department of Naval Architecture, Ocean and Marine Engineering was partially upgraded. An Intel 486DX-33 motherboard was used to replace the existing 386 motherboard. Also in the interest of machine speed, four megabytes of memory were added to give a total of eight megabytes. This made processing of rendered images and animation five times faster. In order to accommodate the large amount of software necessary for the design system and the space needed to store the data files, a 240 megabyte hard drive was added to the existing 80 megabyte hardrive. With these hardware components in was possible to load and run the software required for the project.

5.2a 3D Studio

The heart of the interfaced system is its three dimensional modeling software. The major consideration for this component of the system was its ability to model any object that could appear in vehicle design easily and accurately. Also, its cost and ability to accept and generate many types of graphics files were important features.

Five 3D CAD systems (Intergraph, Microstation PC, BRL CAD, 3D Studio, AutoCAD 12) were investigated for use in the interfaced system. Intergraph's Microstation, used in the Navy's CADDII system, was the first program examined. Microstation is a CAD system operated on Sun and Integraph workstations. However, the high software cost and lack of an available workstation immediately ruled out this option. This led to MicrostationPC which is simply a PC based version of Intergraph's Microstation CAD system. From examination of its use at Advanced Marine Enterprises, it demonstrated exceptional modeling capabilities and was highly recommended by its users. However, it lacked any ability to animate the modeled objects which is one of the criteria established for the design system (see 5.1b). Also considered were versions of AutoCAD and a Ballistic Research Laboratory CAD (BRL CAD) already at USNA.. However, the code intensive nature of these systems requires a relatively long learning curve which made them impractical for the project and academic application. They also lacked the required animation capabilities.

The answer was found in 3D Studio by AutoDesk. It is a desktop computer design system with vast wireframe modeling, rendering and animation capabilities. 3D Studio being wireframe based offers many 2D and 3D modeling capabilities which enables the user to create almost any conceivable object. Although it is a wireframe system which has the previously discussed (Sec. 2.2) problems of fairing, a solution to this issue is offered in section 5.5, Supporting Programs. The importance of object modeling is inherent in computer aided design, but the ability of the software to accurately and easily create objects varies widely. Some systems are developed for a specific purpose such as hull design which they accomplish very well. However, in order to design an entire vehicle, the modeling software must be able to produce all of the required objects. 3D Studio does have limitations, but it has been able to model all objects required for this project.

Another principal feature of 3D Studio is the program's ability to animate, through keyframing, any object produced in or imported into the program. Keyframing refers to the process of creating different key frames, views or positions of the objects and then "playing" them in succession. With 3D Studio, the animation frames then can be rendered from wire frame models to almost photo quality images with shadows and reflections.

Although shadows and reflections do not typically offer the engineer much use, the quality rendering of an engineer's design is vital. Without the ability to present the design to the customer in an appealing manner, the design becomes more difficult to sell. Consequently, time and money are wasted by both engineer and customer. 3D Studio provides this ability through its high quality rendered images and animations.

One limitation of 3D Studio is its inability to analyze any of the characteristics of the objects it creates except for linear dimensions and relative angles. Of particular interest to vehicle design are volume, center of buoyancy, prismatic coefficient, surface area, and section area. In the interests of enhancing the design process, these types of calculations should be nearly "on-line". In order to overcome this, an ASCII file produced by 3D Studio is used with a program written to calculate these characteristics. The ASCII file gives a listing of all the faces (triangles which create object surfaces) and their corresponding vertices for the object. Refer to Figure 12 (page 32) which shows the ASCII file of a square created in 3D Studio.

5.3 APM Tools and Principals

The background for APM is established in Section 4.3. This section of the report serves to discuss the method of application and specific principals used in the search for an optimum submersible hull design. The objective was to construct an analytical means of examining each hull form based on the principals found in Section 4.3. In order to accomplish this, a spreadsheet was built in Quattro Pro for Windows that would take the hull parameters extracted from the geometric data produced in 3D Studio and produce information allowing performance comparisons. The extraction of information from the geometric data, such as wetted surface area and section areas were the initial inputs to the spreadsheet. From these initial hull parameters, further information was produced.

Figure 9 (data sheet) on the following page is a print out of the hull parameter spreadsheet. The initial parameters taken from the geometric data are indicated by the boxed numbers. The section area information not shown in this figure is located in Appendix I. The parameters in Figure 9 are calculated to provide the necessary information for application of the analytical expressions discussed in Section 4.3. With this information, initial comparisons of each hull can be made by comparing wetted surface areas and whether or not some of the hull's parameters approach known optimum values. Discussion of the actual values in Figure 9 is found in Section 6.3 (Performance Comparisons).

To provide a more comprehensive comparison, further information was calculated for each hull. As an example, the spreadsheet analyzing the Series 58, Model 4165 hull is also found on the following page in Figure 10. Printout outs of each hull iteration are found in Appendix I. The discussion of the information within Figure 10 progresses from left to right beginning with the velocity of the vehicle. The range of velocities (1-5 kts) was established from previous race experience with 5 knots being the foreseeable maximum.

April 14, 1993	Series 58	SUBDUE			hull6	hull8	Trident1	Trident2	SQUID
	L/D= 6.567	L/D= 3.509			L/D= 6.140	L/D= 5.516	L/D= 7.017	L/D= 6.580	L/D= 3.948
	D/L 0.152	D/L 0.285			D/L 0.163	D/L 0.181	D/L 0.143	D/L 0.152	D/L 0.253
length (ft)	15.000	9.211		total*	14.895	14.019	14.573	13.425	11.080
Hydraulic Diameter	2.284	2.625			2.426	2.541	2.077	2.040	2.806
wetted surface(ft^2	79.882	54.194	7.057	61.25	82.952	79.560	75.480	72.231	72.004
Tri. volume (ft^3)	37.085	27.266	1.022	28.29	39.764	39.380	32.471	31.079	39.881
Trap vol. (ft^3)	37.081	27.291			40.977	40.775	34.351	31.952	38.657
Max Sec. area (ft^2	4.097	5.032	0.379	5.411	4.623	5.073	3.388	3.270	6.184
Tailcone fineness ra	3.809	1.854			3.078	2.766	3.986	3.617	2.638
prismatic coeff,	0.603	0.547			0.578	0.554	0.696	0.728	0.564

Figure 9 Analysis data spreadsheet illustrating individual hull parameters. *Represents the totals when hull and blister are added.

SUBMERSIBLE HULL OPTIMIZATION SERIES 58 MODEL 4165

LENGTH = 15 VISC = 9.79E-06 at 80 deg F RHO = 1.9844

A(WET) = 79.8821 D/L = 0.152265

APPENDAGES

surface chord (ft)= 0.33 d/l= 0.14993

Swet= 3.11111

Fully appended hul

P.C.= 0.6

V(kts)	V(fps)	RN	ITTC CF	.044/Rn^(1/6) CF	CT=CF*(1+1.5*D/L^1.5+7*D/L^3) CT	CR	R(lbs)	EHP	EPDA CR*Swet	CT*Swet
1	1.687	2.58E+06	0.00385	0.00376	0.00429	0.00044	0.97	0.00297	0.03503	0.34276
1.25	2.109	3.23E+06	0.00369	0.00362	0.00411	0.00042	1.45	0.00555	0.03354	0.32818
1.5	2.531	3.88E+06	0.00356	0.00351	0.00397	0.00041	2.01	0.00927	0.03239	0.31695
1.75	2.952	4.52E+06	0.00346	0.00342	0.00385	0.00039	2.66	0.01429	0.03147	0.30790
2	3.374	5.17E+06	0.00338	0.00335	0.00376	0.00038	3.39	0.02081	0.03070	0.30037
2.25	3.796	5.82E+06	0.00330	0.00328	0.00368	0.00038	4.20	0.02900	0.03004	0.29396
2.5	4.218	6.46E+06	0.00324	0.00322	0.00361	0.00037	5.09	0.03903	0.02947	0.28839
2.75	4.639	7.11E+06	0.00319	0.00317	0.00355	0.00036	6.05	0.05106	0.02897	0.28[illegible]49
3	5.061	7.7[illegible]E+06	0.00314	0.00313	0.00349	0.00036	7.09	0.06528	0.02853	0.27913
3.25	5.483	8.40E+06	0.00309	0.00309	0.00345	0.00035	8.21	0.08182	0.02813	0.27520
3.5	5.905	9.05E+06	0.00305	0.00305	0.00340	0.00035	9.40	0.10087	0.02776	0.27164
3.75	6.326	9.69E+06	0.00302	0.00301	0.00336	0.00034	10.66	0.12258	0.02743	0.26838
4	6.748	1.03E+07	0.00298	0.00298	0.00332	0.00034	11.99	0.14711	0.02712	0.26539
4.25	7.170	1.10E+07	0.00295	0.00295	0.00329	0.00034	13.40	0.17462	0.02684	0.26263
4.5	7.592	1.16E+07	0.00292	0.00292	0.00326	0.00033	14.87	0.20525	0.02658	0.26006
4.75	8.013	1.23E+07	0.00290	0.00290	0.00323	0.00033	16.42	0.23918	0.02633	0.25766
5	8.435	1.29E+07	0.00287	0.00287	0.00320	0.00033	18.03	0.27654	0.02610	0.25542

V(kts)	Rn	CF	CF lam	CT=CFlam[1+(d/l)^1.5+.1(d/l)^2] CT	CR	R(lbs)	EHP	SHP
1	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.00323	0.00538
1.25	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.00601	0.01001
1.5	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.00998	0.01664
1.75	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.01535	0.02558
2	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.02229	0.03714
2.25	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.03098	0.05163
2.5	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.04160	0.06933
2.75	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.05433	0.09055
3	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.06933	0.11555
3.25	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.08678	0.14463
3.5	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.10684	0.17806
3.75	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.12967	0.21612
4	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.15544	0.25907
4.25	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.18431	0.30718
4.5	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.21643	0.36072
4.75	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.25197	0.41996
5	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.29109	0.48514

Figure 10 Analysis calculations spreadsheet for series 58 model 4165.

Then from the velocity in feet per second the Reynolds number was calculated using Equation 5-1.

$$RN=R_n= V^*L/\nu \qquad 5\text{-}1$$

A kinematic viscosity (ν) of $9.79\text{x}10^{-6}$ was used because the saltwater temperature at the race site is approximately 80 degrees. The calculation of C_F was based on Hoerner's approximation of the Schoenherr friction line for the appropriate range of Reynolds numbers, Equation (4-6). For the calculation of C_T Equation (4-7) was used on each hull form. Then C_R was calculated using:

$$C_R= C_T-C_F \qquad 5\text{-}2$$

The residuary drag coefficient was calculated even though it is accounted for in C_T, to allow a comparison of each hull's form drag. Next the bare hull resistance was calculated in pounds using Equation (4-2), and from this, the effective (unappended) horse power (EHP) was then calculated using:

$$EHP= V^*R_T/550 \qquad 5\text{-}3$$

The EHP is the effective horsepower that is required to obtain the velocity (V) for a resulting resistance (R_T) with no account for propulsor efficiency. Therefore, the smaller the resistance, the greater the speed for a given horsepower. The maximum sustained horsepower of a human submerged in water has been measured on a dynamometer to be approximately 0.4 to 0.5 horsepower for a human submerged in water. These horsepower outputs were obtained from experiments performed at the U.S. Naval Academy, independent of this project, to determine optimal cadence for the human propulsor who is pedaling in a free-flooded submersible and breathing compressed air.

Comparison of hull forms based on resistance estimations is more difficult to interpret because of the large size of the V^2 term in Equation (4-2) which can mask small trends in the hull's performance. Therefore, it is more common to make comparisons based on C_T values which plot a more responsive curve. However, such a comparison is valid only for hull forms of constant wetted surface area or volume$^{(2/3)}$. In the case of the human powered submersible, mission accomplishment is the basis for comparison. The mission is to put two humans in a free-flooded submersible, one to drive and the other to provide power, and win a race. Consequently, the hull shapes are driven by the internal arrangements and do not necessarily have constant volume, wetted surface area or length.

To overcome both of the previous dilemmas, another method of comparison frequently used in aerodynamics was chosen. It is called the equivalent parasite drag area (EPDA) and is calculated using:

$$EPDA = C_T * S_{wet} = R_T/q \qquad 5\text{-}4$$

where S_{wet} is the wetted surface area and $q = \rho V^2/2$. EPDA compares the drag area of a streamlined shape to that of a equivalent circular disk set perpendicular to the flow (C_T= 1). This method of comparing the relative performance of various hull forms has only been recently used in marine vehicle design. It is more commonly found in the aerospace industry and has found its way to marine application by use in the design of America's Cup racing yachts. It maintains the responsiveness of C_T plots and at the same time allows the comparison of hull forms that are not of equal length, wetted surface area or volume. By including both C_T and the wetted surface area, the key factor in frictional drag, EPDA allows for relative comparisons to account for vehicle size and shape.

The final section of Figure 10 calculates the assumed appendage drag. These calculations are made by the same Equations used on the hulls. The appendage size for each hull was assumed to be the same for comparison's sake. However, it should be mentioned that the actual size of the appendages for effective operation is dependent on the hull's characteristics and their location and would be expected to be changed for the actual competition vehicle. The appendage drag calculations were primarily conducted to allow total drag calculations to be made. The total drag calculations were then used to calculate the total EHP of the hull. The final calculation was the shaft horsepower (SHP) which is defined by:

$$SHP = EHP/PC \qquad PC = \text{propulsive coeff.} \qquad 5\text{-}5$$

The propulsive coefficient is determined by the design of the screw and its interaction with the hull. This factor accounts for the amount of slip that the screw necessarily experiences as it advances through the water overcoming the drag of the vehicle. Slip represents a loss of horsepower during the transfer of power from the shaft/screw to the

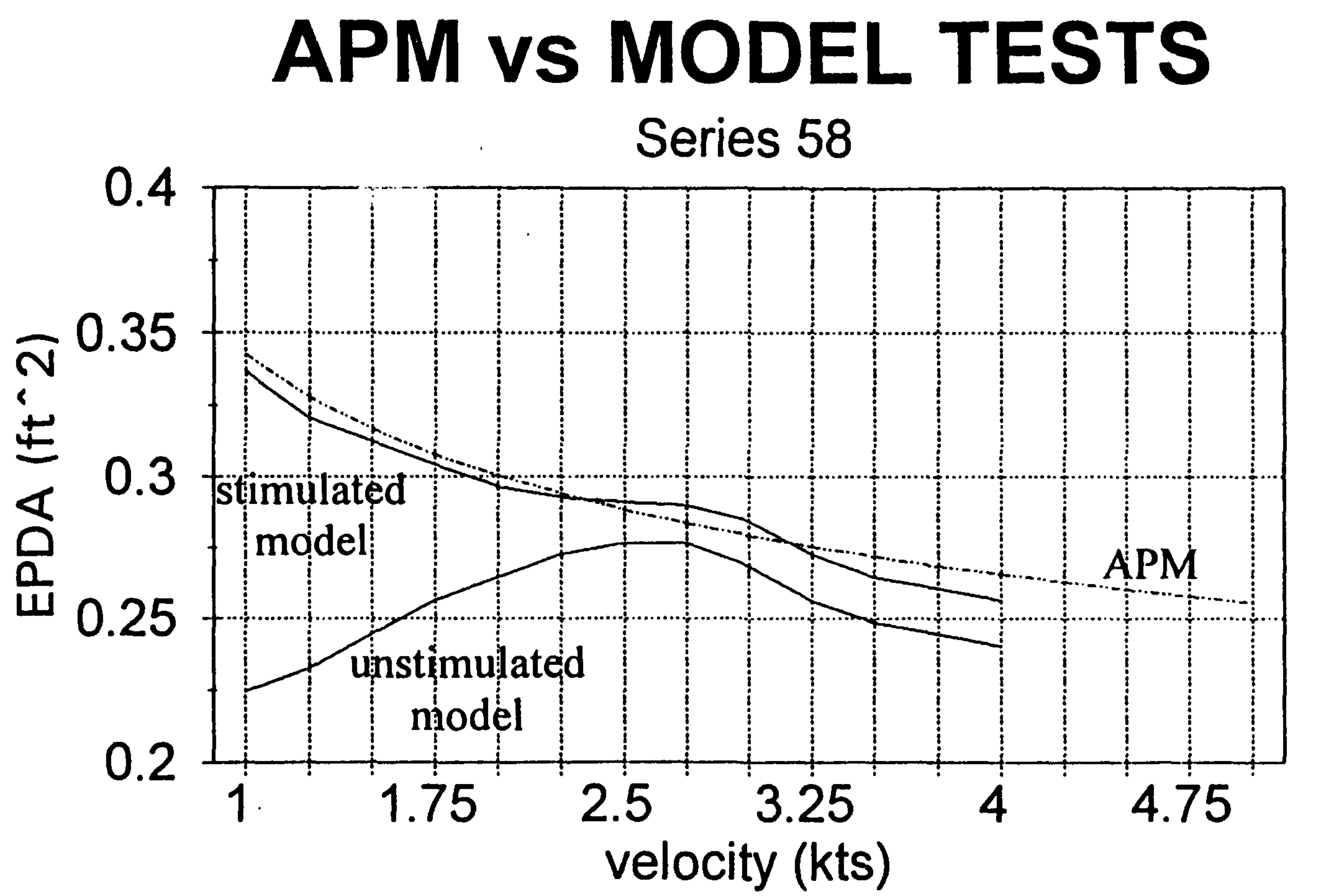


Figure 11 Comparison of APM and model testing results.

water. Therefore, SHP is the horsepower that must be delivered to the drive shaft at the output of the gearbox of the vehicle to overcome the hull form and propeller losses and thus obtain the desired velocity.

In order to examine the results of APM on submersible hull forms, the Series 58 Model 4165 was analyzed and the results compared to those produced during the model testing of that hull form. Figure 11 illustrates both the model data and APM predictions. The solid lines represent the model testing data and correspond to natural transition (lower line) and artificially tripped turbulent flow (upper line). The dotted line which closely corresponds to the stimulated model line is the APM prediction. The region between the two model (solid) lines represents the various C_T values that may occur depending upon location of transition from laminar to turbulent flow along the length of the hull. This point of transition is influenced by factors such as surface roughness and environmental conditions. Environmental conditions typically refer to the state of the fluid, which may be still water or turbulent open ocean. Note that competition speeds above three knots will have primarily turbulent boundary layers. Based on the fact that the APM analysis predicts values in close proximity with the model data, and that the same process is used for each hull form, it has been concluded that this method of analysis will provide a suitable means for estimating relative hull performance.

5.4 CAD/APM Interfacing

With 3D Studio installed and the analysis tools established, the next step became the creation of a program capable of calculating the required object characteristics. With the ASCII file, the basis for the interfacing of the CAD and APM tools was established.

As seen in Figure 12, the ASCII file of an object is a text file which can be easily read into memory and then manipulated to produce useful information. With the ASCII file characteristics in mind, a data translation program was written in the programming language C+ to read the ASCII object file and output the required hull form characteristics of volume, wetted surface and section area.

This was accomplished by vector analysis of the given faces for the object. The faces are triangles created by 3D Studio upon construction of the object. For each face there are three corresponding vertices which coincide within the set of vertices used to

```
Named object: "abox"
Tri-mesh, Vertices: 8     Faces: 12
Vertex list:
Vertex 0:  X: 0.0    Y: 0.0    Z: 1.0
Vertex 1:  X: 2.0    Y: 0.0    Z: 1.0
Vertex 2:  X: 2.0    Y: 1.0    Z: 1.0
Vertex 3:  X: 0.0    Y: 1.0    Z: 1.0
Vertex 4:  X: 0.0    Y: 0.0    Z: 0
Vertex 5:  X: 2.0    Y: 0.0    Z: 0
Vertex 6:  X: 2.0    Y: 1.0    Z: 0
Vertex 7:  X: 0.0    Y: 1.0    Z: 0
Face list:
Face 0:   A:0 B:1 C:2 AB:1 BC:1 CA:0
Material:"AQUA GLAZE"
Face 1:   A:0 B:2 C:3 AB:0 BC:1 CA:1
Material:"AQUA GLAZE"
Face 2:   A:0 B:4 C:5 AB:1 BC:1 CA:0
Material:"AQUA GLAZE"
Face 3:   A:0 B:5 C:1 AB:0 BC:1 CA:1
Material:"AQUA GLAZE"
Face 4:   A:1 B:5 C:6 AB:1 BC:1 CA:0
Material:"AQUA GLAZE"
Face 5:   A:1 B:6 C:2 AB:0 BC:1 CA:1
Material:"AQUA GLAZE"
Face 6:   A:2 B:6 C:7 AB:1 BC:1 CA:0
Material:"AQUA GLAZE"
Face 7:   A:2 B:7 C:3 AB:0 BC:1 CA:1
Material:"AQUA GLAZE"
Face 8:   A:3 B:7 C:4 AB:1 BC:1 CA:0
Material:"AQUA GLAZE"
Face 9:   A:3 B:4 C:0 AB:0 BC:1 CA:1
Material:"AQUA GLAZE"
Face 10:   A:4 B:7 C:6 AB:1 BC:1 CA:0
Material:"AQUA GLAZE"
Face 11:   A:4 B:6 C:5 AB:0 BC:1 CA:1
Material:"AQUA GLAZE"
```

Figure 12 3D Studio ASCII file of a rectangular box define the object's wire mesh. The ASCII object file provides the location of each vertex and then establishes the faces with three of these vertices. It is with this information that a vector analysis of each face is possible.

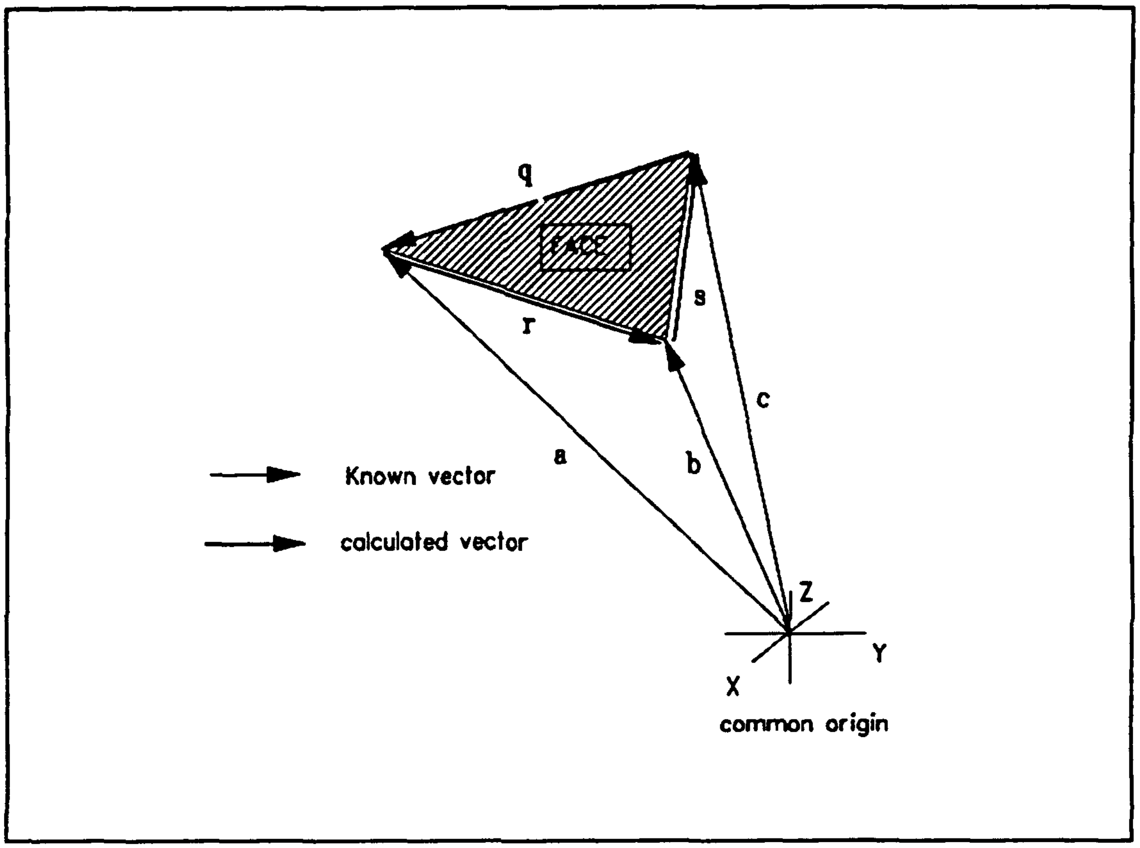


Figure 13 Vector representation of object face in 3D Studio

To calculate the wetted surface area of the object a principal of calculating the area of each triangle and summing them to find the total area is used. By knowing the location of three points (the vertices of the face) with respect to a common origin and thus the vector leading to each, one can calculate the vectors that connect these points by simple vector subtraction, where **q** (the connecting vector)= **a-c** (the known vectors). Refer to Figure 13 which illustrates this principal. Once all the connecting vectors of the triangle are calculated, the area of that triangle may be calculated from:

$$A=1/2|(q-p)x(r-p)| \quad \text{5-1}$$

Note the Equation is a cross product of the two vector subtractions which results in a vector. The magnitude of that vector must then be calculated to find the area. Then the area of each triangle is summed to produce the surface area of the object.

The next characteristic needed is the object volume. A similar vector analysis technique is used to calculate the volume. In this case the known vectors **a,b,c** are used as follows:

$$V=1/6(\mathbf{a}*(\mathbf{b} \times \mathbf{c})) \tag{5-2}$$

This Equation calculates the volume of each pyramid created by the origin and the triangular face. Each of these volumes is summed to produce the object volume.

The final characteristics extracted from the object's geometric data are the section areas. This was made simpler by the fact that each hull form generated in 3D Studio was represented by sets of points located at stations along the length of the wireframe. At each station, numerical integration was applied horizontally to calculate the section area.

In order to validate the data exchange program, simple objects with known characteristics were generated in 3D Studio and run in the program. With a few changes these objects were successfully processed. Then, in order to test the program on a known submersible hull form and for later comparison, the recommended optimum hull from the Series 58 [Gertler 1950] model tests (Model 4165) was synthesized in 3D Studio and processed. Initially, the size of the geometric data file (ASCII) was too large for the program to run. The typical hull form contained 1800 vertices and 2400 faces. However, this was overcome by cutting the hull forms in half and modifying the data management within the program. The program's calculations of Series 58 Model 4165 showed a discrepancy of 0.6% when compared to the given dimensions in the Series 58 report. Refer to appendices II,III for the Series 58 hull characteristics, example output file from the exchange program, and a printout of the data exchange program, respectively.

The ability to extract the hull form characteristics from the geometric data then enabled APM to be applied to the hull forms as they were being generated during the design process. With this ability, an objective comparison of performanc for each hull iteration could be made. This helped to fill the gap within the previous design process by allowing hull comparison of existing hulls like SUBDUE and optimum hull models like the Series 58 Model 4165.

5.5 Supporting Programs

In order to provide a more effective design system and further enhance the design process, additional software packages were added to the system. These include Human CAD, Auto CAD (release 12), and Microsoft Windows 3.1. This section introduces the programs and explains the purpose for their addition.

5.5a **Human CAD**

Human CAD or Mannequin is a stand alone 3D CAD package with the added ability to model the human figures. These figures can be seen in all images of the submersible and its internal arrangements within this report. The mannequins created by Human CAD can be of any size, male or female. Also, the CAD package includes built-in data to produce figures based on nationality. Human CAD fills an immense need for the accurate modeling of humans within a human powered submersible or within any vehicle where humans are part of the internal arrangements. Once the mannequins were created within Human CAD they were exported directly to 3D Studio by use of the .3ds file format which is 3D Studio's work file format. Once in 3D Studio the mannequins can be fully animated or arranged to the designers needs.

5.5b **Autocad release 12**

As previously discussed, Autocad was considered for the 3D CAD system for this project but was not used because of the difficulty and length of time needed to learn how to use it. However, it is readily available at USNA and was therefore employed to enhance the output capabilities of the design process. 3D Studio, because it is relatively new, does not come with many printer drivers, and AutoCAD does. Transfer of geometric data via data exchange files (.dxf) from 3D Studio enabled the system to plot drawings on a wide variety of machines. Also, AutoCAD has an easy to use dimensioning tool which was employed to add dimensions to the objects created in 3D Studio and Human CAD.

AutoCAD also offers a solution to the problem of fairing that is discussed in Section 5.2a. In concept drawing and even more detailed drawings, the wireframe method of modeling produces accurate objects, but for final drawings and offset files of hull forms it is necessary to have faired lines. This is so because the offset file which contains the dimensions of the hull form must be used by the manufacturer to produce the hull. In order to overcome this discrepancy in 3D Studio's ability, a file can be created using the data exchange program that contains all the points defining the hull surface. This file can then be read into AutoCAD and a smooth surface will be fit among the points. This solution is offered should the need arise, but it was not employed in this project because any discrepancies in the drawings from 3D Studio are not detectable in the rendered images.

5.5c Microsoft Windows

Microsoft Windows version 3.1 was added to the system to allow Quattro Pro for Windows and Word Perfect 5.2 for Windows to be run on the computer. It should be noted that due to conflicting memory demands, the CAD systems 3D Studio and Human CAD cannot run within the Windows environment. The problem is due to conflicting memory requirement between the CAD systems and Windows 3.1. Should the software companies resolve this problem, it would give the system added efficiency by decreasing the time spent maneuvering within the system.

6.0 Project Results

This section discusses and explains the application of the design process established by this project for human powered submersible design. A generalized design process is illustrated in Figure 14 [Johnson 1990b] and the following sections address each phase with regard to the design system application. As each phase is addressed, it is illustrated by practical application in designing an optimum submersible for entry into the human powered submarine race.

6.1 Design/Race Requirements

The first step in the design process is to establish the design requirements. The principal design requirements for the human powered submersible are established by the race committee and focus on the safety of the operators and establishing vehicle operating criteria. Chapter 9, Section 1 of the race publication generally states that "For the purposes of this competition a submarine is: a free-flooding (liquid filled) marine vehicle which fully encapsulates both occupants and operates entirely beneath the surface of the water." For further deliberation on the safety and operating requirements refer to Appendix IV which contains Chapter 9 of the race publication. The areas left open to innovation are hull form, internal arrangements, control surfaces, materials and propulsion. For this project, optimization of hull form and the internal components are critical, but considerations were made for the other areas.

6.2 Design Iterations

The design process is inherently iterative which can be seen in the diagram in Figure 14. One purpose of concurrent engineering and this project is to minimize the number of unnecessary iterations during the design phase by attempting to model all the physical variables of the project in one environment. This allows the designer to anticipate design conflicts and avoid them. The human powered submersible design process began with synthesizing the internal arrangements. Past race experience, current testing at the Naval Academy, and the new system's ability to model the submersibles arrangements quickly and accurately soon led to an improved model of the internal arrangements. Refer to Appendix V which has detailed drawings of internal arrangements

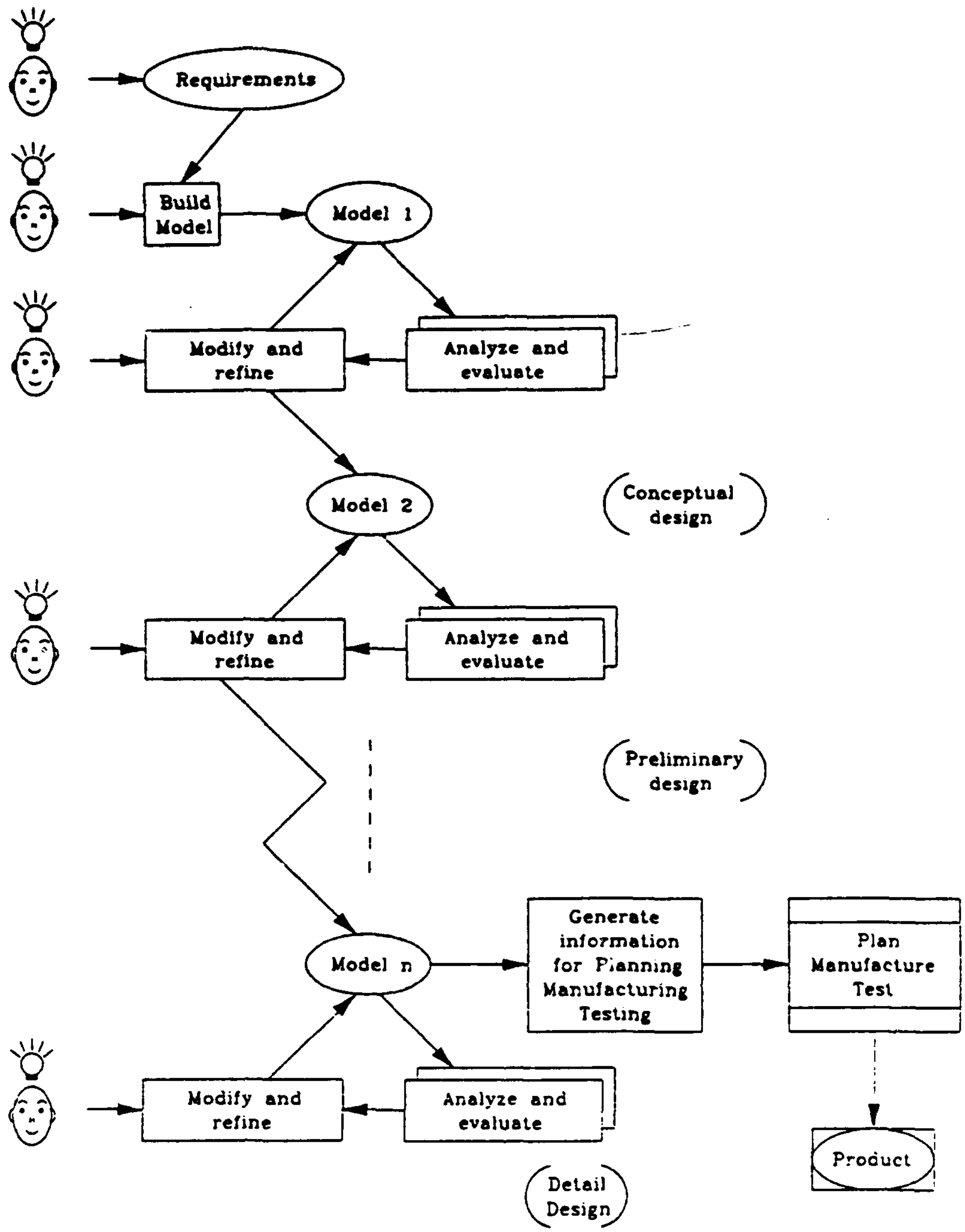


Figure 14 Human powered submersible design process.

before proceeding with this discussion. Also included in Appendix V are flowchart diagrams illustrating both the submersible design process and interfaced design system. Referring to these diagrams now will enable a better understanding of the following discussion.

Per the race rules, the submersible must have a human driver and a human propulsor. It was determined that the position and orientation of the human propulsor was critical to all other elements. For simple logistical reasons the propulsor has been placed aft with respect to the driver, thus allowing a more streamlined hull form than in past designs where the propulsor was placed above the driver. This was also done on the premise that the drive train would incorporate a propeller for thrust that would be located at the stern of the vehicle, requiring the propulsor to be in the rear of the vehicle. Two orientations were considered for the propulsor. He or she would either be in a seated position or in a horizontal position facing down. It was determined from past experiments at the Naval Academy's life support lab, that the propulsor is most efficient when placed in a horizontal position facing down. This position is illustrated by Figure 15. The main reason for this was found in the propulsor's relative depth to his or her regulator. If the regulator is located at or above the mouth, the air must be drawn into the lungs. While locating it below, as in the case of the horizontal position, the study found that the air is lightly forced in to the lungs. Consequently, the propulsor was modeled in the horizontal position and well aft of the driver to allow ample clearance for the propulsive motions. In consideration of the varying size in personnel operating the submarine, the two human figures were modelled with a large frame and six feet five inches tall.

The next step was to examine the motions of the propulsor in order to model the space that is required for the propulsive motions which has been assumed to be a typical pedaling motion. To better understand these motions, SUBDUE's internal arrangements were modeled within 3D Studio and animated. The result was the "pedal zone" which is also illustrated in Figure 15. The pedal zone was defined by the extreme points of motion as seen in the SUBDUE animation for the propulsor's toes, heels, and knees. The driving factor among these three items is the crank shaft length. Past submarines have

Key internal arrangements

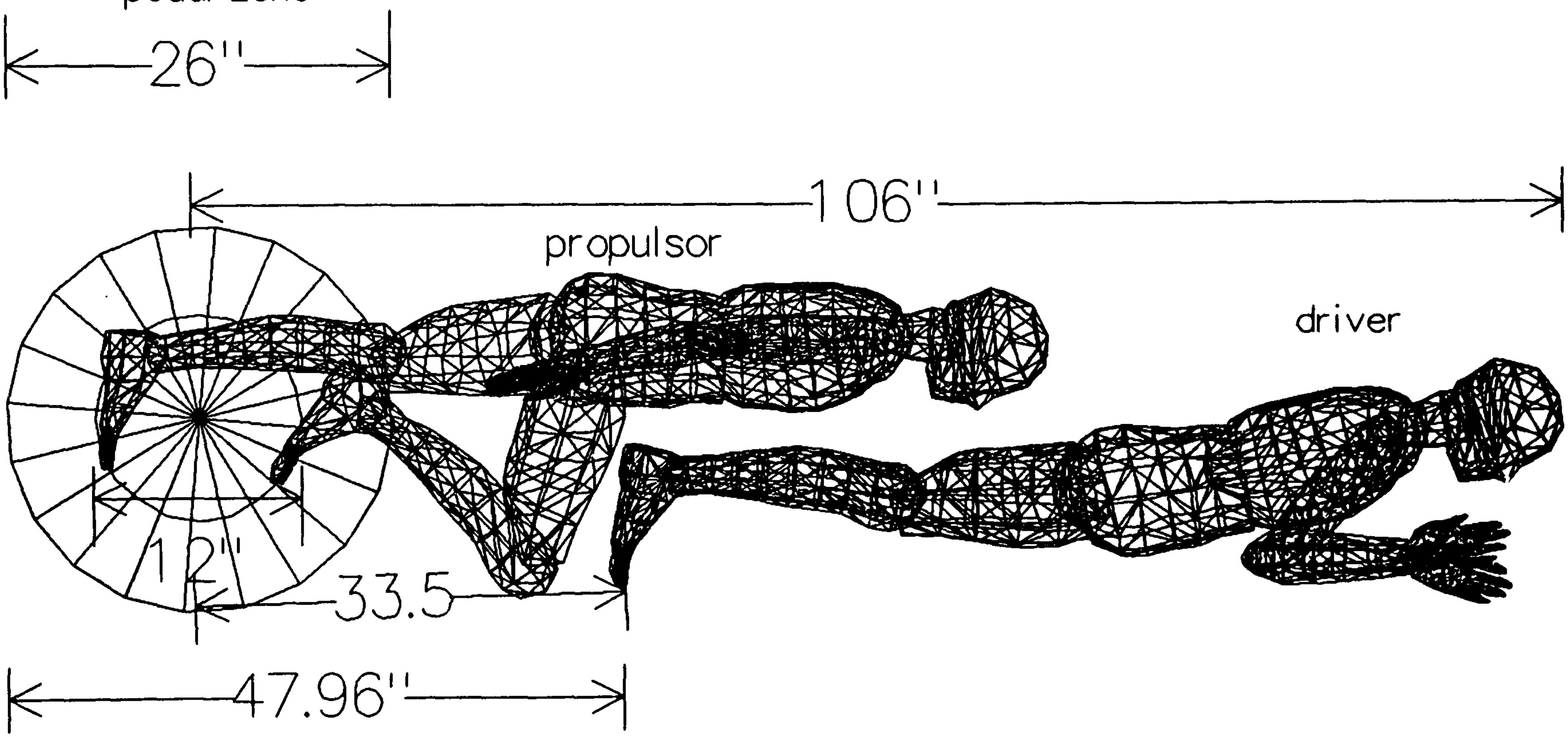


Figure 15 plot produced from Human CAD

used eight inch cranks, but in an attempt to reduce wetted surface area and section areas a six inch crank was planned for this submarine. Consequently, a two dimensional zone was established. In order to provide the third dimension, SUBDUE's existing pedal to pedal width of 14 inches was used, thus establishing the pedal zone which would influence the entire design.

With the dominant internal arrangements transferred from Human CAD to 3D Studio and tentatively in place, the task of modeling the rest of the principal arrangements was undertaken. To provide some guidance as to the location and available space for these items, a working hull form was created in 3D Studio and is referred to as Hull6. The next major internal item was the life support air supply. It has been found in previous years that 200 cubic feet of ambient air is necessary to meet race requirements. These requirements stipulate that 150 percent of the total "needed" air be carried on board. Past designs have used two 100 standard cubic foot scuba bottles. In order to optimize the use of available space, seven, 30 standard cubic feet, smaller air bottles which could be efficiently located throughout the hull and connected by a manifold. The layout of these bottles is illustrated in Appendix V.

One final key aspect of the internal arrangements to be modelled was the control device which is operated by the driver. Adequate space must be allotted for the device and the required motions for its operation. Therefore, a single point control device under development at the Naval Academy was modelled and appropriately arranged with respect to the driver. Knowing the necessary motions for the device's operation allowed the space to be accounted for in the hull form.

In addition, the drive shaft, air manifold, and pedal/gear assembly were modelled in the design. These items and others were not considered critical to the design of the hull form as they would be eventually modified depending upon their final design. However, they were included to provide a better understanding of space allocation within the submarine on the assumption that they could be designed to fit within the available space. Also, having been modelled in 3D Studio, these items can easily be modified or recreated in the presence of the hull form. With the internal arrangements tentatively established within Hull6, they were exported via a .DXF file to AutoCAD release 12.

The top and side views were then plotted on 44x33 inch paper.

The process to design an efficient hydrodynamic hull with minimal wetted surface was begun on these plots. Using the two dimensional top view (half breadth) an optimum profile in shape and size was "fitted" to the internal arrangements. Optimization of the profile's shape was based on the parameters discussed in Section 4.3. This profile is illustrated in Figure 16 and served as the principal waterline for the hull. It was principal in that all other water lines would be derived from this shape. Next, the side view (sheer plan) was taken and a similar process applied. However, in the case of the side view, the profile was closely fitted to the contour of the internal arrangements and less emphasis was placed on optimizing the shape. Refer to Figure 16 which illustrates the side profile. The reasoning for closely fitting the side profile was two-fold. First, the maximum diameter was located at the center of the pedaling gear which is not at the suggested optimum 40 percent of the hull length from the nose. To produce a streamline shape meeting this criterion would certainly mean an impractical increase in wetted surface area. Second, the previous discussion of vehicle hydrodynamics has shown this hull parameter to be less critical than others (Figure 7). The process of generating these profiles was accomplished manually on the plots, a disparity that arose due to time and resource constraints[3]. These profiles were then loaded into 3D Studio's 2D Shaper where a set of three frontal profile shapes had been generated. These three profiles as well as the top and side profiles are shown in Figure 16. The first of the three frontal profiles, a circle, was used for the nose of the submarine. The second, a quasi-elliptical shape, was used for the main body of the hull which encloses the internal arrangements from which it derives its shape. The third, a narrower quasi-elliptic shape, was used from the center of the pedal zone aft to the tip of the tail. All five shapes were then placed in 3D Studio's 3D Lofter to produce the three dimensional wiremesh of the hull form. The top view

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[3]To further increase the efficiency of the design process it has been conceived that future work could be done to compose a program that would analyze the internal arrangements for their geometric extremities and output an optimized profile. This profile would also be influenced by user input parameters which may include the fineness ratio, tail-cone fineness and nose radius.

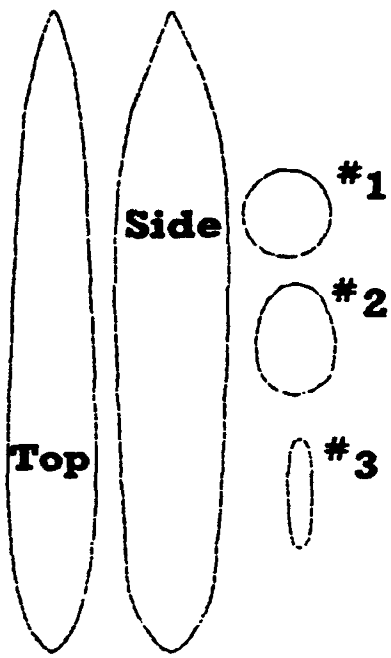

Figure 16 Internal arrangment profiles for Trident1.

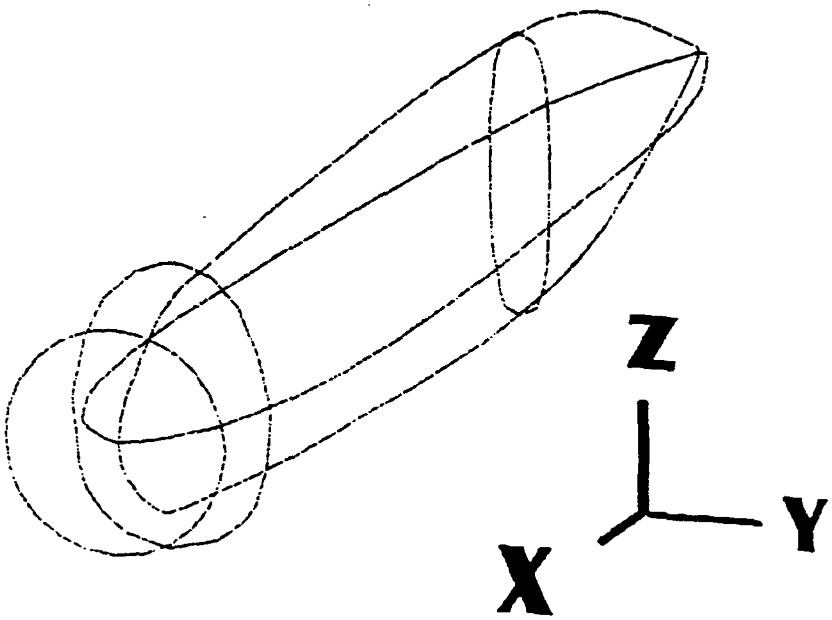

Figure 17 Arrangement of profiles within 3D Studio's Lofter.

(waterplane) represented the XYplane and bounded the Y direction. The side view represented the XZ plane and bounded the Z direction. Finally, the frontal profiles were appropriately placed along the lofting path/X-axis. The lofting path represents a straight line connecting the nose to the tail and is automatically scaled to the appropriate length as defined by the top and side profiles. A diagram showing the arrangement of the shapes is provided in Figure 17.

The command to make the object is then selected, and 3D Studio two dimensionally scales the frontal profiles along their appropriate segments of the path, to fit both the top and side profiles. At previously designated points along the path (stations), a set of vertices is generated associated with that point on the X axis. These sets of vertices are automatically placed in the 3D Editor and appropriately linked to form the 3D wiremesh representing the hull form. This hull form, the first produced in this manner, is fittingly named Trident1. This process from the 2D Shaper up to the 3D Editor can then be designated as a "project" and saved as one file with all shapes, path, meshes, and program settings intact. This makes regeneration of the hull wireframe a simple matter only taking minutes even when vital changes to any of the initial profiles occur.

The result of this design approach is a submersible of logically related water plane shapes which were derived from the original top profile and effectively stacked atop or added below primary plane. The hull design methodology used in this project was initially intended to exploit 3D Studio's model building method in effectively synthesizing a hull form. During the process a recent article was found that discussed the use of a similar approach in designing an aerodynamic fairing for the current (September 1992) world speed record human powered cycle, *Cheetah* [Ashley 1993]. The fairing operated at Reynold's numbers in the 4 million range which is within the human powered submersibles range.

According to Ashley's article:

> The controversial approach the team took in developing the shape of the Cheetah's fairing was to reduce drag and increase its aerodynamic design by optimizing the fairing's aerodynamics rather than minimize its surface area. [Ashley 1993]

The design approach used to construct the fairing is best illustrated by Figure 18 which was taken from [Ashley 1993].

Aerodynamic fairing. Cheetah's aerodynamic fairing—the secret of its record-setting speed—is composed of a series of drag-minimizing airfoil sections stacked one on top of the other.

Figure 18 Design approach for Cheetah's fairing construction.

Once the Trident1 had been generated, the internal arrangements were merged into the "project" to insure their fit. Having both the internal components and the hull form in the same environment enables further adjustment of all objects. This eliminates unnecessary iterations that occur due to conflict between primary components and the hull form when these items are produced by separate systems. Therefore, the time spent on fitting the hull and internal arrangements is decreased, and the design process of focusing on optimizing the entire submersible is allowed.

Once the designer is satisfied, the submersible's hull form is exported from 3D Studio using the ASCII format. Now running in the Windows environment, this file, containing the hull's geometric data, is read by the data exchange program which outputs the hull characteristics. The analysis spreadsheet is then opened, and the hull characteristics are imported to the "data sheet" which is shown in Appendix I. The data sheet served as the principal means by which hull iterations were preliminarily evaluated. This was accomplished by comparing a hull's resulting characteristics to the suggested optimum one discussed in Section 5.2. Then, by moving to the appropriate APM analysis page of the spreadsheet, the hull can be evaluated based on its total drag, EHP and SHP requirements, and EPDA.

6.3 Final Design

Although several modest changes were made, the evaluation of the Trident1 hull form in the APM spreadsheet concluded the first iteration in the design process. From the APM analysis of Trident1, it was discovered that by shortening the tail length the hull form could be made to approach the suggested optimum hull parameters of fineness ratio, tail-cone ratio and lower wetted surface area, consequently improving the overall performance of the hull.

To accomplish this task, the "project" file containing the shapes used to model Trident1 was reloaded into 3D Studio. It was determined that shortening the Trident1 profiles by 14 inches would result in a hull form that better approached the suggested optimum parameters. This modification of the top and side profiles is shown in Figure 19. Once this modification was made, Trident2, the final hull, was generated and exported for evaluation. The modification proved successful and reduced the EPDA and consequently the drag when compared to that of Trident1. These performance improvements are discussed and illustrated in section 6.4. The final design's drawings are in Appendix V. The drawings include wireframe plots of the hull and internal arrangements that have been dimensioned in AutoCAD and full color renderings of the wireframes produced by 3D Studio.

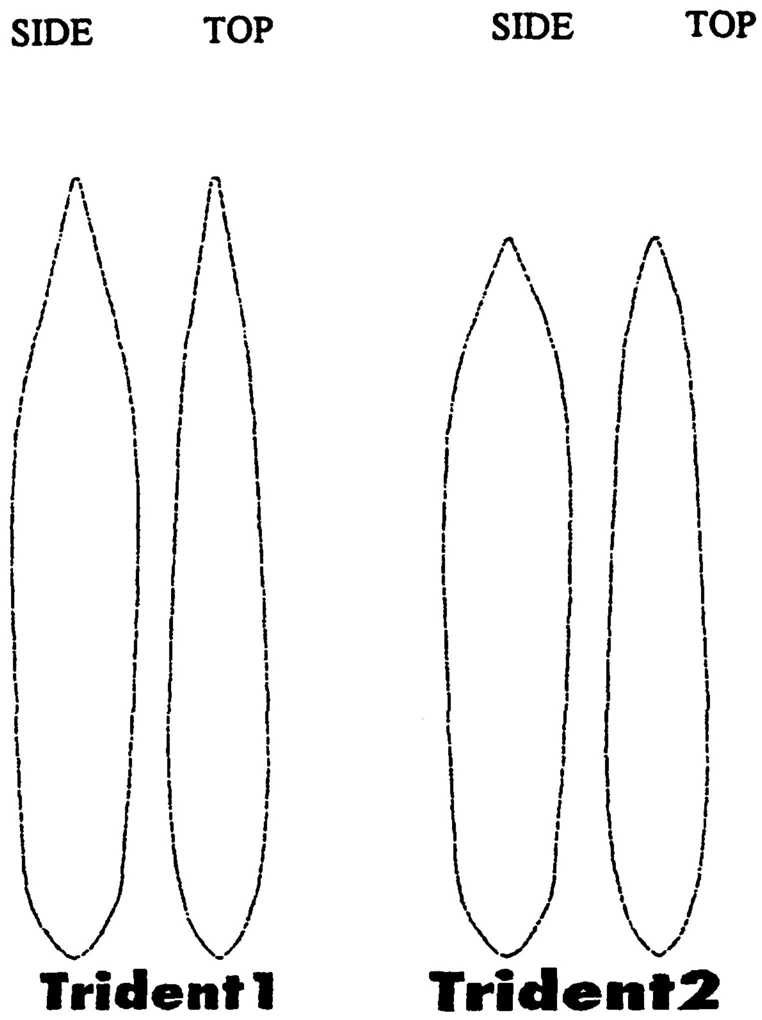

Figure 19 Modified profiles for Trident2 model.

6.4 Performance Comparisons

To substantiate the APM analysis process further and to provide a basis for performance comparison, the Naval Academy's previous entries to the Human Powered Submarine Race, SUBDUE and SQUID, were modelled in 3D Studio and analyzed using the same process as the newly generated hull forms.

From the spreadsheet APM analysis of each submersible (Appendix I), several graphs were produced to compare the relative performance of the various hull forms. The first graph (Figure 20) to be examined was the section area curves of each hull. Although as previously discussed there exists no general analytical expression for the section area curve, many arguments based on Figure 20 can be made for the relative performance of each hull. First, the rate of change in the tail section of SUBDUE more than likely caused separation. If this occurred, the drag estimates for SUBDUE produced in this report are much too low. Also, the addition of blisters to SUBDUE, necessary to accommodate the air bottles, adversely affected the hydrodynamic performance of the vehicle by increasing the pressure drag. Their presence could have moved the point of separation forward on the hull which also increases drag. On the other hand, the Trident hulls and Model 4156 exhibited a more streamlined curve and a smaller section area rate of change in the tail section. This leads one to believe that separation is unlikely, and therefore the flow will remain attached along the length of the hull. Also, partial laminar flow over the hull may occur, therefore, resulting in the actual vehicle drag being less than predicted in this report because of the turbulent flow assumption.

Second, a more analytical method of comparison was plotted using the respective EPDA calculations for each hull. Figure 21 illustrates the predicted decrease in drag that would be achieved by Trident2 over SUBDUE and SQUID. Again, the equivalent parasite drag area (EPDA) is a relative comparison based on the drag coefficient, C_T, and the wetted surface area. Therefore, on a relative basis, it can be concluded that the Trident2 hull form offers the least drag and consequently will enjoy increased performance over the previous Naval Academy hull forms. It can also be seen in Figure 21 that the Trident hulls' performance should surpass that of the Series 58 hull. This was

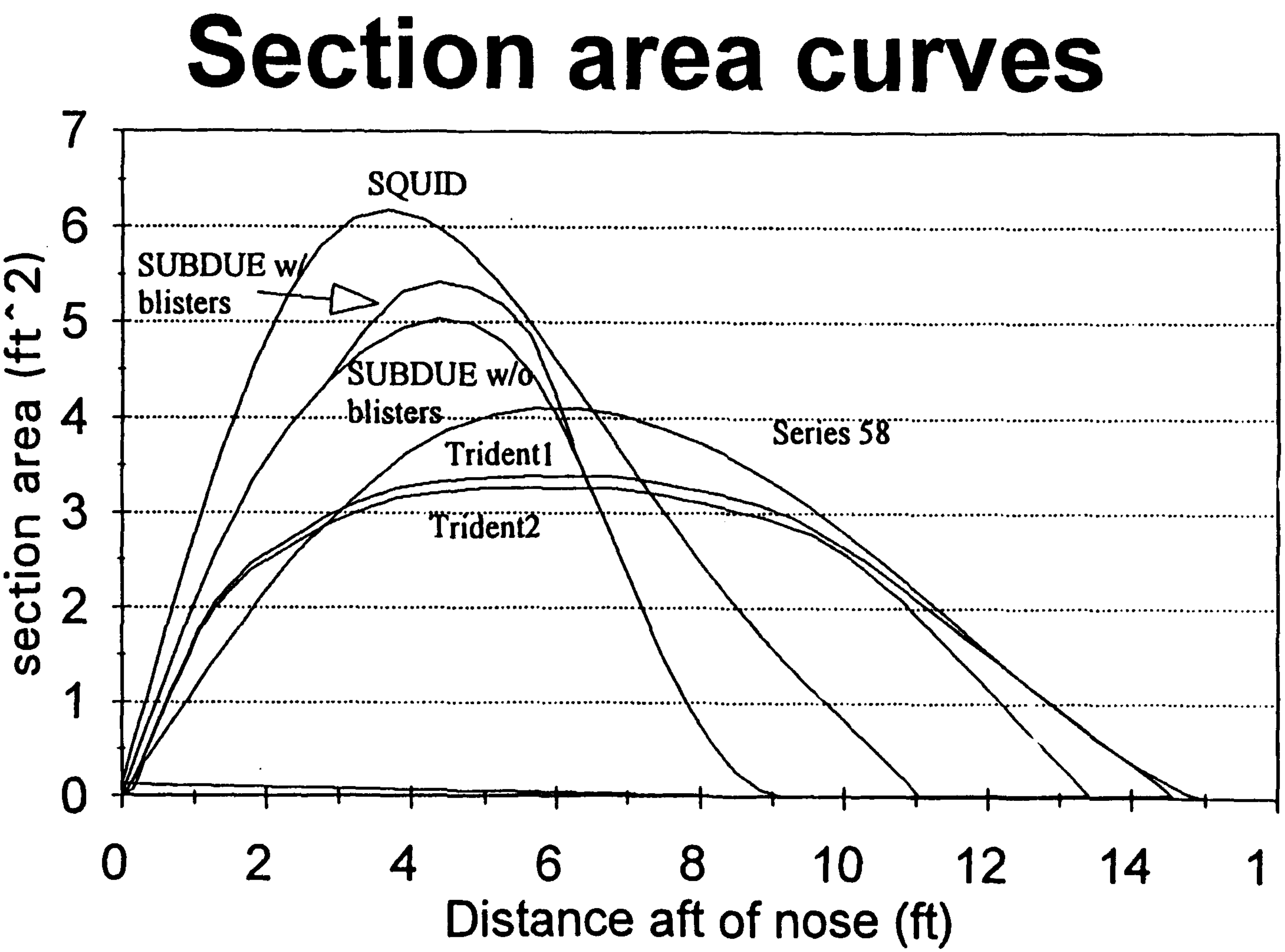

Figure 20 Hull form section area curves.

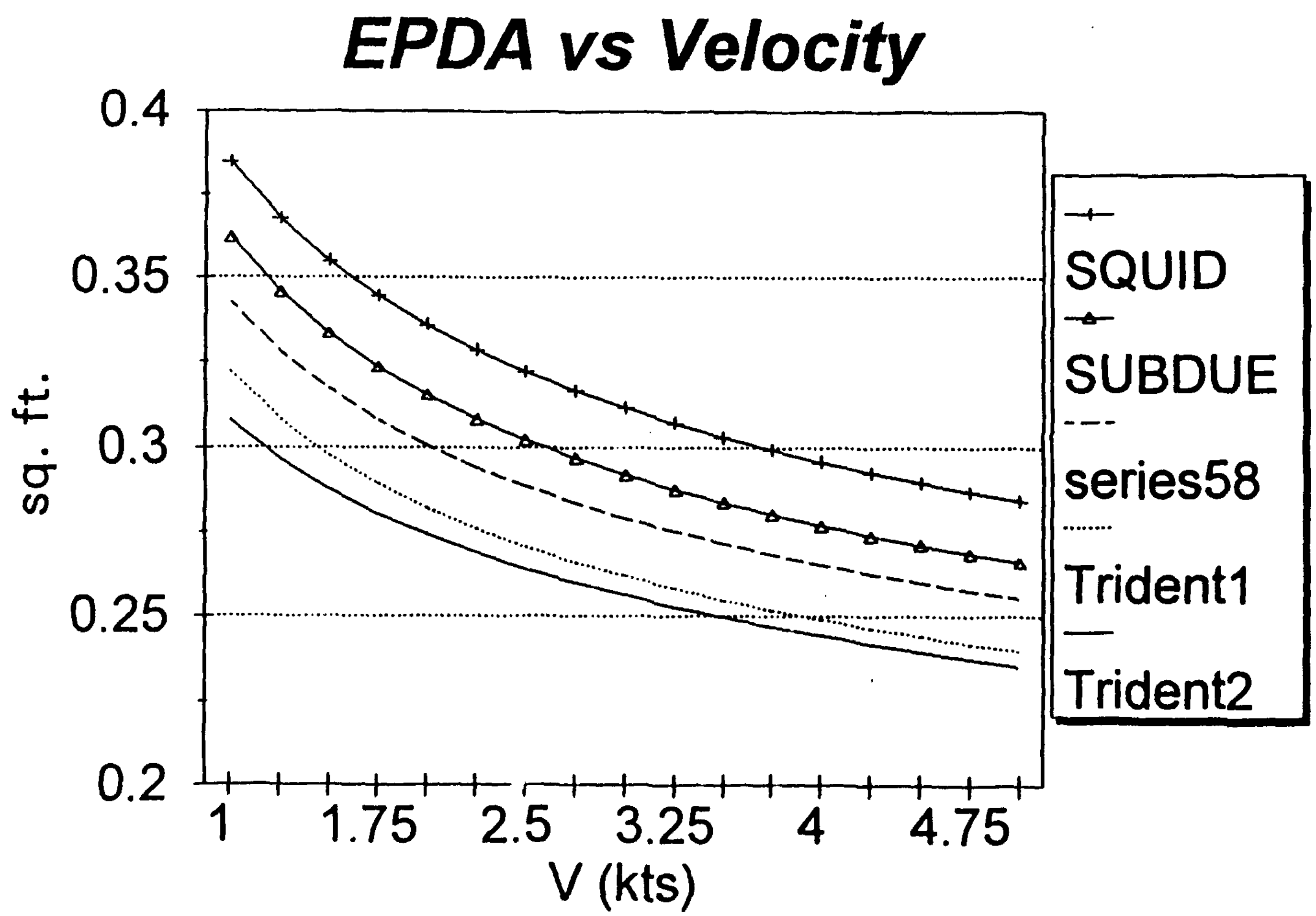

Figure 21 EPDA-equivalent parasite drag area ($C_T * S_{wet}$).

made possible by the reduced wetted surface area of the Trident hulls due to their non-axisymmetric shape.

Third, each hull form's analytically predicted SHP was plotted versus velocity in knots (Figure 22). It is immediately apparent from this figure that the attainable velocity is closely governed by the SHP. Over the scope of the hull forms plotted on this diagram, the variation in obtainable velocity for a given horsepower is almost 0.5 kts. Considering the operating range, established from past experience, of 0 to 5 knots, a 0.5 knot increase is at least a 10 percent gain in speed. Examining Figure 22 along the "Max Expected Horsepower" (MEH) line of 0.5 horsepower reveals that for a given horsepower the Trident2 vehicle will be the fastest. The MEH line was established by experiments at the Naval Academy in which a diver was pedalling completely submerged and breathing compressed air. The intersection of the MEH line and Trident2's SHP curve estimates an obtainable speed of approximately 4.8 knots with the assumed propulsive coefficient and appendage drag.

Finally, in order to illustrate the sensitivity of the vehicles speed to the propeller efficiency, a plot (Figure 23) was made of Trident2's SHP for various propulsion coefficients, P.C., ranging from .4 to .6. Also included in the plot is the series 58 SHP line from the previous graph to help emphasize this sensitivity. It can be seen in Figure 23 that a reduction of P.C. from .5 to .4 will negate all performance advantages the Trident2 hull had gained over the other hull forms in hull drag reduction. It is therefore stressed that without an efficient propeller, the hull optimization process becomes immaterial.

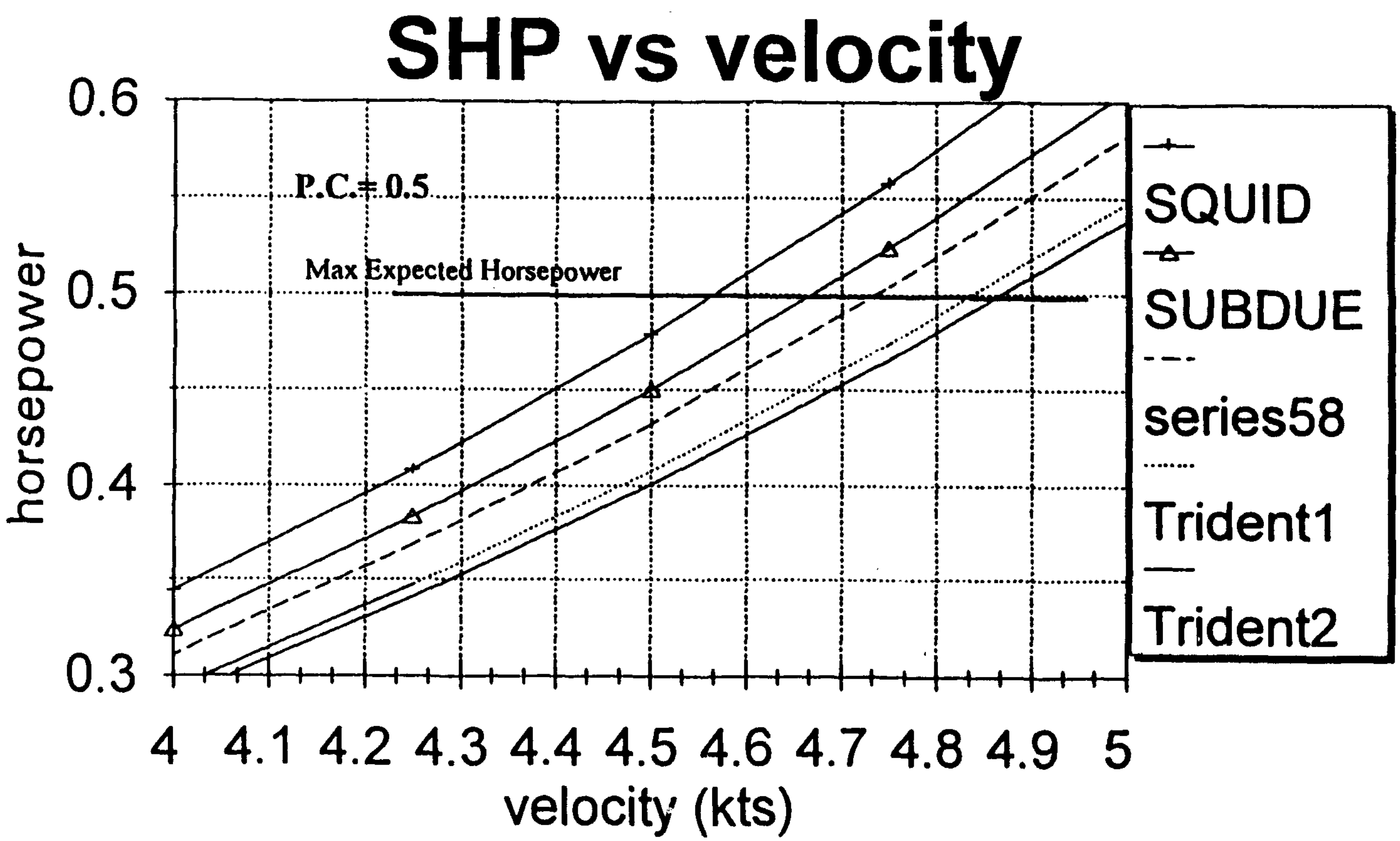

Figure 22 Required shaft horsepower (SHP) plotted a function of veloctiy.

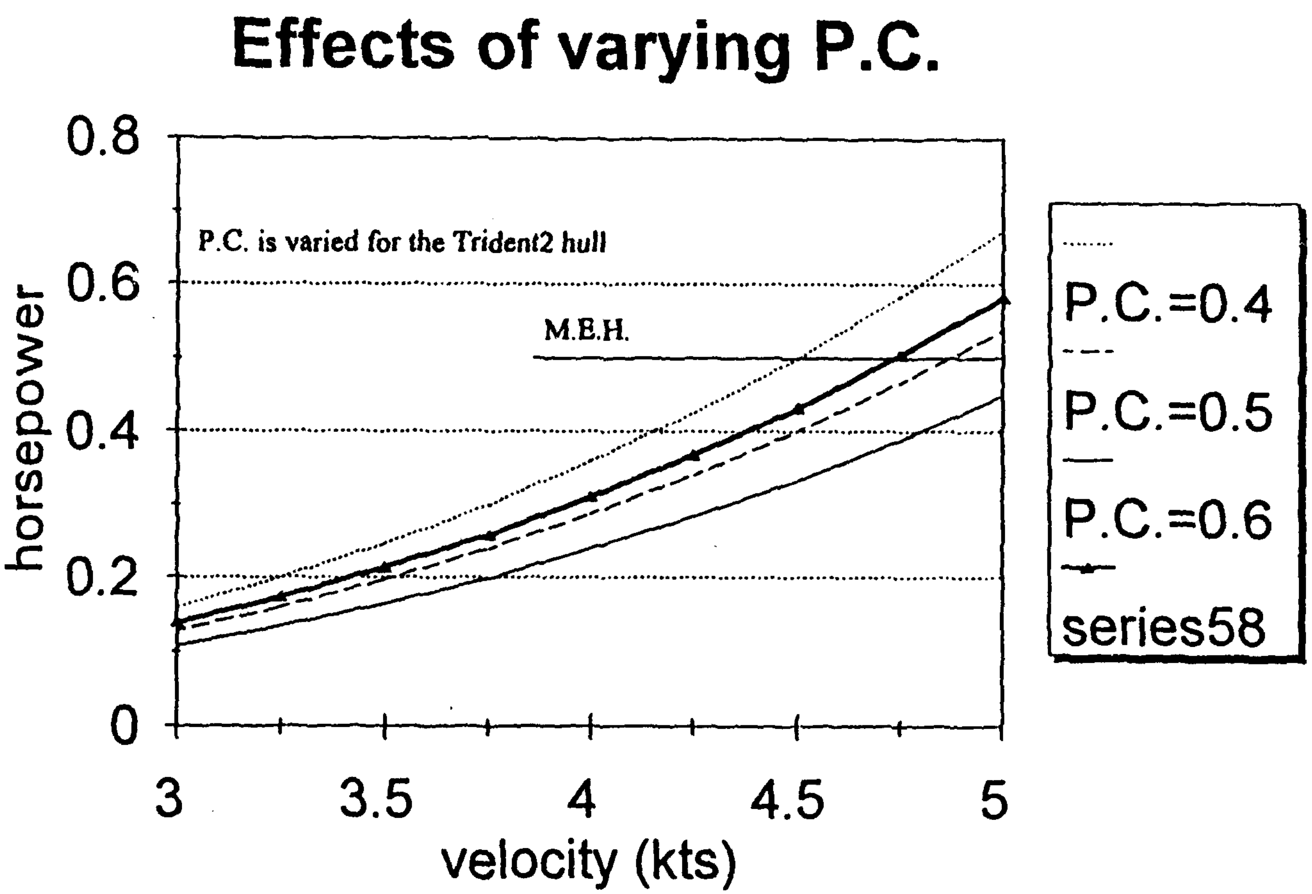

Figure 23 Sensitivity of SHP as a function of propulsive coefficient

7.0 CONCLUSIONS

On the basis of the research involved in this project and the results obtained from this human powered submersible design, several conclusions have been made. First, application of the concurrent design methodology through interfaced design tools provided a more efficient means of design than previously possible. Even though a limited application of the methodology was involved in this project, the possibilities of expanding the interfaces to include finite element analysis, propeller evaluation by CFD, and more leads to the conclusion that complete design of the optimized submersible or any marine vehicle is possible. Also, the employment of interfaced design tools vice integrated ones has made the realization of true concurrent engineering feasible without large investments for the creation of an integrated system. Second, the employment of analytical parametric methods of hull form analysis is an effective method for comparative performance analysis. However, the Equations from Hoerner and data from the series 58 tests are five decades old which leads one to believe that with the expansion of technology, new and more accurate tests could be made to further investigate the relationship between the frictional and residuary drag coefficients. The model tests should include non-axisymmetric model series investigating the relationship of the major to minor axis ratio and the hydrodynamic efficiency of stacking optimized waterplane shapes for hull design. Also, continued examination of the section area curve is necessary to provide a better understanding of the hydrodynamic consequences with regard to the curves rate of change. Finally, future work considerations should be given to the data exchange program developed for this project. The first concern would be to expand the program to output the hull geometric data in a traditional waterplane offsets format. The second is to investigate the possibility of further expanding the program to analyze a vehicle's internal arrangements and produce an optimized hull form based on user established parameters and the extremities of the internal components.

8.0 ACKNOWLEDGMENTS

This Trident Research project derives its accomplishments from the many resources available at the United States Naval Academy. The most important of these resources are its quality faculty and staff. The contributions made to this project by Professor Bruce Johnson, U.S. Naval Academy NAOME Department, and LCDR William Davidson, USN, CEC, U.S. Naval Academy NAOME Department, are very much appreciated. Also, special thanks is expressed to Mrs. Nancy Harris, U.S. Naval Academy Hydromechanics Laboratory, for her continual assistance. Finally, the author acknowledges the U.S. Naval Academy's Trident Scholar Committee which provided the opportunity to conduct this research and development project.

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APPENDIX I

APM analysis spreadsheet data

April 14, 1993

	Series 58	SUBDUE			hull6	hull8	Trident1	Trident2	SQUID
	L/D= 6.567	L/D= 3.509			L/D= 6.140	L/D= 5.516	L/D= 7.017	L/D= 6.580	L/D= 3.948
	D/L 0.152	D/L 0.285			D/L 0.163	D/L 0.181	D/L 0.143	D/L 0.152	D/L 0.253
length (ft)	15.000	9.211		total*	14.895	14.019	14.573	13.425	11.000
Hydraulic Diameter	2.284	2.625			2.426	2.541	2.077	2.040	2.806
wetted surface(ft^2)	79.882	54.194	7.057	61.25	82.952	79.560	75.480	72.231	72.004
Trl. volume (ft^3)	37.085	27.266	1.022	28.29	39.764	39.380	32.471	31.079	39.881
Trap vol. (ft^3)	37.081	27.291			40.977	40.775	34.351	31.952	38.657
Max Sec. area (ft^2)	4.097	5.032	0.379	5.411	4.623	5.073	3.388	3.270	6.184
Tailcone fineness ratio	3.809	1.854			3.078	2.766	3.986	3.617	2.638
prismatic coeff.	0.603	0.547			0.578	0.554	0.696	0.728	0.564

Series 58

		Sec. area	volume
station number	0.00	0.00	0.00
station number	0.16	0.08	0.01
station number	0.30	0.34	0.04
station number	0.60	0.69	0.19
station number	0.90	1.01	0.44
station number	1.20	1.35	0.80
station number	1.50	1.63	1.25
station number	1.90	2.09	2.00
station number	2.25	2.43	2.79
station number	2.55	2.69	3.56
station number	3.30	3.22	5.70
station number	3.90	3.61	7.81
station number	4.50	3.89	10.00
station number	5.10	4.05	12.45
station number	5.70	4.10	14.89
station number	6.30	4.10	17.35
station number	6.90	4.03	19.70
station number	7.50	3.89	22.16
station number	8.20	3.63	25.00
station number	9.12	3.28	28.02
station number	9.48	3.09	29.15
station number	9.90	2.96	30.40
station number	10.50	2.51	32.01
station number	10.98	2.20	33.13
station number	11.40	1.94	34.01
station number	12.00	1.55	35.05
station number	12.60	1.16	35.86
station number	13.50	0.61	36.67
station number	13.80	0.47	36.83
station number	14.10	0.32	36.95
station number	14.44	0.18	37.04
station number	14.70	0.08	37.07
station number	14.81	0.04	37.08
station number	15.00	0.00	37.08

SUBDUE

	Sec. area		volume
0.00	0.00		0.00
0.00	0.00		0.00
0.07	0.14		0.00
0.26	0.55		0.07
0.55	1.17		0.32
0.92	1.91		0.89
1.35	2.46		1.87
1.82	3.34		3.27
2.31	3.92	blister	5.07
2.83	4.37	0.00	7.19
3.34	4.71	0.20	9.55
3.85	4.94	0.30	11.99
4.34	5.03	0.30	14.44
4.81	4.99	0.30	16.77
5.23	4.80	0.30	18.85
5.63	4.40	0.30	20.64
5.97	4.06	0.20	22.14
6.30	3.57	0.00	23.39
6.61	3.04		24.41
6.91	2.51		25.24
7.20	1.90		25.90
7.50	1.47		26.43
7.82	0.99		26.81
8.13	0.50		27.07
8.50	0.27		27.22
8.85	0.07		27.28
9.21	0.00		27.29

hull6

	Sec. area	volume
0.00	0.10	0.00
0.11	0.40	0.03
0.22	0.66	0.08
0.33	0.82	0.16
0.44	0.94	0.26
0.55	1.07	0.37
0.67	1.21	0.50
0.78	1.35	0.64
0.89	1.40	0.80
1.39	1.91	1.46
1.90	2.32	2.73
2.41	2.70	4.01
2.92	3.06	5.47
3.43	3.32	7.09
3.93	3.59	8.84
4.44	3.87	10.73
4.95	4.05	12.74
5.57	4.19	15.29
6.19	4.33	17.93
6.81	4.49	20.66
7.43	4.62	23.48
8.05	4.47	26.29
8.66	4.29	29.00
9.28	3.96	31.33
9.90	3.63	33.90
10.53	3.04	35.98
11.15	2.32	37.66
11.77	1.70	38.91
12.40	1.17	39.91
13.02	0.74	40.40
13.65	0.41	40.76
14.27	0.14	40.93
14.89	0.00	40.98

hull8

	Sec. area	volume
0.00	0.24	0.00
0.58	1.04	0.37
1.16	1.63	1.15
1.75	2.16	2.26
2.33	2.59	3.64
2.91	2.99	5.17
3.49	3.38	7.12
4.08	3.78	9.21
4.66	4.10	11.51
5.24	4.34	13.97
5.82	4.50	16.54
6.41	4.82	19.30
6.99	5.07	22.19
7.57	4.99	25.12
8.15	4.86	27.98
8.74	4.44	30.69
9.32	4.03	33.16
9.91	3.25	35.34
10.49	2.56	37.00
11.08	1.94	38.32
11.67	1.41	39.31
12.26	0.97	40.01
12.84	0.60	40.47
13.43	0.22	40.71
14.02	0.00	40.77

Trident1

	Sec. area	volume
0.00	0.02	0.00
0.08	0.09	0.00
0.25	0.34	0.04
0.34	0.49	0.08
0.34	0.87	0.22
0.40	1.13	0.35
0.82	1.35	0.52
1.00	1.78	0.93
1.29	2.06	1.33
1.79	2.47	2.08
2.29	2.71	2.77
2.79	2.96	3.19
3.29	3.12	4.71
3.79	3.26	6.31
4.30	3.32	9.95
4.80	3.37	11.62
5.30	3.38	13.31
5.80	3.39	15.00
6.29	3.39	16.69
6.79	3.38	18.38
7.30	3.35	20.07
7.79	3.27	21.72
8.29	3.19	23.34
8.80	3.09	24.91
9.29	2.96	26.43
9.80	2.81	27.87
10.30	2.50	29.20
10.80	2.17	30.37
11.30	1.80	31.36
14.57	0.03	34.35

Trident2

	Sec. area	volume
0.00	0.00	0.00
0.04	0.04	0.00
0.08	0.08	0.00
0.17	0.19	0.01
0.25	0.33	0.04
0.30	0.40	0.05
0.34	0.48	0.07
0.44	0.63	0.13
0.54	0.85	0.21
0.61	0.97	0.27
0.68	1.10	0.34
0.75	1.21	0.42
0.83	1.32	0.50
0.95	1.35	0.69
1.08	1.74	0.90
1.19	1.87	1.10
1.29	2.00	1.31
1.54	2.21	1.83
1.79	2.40	2.41
2.04	2.33	3.02
2.29	2.63	3.67
2.54	2.75	4.34
2.79	2.87	5.04
3.04	2.95	5.77
3.29	3.05	6.52
3.54	3.10	7.29
3.79	3.16	8.07
4.05	3.19	8.86
4.30	3.21	9.66
4.55	3.23	10.47
4.80	3.26	11.28
5.05	3.26	12.10
5.30	3.26	12.91
5.55	3.27	13.73
5.80	3.27	14.55
6.04	3.27	15.36
6.29	3.26	16.17
6.54	3.26	16.99
6.79	3.26	17.81
7.04	3.24	18.63
7.30	3.22	19.43
7.54	3.18	20.23
7.79	3.15	21.02
8.04	3.11	21.80
8.29	3.07	22.57
8.54	3.02	23.34
8.80	2.97	24.09
9.04	2.91	24.83
9.29	2.85	25.54
9.54	2.78	26.24
9.80	2.71	26.93
10.05	2.55	27.59
10.30	2.41	28.21
10.55	2.24	28.79
10.80	2.09	29.33
11.05	1.90	29.83
11.30	1.72	30.28
12.36	0.69	31.37
13.43	0.03	31.92

SQUID

	Sec. area	volume
0.00	0.13	0.00
0.14	0.51	0.05
0.36	1.11	0.22
0.65	1.87	0.66
1.00	2.73	1.46
1.39	3.47	2.72
1.82	4.33	4.47
2.27	3.36	6.66
2.73	3.79	9.21
3.20	4.09	12.04
3.68	4.18	14.94
4.16	4.60	17.91
4.65	5.01	20.02
5.14	5.45	23.30
5.63	4.99	26.14
6.12	4.40	28.45
6.60	3.96	30.30
7.09	3.44	32.29
7.57	2.94	33.85
8.05	2.45	35.12
8.53	1.99	36.10
9.00	1.57	37.02
9.48	1.19	37.68
9.95	0.86	38.17
11.00	0.00	38.66

SUBMERSIBLE HULL OPTIMIZATION HULL6

LENGTH 14.895 VISC = 9.79E-06 at 80 deg F RHO = 1.9844 APPENDAGES surface chord (ft) 0.33333 Fully appended hull

A(WET) = 82.9519 D/L = 0.1629 P.C.= 0.4 d/l= 0.14993 P.C.= 0.5000

Swet= 3.11111

ITTC .044/Rn CT=CF*(1+1.5*D/L^1.5+7*D/L^3) CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

			ITTC	.044/Rn					EPDA									
V(kts)	V(fps)	RN	Cf	Cf	Ct	Cr	Swet:R(lbs)	EHP	Cr*Swet	Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	2.57E+06	0.00386	0.00376	0.00435	0.00050	1.02	0.00313	0.04123	0.36122	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.0034	0.0068
1.25	2.109	3.21E+06	0.00369	0.00362	0.00417	0.00048	1.53	0.00585	0.03948	0.34585	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.0063	0.0126
1.5	2.531	3.85E+06	0.00357	0.00351	0.00403	0.00046	2.12	0.00976	0.03812	0.33401	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.0105	0.0210
1.75	2.952	4.49E+06	0.00347	0.00343	0.00391	0.00045	2.81	0.01506	0.03703	0.32447	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.0161	0.0322
2	3.374	5.13E+06	0.00338	0.00335	0.00382	0.00044	3.58	0.02193	0.03613	0.31653	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.0234	0.0468
2.25	3.796	5.77E+06	0.00331	0.00328	0.00373	0.00043	4.43	0.03056	0.03536	0.30977	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.0325	0.0651
2.5	4.218	6.42E+06	0.00325	0.00323	0.00366	0.00042	5.36	0.04113	0.03469	0.30390	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.0437	0.0874
2.75	4.639	7.06E+06	0.00319	0.00318	0.00360	0.00041	6.38	0.05381	0.03410	0.29873	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.0571	0.1141
3	5.061	7.70E+06	0.00314	0.00313	0.00355	0.00040	7.47	0.06878	0.03357	0.29413	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.0728	0.1457
3.25	5.483	8.34E+06	0.00310	0.00309	0.00350	0.00040	8.65	0.08622	0.03310	0.28999	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.0912	0.1824
3.5	5.905	8.98E+06	0.00306	0.00305	0.00345	0.00039	9.90	0.10629	0.03267	0.28623	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.1123	0.2245
3.75	6.326	9.62E+06	0.00302	0.00302	0.00341	0.00039	11.23	0.12917	0.03228	0.28280	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.1363	0.2725
4	6.748	1.03E+07	0.00299	0.00298	0.00337	0.00038	12.63	0.15501	0.03192	0.27964	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.1633	0.3267
4.25	7.170	1.09E+07	0.00296	0.00295	0.00334	0.00038	14.11	0.18399	0.03159	0.27673	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.1937	0.3874
4.5	7.592	1.15E+07	0.00293	0.00293	0.00330	0.00038	15.67	0.21627	0.03128	0.27402	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.2275	0.4549
4.75	8.013	1.22E+07	0.00290	0.00290	0.00327	0.00037	17.30	0.25202	0.03099	0.27150	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.2648	0.5296
5	8.435	1.28E+07	0.00287	0.00288	0.00324	0.00037	19.00	0.29138	0.03072	0.26913	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.3059	0.6119

SUBMERSIBLE HULL OPTIMIZATION Hull8

LENGT	14.02	VISC =	9.79E-06		at 80 deg F		RHO =	1.9844			APPENDAGES			surface chord (ft)		0.33	Fully appended hull	
A(WET)	79.56	D/L =	0.163026				P.C.=	0.4						d/l=	0.14993	Swet=	P.C.=	0.5

ITTC .044/Rn^(1/6) CT=CF*(1+1.5*D/L^1.5+7*D/L^3)

CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

V(kts)	V(fps)	RN	Cf	Cf	Ct	Cr	Swet:R(lbs	EHP	EPDA Cr*Swet	Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	2.42E+06	0.00390	0.00380	0.00435	0.00044	0.98	0.00301	0.03550	0.34736	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.0033	0.0065
1.25	2.109	3.02E+06	0.00374	0.00366	0.00422	0.00048	1.48	0.00568	0.03853	0.33704	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.0061	0.0123
1.5	2.531	3.62E+06	0.00361	0.00355	0.00407	0.00047	2.06	0.00947	0.03720	0.32544	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.0102	0.0204
1.75	2.952	4.23E+06	0.00350	0.00346	0.00396	0.00045	2.72	0.01461	0.03613	0.31609	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.0157	0.0313
2	3.374	4.83E+06	0.00342	0.00338	0.00386	0.00044	3.47	0.02128	0.03524	0.30831	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.0227	0.0455
2.25	3.796	5.44E+06	0.00334	0.00332	0.00378	0.00043	4.30	0.02964	0.03449	0.30168	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.0316	0.0632
2.5	4.218	6.04E+06	0.00328	0.00326	0.00370	0.00042	5.20	0.03989	0.03383	0.29594	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.0425	0.0849
2.75	4.639	6.64E+06	0.00323	0.00321	0.00364	0.00042	6.19	0.05218	0.03325	0.29088	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.0554	0.1109
3	5.061	7.25E+06	0.00318	0.00316	0.00358	0.00041	7.25	0.06670	0.03274	0.28637	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.0708	0.1415
3.25	5.483	7.85E+06	0.00313	0.00312	0.00353	0.00040	8.39	0.08360	0.03227	0.28232	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.0886	0.1771
3.5	5.905	8.45E+06	0.00309	0.00308	0.00349	0.00040	9.60	0.10306	0.03185	0.27864	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.1090	0.2180
3.75	6.326	9.06E+06	0.00305	0.00305	0.00340	0.00035	10.78	0.12404	0.02775	0.27157	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.1311	0.2623
4	6.748	9.66E+06	0.00302	0.00301	0.00336	0.00034	12.13	0.14885	0.02744	0.26853	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.1572	0.3144
4.25	7.170	1.03E+07	0.00299	0.00298	0.00333	0.00034	13.55	0.17667	0.02716	0.26571	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.1864	0.3727
4.5	7.592	1.09E+07	0.00296	0.00296	0.00329	0.00034	15.04	0.20765	0.02689	0.26310	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.2188	0.4377
4.75	8.013	1.15E+07	0.00293	0.00293	0.00326	0.00033	16.61	0.24196	0.02664	0.26066	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.2548	0.5095
5	8.435	1.21E+07	0.00290	0.00290	0.00323	0.00033	18.24	0.27974	0.02641	0.25838	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.2943	0.5886

SUBMERSIBLE HULL OPTIMIZATION — SERIES 58 MODEL 4165

LENGT 15 VISC = 9.79E-06 at 80 deg F RHO = 1.9844
A(WET) 79.8821 D/L = 0.152265 P.C.= 0.4

APPENDAGES: surface chord (ft) 0.33; d/l= 0.14993; Swet= 3.11111 — Fully appended hull P.C.= 0.5

ITTC .044/Rn^(1/6) CT=CF*(1+1.5*D/L^1.5+7*D/L^3)

CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

V(kts)	V(fps)	RN	Cf	Cf	Ct	Cr	Swet:R(lbs	EHP	EPDA Cr*Swet	EPDA Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	2.58E+06	0.00385	0.00376	0.00429	0.00044	0.97	0.00297	0.03503	0.34276	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.0032	0.0065
1.25	2.109	3.23E+06	0.00369	0.00362	0.00411	0.00042	1.45	0.00555	0.03354	0.32818	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.0060	0.0120
1.5	2.531	3.88E+06	0.00356	0.00351	0.00397	0.00041	2.01	0.00927	0.03239	0.31695	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.0100	0.0200
1.75	2.952	4.52E+06	0.00346	0.00342	0.00385	0.00039	2.66	0.01429	0.03147	0.30790	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.0153	0.0307
2	3.374	5.17E+06	0.00338	0.00335	0.00376	0.00038	3.39	0.02081	0.03070	0.30037	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.0223	0.0446
2.25	3.796	5.82E+06	0.00330	0.00328	0.00368	0.00038	4.20	0.02900	0.03004	0.29396	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.0310	0.0620
2.5	4.218	6.46E+06	0.00324	0.00322	0.00361	0.00037	5.09	0.03903	0.02947	0.28839	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.0416	0.0832
2.75	4.639	7.11E+06	0.00319	0.00317	0.00355	0.00036	6.05	0.05106	0.02897	0.28349	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.0543	0.1087
3	5.061	7.75E+06	0.00314	0.00313	0.00349	0.00036	7.09	0.06528	0.02853	0.27913	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.0693	0.1387
3.25	5.483	8.40E+06	0.00309	0.00309	0.00345	0.00035	8.21	0.08182	0.02813	0.27520	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.0868	0.1736
3.5	5.905	9.05E+06	0.00305	0.00305	0.00340	0.00035	9.40	0.10087	0.02776	0.27164	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.1068	0.2137
3.75	6.326	9.69E+06	0.00302	0.00301	0.00336	0.00034	10.66	0.12258	0.02743	0.26838	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.1297	0.2593
4	6.748	1.03E+07	0.00298	0.00298	0.00332	0.00034	11.99	0.14711	0.02712	0.26539	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.1554	0.3109
4.25	7.170	1.10E+07	0.00295	0.00295	0.00329	0.00034	13.40	0.17462	0.02684	0.26263	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.1843	0.3686
4.5	7.592	1.16E+07	0.00292	0.00292	0.00326	0.00033	14.87	0.20525	0.02658	0.26006	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.2164	0.4329
4.75	8.013	1.23E+07	0.00290	0.00290	0.00323	0.00033	16.42	0.23918	0.02633	0.25766	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.2520	0.5039
5	8.435	1.29E+07	0.00287	0.00287	0.00320	0.00033	18.03	0.27654	0.02610	0.25542	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.2911	0.5822

SUBMERSIBLE HULL OPTIMIZATION   SQUID HULL

LENGTH 11.0797 VISC = 9.79E-06 at 80 deg F   RHO = 1.9844   APPENDAGES   surface chord (ft) 0.33333 Fully appended hull

A(WET) = 72.0042 D/L = 0.2533   d/l= 0.14993   P.C.= 0.5

Swet= 3.11111

ITTC .044/Rn CT=CF*(1+1.5*D/L^1.5+7*D/L^3)   CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

V(kts)	V(fps)	RN	Cf (ITTC)	Cf (.044/Rn)	Ct	Cr	Swet:R(lbs)	EHP	EPDA Cr*Swet	EPDA Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	1.91E+06	0.00409	0.00395	0.06534	0.00125	1.09	0.00333	0.08985	0.38454	7.01E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.0036	0.0072
1.25	2.109	2.39E+06	0.00391	0.00381	0.00511	0.00119	1.62	0.00622	0.08592	0.36770	8.76E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.0067	0.0133
1.5	2.531	2.86E+06	0.00378	0.00369	0.00493	0.00115	2.25	0.01037	0.08289	0.35475	1.05E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.0111	0.0222
1.75	2.952	3.34E+06	0.00366	0.00360	0.00478	0.00112	2.98	0.01598	0.08045	0.34433	1.23E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.0170	0.0341
2	3.374	3.82E+06	0.00357	0.00352	0.00466	0.00109	3.79	0.02326	0.07843	0.33567	1.40E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.0247	0.0495
2.25	3.796	4.30E+06	0.00349	0.00345	0.00456	0.00107	4.69	0.03239	0.07671	0.32830	1.58E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.0344	0.0687
2.5	4.218	4.77E+06	0.00343	0.00339	0.00447	0.00104	5.68	0.04356	0.07522	0.32191	1.75E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.0461	0.0923
2.75	4.639	5.25E+06	0.00337	0.00334	0.00439	0.00103	6.75	0.05697	0.07390	0.31629	1.93E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.0602	0.1205
3	5.061	5.73E+06	0.00331	0.00329	0.00432	0.00101	7.91	0.07280	0.07273	0.31128	2.10E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.0769	0.1537
3.25	5.483	6.20E+06	0.00327	0.00325	0.00426	0.00100	9.15	0.09121	0.07168	0.30678	2.28E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.0962	0.1923
3.5	5.905	6.68E+06	0.00322	0.00321	0.00420	0.00098	10.47	0.11241	0.07073	0.30271	2.45E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.1184	0.2368
3.75	6.326	7.16E+06	0.00318	0.00317	0.00415	0.00097	11.87	0.13656	0.06986	0.29898	2.63E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.1436	0.2873
4	6.748	7.64E+06	0.00315	0.00314	0.00410	0.00096	13.35	0.16383	0.06906	0.29556	2.80E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.1722	0.3443
4.25	7.170	8.11E+06	0.00311	0.00310	0.00406	0.00095	14.91	0.19441	0.06832	0.29240	2.98E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.2041	0.4082
4.5	7.592	8.59E+06	0.00308	0.00307	0.00402	0.00094	16.55	0.22846	0.06763	0.28946	3.15E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.2396	0.4793
4.75	8.013	9.07E+06	0.00305	0.00305	0.00398	0.00093	18.27	0.26615	0.06699	0.28673	3.33E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.2790	0.5579
5	8.435	9.55E+06	0.00302	0.00302	0.00395	0.00092	20.06	0.30766	0.06640	0.28417	3.50E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.3222	0.6444

SUBMERSIBLE HULL OPTIMIZATION SUBDUE HULL

LENGT	9.21	VISC =	9.79E-06	at 80 deg F	RHO =	1.9844	APPENDAGES	surface chord (ft)	0.33333 Fully appended hull
A(WET)	61.2511	D/L =	0.2850		P.C.=	0.4		d/l= 0.14993	P.C.= 0.5
								Swet= 3.11111	

ITTC .044/Rn^(1/6) CT=CF*(1+1.5*D/L^1.5+7*D/L^3) CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

V(kts)	V(fps)	RN	Cf	Cf	Ct	Cr	Swet:R(lb	EHP	EPDA Cr*Swet	EPDA Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	1.59E+06	0.00425	0.00407	0.00591	0.00166	1.02	0.00313	0.10158	0.36193	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.0034	0.0068
1.25	2.109	1.98E+06	0.00406	0.00393	0.00565	0.00158	1.53	0.00585	0.09705	0.34579	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.0063	0.0126
1.5	2.531	2.38E+06	0.00392	0.00381	0.00544	0.00153	2.12	0.00975	0.09357	0.33339	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.0105	0.0209
1.75	2.952	2.78E+06	0.00380	0.00371	0.00528	0.00148	2.80	0.01501	0.09077	0.32342	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.0161	0.0321
2	3.374	3.17E+06	0.00370	0.00363	0.00515	0.00144	3.56	0.02184	0.08845	0.31514	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.0233	0.0466
2.25	3.796	3.57E+06	0.00362	0.00356	0.00503	0.00141	4.40	0.03040	0.08647	0.30810	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.0324	0.0647
2.5	4.218	3.97E+06	0.00355	0.00350	0.00493	0.00138	5.33	0.04087	0.08476	0.30200	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.0434	0.0869
2.75	4.639	4.36E+06	0.00348	0.00344	0.00484	0.00136	6.33	0.05343	0.08325	0.29664	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.0567	0.1134
3	5.061	4.76E+06	0.00343	0.00339	0.00477	0.00134	7.42	0.06825	0.08191	0.29186	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.0723	0.1446
3.25	5.483	5.16E+06	0.00338	0.00335	0.00469	0.00132	8.58	0.08550	0.08071	0.28757	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.0905	0.1809
3.5	5.905	5.55E+06	0.00333	0.00331	0.00463	0.00130	9.81	0.10535	0.07962	0.28368	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.1113	0.2226
3.75	6.326	5.95E+06	0.00329	0.00327	0.00457	0.00128	11.12	0.12795	0.07862	0.28013	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.1350	0.2701
4	6.748	6.35E+06	0.00325	0.00323	0.00452	0.00127	12.51	0.15348	0.07771	0.27687	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.1618	0.3236
4.25	7.170	6.74E+06	0.00322	0.00320	0.00447	0.00125	13.97	0.18209	0.07686	0.27386	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.1918	0.3836
4.5	7.592	7.14E+06	0.00318	0.00317	0.00443	0.00124	15.50	0.21394	0.07608	0.27107	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.2251	0.4502
4.75	8.013	7.54E+06	0.00315	0.00314	0.00438	0.00123	17.10	0.24920	0.07535	0.26847	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.2620	0.5240
5	8.435	7.93E+06	0.00312	0.00312	0.00434	0.00122	18.78	0.28802	0.07466	0.26603	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.3026	0.6051

SUBMERSIBLE HULL OPTIMIZATION   TRIDENT SCHOLAR HULL DESIGN

LENGT 14.6 VISC = ******* at 80 deg F RHO = 1.9844 APPENDAGES surface chord (ft) 0.33 Fully appended hull

A(WET) 75.4798 D/L = 0.1425 P.C.= 0.4 d/l= 0.14993 P.C.= 0.5

Swet= 3.11111

ITTC .044/Rn^(1/6) CT=CF*(1+1.5*D/L^1.5+7*D/L^3)

CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

V(kts)	V(fps)	RN	Cf	Cf	Ct	Cr	Swet:R(lbs	EHP	EPDA Cr*Swet	Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	2.52E+06	0.00387	0.00377	0.00426	0.00039	0.91	0.00279	0.02952	0.32184	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.0030	0.0061
1.25	2.109	3.14E+06	0.00371	0.00364	0.00408	0.00037	1.36	0.00521	0.02826	0.30812	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.0057	0.0113
1.5	2.531	3.77E+06	0.00358	0.00353	0.00394	0.00036	1.89	0.00870	0.02729	0.29755	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.0094	0.0188
1.75	2.952	4.40E+06	0.00348	0.00344	0.00383	0.00035	2.50	0.01342	0.02651	0.28903	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.0145	0.0289
2	3.374	5.03E+06	0.00339	0.00336	0.00374	0.00034	3.18	0.01954	0.02586	0.28194	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.0210	0.0420
2.25	3.796	5.66E+06	0.00332	0.00330	0.00366	0.00034	3.94	0.02722	0.02530	0.27591	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.0292	0.0584
2.5	4.218	6.29E+06	0.00326	0.00324	0.00359	0.00033	4.78	0.03663	0.02482	0.27067	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.0392	0.0784
2.75	4.639	6.92E+06	0.00320	0.00319	0.00352	0.00032	5.68	0.04792	0.02440	0.26606	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.0512	0.1024
3	5.061	7.55E+06	0.00315	0.00314	0.00347	0.00032	6.66	0.06126	0.02402	0.26195	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.0653	0.1306
3.25	5.483	8.18E+06	0.00311	0.00310	0.00342	0.00031	7.70	0.07679	0.02368	0.25826	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.0817	0.1635
3.5	5.905	8.80E+06	0.00307	0.00306	0.00338	0.00031	8.82	0.09466	0.02338	0.25491	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.1006	0.2013
3.75	6.326	9.43E+06	0.00303	0.00303	0.00334	0.00031	10.00	0.11503	0.02310	0.25185	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.1221	0.2442
4	6.748	1.01E+07	0.00300	0.00299	0.00330	0.00030	11.25	0.13804	0.02284	0.24903	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.1464	0.2927
4.25	7.170	1.07E+07	0.00297	0.00296	0.00326	0.00030	12.57	0.16385	0.02260	0.24643	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.1735	0.3471
4.5	7.592	1.13E+07	0.00294	0.00294	0.00323	0.00030	13.95	0.19259	0.02238	0.24402	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.2038	0.4075
4.75	8.013	1.19E+07	0.00291	0.00291	0.00320	0.00029	15.40	0.22442	0.02217	0.24177	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.2372	0.4744
5	8.435	1.26E+07	0.00288	0.00289	0.00318	0.00029	16.92	0.25947	0.02198	0.23966	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.2740	0.5480

SUBMERSIBLE HULL OPTIMIZATION TRIDENT2 SCHOLAR HULL DESIGN

LENGT 13.425 VISC = 9.79E-06 at 80 deg F RHO = 1.9844 APPENDAGES surface chord (ft) 0.33 Fully appended hull

A(WET) 72.2311 D/L = 0.1520 P.C.= 0.4 d/l= 0.14993 P.C.= 0.5

Swet= 3.11111

ITTC .044/Rn^(1/6) CT=CF*(1+1.5*D/L^1.5+7*D/L^3) CT=CFlam[1+(d/l)^1.5+.1(d/l)^2]

			ITTC						EPDA		APPENDAGES							
V(kts)	V(fps)	RN	Cf	Cf	Ct	Cr	Swet:R(lb	EHP	Cr*Swet	Ct*Swet	Rn	Cf	Cf lam	Ct	Cr	J:R(lbs)	EHP	SHP
1	1.687	2.31E+06	0.00394	0.00383	0.00426	0.00032	0.87	0.00267	0.02328	0.30771	7.007E+04	0.06853	0.00502	0.00532	0.00030	0.07	0.00293	0.005851
1.25	2.109	2.89E+06	0.00377	0.00369	0.00410	0.00034	1.31	0.00502	0.02427	0.29648	8.759E+04	0.06603	0.00449	0.00476	0.00027	0.10	0.00547	0.01094
1.5	2.531	3.47E+06	0.00364	0.00358	0.00398	0.00034	1.83	0.00841	0.02481	0.28761	1.051E+05	0.06405	0.00410	0.00434	0.00025	0.13	0.00912	0.018249
1.75	2.952	4.05E+06	0.00353	0.00349	0.00388	0.00035	2.42	0.01301	0.02510	0.28031	1.226E+05	0.06243	0.00379	0.00402	0.00023	0.16	0.01407	0.028133
2	3.374	4.63E+06	0.00345	0.00341	0.00380	0.00035	3.10	0.01900	0.02523	0.27414	1.401E+05	0.06105	0.00355	0.00376	0.00021	0.20	0.02047	0.040935
2.25	3.796	5.20E+06	0.00337	0.00334	0.00372	0.00035	3.84	0.02652	0.02527	0.26881	1.577E+05	0.05986	0.00334	0.00355	0.00020	0.23	0.02850	0.056994
2.5	4.218	5.78E+06	0.00331	0.00328	0.00366	0.00035	4.66	0.03575	0.02525	0.26413	1.752E+05	0.05882	0.00317	0.00336	0.00019	0.27	0.03832	0.076636
2.75	4.639	6.36E+06	0.00325	0.00323	0.00360	0.00035	5.55	0.04683	0.02519	0.25997	1.927E+05	0.05790	0.00303	0.00321	0.00018	0.32	0.05009	0.100184
3	5.061	6.94E+06	0.00320	0.00319	0.00355	0.00035	6.51	0.05992	0.02510	0.25623	2.102E+05	0.05706	0.00290	0.00307	0.00017	0.36	0.06398	0.127955
3.25	5.483	7.52E+06	0.00315	0.00314	0.00350	0.00035	7.54	0.07517	0.02499	0.25283	2.277E+05	0.05631	0.00278	0.00295	0.00017	0.41	0.08013	0.16026
3.5	5.905	8.10E+06	0.00311	0.00311	0.00346	0.00034	8.64	0.09274	0.02486	0.24973	2.452E+05	0.05561	0.00268	0.00284	0.00016	0.46	0.09870	0.197405
3.75	6.326	8.67E+06	0.00308	0.00307	0.00342	0.00034	9.80	0.11276	0.02473	0.24687	2.628E+05	0.05498	0.00259	0.00275	0.00016	0.51	0.11985	0.239694
4	6.748	9.25E+06	0.00304	0.00304	0.00338	0.00034	11.03	0.13538	0.02459	0.24423	2.803E+05	0.05439	0.00251	0.00266	0.00015	0.56	0.14371	0.287425
4.25	7.170	9.83E+06	0.00301	0.00301	0.00335	0.00034	12.33	0.16075	0.02444	0.24178	2.978E+05	0.05384	0.00243	0.00258	0.00015	0.61	0.17045	0.340894
4.5	7.592	1.04E+07	0.00298	0.00298	0.00332	0.00034	13.69	0.18902	0.02429	0.23949	3.153E+05	0.05333	0.00236	0.00251	0.00014	0.66	0.20020	0.400393
4.75	8.013	1.10E+07	0.00295	0.00295	0.00329	0.00033	15.12	0.22031	0.02415	0.23734	3.328E+05	0.05285	0.00230	0.00244	0.00014	0.72	0.23311	0.466211
5	8.435	1.16E+07	0.00293	0.00293	0.00326	0.00033	16.61	0.25477	0.02400	0.23532	3.503E+05	0.05240	0.00224	0.00238	0.00014	0.78	0.26932	0.538635

APPENDIX II

Series 58 model 4165
model testing results

X/L	X in inches	Y/D	Y in inches
0.00	0.00	0.0000	0.000
.02	2.16	.1423	2.195
.04	4.32	.2020	3.117
.06	6.48	.2476	3.820
.08	8.64	.2855	4.405
.10	10.80	.3179	4.905
.12	12.96	.3462	5.341
.14	15.12	.3710	5.724
.16	17.28	.3930	6.063
.18	19.44	.4123	6.361
.20	21.60	.4260	6.573
.22	23.76	.4439	6.849
.24	25.92	.4565	7.043
.26	28.08	.4674	7.211
.28	30.24	.4765	7.352
.30	32.40	.4841	7.469
.32	34.56	.4900	7.560
.34	36.72	.4944	7.628
.36	38.88	.4976	7.677
.38	41.04	.4994	7.705
.40	43.20	.5000	7.714
.42	45.36	.4995	7.707
.44	47.52	.4978	7.680
.46	49.68	.4950	7.637
.48	51.84	.4911	7.577
.50	54.00	.4864	7.504
.52	56.16	.4806	7.415
.54	58.32	.4739	7.312
.56	60.48	.4665	7.197
.58	62.64	.4580	7.066
.60	64.80	.4486	6.921
.62	66.96	.4384	6.764
.64	69.12	.4273	6.593
.66	71.28	.4154	6.409
.68	73.44	.4026	6.212
.70	75.60	.3890	6.002
.72	77.76	.3743	5.775
.74	79.92	.3583	5.536
.76	82.08	.3422	5.280
.78	84.24	.3245	5.007
.80	86.40	.3059	4.720
.82	88.56	.2861	4.414
.84	90.72	.2652	4.092
.86	92.88	.2429	3.749
.88	95.04	.2193	3.383
.90	97.20	.1941	2.995
.92	99.36	.1672	2.580
.94	101.52	.1383	2.134
.96	103.68	.1065	1.643
.98	105.84	.0699	1.078
1.00	108.00	0.0000	0.000

Formula:

$$y^2 = a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 + a_6 x^6$$

where $a_1 = + \ 1.000000$

$a_2 = + \ 0.837153$

$a_3 = - \ 8.585996$

$a_4 = + \ 14.075954$

$a_5 = - \ 10.542535$

$a_6 = + \ 3.215422$

Wetted Surface Coefficient $= \dfrac{S}{\pi L D}$

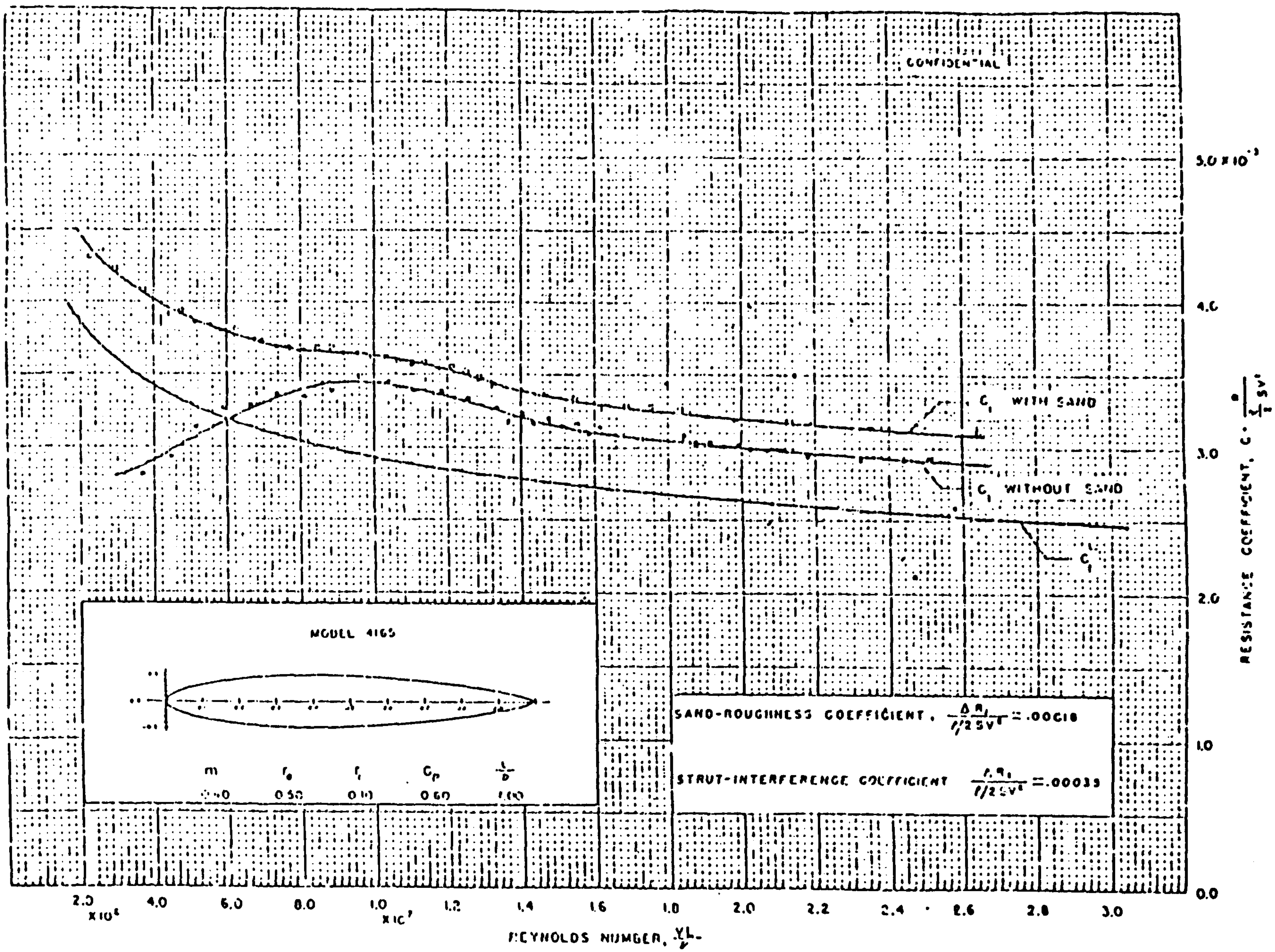
$= 0.7374$

Longitudinal Center of Buoyancy $= \dfrac{\bar{X}}{L}$

$= 0.4484$

Model Particulars:

Length, ft	9.000
Diameter, ft	1.286
Nose radius, ft	0.0918
Tail radius, ft	0.0184
Wetted surface, ft^2	26.81
Volume, ft^3	7.011
Longitudinal center of buoyancy, ft from nose	4.036


CONFIDENTIAL
C_t WITH SAND
C_t WITHOUT SAND
C_f
MODEL 4165
m r_e r_i C_p $\frac{L}{D}$
0.40 0.50 0.10 0.60 1.00
SAND-ROUGHNESS COEFFICIENT, $\frac{\Delta R}{\rho/2\,SV^2}$ = .00018
STRUT-INTERFERENCE COEFFICIENT $\frac{\Delta R}{\rho/2\,SV^2}$ = .00035
RESISTANCE COEFFICIENT, $C = \frac{R}{\frac{\rho}{2} SV^2}$
REYNOLDS NUMBER, $\frac{VL}{\nu}$
3.0 x 10^-3
4.0
3.0
2.0
1.0
0.0
2.0 x10^6
4.0
6.0
8.0
1.0 x10^7
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

APPENDIX III

DATA EXCHANGE PROGRAM

```
/* KYLE.C -- This program reads an ascii file created by 3DStudio and calculates the wetted surface, the volume,
and the sectional areas. The file should be of the following

        format:
Ambient light color: Red=0.3 Green=0.3 Blue=0.3

Named object: "box"
Tri-mesh, Vertices: 8     Faces: 12
Vertex list:
Vertex 0:  X: 1     Y: -0.5    Z: -0.5
Vertex 1:  X: -3     Y: -0.5    Z: -0.5
Vertex 2:  X: 1     Y: 0.5    Z: -0.5
Vertex 3:  X: -3     Y: 0.5    Z: -0.5
Vertex 4: X: 1     Y: -0.5     Z: 0.5
Vertex 5: X: -3     Y: -0.5     Z: 0.5
Vertex 6: X: 1     Y: 0.5     Z: 0.5
Vertex 7: X: -3     Y: 0.5     Z: 0.5
Face list:
Face 0:    A:0 B:4 C:1 AB:1 BC:1 CA:0
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 1:    A:0 B:1 C:5 AB:0 BC:1 CA:1
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 2:    A:0 B:2 C:6 AB:1 BC:1 CA:0
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 3:    A:0 B:6 C:4 AB:0 BC:1 CA:1
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 4:    A:4 B:6 C:3 AB:1 BC:1 CA:0
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 5:    A:4 B:3 C:1 AB:0 BC:1 CA:1
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 6:    A:1 B:3 C:7 AB:1 BC:1 CA:0
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 7:    A:1 B:7 C:5 AB:0 BC:1 CA:1
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 8:    A:5 B:7 C:2 AB:1 BC:1 CA:0
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 9:    A:5 B:2 C:0 AB:0 BC:1 CA:1
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 10:    A:2 B:7 C:3 AB:1 BC:1 CA:0
Material:"YELLOW PLASTIC"
Smoothing:  1
Face 11:    A:2 B:3 C:6 AB:0 BC:1 CA:1
Material:"YELLOW PLASTIC"
Smoothing:  1

*/Program begins here. To run type: Kyle.exe <ASCII file> <output file>.

#include <stdio.h>
```

```
#include <math.h>
#include <io.h>
#include <stdlib.h>
#define NUMV 700
#define NUMF 1300

void main(argc,argv)
int argc;
char *argv[];
{
FILE *fp, *fopen();
FILE *TDFILE = stdin;
char header1[80];
char header2[80];
char header3[80];
char header4[80];
char header5[80];
char header6[80];
char header7[80];
char header8[80];
char header9[80];
char header10[80];
char name[10];
char numvert[10];
char numface[10];
char vertx[20],verty[20],vertz[20];
char facea[20],faceb[20],facec[20];

int v,f,intx,numofstats;
int vertflag,numofverts,numoffaces;
int x,y,z,a,b,c,i,j,k,flagx,h,flag;
int ks[60],face[NUMF][3];

float ax,ay,az,bx,by,bz;
float xx,yy,zz,area,vol,volsum,areasum,statarea,statsum[60];
float vert[NUMV][3];
float vertnew;
float tempx,realx,y1,z1,y2,z2,x1;
float stat[60][20][3];

/* opens the input file */

   fp=fopen(argv[1],"r");

/* reads the various header lines from file */

        fgets(header1,79,fp);
        fgets(header1,79,fp);
        fgets(header1,79,fp);
/*      if (header1[0]=='N')
                {
                for (i=15;i<100;i++)
                        {
                        name[i-15]=header1[i];
                        if (header1[i+1]=='"')
                          break;
                        }
                }
*/
```

```
        fgets(header4,79,fp);

/* gets the number of vertices and number of faces from file */

  if (header4[0]=='T')
                {
                v=0;
                f=0;
                flagx=0;
                for (i=20;i<100;i++)
                        {
                        if (header4[i]!='F')
                                {
                                numvert[v]=header4[i];
                                v++;
                                }
                        else
                                break;
                        }
                        numofverts=atoi(numvert);

                for (j=i+6;j<i+16;j++)
                        {
                          numface[f]=header4[j];
                          f++;
                        }
                numoffaces=atoi(numface);
                }

        fgets(header5,79,fp);

/* gets the X Y and Z values from file and puts into vert array */

        for (j=0;j<numofverts;j++)
                {
                fgets(header6,70,fp);
                while (header6[0]!='V')
                        fgets(header6,79,fp);
                x=0;
                y=0;
                z=0;
                flagx=0;
                for (i=0;i<100;i++)
                        {
                        if (header6[i]=='X')
                                {
                                flagx=1;
                                i+=2;
                                }
                        if (header6[i]=='Y')
                                {
                                vert[j][1]=atof(vertx);
                                flagx=2;
                                i+=2;
                                }
                        if (header6[i]=='Z')
                                {
                                flagx=3;
                                i+=2;
```

```
                                }
                        if (flagx==1)
                                {
                                vertx[x]=header6[i];
                                x++;
                                }
                        if (flagx==2)
                                {
                                vert[j][2]=atof(verty);
                                verty[y]=header6[i];
                                y++;
                                }
                        if (flagx==3)
                                {
                                vertz[z]=header6[i];
                                z++;
                                }
                        }
                vert[j][3]=atof(vertz);
                }

/* gets the the vertex numbers for each face and puts into face array */

        fgets(header7,79,fp);
        for (j=0;j<numoffaces;j++)
                {
                fgets(header8,79,fp);
                while (header8[0]!='F')
                        fgets(header8,79,fp);
                fgets(header9,79,fp);
                while (header9[0]!='M')
                        fgets(header9,79,fp);
                fgets(header10,79,fp);
                while (header10[0]!='S')
                        fgets(header10,79,fp);
                a=0;
                b=0;
                c=0;
                flagx=0;
                for (i=0;i<100;i++)
                        {
                        if (header8[i]=='A')
                                {
                                flagx=1;
                                i=i+2;
                                }
                        if (header8[i]=='B')
                                {
                                face[j][1]=atoi(facea);
                                flagx=2;
                                i=i+2;
                                }
                        if (header8[i]=='C')
                                {
                                face[j][2]=atoi(faceb);
                                flagx=3;
                                i=i+2;
                                }
                        if (flagx==1)
```

```
                                        {
                                        facea[a]=header8[i];
                                        a++;
                                        }
                                if (flagx==2)
                                        {
                                        faceb[b]=header8[i];
                                        b++;
                                        }
                                if (flagx==3)
                                        {
                                        facec[c]=header8[i];
                                        c++;
                                        }
                                }
                        face[j][3]=atoi(facec);
                        }
/* closes input file */
        fclose(fp);
/* opens output file */
        fp=fopen(argv[2],"w");
/* calculates the wetted surface area */
    areasum=0.0F;
        for (i=0;i<numoffaces;i++)
                        {
                        ax=vert[face[i][1]][1]-vert[face[i][2]][1];
                        ay=vert[face[i][1]][2]-vert[face[i][2]][2];
                        az=vert[face[i][1]][3]-vert[face[i][2]][3];
                        bx=vert[face[i][1]][1]-2*vert[face[i][2]][1]+vert[face[i][3]][1];
                        by=vert[face[i][1]][2]-2*vert[face[i][2]][2]+vert[face[i][3]][2];
                        bz=vert[face[i][1]][3]-2*vert[face[i][2]][3]+vert[face[i][3]][3];
                        xx=ay*bz-by*az;
                        yy=-(ax*bz-bx*az);
        zz=ax*by-bx*ay;
        area=.5F*sqrt(pow(xx,2)+pow(yy,2)+pow(zz,2));
        areasum=areasum+area;
        }
        fprintf(fp,"Wetted Surface Area = %f\n",areasum);
/* calculates the volume */
    volsum=0.0F;
    for (i=0;i<numoffaces;i++)
                        {
        xx=vert[face[i][1]][1]*(vert[face[i][2]][2]*vert[face[i][3]][3]-vert[face[i][3]][2]*vert[face[i][2]][3]);
        yy=vert[face[i][1]][2]*(vert[face[i][2]][1]*vert[face[i][3]][3]-vert[face[i][3]][1]*vert[face[i][2]][3]);
        zz=vert[face[i][1]][3]*(vert[face[i][2]][1]*vert[face[i][3]][2]-vert[face[i][3]][1]*vert[face[i][2]][2]);
        vol=1.0F/6.0F*fabs((xx)-(yy)+(zz));
        volsum=volsum+vol;
        }
    fprintf(fp,"Volume = %f\n",volsum);

/* rearranges the vertices so X values are the same */
    j=1;
    k=0;
    intx=vert[0][1]*1000;
    tempx=intx/1000.0F;
        stat[1][1][1]=vert[0][1];
        ks[1]=0;
        for (i=0;i<numofverts;i++)
                        {
```

```
                intx=vert[i][1]*1000;
                vertnew=intx/1000.0F;
                h=j;
                while(h>0)
                {
                intx=stat[h][1][1]*1000;
                tempx=intx/1000.0F;
                if (vertnew==tempx)
                        {
                        ks[h]++;
                        stat[h][ks[h]][1]=vert[i][1];
                        stat[h][ks[h]][2]=vert[i][2];
                        stat[h][ks[h]][3]=vert[i][3];
                        flag=1;
                        }
                h--;
                }
        if (flag==0)
          {
          j++;
          ks[j]=1;
                        stat[j][1][1]=vert[i][1];
                        stat[j][1][2]=vert[i][2];
                        stat[j][1][3]=vert[i][3];
          }
         flag=0;
        }
          numofstats=j;
          statarea=0.0F;
/* calculates the sectional areas */
          for (j=1;j<=numofstats;j++)
        {
          statsum[j]=0.0F;
          for (k=2;k<=ks[j];k++)
                {
                                x1=stat[j][k][1];
             y1=stat[j][k-1][2];
                                y2=stat[j][k][2];
                                z1=stat[j][k-1][3];
                                z2=stat[j][k][3];
                                statarea=fabs(z1-z2)*fabs(y2+y1)/2.0F;
                statsum[j]=statsum[j]+statarea;
                        }
                x1=stat[j][1][1];
          y1=y2;
                z1=z2;
                y2=stat[j][1][2];
                z2=stat[j][1][3];
          statarea=fabs(z1-z2)*fabs(y2+y1)/2.0F;
                statsum[j]=statsum[j]+statarea;
                        fprintf(fp,"x = %f station area = %f\n",stat[j][1][1],statsum[j]);
          }
/* closes the output file */
          fclose(fp);}
```

```
			x1=stat[j][1][1];
		y1=y2;
			z1=z2;
			y2=stat[j][1][2];
			z2=stat[j][1][3];
		statarea=fabs(z1-z2)*fabs(y2+y1)/2.0F;
			statsum[j]=statsum[j]+statarea;
				fprintf(fp,"x = %f station area = %f\n",stat[j][1][1],statsum[j]);
		}
/* closes the output file */
		fclose(fp);}
```

SAMPLE OUTPUT FILE FOR SUBMERSIBLE (*Half-hull* (inches))

```
Wetted Surface Area = 5434.545898
Volume = 28054.537109
x = -81.967644 station area = 1.572878
x = -80.967560 station area = 6.342616
x = -78.940498 station area = 24.299978
x = -77.867294 station area = 35.340561
x = -75.429039 station area = 62.769066
x = -73.766945 station area = 81.639130
x = -72.158989 station area = 97.458115
x = -69.010338 station area = 128.462799
x = -66.430588 station area = 148.134155
x = -60.430084 station area = 177.665482
x = -54.429581 station area = 195.011520
x = -48.429073 station area = 213.036545
x = -42.428570 station area = 224.990005
x = -36.428070 station area = 234.890488
x = -30.427567 station area = 238.814499
x = -24.427063 station area = 242.424728
x = -18.426559 station area = 243.223877
x = -12.426064 station area = 243.934479
x = -6.441582 station area = 243.802582
x = -0.441582 station area = 243.568329
x = 5.575447 station area = 241.107956
x = 11.558418 station area = 235.424454
x = 17.558418 station area = 229.797363
x = 23.576958 station area = 222.657272
x = 29.558418 station area = 213.148544
x = 35.577965 station area = 202.609451
x = 41.578468 station area = 180.277664
x = 47.578972 station area = 156.562485
x = 53.579475 station area = 129.503799
x = 92.909462 station area = 1.891162
```

APPENDIX IV

Bi-annual Human Powered Race Committee

Chapter 9 - Design Requirements

9.0 SUBMARINE DESIGN AND SAFETY REQUIREMENTS

For the purpose of this competition a submarine is: a free- flooding (liquid filled) marine vehicle which fully encapsulates both occupants and operates entirely beneath the surface of the water.

9.1 SUBMARINE DESIGN REQUIREMENTS

9.1.1 Submarines must operate with two persons, hereafter referred to as "submarine crew"; one will be responsible for propulsion and the other for non-propulsion duties such as navigation, steering and safety.
9.1.2 The submarine crew (pilot and propulsor) may not switch positions or functions once a race has started.
9.1.3 Drag Reduction: If drag reduction materials are used, contestants must submit documentation attesting to the fact that the State of Florida and/or federal agencies have approved use of this material in the submarine races. Questionable materials or documentation will result in the disapproval of the use of drag reduction material.
9.1.4 All submarines must be able to withstand a three- knot towing speed. Vehicle tow points are left to the discretion of the designer.
9.1.5 All submarines must be fitted with two attachment points on the underside for hooking on the draw -down/starting bridle (See Section 10.2.2). One point must be located a maximum of 2 feet aft of the bow, for submarine positioning on the start line. The location of the second point, which should optimize trim when the submarine is restrained by the bridle and permit easy access for bridle release, is left to the discretion of the designer.
9.1.6 All changes to submarines which have already been approved must be submitted in final form in writing to the judges no later than April 16, 1993.

9.2 PROPULSION SYSTEMS

9.2.1 Propulsion system must be human powered. Stored power systems are not allowed except for non propulsion/control related equipment.
9.2.2 Energy storage devices such as flywheels are not permitted; all power systems must be direct drive without decouplers.
9.2.3 The propulsor and only the propulsor must supply all of the propulsive force used by the submarine. By definition, the submarine includes all submarine and safety equipment.
9.2.4 While exhaust air for the crew can be exhausted either internally or externally to the submarine, participants are reminded that compressed air cannot be used as a propulsive energy device.
9.2.5 Control surfaces may not be electrically operated.

9.3 LIFE SUPPORT SYSTEMS

9.3.1 All submarine subsystems with the exception of ballast subsystem must be wet and free- flooding (Liquid not air filled). Primary and emergency air supply must be on board for each person. In particular, primary and emergency crew air supplies may be used only for life support.

9.3.2 All submarines must provide a primary air supply with at least 150% of the air required for the crew to propel the submarine through the 800 meter course at 1- meter depth. Participating teams must provide air consumption data and submit the Air Consumption Form by May 14, 1993. (Form will be provided to those contestants who have been accepted). This data shall be for the crew operating the submarine during tests in a pool, or in open water, at a nominal 7- meter depth under the combined conditions of 10- minute warm up, 20- minute race- work level and 5- minute cool- down (See Appendix E, " Air Requirements "). The primary air supply for the race events must provide 150% of this amount.

9.3.3 Regulators: A list of approved regulators is provided in Appendix F. All other regulators will require prior approval by judges. Request for permission to use a regulator that is not included in Appendix F, should be addressed in writing to Or. Ace
Summer, Chairman of the Judges Panel.

9.3.4 All air supply tanks must have a current visual inspection and hydrostatic test.

9.3.5 Each crew member's emergency air supply must consist of:

(A) A spare air pony bottle for emergency use only (to be worn at all times) with no less than 1.7 cubic feet of compressed air and

(B) An attached regulator.

9.3.6 The pony bottle air supply system with regulator is a safety device for use only
in emergency situations. Its use in normal racing operations (launch, warm -up, cool-
down, racing, recovery, etc .) will result in disqualification.

9.3.7 Each crew member must wear an inflatable buoyancy compensator with both automatic (compressed air and/or CO^2) and oral inflation capabilities; automatic inflation cannot be accomplished through primary air supply.

9.3.8 Life -support systems air cannot be used for submarine ballast. Also, all ballast
systems must be closed systems. Use of soft bladders will give rise to significant safety
issues.

9*4 SAFETY REQUIREMENTS

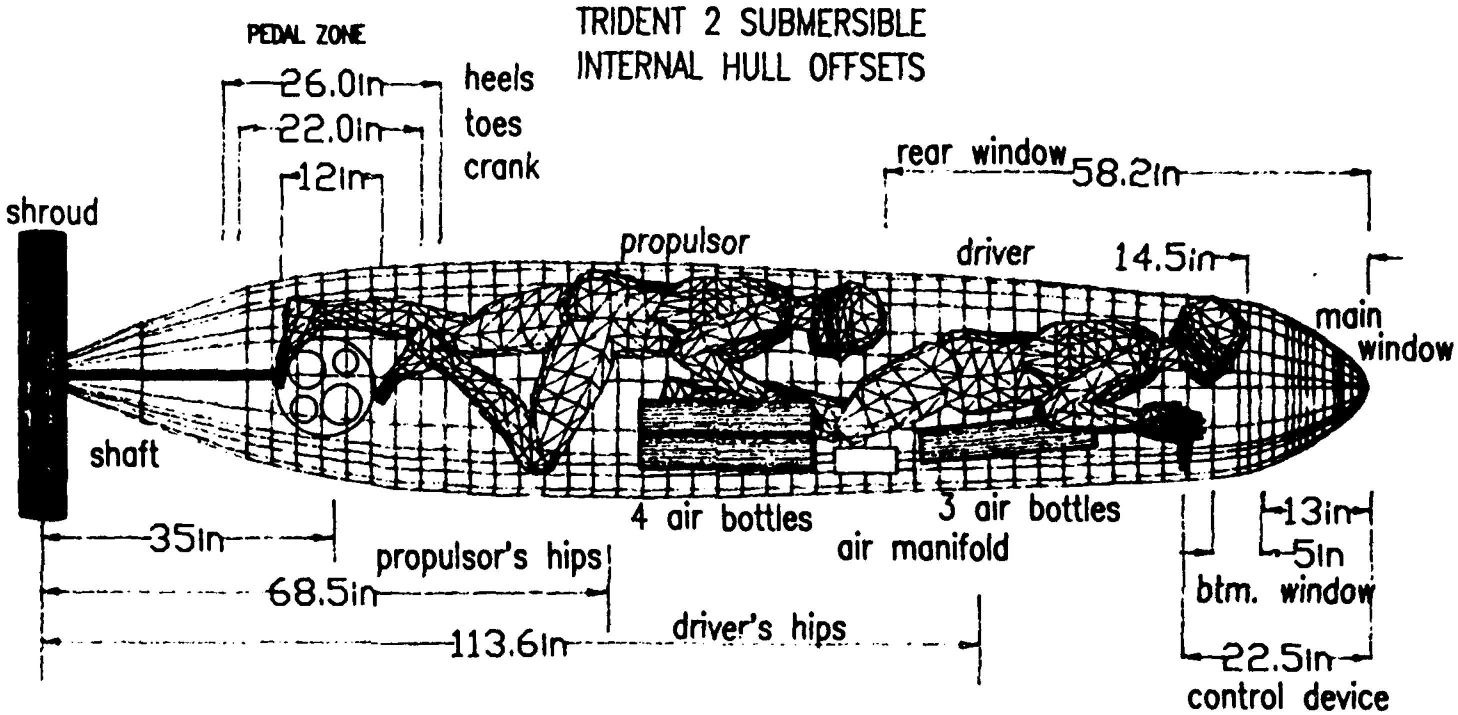
9.4.1 Each crew member must have a deadman switch which automatically releases a
safety buoy to the surface in the event he is disabled. The buoy must not be less than 6 inches in diameter, must have at least 2 pounds positive buoyancy submerged and be
international orange in color. It must be attached to the submarine by thirty feet of 1/16

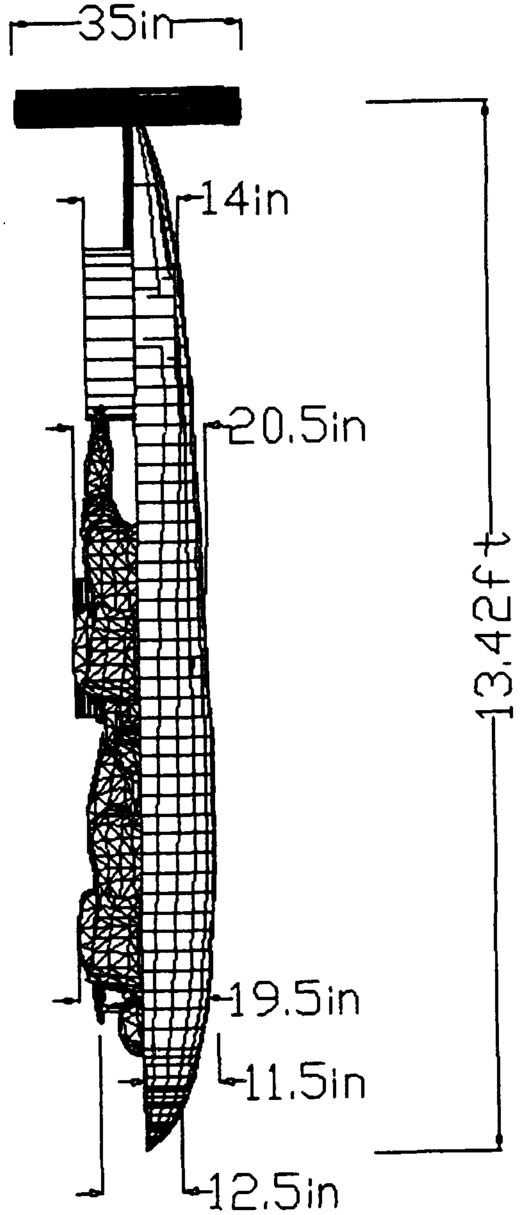
inch nylon line.
9.4.2 The deadman switches for both occupants must operate automatically with no more
than a 10 second delay during the time trial and elimination races. Submarines with malfunctioning inoperative deadman systems are subject to disqualification.
9.4.3 The occupant compartment must be readily accessible with a hatch or canopy release mechanism which is operable from inside and outside of the vehicle. The main entry and exit hatches must be marked with a 4 inch square patch of bright orange tape or paint and with clearly visible release instructions. occupants must be visible to safety divers at all times (this may require a viewport for the propulsor) to ensure the safety of the crew.
9.4.4 If in use, personal restraint systems must incorporate a single point, quick release mechanism. All restraint devices, including foot straps and air hoses, must be marked with bright orange tape or paint and be easily releasable by safety personnel. If the foot straps are too difficult to be manually released, a remote release system must be integrated into the entire submarine emergency evacuation system. Crew restraint devices must be easily visible, accessible, and removable by safety divers.
9.4.5 Each submarine must carry a flashing strobe light which flashes a minimum of 250,000 peak lumens with each pulse and is visible in clear water for 17 meters. Strobes must flash once per second for a minimum of one hour, be visible in the horizontal plane for 360 degrees, and be operating when the submarine is manned and in the water.
9.4.6 Each submarine must tow a small buoy along the surface. The attachment line will be provided by contestants. The buoy must be on the surface at all times and remain attached to the submarine at all times or the submarine will be disqualified. Specification of the towed buoy requirements may be found in Appendix G, "Specifications Of The Towed Surface Buoy Requirements. " Surface buoy tether management systems are permitted.
9.4.7 All submarines must be painted with high visibility colors and have a 0.5 meter x 0.5 meter dayglow patch atop the submarine for its assigned race number. In the case of partially or entirely transparent submarines, the submarine crew and the inner workings must be highly visible.
9.4.8 Official race numbers will be assigned by the Race Committee. These numbers must be painted on or attached to two sides and the top of the submarine. Numbers must be black, at least 0.5 meters high and be Helvetica type face. The Official race number must also be clearly displayed on the surface tow buoy.
9.4.9 Sufficient in- water test time for the submarine is imperative for a safe, competitive system design.
9.4.10 Part of the pilot's/navigator's responsibility is to ensure safe operation of the submarine; make sure his/her functions do not cause overload, thereby creating a significant safety issue.

APPENDIX V

Trident2 drawing and images

TRIDENT 2 SUBMERSIBLE
INTERNAL HULL OFFSETS

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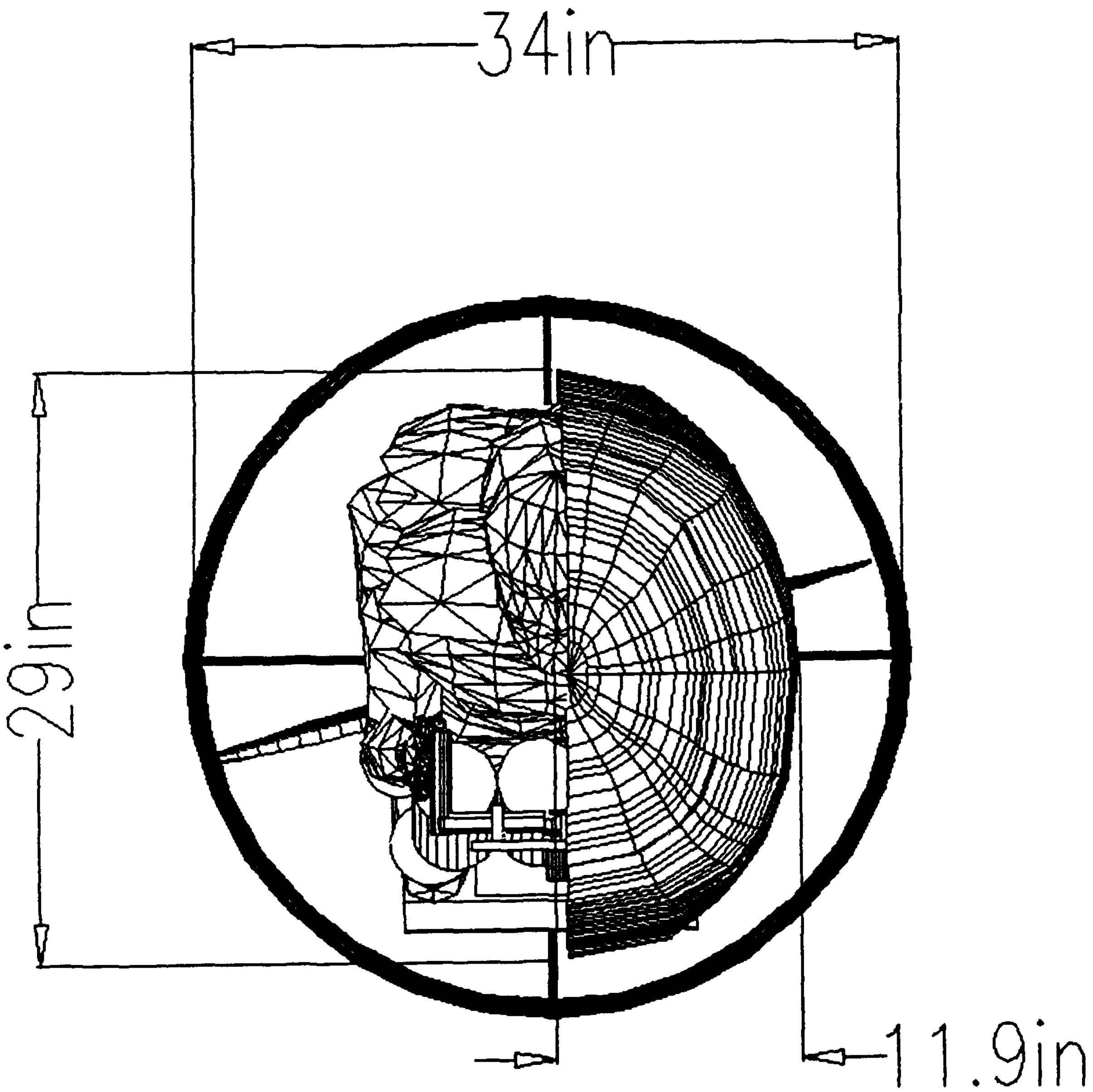
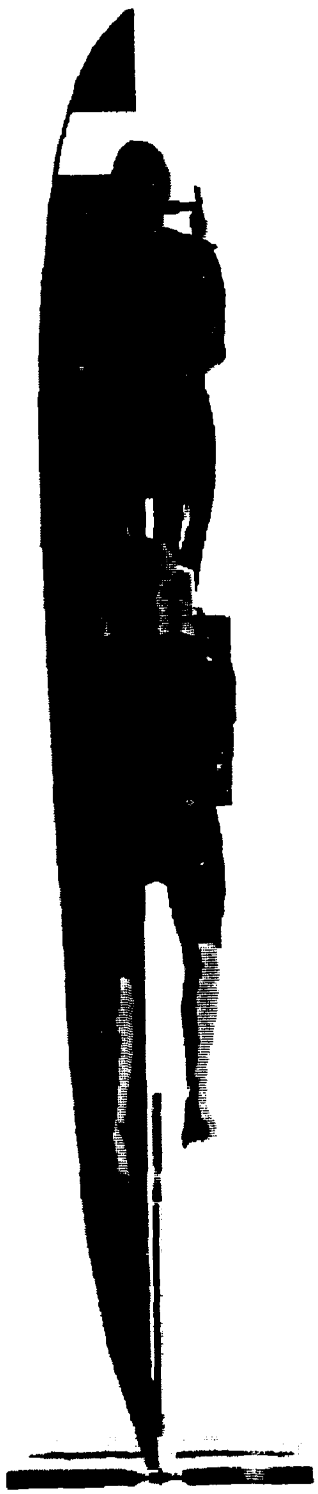
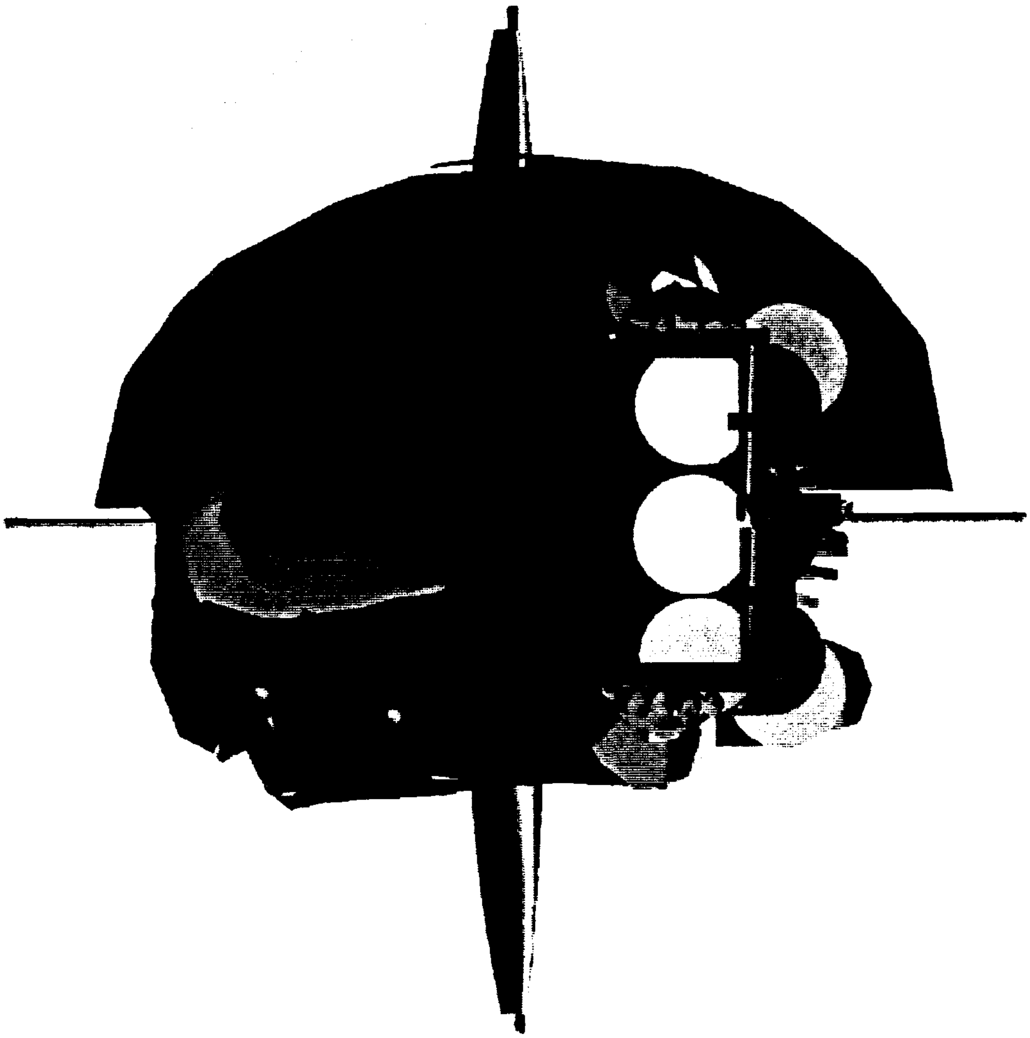
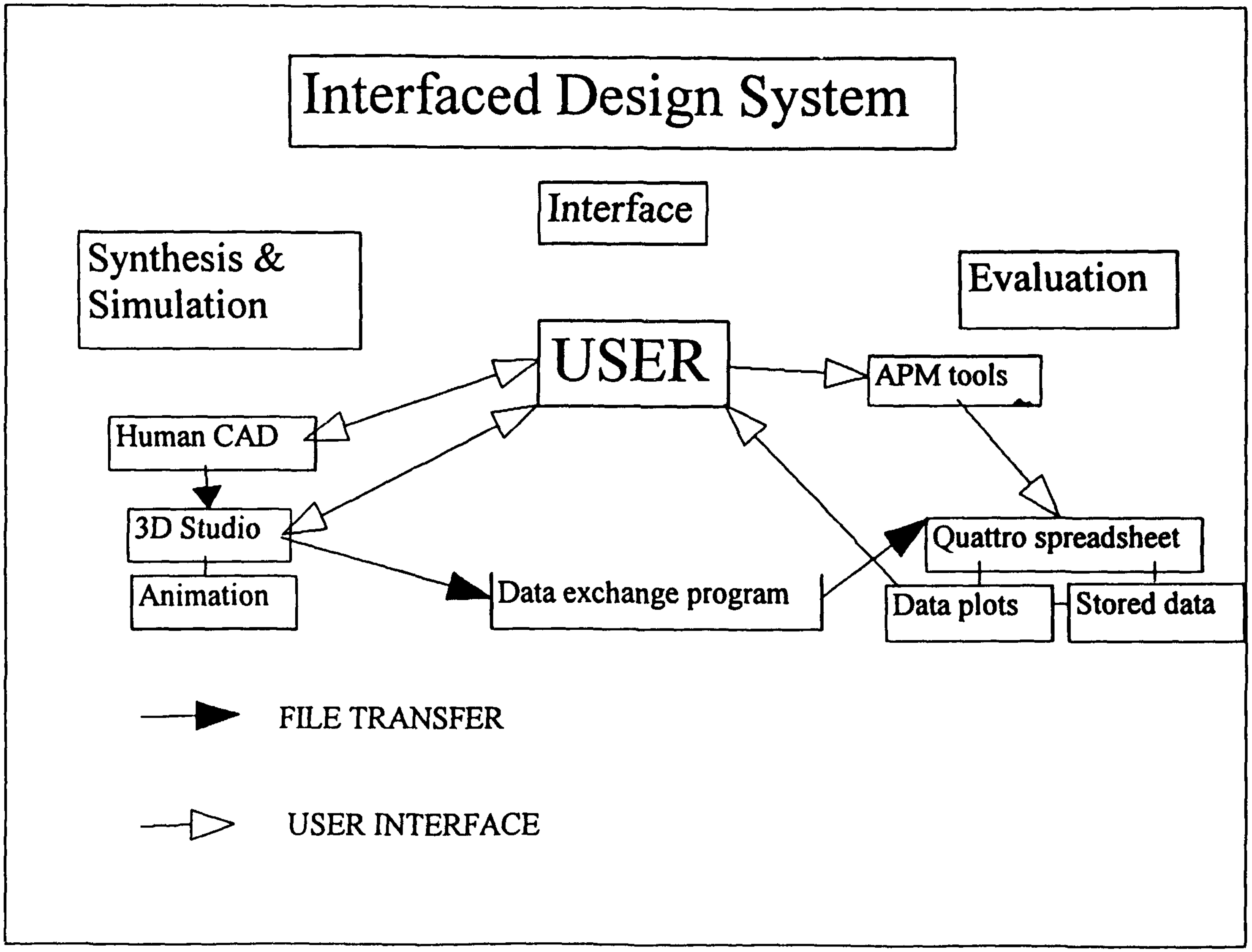
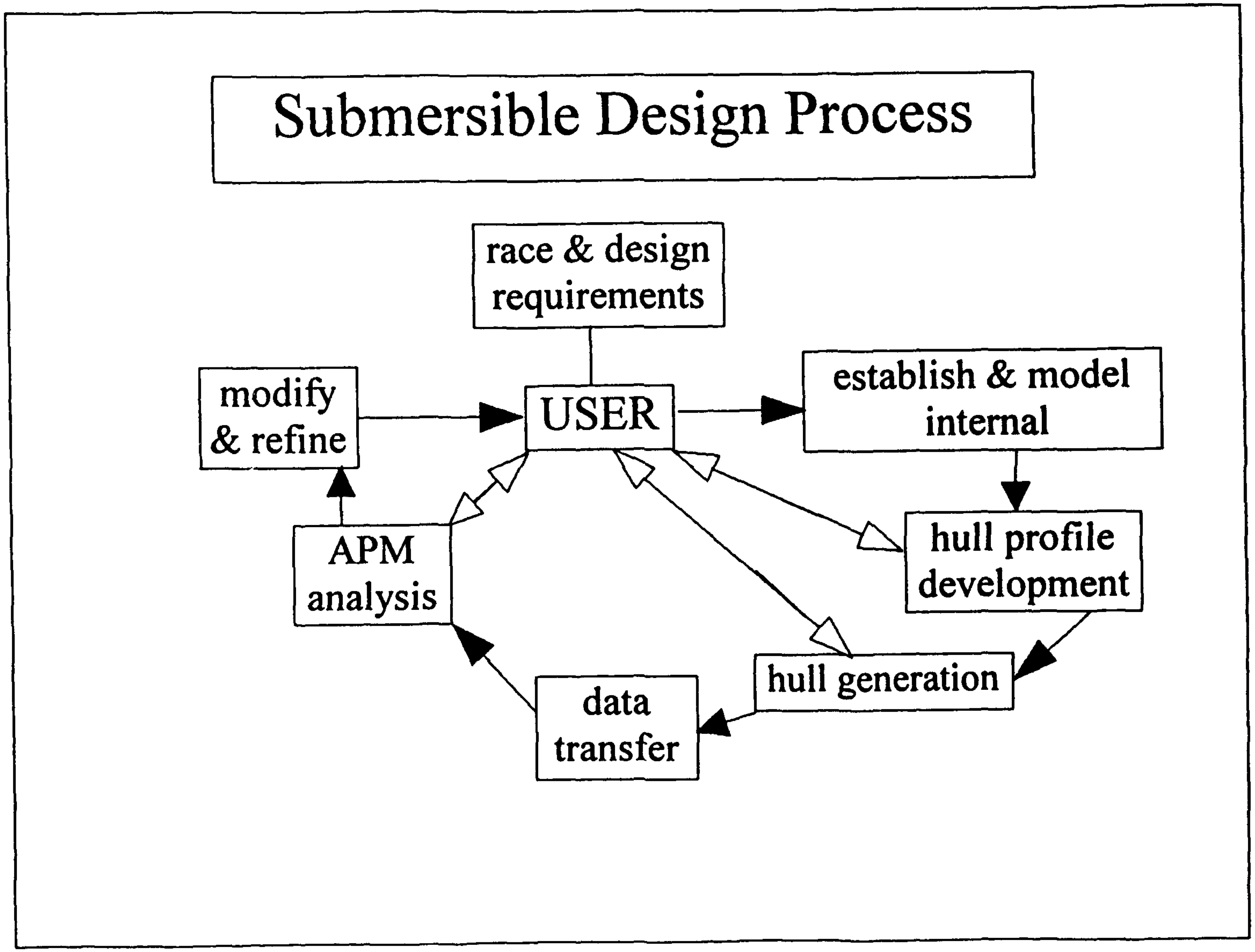
14in
20.5in
13.42ft
19.5in
11.5in
12.5in


34in
29in
11.9in






Interfaced Design System
Interface
Synthesis &
Simulation
Evaluation
USER
APM tools
Human CAD
3D Studio
Animation
Data exchange program
Quattro spreadsheet
Data plots
Stored data
FILE TRANSFER
USER INTERFACE


Submersible Design Process
race & design requirements
modify & refine
USER
establish & model internal
APM analysis
hull profile development
hull generation
data transfer