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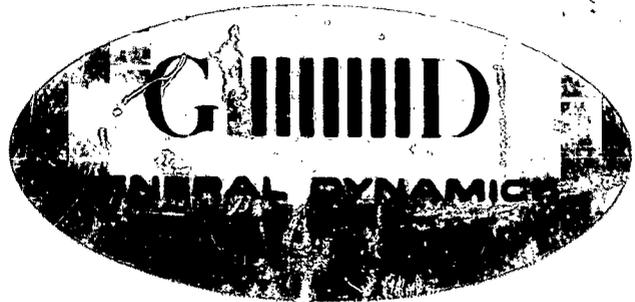
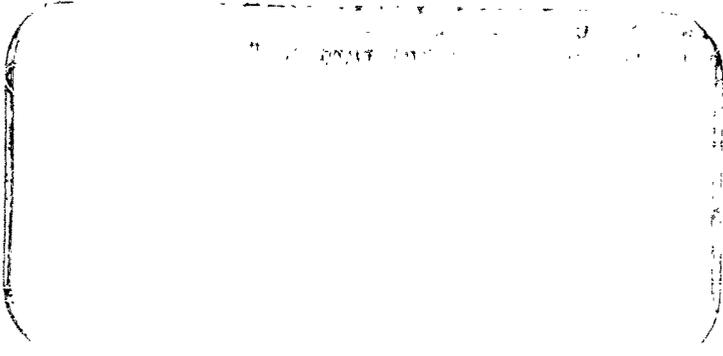
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**DESIGN STUDY REPORT****A SURVEY  
OF  
CONVENTIONAL AND UNCONVENTIONAL  
SUBMARINE PROPULSION SYSTEMS (U)**

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DESIGN STUDY REPORT

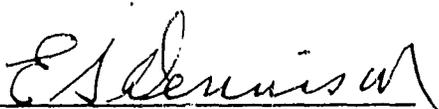
A SURVEY  
OF  
CONVENTIONAL AND UNCONVENTIONAL  
SUBMARINE PROPULSION SYSTEMS (U)

Contract NOnr 3383(00) (FBM)

by

T. J. Gerken  
Research and Development Department

GENERAL DYNAMICS/ELECTRIC BOAT  
Groton, Connecticut

Approved: 

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Chief Development Engineer

C413-63-043  
April 30, 1963

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Abstract

## ABSTRACT

A survey is made of a variety of conventional and unconventional submarine propulsion systems. Included are three all-mechanical systems, two inboard turboelectric systems, and six inboard/outboard turboelectric systems incorporating free-flooding propulsion motors. Some of these systems also provide ship control features in addition to the requisite normal propulsion.

A current FBM ship, SSB(N)616, is used as a reference design throughout, and only the propulsion system is varied. The propulsion system as considered here starts at the main steam line and ends with generation of thrust. It includes one or more steam turbine prime movers, mechanical or electric power transmissions, and propulsors.

The eleven systems are described and compared, and four are indicated as offering potential improvements over the current propulsion system.

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**ACKNOWLEDGEMENT**

This survey and the preceding reports prepared under this contract collectively represent:

The endeavors of a variety of groups and individuals within the General Dynamics/Electric Boat organization Consultation, under subcontract, with several other organizations:

General Electric Company  
Elliott Company  
Continental Bearing Research Corporation  
Cambridge Acoustical Associates

Information from numerous manufacturers, furnished on a courtesy basis.

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## TABLE OF CONTENTS

ABSTRACT	1
ACKNOWLEDGEMENTS	111
REFERENCES	ix
I INTRODUCTION	1
Criteria for Comparison	1
Systems Considered	2
Acoustics	4
II CONCLUSIONS	11
Favorable Systems	11
Program for Further Investigation	13
III DETAILED DESCRIPTION OF SYSTEMS	15
Geared Drive Turbine System	17
Geared Drive Turbine System with Reversible Pitch Propeller	29
Pumpjet System	35
AC-DC Electric System	43
Acyclic Electric System	55
Novel Electric Propulsion System	69
Tandem Propeller System	87
Inboard Flooded Motor System	107
Controllable Pod Motor System	117
Controllable Pod Motor System with Sail Pods	131
Cycloidal Propeller System	143
IV COMPARISON OF SYSTEMS	157
Variables Which Do Not Affect Results	157
Variables Which Do Affect Results	158
General Discussion	171
APPENDIX A, SHAFTLESS MOTORS	179
APPENDIX B, EXCITING FORCES DUE TO UNBALANCE	181

## CONFIDENTIAL

## LIST OF FIGURES

	Page
1. Ability to Hear and Be Heard vs Ship Speed	6
2. Auxiliary Machinery, Main Machinery, and Flow Noise vs Ship Speed	6
3. Geared Drive Turbine System, Ship and Propulsion Machinery	18
4. Geared Drive Turbine System, Depth vs Speed for Inception of Propeller Cavitation	27
5. Geared Drive Turbine System with Reversible Pitch Propeller, Ship and Propulsion Machinery	30
6. Pumpjet System, Ship and Propulsion Machinery	36
7. Pumpjet System, Shroud and Propeller	37
8. AC-DC Electric System, Ship and Propulsion Machinery	44
9. AC-DC Electric System, Electric Power One-Line Diagram	45
10. AC-DC Electric System, Electric Power and Control Diagram	47
11. Acyclic Electric System, Ship and Propulsion Machinery	56
12. Acyclic Electric System, Electric Power One-line Diagram	57
13. Acyclic Electric System, Acyclic Machine Schematic Diagram	58
14. Acyclic Electric System, Typical Acyclic Generator	60
15. Novel Electric Propulsion System, Ship and Propulsion Machinery	70
16. Novel Electric Propulsion System, Electric Power One-line Diagram	71
17. Novel Electric Propulsion System, Propulsion Motors and Propellers	73
18. Novel Electric Propulsion System, Propulsion Motors and Propellers	75
19. Tandem Propeller System, Ship and Propulsion Machinery	88
20. Tandem Propeller System, Electric Power One-line Diagram	89
21. Tandem Propeller System, Propulsion Motor and Propeller	91
22. Tandem Propeller System, Maximum Turning Moment vs Ship Speed	98

	Page
23. Inboard Flooded Motor System, Ship and Propulsion Machinery	108
24. Inboard Flooded Motor System, Electric Power One-line Diagram	109
25. Inboard Flooded Motor System, Propulsion Motors and Propeller	111
26. Controllable Pod Motor System, Ship and Propulsion Machinery	118
27. Controllable Pod Motor System, Electric Power One-line Diagram	119
28. Controllable Pod Motor System, Propulsion Motor and Propeller, Stern Pod	121
29. Controllable Pod Motor System, Propulsive Efficiency vs Hub-Tip Ratio	125
30. Controllable Pod Motor System, Minimum Cavitation-free Depth vs Rotor Tip Diameter	126
31. Controllable Pod Motor System with Sail Pods, Ship and Propulsion Machinery	132
32. Controllable Pod Motor System with Sail Pods, Electric Power One-line Diagram	133
33. Controllable Pod Motor System with Sail Pods, Propulsion Motor and Propeller, Sail Pod	135
34. Controllable Pod Motor System with Sail Pods, Propulsive Efficiency vs Hub-Tip Ratio	139
35. Cycloidal Propeller System, Ship and Propulsion Machinery	144
36. Cycloidal Propeller System, Electric Power One-line Diagram	145
37. Cycloidal Propeller System, Propulsion Motor and Propeller	147
38. Cycloidal Propeller System, Propeller Schematic Diagram	150
39. Relative Unbalance of Turbines and Generators at Maximum Speed	182

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I

INTRODUCTION

This report covers a survey type of study, encompassing the various flooded electric motor submarine propulsion systems so far considered under the contract, plus several additional electric and non-electric propulsion systems. The objective is to provide a single comprehensive comparison of all of the systems.

CRITERIA FOR COMPARISON

The goal of each of these systems is to attain improved operational performance compared with current practice. Thus, the first set of criteria used for comparison is:

- Noise
- Ship Control
- Depth
- Speed
- Armament

Design and construction are, of course, an essential preliminary to the operational ship. Thus, the second set of criteria used for comparison is:

- Size
- Weight
- Efficiency
- Reliability
- Installation
- Maintenance
- Manning
- Development Risk

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## SYSTEMS CONSIDERED

The systems considered in this report are briefly described below. The novel electric propulsion system and the tandem propeller system were previously studied separately under this contract.<sup>1-4\*</sup> The inboard flooded motor system and the two pod motor systems are the most promising of eleven other flooded motor systems which were previously surveyed under this contract<sup>5</sup>. The geared drive turbine system represents current practice, and serves as the reference system.

Mechanical Systems

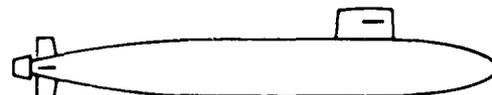
Geared drive turbine system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by high speed turbines through a reduction gear.



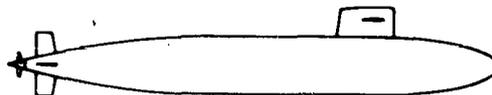
Geared drive turbine system with reversible pitch propeller consists of a single, reversible pitch propeller, located at the stern of the ship and driven by high speed turbines through a reduction gear.



Pumpjet system consists of a single pumpjet, located at the stern of the ship and driven by high speed turbines through a reduction gear.

Inboard Turboelectric Systems

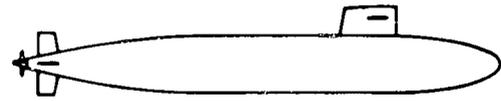
AC-DC electric system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by a combination of AC and DC machinery.



\*Superscripts refer to references listed on page ix.

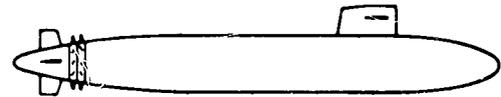
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Acyclic electric system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by acyclic machinery.

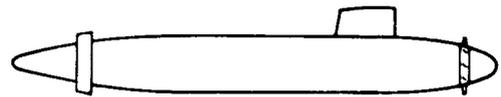


Inboard/Outboard Turboelectric Systems

Novel electric propulsion system consists of a pair of hull-sized, counter-rotating, fixed pitch propellers, located near the stern of the ship and driven by large, inside-out, free-flooding electric motors within the propeller hubs.



Tandem propeller system consists of a pair of hull-sized, counter-rotating, collectively and cyclically variable pitch propellers, located one near each end of the ship and driven by large, inside-out, free-flooding electric motors within the propeller hubs. Transverse control forces are also produced by the propellers, and conventional control surfaces are omitted.

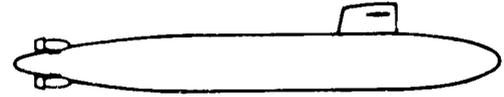


Inboard flooded motor system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by a pair of inside-out, free-flooding electric motors within the hull envelope but outside the pressure hull.

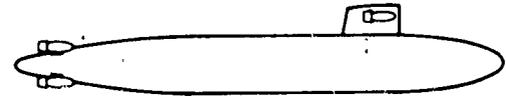


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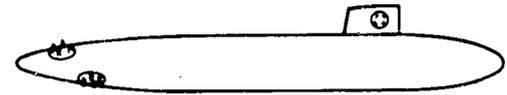
Controllable pod motor system consists of four pumpjets, located on the stern control surfaces and driven by free-flooding electric motors. The propellers and motors are arranged to pivot with the control surfaces.



Controllable pod motor system with sail pods consists of the preceding system with four pods located on the stern control surfaces and two pods with shrouded propellers located on the sail control surfaces.



Cycloidal propeller system consists of four cycloidal propellers, located near the stern of the ship and driven by free-flooding electric motors within the hull envelope but outside the pressure hull, and two cycloidal propellers located on the sail and driven similarly.



#### ACOUSTICS

Acoustics is emphasized in this report, since it is a particularly important factor in the comparison of propulsion systems.

The acoustical evaluation identifies known and potential sources of noise, and suggests means for their control. Radiated noise leading to detection of the submarine and self-noise interfering with the ship's sonar system are both considered. The known parameters of the noise generating mechanisms are listed with a view toward quantitative evaluation of the particular propulsion system components.

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Each of the propulsion systems includes one or more steam turbines and one or more propellers. Of the all-mechanical systems, only those using a geared down, high speed turbine are considered. The turboelectric systems include generators and electric motors of various kinds. After each system has been treated in detail, an attempt is made to compare the acoustical characteristics of each propulsion system with respect to the others.

Energy conversion in all of the propulsion systems begins with a source of heat (steam) and ends with the kinetic energy of motion of the submarine. At each energy conversion stage some amount of the energy is converted to acoustic energy by one or more noise-generating mechanisms, some of which are well understood. Since all propulsion systems consist of different arrangements of the same basic energy conversion devices, the noise-generating mechanisms associated with each such device are listed in Table 1. Specific advantages and disadvantages of each arrangement are included in the examination of the individual systems.

The effect of the transmission path of noise from the source to the water is a major factor in the determination of self- and radiated noise. The use of vibration isolation techniques is recommended wherever feasible. The features of the detection system also play a major role in the detection, location, and classification of the submarine. The signal-to-noise ratio, the directivity of the listening array, the statistical nature of the signal, and the sophistication of the processing system must be considered in the overall evaluation of the acoustical effectiveness of a propulsion system. Pertinent aspects of the particular propulsion systems relating to these factors are discussed.

Since the submarine's ability to hear may be as important as its ability to avoid detection, self-noise and radiated noise considerations are stressed equally in this comparison. Figure 1 is a qualitative graph

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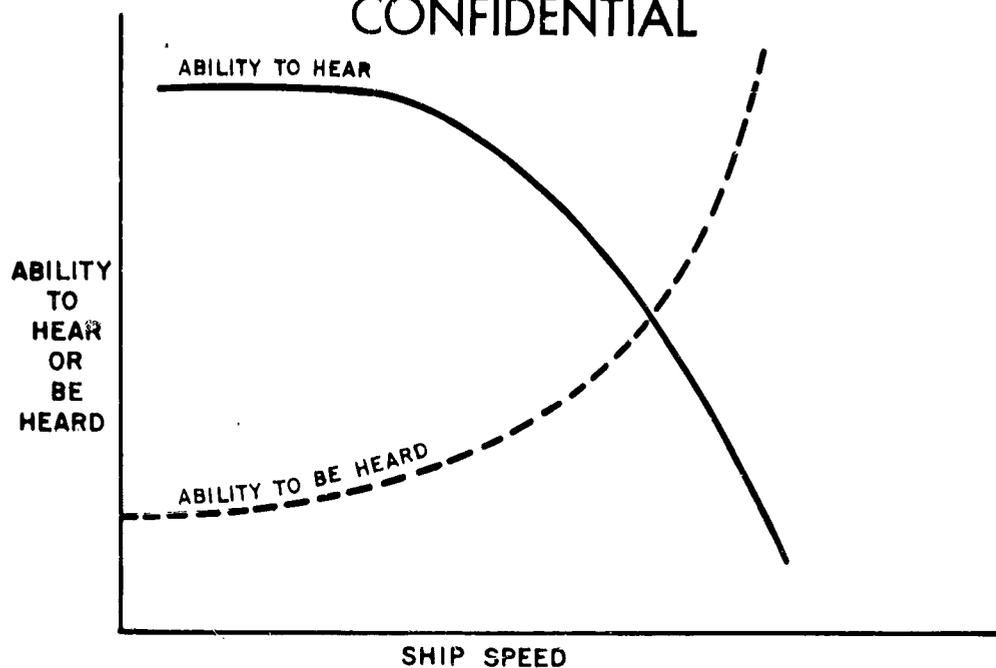


Figure 1 Ability to Hear and Be Heard vs Ship Speed

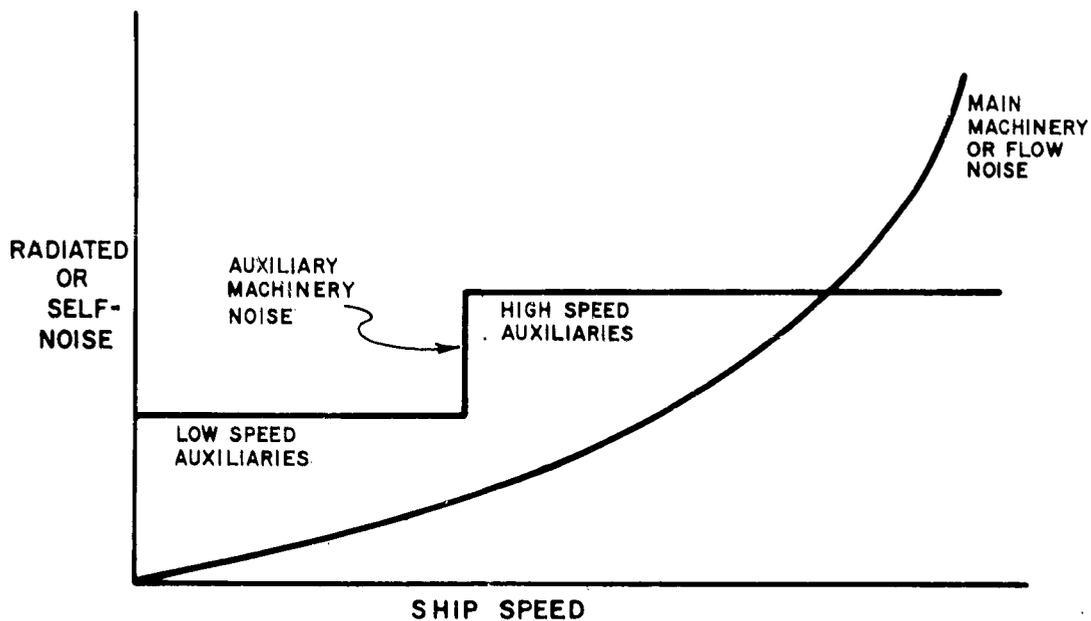


Figure 2 Auxiliary Machinery, Main Machinery, and Flow Noise vs Ship Speed

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MECHANICAL	FLUID DYNAMIC	ELECTROMECHANICAL
eccentricity non-roundness oil film impact in bearings thinning oil film instability gear tooth, and web resonances*	Steady steam flow Interaction of steam with turbine blades Flow excited resonances of cavities Boiling and condensation in associated equipment	None
eccentricity gear teeth bearings and between gear teeth resonances*	"Pumping" of lubricant as teeth mesh	None
shaft eccentricity oil film impact in bearings resonances*	Cooling air flow through rotor slots and end fans	Forces induced in structure by time and space varying magnetic fields, accentuated by non-uniformity and eccentricity of rotor and stator structure Magnetostrictive forces in magnetic core due to fluctuating magnetic fields Housing resonances*
as listed above regarding direct coupling of vibrations to the water excitation of torsional and beam hull (pod configuration only)	Fluctuating hydrodynamic pressures generated by non-uniform rotor structure and surface finish Pumping action of water around rotor due to thrust modulation Cavity resonances*	Mechanisms listed above
oil film thrust bearing friction, impact, oil film phenomenon vibrations of blades and shaft*	Blade rotation radiation (Gutin noise) Interaction of blade pressure field with hull and appendages Thrust modulation due to non-uniform wake profile Cavitation Vortex shedding Blade rate enhancement and higher frequencies due to multiple props	None
gaps of shroud, stator blades, and structure*	Interaction of blade pressure field with stator blades and shroud support wakes Cavity resonances*	None

2

TABLE 1 - Noise Generating Mechanisms of Propulsion System Components

of this phenomenon, and illustrates the importance of speed and power on the radiated and self-noise signature of the submarine. The two most important factors influencing self-noise are the auxiliary machinery noise at low speed and flow noise at medium to high speeds. This is qualitatively shown in Figure 2. This is a great simplification of the problem in that no mention of noise frequency is given, which must be considered for different detection and detecting type sonar systems. It does, however, illustrate one important point, namely, the large gains that can be made with improved auxiliary plant flexibility, i.e., a load following or power demand system.

In recent designs much attention has been given to sound isolation of main engines and turbogenerators since they were the principal machinery items detected in the radiated far field.

Figure 2 is illustrative of many of the present auxiliary systems that have been identified with self-noise problems, e.g., main and auxiliary circulating water, condensate, feed, and hydraulic pumps. At best, some of these systems have a 1/2 speed mode which lowers the horsepower to 1/8 and, consequently, the noise by a factor given by Ross<sup>10</sup> as  $13 \log \text{HP db}$ . Since horsepower is proportional to  $\text{rpm}^3$ , noise level =  $13 \log \text{rpm}^3 = 39 \log \text{rpm db}$ .

On numerous occasions General Dynamics/Electric Boat has demonstrated that lowering the speed of pumping systems lowers the radiated and/or self-noise due to those particular systems. This, in effect, lowers the auxiliary plant noise step function curve of Figure 2 and "matches" it to the main plant or flow noise curve. This design philosophy is one of the reasons why the SS(N)597 has such comparatively outstanding self-noise characteristics, i.e., low horsepower and auxiliary power plant flexibility. With the advent of variable speed AC devices, this concept is being applied to FBM submarines.<sup>11</sup>

The above comments relative to the auxiliary plant noise are included as a reminder that main engine and TG acoustical design alone is not sufficient for a quiet ship. The auxiliary plant must be included, as is stressed in Reference 12 .

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At the high end of the speed curves, again other factors may be contributing in a major way to the radiated noise spectrum. For example, recently Dyer<sup>13</sup> has shown that flow-induced vibrations at high speeds may be responsible for a significant portion of the radiated noise spectrum. Above the cavitation depth, spikes at propeller blade rate and harmonics are enhanced by bubble vibrations, and have been shown by Alexandrov<sup>14</sup> to generate noise levels proportional to nearly the fifth power of propeller rpm. The acoustic differences between propulsion systems with similar characteristics may thus become second order effects under certain operational conditions. Therefore, just as the auxiliary systems must be considered in low speed operations, hydrodynamic effects must be evaluated in the higher speed modes for both self- and radiated noise.

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Conclusions

## II CONCLUSIONS

It is important, first, to recognize that while this survey covers main propulsion machinery, the auxiliary machinery exerts a substantial and often dominant influence on noise and other factors of interest. To fully exploit advances in main machinery, concurrent advances in auxiliary machinery are essential.

The geared drive turbine system, which serves as the reference system in this report, is the propulsion system in current use in nuclear-powered submarines. It is characterized by light weight and high overall efficiency, and in these respects it presents a formidable starting point from which to make further improvement. Further, the associated control surfaces and ballasting type hovering system provide satisfactory maneuvering and hovering under most operating conditions. There is, however, always room for improvement in acoustics, and also opportunity for improvement in submergence depth and clear access to the stern of the ship for tactical uses.

### FAVORABLE SYSTEMS

Several systems were found to have good potential for acoustic improvement, and some of these also offer improvement with respect to shaft seals and stern access. These are described below under two separate general approaches.

#### Retention of the Single Propeller, Shaft, and Seal

In this context the approach is a new turboelectric plant, featuring acyclic main machinery and a completely redesigned auxiliary plant. The acyclic electric system offers major gains acoustically, and if a satisfactory means for backing can be devised, the use of a pumpjet type propulsor would further enhance the system both acoustically and hydrodynamically.

The 300 rpm propeller speed selected for this study offers main machinery of almost equal weight to that of the 200 rpm geared drive turbine system, but at an excessive tradeoff in propulsive efficiency and cavitation-free depth. A somewhat lower speed would better balance the weight vs hydrodynamics tradeoff.

Alternately, the AC-DC electric system offers, as the next most attractive system, main machinery which is all non-developmental. Here the tradeoff with weight is not quite as good, but some of the difference may well be narrowed by using propulsion power to drive auxiliaries. Again, if a satisfactory means for backing can be devised, the use of a pumpjet type propulsor would further enhance the system both acoustically and hydrodynamically.

The acoustic value of DC electric drive, offered by the acyclic electric system over the full speed range and the AC-DC electric system over part of the speed range, has been well demonstrated by experience with the SS(N)597, TULLIBEE. The acyclic machinery also offers a potentially good impedance match with possible future energy sources such as thermionic converters, which are also characterized by low voltage and high current.

#### Departure from the Single Propeller, Shaft, and Seal

In this context the approach is completely different, consisting of a new turboelectric plant featuring different numbers and types of propellers, flooded propulsion motors, and a completely redesigned auxiliary plant. Two widely different sets of outboard machinery are of interest. The novel electric propulsion system has two large, slow speed, counter-rotating propellers, and offers favorable acoustic performance and outstanding hydrodynamic performance. The controllable pod motor system has four small, high speed, pumpjet type propulsors, and offers favorable acoustic performance and average hydrodynamic performance. (A means of backing with the pumpjets remains to be devised, but the alternative of using simple shrouded propellers is always available.)

Both of these systems, and particularly the novel electric propulsion system, have increased weight. However, in addition to weight, hydrodynamics, and acoustics, other factors enter into the overall tradeoff. These are the absence of a propeller shaft and seal, allowing essentially unlimited submergence depth in this respect, and the presence of a large access to the stern of the ship for sonar and armament.

#### PROGRAM FOR FURTHER INVESTIGATION

The foregoing selection of favorable systems is necessarily based upon what information is currently available and upon judgements of potential value. Study has now reached a point at which extensive attention to certain major areas is necessary to verify the conclusions. These are outlined below. The first three items apply to the inboard/outboard turboelectric systems only.

##### Propulsion Motor Environmental Protection

While small flooded motors have been built, the propulsion motors in this study are so much larger that size effect becomes important. This raises the question of whether very large masses of sealed electromagnetic structure can be manufactured without imperfection and operated successfully in sea water. While there is good confidence for success, this question can only be resolved by manufacturing and testing at substantially full scale. A full size stator formette of perhaps six feet circumferential length is an adequate subject for this purpose; it is not necessary to build the entire machine. This formette can also readily supply useful information on direct acoustic coupling of the motor to the surrounding water.

##### Propulsion Motor Bearings

While the propulsion motor bearing design is based on experience with water-lubricated bearings, here too size effect becomes important, raising the question of whether very large water-lubricated bearings

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## Conclusions

can be operated successfully in the submarine environment. Again, there is good confidence for success, but the question can only be resolved by testing. In this case a one-half scale thrust bearing is an adequate subject for testing.

### Propulsion Motor Windage Loss

This type of loss is of considerable importance, but cannot be predicted analytically with any reasonable accuracy. This loss can only be determined by model testing, after which methods can be developed for making reasonable predictions for other comparable machine configurations.

### Ship Design

In order to obtain a reliable assessment of the overall effects and many ramifications of incorporating one of these propulsion systems in a ship, a serious preliminary ship design effort is required. This is particularly true for the inboard/outboard systems, and allows optimizing the machinery and ship together for the desired operational characteristics, which has not previously been attempted.

### Acoustics

As a part of the ship design effort, more detailed acoustic study of the propulsion machinery itself and the combination of machinery and ship is necessary. An important part of this work for the inboard/outboard systems, which have propulsion motor windings and iron exposed to the sea, is testing to assess direct acoustic coupling to the surrounding water. It has not been possible to generate substantial information on this point, and whether or not it is troublesome can only be resolved by testing at substantially full scale. This can be conveniently done in conjunction with the environmental protection testing previously mentioned.

Also necessary in this effort is study of auxiliary machinery to obtain noise levels commensurate with those of the main machinery and to take advantage of power supplies available in the main propulsion machinery.

## III

## DETAILED DESCRIPTION OF SYSTEMS

This section describes each propulsion system with respect to its electrical, mechanical, hydrodynamic, and acoustic design, and comments on its favorable and unfavorable features.

For this study, an S5W steam supply is used throughout. A constant total propulsion turbine shaft power is assumed for all systems, and to make some of the earlier work directly usable this power is set at 15,300 turbine shp. The propeller shp varies, depending upon the machinery efficiency for each particular system.

The systems as described are generally not offered as optimized designs, but are believed to be within the bounds of reality for each type of machinery considered. Further, the extent of prior study and design of individual systems varies over a very wide range. Thus, in comparing systems only large differences can be regarded as significant.

When necessary to refer to a submarine, ships such as the SS(N)523 and the SSB(N)616 are utilized. However, to the extent practical, ship designs have been divorced from the study, not because this is a desirable approach, but rather because development of suitable ship designs would have required much greater time and funding than did the remainder of the study. Maximum ship speeds are based upon the SSB(N)616 EHP vs speed characteristic without change, except that where control surfaces are modified or removed this is accounted for. Reference ship control forces, both underway and hovering, are also those of the SSB(N)616.

Some of the data in this report differ from that in the previous reports prepared under this contract. This arises from either design improvement or reworking of the data to a consistent basis.

With respect to the electric propulsion systems, conventional motor terminology such as "air gap" and "windage loss" is used throughout, although in some cases the motors are in fact immersed in water.

GEARED DRIVE TURBINE SYSTEM

This system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by high speed turbines through a reduction gear. An artist's conception of the ship and machinery is shown in Figure 3. This system is typical of current practice.

Mechanical Design

Propulsion power is developed in two 6000 rpm turbines and delivered to a single propeller shaft at 200 rpm through a reduction gear. Propeller speed is controlled by varying the turbine speed. Backing is accomplished with turbine astern stages. Conventional fixed and movable control surfaces are fitted at the stern and on the sail, and the movable surfaces are actuated by hydraulic rams.

The propeller shaft has a flexible coupling at the inboard end, and is otherwise rigidly supported in journal bearings. Other appurtenances include a thrust bearing, clutch, hull penetration seal, and emergency propulsion motor. The latter is a 150 HP, slow speed DC motor integral with the shaft. It provides low speed creep or take-home propulsion, using power from the ship's DC electric plant.

Since the power train is completely mechanical, it is necessary that the entire set of machinery be installed to a single alignment. The use of flexible couplings at the reduction gear allows some relative movements of the components, but does not obviate accurate alignment. The propeller shaft is rigidly supported by bearings at several locations along the hull, including a relatively crude, rubber, water-lubricated journal bearing at the outboard end. The turbines and reduction gear are vibration isolated as a single unit.

The machinery requires a high order of precision in manufacture of large parts, and careful balancing of the high speed components. However, it possesses the basic simplicity of continuously rotating

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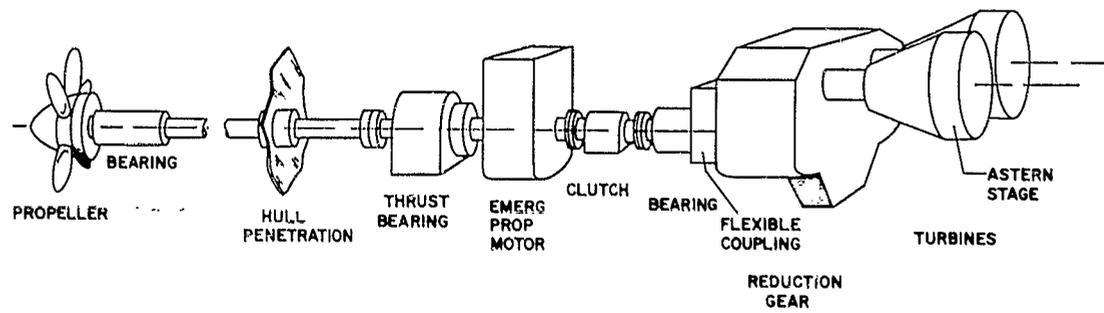
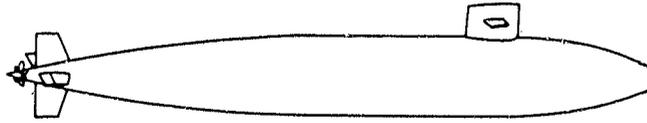


Figure 3 Geared Drive Turbine System, Ship and Propulsion Machinery

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machinery, and has been developed and applied extensively in both commercial and naval fields. It has ample reliability for the application, and the reliability is actually determined largely by the auxiliary systems. The system as shown has duplicated propulsion turbines, and it can also be built in a twin screw version, with gears, shafts, and propellers also duplicated, but at some sacrifice of propulsive efficiency.

Scheduled maintenance for the major components is very infrequent. The outboard propeller shaft bearing clearance is checked when the ship is drydocked, and replacement is made when the clearance becomes excessive. The time interval between replacements varies with operating conditions, but is on the order of one to three years. Otherwise, the only major scheduled maintenance is an inspection during ship overhauls. Most of the maintenance is confined to the auxiliary systems.

The machinery length and weight is shown by major components in Table 2. The lengths correspond to propulsion turbines side by side and other components in tandem.

TABLE 2 - Geared Drive Turbine System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship ft</u>	<u>Weight lb</u>
2 Propulsion turbines	8.5	49,000
1 Reduction gear	8.5	78,000
1 Emergency propulsion motor	5.0	42,000
1 Shaft and appurtenances	52.0	77,000
1 Propeller	<u>7.0</u>	<u>24,000</u>
Total	81.0	270,000

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Transmission losses in this system are small. The total loss from turbine shafts to propeller is 3%.

The single screw leaves the stern generally inaccessible for sonar or armament. The bow, however, is completely free of propulsion machinery.

Each watch section of the ship's engineering department consists of three supervisory personnel (Engineering Officer, Engineering Chief, and Machinery Watch Supervisor) and a twelve-man crew. Of the twelve crew members, three are located in the maneuvering room, operating control panels for the reactor plant, electric plant, and steam plant. Five others are stationed in the engine room, auxiliary machinery rooms, and reactor area. The remaining four are roving watches.

Hydrodynamic Design

This system is the conventional propulsion system used on all recent nuclear-powered submarines. The SS(B)N 616 submarine is used as a standard of comparison for all of the following propulsion systems. The propulsion characteristics of this system are shown in Table 3.

TABLE 3 - Geared Drive Turbine System,  
Propulsion Characteristics

Propeller Hub horsepower	14,900 hp
Effective horsepower (fully appended)	11,300 hp
Propeller speed	200 rpm
Propeller diameter	16 feet
Number of blades	7

These characteristics result in a maximum speed of 21.2 knots and a propulsive coefficient of 0.76. The propeller cavitation characteristics appear in Figure 4. The minimum cavitation-free depth of this submarine at full speed is approximately 670 ft.

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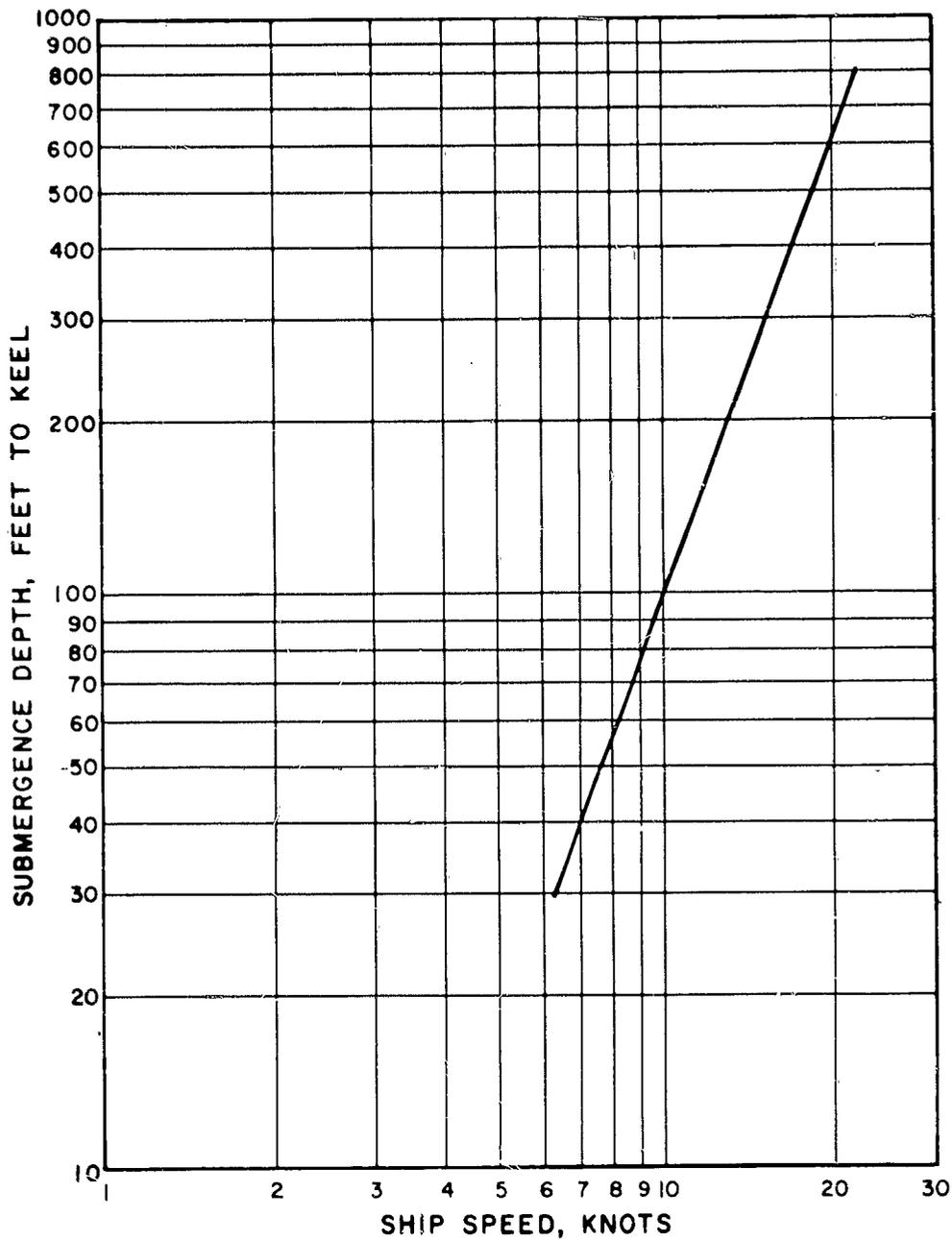


Figure 4 Geared Drive Turbine System, Depth vs Speed for Inception of Propeller Cavitation

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A summary power balance is shown in Table 4.

TABLE 4 - Geared Drive Turbine System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Gear and shaft losses	3
Propulsor losses	23
Effective horsepower	74
Overall propulsive efficiency, EHP/Turbine shp	74%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	76%

Acoustic Design

Conventional geared steam turbine with vibration isolated main turbines and reduction gear are considered.

The following comments are based on the noise characteristics of the SSB(N)608 class with which the builder, General Dynamics/Electric Boat, is most familiar and also on David Taylor Model Basin and United States Navy Engineering Experiment Station Laboratory noise reports on the SS(N)593, which was undergoing noise trials and further noise control measures until its loss.

Noise Contribution by Propulsion System Components

Steam Turbines - The 6000 rpm steam turbines produce discrete and broadband noise. Discrete noises are principally the fundamental (once-per-rev) and harmonics of the rotation noise due to rotor unbalance, eccentricity, and "egg-shaped" journals, and the interaction of steam with the turbine blades at frequencies of rpm x n/60, where n is the number of blades. Harmonics of these frequencies are

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Detailed Description  
Geared Drive Turbine

often found but are reduced in amplitude.<sup>15</sup> Broadband noise is caused by steam flow through pipes, valves, and nozzles. Both types of noise can be controlled to some extent by using vibration isolation devices at all attachment points.

Recent trials of two ships of the SSB(N)608 class revealed that isolation was not completely effective in reducing main turbine fundamental noise. Long range detection of turbine fundamental was made at speeds above 150 rpm. Other ships (including the SS(N)593) utilizing rubber-mounted main engines were not detected. Apparently, seemingly small differences in the bedplate-main turbine geometry, box girder, or type of flexible shaft coupling are the factors influencing the efficiency of transmission of this low frequency energy to the water. More understanding is needed in this area. Certainly, reduction of turbine rpm reduces the radiated noise, due to lower fundamental frequencies at less power which are less efficiently radiated. This was dramatically shown on SS(N)597 propulsion TG sets (non-isolated) <sup>16</sup> by the decrease in range detectable for 1100 rpm vs 2400 rpm conditions.

Unidentifiable low frequency sounds (<15 cps) have been detected from some of the recently constructed submarines. Also, low frequency, high amplitude vibration has been observed on the isolated main propulsion plants, and is believed to be due to the main shafting restraint which compromises the low frequency mounting effectiveness of the 6 cps sound isolation mounts.<sup>15</sup>

As a result of Lighthills' familiar "eighth power law", reduced steam velocity reduces the broadband noise associated with flow noise in steam passages. Using multiple machines increases the possibility of detection due to beats, but reduces the overall noise level since the machines operate with random phase. In general, the sum of the acoustic powers of several machines is less than the total acoustic power of one large machine. For aural detection, a range of 1 to 10 cps modulation frequency results in optimum detectability. Sinusoidal modulation

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is more difficult to detect than square wave or "on-off" modulation. The detectable modulation amplitude in the latter case is only 5 percent of the continuous broadband noise amplitude.<sup>17</sup> Electronic detection of modulated signals may be enhanced by using demodulation systems.

Secondary noise sources are bearing noise and steam cavity resonances, both of which produce discrete frequencies. These can also be expected to be less pronounced on slower turbines. Since main condensers are practically an integral part of the main turbine (although decoupled structurally from the main turbine exhaust trunk in this design by a rubber boot), they are rigidly fastened to the hull. Steam exhaust velocity in some designs has been found to be at sonic velocity, especially at low steaming rates. This is a potential high level noise source and can be avoided by appropriate exit velocity and condenser design.

Reduction Gear - Gears produce strong discrete frequency signals at relatively high frequencies (400 to 1 kc and higher). Impact noise between gear teeth, pumping of lubricants as teeth mesh, and shaft eccentricities contribute to the noise output. Spikes can therefore be expected at once-per-rev for each shaft, at the tooth-meshing frequency, and at higher harmonics. Although present isolation techniques have generally proved to be very effective, the absence of reduction gears is an important factor in favor of propulsion systems using either direct-coupled turbines or generators and motors.

Single Stern-mounted Fixed Pitch Propellers - Propellers contribute to self-noise and radiated noise in the following diverse ways:

Direct radiation due to rotating pressure field at the fundamental and harmonics of the blade rate frequency (Gutin radiation).<sup>18</sup>  
This is relatively unimportant.

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Detailed Description  
Geared Drive Turbine

Excitation of nearby hull plating, control surfaces, and sea chests through the fluctuating hydrodynamic pressures (near field), usually requiring coincidence of blade rate with a resonance in the secondary radiating element. This is generally remedied by local modifications after the phenomenon has been found to occur.

Thrust modulation of propeller and shaft due to non-uniform wake caused by stern planes, sail, and angle of attack of the hull. Radiation originates at the blades, the shaft, and especially at the hull due to excitation of longitudinal hull modes. Coincidence of resonances of blades, shaft, and the various hull modes with the blade rate enhance this source of radiated and self-noise. Spikes at blade rate and harmonics have been observed at long ranges. This is found to be an important consideration at medium and high speeds when comparing various propulsion systems which vary considerably as to blade rate frequency, particularly in the systems involving counter-rotating propellers.

Cavitation noise for a stern propeller includes a spike at blade rate as well as strong broadband noise. The intensity of this noise increases sharply with increasing hull speed, but decreases with increasing depth. This is very important, is dependent on screw design, and in general can be avoided by suitable ship operations.

Broadband noise occurring well below normal cavitation depth has been observed on the newer ships using seven-bladed propellers, especially SSB(N)608 class. It occurs at speeds greater than 10 knots and ranges from 400-1000 cps with considerable acoustic source strength. The noise is modulated at blade rate and to some degree at shaft rate. There is considerable circumstantial evidence that it is caused by the seven-bladed propeller.<sup>19</sup> It has been hypothesized that the cause is vortex shedding.<sup>20</sup> This has been found to be very important on certain ships.

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"Propeller singing" is produced by periodic vortex shedding. Singing noise is enhanced by torsional and flexural resonances of the propeller blades. Significant frequencies (blade resonances) generally lie above blade rate frequencies. When this occurs, it is very important.

Shaft Squeal is produced by shaft and bearing friction. When this occurs, it is very important.

A thorough discussion of propeller noise is contained in the original novel electric propulsion system study<sup>1</sup>, in which comparisons are given for single stern-mounted fixed propeller and the novel electric propulsion system configuration (discussed later).

#### Noise Contribution by Systems Other Than Propulsion

The auxiliary machinery of the S5W power plant and the machinery external to the power plant control the radiated and especially the self-noise at low speeds. Dominating the discrete low frequency spectra are the fundamental frequencies of the high horsepower pumps and motors. These devices, especially the sea-connected pumps, also produce broadband noise of high levels. The principal contributors of auxiliary system noise are:

Main Sea Water Pump	RCFW Pump
Auxiliary Sea Water Pump	Main Coolant Pump
Condensate Pump	A/C Sea Water Pump
Chilled Water Pump	Hydraulic Plant
Feed Pump	Trim and Drain Pump
Lube Oil Pump	High Horsepower Fans

Some of these systems are by necessity connected directly to the pressure hull and bulkheads through sea chests, connections to condensers and heat exchangers, bulkhead and tank penetrations, and hydraulic rams. When located forward in the ship the flanking paths become quite serious, such as in the hydraulic plant to the sail plane rams.

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Rotational and vane frequencies are very effectively shorted to and through the hull or along the water path to sensitive sonar hydrophones. This has been the controlling noise parameter in the important signal-to-noise ratio term of the sonar equation of several of our most important sonars, and has rendered them virtually useless, viz., Puffs, Hindsight, and BQQ-3 Mid and Stern Array, and all phones of BQQ-3 at frequencies <60 cps.

Thus, neither the propeller, the main engines, nor the ship service turbogenerator, but auxiliaries represent the most pressing low speed sonar self-noise problem. These comments refer to all designs. A design similar to the S5W auxiliary plant is used in the three all-mechanical systems.

#### Influence of Overall System on Noise Level

Auxiliary machinery noise limits such a ship in its low speed ability to hear. Auxiliary noise also is the controlling factor in low speed radiated noise. Blade rate, high horsepower fast auxiliaries, flow noise and, to some degree, main engine all contribute to the radiated and self-noise spectrum at high speeds.

The inherent disadvantages of the all-mechanical, geared-turbine drive are large rotational forces of the turbines, high level noise at high frequencies from the gears, and a direct path via the "flexible" coupling of vibrations to the water along the propeller shaft. Isolation mounts are used for the turbine-gear combination even though a "leak" is created by the shaft.

The dynamic characteristics of the shafting, thrust bearing, and associated hydraulic isolation devices (e.g., shaft vibration reducer) play an important part in the noise generated by hull mode vibrations. The location of the thrust bearing closer to a nodal region of the low order accordion modes reduces the excitation of these modes. However,

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the entire problem of mode excitation and coupling requires more study. In general, the proximity of the propeller blade rate frequencies to the natural frequencies of the hull modes favors a thrust bearing location away from the stern. A second consideration in the thrust bearing location is that beam modes and asymmetric flexural modes are excited by the moment exerted on the hull by the typical thrust bearing foundation attached near the bottom of the hull. While many of the modes excited by a moment are poor radiators, the self-noise level due to the strong near fields of these modes may be quite high. To minimize moment excitation, symmetrical thrust bearing foundations are desirable. (The symmetrical thrust bearing foundation is an inherent design feature of the novel electric propulsion system motor discussed later.)

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## GEARED DRIVE TURBINE SYSTEM WITH REVERSIBLE PITCH PROPELLER

This system consists of a single, reversible pitch propeller located at the stern of the ship and driven by high speed turbines through a reduction gear. An artist's conception of the ship and machinery is shown in Figure 5.

Mechanical Design

The mechanical design is the same as that for the geared drive turbine system, except that the propulsion turbine astern stages are omitted and the propeller pitch is reversible.

The reversible pitch feature of the propeller is intended for backing only. The propeller blades are positioned to either full ahead or full astern pitch, and no attempt is made to position them at intermediate pitches. Thus, the simplest of operating mechanisms and control systems can be used.

The blades are all moved by a single hydraulic ram in the propeller hub. The ram is simply pressurized on one side and drained on the other. It is stopped mechanically at the end of its travel, and held in this position by the oil pressure. The interior of the hub is filled with oil maintained at sea pressure, so that the seals where the blades penetrate the hub operate at substantially zero differential pressure.

The machinery length and weight are shown by major components in Table 5. The lengths correspond to propulsion turbines side by side and other components in tandem.

The number of propeller blades (7) exceeds that of existing reversible or controllable pitch propellers. This does not indicate lack of practicality, however, but rather lack of applications. Development is straightforward.

The crew is substantially identical to that for the geared drive turbine system.

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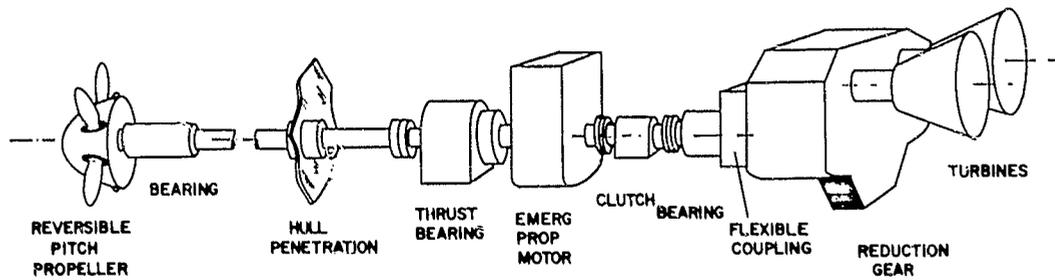
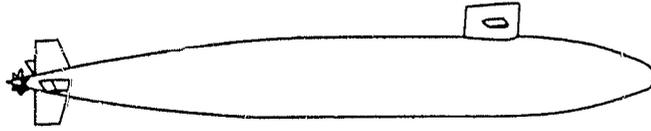


Figure 5 Geared Drive Turbine System with Reversible Pitch Propeller, Ship and Propulsion Machinery

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Detailed Description  
Geared Drive Turbine  
with R. P. Propeller

TABLE 5 - Geared Drive Turbine System with  
Reversible Pitch Propeller,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship ft</u>	<u>Weight lb</u>
2 Propulsion turbines	7.5	42,000
1 Reduction gear	8.5	78,000
1 Emergency propulsion motor	5.0	42,000
1 Shaft and appurtenances	52.0	77,000
1 Propeller	<u>13.0</u>	<u>58,000</u>
	86.0	297,000

Hydrodynamic Design

This propulsion scheme employs a conventional type propeller that has a two-position pitch changing capability. The purpose of the pitch changing is to offer an alternate means of backing and to provide better backing capability for the ship.

The performance of the propeller for both forward and backing motion was determined using open water test results from Reference 9, maximizing the propulsive efficiency for the given power and wheel speed, and adjusting the efficiency for the number of blades. The ship makes a maximum forward speed of 21.2 knots at a propulsive coefficient of 0.76. The propeller dimensions are shown in Table 6.

TABLE 6 - Geared Drive Turbine System  
with Reversible Pitch Propeller,  
Propeller Dimensions

Tip diameter	16 feet
Hub diameter	4.8 feet
Expanded area/Annulus area	0.87
Number of blades	7
Pitch/Diameter ratio (Forward motion)	0.87
Wheel speed	200 rpm

The ship equipped with this propeller is expected to make a maximum speed of 14.2 knots in backing motion at a propulsive coefficient of 0.26. The pitch/diameter ratio to obtain this backing performance is 0.60. This efficiency and speed are greater than those for the geared drive turbine system in a similar maneuver. This comparison is made from test data obtained from model tests of an FBM vessel with adjustments made in efficiency for the number of blades. The data was obtained simulating deep submergence runs, thereby precluding comment on cavitation.

Since the backing performance with a reversible pitch propeller is superior to that with a fixed pitch propeller, the time from ahead full speed to zero speed is shorter for the vessel equipped with the reversible pitch propeller. A summary power balance is shown in Table 7.

TABLE 7 - Geared Drive Turbine System with Reversible Pitch Propeller, Power Balance

<u>Forward Motion (Positive Pitch)</u>		
<u>Item</u>		<u>% of turbine Shp</u>
Turbine shaft power		100
Gear and shaft losses		3
Propulsor losses		23
Effective horsepower		74
Overall propulsive efficiency, EHP/Turbine shp	74%	
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	76%	
<u>Reverse Motion (Negative Pitch)</u>		
<u>Item</u>		<u>% of turbine Shp</u>
Turbine shaft power		100
Gear and shaft losses		3
Propulsor losses		72
Effective horsepower		25
Overall propulsive efficiency, EHP/Turbine shp	25%	
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	26%	

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22.

Reduction Gear - See geared drive turbine system, page 24.

Single Reversible Pitch Propeller - All of the noise sources described for the geared drive turbine system (page 24) apply. In addition, the necessarily large hub required to accommodate the pitch reversing devices may create a more turbulent wake and vortex shedding, resulting in increased flow noise. The broadband noise previously described may also be accentuated.

Influence of Overall System on Noise Level

The previous discussion for the geared drive turbine system (page 27) applies here. In addition, the higher mass of the reversible pitch propeller will alter the resonant frequencies of the longitudinal and transverse modes of the shaft system. The vibrational amplitude of certain modes can be expected to increase unless the additional kinetic energy is compensated for by larger propeller damping. Adding mass to a single degree of freedom system raises its Q and lowers its natural frequency. Additional damping reduces the Q, resulting in a higher driving point impedance. Compared to a propeller made from a single casting, the reversible propeller is made up of numerous connected parts and also contains a number of hydraulic devices. Friction and viscous losses therefore result in a larger amount of damping of the shaft vibrations.

PUMPJET SYSTEM

This system consists of a single pumpjet, located at the stern of the ship and driven by high speed turbines through a reduction gear. An artist's conception of the ship and machinery is shown in Figure 6.

Mechanical Design

The mechanical design is the same as for the geared drive turbine system, except that the open screw propeller is replaced by a pump consisting of a fixed shroud, a single row of stator blades, and a single row of rotor blades. The rotor or propeller speed is the same, 200 rpm.

A cross sectional view of the shroud and propeller is shown in Figure 7. The shroud is supported from the hull, forward of the propeller, and the stator blades are supported from the shroud aft of the propeller. Very rigid construction of the shroud is necessary to avoid deflections which would close the small clearance at the propeller blade tips.

The machinery length and weight are shown by major components in Table 8. The lengths correspond to propulsion turbines side by side, the propeller and shroud concentric, and other components in tandem.

TABLE 8 - Pumpjet System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship ft</u>	<u>Weight lb</u>
2 Propulsion turbines	8.5	49,000
1 Reduction gear	8.5	78,000
1 Emergency propulsion motor	5.0	42,000
1 Shaft and appurtenances	52.0	77,000
1 Shroud, supports, and stator blades	17.5	71,000
1 Propeller	3.5	23,000
Total	85.0	340,000

Note: Total length is less than sum of parts due to overlap

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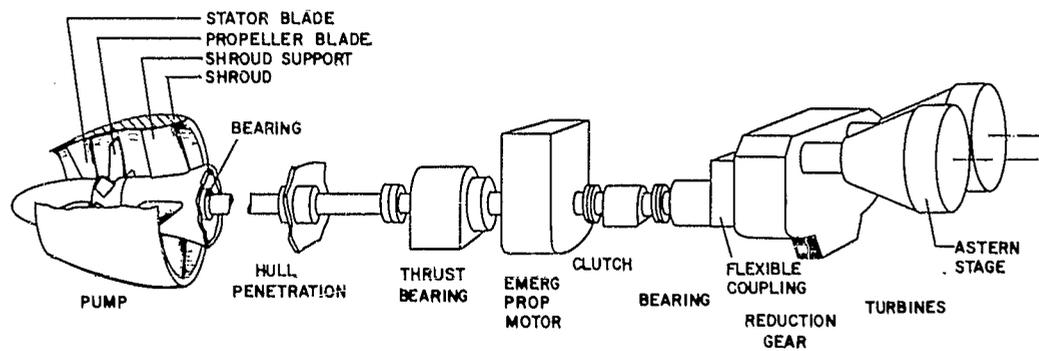
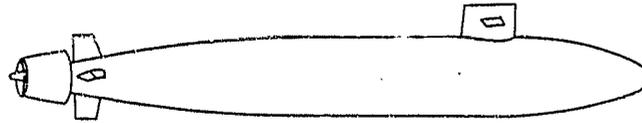
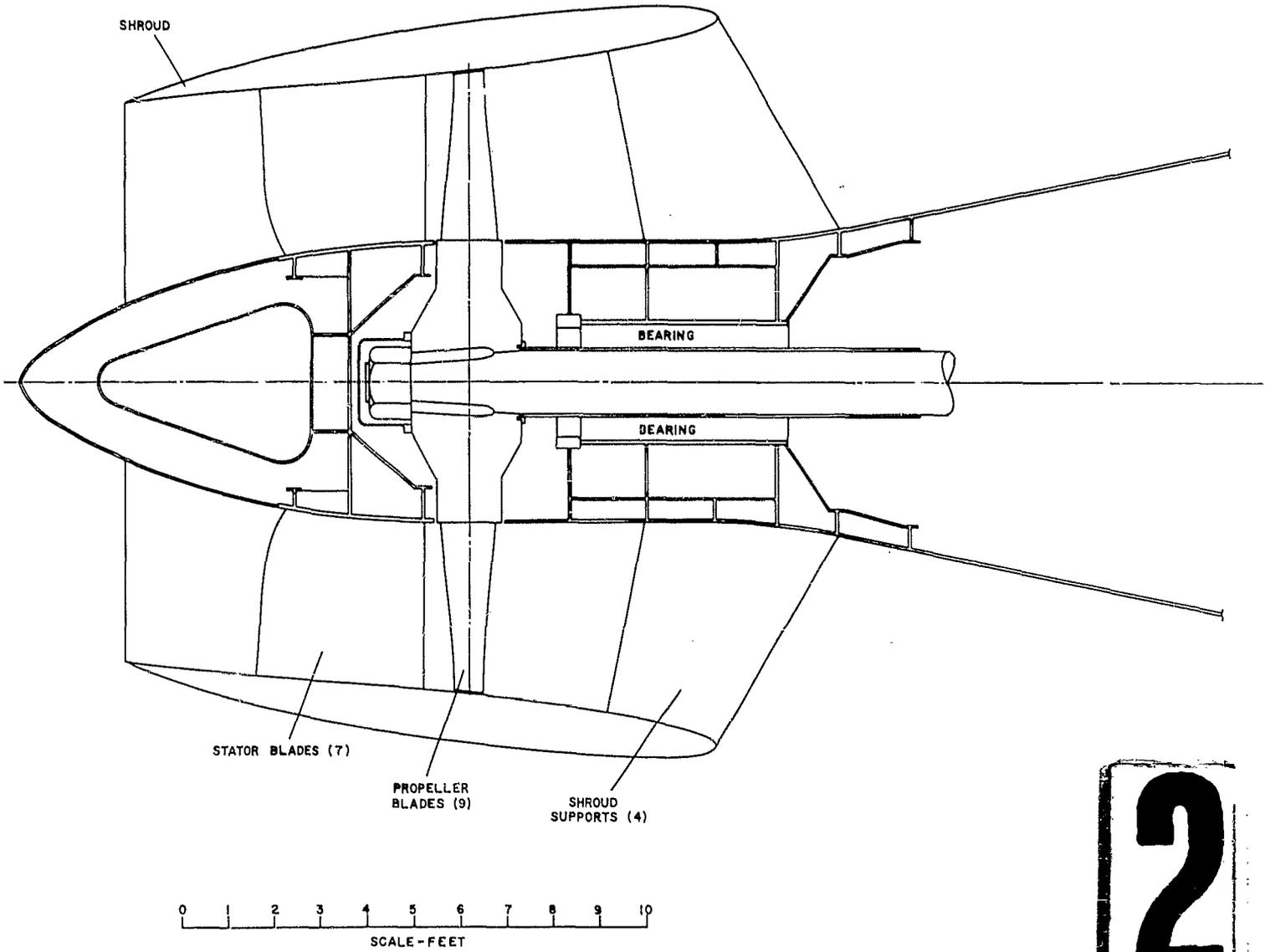


Figure 6 Pumpjet System, Ship and Propulsion Machinery

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Figure 7 Pumpjet System, Shroud and Propellers

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As with the geared drive turbine system, the single propeller leaves the stern generally inaccessible for sonar or armament. However, the shroud can offer some protection against fouling cables of towed devices. The bow is still completely free of propulsion machinery.

The crew is identical to that for the geared drive turbine system.

Hydrodynamic Design

This pumpjet propulsion system replaces the conventional propeller in the geared turbine drive system. No change in hull lines or shafting is considered and the design shaft speed of 200 rpm is unchanged.

A complete hydrodynamic design of a pumpjet propulsion system for a submarine of the SSB(N)616 class has been prepared under Bureau of Ships contract\* and is reported in Reference 6. The details of this design are shown in Table 9.

TABLE 9 - Pumpjet System,  
Pumpjet Details

Shroud length	12.8 ft.
Shroud maximum diameter	15.89 ft.
Rotor diameter	13.3 ft.
Hub diameter	5.98 ft.
Number of rotor blades (NACA 16 series)	9
Number of stator blades (NACA 16 series)	7
Shroud (NACA 0008-64 series)	-

The above design results in a computed propulsive efficiency of 0.87 and a speed of 21.9 knots. The minimum cavitation-free depth at maximum speed is estimated to be 100 ft.

Since the above design and analysis were done for the same hull form and control surfaces as the SSB(N)616, the only change in stability and

\*NObs 84879

**Detailed Description  
Pumpjet**

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control of the vessel is due to the additional damping in yaw and pitch offered by the shroud. The large damping of rotation about the transverse axes of the ship due to the shroud of the pumpjet increases the turning radius substantially.

The reverse thrust characteristics of this system are poor. From test results of similar pumpjet systems, the reverse thrust is approximately 10% of forward thrust. This is a troublesome defect for which no satisfactory solution has been found.

A summary power balance is shown in Table 10.

TABLE 10 - Pumpjet System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Gear and shaft losses	3
Propulsor losses	12
Effective horsepower	85
Overall propulsive efficiency, EHP/Turbine shp	85%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	87%

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbine - See geared drive turbine system, page 22.

Reduction Gear - See geared drive turbine system, page 24.

Single Pumpjet - The pumpjet characteristics which influence the noise level include:

A larger number of rotating blades

A shroud surrounding the propeller which provides uniform loading over the full length of the blades

Stator blades immediately aft of the propeller

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The higher number of blades compared to the conventional propeller increases the blade rate frequency and thereby the chance of excitation of higher ordered hull modes. On the other hand, reduced power levels in the range of the low ordered modes will reduce their vibration levels as evidenced by 5- and 7-bladed comparisons.<sup>15</sup> The Gutin noise radiation level is reduced by the larger number of blades. A slight increase in signal-to-noise ratio is expected due to higher blade rate frequency relative to lower ocean ambient. The shroud appears to have an opposing effect as based on experience with shrouded propellers (viz., USS WITEK). The shroud also appears to greatly reduce the radiation of cavitation noise due to shielding.

It is expected that the interaction between the closely spaced rotor and stator blades will result in blade passing frequencies and, hence, strong thrust modulation, possibly at frequencies higher than propeller blade rate. This question can be studied using an approach analogous to the one used by Brosens to show that the principal frequency component of thrust modulation for counter-rotating propellers is the sum of the blade rates of the two propellers.<sup>22</sup>

The noise radiated by the hull modes due to thrust modulation is as described for the geared drive turbine system (page 25). Resonances of the shroud, its supporting structure, and the shroud cavity near the blade rate must be calculated before construction and avoided by proper design.

#### Influence of Overall System on Noise Level

Except for the differences attributable to the pumpjet propeller, the discussion presented for the geared drive turbine system (page 27) applies also to this system.

## AC-DC ELECTRIC SYSTEM

This system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by a combination of AC and DC machinery. An artist's conception of the ship and machinery is shown in Figure 8.

Electrical Design

A one-line diagram of the system is shown in Figure 9. For high power operation, propulsion power is developed in a single 3600 rpm AC turbine generator set, and is delivered to a 300 rpm motor which turns the single propeller shaft. Propeller speed is controlled by varying the turbine speed. Backing is accomplished by electrical switching. For low power operation, propulsion power is developed in two 3600 rpm DC generators driven by the ship service turbines, and is delivered to two 138 rpm motors which also turn the single propeller shaft. Propeller speed is controlled by field control of the generators, and backing is also accomplished in this way. During high power operation, one DC generator provides excitation power for the AC machinery.

The system is ordinarily used as a DC plant, with its attendant more favorable acoustic and operational characteristics. However, high power AC plant operation is available when the tactical situation demands. Maximum ship speed with the DC system is 45% of full speed.

A somewhat more detailed diagram of the system is shown in Figure 10. The DC propulsion system involves a series loop connecting the DC propulsion generators and the double armature DC motor. Set-up switches enable using any combination of generators and motors. For emergency operation, the propulsion motor is directly connected to the ship's battery.

The DC generator fields are energized from the ship's DC bus, through rheostats which enable the operator to exercise manual control of the generator fields. Adjustment of the rheostats permits variation of the generated voltage through the range 0 to 600 volts: Since this voltage is applied across a propulsion motor armature, speed variation

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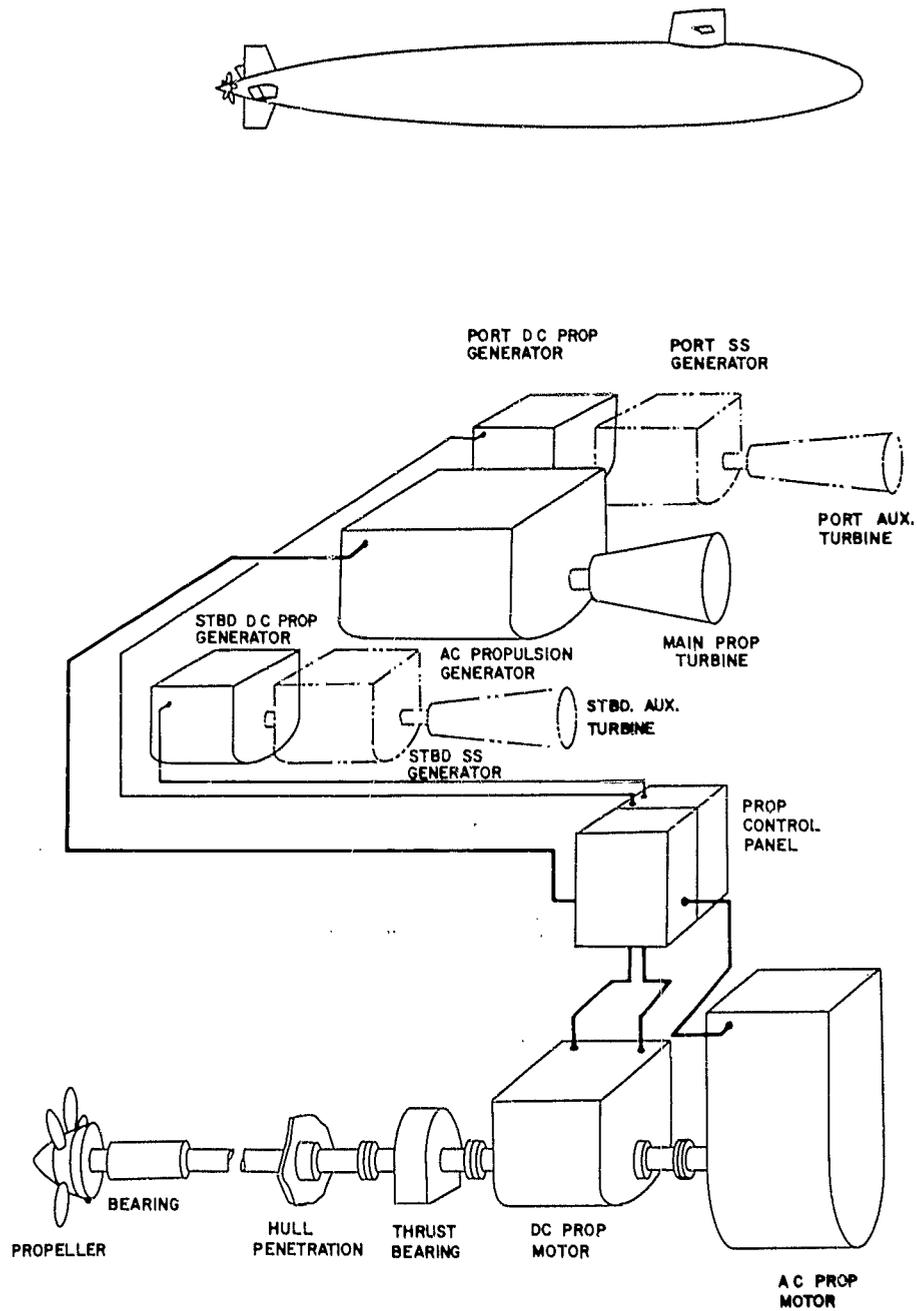


Figure 8 AC-DC Electric System, Ship and Propulsion Machinery

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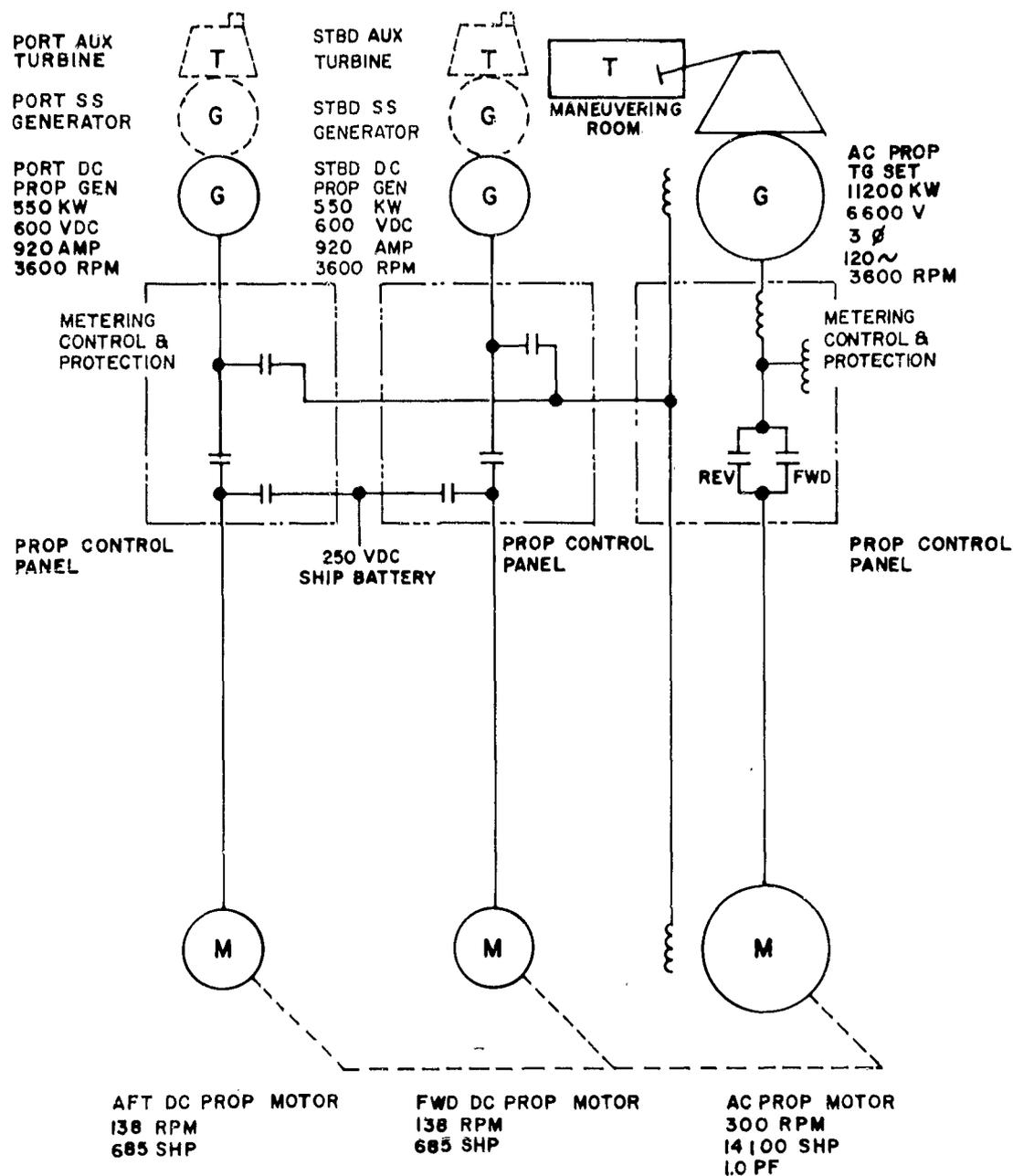


Figure 9 AC-DC Electric System, Electric Power One-Line Diagram

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is thereby obtained. Reversing is obtained by reversal of the generator fields. The motor fields normally are maintained at a constant value except when in the emergency propulsion mode.

The ship service electric load for low propulsion power levels is sufficiently low so that no increase in rating of the ship service turbines is necessary to drive the DC propulsion generators.

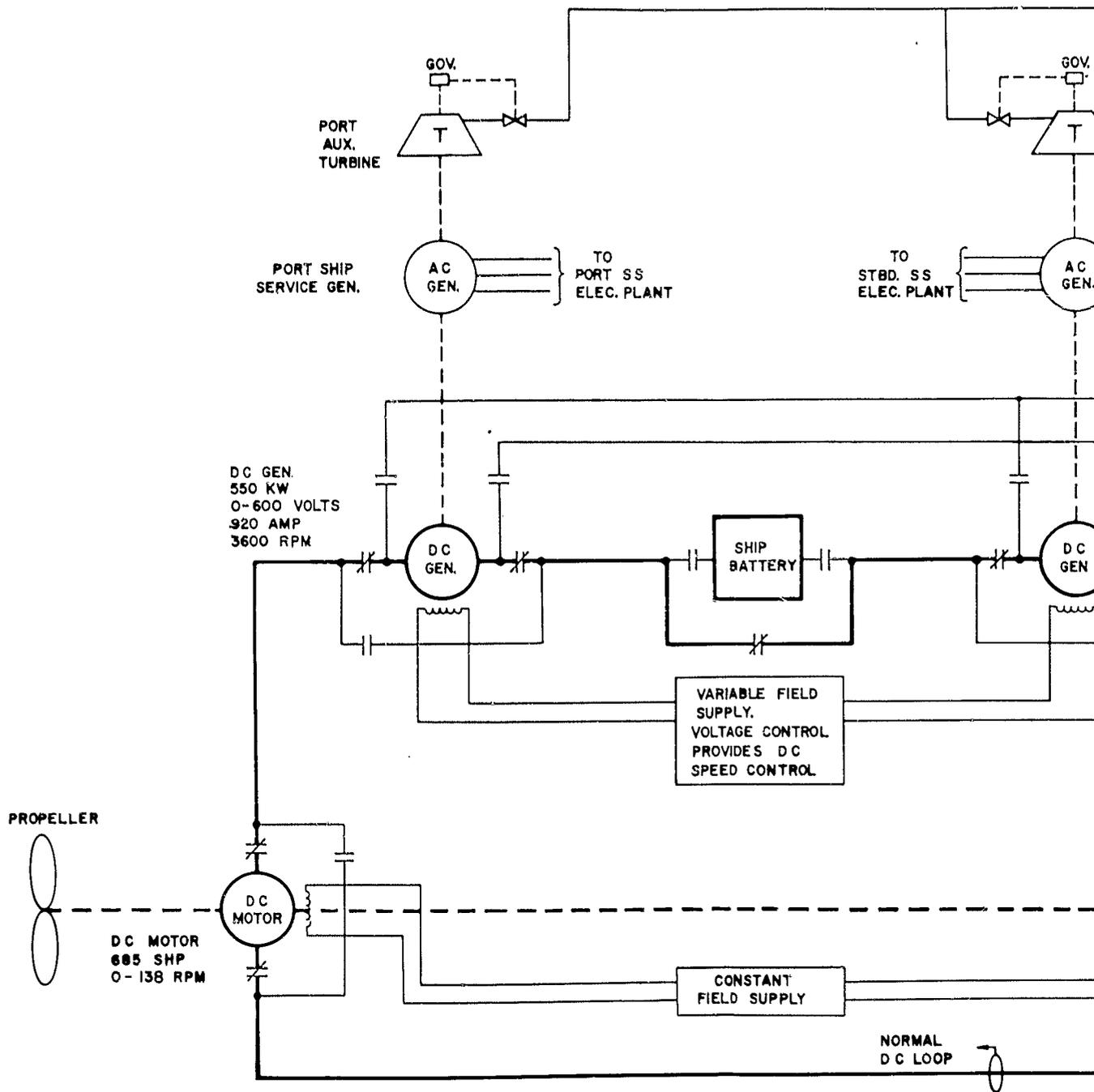
The AC propulsion system includes one three-phase AC synchronous motor directly connected to one three-phase AC synchronous generator which is driven by the main turbine. Speed control of the AC motor is accomplished by frequency control in the range 36 to 120 cycles, which is in turn controlled by adjustment of the main turbine steam throttle. A reversing capability is provided by no-load switching. DC excitation power for both of the main AC machines is normally furnished by one of the DC propulsion generators, which, having been sized for propulsion, is more than ample for excitation requirements.

The unusual combination of 3600 rpm and 120 cycles is not of major consequence to the main propulsion machinery itself, but it does offer a convenient means to effect some quieting of auxiliary machinery. Selected auxiliaries, if designed for 120 cycles at full speed and energized from the propulsion generator, would run at a speed proportional to the propeller speed, rather than at constant full speed with a consequent reduction in noise. Below some minimum propeller speed or plant power, these auxiliaries would be energized from the 60-cycle ship service system and run at half-speed. Such a scheme is used effectively in the Coast Guard Cutter OWASCO, although not for noise reduction reasons but rather to minimize the size of the ship service electric plant.

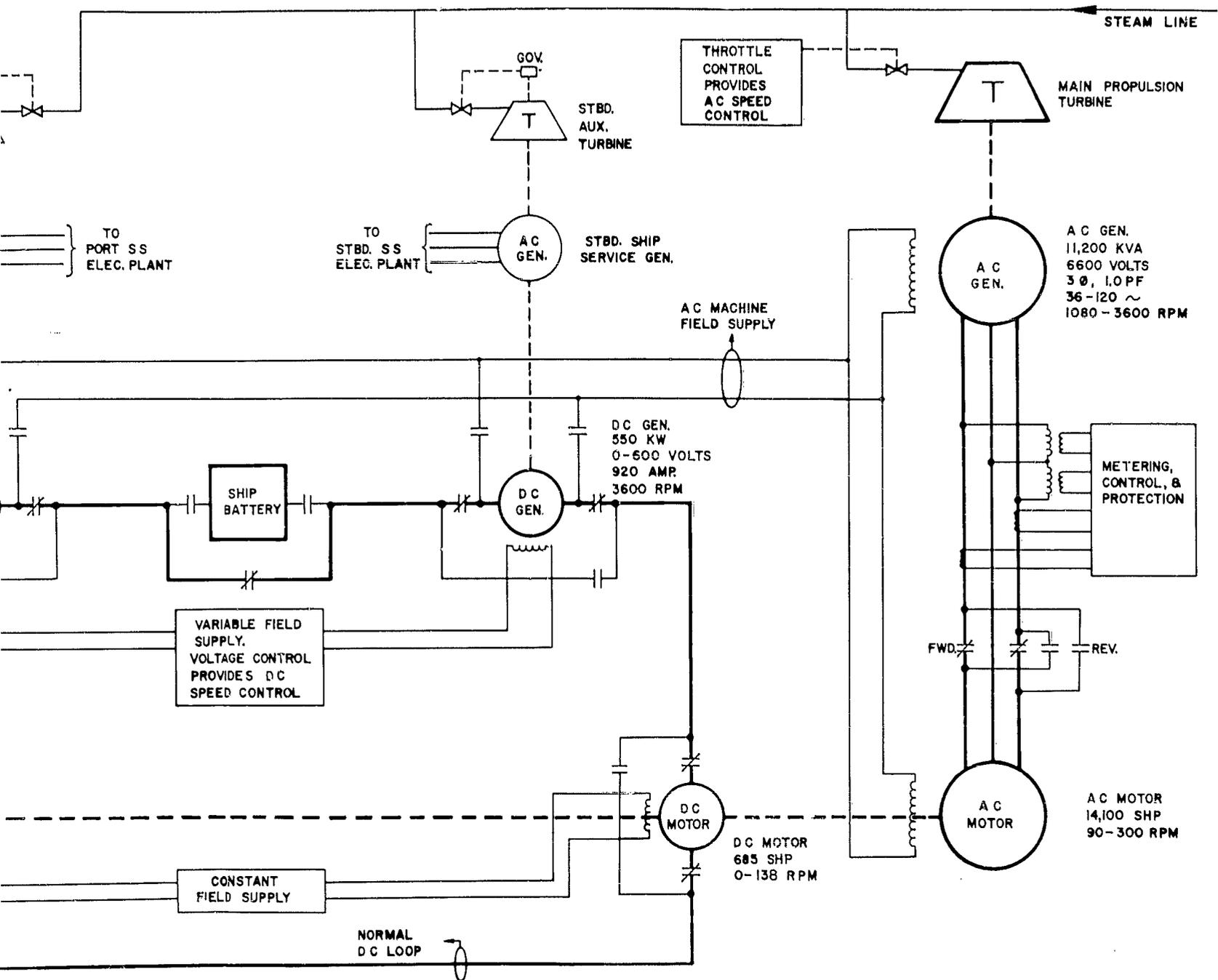
#### Mechanical Design

Conventional fixed and movable control surfaces are fitted at the stern and on the sail, and the movable surfaces are actuated by

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Figure 10 AC-DC Electric System, Electric Power and Control Diagram

hydraulic rams. The propeller and shaft are similar to those for the geared drive turbine system. The DC propulsion motors, which are physically in one enclosure in double armature configuration, are substantially larger than the emergency propulsion motor in the geared drive turbine system. The inboard end of the shaft is driven by the AC motor.

All machinery required for this system is conventional hardware, and can be designed and built by the application of conventional engineering, design, and production procedures. No prototype machinery is required.

Maintenance is confined principally to the auxiliary systems. Scheduled maintenance for the major components consists primarily of inspection and replacement of brushes in the electrical machines. The stern tube bearing maintenance is the same as for the geared drive turbine system.

The introduction of electrical machinery leads to some reduction in reliability, although it need not necessarily be large. Reliability is enhanced by the multiplicity of machines, and is still determined largely by the auxiliary systems.

The machinery length and weight are shown by major components in Table 11. The lengths correspond to the main propulsion and ship service turbine generator sets all side by side, propulsion control panels side by side, and other components in tandem. (In a preliminary study, this system was satisfactorily arranged within an SS(N)593 hull.)

The motors and shafting must be installed to a single alignment. The turbine generator sets, however, are installed independently and are vibration isolated.

A summary of losses is included later in the hydrodynamics discussion.

TABLE 11 - AC-DC Electric System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship, ft</u>	<u>Weight, lb</u>
1 Main propulsion TG set	29.5	112,000
2 DC generators	(5.5)	8,000
3 Propulsion control panels	3.0	15,000
1 AC propulsion motor	19.0	170,000
2 DC propulsion motors (in on enclosure)	11.0	45,000
1 Shaft and appurtenances	41.5	47,000
1 Propeller	<u>4.0</u>	<u>9,000</u>
Total	108.0	406,000

Although slightly smaller than the screw in the geared drive turbine system, the single screw still leaves the stern generally inaccessible for sonar or armament. The bow is still completely free of propulsion machinery.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

#### Hydrodynamic Design

This system employs a conventional, single, fixed pitch propeller designed to operate at 300 rpm and absorb 14,100 horsepower. The propeller was selected from the Troost charts by maximizing the propulsive efficiency for the given power and wheel speed. The ship is estimated to make 19.8 knots at a propulsive coefficient of 0.66. The efficiency and speed are less than those of the geared drive turbine system due to a higher propeller thrust coefficient.

It is estimated that a minimum depth of 900 ft. is required to prevent cavitation at full speed. This is attributable to the high propeller

tip speeds that evolve from the Troost charts when the propulsive efficiency is maximized. A reduction in the tip speed by decreasing the tip diameter would improve the minimum cavitation-free depth, but since the propeller is already highly loaded, a reduction in diameter does not seem feasible.

The propeller dimensions are shown in Table 12, and summary power balance is shown in Table 13.

TABLE 12 - AC-DC Electric System,  
Propeller Dimensions

Tip diameter	12.2 ft.
Hub diameter	2.0 ft.
Expanded area/Annulus area	0.60
Number of blades	7

TABLE 13 - AC-DC Electric System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
AC generator loss	2
AC motor loss	6
Shaft loss	0
Propulsor loss	31
Effective horsepower	61
Overall propulsive efficiency, EHP/Turbine shp	61%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	66%

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Acoustic Design

Noise Contribution by Propulsion System Components

Auxiliary Steam Turbines - See geared drive turbine system, page 22. Constant speed of 3600 rpm makes vibration isolation a straightforward and effective acoustic design measure. Since no external shafting or flexible coupling is required, there is no need for a compromise in mounting. Relatively light weight rotors in turbines and generators permit optimum balance.

Main Steam Turbine - See geared drive turbine system, page 22. The speed range of 1080 to 3600 rpm makes vibration isolation possible although of limited effectiveness at low speeds near 1000 rpm. Since the unit operates but momentarily below 1800 rpm, isolation is quite feasible and can be effective at full speed. The large turbine and generator rotor mass of 64,000 lbs and the high speed of 3600 rpm are important features in this design. Unbalance forces will be larger on this unit than any of the other designs, with one exception, the cycloidal propeller system. This is illustrated in Figure 39 (page 182) and described in Appendix B (page 181).

AC and DC Propulsion Generators - Noise sources are of mechanical, magnetic, and aerodynamic origin. Mechanical noise sources are similar to those described for the geared drive turbine system (page 22). Magnetic sources of noise are the fluctuating magnetic forces acting on the frame and magneto-strictive forces exciting the cores. The resulting frequencies include slot frequencies and the fundamental and harmonics of the generator frequency. In contrast to DC generators, AC generators produce higher noise levels at the harmonic frequencies. Abrupt current reversals result in magnetically induced forces having a broad frequency spectrum. Consequently, circumferential stator (lobar) mode resonance frequencies are kept as high as possible by making the stator frame very rigid. Recent designs include reduction of all abrupt changes in magnetic fields with the result of lower vibration levels. The generators are vibration isolated with their turbines.

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Aerodynamic sources of noise include end fans and rotor cooling slots. While the end fans produce broadband noise with a maximum level at the blade rate, the rotor noise occurs primarily at the cooling slot passing frequency. These aerodynamic sources generally contribute only to air-borne noise within the pressure hull, but can be serious if the reverberant levels in the compartments are in the 100+ db range.<sup>23</sup>

AC and DC Propulsion Motors - All electrical noise sources discussed previously apply also to the propulsion motors. The lower rpm will result in a lower level of both radiated and self-noise. Isolation mounts having a low natural frequency cannot be used since the rpm range of the motor corresponds to 0 to 5 cps. A distributed mount having a relatively high natural frequency (25 to 50 cps) can provide high frequency isolation which may be of limited value for reducing slot-passing frequencies and broadband noise. The mount frequency selected must be different from any exciting frequency.

Single Fixed Pitch Stern-Mounted Propeller - See geared drive turbine system, page 24.

Auxiliary Plant Noise - This plant uses a variety of AC and DC power sources, and a variety of auxiliary system configurations and flexibility can be incorporated in the design. For example, variable speed (high slip) AC motors and variable frequency devices deriving their source from the main AC turbine generator can be used. This comment also applies to the remainder of the power plants to be considered.

#### Influence of Overall System on Noise

This design, using strictly vibration isolated turboelectric units, has certain advantages over geared turbine and non-isolated type plants. At speeds below 45%, only the DC generators and motors are in use. This is an important silencing feature and is analgous to SS(N)597 PTG mode. Structureborne sound from the turbine is not transmitted to the

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propeller shaft, there being no direct mechanical coupling. Alignment with the propeller shaft is not necessary and therefore the turbine generators can be isolated very resiliently and at the optimum location. An abundance and a variety of electric power is available, which makes possible ingenious auxiliary system designs. The unbalance forces due to the heavy mass and high speed of the AC generator may compromise the design, unless isolation is very effective.

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## ACYCLIC ELECTRIC SYSTEM

This system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by acyclic machinery. An artist's conception of the ship and machinery is shown in Figure 11.

Electrical Design

A one-line diagram of the system is shown in Figure 12. Propulsion power is developed in two 3600 rpm DC turbine generator sets, and is delivered to two 300 rpm motors which turn the single propeller shaft. Propeller speed is controlled by field control of the generators, and backing is also accomplished in this way. The propulsion turbine generator sets run at constant speed, and also drive the-ship service generators, thereby eliminating separate ship service turbines.

The turbines in the turbine generator sets are standard hardware. The propulsion control panels are also standard hardware, and include excitation control, protective relaying, and metering. No switching is included, since backing is accomplished by field control, and the main power buswork does not enter these panels at all.

The propulsion generators and motors are of the acyclic type, also historically referred to as "unipolar" and "homopolar". While this is not a fundamentally new machine, it is not a common machine, and its principles of operation are therefore briefly discussed here.

Figure 13 illustrates the basic principles of construction and operation of the acyclic machine (polarity shown is for a generator). The rotor is machined from a solid steel forging. Surrounding the rotor are the cylindrical stator poles and frame. Magnetic flux, provided by two annular coils concentric with the shaft, enters the rotor uniformly through the main air gap at the center of the machine, passes axially under the collectors, and leaves the rotor through the flux-return gaps at both ends

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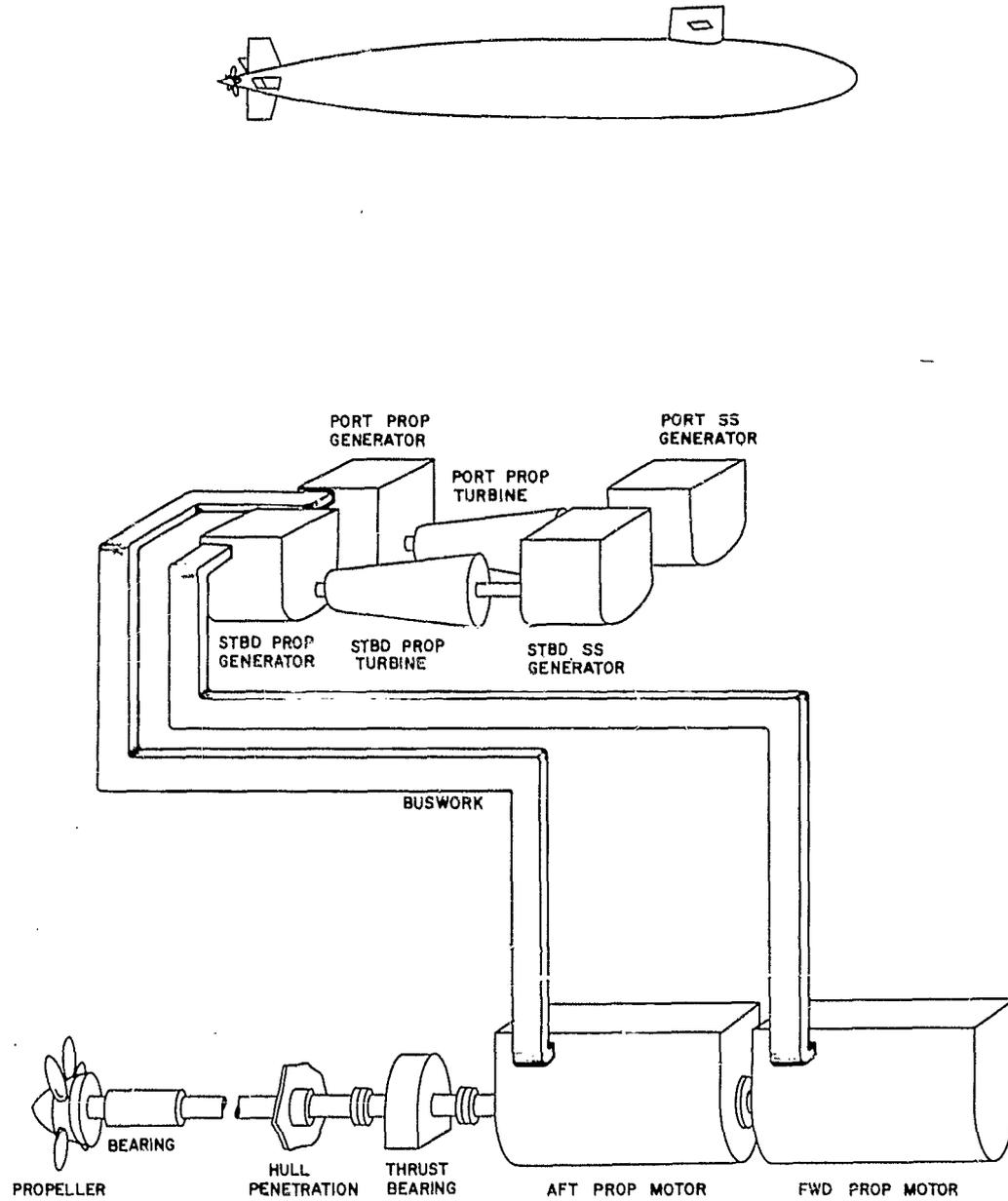


Figure 11 Acyclic Electric System, Ship and Propulsion Machinery

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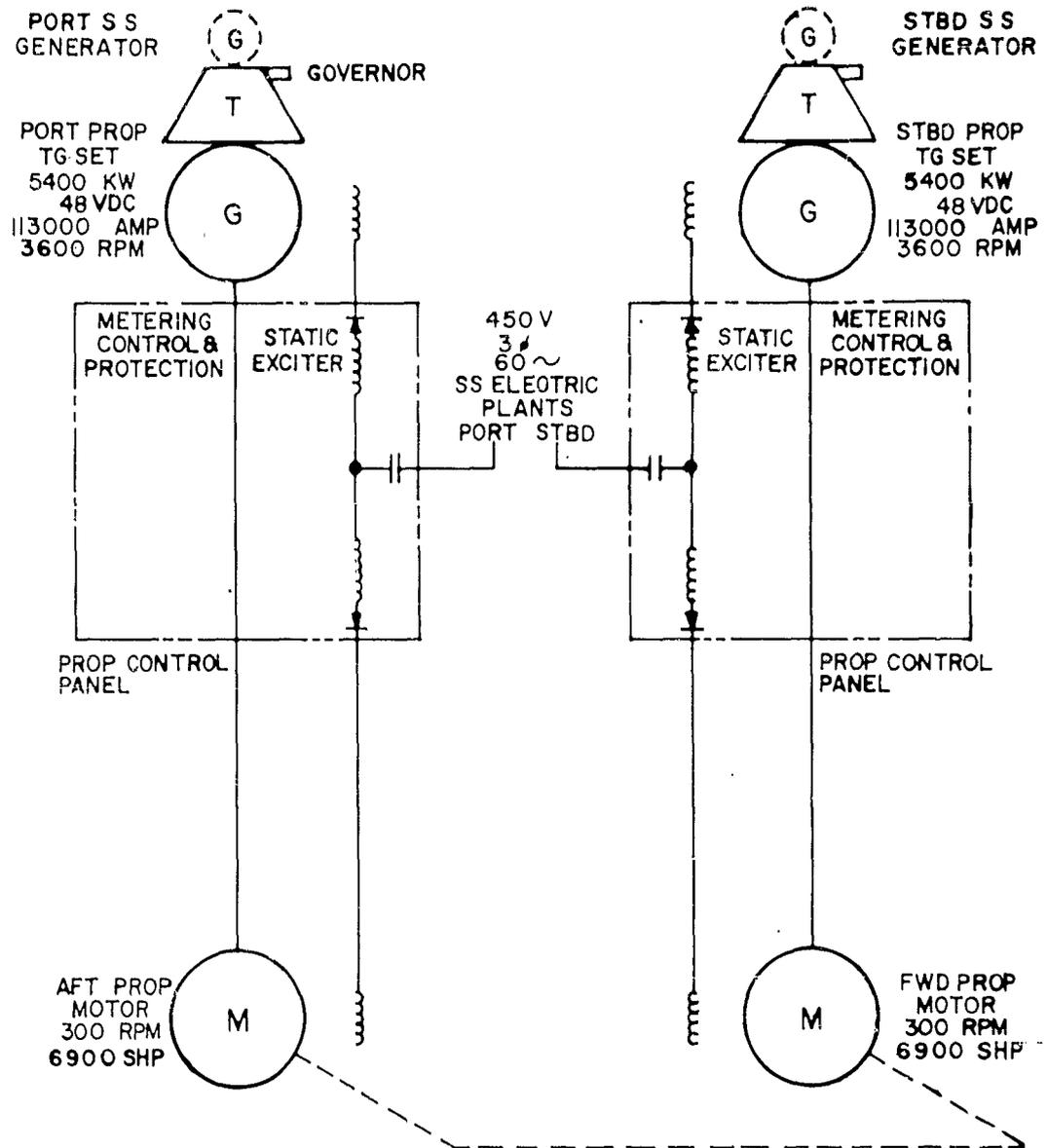
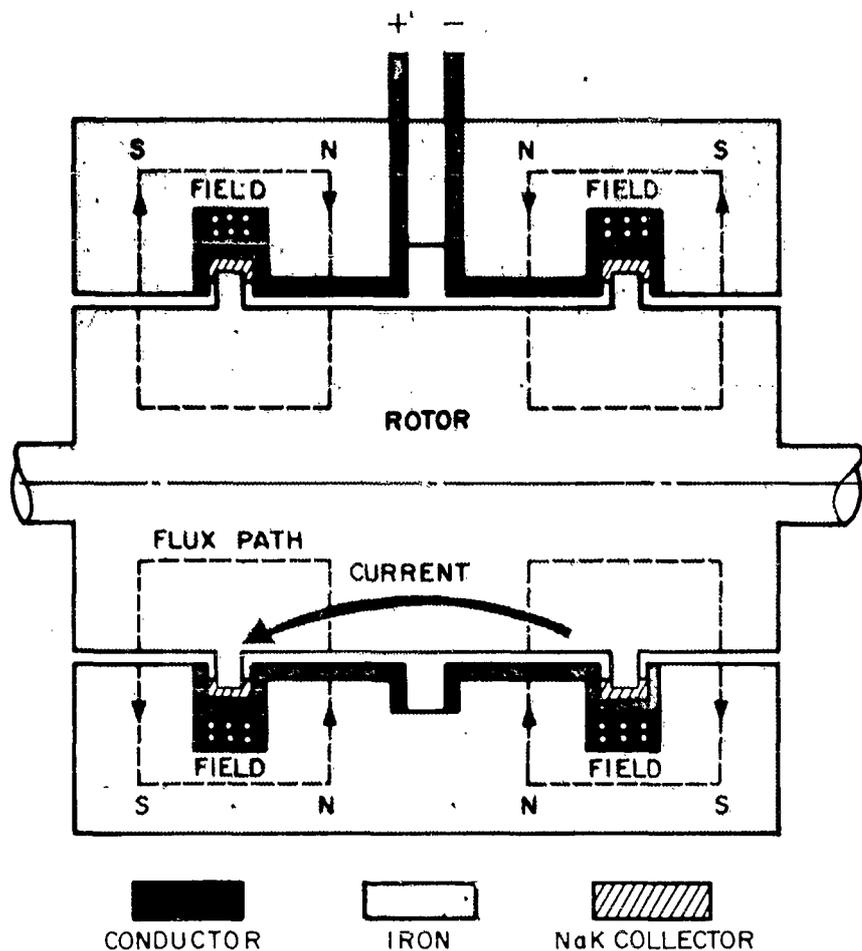


Figure 12 Acyclic Electric System, Electric Power One-line Diagram

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Courtesy of General Electric Co.

Figure 13 Acyclic Electric System, Acyclic Machine Schematic Diagram

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Detailed Description  
Acyclic Electric

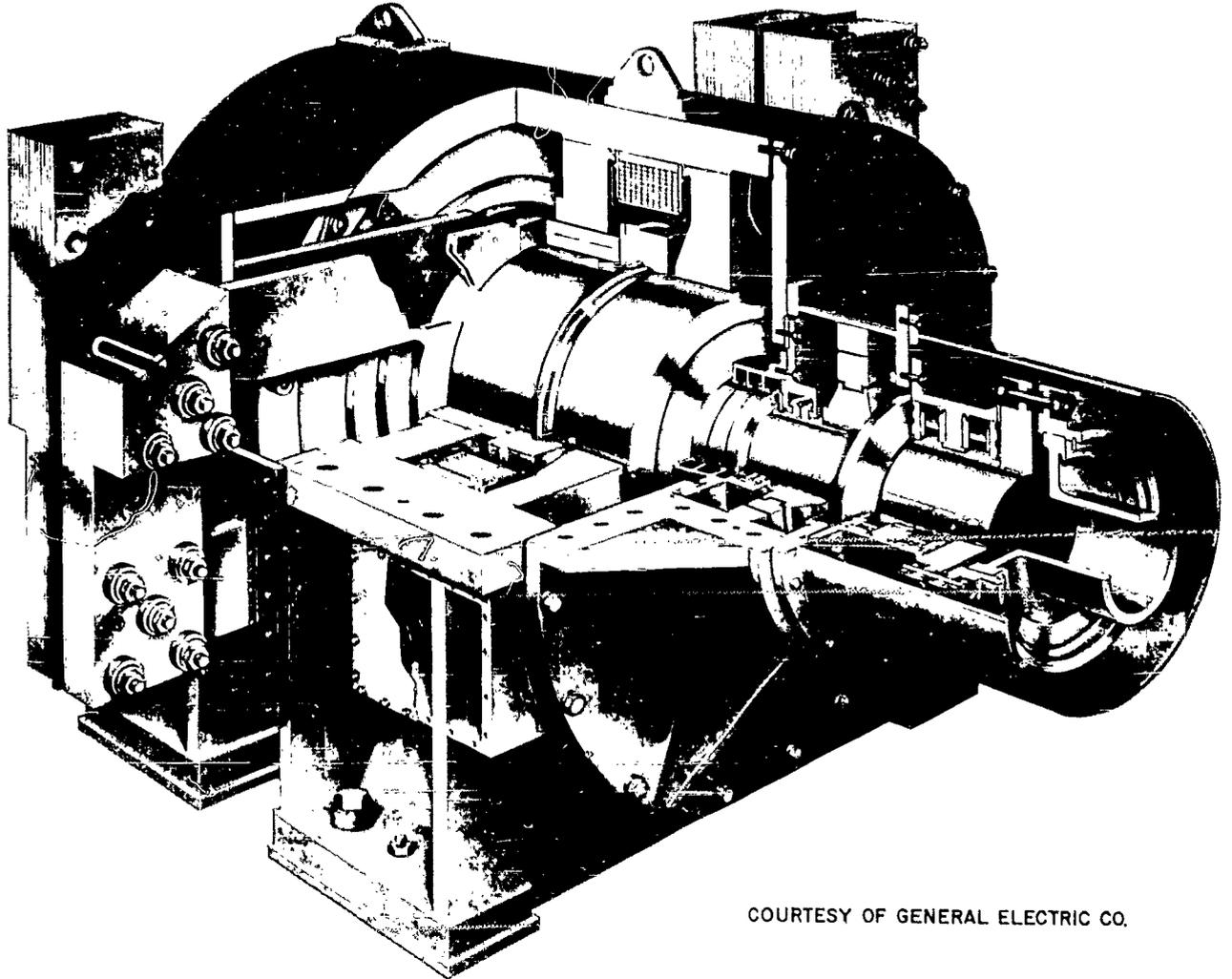
of the machine. Maximum DC voltage is generated between the two collectors. The voltage generated between each collector and the end of the rotor is of opposite polarity and of such magnitude that the two ends of the rotor are at the same potential.

The current is conducted in the stator, between the collectors and the terminals at the center of the machine, through cylindrical compensating windings which reduce the demagnetizing effect of the rotor current.

In addition to its magnetic function, the rotor iron also serves as a one-turn conductor. Having only one turn, the machine is characterized by very low voltage and very high current. Difficulty in collecting the very high current has severely limited the usefulness of this machine until the recent development of liquid metal collectors. This has made the machine practical, and it is now finding commercial application. Figure 14 shows a cutaway view of a complete machine. Note that the transverse cut is made at the center of the electromagnetic parts of the machine, and thus only half of the rotor length is shown.

This type of machine is not susceptible to the variation in parameters which can be accomplished with more common machines. The one-turn rotor precludes changing the ratio of voltage and current by changing turns and circuits. The maximum flux is limited by the cross section of the rotor at the collectors, since all flux must pass axially through this area. The peripheral velocity is limited by the collectors. The current is limited by the resistivity of the rotor and the ability to remove heat. The parameters are so constrained that once either voltage, current, or speed is specified, the optimum power output of the machine is uniquely determined. Other combinations of parameters necessitate using several machines or off-optimum designs. (Optimum as used here implies full utilization of

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Figure 14 Acyclic Electric System, Typical  
Acyclic Generator

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materials.) Nevertheless the results can be impressive. The propulsion generator in this system is rated 5.4 MW at 3600 rpm, yet it is only 4 feet long and 2.5 feet wide. It is smaller than the 2 MW ship service generator and of equal weight.

This machine is ordinarily used as a generator, with electric power as the end product, and electromechanical power transmission is ordinarily accomplished with the more common types of machines. Its consideration here for electromechanical power transmission arises from its favorable acoustic characteristics, filling a requirement largely peculiar to the submarine application.

As can be seen in Figure 12, each motor is directly and permanently bussed to its respective generator. All control is exercised by field control, with very modest amounts of power: rated motor field power is 6 kw, and rated generator field power is 5 kw. In operation, the motor field currents are held constant, and the generator field currents are varied, thereby providing speed control by armature voltage control. As might be expected from their construction, these machines exhibit very long field time constants, but with reasonable field forcing a one-second time constant is easily realized.

Since field control is used, the turbine generator sets can run at a constant speed, which serves to simplify and enhance the effectiveness of the resilient acoustic mounting. It also permits driving the ship service generators from the same turbines, thereby eliminating the ship service turbines.

The buswork connecting the generators and motors has two conductors. The copper cross sectional area is  $75 \text{ in}^2$ /conductor and the full power loss is 2 kw/ft/conductor. Each conductor is physically divided into several flat busbars, which are interleaved with those of the other conductor to minimize external magnetic fields. Since the voltage is so low, insulation between conductors is minimal and mechanical

support is simple. The bus enclosure, in addition to the normal functions of equipment and personnel protection, also serves to further suppress external magnetic fields and contains the machine coolant, which is also circulated through the buswork for heat removal. The buswork constitutes a substantial structural member, and a short section of it is made flexible so as to avoid shorting the turbine generator set resilient mountings.

Motor loss is 5%, and generator loss is also 5%. A summary of losses is included later in the hydrodynamics discussion.

Design of acyclic machinery as applied to a submarine is covered in more detail in Reference 28. Material for this report was furnished by the General Electric Company, and represents more recent numerical data.

#### Mechanical Design

Conventional fixed and movable control surfaces are fitted at the stern and on the sail, and the movable surfaces are actuated by hydraulic rams. The propeller and shaft are the same as those for the AC-DC electric system.

The machinery is a collection of conventional hardware, except that the electrical machines are new. As previously noted, the principal reason for interest in these machines is their acoustic potential. In steady state operation, the current, flux, and forces are all constant in both space and time, thus minimizing electromagnetic vibration. The rotor is a solid cylinder, always circular in cross section and machined all over, contributing to good mechanical balance. The machines are small and light (as electrical machines), but of particular value is the light weight of the rotating parts: 1800 lb for a generator rotor and 6500 lb for a motor rotor.

The acyclic machine is characterized by simplicity, both basically and practically. The principal departure is the liquid metal current collector, which uses an alloy of sodium and potassium (NaK). NaK is reactive with both air and water, and a nitrogen atmosphere is therefore maintained inside the machines. To further prevent the possibility of reaction, the machine is cooled and lubricated with tricresyl phosphate (TCP), which is nonreactive with NaK. The NaK is circulated through a heat exchanger where it is cooled by the TCP fluid. Thus, the machine requires three auxiliary systems:

- Lube oil and cooling system
- NaK circulating system
- Nitrogen atmosphere control system

Heat is ultimately rejected to the auxiliary sea water system, as with conventional lube oil systems.

While the NaK represents a hazardous material, extensive satisfactory experience with handling far greater quantities in a submarine is available from the original SS(N)575 power plant. A small number of large acyclic machines have been built and successfully operated. All of these machines have been applied as generators, and it was therefore possible to retain the NaK in the collectors with centrifugal forces. This is not practical for a motor application, and some means of containing the NaK at slow and zero speed is required. It has not been worked out simply because there was no application requiring it.

The machinery length and weight is shown by major components in Table 14. The lengths correspond to propulsion turbine generator sets side by side, propulsion control panels side by side, and other components in tandem. In addition, credit is shown for certain ship service electric plant equipment which is eliminated.

TABLE 14 - Acyclic Electric System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in Ship, ft</u>	<u>Weight, lb</u>
2 Propulsion turbine generator sets	15.5	112,000
2 Propulsion control panels	3.0	5,000
2 Propulsion motors	16.0	144,000
1 Shaft and appurtenances	41.5	47,000
1 Propeller	<u>4.0</u>	<u>9,000</u>
Total	80.0	317,000
2 Ship service turbines		36,000
Net Weight		281,000

Note: Propulsion turbine generator set data does not include ship service generators, but does include turbine capacity to drive these generators.

The motors and shafting must be installed to a single alignment. The turbine generator sets, however, are installed independently and are vibration isolated.

Maintenance is confined principally to the auxiliary systems. The liquid metal "brushes" of course do not wear. The stern tube bearing maintenance is the same as for the geared drive turbine system.

Although somewhat more complex than a reduction gear, the machinery is simple. As with the geared drive turbine system, reliability is determined largely by the auxiliary systems. Reliability is enhanced by duplicated portions of the machinery.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

Hydrodynamic Design

Hydrodynamic design for this system is identical to that for the AC-DC electric system (page 50). Due to slightly different machine efficiencies, the speed is about 0.1 knot lower.

A summary balance is shown in Table 15.

TABLE 15 - Acyclic Electric System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	5
Motor and bus loss	5
Shaft loss	0
Propulsor loss	31
Effective horsepower	59
Overall propulsive efficiency, EHP/Turbine shp	59%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	66%

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22. Constant speed of 3600 rpm makes vibration isolation a straightforward and effective acoustic design measure. Since no external shafting or flexible coupling is required, there is no need for a compromise in mounting. Relatively light weight rotors in turbines and generators permit optimum balance. The path of the heavy copper bus work from generator to motor constitutes a potential noise flanking path in this design that could short out some of the turbogenerator noise to the hull, therefore a flexible section in the bus is included.

DC Propulsion Generators - Acyclic generators are essentially free of any ripple content and therefore approach the battery in terms of noise characteristics. This is a very important quieting parameter. Conventional DC and especially AC generators have a ripple content in the wave form and strong current reversals which cause "square waves" in the current wave form, which in turn are connected to mechanical vibrations that are capable of exciting the normal modes of the machine frame at their natural frequencies.

Acyclic rotors are homogeneous structures and thus lower mechanical forces due to rotor eccentricity can be expected. Pole passing and slot noise are absent. Modern submarine motor and generator noise design has progressed to a high degree, and broadband and pulse-excited resonances have now become important "spikes" in motor and generator noise spectra. Acyclic machines minimize these sources of periodic force excitation common to presently used machinery.

Since these machines require liquid NaK and TCP fluid to be circulated for cooling purposes, and the design requires high peripheral velocity of rotor, some fluid system noise may be encountered.

The generators are vibration isolated with their turbines.

DC Propulsion Motors - The acyclic motors make a lower contribution to the noise level due to magnetic forces for the same reasons presented above for the generators.

The low speed range of the motor (0 to 5 cps) precludes the use of low frequency vibration mounts. High frequency mounts may be used as suggested for the AC-DC electric system (page 53).

Single Fixed Pitch Stern-mounted Propeller - See geared drive turbine system, page 24.

Influence of Overall System on Noise Level

The use of acyclic DC generators and motors is expected to have a decided advantage in terms of noise level. Dividing the load between two TG sets and two motors has the advantage of reduced vibration levels due to lack of phase coherence, but the disadvantage of potential beats between machines. The probability of detection of a signal having a regular beat is considerably higher than that of a steady signal, because of the lower recognition differential which characterizes the former. Since all systems, including to a degree the AC-DC electric system, utilize two or more prime movers, this argument applies to all systems. This particular system has the lowest fundamental unbalance force, due to the relatively small, light weight rotors (see Figure 39, page 182).

**NOVEL ELECTRIC PROPULSION SYSTEM**

This system consists of a pair of hull-sized, counter-rotating, fixed pitch propellers, located near the stern of the ship and driven by large, inside-out, free-flooding electric motors within the propeller hubs. An artist's conception of the ship and machinery is shown in Figure 15.

Electrical Design

A one-line diagram of the system is shown in Figure 16. Propulsion power is developed in two 1800 rpm AC turbine generator sets, and is delivered to two 50 rpm motors, each of which is integral with its propeller. Propeller speeds are controlled by varying the turbine speeds. Backing is accomplished with astern stages in the turbines. As can be seen in Figure 15, the motors are located outside the pressure hull, and operate free flooding.

The turbine generator sets are standard hardware, except that reversing stages are included. The propulsion control panels are also standard hardware, and include excitation control, protective relaying, metering, and disconnecting equipment. No switching is included since backing is accomplished by reversing the generator direction of rotation. In operation, the motors follow the turbine speeds nearly synchronously, except that during reversal there is a brief (but not troublesome) loss of generator/motor coupling as the generator goes through zero speed.

Hull penetrations for the cables to the motors consist of steel clad copper pins, glass sealed to a steel web, and potted on both outboard and inboard sides to exclude sea water and condensation, respectively. Six  $\emptyset$  penetrations are required for each motor. These are discussed more extensively in Reference 1.

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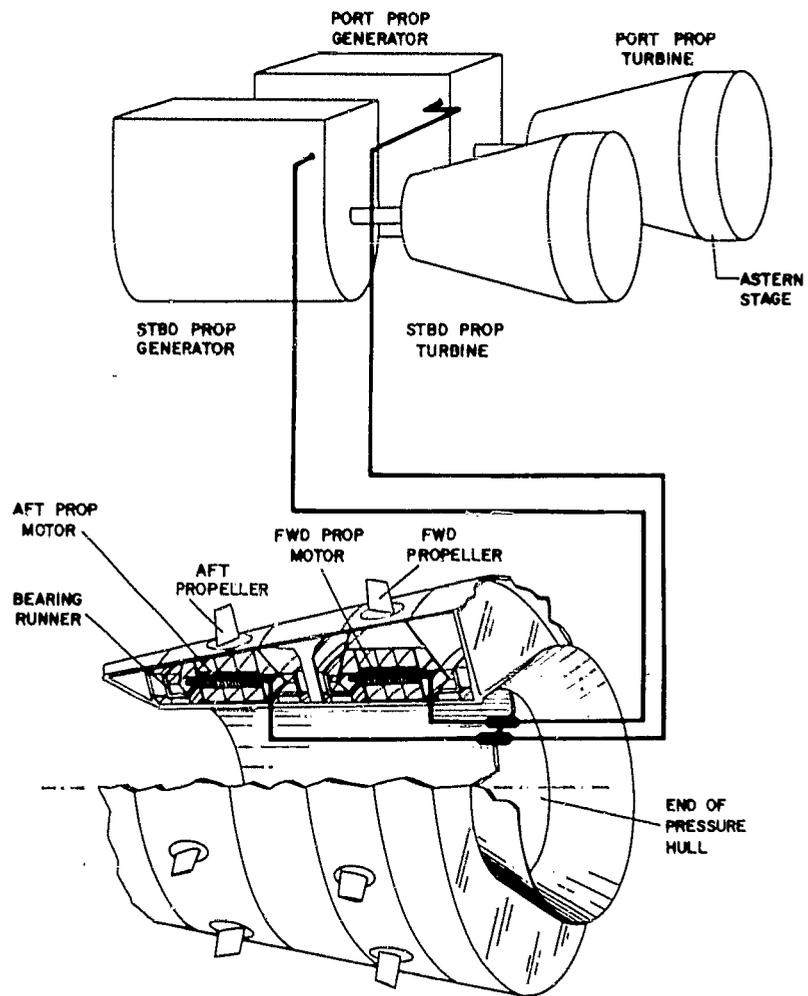
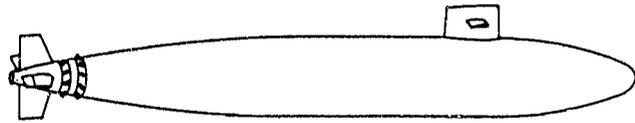


Figure 15 Novel Electric Propulsion System,  
Ship and Propulsion Machinery

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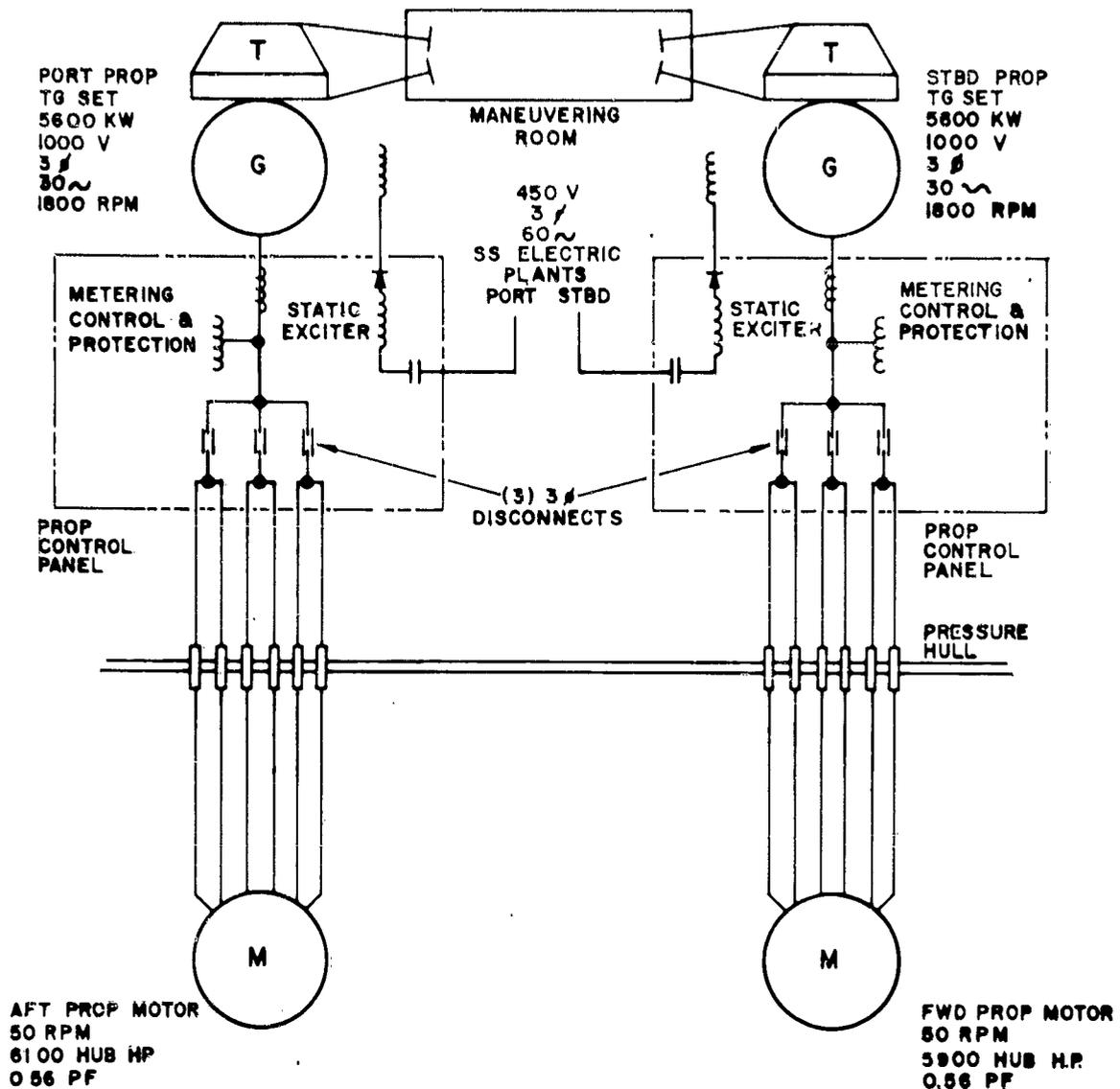


Figure 16 Novel Electric Propulsion System, Electric Power One-line Diagram

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A cutaway perspective view of the motors and propellers is shown in Figure 17, and a cross sectional view is shown in Figure 18. The motors are squirrel cage induction machines, with the rotor outside the stator and an integral part of the propeller hub. Since they operate free flooding, the iron is protected by interlamination and external epoxy coatings, and the stator windings are separately protected by polyethylene insulation. A canned design is impractical due to excessive eddy current loss in the stator can.

Each motor stator winding has six circuits, paralleled in its propulsion control panel. In the event of a casualty to one circuit, that circuit and the one diametrically opposite can be disconnected and operation of the motor continued at proportionately reduced power.

Motor electrical loss is 13%, and generator total loss is 2%. A summary of losses is included later in the hydrodynamics portion.

The electrical design of this system is covered in considerably more detail in Reference 1. Synchronous machinery which could also be used with this system and which would offer improved efficiency is described in Reference 3.

#### Mechanical Design

Conventional fixed and movable control surfaces are fitted at the stern and on the sail, and the movable surfaces are actuated by hydraulic rams. In this case, however, the stern surfaces are aft of the propellers, rather than forward.

The inboard machinery is a collection of conventional hardware, but the outboard machinery is of course new. The turbine generator sets are vibration isolated. The motors are foundationed on a 12-foot OD cylinder extended from the after end of the pressure hull. This cylinder is free flooding, and therefore dimensionally insensitive to

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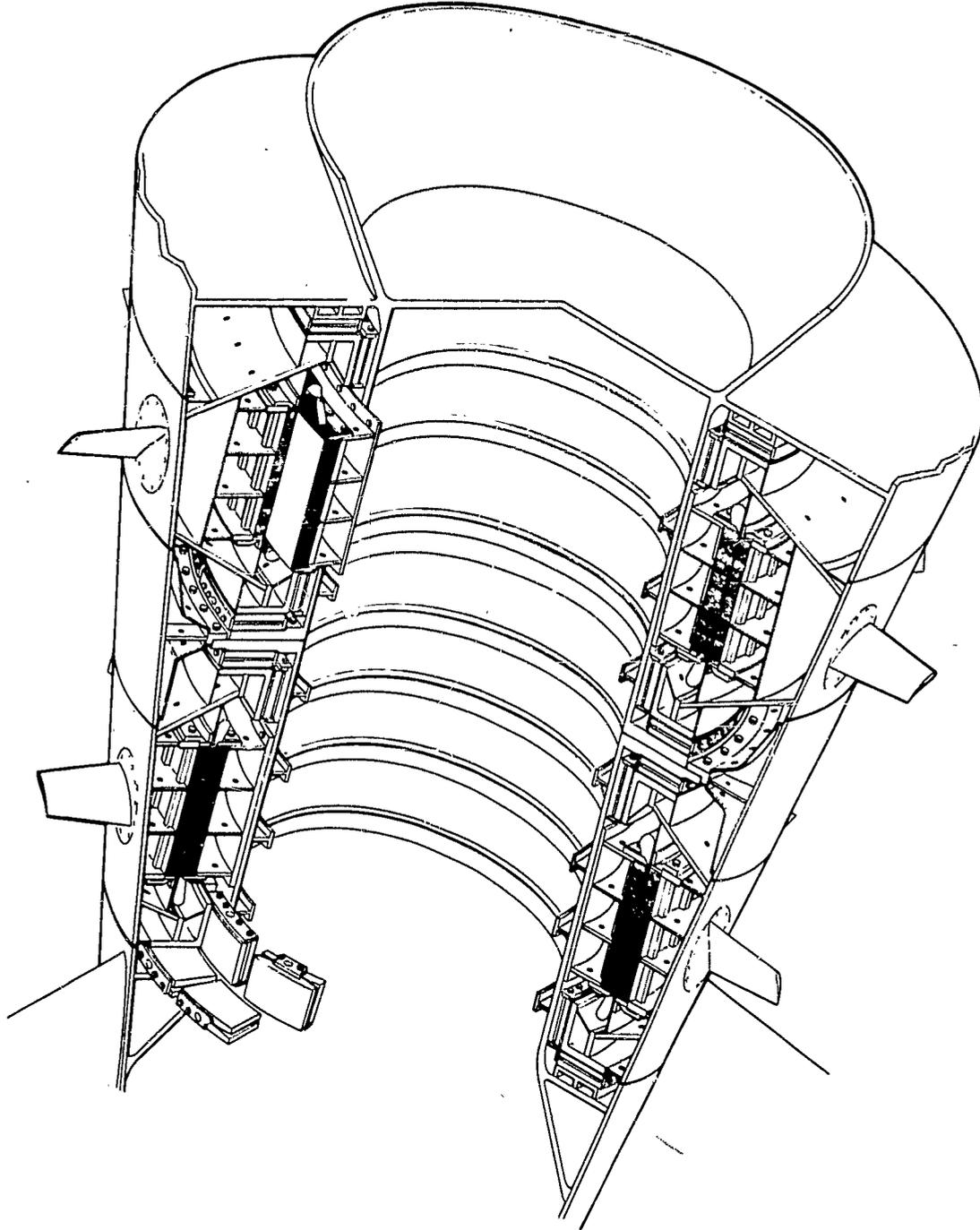


Figure 17 Novel Electric Propulsion System,  
Propulsion Motors and Propellers

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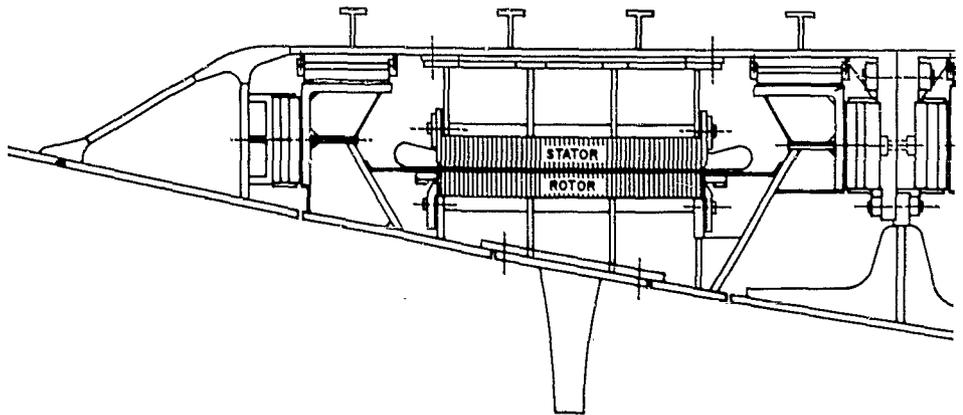
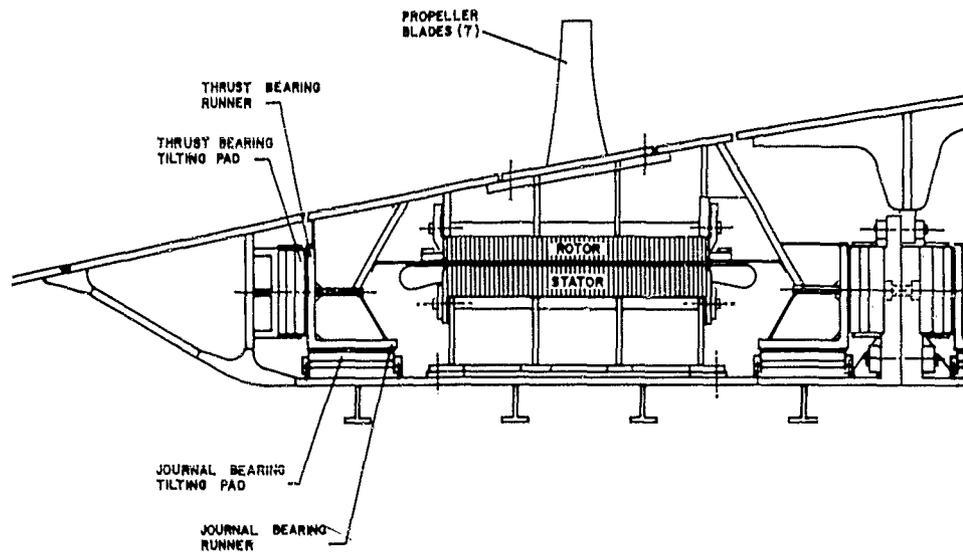
submergence pressure. It is machined on its outside diameter prior to welding to the hull. The stator, machined on its inside diameter, is furnished in three 120° segments, which are bolted to the cylinder.

The rotor is integral with the propeller hub, which also includes a thrust and journal bearing runner on each end. After installation of the stationary parts of the bearings, the two 180° rotor-hub segments are bolted together around the stator. The stationary parts of the bearings consist of tilting pads with graphite impregnated phenolic faces. The bearings run in sea water, and operate in the boundary lubricated regime, at a unit loading on the order of 30 psi based on projected area. The tilting feature of the pads promotes good alignment and reduced starting torque, but is not expected to provide hydrodynamic film lubrication, since surface irregularities and local asperities probably exceed the film thickness. However, if any film were to develop, this would of course be a desirable condition. Another approach to bearings is discussed in Appendix A, page 179.

The bearing pad wear is estimated to be on the order of 2 mils/month, and pad replacement is thus required annually. This constitutes the major scheduled maintenance for the system. Most of the remaining maintenance is confined to the auxiliary systems. As presently shown, it is necessary to remove the rotor-hub assemblies for bearing replacement, and this provides an incidental opportunity to generally inspect the motors.

The use of electric power and control equipment, as compared to straight mechanical power transmission, leads to some reduction in reliability. With a view towards the fact that what is absent cannot fail, the electric control hardware for reversing has been substantially eliminated by using standard astern stages in the turbine generator sets, and the shaft lube oil system is of course absent.

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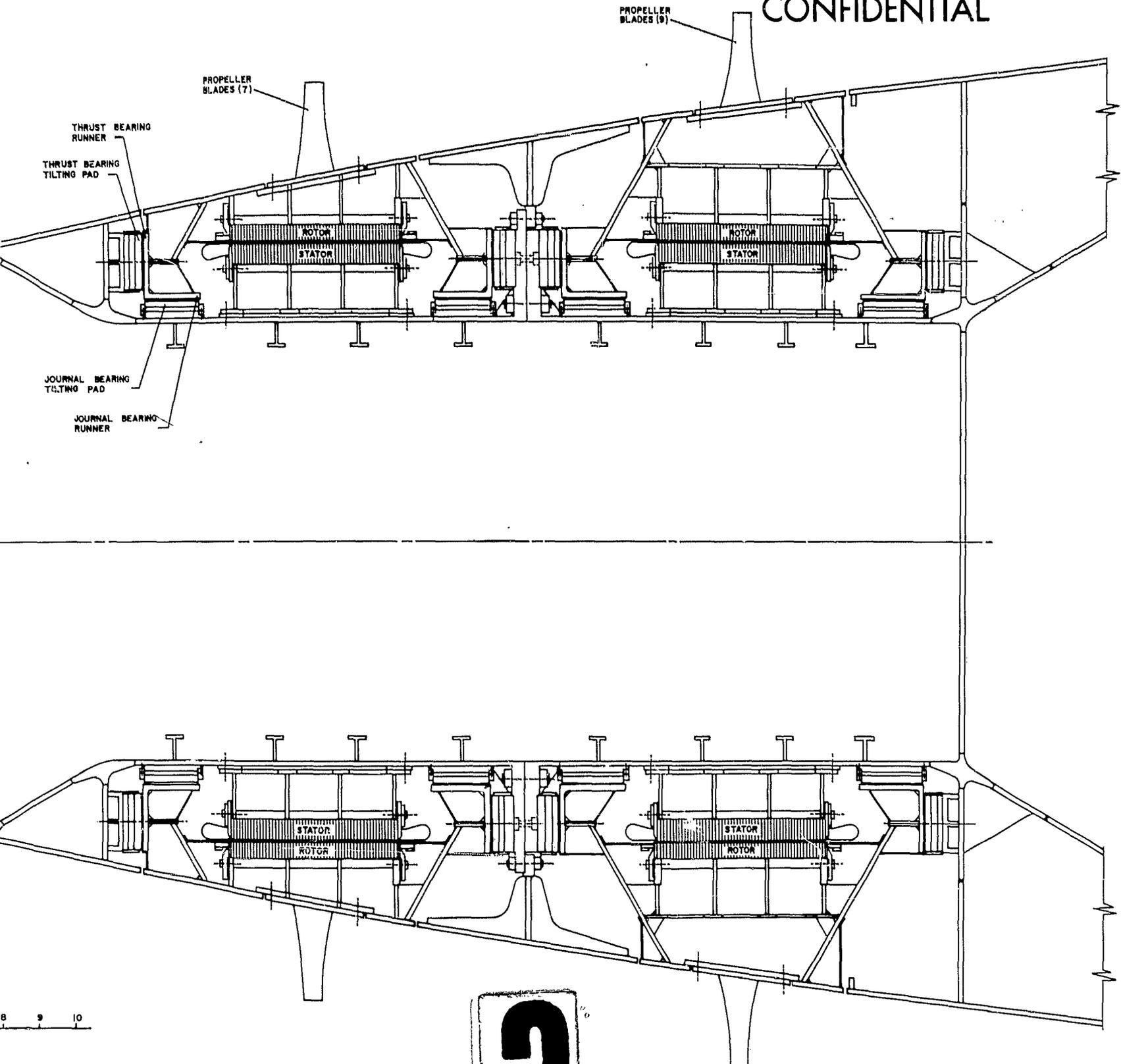


Figure 18 Novel Electric Propulsion System, Propulsion Motors and Propellers

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The electrical system is nevertheless more complex, but it should be recognized that propulsion equipment is normally well engineered and manufactured, and that the reduction in reliability will not necessarily be large. In addition, casualty control is aided by the duplication of turbine generators, motors, and propellers, and the previously mentioned capability for disconnecting portions of the motor stator windings to isolate electrical casualties. Overall reliability is still strongly affected by the auxiliary systems.

The machinery length and weight are shown by major components in Table 16. The lengths correspond to propulsion turbine generator sets side by side, propulsion control panels side by side, hull penetrations side by side, and motors in tandem.

TABLE 16 - Novel Electric Propulsion System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship ft</u>	<u>Weight lb</u>
2 Propulsion turbine generator sets	34.0	461,000
2 Propulsion control panels	3.0	7,000
12 Hull electrical penetrations	3.0	6,000
2 Propulsion motors and propellers	<u>23.0</u>	<u>558,000</u>
Total	63.0	1,032,000

Motor friction loss is 2%, and motor windage loss is 3% for the after motor and 6% for the forward motor. This windage loss includes the loss for the entire rotating assembly except the surface of the propeller hub fair with the hull. Windage loss is the dominant factor limiting the maximum propeller speed.

The motor configuration leaves a 10-foot diameter access to the stern for sonar or armament. For example, Reference 1 shows this space accommodating four torpedo tubes and their ejection pump. In this case it was not necessary to disturb the stern control surface stocks. For completely clear access, another support arrangement for the control surfaces is required. This stern access is also very well suited to towing applications, since there is excellent protection against fouling cables of towed devices. The bow remains completely free of propulsion machinery.

The flooded motors are of course development items. Small flooded motors have been built, but the principal areas of interest here are size effects in both manufacture and operation of the large mass of sealed electromagnetic structure and the large water-lubricated bearings. However, there is good reason to expect successful development. The hull penetrations are also development items due to their unusually large size, but development here is straightforward.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

The mechanical design of this system is covered in considerably more detail in Reference 1. Synchronous machinery which could be used with this system and which would offer reduced weight is described in Reference 3.

#### Hydrodynamic Design

This propulsion system consists of counter-rotating propeller blades running on ring-like hubs forward of the control surfaces.

A complete hydrodynamic design of this type of propulsion system for a submarine similar to the SS(N)593 has been prepared under Office of Naval Research contract \* and is reported in Reference 1. Adapting this

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\* NONr 3383(00)

design procedure to an SSB(N)616 class submarine results in a propulsive efficiency of 0.93 and a maximum speed of 20.5 kts. The propellers are cavitation free at full power for any depth greater than 23 ft to the propeller axis.

The axial distance between propellers is determined by motor and bearing space requirements. The effect of the relatively large axial distance between blade rows is accounted for in the design procedure. Propeller details are shown in Table 17.

TABLE 17 - Novel Electric Propulsion System, Propeller Details

<u>Item</u>	<u>Aft</u>	<u>Fwd</u>
Tip diameter	24.69 ft.	28.11 ft.
Hub diameter	19.46 ft.	23.21 ft.
Speed	50 rpm	50 rpm
Number of blades	7	9

This blade system of a counter-rotating propeller with large hub diameter is inherently efficient, since it makes it possible to sweep a large annular area with relatively short blades having a low tip speed, and the rotational kinetic energy of the wake is largely eliminated. However, the overall performance is less efficient than that of the geared drive turbine system due to large hydrodynamic losses on the outer surfaces of the hubs and substantial machinery losses. The effect of the slipstream on the control surfaces will result in improved control, especially at low speeds.

The backing effectiveness of the counter-rotating propeller is at least as good as that of a conventional propeller.

A summary power balance is shown in Table 18.

TABLE 18 - Novel Electric Propulsion  
System, Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	2
Motor electrical loss	13
Motor friction loss	2
Motor windage loss	4
Propulsor loss	6
Effective horsepower	73
Overall propulsive efficiency, EHP/Turbine shp	73%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	93%

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22. These turbines, due to their lower rotational speed (consider range of speeds as 180 to 1800 rpm), generate a lower noise level. This is offset by the large weight of the combined turbine and generator rotor.

Isolation mounts are useful only near full speed (>1200 rpm), since the turbine rpm is proportional to the motor rpm. At slow speeds (<1000 rpm), the once-per-rev excitation approaches the mounting natural frequencies of the presently used mounts. Use of mounts at high rpm, which have a low speed "lock-out" feature, is suggested in Reference 1. It is difficult to attach quantitative values to the force unbalance of such a system using locked-unlocked mounts and rotors of such large masses, therefore, it is a primary area of concern for this design.

AC Propulsion Generators - See AC-DC electric system, page 52.

Somewhat lower noise levels can be expected from the generators due to the lower rpm and lower line frequency. The generators are vibration isolated with their turbines, and since the speed range of the generators is the same as that of the turbines, the same comment on isolation mounts presented above holds true.

Free-flooding AC Propulsion Motors - See AC-DC electric system, page 53. The following discussion amplifies the original novel electric propulsion system feasibility study, Reference 1.

A number of unique features have a strong effect on the radiated and self-noise characteristics of this propulsion system. The direct coupling of rotor and stator vibrations to the water and the entire structure being rigidly connected to a cylindrical foundation aft of the pressure hull provide the most efficient means of radiating mechanically and magnetically induced vibrations.

The outboard motors of SSB(N)598 and 608 class submarines, although not designed as quiet machines, are known to be serious noise sources.<sup>24</sup> The General Electric Company on the other hand predicts low vdb levels of the stator shell at line frequencies (65 vdb) and at the high rotor-stator interaction frequencies (10-40 vdb).<sup>25</sup>

The cavities around the rotor, the air gap itself, and other free-flooded spaces in the motor are subject to cavity resonances excited by hydrodynamic forces of the propeller. The cooling water flow (estimated at 150 gpm) through the air gap and rotor may also excite cavity resonances. Thrust modulation produces a periodic pumping of the water through the circumferential spaces between the hub and the hull. All of these hydrodynamic effects constitute potential sources of acoustic energy. For example, assuming that only the volume of water in the space is affected (the interior volume changes can be nullified by pressure release devices such as air bladders, or cellular rubber or plastic), the pressure level at one yard due to an axial displacement amplitude of 2 mils is about 95 db at the aft propeller blade rate and 110 db at the sum of blade rates.

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While cavity resonances of sea chests are the result of air-backed plating, the water-filled cavity which is also surrounded with water will have a higher resonant frequency. The effects of plate stiffness and transmission of sound energy through these plates remains to be investigated before the contributions of cavity resonances of the propulsion motor to the radiated and self-noise can be evaluated. Cancellation can be expected between the slots at either end of each of the two rotors since these signals are always out of phase. Since the blade rate for each rotor is different, cancellation may or may not occur between the forward slot of the aft prop and the aft slot of the forward prop.

The calculated values still represent a conservative estimate of radiation from the slots, since volume change within the cavities was neglected. These values are an order of magnitude lower than pressures calculated for blade rate radiation of conventional propeller designs, but they may become significant as blade rate and other sources of noise are reduced.

Stick-slip friction may cause the pivoted thrust bearing pads to vibrate unless all possible means of damping the components are exploited. Other sources of noise include the resonant excitation of the rotor and stator structure. For example, the vdb level of a recent submarine emergency propulsion motor at the lobar modes of the stator frame was found to be ~70 vdb. One crude manner of predicting the vibration levels of similar modes of the novel electric propulsion system motors is to add  $10 \log$  (ratio of horsepower), therefore obtaining for the 6000 HP motor 85 to 95 vdb. The resulting noise level, referred to one yard, may be on the same order of magnitude as the blade rate noise for a conventional propeller. Accurate balancing and careful rotor design to avoid resonances is extremely important.

Hull-sized Fixed Pitch Counter-rotating Propellers - The general discussion of propeller noise for the geared drive turbine system (page 24) applies. All of these factors must be considered with

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respect to the propeller configuration, and have indeed been thoroughly discussed in Reference 1. The following remarks supplement those in Reference 1 and include a restatement of the summary.

Steady forces, i.e., rotational forces moving with the propeller, will be much lower than with conventional single propellers. The effect of sound radiation from adjacent surfaces can be important and the close proximity of the blades to the hull increases this effect. This is particularly true in the region of localized plate modes. However, the pressure field acts normal to the hull and, therefore, blade frequencies from both steady and unsteady forces are less efficiently coupled to the longitudinal modes than is the case with conventional single stern propellers. In the latter case, it has been shown that the fluid coupling associated with the single stern propeller near field accounts for approximately one-third of the energy flow from the propeller into the longitudinal mode. Therefore, this factor assumes practical importance where the structural energy path (e.g., shafting) is expected to have lower levels as is the case with the novel electric propulsion system. The conclusions still holds that the radiated noise due to the pressure field acting on the adjacent hull must be carefully evaluated.

Unsteady hydrodynamic forces account for the major acoustic problems associated with conventional single stern fixed pitch propellers. This includes vortex shedding, singing, cavitation, and blade rate frequencies. Specifically, vortex shedding is dependent on the velocity profile of the flow entering the blading, and this factor must be studied in particular relation to the aft set of novel electric propulsion system blading. However, there is no apparent reason that this should present an acoustical problem.

Singing is a special case, and if it occurs, it will be of lower intensities and more amenable to correction. In cavitation, the novel electric propulsion system design has a major advantage over

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current designs. It can theoretically operate at maximum speed at 23 ft centerline depth without cavitating. This fact constitutes one of the most obvious and significant tactical advantages over conventional single screw submarines in terms of radiated noise at medium to high speeds.

Blade rate radiation is a complex subject which was briefly discussed under the geared drive turbine system. In Reference 1, a 10-15 db reduction was predicted with the novel electric propulsion system, due principally to reduced blade loading and lower tip velocities. It appears that this figure may be too conservative, inasmuch as Tsakonas and Breslin have shown that "a counter-rotating propeller system has vibratory characteristics much superior to an equivalent single propeller...."<sup>26</sup> This is due to phase cancellation effects, independent of tip speed and blade loading, which result in reduced level of blade rate harmonics. On the other hand, Brosens and Strasberg have shown that the principal component of alternating thrust will be at the sum of the blade rate frequencies, i.e.,  $5.8 + 7.5 = 13.3$  cps at maximum speed. This thrust acts on the aft propeller and, although the amplitude will be considerably lower than for a single stern propeller, it occurs in the same frequency range as the lowest ordered hull longitudinal mode.

In the discussion of the geared drive turbine system, it was noted that the replacement of a thrust bearing foundation structure attached to the lower shell by a circumferential structure could prove advantageous. Junger points out that it is desirable to allow energy to be fed into the non-radiating flexural modes and that the novel electric propulsion system symmetrical arrangement may actually be less effective in reducing the energy fed into the principal longitudinal radiating modes. The massiveness of the rotor assembly and bearings does not change the coupling of forces to the hull due to the relatively high impedance offered by the longitudinal modes. On the other hand, the potential reduction of beam modes due to the symmetrical thrust input results in lower near field pressures and thus improved self-noise characteristics.

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Considering the types of forces and structures involved, the original conclusion that the overall sound radiation at blade rate frequencies is considerably reduced (by at least 15-20 db) still holds.

#### Influence of Overall System on Noise Level

The omission of the hull penetrating shaft is a favorable feature and the overall acoustical characteristics of the propeller system are very good. This feature, combined with the application of acoustical engineering to the variable speed propulsion turbine generators, the ship service turbine generators, and auxiliary systems, gives the novel electric propulsion system a relatively high rating.

As earlier noted, it is essential that the potential problems due to direct coupling of the free-flooding motors to the sea be thoroughly studied. This can be accomplished only by experimenting with components at approximately full scale.

## TANDEM PROPELLER SYSTEM

This system consists of a pair of hull-sized, counter-rotating, collectively and cyclically variable pitch propellers, located one near each end of the ship and driven by large, inside-out, free-flooding electric motors within the propeller hubs. Transverse control forces are also produced by the propellers, and conventional control surfaces are omitted. An artist's conception of the ship and machinery is shown in Figure 19.

Electrical Design

A one-line diagram of the system is shown in Figure 20. Propulsion power is developed in two 1800 rpm AC turbine generator sets, and is delivered to two 50 rpm motors, each of which is integral with its propeller. Propeller speeds are controlled by varying the turbine speeds. Backing is accomplished by collective pitch change. Ship control is accomplished by cyclic pitch change. Each propeller blade is fitted with an individual, oil-filled, electric actuator which controls its pitch. Electric power to operate the actuators is transferred to the hub by a rotary transformer which is an integral part of the propulsion motor. This transformer also provides excitation power for the motor field. Control information for the blade actuators is transferred to the propeller hub magnetically. As can be seen in Figure 19, the motors are located outside the pressure hull and operate free flooding.

The turbine generator sets are standard hardware. The propulsion control panels are also standard hardware, and include excitation control, protective relaying, metering, and disconnecting equipment. No switching is included and the motors are not reversed. In operation, the motors follow the turbine speeds synchronously, and the turbines are governed at speeds ordered by the ship control system. The ship control system consists of a computer, display, and operator's control stick. It computes and orders propeller speed, collective pitch, cyclic pitch,

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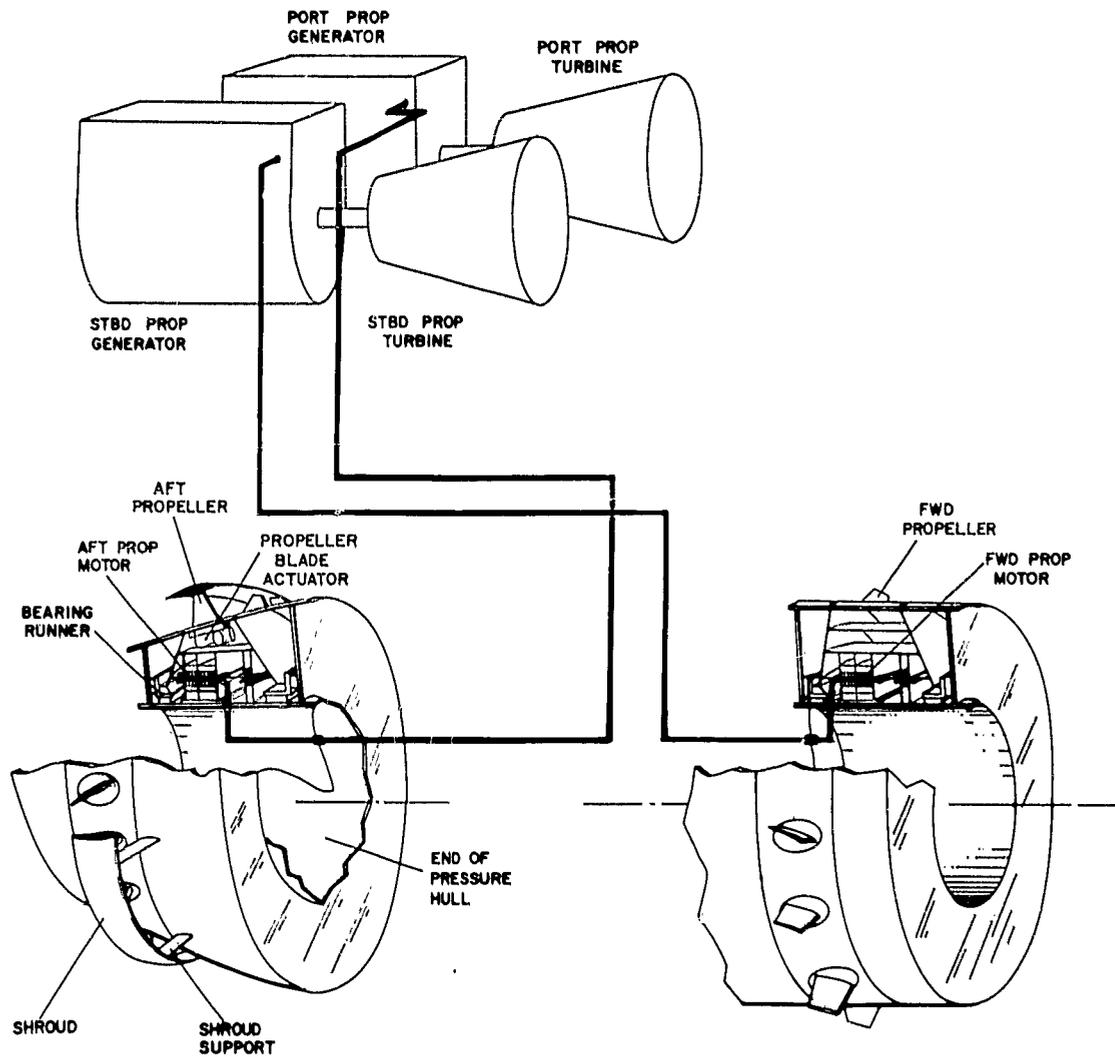
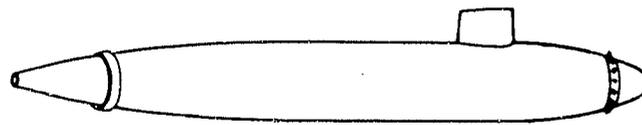


Figure 19 Tandem Propeller System, Ship and Propulsion Machinery

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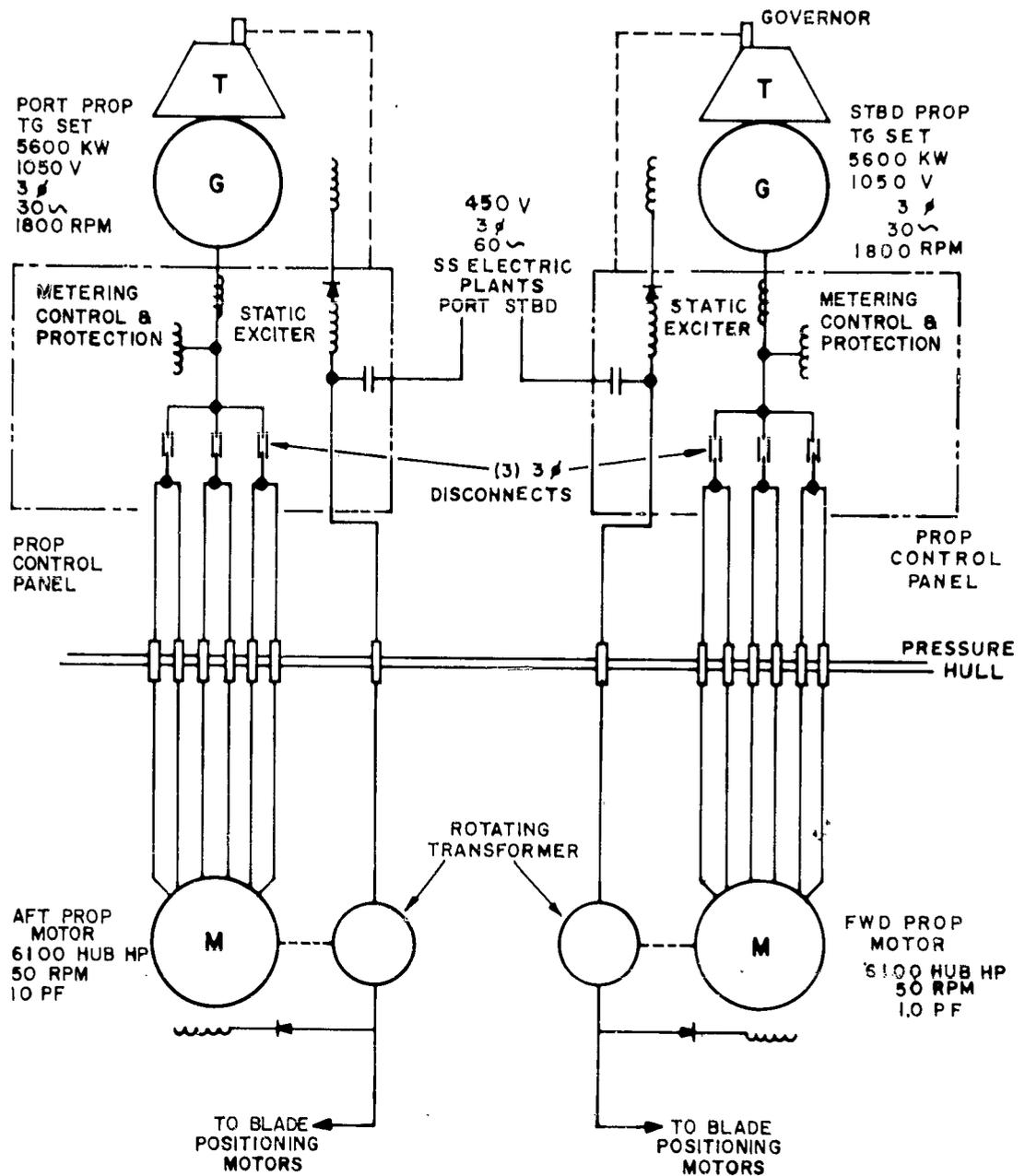


Figure 20 Tandem Propeller System, Electric Power One-line Diagram

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and cyclic pitch axis for each propeller so as to make the ship execute the desired operating condition or maneuver. During certain operational maneuvers, the bow propeller is not used. In this event the motor is de-energized. Its turbine generator set may or may not be running depending upon the maneuver or mission.

The hull electrical penetrations are similar to those for the novel electric propulsion system motors. A cross sectional view of a motor and propeller is shown in Figure 21. The motors are round rotor synchronous machines, with the rotor outside the stator and an integral part of the propeller hub. The fields are excited from rotating transformers and rectifiers which are integral with each motor.

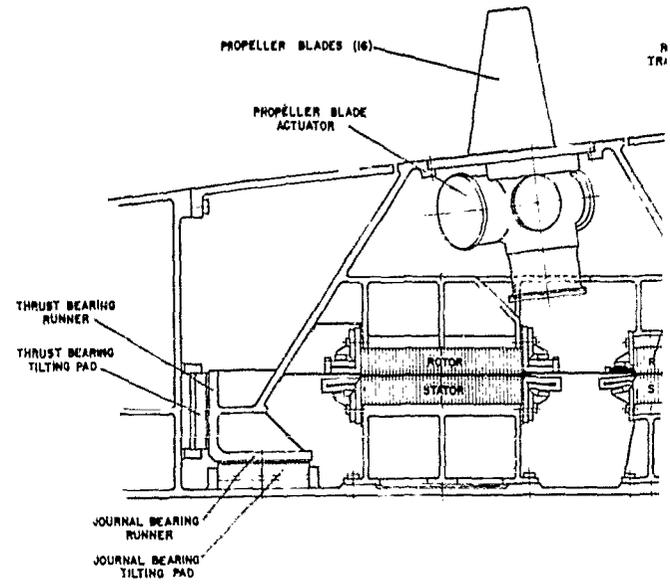
The rotating transformers are similar to wound rotor induction motors. Voltage is induced in the rotor winding partly due to rotation of the magnetic field and partly due to physical rotation of the rotor in the opposite direction. Each transformer is rated 300 kw; 200 kw is used for the field and 100 kw for the blade actuators.

Although they are synchronous machines, the motors are otherwise much the same as the novel electric propulsion system induction motors (page 72). Since the power factor is unity instead of 0.56, there is a significant reduction in line current, which is also reflected in the turbine generator set size.

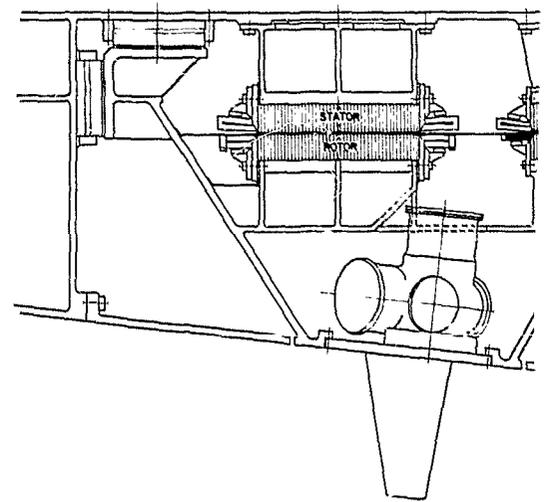
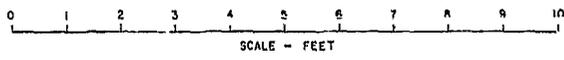
Because of the presence of the pitch changing system, it is difficult to determine precisely just which electrical losses should be charged to the motor. However, for comparison purposes the motor electrical loss may be considered to be 8%. Generator total loss is 2%. A summary of losses is included later in the hydrodynamics portion.

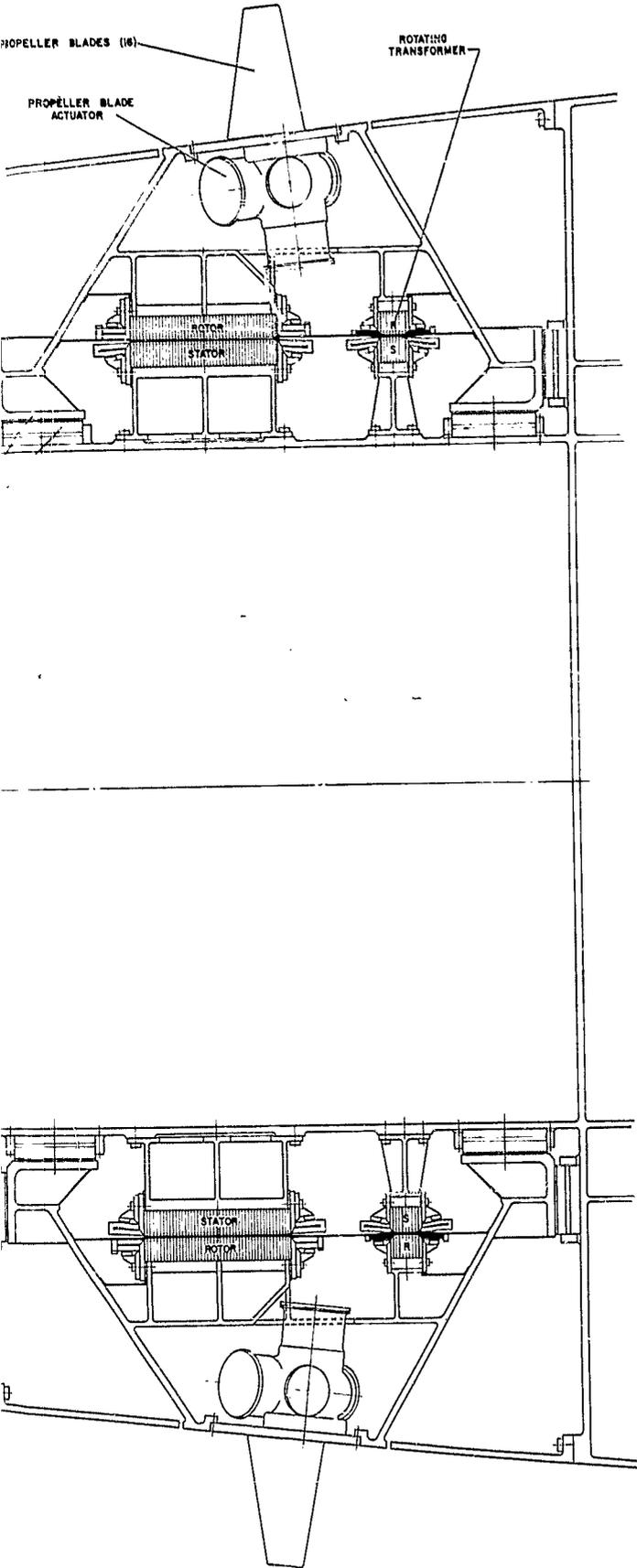
The propeller blade actuators consist of 1200 rpm, 7.5 hp induction motors driving the blade spindles through 100:1 worm gears. Solid

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Figure 21 Tandem Propeller System, Propulsion Motor and Propeller

state controllers provide closed loop position control. Each actuating mechanism and controller is housed in an oil-filled\* enclosure, equalized to ambient sea pressure, and providing a favorable environment.

Position information for the blades is received via a series of devices similar to E core transformers which are distributed around the hub and hull. A separate device is mounted on the hub for each blade at the corresponding angular location of the blade on the hub. A series of devices are also mounted on the hull, separated from the rotating devices by a small air gap. The stationary devices are each excited at a frequency commensurate with the desired blade pitch at that particular location around the hull. The rotating devices pick up these frequency signals as they pass by, and the blade actuators position the blades accordingly. While this information transfer system yields stepwise pitch changes, the steps can be made small and there is no need to know the angular position of the propeller hub; therefore, there is great flexibility in pitch programming.

The electrical design of this system, including both propulsion machinery and pitch changing equipment, is covered in considerably more detail in Reference 3.

#### Mechanical Design

Since ship control forces are provided by the propellers, conventional fixed and movable control surfaces are omitted from both the stern and the sail.

The inboard machinery is a collection of conventional hardware, but the outboard machinery is of course new. The turbine generator sets are vibration isolated. The motors are foundationed on 13.5-foot OD cylinders extended from each end of the pressure hull. These cylinders are free flooding, and therefore dimensionally insensitive to

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\* Although "oil" is used for convenience, actually the fluid is polyalkylene glycol, which is miscible with sea water and thus would not rise to the surface if the enclosure were ruptured.

submergence pressure. The motor general construction and assembly are similar to that of the novel electric propulsion system motors (page 74).

Comments with respect to maintenance, reliability, and casualty control for the novel electric propulsion system (page 74) apply here also. The large separation of propellers reduces the probability of damage occurring to both simultaneously. The pitch changing system introduces additional complexity, but the entire hydraulic control system for the conventional control surfaces, which is also quite complicated when examined in detail, is entirely eliminated.

The machinery length and weight are shown by major components in Table 19. The lengths correspond to propulsion turbine generator sets side by side, propulsion control panels side by side, two groups of hull penetrations in tandem, and motors in tandem. In addition, credit is shown for certain conventional ship control equipment which is eliminated.

TABLE 19 - Tandem Propeller System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship, ft</u>	<u>Weight, ft</u>
2 Propulsion turbine generator sets	29.0	357,000
2 Propulsion control panels	3.0	7,000
12 Hull electrical penetrations	6.0	6,000
2 Propulsion motors and propellers	<u>24.0</u>	<u>670,000</u>
Total	62.0	1,040,000
- Control surfaces and appurtenances		213,000
- Hydraulic equipment		22,000
- Hovering equipment		<u>75,000</u>
Total		310,000
Net Weight		730,000

Motor friction loss is 3% and motor windage loss is 8%. This windage loss includes the loss for the entire rotating assembly except the surface of the propeller hub fair with the hull.

The motor configuration leaves an 11.5-foot diameter access to both the stern and bow for sonar or armament. Since there are no conventional control surfaces, there are no supporting stocks to be considered, and the access is always clear in this respect.

The stern access is similar to that of the novel electric propulsion system, and the same discussion (page 78 ) applies here. The bow access permits installation of torpedo tubes, but the presence of the motor physically disrupts some types of sonar array, the BQR-7 for example.

Development of the propulsion motors and hull penetrations is much the same as for the novel electric propulsion system (page 69). Development of the pitch changing system is straightforward.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

The mechanical design of this system, including both propulsion machinery and pitch changing equipment, is covered in considerably more detail in Reference 3.

#### Hydrodynamic Design

This system consists of two large hub-tip ratio propellers, with one mounted near each end of the ship. Pitch is controlled both collectively and cyclically to obtain propeller torque and thrust vector control. This provides six-degree of freedom control of the ship, allowing unconventional maneuvers and obviating conventional control surfaces. Intrinsically, the ship is not directionally stable, but is rendered effectively stable by an automatic control system which

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is part of the previously mentioned ship control system. Some stabilizing force is also contributed by the shroud on the stern propeller.

#### Underway Control and Propulsion

An extensive analytic investigation of stability and control is reported in Reference 27. Data therein, with some subsequent information, leads to the following conclusions:

The system offers smaller control forces than the conventional submarine control system at high speeds.

Overall stability and control is feasible with an automatic control system.

Since the hydrodynamic forces available for maneuvering on the conventional submarine are larger than those on this configuration, the system requires a greater percentage of the available hydrodynamic forces to produce a given maneuver than the conventional submarine.

At speeds below 6 knots, the turning performance of the system is superior to that of the conventional submarine (see Figure 22, page 98).

At high speeds, the minimum turning radius of the system is approximately five times greater than that of the conventional submarine.

To produce pure sideforces at zero and nearly zero forward speeds, counter-thrusting collective pitch must be used.

The system is capable of maximum diving rates comparable to a conventional submarine.

In the above investigation no attempt was made to introduce the effects of blade cascading, swirl, and propeller interaction.

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Propeller performance for the bow propeller will be markedly different from that for the stern propeller. The stern propeller is comparable to that of the forward propeller of the novel electric propulsion system, and a high propulsive efficiency is expected. The bow propeller, due to its location, is expected to perform similarly to an open water propeller. This open water operation, coupled with the large hydrodynamic losses on the outer surface of the hub, results in a lower propulsive efficiency. In addition, the slip stream effect of the bow propeller results in an increase in the drag of the vessel. However, elimination of all control surfaces results in a decrease in drag. Test data is necessary to establish the net result.

In order to estimate the speed, it is assumed that the decrease in drag due to the removal of control surfaces is equal to the slip stream effect of the bow propeller. Thus, the maximum speed is 19.5 knots at a propulsive efficiency of 0.76. The maximum speed with only one propeller operating depends upon which propeller is operating, but is approximately 15.5 knots.

Figure 22 shows curves of maximum turning moment as a function of ship speed for a ship of the SSB(N)616 length with tandem propellers.<sup>29</sup> Also shown for reference is a comparable curve for the SSB(N)616 with conventional control surfaces.<sup>30</sup> As the four curves for the tandem propeller system imply, there are several possible modes of operation.

First, the ship can be driven by both propellers together, the stern propeller alone, or the bow propeller alone. For the purposes of this discussion, the two propellers are assumed to be identical and independent with respect to generation of maximum transverse forces,<sup>29</sup> but their effectiveness in controlling the ship is not identical. In particular, control of the ship is not satisfactory at the high end of the speed range attainable using the bow propeller alone<sup>27</sup>; however, this is a very unusual operating condition.

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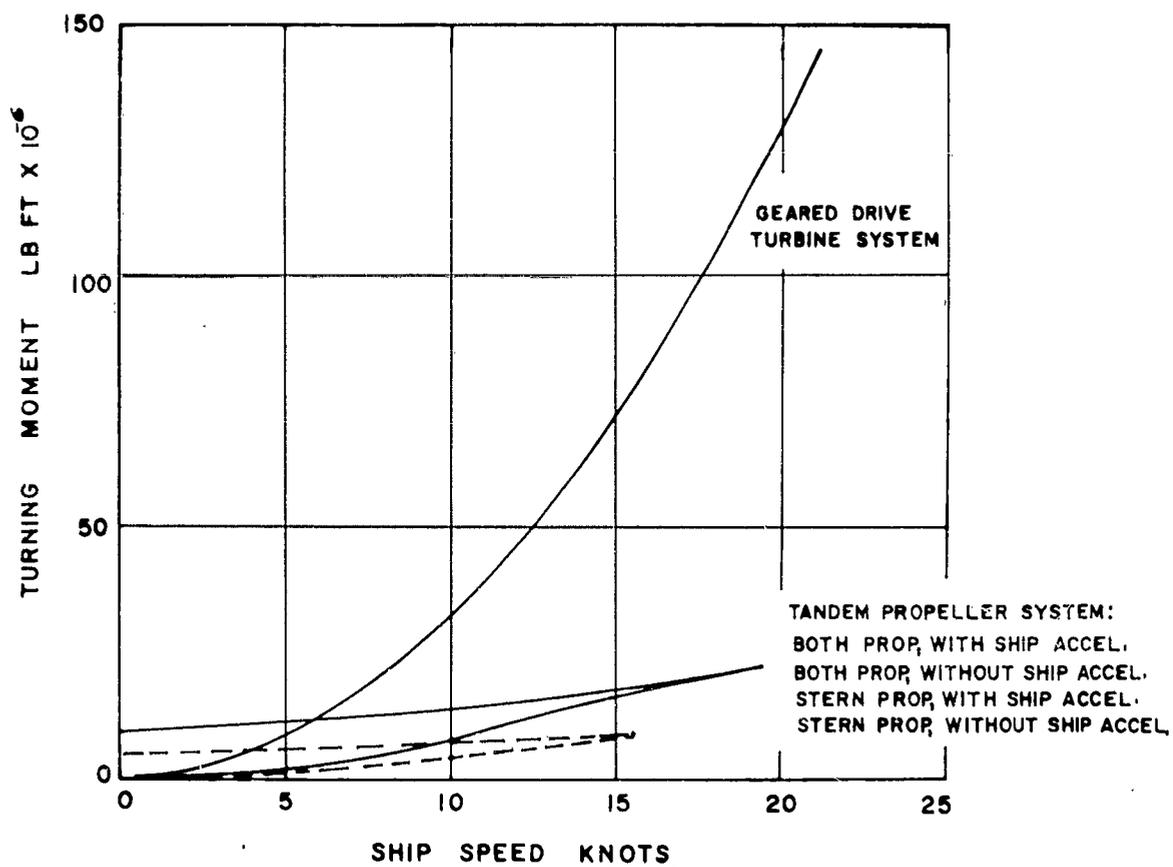


Figure 22 Tandem Propeller System,  
Maximum Turning Moment vs  
Ship Speed

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Second, the constraints imposed upon ship speed affect the maximum turning moment. If the ship is not allowed to be accelerated longitudinally, the transverse force is limited by the restraint on longitudinal force. If the ship is allowed to be accelerated longitudinally, there is no restraint on longitudinal force and the transverse force is not limited thereby.

Thus, the four combinations of number of propellers and ship speed constraint yield the four curves in Figure 22. Also possible with two propellers is a mode in which the propeller longitudinal forces are opposite in direction and generally unequal in magnitude. Since the net longitudinal force is the difference, this affords considerable opportunity to fix transverse and longitudinal forces independently. Hovering, discussed later, is a special case of this mode in which the longitudinal forces are equal, giving no net longitudinal force; the transverse forces have the same direction instead of opposite directions, giving vertical force but no moment. Other variations are readily visualized which, along with propeller torque control, give full six-degree of freedom control of the ship.

While there is considerable hydrodynamic flexibility in this system, the bow propeller and machinery and the high rpm and power required to develop maximum transverse forces impose acoustic restraints. Maximum hydrodynamic performance and maximum acoustic performance are mutually exclusive, and a choice is necessary to suit the operational conditions prevailing at the moment. This is discussed further under acoustic design.

Due to the cyclic variation in pitch of the propeller blades, cavitation may occur during the periods when the blade section angle of attack is above the optimum. If this occurs, cavitation performance of these propellers will be degraded compared to that of the novel electric propulsion system propellers. However, there are two mitigating factors: cyclic pitch variation is a minimum for a straight

course, being only large enough for stabilizing; and each blade experiences a higher angle of attack for only part of each propeller revolution, and since the occurrence of cavitation is not instantaneous, it may be suppressed.

Since the blade pitch is controlled and full power is available, this system offers improved backing performance.

A summary power balance is shown in Table 20.

TABLE 20 - Tandem Propeller System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	2
Motor electrical loss	8
Motor friction loss	3
Motor windage loss	8
Propulsor loss	18
Effective horsepower	61
Overall propulsive efficiency, EHP/Turbine shp	61%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	76%

#### Hovering

The capability of a hovering system to control the depth of an FBM submarine when launching missiles in a sea state is related to the following thrust-producing equipment capacities:

Maximum vertical thrust which can be generated

Maximum vertical thrust time rate of change

The linearity of produced thrust with respect to the ordered thrust

Maximum vertical thrust and maximum thrust rate are important in regard to the magnitude and time rate of change of disturbance forces.

It is estimated in the case of the design of a hovering system for the SSB(N)616 class of submarine that disturbance forces may be defined as shown in Table 21 in the ranges of frequencies of occurrence.

TABLE 21 - SSB(N)616, Disturbance Forces for Hovering, Sea State 5

	<u>Low Frequencies*</u>	<u>High Frequencies*</u>	<u>Missile Launching</u>
Disturbing Force Magnitude, lb	4,000 avg 20,000 peak	500,000 peak at 0.125 cps	13,000**
Frequency Range, cps	0-0.005	0.1-1.0	0.01

\* High frequency range taken from Sea State 5 spectrum. Low Frequency range estimated from suction force due to sea state.

\*\* Estimated effective value

From this information, estimates of required thrust and thrust rate of generation to effectively hover are as shown in Table 22.

TABLE 22 - Thrust and Thrust Rate for Hovering

<u>Condition</u>	<u>Thrust, lb</u>	<u>Thrust Rate, lb/sec</u>
4,000 lb at 0 cps	4,000	--
20,000 lb at 0.0015 cps	20,000	400
13,000 lb at 0.01 cps	13,000	520
500,000 lb at 0.125 cps	500,000	250,000

The SSB(N)616 hovering system has capabilities based on the depth control tank capacity and flooding or blowing rates at 90 feet depth to keel of 80,000 lb/tank and 700 lb/second, and is not designed to control against the high frequency sea state conditions. The tandem propeller system can develop, by using both propellers, a maximum vertical thrust of 52,000 lb at a rate of 104,000 lb/second. It appears then that a slight improvement over the present SSB(N)616 system is possible with respect to minimizing depth error.

Other favorable factors to be considered in using a thrust generating system as compared to a ballasting system are:

The ballasting rates of the SSB(N)616 system are affected by operating depth. The flooding rate is determined by the difference between sea pressure and pressure within the hull, and hovering capability approaches zero as depth decreases.

Duration of hovering is limited by the capacity of the depth control tanks in the ballasting system. The present approach includes a means of switching over tanks when the flood tank is full and the blow tank is empty, but it is necessary to operate the high pressure air compressors to bring down the pressure in the ship following the venting of air from the empty blow tank at the time of switchover.

High pressure air consumption is not affected by the thrust system.

The thrust system offers a possibility for improving zero or low speed depth keeping at periscope depth. The present SSB(N)616 ballasting system does not give adequate control in high sea states at periscope depth.

#### Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See novel electric propulsion system, page 80.

AC Propulsion Generators - See novel electric propulsion system, page 81.

Free-flooding AC Propulsion Motors - See novel electric propulsion system, page 81.

Variable Pitch Tandem Propeller Pair - See novel electric propulsion system, page 82. The interaction between counter-rotating propellers, discussed for the novel electric propulsion system, does not apply since the propellers in this case are separated by almost the length of the hull. The acoustical generating characteristics of the bow propulsion system introduce a new set of conditions which require careful study, particularly with respect to self-noise and sonar. The near field propeller noise covers a wide frequency spectrum and varies widely according to speed, power, and hydrodynamic flow.

Hovering requires operation of the bow propeller. This will adversely affect the self-noise in the bow area, since it is extremely difficult to reduce propeller and machinery self-noise in adjacent hull areas.

Slow speed can be realized with the bow propeller stopped and feathered. Some excess of flow noise is expected over that obtained on the quietest (smoothest) designs due to the feathered propeller. This is partially offset by the smaller blade area of the stern propeller and associated smaller noise therewith.

At moderate to medium speeds, the bow propeller induces additional turbulence, thereby causing increased flow noise which affects sonar transducers locally. As speed is further increased, the serious flow noise limitation of all conventional hull designs also applies to this design, supplemented by propeller and machinery noise above about 15.5 knots when the bow propeller must be operated.

The possibility of moving sonar arrays away from the bow area naturally arises, but the entire subject of sonar location with respect to the hull, appendages, and equipment is very complex, and there are no

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simple solutions such as moving an array into the sail area. For example, the sail area has higher self-noise levels even at low speeds due to proximity to machinery and equipment spaces, and at moderate speeds the increase in self-noise due to flow noise occurs earlier and more rapidly than at the bow. The sail area is also in close acoustic proximity to the bow propulsion equipment. The trend in submarine hull-mounted sonars is the fuller utilization of the entire length of the hull so that sonar array requirements must be considered as an integral part of hull design.

The radiated noise characteristics can also be considered as a function of system operation and speed. At low speeds, propeller noise (including blade frequencies) is not a problem (see discussion on novel electric propulsion system). At low to medium speeds, the forward bow system can be feathered and secured so that the thrust variations acting on the submarine are determined by the aft propulsion system. These thrust variations may actually be of somewhat lower magnitude than those of the novel electric propulsion system and occur at frequencies slightly below the longitudinal resonances of the hull. In principle, it is also possible to vary the propeller pitch so as to accommodate the irregular wake, but in practice, this is believed to be a problem of such technical difficulty as to preclude materially reducing thrust variations caused by changing wake characteristics and the fluctuating turbulent boundary layer. Supports for the shroud on the stern propeller introduce multiples of blade rate noise.

At medium to high speeds, with the bow propeller operating, the bow propulsion system contributes to propeller noise but to a lesser degree than the novel electric propulsion system due to its favorable location in an open water, free-flow condition. However, blade frequencies and other propeller noise are nevertheless still present and contribute to the radiated noise spectrum. Further, thrust variations at blade frequencies, although reduced, react on the forward hull.

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This force, combined with that of the stern propulsion system, tends to more readily excite the lower ordered hull modes, especially the important longitudinal modes. Another factor, which would require model studies, is the possible interaction in the form of beating between the bow and stern propellers. Directivity patterns, particularly in the forward direction, can be unfavorable.

#### Influence of Overall System on Noise Level

The radiated far field noise at low speeds is expected to be of the same order as that of the other systems with flooded motors. At medium speeds, propeller noise and particularly blade frequencies should be the lowest of any system. At high speeds, with both propellers in use, noise levels will be comparable to that of the novel electric propulsion system.

Self-noise in terms of bow-mounted sonar systems results in an unfavorable acoustical rating for some of the modes of operation of this system. Few methods of reducing this self-noise, except by use of towed sonar, are available. In the discussion of hydrodynamic design, it was noted that maximum hydrodynamic performance and maximum acoustic performance are mutually exclusive. The following two paragraphs indicate the conflicting features but do not indicate which features should be favored, since this choice must be made to suit the operational conditions prevailing at the moment.

The bow propeller must be used for hovering, and the noise generated is new noise where there would otherwise be none. The forward propeller must also be used for speeds in excess of 15.5 knots, but since flow noise would become important at about this speed even without the bow propeller being present, the noise generated is additional rather than new noise. In addition to the noise source at the bow, the general machinery noise is disproportionately large while maximum transverse forces are being developed. When large forces are being developed, the propeller speed and power are quite high, although they

are unlikely to be required for extended periods of time. For maximum force at zero ship speed, the propeller speed is 100% and the power is on the order of 50%. For maximum force above 15.5 knots, the propeller speed is 100% and the power is on the order of 100%, and possibly even higher.

For speeds below 15.5 knots, the option is available to use only the stern propeller. This removes the self-noise source at the bow, except for some increase in flow noise from the feathered propeller compared to no propeller. However, it is then necessary to accept the lower curves in Figure 22 (page 98 ) for transverse forces. When maximum force is required, the propeller speed is 100%, and the power is on the order of 50% at 0 knots and on the order of 100% at 15.5 knots.\*

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\*Since only one propeller is running, this represents 25 to 50% of total plant power.

## INBOARD FLOODED MOTOR SYSTEM

This system consists of a single, fixed pitch propeller, located at the stern of the ship and driven by a pair of inside-out, free-flooding electric motors within the hull envelope but outside the pressure hull. An artist's conception of the ship and machinery is shown in Figure 23.

Electrical Design

A one-line diagram of the system is shown in Figure 24. Propulsion power is developed in two 2800 rpm AC turbine generator sets, and is delivered to two 150 rpm motors which support and turn a single propeller. Propeller speed is controlled by varying the turbine speed. Backing is accomplished with astern stages in the turbines. As can be seen in Figure 23, the motors are located outside the pressure hull and operate free flooding.

The turbine generator sets are standard hardware, except that reversing stages are included. The propulsion control panels are also standard hardware and include excitation control, protective relaying, metering, and disconnecting equipment. No switching is included since backing is accomplished by reversing the generator direction of rotation. In operation, the motors follow the turbine speed synchronously and, since the motors are mechanically connected, the generators are also constrained to operate synchronously.

Hull electrical penetrations are similar to those for the novel electric propulsion system motors.

A cross sectional view of the motors and propeller is shown in Figure 25. The motors are round rotor synchronous machines, with the rotor outside the stator. The fields are excited from rotary exciters and rectifiers which are located around the forward journal bearing. Protection against overvoltages during starting and loss of synchronism is provided by a solid state control on the rotor.

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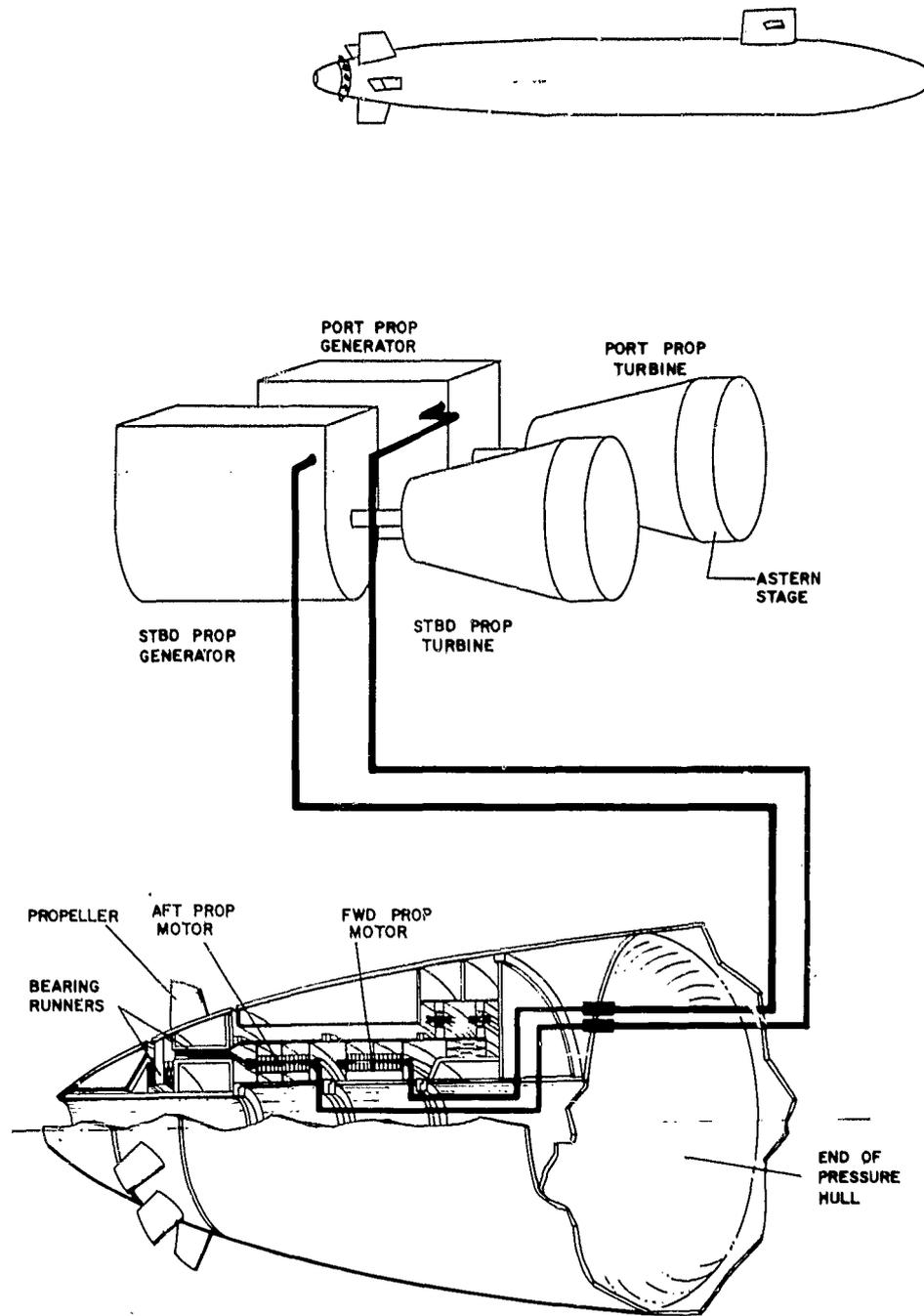


Figure 23 Inboard Flooded Motor System, Ship and Propulsion Machinery

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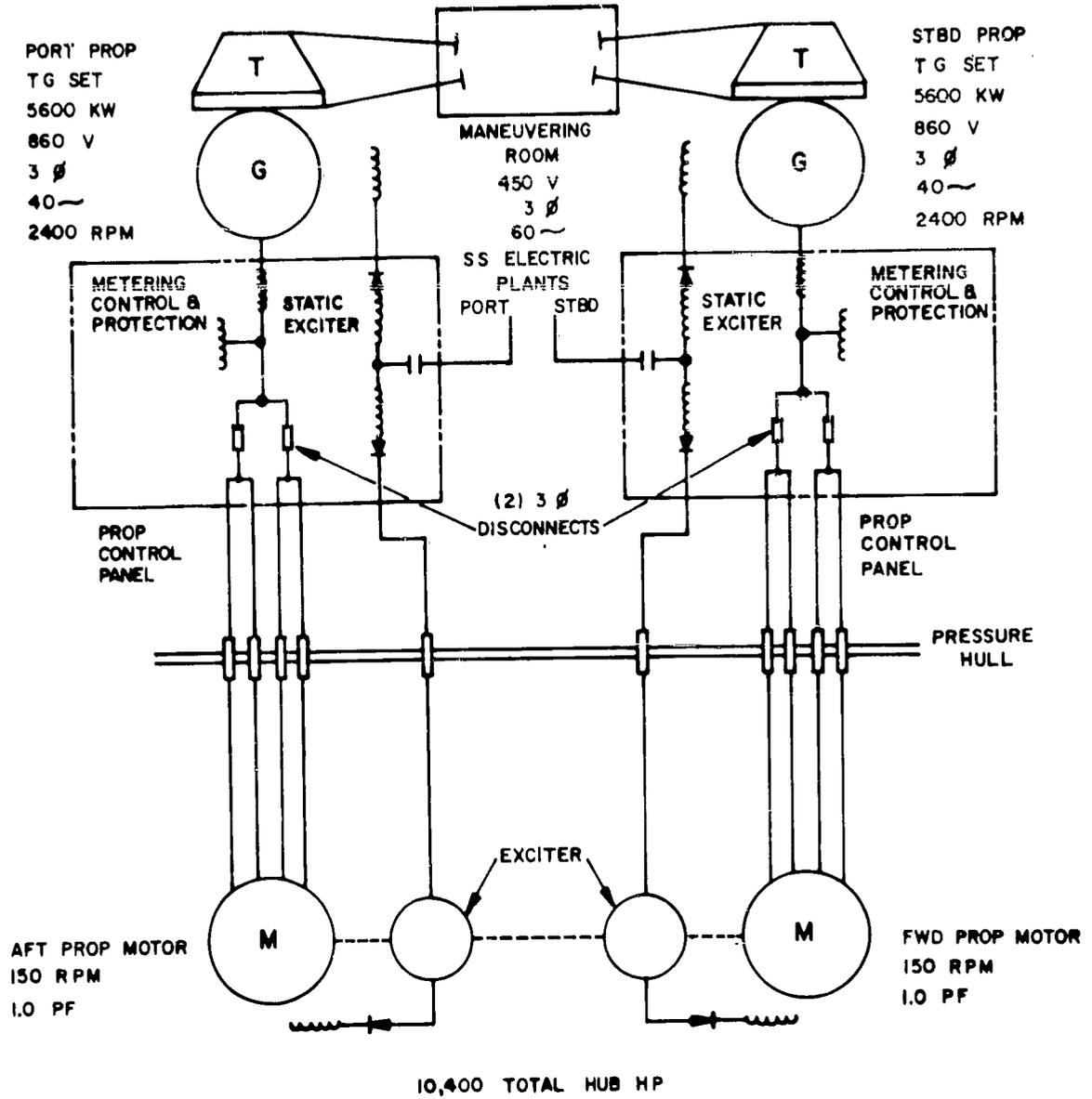


Figure 24 Inboard Flooded Motor System,  
Electric Power One-line Diagram

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The rotary exciters are rotating armature AC generators. The stators are excited with DC power, and the AC power generated in the rotor winding is rectified on the rotor. This type of exciter produces no output at zero speed, but this is satisfactory for the application. (In the tandem propeller case, power is required on the rotor even at zero speed for the propeller blade actuators.)

The environmental protection is the same as for the novel electric propulsion system motors (page 72).

Motor electrical loss is 7%, and generator electrical loss is 2%. A summary of losses is included later in the hydrodynamics portion.

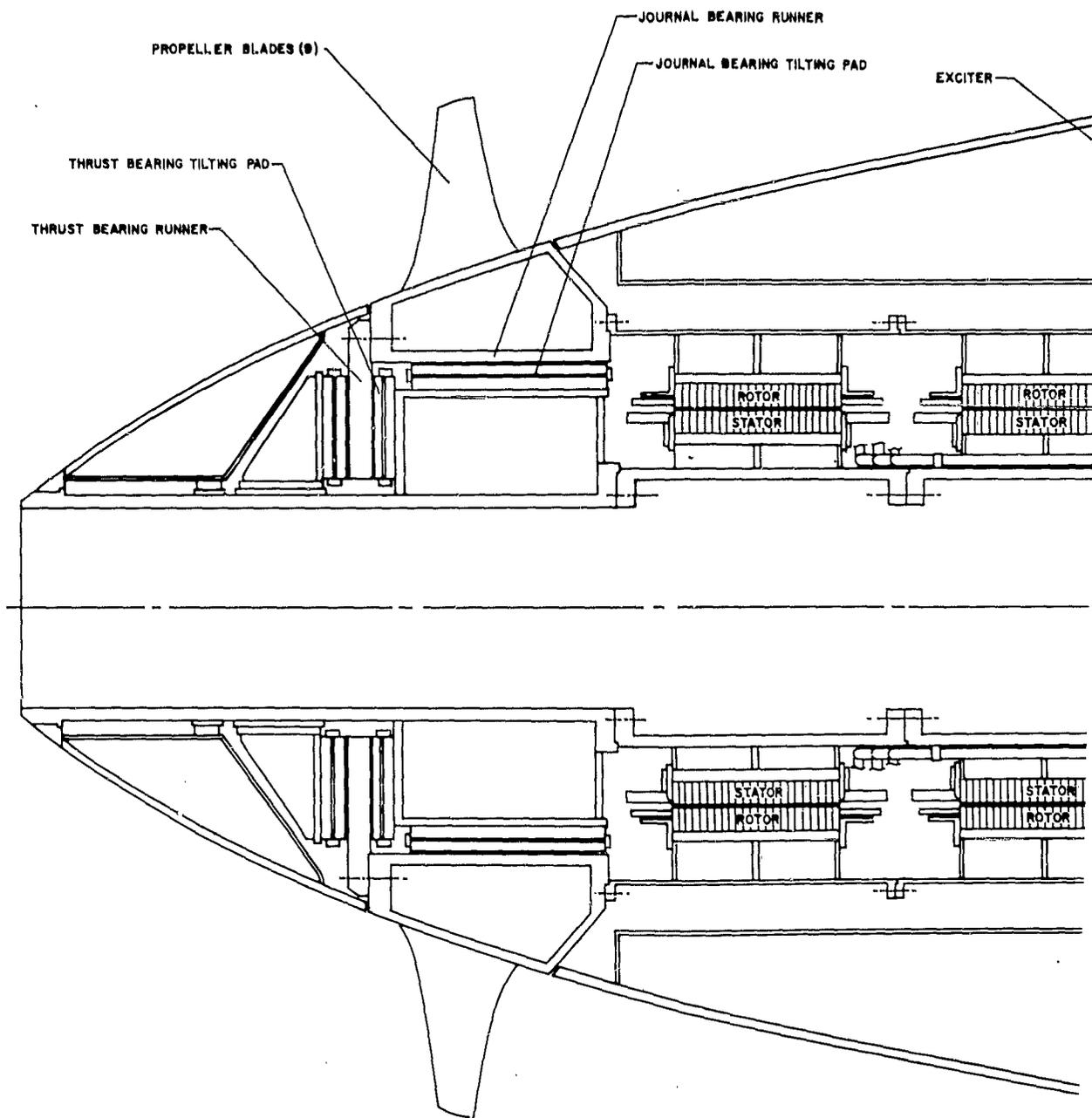
The electrical design of this system is covered in considerably more detail in Reference 5.

#### Mechanical Design

Conventional fixed and movable control surfaces are fitted at the stern and on the sail, and the movable surfaces are actuated by hydraulic rams.

The inboard machinery is a collection of conventional hardware, but the outboard machinery is of course new. The turbine generator sets are vibration isolated. The motors are cantilevered from the after end of the pressure hull. The cylinder supporting the motors and propellers is a part of the motor frame and is free flooding and, therefore, dimensionally insensitive to submergence pressure. The motor parts are complete rings, assembled axially and bolted together at machined, flanged joints.

The single propeller is supported by the motors, and the bearings are of the same type as those in the novel electric propulsion system motors (page 74), but of smaller diameter.



1

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INTERNAL BEARING RUNNER

INTERNAL BEARING TILTING PAD

EXCITER

ROTOR  
STATOR

ROTOR  
STATOR

STATOR  
ROTOR

STATOR  
ROTOR

2

Figure 25 Inboard Flooded Motor System, Propulsion Motors and Propeller

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Comments with respect to maintenance and reliability for the novel electric propulsion system (page 74 ) apply here also. Casualty control is somewhat different, since there is only one propeller. However, the turbine generator sets and electrical parts of the motors are still duplicated.

The machinery length and weight are shown by major components in Table 23. The lengths correspond to propulsion turbine generator sets side by side, propulsion control panels side by side, hull penetrations side by side, motors in tandem, and propeller concentric with motors.

TABLE 23 - Inboard Flooded Motor System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship, ft</u>	<u>Weight, lb</u>
2 Propulsion turbine generator sets	31.0	291,000
2 Propulsion control panels	3.0	7,000
8 Hull electrical penetrations	3.0	4,000
2 Propulsion motors and propeller	<u>29.5</u>	<u>502,000</u>
Total	66.5	804,000

Motor friction loss is 1% and motor windage loss is 22%. This windage loss includes the loss for the entire rotating assembly, except the surface of the propeller hub fair with the hull. These losses are given as a percent of the total input power of the two motors.

The motor configuration leaves a 4-foot diameter access to the stern for sonar or armament. The bow remains completely free of propulsion machinery.

Development of the propulsion motors and hull penetrations is much the same as for the novel electric propulsion system (page 69).

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

The mechanical design of this system is covered in considerably more detail in Reference 5.

Hydrodynamic Design

This system employs a single, fixed pitch propeller which operates at 150 rpm and 10,400 hub horsepower.

The propeller was selected from the Troost propeller charts to operate at the highest propulsive coefficient for the given power and wheel speed. Due to its unconventionally large hub, the Troost data is not directly applicable to this propeller. However, it was assumed that the performance would be the same as that of a Troost propeller of the same expanded area, swept area, and tip speed. The resulting propeller dimensions are shown in Table 24.

TABLE 24 - Inboard Flooded Motor System,  
Propeller Details

Hub diameter	13.68 ft.
Tip diameter	20.50 ft.
Expanded blade area/annulus area	0.60
Number of blades	9

The maximum speed is 18.0 knots at a propulsive coefficient of 0.74. The reduction in propulsive coefficient compared to the geared drive turbine system is due to higher blade loadings resulting from the reduced rpm for this design. The speed is lower because the propulsive coefficient and the available power are less than for the geared drive turbine system. Increasing the propeller power to that of the geared drive turbine system would increase the speed to 21.0 knots.

The minimum cavitation-free depth at full power for this design is estimated at 660 feet, almost the same as the 670-foot critical depth for the geared drive turbine system. This is because the design was not compromised for cavitation. For example, consider a smaller (less efficient) propeller with a diameter of 17.5 feet. The resulting lower tip speed decreases the minimum cavitation-free depth to 280 feet. The reduced efficiency of the smaller wheel results in a speed of 16 knots instead of 18 knots.

Since the propeller does not have a large effect on control or stability, ship control remains the same as for the geared drive turbine system.

A summary power balance is shown in Table 25.

TABLE 25 - Inboard Flooded Motor System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	2
Motor electrical loss	7
Motor friction loss	1
Motor windage loss	21
Propulsor loss	18
Effective horsepower	51
Overall propulsive efficiency, EHP/Turbine shp	51%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	74%

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22 , and novel electric propulsion system, page 80.

AC Propulsion Generators - See novel electric propulsion system, page 81.

Free-flooding AC Propulsion Motors - See novel electric propulsion system, page 81.

Single Stern-mounted Fixed Pitch Propeller - See geared drive turbine system, page 24. Although this propeller is not of conventional design and is a smaller version of the hull-sized propeller discussed in the novel electric propulsion system, its location at the stern will result in noise characteristics similar to those of a conventional propeller.

#### Influence of Overall System on Noise Level

Except for the differences in the propeller design, the discussion for the novel electric propulsion system (page 85) also applies to this system.

## CONTROLLABLE POD MOTOR SYSTEM

This system consists of four pumpjets located on the stern control surfaces and driven by free-flooding electric motors. The propellers and motors are arranged to pivot with the control surfaces. An artist's conception of the ship and machinery is shown in Figure 26.

Electrical Design

A one-line diagram of the system is shown in Figure 27. Propulsion power is developed in two 2800 rpm AC turbine generator sets and is delivered to four 400 rpm motors, each of which drives a separate propeller. Propeller speeds are controlled by varying the turbine speeds. Backing is accomplished with astern stages in the turbines. As can be seen in Figure 26, the motors are located outside the pressure hull and operate free flooding.

The turbine generator sets are standard hardware, except that reversing stages are included. The propulsion control panels are also standard hardware, and include excitation control, protective relaying, metering, and disconnecting equipment. No switching is included since backing is accomplished by reversing the generator direction of rotation. In operation, the motors follow the turbine speeds nearly synchronously, except that during reversal there is a brief (but not troublesome) loss of generator/motor coupling as the generator goes through zero speed.

The hull electrical penetrations are similar to those for the novel electric propulsion system motors.

A cross sectional view of a motor and propeller is shown in Figure 28. The motors are squirrel cage induction machines, with the rotor inside the stator in the conventional manner. The environmental protection is the same as for the novel electric propulsion system motors (page 72).

Although these motors are free flooding, the pod configuration lends itself to oil-filled construction. This would allow the use of more

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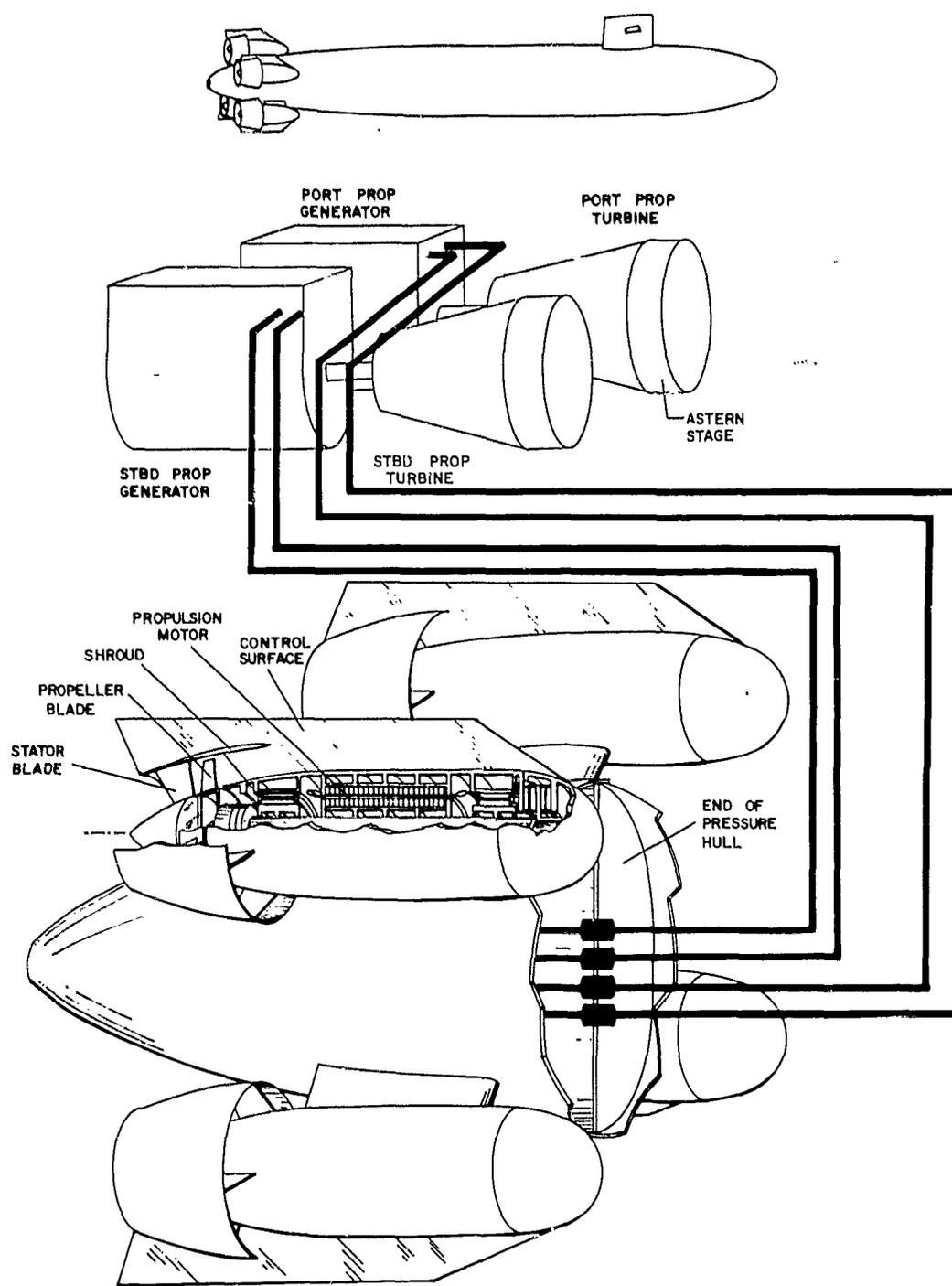


Figure 26 Controllable Pod Motor System,  
Ship and Propulsion Machinery

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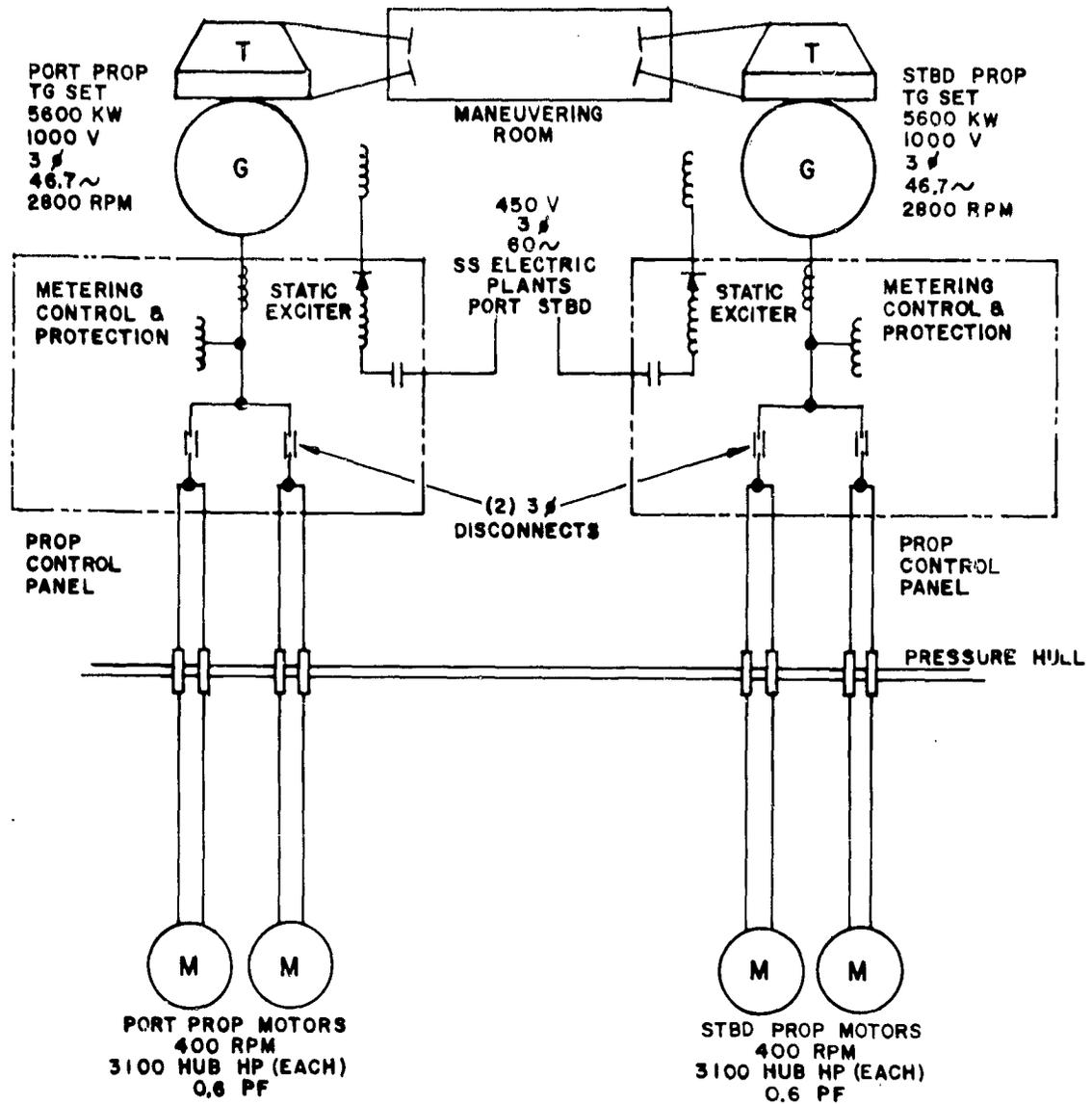


Figure 27 Controllable Pod Motor System,  
Electric Power One-line Diagram

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conventional electromagnetic materials and bearings. While a shaft seal is required, it would operate at substantially zero differential pressure. The bearings would be smaller, but the windings and iron would probably be larger due to relatively poor heat transfer to the oil, so that to a first approximation the overall size and weight would be unchanged.

Motor electrical loss is 10%, and generator total loss is 2%. A summary of losses is included later in the hydrodynamics portion.

#### Mechanical Design

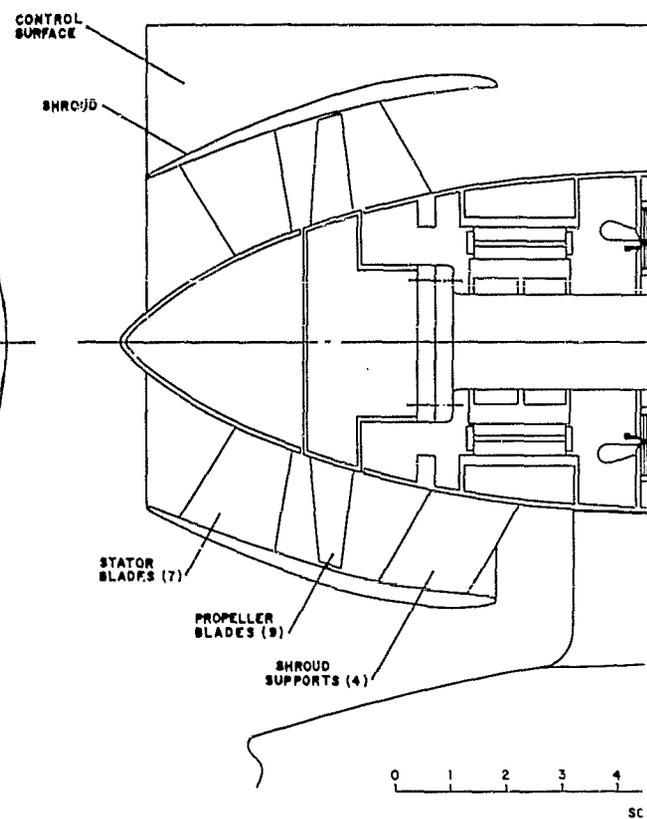
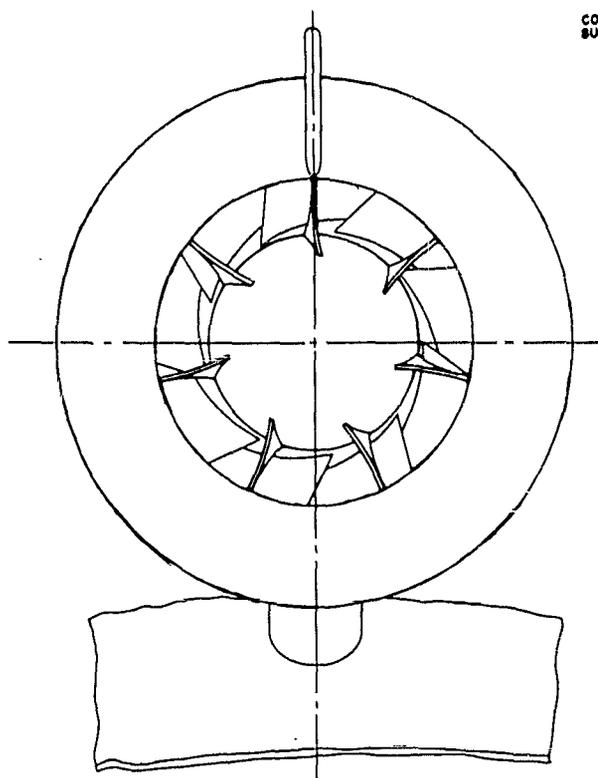
Movable control surfaces incorporating the pods are fitted at the stern, and conventional control surfaces are fitted on the sail. All are actuated by hydraulic rams. The stern surfaces are mounted in an X arrangement to minimize draft, beam, and emergence of the top pods when the ship is surfaced.

The inboard machinery is a collection of conventional hardware, but the outboard machinery is of course new. The turbine generator sets are vibration isolated. The motors are mounted on stocks, similar to conventional control surfaces, and the electric cables run either inside or adjacent to the stocks. The stators and rotors are each furnished as single pieces, and the motors are assembled by axially inserting the rotors in the stators.

Each propeller is supported by its respective motor, and the bearings are of the same type as those in the novel electric propulsion system motors (page 74), but of much smaller diameter.

Comments with respect to maintenance and reliability for the novel electric propulsion system (page 74) apply here also. Casualty control is further improved by the presence of four mechanically and electrically separated propellers and motors.

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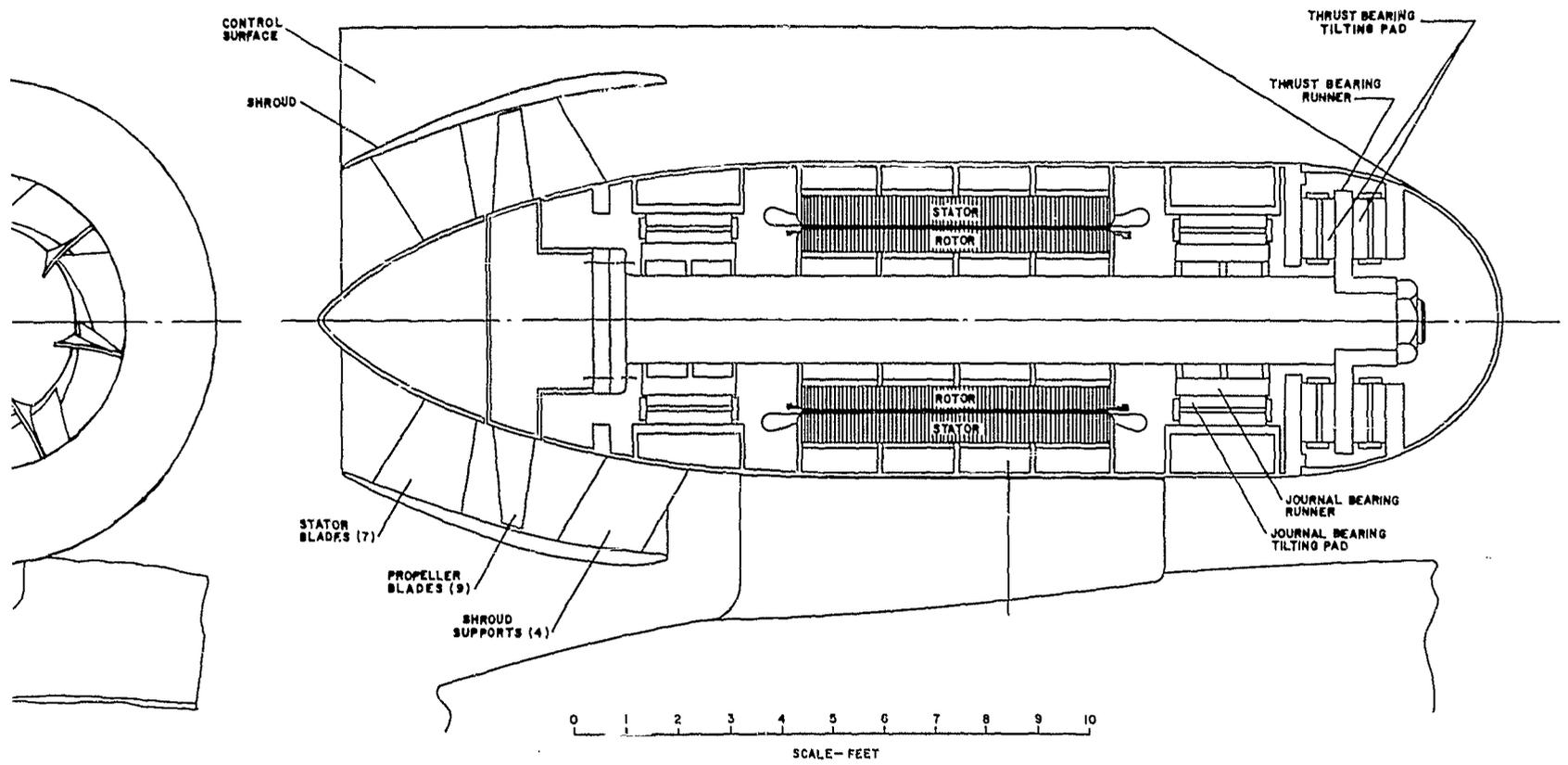


Figure 28 Controllable Pod Motor System,  
Propulsion Motor and Propeller,  
Stern Pod

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## Detailed Description Controllable Pod Motor

The machinery length and weight are shown by major components in Table 26. The lengths correspond to propulsion turbine generator sets side by side, propulsion control panels side by side, hull penetrations side by side, and propulsion motors side by side.

In addition, credit is shown for certain conventional ship control equipment which is eliminated.

TABLE 26 - Controllable Pod Motor System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship, ft</u>	<u>Weight, lb</u>
2 Propulsion turbine generator sets	31.5	334,000
2 Propulsion control panels	3.0	7,000
8 Hull electrical penetrations	3.0	4,000
4 Propulsion motors and propellers	<u>23.0</u>	<u>430,000</u>
Total	60.5	775,000
- Stern fixed and movable control surfaces		140,000
Net Weight		635,000

Motor friction loss is 2% and motor windage loss is 6%. This windage loss includes the loss for the entire rotating assembly, except the surface of the propeller hub fair with the pod.

The pod arrangement leaves an 8-foot square access to the stern for sonar or armament. The bow remains completely free of propulsion machinery.

Development of the propulsion motors and hull penetrations is much the same as for the novel electric propulsion system (page 69). The oil-filled version would afford a somewhat simpler development.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

Hydrodynamic Design

This configuration consists of four pods mounted on stub control surfaces. A pumpjet is indicated, since the shroud greatly increases the stabilizing and control effectiveness as compared with unshrouded propellers mounted in the same manner, and it provides superior cavitation characteristics.

All four pods are of equal power, with a speed of 400 rpm. Location of these pods places the propulsion units completely out of the wake of the vessel. Because of this, the pumpjets are analyzed as operating in a uniform free stream with the stream velocity equal to the speed of the vessel. The propulsive efficiency of these pumpjets was computed by the method outlined in Reference 7. The ratio of velocity at the pump inlet to the local stream velocity was established such that there is no nozzle effect after the rotor, i.e., the axial velocity through the pump is equal to the ultimate jet velocity. Under this assumption, the effect of pump diameter on propulsive efficiency was determined.

The results appear in Figure 29 expressed as a function of hub-tip diameter ratio. It is readily seen that the propulsive efficiency increases with increasing diameter. However, the cavitation-free depth also increases with increasing hub-tip ratio. Figure 30 is a plot of the minimum cavitation-free depth versus rotor tip diameter for a rotor speed of 400 rpm. From these plots it is apparent that a compromise must be made between good propulsive efficiency and shallow operating depth. Referring to Figure 29, it is seen that the propulsive efficiency for comparable pumpjets (pumpjets of equal flow area) increases as the hub diameter decreases. This is also favorable to cavitation, since for a constant pump area the rotor tip diameter decreases as the rotor hub diameter decreases. The

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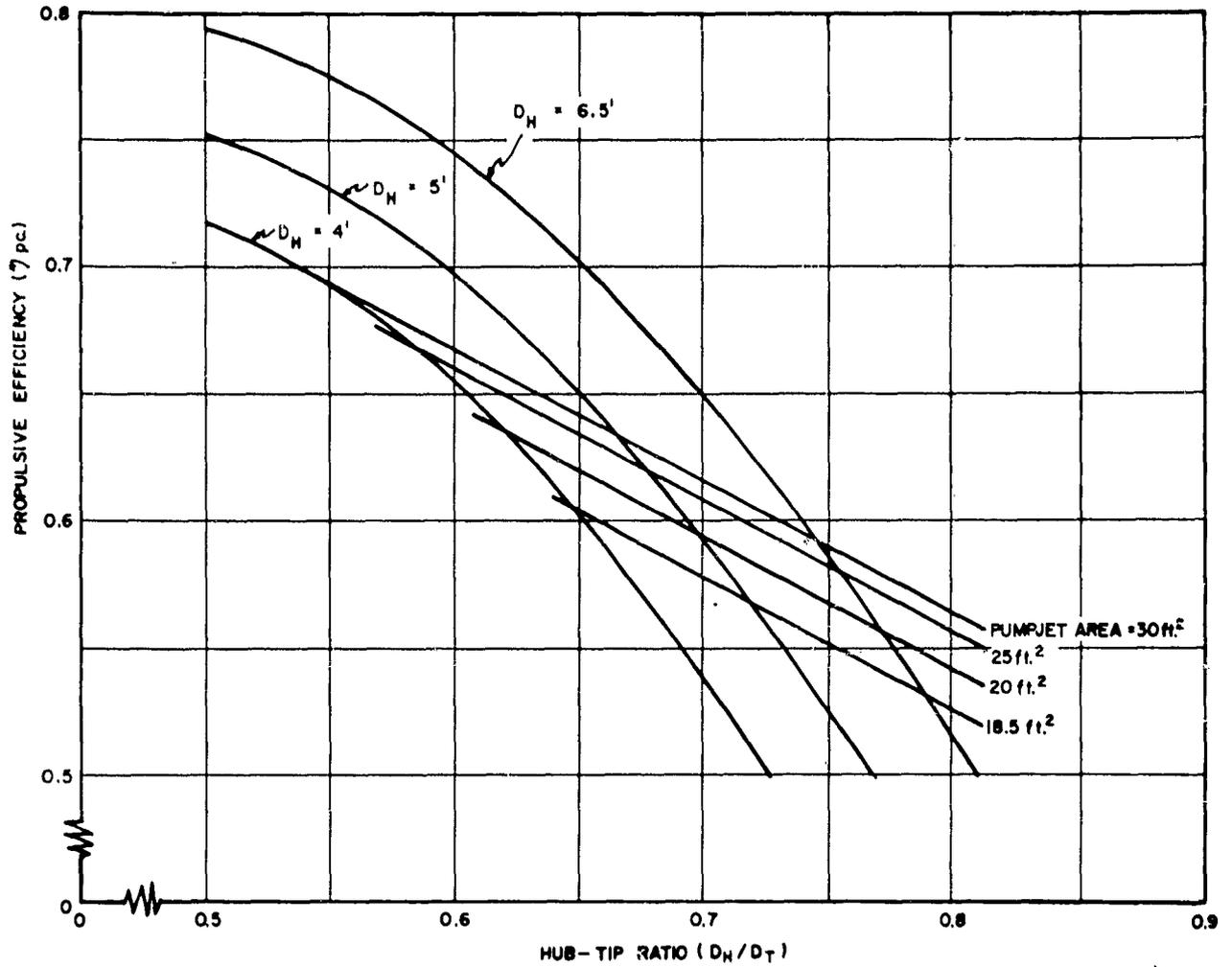


Figure 29 Controllable Pod Motor System, Propulsive Efficiency vs Hub-Tip Ratio

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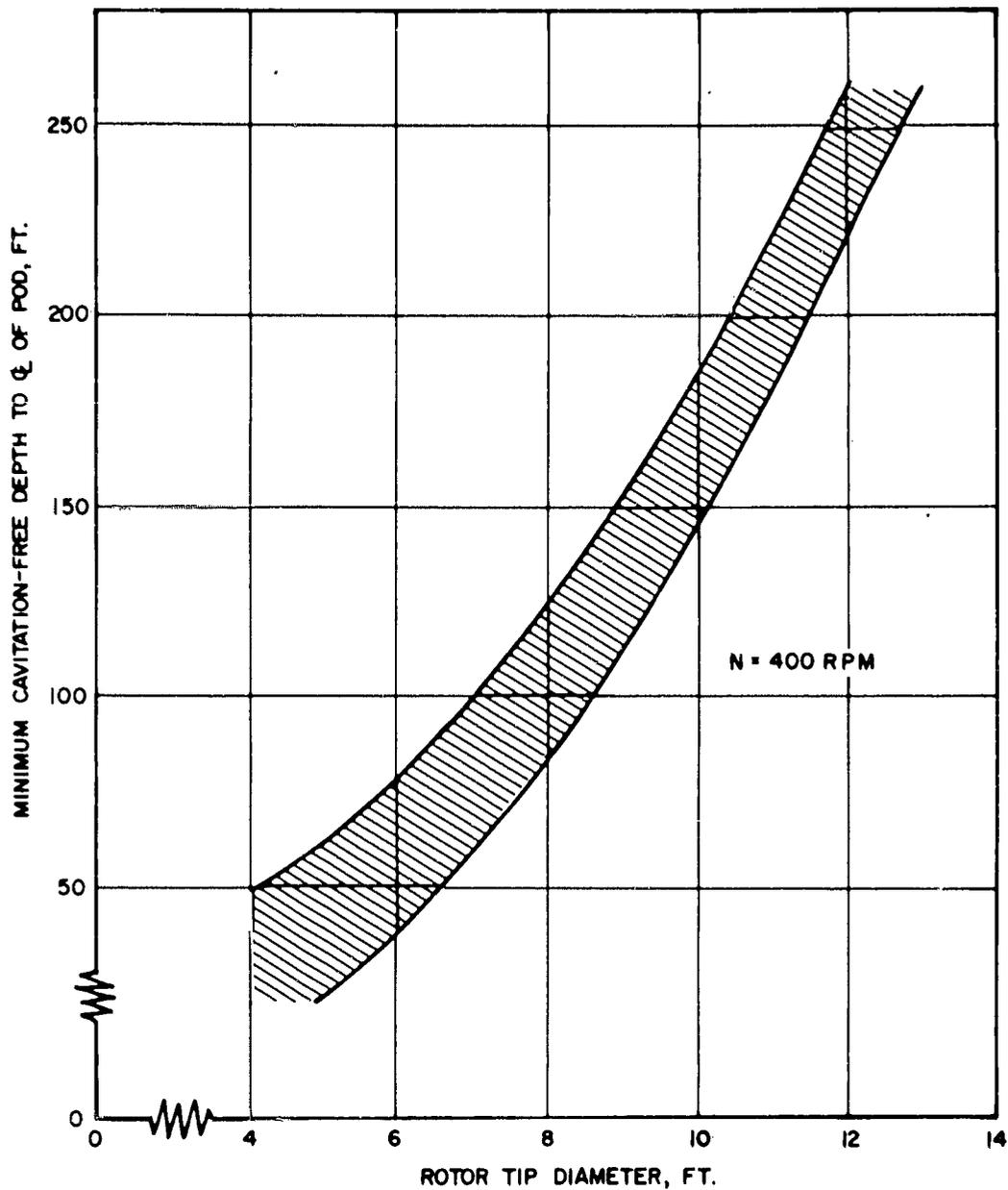


Figure 30 Controllable Pod Motor System,  
Minimum Cavitation-free Depth  
vs Rotor Tip Diameter

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minimum hub diameter is restricted by the overall diameter of the driving motor. With a hub diameter of 4 feet, it is estimated from Reference 6 that a minimum cavitation-free depth of 90 feet and a propulsive efficiency of 0.72 are obtained. This performance is similar to that of the geared drive turbine system with much better cavitation characteristics.

Although the propulsive efficiency for this configuration is similar to that of the geared drive turbine system, the shaft horsepower available to the propulsors is less due to the machinery losses. The net result is that the maximum speed is 19.6 knots.

Due to the high rotor speed, it is necessary to keep the rotor as small as possible, and stator blades are indicated to attain a good efficiency. However, the use of stator blades results in poor reverse thrust characteristics. The details of this propulsor are shown in Table 27.

TABLE 27 - Controllable Pod Motor System,  
Pumpjet Details

Hub diameter	4.0 ft.
Tip diameter	8.0 ft.
Shroud length	6.5 ft.
No. of rotor blades	9
No. of stator blades	7

Each pod deflects through a control angle of  $\pm 30^\circ$ . The shroud and stub control surface area of the pods are sufficient to provide approximately the same stability and control effectiveness as conventional rudders and diving planes. Improved control at low speeds is achieved by directing the thrust to produce a transverse component. For steady sailing at low speed this thrust is very low, and to obtain

appreciable improvement in control the propeller speed and thrust are briefly increased during the maneuver. For zero advance speed and a 30° pod angle, a maximum turning moment of about 6 million lb ft is realized. If an extreme pod angle is assumed, namely 90°, the moment is twice as large.

A summary power balance is shown in Table 28.

TABLE 28 - Controllable Pod Motor System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	2
Motor electrical loss	10
Motor friction loss	2
Motor windage loss	6
Propulsor loss	22
Effective horsepower	58
Overall propulsive efficiency, EHP/Turbine shp	58%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	72%

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22 , and novel electric propulsion system, page 80.

AC Propulsion Generators - See novel electric propulsion system, page 81.

Free-flooding AC Propulsion Motors in Pods - The discussion of free-flooding motors in the novel electric propulsion system (page 81 )

applies here, insofar as there is direct coupling of the motors to the radiating surfaces. Structural vibrations may be enhanced by the cantilevered arrangement, and it is possible that hull torsional modes may be more readily excited. This depends upon details of hull mode coupling, i.e., energy fed into flexural and longitudinal modes. In general, the structural configuration involving smaller radiating surfaces and cantilevered struts lends itself well to acoustical engineering and noise control.

Pod-mounted Pumpjets - The general noise radiating mechanisms are those discussed for the pumpjet system (page 40 ). The relatively high speed and larger number of blades can result in excitation of higher ordered longitudinal hull modes at higher speeds. The location of the pods, however, provides a more uniform in-flow velocity pattern, thereby reducing thrust modulations. The symmetrical spacing around the after hull and the relatively larger spacing from the hull will reduce the interaction with the hull, although the dynamic characteristics of the structures still require careful design. The overall result is a significant reduction in radiated and self-noise levels at blade frequencies resulting from hull vibrations.

A disadvantage is the direct interaction between the propellers as sound sources themselves. This gives rise to more complicated (but possibly more uniform) directivity patterns. The possibility of an increase in detection probability due to interaction beating and modulation effects must be considered carefully, as well as the peculiar propeller noise characteristics which may provide more readily distinguished classification information. In other words, lower noise levels, less cavitation, and reduced blade rate may be offset by unusual noise characteristics. These must be guarded against.

Attention to the design of hydraulic and mechanical systems for the movable control surface is necessary in order to guard against noise, particularly in low speed quiet operations.

Influence of Overall System on Noise Level

The advantages and disadvantages are similar to those of other free-flooding turboelectric systems. Although the propeller frequencies are higher, the resultant propeller noise may be reduced in all cases.

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Detailed Description  
Controllable Pod Motor  
with Sail Pods

#### CONTROLLABLE POD MOTOR SYSTEM WITH SAIL PODS

This system consists of the preceding system with four pods located on the stern control surfaces and two pods with shrouded propellers located on the sail control surfaces. An artist's conception of the ship and machinery is shown in Figure 31.

#### Electrical Design

A one-line diagram of the system is shown in Figure 32. Propulsion power is developed in two 2400 rpm AC turbine generator sets, and is delivered to six 400 rpm motors, each of which drives a separate propeller. Propeller speeds are controlled by varying the turbine speeds. Backing is accomplished by electrical switching. As can be seen in Figure 31, the motors are located outside the pressure hull and operate free flooding.

The turbine generator sets are standard hardware. The propulsion control panels are also standard hardware, and include excitation control, protective relaying, metering, and switching equipment. While a switching type reversing scheme is optional in the preceding system, it is required here, since the two forward pods are used for hovering, which requires frequent and fast propeller reversals. Reversal of the turbines is impractical for this purpose since it occurs an order of magnitude too slowly.

With a turbine generator set running at 35% speed, in excess of 100% motor torque is available over most of the motor speed range during hovering. The switching arrangement is very flexible, allowing the port and starboard pods to be energized from their respective turbine generator sets during normal operation, and the sail pods and stern pods to be energized from separate turbine generator sets while hovering.

The hull electrical penetrations are similar to those for the novel electric propulsion system motors.

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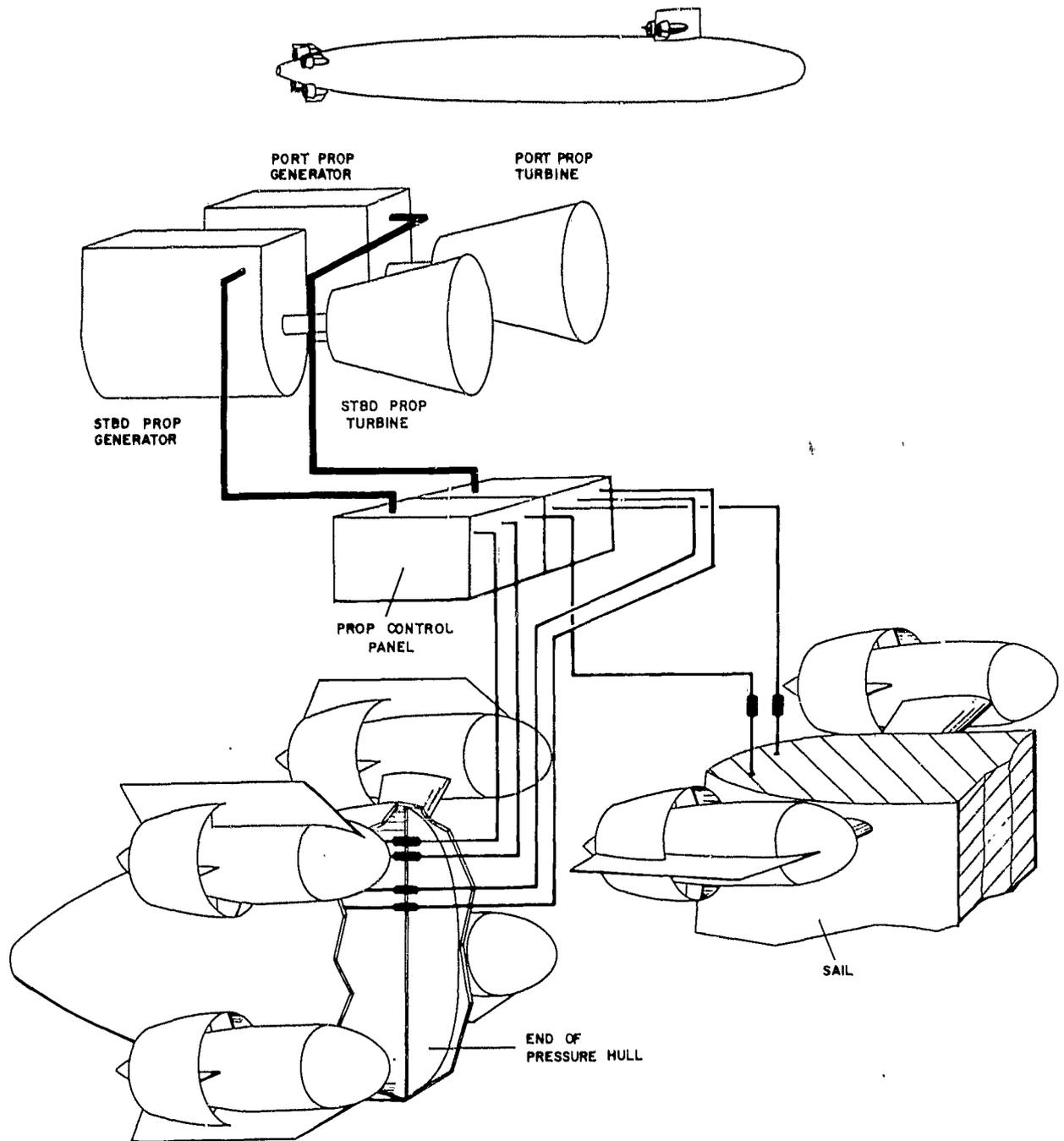


Figure 31 Controllable Pod Motor System with Sail Pods, Ship and Propulsion Machinery

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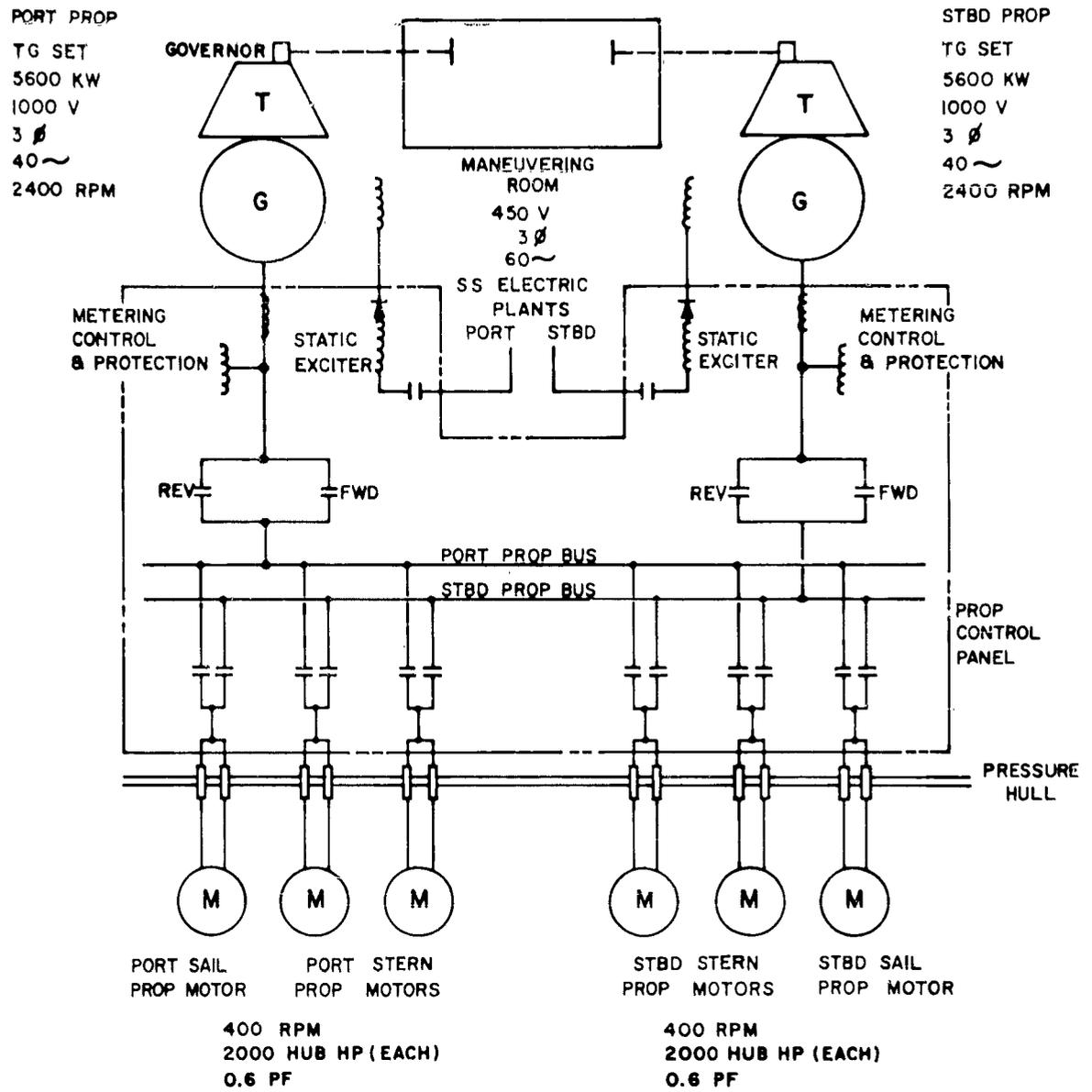


Figure 32 · Controllable Pod Motor System with Sail Pods, Electric Power One-line Diagram

A cross sectional view of a motor and propeller is shown in Figure 33. Except for the smaller rating, the electrical design of the motors is substantially the same as for the controllable pod motor system motors (page 117).

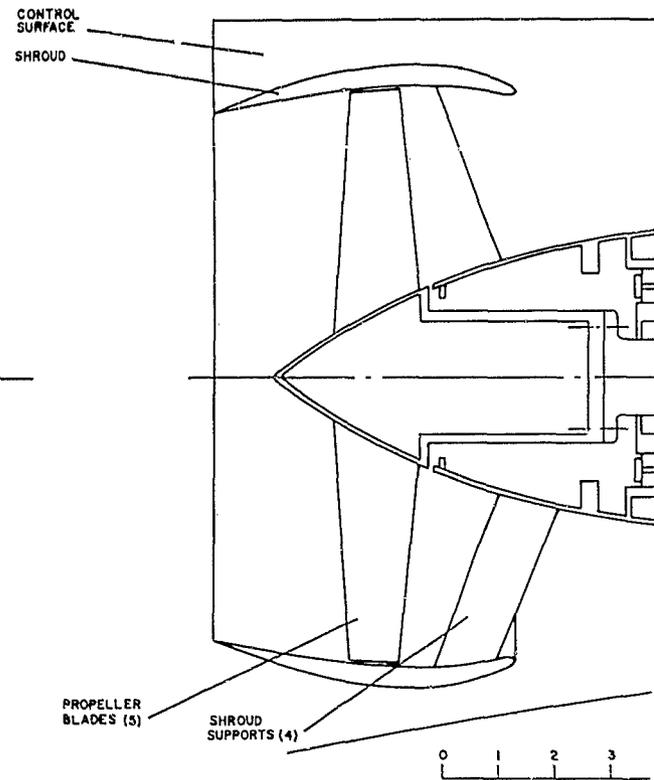
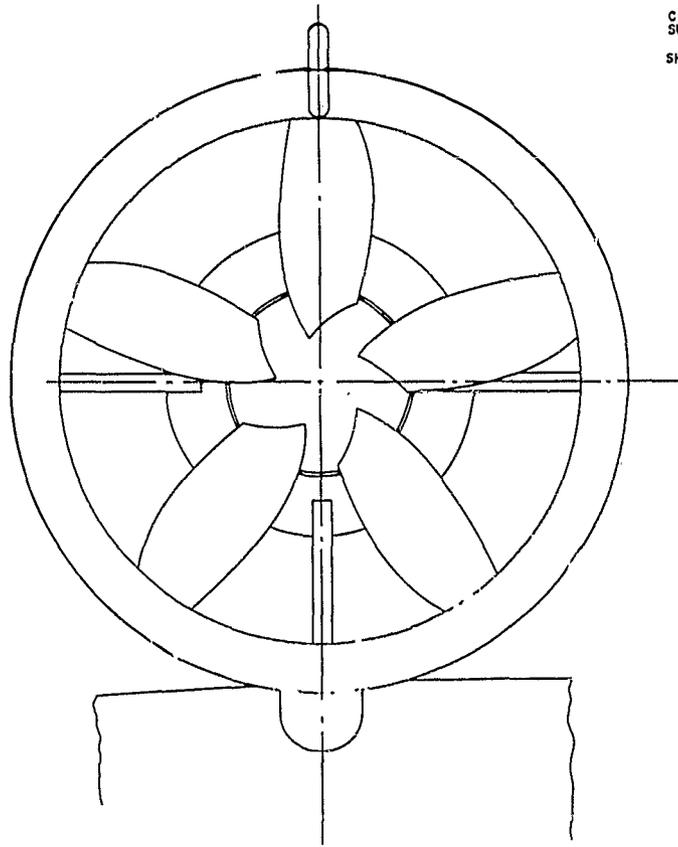
Motor electrical loss is 10%, and generator total loss is 2%. A summary of losses is included later in the hydrodynamics portion.

#### Mechanical Design

Movable control surfaces incorporating the pods are fitted at the stern and on the sail. All are actuated by hydraulic rams. The stern surfaces are mounted in an X arrangement to minimize draft, beam, and emergence of the top pods when the ship is surfaced. The sail pods are of course completely clear of the water when the ship is surfaced. All pods have sufficient range of movement to be tilted so as to be in planes transverse to the ship centerline for hovering.

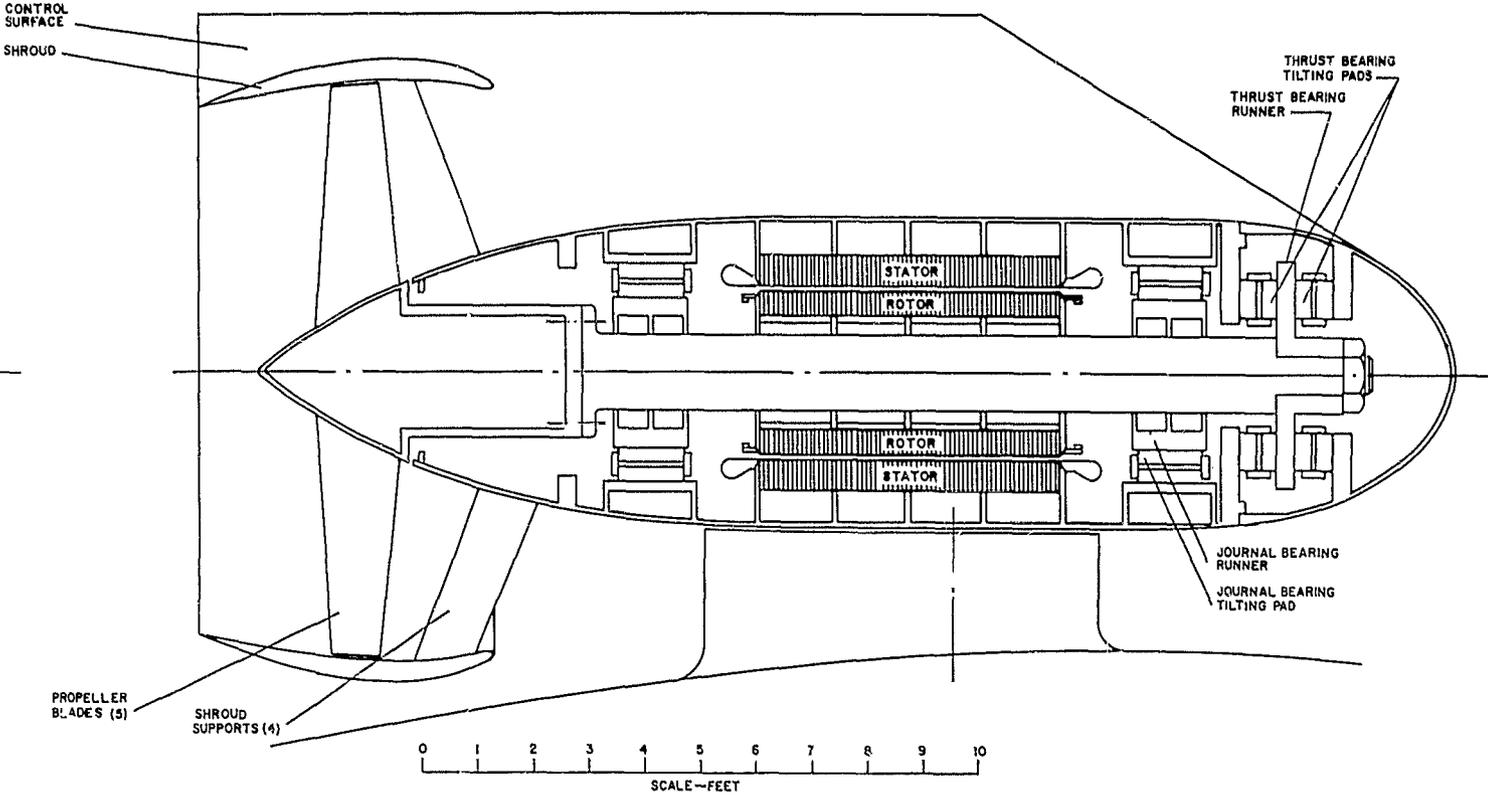
The mechanical design of this system is much the same as for the controllable pod motor system (page 120). The stern pods are similar, except smaller. The sail pods, one of which is shown in Figure 33, have different propellers and shrouds and do not have stator blades, so as to provide the necessary reverse thrust for hovering. Thus, for the sail pods the shroud need not support the stator blades or the stationary fairing aft of the propellers; in this case the fairing rotates with the propeller. The six motors are identical, and only the hydrodynamic parts are different.

The machinery length and weight are shown by major components in Table 29. The lengths correspond to propulsion turbine generator sets side by side, hull penetrations side by side, stern pods side by side, and sail pods side by side. In addition, credit is shown for certain conventional ship control equipment which is eliminated.



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Figure 33 Controllable Pod Motor System with Sail Pods, Propulsion Motor and Propeller, Sail Pod

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TABLE 29 - Controllable Pod Motor System with Sail Pods,  
 Machinery Length and Weight  
 (Data shown is for one ship)

<u>Item</u>	<u>Length in ship, ft</u>	<u>Weight, lb</u>
2 Propulsion turbine generator sets	30.0	358,000
1 Propulsion control panel	3.0	16,000
12 Hull electrical penetrations	3.0	6,000
6 Propulsion motors and propellers	<u>44.0</u>	<u>459,000</u>
Total	80.0	839,000
- Sail control surfaces		23,000
- Stern fixed and movable control surfaces		140,000
- Hovering equipment		<u>75,000</u>
Total		238,000
Net Weight		601,000

Motor friction loss is 2% and motor windage loss is 9%. This windage loss includes the loss for the entire rotating assembly except the surface of the propeller hub fair with the pod.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

Hydrodynamic Design

This system consists of four pods on the stern, mounted as in the previous system, and two pods mounted on the sail. The pods on the sail provide hovering control prior to and during missile firing.

Due to the function of the sail pods, the configuration of the propulsors in these pods differs from those in the stern pods. Since

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positive and negative thrust are necessary for a hovering control, these propulsors must have comparable performance for forward and reverse speed; this necessitates that they have no stator blades. Since they will be used for control during vessel movement, the added control surface of a shroud is necessary. To obtain a reasonable propulsive efficiency without a stator section, the propeller diameter must be increased. With the diameter increased, the minimum cavitation depth is increased.

All six pods are of equal power with a speed of 400 rpm. The analysis of performance of the stern pods is identical to the analysis for the previous system (page 124). Figure 34 shows the effects of diameter on stern pod propulsive efficiency. A hub diameter of 4 ft and a tip diameter of 8 ft result in an estimated cavitation-free depth of 90 ft and a propulsive efficiency of 0.76 for these stern pods.

The shrouded propellers in the sail have a tip diameter of 10 ft, a hub diameter of 2 ft, and a shroud length of 5 ft, resulting in an estimated cavitation-free depth of 200 ft and a propulsive efficiency of 0.60.

The combined propulsive efficiency for this configuration is 0.72, with a full power cavitation-free depth of 200 ft to the centerline of the sail pods.

Although the propulsive efficiency for this configuration is similar to that of the geared drive turbine system, the shaft horsepower available to the propulsors is less due to the machinery losses. The net result is that the maximum speed is 19.3 knots. The pumpjet propulsors have poor reverse thrust characteristics.

The underway stability and control for this system are the same as for the previous system (page 127), and comments with respect to slow speed control also apply. In this case the turning moment for zero

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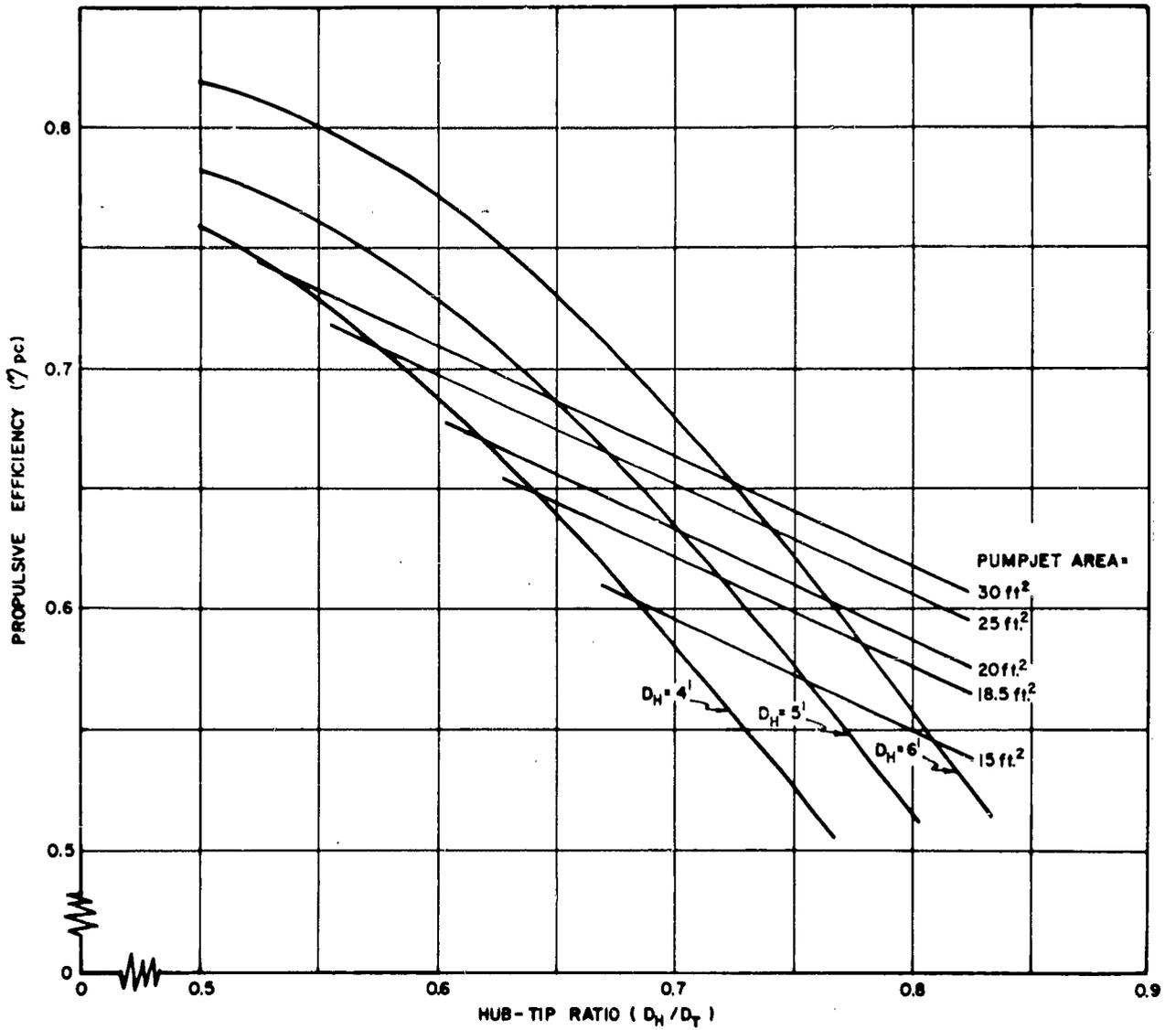


Figure 34 Controllable Pod Motor System with Sail Pods, Propulsive Efficiency vs Hub-Tip Ratio

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advance speed is about 4 million lb ft for a 30° pod angle, and is again twice as large for a 90° pod angle. While surfaced, the sail pods are of course not useful for propulsion or control.

A summary power balance is shown in Table 30.

TABLE 30 - Controllable Pod Motor System  
with Sail Pods, Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	2
Motor electrical loss	10
Motor friction loss	2
Motor windage loss	9
Propulsor loss	21
Effective horsepower	56
Overall propulsive efficiency, EHP/Turbine shp	56%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	72%

Hovering control is accomplished with the sail pods tilted to a vertical position. The two sail pods each furnish a force on the order of 27,000 lb for zero advance speed, or a total force of 54,000 lb. The thrust rate is related to the propeller acceleration in a non-linear manner and the maximum value is about 40,000 lb/second. The stern pods are used for trim control while hovering.

Comments with respect to hovering for the tandem propeller system (page 100) apply here also. Again, a slight improvement is possible with respect to minimizing depth error, and there are advantageous incidental features.

Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22.

AC Propulsion Generator - See novel electric propulsion system page 81.

Free-flooding AC Propulsion Motors in Pods - See controllable pod motor system, page 128.

Pod-mounted Pumpjets and Shrouded Propellers - The pumpjets located on the stern control surfaces are similar to those of the previous system (page 129). The two shrouded propellers located on the sail also have the advantages of reduced propeller radiation and cavitation level. In addition, the absence of stator blades may reduce the thrust modulation vibrations. Unfortunately, their location in proximity to the bow sonar gear is an unfavorable feature.

Torsional vibrations may also be generated by the sail-mounted pods. The thrust produced by the sail-mounted propulsion pods exerts a large moment on the hull, thereby exciting beam modes in the vertical plane. Although these modes are inefficient radiators, they tend to produce strong near field sound waves which largely contribute to the self-noise of the submarine.

Influence of Overall System on Noise Level

Except for the undesirable effects on sonar operation by the two forward pods, the comments of the previous system (page 130) apply also to this propulsion system.

## CYCLOIDAL PROPELLER SYSTEM

This system consists of four cycloidal propellers located near the stern of the ship and driven by free-flooding electric motors within the hull envelope but outside the pressure hull, and two cycloidal propellers located on the sail and driven similarly. An artist's conception of the ship and machinery is shown in Figure 35.

Electrical Design

A one-line diagram of the system is shown in Figure 36. Propulsion power is developed in two 4800 rpm AC turbine generator sets, and is delivered to six 240 rpm motors. Propeller speeds are controlled by varying the turbine speeds. Propeller thrust can be in any direction perpendicular to its axis, and both backing and ship control are accomplished by pitch change. The ship is not intrinsically directionally stable, and an automatic control system is included to render it effectively stable. Each propeller includes an oil-filled hub containing mechanical pitch changing equipment and an oil-filled hydraulic or electric control mechanism for the hub internals. As can be seen in Figure 35, the motors are located outside the pressure hull, and operate free flooding.

The turbine generator sets are standard hardware. The propulsion control panels are also standard hardware and include excitation control, protective relaying, metering, and switching equipment. Switching is included for interchanging the propeller and turbine generator connections for hovering. The arrangement is very flexible, allowing the port and starboard motors to be energized from their respective turbine generator sets during normal operation, and the sail pods and stern pods to be energized from separate turbine generator sets while hovering. In operation, the motors follow the turbine speeds nearly synchronously.

Hull electrical penetrations are similar to those for the novel electric propulsion system motors.

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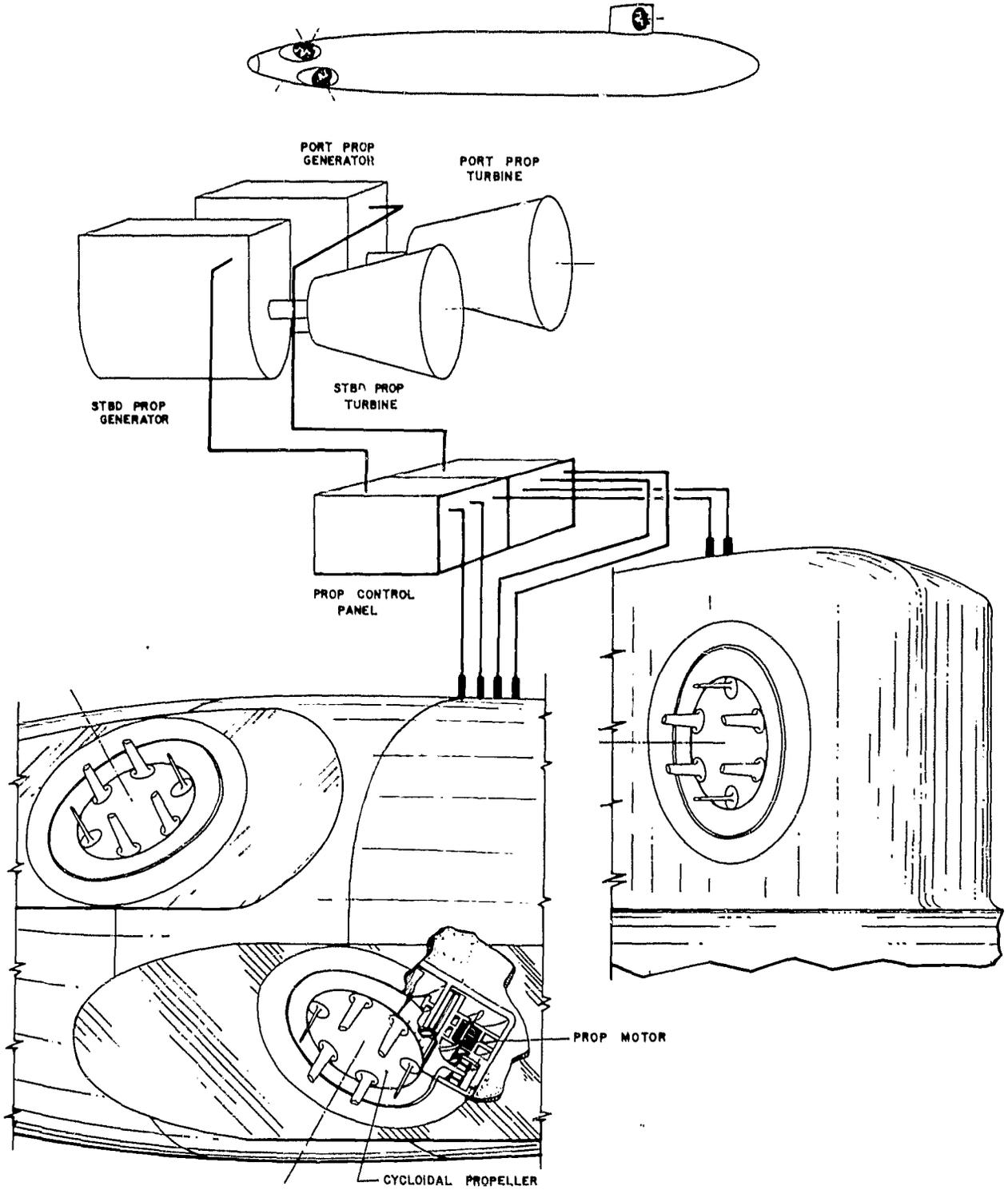


Figure 35 Cycloidal Propeller System, Ship and Propulsion Machinery

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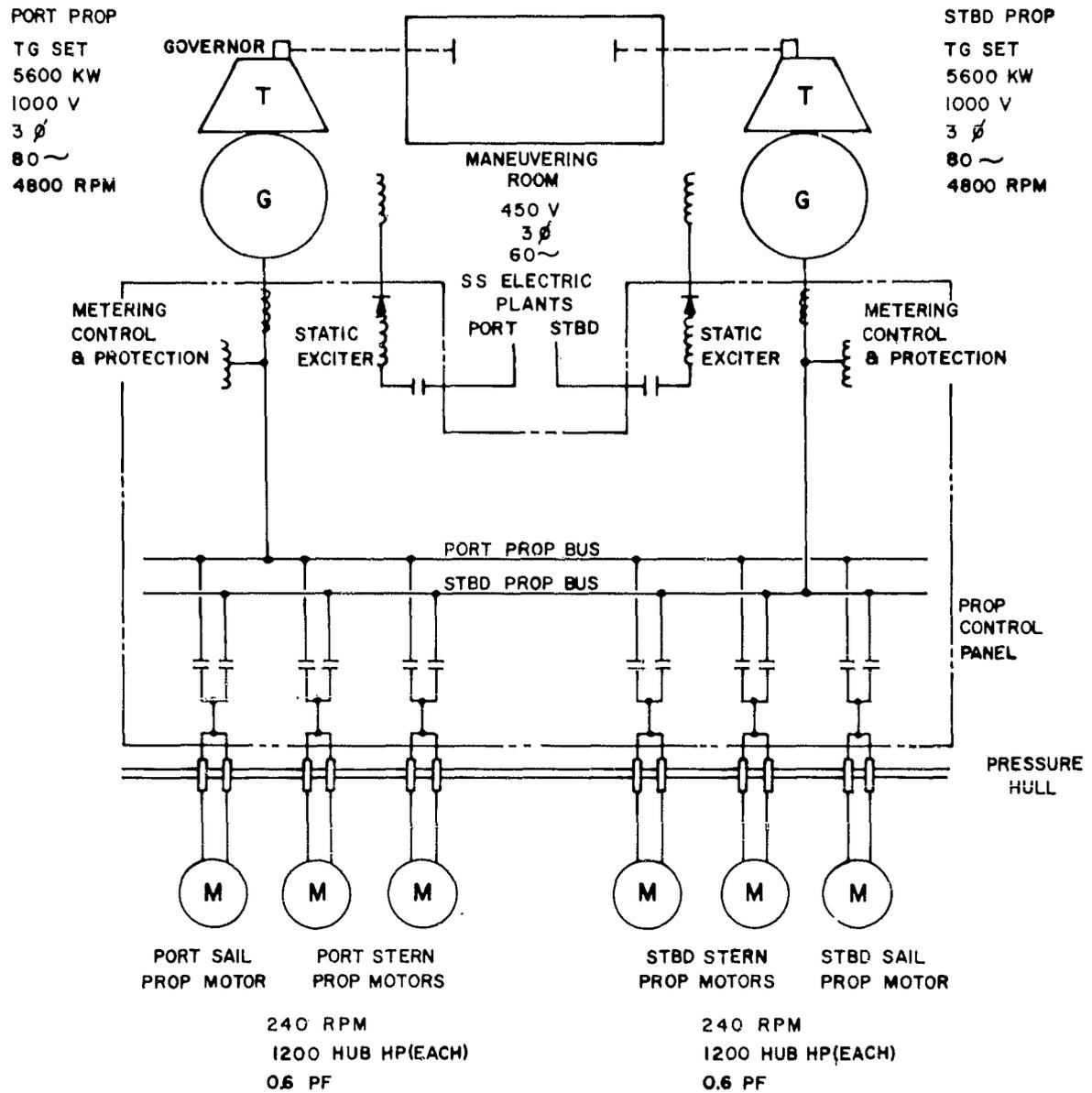


Figure 36 Cycloidal Propeller System, Electric Power One-line Diagram

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A cross sectional view of a motor and propeller is shown in Figure 37. The motors are squirrel cage induction machines, with the rotor inside the stator in the conventional manner. The environmental protection is the same as for the novel electric propulsion system motors (page 72).

Motor electrical loss is 15% and generator total loss is 2%. A summary of losses is included later in the hydrodynamics portion.

#### Mechanical Design

Since ship control forces are provided by the propellers, conventional fixed and movable control surfaces are omitted from both the stern and the sail. The sail-mounted propellers serve not only for normal propulsion and control but also for hovering control. The stern propellers are mounted in an X arrangement to minimize draft, beam, and emergence of the top propellers when the ship is surfaced. The sail propellers are, of course, completely clear of the water when the ship is surfaced.

The inboard machinery is a collection of conventional hardware, while much of the outboard machinery is of course new. The turbine generator sets are vibration isolated. The motors are built in something analogous to the frame of a conventional machine. This frame is free flooding and, therefore, dimensionally insensitive to submergence pressure. The frame is foundationed on free-flooding structure, and the motor rotor, pitch control mechanism, and propeller hub are assembled axially from the outboard end, with the outboard thrust bearing pads temporarily unbolted. The bearings are of the same type as those in the novel electric propulsion system motors (page 74). The cycloidal propeller has blade actuating and control mechanisms filled with oil equalized to sea pressure so as to run in a flooded environment, but is otherwise quite similar to its surface ship counterpart.

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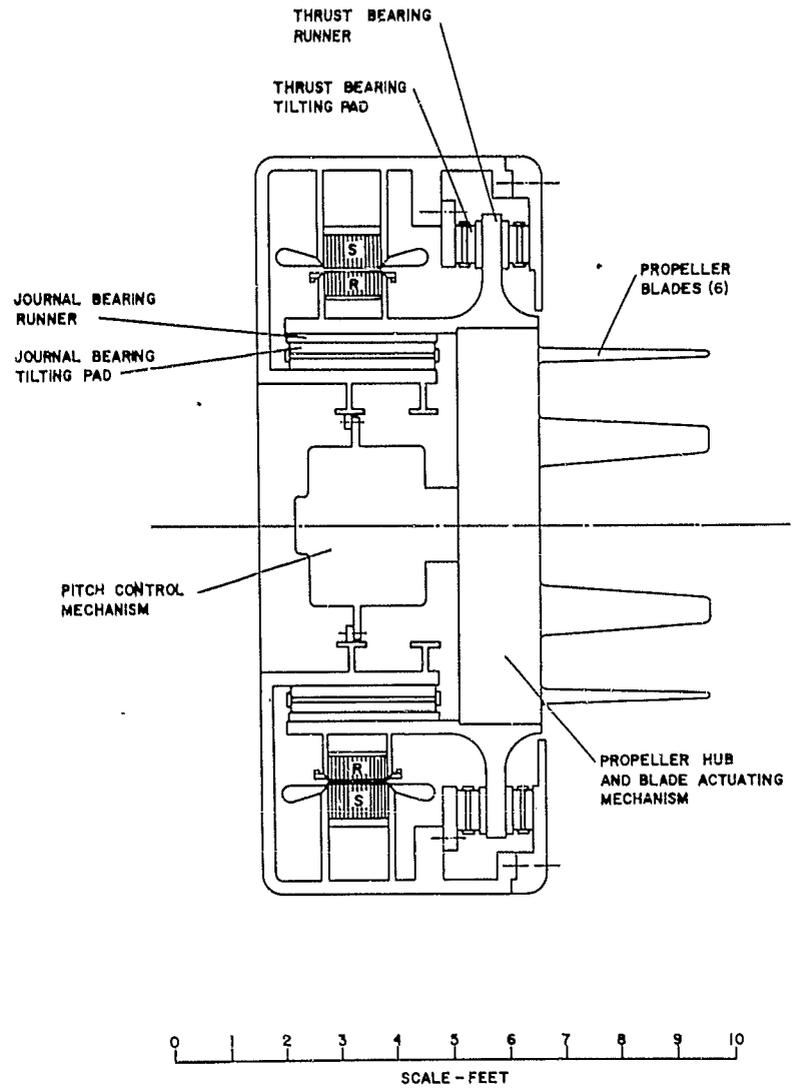


Figure 37 Cycloidal Propeller System, Propulsion Motor and Propeller

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Cycloidal propellers are not a recent development, nor is their application to submarines unprecedented (Germany started such a development for U-boats in WW II). However, until recent years, there has been very little interest generated in the United States regarding these units. Consequently, its principles of operation are briefly discussed here.

A schematic diagram of the cycloidal propeller is shown in Figure 38. The blades occupy certain points, B, on the orbit circle. The perpendiculars to the chordlines of these blades all converge at one point, N, called the steering center. The amount that the steering center is displaced from the orbit center, O, is a measure of the pitch, and by definition the pitch ratio  $p/d = (ON/OB)\pi$ . By moving the steering center along the x-x axis, a continuously variable range of pitch ratios is achieved, from full ahead through zero to full reverse. (The steering center in the actual propeller moves only a few inches, but this small movement is mechanically amplified by levers to produce the large movement required of imaginary point N.) The maximum pitch ratio cannot exceed much more than  $0.80\pi$  because of mechanical impracticalities. However, this is high enough to yield satisfactory propeller efficiencies.

Figure 38 also indicates the relationship between the location of the steering center and the direction of thrust. Angular movement of point N about point O effects a corresponding angular change of the thrust vector about point O. Thus, the steering center may be moved radially out from the orbit center as well as angularly about it, constituting the pitch and thrust direction control, respectively.

The pitch and thrust direction mechanisms in the hub are driven by two independent concentric shafts entering the hub opposite the blades.

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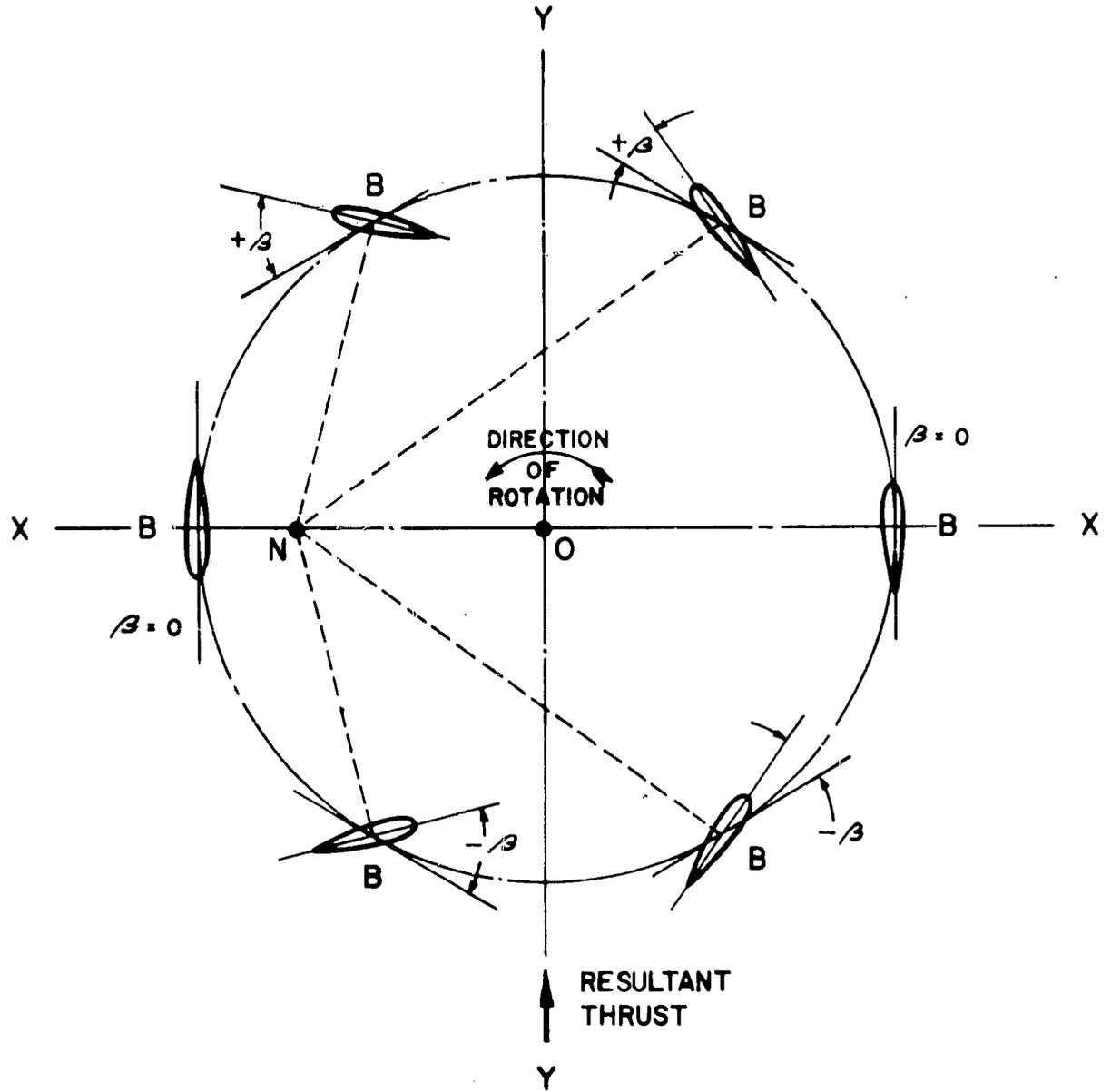


Figure 38 Cycloidal Propeller System,  
Propeller Schematic Diagram

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**Detailed Description  
Cycloidal Propeller**

Each shaft is actuated by an electric or hydraulic motor through a worm gear. The time to reach diametrically opposite extremes for pitch and thrust direction control is about one second.

All moving parts are either free flooded or immersed in oil equalized to sea pressure. The hub, propeller blades, blade actuating mechanism, and pitch control mechanism constitute a single package which is easily removed from the hull for inspection or replacement. Replacement of just the blades may be done without removing the entire assembly.

The mechanical complexity of the cycloidal propeller at first appears objectionable when compared with a conventional screw propeller. However, the cycloidal propeller replaces other complex equipment, such as the entire hydraulic control system for conventional control surfaces and the conventional hovering system, as well as eliminating the astern stages and associated equipment in the conventional turbines.

Comments with respect to maintenance and reliability for the novel electric propulsion system (page 74) apply here also.

Casualty control is further improved by the presence of six mechanically and electrically separated propellers and motors. While the cycloidal propeller blades appear particularly vulnerable to damage, they have in some instances proved more durable than screw propellers. Furthermore, the propeller is designed so that the blades will break without damaging the remainder of the mechanism, and it can continue running without gross degradation of performance even with half the blades missing.

The machinery length and weight are shown by major components in Table 31. The lengths correspond to propulsion turbine generator sets side by side, propulsion control panels side by side, stern hull penetrations side by side, and pairs of motors in tandem. In addition, credit is shown for certain conventional ship control equipment which is eliminated.

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TABLE 31 - Cycloidal Propeller System,  
Machinery Length and Weight  
(Data shown is for one ship)

<u>Item</u>	<u>Length in ship, ft</u>	<u>Weight, lb</u>
2 Propulsion turbine generator sets	24.0	250,000
1 Propulsion control panel	3.0	16,000
12 Hull electrical penetrations	3.0	6,000
6 Propulsion motors and propellers	<u>39.0</u>	<u>960,000</u>
Total	69.0	1,232,000
- Control surfaces and appurtenances		213,000
- Hydraulic equipment		22,000
- Hovering equipment		75,000
Total		<u>310,000</u>
Net Weight		922,000

Motor friction loss is 6% and windage loss is 32%. This windage loss includes the loss for the entire rotating assembly except the surface of the propeller hub fair with the hull.

The motor configuration leaves a 6-foot square access to the stern for sonar or armament. With no conventional control surfaces, there are no supporting stocks in way of this access. The bow remains completely free of propulsion machinery.

The motor frame size is such that it will not fair at all well into a circular hull of reasonable diameter near the stern. However, since this part of the hull is free flooding, it is not essential that it be absolutely circular. The two forward motors necessitate a major enlargement of the sail.

Development of the propulsion motors and hull penetrations is much the same as for the novel electric propulsion system (page 69). Cycloidal propellers have been built in this size, and development is straightforward, consisting primarily of adapting it to the environment and minimizing noise generation.

The crew size is the same as for the geared drive turbine system, although there is some variation in duties of several of the men.

Hydrodynamic Design

This system consists of six cycloidal propellers, four mounted on the stern and two mounted on the sail. The sail propellers provide hovering control prior to and during missile firing.

All six propellers are of equal power, size, and configuration. The propeller details are shown in Table 32.

TABLE 32 - Cycloidal Propeller System,  
Propeller Details

Orbit diameter	6 ft
Propeller speed	240 rpm
Eccentricity setting of propeller	0.8
Advance coefficient	0.45
Number of blades	6
Height of blades	3 ft
Blade chord at root	1.0 ft
Blade sections	Symmetrical

Dimensions presented in Table 32 are based on a true cycloidal blade motion. The net thrust produced by these propellers is perpendicular to the axis and its direction is determined by the angular location of the steering center of the blades. This angular orientation can be changed to orient the thrust in any direction in the plane normal to the propeller axis.

The propulsive efficiency was computed by the method outlined in Reference 8 and determined to be 0.60. This results in a maximum speed of 15.5 knots.

Due to the lack of cavitation test data, cavitation performance of these propellers can only be speculative. But due to the cycloidal motion, the angle of attack of the blade section changes with rotation of the rotor; blade suction cavitation will probably occur at the higher angles of attack. However, each blade experiences this high angle of attack twice during each cycle, and since the occurrence of cavitation is not instantaneous, cavitation may be suppressed.

The available force for control at high speeds is much less than the force available from the conventional control surfaces. However, control is improved at very low speeds. For zero advance speed, a maximum turning moment of about 18 million lb ft is realized. The ship is not directionally stable, and an automatic control system is necessary to make it effectively stable.

A summary power balance is shown in Table 33.

TABLE 33 - Cycloidal Propeller System,  
Power Balance

<u>Item</u>	<u>% of turbine Shp</u>
Turbine shaft power	100
Generator loss	2
Motor electrical loss	15
Motor friction loss	6
Motor windage loss	32
Propulsor mechanical and hydrodynamic loss	20
Effective horsepower	25
Overall propulsive efficiency, EHP/Turbine shp	25%
Hydrodynamic propulsive efficiency, EHP/Propeller hub hp	60%

Hovering control is accomplished with the sail propellers. The two sail propellers each furnish an upward force of about 30,000 lb, or a total force of 60,000 lb. The thrust rate is about 120,000 lb/second. The stern propellers are used for trim control during hovering.

Comments with respect to hovering for the tandem propeller system apply here also. Again, a slight improvement is possible with respect to minimizing depth error, and there are advantageous incidental features.

#### Acoustic Design

Noise Contribution by Propulsion System Components

Steam Turbines - See geared drive turbine system, page 22 , and novel electric propulsion system, page 80.

AC Propulsion Generators - See novel electric propulsion system, page 81.

Free-flooding AC Propulsion Motors - See novel electric propulsion system, page 81.

Cycloidal Propellers - Little detail is known about the forces involved in such a propeller system. In addition to the noise sources previously described that are common to a machine directly coupled to the water (page 81 ), this system has additional mechanisms and moving parts necessary to continuously oscillate each propeller blade in its hub. In noise control it is axiomatic that increasing the moving parts and types of motion, i.e., rotary, reciprocating, oscillatory, etc., will increase the types and level of noise.

It is not clear how blade rate would be generated in such a device. Certainly, there are big differences between propellers oriented  $90^\circ$  to wakes vs near parallel orientation to wakes, as with the cycloidal system. Blade passing frequency is expected to be much different and/or minimized. The absence of control surfaces and the X arrangement of the four stern propellers also suggest lower blade rate. Unfortunately, two units are located in the sail which impair sonar and overall acoustic performance.

## IV

**COMPARISON OF SYSTEMS**

This section compares the eleven submarine propulsion systems considered in this report. Those variables which do not significantly affect the results are first segregated and dismissed, after which the significant variables are discussed, with particular emphasis on acoustics. This is followed by a general discussion of the systems.

**VARIABLES WHICH DO NOT AFFECT RESULTS**

Those variables which do not significantly affect the results of the comparison are first dismissed, so that they do not becloud the principal issues. This does not imply that these variables are unimportant, but rather that there is not much difference between systems in these respects, or that the variable is not readily susceptible to evaluation. The items discussed here are reliability and casualty control, installation, maintenance, manning, and cost.

Reliability of all of the systems is not equal, but is in all cases acceptable. In many cases, improved casualty control operates to counterbalance reductions in reliability, so as to allow continued operation after a failure does occur. The auxiliary systems strongly affect, and in some cases largely determine, the overall reliability.

Installation is markedly different for each type of system, but is in all cases practical.

Scheduled maintenance is different for each type of system, but not burdensome for any. Breakdown maintenance on the flooded propulsion motors does require drydocking the ship for access, but conversely all parts can be replaced without opening the pressure hull. Most maintenance is confined to the auxiliary machinery rather than the main machinery.

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Manning is identical in number for all systems, although there is some variation in duties of a few of the crew. Manning for the electric propulsion systems is not greater than for the all-mechanical systems because the propulsion control panels are not normally manned stations; what little manual control is required is exercised from the steam plant control panel. Credit for one-man control of pitch and yaw in the tandem propeller system is not taken, since this is an option which can be exercised for the other systems also using a method such as SQUIRE.

Except for the geared drive turbine system, cost is difficult to determine with any reasonable degree of confidence. However, while cost will vary considerably, it is not in any case believed to be so high as to disqualify any system for cost alone.

#### VARIABLES WHICH DO AFFECT RESULTS

Table 34 (page 175) shows a summary comparison of the systems. The first group of items are operational parameters and are important unto themselves. The second group of items affect the operational parameters and, thus, are indirectly important. The items are discussed in the order shown.

#### Noise

Table 35 (page 177) is a summary of acoustic features of the eleven systems, including advantages, disadvantages, possible areas of improvement, and areas for study. The following comments supplement those in Table 35.

One overall aspect of the propulsion systems surveyed is that the components of the last six systems in Table 35 weigh from 300 to 500 tons. With the exception of the tandem propeller system which has part of the weight forward, placing such large masses at one end of the hull causes the driving point impedance of the low order hull modes to increase. This results in larger amplitudes of vibration near the bow and reduced

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amplitudes near the stern\*, and may result in an overall lower radiated noise due to thrust modulation. However, the dynamic effects of the large weights are minimized when they are vibration isolated, and in such cases the masses are de-coupled from the hull as long as their frequency of vibration is sufficiently above the natural frequency of the mounting.

The three all-mechanical systems, which are really the currently existing system with variations, have S5W type main and auxiliary plants, while the turboelectric systems have new auxiliary plants designed to substantially improve acoustic performance. While this at first appears to introduce another variable into the comparison of systems, actually it recognizes the practical matter that auxiliary plant changes for the existing type of system will be evolutionary rather than revolutionary, and that a comprehensive new design of the auxiliary plant will only be undertaken in conjunction with new main machinery.

The acyclic electric system offers potential order-of-magnitude gains acoustically and, therefore, is worthy of serious study. It is recognized that there are many engineering problems which must be solved. The fact that propeller noise will remain essentially unchanged from conventional systems constitutes a serious disadvantage, and concurrent study of other types of propulsors is also required.

The AC-DC electric system offers attractive possibilities, particularly in the area of auxiliary systems. As in the case of the acyclic system, the propeller-shafting design requires further study. The turboelectric plants have the advantage of no main shaft coupling to the main engine, but balancing and isolation effectiveness of large machines must be developed to a higher state.

The novel electric propulsion system has several unique advantages due to the low speed counter-rotating propellers. Low tip speed and reduced

\*In current designs the amplitudes in all modes are highest at the stern.

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blade loading minimize blade rotation noise, both radiated and near field. In addition, reduced thrust modulation can be expected. The advantages of counter-rotation appear in a further reduction of rotation noise and thrust modulation. The low blade rate frequencies are an advantage over higher blade rate propulsion systems in that the detectability is reduced due to the higher ambient levels at low frequencies. Further study is required on the effect of near field pressures acting directly on the adjacent hull. The externally mounted machinery which is directly coupled to the hull constitutes a potential problem. Externally located machinery, however, should radiate only from a limited region of the hull if isolation breaks, discontinuities, and isolation mounts are successful in decoupling the propulsion section from the adjoining hull. Acoustical treatment of the limited region, for example, using  $\rho c$  coatings\* is entirely feasible and should prove effective.

The controllable pod motor system also has attractive acoustical features which are predominantly associated with propeller noise. There are, however, conflicting questions such as whether the reduced thrust variations are offset by higher blade frequencies and more efficient direct radiation through the motor pods. As is the case with the novel electric propulsion system, the concept appears to be amenable to thorough noise control measures such as coating of the shrouds and support structures. Also, reduction of structureborne sound to the hull via the steering planes is also feasible. There is a lower interaction with the hull via the fluid-borne path due to a somewhat larger spacing. Shrouds reduce cavitation noise radiation and propeller rotation noise. The pod location minimizes the effects of an unsymmetrical wake due to the sail, and will operate in the free stream. This is an important advantage in terms of reduced thrust variations. The shrouds themselves help

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\* $\rho c$  refers to pressure release coating, not  $\rho c$  matching with water.

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to produce a uniform inflow to the rotor blades. For a lower noise level, lower rpm and reduced rotor weight are desirable.

The pumpjet system is based on the conventional S5W auxiliary plant and propulsion machinery. The pumpjet does offer acoustical gains in lower propeller noise, but it is necessary to redesign the entire propulsion and auxiliary plant to obtain the necessary acoustical gains which are possible with the turboelectric systems.

The geared drive turbine system has several serious limiting acoustical characteristics such as blade rate, main turbine for certain submarines, S5W auxiliary plant, and highly variable self-noise characteristics. In the case of the SSB(N)608 class, however, low speed bow self-noise is very favorable. Inboard systems requiring a hull penetrating shaft have the disadvantage that all noise control measures are limited by the flanking path consisting of the shaft and its seals, bearings, and couplings. In addition, other flanking paths within the hull are very numerous and the whole hull is a potential radiating surface. Current redesign efforts are making significant improvements, particularly in the low power conditions of the auxiliary plant. However, the most efficient and effective acoustical improvements require new, imaginative approaches.

Finally, a few general remarks should aid in comparing the various systems:

Systems, in which auxiliary load demand is met as the propeller power and rpm change, have the advantage of minimum detectability and maximum sonar hearing ability at all speeds.

The location of propulsion and auxiliary machinery and, in fact, other subsidiary electronic and electrical cooling systems must be minimized in the forward areas to avoid low speed self-noise interference. It is also important to realize that the sonar base

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line is an extended one for several systems and, therefore, the effort to provide a quiet environment in mid and stern locations must continue. The goal of providing a uniformly quiet platform with noise levels comparable to ambient sea noise is, however, very difficult to accomplish and, therefore, the bow area must continue to be a sonar area as far as possible.

This basic requirement also applies to medium speed ranges where flow-induced noise begins to predominate. The bow area with the most favorable hydrodynamic form and boundary layer conditions offers the most promise for extending passive sonar capability over a wider speed range.

It is possible that remotely-towed sonars may give a new dimension to submarine sonar capability. This development might in the future provide more flexibility in the choice and location of hull-mounted propulsion systems.

#### Ship Control

Conventional control surfaces provide ample directional stability and control at high ship speed, and no effort was made to improve upon this. All systems offer substantially this performance, except the tandem propeller and cycloidal propeller systems. These systems require automatic control systems to render the ship effectively directionally stable (although the shroud on the stern tandem propeller contributes some stabilizing force), and both provide lower control forces at high ship speeds. Their control forces are inherently limited since they are developed by the propellers, and can thus only be a fraction of the ahead thrust. By comparison, the conventional rudders are favorably located for exerting a turning moment, and develop a transverse force of about 500,000 lb at full speed, which is nearly 3 times rated ahead propeller thrust. However, the comparison is not quite so extreme when it is recognized that the conventional control surfaces are sized for

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Systems Comparison  
Ship Control

stability rather than control, and that some reduction in high speed control force could be accepted without serious consequence.

At very low ship speed, the situation is reversed. Control forces from conventional control surfaces become smaller with decreasing ship speed, as shown in Figure 22 (page 98), and are zero at zero speed. Control forces from the tandem propeller system also decrease with ship speed, but the available turning moment at zero speed is still about 9 million lb ft. Variation of control force with ship speed for the cycloidal propeller is unknown, but the available turning moment at zero speed is about 18 million lb ft. Since the thrust can be directed, the controllable pod motor system and the controllable pod motor system with sail pods also offer somewhat improved slow speed control if the propeller speed is briefly increased during the maneuver. Under this condition and with a normal pod angle of  $30^{\circ}$ , the turning moments available at zero speed are about 6 million and 4 million lb ft, respectively. The novel electric propulsion system also offers improved control under this condition, since the control surfaces deflect the propeller slip stream.

Three of the systems provide vertical thrust for hovering in lieu of a ballasting type control. The maximum vertical force available is 52,000 lb for the tandem propeller system, 54,000 lb for the controllable pod motor system with sail pods, and 60,000 lb for the cycloidal propeller system.\* The rapid control of thrust magnitude and direction

\*Still another approach is a thruster type hovering system with identical units beyond each end of the pressure hull, each consisting of a vertical duct enclosing a controllable and reversible pitch propeller driven by a flooded motor. Such a system capable of producing a total vertical force of 50,000 lb and a force rate of 50,000 lb/sec has very roughly these parameters: 86-inch diameter ducts, 2,000 hp total motor shp, and 120,000 lb total weight.

allows faster and stronger reaction to disturbance forces, with a slight improvement in minimizing depth error. There is no opportunity for marked improvement, as can be seen by inspection of Table 22 (page 101). The low frequency disturbances are generally already handled satisfactorily by the ballasting system, and neither the ballasting nor thrust systems can appreciably counteract the high frequency disturbance forces (which fortunately do not seriously affect hovering). The three thrust systems do offer improvement with respect to the use of the high pressure air system and its noisy compressors for extended hovering. Considering departures from present practice, the performance of the thrust systems is not affected by submergence depth, and they offer potential for improved zero or slow speed depth keeping at periscope depth in heavy seas.

With respect to longitudinal control of the ship, backing performance varies somewhat between systems, but the major difference is that systems with pumpjet type propulsors have almost no backing thrust. Systems which have control of propeller pitch, full power available for backing, or both, exhibit improved backing performance.

While high speed ship control is generally adequate, and indeed some reduction would not be serious, there is a need for improved slow speed control. Four of the systems provide modestly improved slow speed control, but the two pod motor systems have little backing thrust and the two systems with cyclically variable pitch propellers require a marked sacrifice in high speed control. While backing requirements for stopping are often not rigidly fixed, thrust of at least the order of rated ahead thrust is normally required, and that furnished by the various pumpjet propulsors is an order of magnitude smaller. Hovering control is generally adequate, but improvement is useful; three of the systems provide slightly improved hovering, but at previously noted unfavorable tradeoffs. The tandem propeller system is unique in its ability to provide six-degree of freedom control of the ship.

CONFIDENTIAL

Systems Comparison  
Depth

By considering variations of the systems as described in this report, it is possible to make the backing performance of the two pod motor systems, which have pumpjet propulsors at the stern, satisfactory by removing the stator blades. This renders the propulsors simple shrouded propellers, which have backing thrust comparable to that of an open propeller. The shroud remains, providing stability and control for the ship. This change comes at some decrease in propulsive efficiency, increase in cavitation-free depth, and increase in propeller size. Another variation is sizing the lower pods with shrouded propellers for surfaced propulsion and surfaced and submerged backing, and retaining pumpjets on the upper pods for improved submerged propulsive efficiency.

#### Depth

The all-mechanical systems and the inboard turboelectric systems all require a propeller shaft to penetrate the hull. The rotating seal at this penetration has been troublesome at current submergence depths, and promises to be more so at greater depths. The hydrostatic thrust from sea pressure on the propeller shaft is currently less than rated propeller thrust and is simply carried by the thrust bearing. However, at greater depths this hydrostatic thrust will become burdensome.

The inboard/outboard turboelectric systems, with flooded propulsion motors, do not require this rotating hull penetration, and the nearest analogous component is the static electrical penetration. While the motor insulation has only been tested to 3500 psi, it is considered to be useful to 10,000 psi. This corresponds to 23,000 ft submergence, which encompasses the full depth of 98% of the ocean area.

There is a need for deeper submergence, and while sufficient ingenuity will allow going significantly deeper with the shaft penetration, the flooded motor offers a fundamentally different approach with a single solution for any conceivable depth of interest for a combatant submarine.

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There is of course much more to building a much deeper submergence ship than just solving shaft penetration problems. Since the hull weight is a larger percentage of the total weight, there is, naturally, interest in lighter rather than heavier machinery. However, there is also interest in placing equipment outboard so as to minimize the hull size, using buoyant materials for buoyancy. The flooded motors are amenable to this, and a substantial part of the void space in the motors themselves can be filled with buoyant material to carry a part of the motor weight.

Speed

Table 34 (page 175) shows the maximum ship speed for each system, with the SSB(N)616 for a reference hull. Only the pumpjet system offers a speed higher than that for the geared drive turbine system. In the remaining cases the speeds are lower. However, with the exception of the inboard flooded motor system and the cycloidal propeller system, the reduction in speed is less than 10%.

These speeds do not, in general, reflect model test data, but do nevertheless indicate approximately what can be expected.

Armament

Table 34 (page 175) shows the stern access available with each system. This access consists of a clear tunnel-shaped space extending from the after end of the pressure hull to the end of the ship. Its usefulness to the combatant submarine is in the general categories of sonar, particularly the towed variety, and weapons launching.

Stern access is only offered by the inboard/outboard turboelectric systems, with flooded propulsion motors. It permits towing from the most desirable part of the ship, the extreme after end, and affords excellent protection against fouling of cables of the towed devices. With respect to weapons launching, it affords the opportunity to launch with little or no restriction on ship speed.

The access size depends upon the application and design of the particular ship, but the sizes shown in Table 34 indicate roughly what can be expected. While some stern access can be obtained with geared machinery by the simple expedient of using two screws, the novel electric propulsion system and the tandem propeller system provide a large access, and the pod motor systems provide some freedom to locate the access off the centerline of the ship.

### Size

Size is difficult to evaluate, since it is most significant in the context of a fully arranged and optimized ship design, which as earlier noted could not be attempted. The comparison of sizes is therefore based upon the sum of the lengths of major components in each system, placed as they would probably be arranged in the ship. This gives a rough indication of the hull length required to enclose each system, since the major components occupy a large part of the hull cross section at their location.

Table 34 (page 175) shows this length for each system. With one exception, the systems are all about the same length as the geared drive turbine system, or else shorter. The AC-DC electric system is appreciably longer, but not apparent from the table is the fact that the ship service turbine generator sets also fit within this same length, which is not true of the other systems. Taking credit for this would reduce the length by 14 feet. Similarly, for the acyclic electric system credit is not taken for the saving of the turbine part of the ship service turbine generator set: 6 feet.

### Weight

The most significant weight for comparison is the surfaced displacement of a fully arranged and optimized ship design, but this could not be attempted. The comparison of weights is therefore based upon the sum of the weights of the major components in each system. Where applicable,

credit is taken for the weight of ship control and ship service electric plant components which are eliminated because their functions are performed by the propulsion system, and the net weights are used for comparison purposes. For lack of better information, differences in displacements can be assumed, to a first approximation, to be proportional to differences in net system weights.

Table 34 (page 175) shows the weight for each system. Generally, it reflects two factors operating simultaneously:

Weight increases as rpm decreases

Electric machinery weighs more than mechanical machinery, and inboard/outboard electric machinery weighs more than inboard electric machinery.

The latter is true due to very conservative design for good acoustic performance in the flooded motor, and a limitation on minimum flooded motor pole pitch, which in turn limits the maximum frequency and thus maximum generator speed.

The all-mechanical systems run at 200 rpm, and the inboard turboelectric systems run at 300 rpm. The inboard/outboard turboelectric systems run at a variety of speeds and have a variety of configurations. The acyclic electric system shows unusually low weight for an electric system, resulting from the unusually effective use of materials possible in acyclic machines.

The particularly large weights of the inboard/outboard turboelectric systems, as compared to the geared drive turbine system, are disturbing. While not to be ignored, these weights should be recognized as representing only main machinery, which is a part of the overall propulsion plant, and which in turn is a part of the ship. The effects on the overall ship are therefore far smaller than the 4:1 range of main machinery weights. In addition, the geared drive turbine system weight is derived from the extensive design effort required for actual construction, and is thus a well established figure, while the inboard/outboard

turboelectric system weights are derived from only preliminary designs, necessarily done conservatively. Furthermore, while not exploited in the designs in this report, the use of buoyant materials in much of the motor void space offers a material reduction in motor weight.

Thus, while of considerable importance, the large weights of the inboard turboelectric systems are not alone reason for rejecting these systems.

### Efficiency

Efficiency is determined assuming the same total turbine shp to be available for propulsion in each system. Variations in ship service electric load, which would be of interest in a detailed investigation, are ignored.

Table 34 (page 175) shows two efficiencies for each system. The hydrodynamic efficiency is the ratio of effective horsepower to shaft horsepower at the propeller hub, and is indicative of the hydrodynamic performance of each system. The overall efficiency is the ratio of effective horsepower to shaft horsepower at the turbine shaft, and is indicative of the overall performance of each system. By observing the difference (or more properly, the ratio) between the two efficiencies, the machinery performance can be inferred.

Several general observations can be made from Table 34:

The overall efficiency of the geared drive turbine system is exceeded only by that of the pumpjet system.

The machinery efficiency for systems with all machinery (except of course the propeller) inboard is good in relation to that for the inboard/outboard systems.

The hydrodynamic efficiency of many of the systems is about the same as for the geared drive turbine system. The pumpjet system and the novel electric propulsion system have unusually high efficiencies, and the cycloidal propeller system has an unusually low efficiency.

A factor which can easily dominate the efficiency of the flooded propulsion motors is windage loss. Because of its potentially large magnitude, this is the most critical loss, but unfortunately, it is also the least susceptible to analytical determination. It has a number of different values, equal to the number of independent calculations made. The windage losses shown in this report are the highest of three independent calculations, and the most that can be said for their accuracy is that a consistent method was used for all of the systems.

Despite the difficulty in determining a value for this loss, it is known to be very much dependent upon the detailed geometry and size of the motor, and to be a strong (cubic) function of the rpm. Consequently, it is ordinarily susceptible to reduction to a reasonable value in a specific detailed design.

The windage loss for the inboard flooded motor system is particularly high, but is not an inherent feature. It can be designed out by decreasing the speed, but at an increase in size and weight. The windage loss for the cycloidal propeller system is even higher, and is an inherent feature. It can be improved by design effort, but neither the propeller diameter nor speed can be greatly decreased, nor can the motor diameter be greatly decreased.

#### Development Risk

Development, if measured in time or cost, varies over a wide range between systems. However, the interest here is limited to the more basic confidence for success, or as shown in Table 34 (page 175), risk of failure.

One group of systems has no risk of failure. The geared drive turbine system, the pumpjet system, and the AC-DC electric system are engineered and designed for the application, but represent conventional hardware. There is no development involved.

A second group of systems has a minor risk of failure. The propeller in the geared drive turbine system with reversible pitch propeller, the acyclic machines in the acyclic electric system, and the cycloidal propellers (motors are discussed below) in the cycloidal propeller system represent development items, but there is a body of knowledge, experience, and previously built equipment that makes the development straightforward.

A third group of systems has a small risk of failure. The flooded propulsion motors in all of the inboard/outboard turboelectric systems represent development items requiring extensive development work. While a few small flooded motors have been built, the propulsion motors are so much larger that previous experience is not directly applicable. The areas of interest are whether very large masses of sealed electro-magnetic structure can be manufactured without imperfection and operated successfully in sea water, and whether very large water-lubricated bearings can be operated successfully in the submarine environment. These are both questions of size effect, and while they presently introduce a minor risk of failure, these questions can be resolved before proceeding by some large scale experimental work.

#### GENERAL DISCUSSION

This survey covers main propulsion machinery, but mention of auxiliary machinery pervades the entire report. It is again emphasized here that auxiliaries exert a substantial and often dominant influence on noise, reliability, and maintenance, and that to be fully effective, advances in main machinery must be accompanied by advances in auxiliary machinery.

It is first necessary to recognize that satisfactory acoustic performance is a necessary, but not sufficient, condition to make a system acceptable. Unsatisfactory acoustic performance is therefore by itself cause for rejecting a system, and several of the systems are in this category. The controllable pod motor system with sail pods and the cycloidal propeller system have propellers and machinery forward, in the sail, and

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are unsatisfactory acoustically. The tandem propeller system has a propeller and machinery further forward, at the bow, and it too is unsatisfactory acoustically when this propeller is operating. However, the ship can be operated with the bow propeller stopped and feathered, except when it is necessary to develop large control forces, hover, or run at the top few knots of the speed range. Operating the ship in this manner minimizes interference with forward sonar.

The geared drive turbine system with reversible pitch propeller does not offer real advantage. Although it can improve backing performance, this is not ordinarily of great consequence. Since a steam turbine is easily reversed, the choice is one of hydraulics in the propeller hub vs astern stages in the turbines, and the choice naturally falls to the simple, accessible, inboard astern stages.

The pumpjet system offers good propulsive efficiency and acoustic performance, but it also offers altogether inadequate backing thrust. Until some means is devised for obtaining worthwhile backing thrust, this system is not practical.

The inboard flooded motor system has a relatively low acoustic rating and otherwise does not offer maximum advantage of the flooded propulsion motor.

The geared drive turbine system has wide application as the system in current use in all but one of our nuclear-powered submarines. This system is characterized by light weight and high overall efficiency, but is not outstanding acoustically.

The acyclic electric system offers marked acoustical improvement, in the context of inboard machinery, and the AC-DC electric system is next most attractive in this respect. These electric propulsion systems offer the possibility of using propulsion machinery to partially or completely furnish ship service electric power. The AC-DC system has

CONFIDENTIAL

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Systems Comparison  
General Discussion

a variety of power sources available, and the acyclic system allows approaching or achieving an auxiliary power supply whose frequency is proportional to main propulsion power.

The relatively high acoustic rating of the acyclic and AC-DC electric systems recognizes the major disadvantage of propeller noise, including blade frequencies, at medium to high speeds. This factor could serve to uprate the next two systems, i.e., novel electric propulsion system and the controllable pod motor system.

The novel electric propulsion system offers acoustic improvement, in both inboard and outboard components, plus a large stern access and the absence of a shaft and seal. The controllable pod motor system is next most attractive in these respects. Both of these systems have burdensome weights and potential acoustic problems in direct coupling to the sea, and in the latter case, unusual (though not necessarily unfavorable) propeller noise.

CHARACTERISTIC SYSTEM	NOISE						SHIP	
	SELF			RADIATED			PITCH AND YAW AT HIGH SPEED	PITCH AND YAW AT LOW SPEED
	HIGH SPEED	LOW SPEED	HOVERING	HIGH SPEED	LOW SPEED	HOVERING		
GEARED DRIVE TURBINE SYSTEM	REFERENCE SYSTEM • 2	REFERENCE SYSTEM • 2						
GEARED DRIVE TURBINE SYSTEM WITH REVERSIBLE PITCH PROPELLER	SAME • 2	SAME AS REFERENCE SYSTEM • 2	SAME AS REFERENCE SYSTEM • 2					
PUMPJET SYSTEM	LESS + 1	SAME • 2	SAME • 2	LESS + 1	SAME • 2	SAME • 2	REDUCED - 3	REDUCED - 3
AC-DC ELECTRIC SYSTEM	SAME • 2	LESS + 1	LESS + 1	SAME • 2	LESS + 1	LESS + 1	SAME AS REFERENCE SYSTEM • 2	SAME AS REFERENCE SYSTEM • 2
ACYCLIC ELECTRIC SYSTEM	SAME • 2	LESS + 1	LESS + 1	SAME • 2	LESS + 1	LESS + 1	SAME AS REFERENCE SYSTEM • 2	SAME AS REFERENCE SYSTEM • 2
NOVEL ELECTRIC PROPULSION SYSTEM	LESS + 1	IMPROVED + 1	IMPROVED +					
TANDEM PROPELLER SYSTEM	INCREASED - 3	LESS* + 1	INCREASED - 3	LESS + 1	LESS + 1	LESS + 1	REDUCED - 3	IMPROVED** SAME AS REFERENCE SYSTEM** + 1
INBOARD FLOODED MOTOR SYSTEM	SAME • 2	LESS + 1	LESS + 1	SAME • 2	LESS + 1	LESS + 1	SAME AS REFERENCE SYSTEM • 2	SAME AS REFERENCE SYSTEM • 2
CONTROLLABLE POD MOTOR SYSTEM	LESS + 1	SAME AS REFERENCE SYSTEM • 2	IMPROVED + 1					
CONTROLLABLE POD MOTOR SYSTEM WITH SAIL PODS	INCREASED - 3	INCREASED - 3	INCREASED - 3	LESS + 1	LESS + 1	LESS + 1	SAME AS REFERENCE SYSTEM • 2	IMPROVED + 1
CYCLOIDAL PROPELLER SYSTEM	INCREASED - 3	INCREASED - 3	INCREASED - 3	LESS + 1	LESS + 1	LESS + 1	REDUCED - 3	IMPROVED + 1

\*With only stern propeller operating.

\*\*Upper comment applies if bow propeller is operated, lower comment applies if bow propeller is stopped and feathered.

**NOTES:**

Characteristics in this table are defined as follows:

Noise - Comment on noise compared with that of reference system

Ship control - Comment on ship control capability with respect to that of reference system

Depth - Maximum operating submergence depth for machinery

Speed - Maximum submerged ship speed

Armament - Size of stern access for sonar or armament

Size - Sum of lengths of major machinery components, placed as they would probably be arranged in the ship

Weight - Sum of weights of major machinery components

Development risk - General comment on risk of failure to develop successfully

Efficiency - Hydrodynamic propulsive efficiency, EHP/Propeller hub hp, and overall propulsive efficiency, EHP/Turbine shp

The following characteristics are omitted from the tabulation since differences between systems are not large:

Reliability and casualty control  
Installation  
Maintenance  
Manning

1

S  
+  
-  
N  
r  
q  
n  
p  
t  
h  
In

HOVERING	SHIP CONTROL				SUBMERGENCE DEPTH	MAXIMUM SPEED	ARMAMENT	MACHINERY SIZE	MACHINERY WEIGHT
	PITCH AND YAW AT HIGH SPEED	PITCH AND YAW AT LOW SPEED	BACKING DOWN	HOVERING					
REFERENCE SYSTEM ● 2	REFERENCE SYSTEM ● 2	REFERENCE SYSTEM ● 2	REFERENCE SYSTEM ● ?	REFERENCE SYSTEM ● 2	REFERENCE SYSTEM; SHAFT AND SEAL RE- QUIRED; SUBSTANTIAL IMPROVEMENT POSSIBLE ● 2	100% ● 2	NO STERN ACCESS ● 6	81.0 FT. LONG ● 7	270,000 LB ● 1
SAME ● 2	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	IMPROVED + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	100% ● 2	NO STERN ACCESS ● 5	86.0 FT. LONG ● 9	297,000 LB ● 3
SAME ● 2	REDUCED — 3	REDUCED — 3	REDUCED — 3	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	103% ● 1	NO STERN ACCESS ● 6	85.0 FT. LONG ● 8	340,000 LB ● 4
LESS + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	IMPROVED + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	94% ● 4	NO STERN ACCESS ● 6	108.0 FT. LONG ● 10	406,000 LB — 5
LESS + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	IMPROVED + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	93% ● 5	NO STERN ACCESS ● 6	80.0 FT. LONG ● 6	281,000 LB ● 2
LESS + 1	IMPROVED + 1	IMPROVED + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	97% ● 3	10 FT. DIA. STERN ACCESS + 2	63.0 FT. LONG + 3	1,032,000 LB — 11
LESS + 1	REDUCED — 3	IMPROVED** SAME AS REFERENCE SYSTEM** + 1/2	IMPROVED + 1	IMPROVED + 1	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	92% ● 6	11.5 FT. DIA. STERN ACCESS + 1	62.0 FT. LONG + 2	730,000 LB — 8
LESS + 1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	85% ● 8	4 FT. DIA. STERN ACCESS + 5	66.5 FT. LONG + 4	804,000 LB — 9
LESS + 1	SAME AS REFERENCE SYSTEM ● 2	IMPROVED + 1	REDUCED — 3	SAME AS REFERENCE SYSTEM ● 2	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	93% ● 5	8 FT. SQ. STERN ACCESS + 3	60.5 FT. LONG + 1	635,000 LB — 7
LESS + 1	SAME AS REFERENCE SYSTEM ● 2	IMPROVED + 1	REDUCED — 3	IMPROVED + 1	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	91% ● 7	8 FT. SQ. STERN ACCESS + 3	80.0 FT. LONG ● 6	601,000 LB — 6
LESS + 1	REDUCED — 3	IMPROVED + 1	SAME AS REFERENCE SYSTEM ● 2	IMPROVED + 1	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	73% — 9	6 FT. SQ. STERN ACCESS + 4	69.0 FT. LONG ● 5	922,000 LB — 10

ating.

propeller is operated, lower  
propeller is stopped and feathered.

following characteristics are omitted from the  
comparison since differences between systems are not  
significant:

availability and casualty control  
installation  
maintenance  
training

Symbols in lower left part of boxes indicate:

- ++ Much more favorable than geared drive turbine system
- + Significantly more favorable than geared drive turbine system
- About same as geared drive turbine system
- Significantly less favorable than geared drive turbine system
- Much less favorable than geared drive turbine system

Numbers in lower right part of boxes indicate sequential ranking, with no. 1 most favorable. Note that this is a qualitative ranking, and that equal differences in ranking number do not imply equal differences in value of the particular characteristic. Note also that in some cases the ranking depends upon insignificantly small differences in numerical values of the particular characteristic.

2

SUMM

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	HOVERING	SUBMERGENCE DEPTH	MAXIMUM SPEED	ARMAMENT	MACHINERY SIZE	MACHINERY WEIGHT	MACHINERY AND PROPELLER EFFICIENCY	DEVELOPMENT RISK
	REFERENCE SYSTEM ● 2	REFERENCE SYSTEM; SHAFT AND SEAL RE- QUIRED; SUBSTANTIAL IMPROVEMENT POSSIBLE ● 2	100% ● 2	NO STERN ACCESS ● 6	81.0 FT. LONG ● 7	270,000 LB ● 1	74% OA 76% HYD ● 2	NONE ● 1
1	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	100% ● 2	NO STERN ACCESS ● 6	86.0 FT. LONG ● 9	297,000 LB ● 3	74% OA 76% HYD ● 2	MINOR; DEVELOPMENT STRAIGHTFORWARD ● 2
	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	103% ● 1	NO STERN ACCESS ● 6	85.0 FT. LONG ● 8	340,000 LB ● 4	85% OA 87% HYD + 1	NONE ● 1
	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	94% ● 4	NO STERN ACCESS ● 6	108.0 FT. LONG ● 12	405,000 LB — 5	61% OA 66% HYD — 4	NONE ● 1
	SAME AS REFERENCE SYSTEM ● 2	SAME AS REFERENCE SYSTEM ● 2	93% ● 5	NO STERN ACCESS ● 6	80.0 FT. LONG ● 6	281,000 LB ● 2	59% OA 66% HYD — 5	MINOR; DEVELOPMENT STRAIGHTFORWARD ● 2
2	SAME AS REFERENCE SYSTEM ● 2	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	97% ● 3	10 FT. DIA. STERN ACCESS + 2	63.0 FT. LONG + 3	1,032,000 LB — 11	73% OA 93% HYD ● 3	SMALL; DEVELOPMENT EXTENSIVE, BUT RISK PREDICTABLE BY EXPERIMENTAL WORK — 3
1	IMPROVED + 1	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	92% ● 6	11.5 FT. DIA. STERN ACCESS + 1	62.0 FT. LONG + 2	730,000 LB — 8	61% OA 76% HYD — 4	SMALL; DEVELOPMENT EXTENSIVE, BUT RISK PREDICTABLE BY EXPERIMENTAL WORK — 3
	SAME AS REFERENCE SYSTEM ● 2	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	85% ● 8	4 FT. DIA. STERN ACCESS + 5	66.5 FT. LONG + 4	804,000 LB — 9	51% OA 74% HYD — 8	SMALL; DEVELOPMENT EXTENSIVE, BUT RISK PREDICTABLE BY EXPERIMENTAL WORK — 3
	SAME AS REFERENCE SYSTEM ● 2	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	93% ● 5	8 FT. SQ. STERN ACCESS + 3	60.5 FT. LONG + 1	635,000 LB — 7	58% OA 72% HYD — 6	SMALL; DEVELOPMENT EXTENSIVE, BUT RISK PREDICTABLE BY EXPERIMENTAL WORK — 3
	IMPROVED + 1	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	91% ● 7	8 FT. SQ. STERN ACCESS + 3	80.0 FT. LONG ● 6	601,000 LB — 6	56% OA 72% HYD — 7	SMALL; DEVELOPMENT EXTENSIVE, BUT RISK PREDICTABLE BY EXPERIMENTAL WORK — 3
	IMPROVED + 1	PRACTICALLY UNLIMITED; SHAFT AND SEAL ABSENT ++ 1	73% — 9	6 FT. SQ. STERN ACCESS + 4	69.0 FT. LONG ● 5	922,000 LB — 10	25% OA 60% HYD — 9	SMALL; DEVELOPMENT EXTENSIVE, BUT RISK PREDICTABLE BY EXPERIMENTAL WORK — 3

part of boxes indicate:  
 more favorable than geared drive turbine  
 more favorable than geared drive  
 geared drive turbine system  
 more favorable than geared drive  
 more favorable than geared drive turbine

part of boxes indicate sequential  
 more favorable. Note that this is a  
 that equal differences in ranking  
 equal differences in value of the  
 characteristic. Note also that in some cases  
 on insignificantly small differences  
 the particular characteristic.



TABLE 34  
 SUMMARY COMPARISON OF SYSTEMS

SYSTEM ↓	TYPE OF COMMENT →	ADVANTAGES	DISADVANTAGES OR LIMITING ACOUSTIC CHARACTERISTICS	POSSIBLE IMPROVEMENTS
GEARED DRIVE TURBINE SYSTEM <sup>1</sup>		Best sonar platform to date at bow (SSB/N1608 class)	Blade rate SSW auxiliary plant Main turbine noise detected on some ships Shaft noise	Cure broadband noise Pumpjet propulsor Major redesign of ac
GEARED DRIVE TURBINE SYSTEM WITH REVERSIBLE PITCH PROPELLER <sup>1</sup>		Possible damping in blade joints at hub Reduced singing probability	Blade rate Possible hub vortex SSW auxiliary plant Shaft noise	Blade damping Major redesign of ac
PUMPJET SYSTEM <sup>1</sup>		Lower blade rate level Shroud reduces radiation	Blade rate numerically increased Blade passing frequency may increase due to spacing SSW Auxiliary Plant Shaft noise	Major redesign of ac
AC-DC ELECTRIC SYSTEM		Good isolation of AC/DC TG sets Variable source of DC and AC power attractive for auxiliary systems DC power at low speed No shaft coupling to main engine No gears	Propeller noise Blade rate high due to 300 RPM Motors rigid to hull Shaft noise	3-blade propeller Pumpjet propulsor Distributed isolation Balance technology
AC CYCLIC ELECTRIC SYSTEM		Good isolation of TG sets Great variety in auxiliary systems possible DC power Light rotor weights Good sonar platform No shaft coupling to main engine No gears	Same as AC-DC electric system	Same as AC-DC elec
NOVEL ELECTRIC PROPULSION SYSTEM		Lower thrust modulation Lower numerical blade rate Lower blade rate radiation No shaft coupling to main engine No gears	No isolation below about 500 RPM of TG set Motor directly coupled to sea	Balance technology Noise control measure rotor $f_c$ coating on motor
TANDEM PROPELLER SYSTEM		Same as novel electric propulsion system No local interaction between propellers Shroud on after propeller reduces radiation No control surface wakes No control surface hydraulics	Same as novel electric propulsion system Bow propeller self noise <sup>2</sup> Boundary layer forward <sup>2</sup> Many mechanisms forward <sup>2</sup> Detectability increase due to bow and stern propellers <sup>2</sup> Reinforcement of longitudinal modes by excitation source fore and aft <sup>2</sup> Cavitation due to pitch variation during rotation	Same as novel elect
INBOARD FLOODED MOTOR SYSTEM		No shaft coupling to main engine No gears	Same as novel electric propulsion system Blade rate same as geared drive turbine system	Same as novel elect
CONTROLLABLE POD MOTOR SYSTEM		Uniform inflow Location of pods relative to sail wake Reduced area of radiation Shroud reduces radiation Lower interaction with hull No shaft coupling to main engine No gears	Same as novel electric propulsion system Higher numerical blade rate Beating detection due to multiple external sources	Same as novel elec
CONTROLLABLE POD MOTOR SYSTEM WITH SAIL PODS		Same as controllable pod motor system Lower blade loading; blade rate radiation reduced Lower power per pod	Same as controllable pod motor system Higher numerical blade rate Self-noise forward	Same as novel elec Revert to controll
CYCLOIDAL PROPELLER SYSTEM		Possibly lower blade rate Location of propellers relative to sail wake No control surface wake No control surface hydraulics No shaft coupling to main engine No gears	Same as novel electric propulsion system Self-noise forward Cycloidal mechanism noise Cavitation due to pitch variation during rotation	Same as novel elec Eliminate sail wake If necessary

1. SSW auxiliary plant is used with first three (all-mechanical) systems; new design is used with other systems.

2. Comment applies only if bow propeller is operated.



CONFIDENTIAL

2

TABLE 35  
ACOUSTIC APPRAISAL OF SYSTEMS

CATEGORIES OR LIMITING ACOUSTIC CHARACTERISTICS	POSSIBLE IMPROVEMENTS	AREAS OF STUDY BEFORE PROCEEDING OR ACOUSTICALLY RE-APPRAISING
dry plant noise detected on some ships	Cure broadband noise Pumpjet propulsor Major redesign of auxiliary plant	Blade rate Mount and shaft coupling isolation effectiveness Self-noise mild to aft
vortex dry plant	Blade damping Major redesign of auxiliary plant	Propeller noise characteristics
numerically increased sing frequency may increase due to spacing Auxiliary Plant	Major redesign of auxiliary plant	Sum and difference of blade rate of rotor and stator blades Blade passing and thrust modulation
noise high due to 300 RPM igid to hull	3-blade propeller Pumpjet propulsor Distributed isolation media for motors Balance technology improvement for very heavy rotors	Blade rate and propeller noise Isolation effectiveness for such a large TG set Balancing of heavy rotors Type auxiliary plant
AC-DC electric system	Same as AC-DC electric system	Blade rate and propeller noise Acoustic characteristics of cyclical machines Bus isolation Type auxiliary plant
ion below about 500 RPM of TG set rectly coupled to sea	Balance technology improvement for very heavy rotors Noise control measures in and on motor stator and rotor $R_c$ coating on motor	Blade rate phenomena, especially nearness of two propellers Importance or need for isolation at below 900 RPM, effectiveness of 5 cps mounts at frequency $> 5\sqrt{2}$ and $< 20$ cps for heavy rotors Motor friction and slot pumping noise Direct coupling of motor noise to the sea Type auxiliary plant
novel electric propulsion system peller self noise <sup>2</sup> y layer forward <sup>2</sup> echanisms forward <sup>2</sup> villity increase due to bow and stern propellers <sup>2</sup> ement of longitudinal modes by excitation source i ut <sup>2</sup> on due to pitch variation during rotation	Same as novel electric propulsion system	Same as novel electric propulsion system, except hydrodynamics Blade rate relevant to longitudinal mode excitation by two widely separated sources Multiple source detectability Hydrodynamics of flow noise at bow propeller Influence of motor and control noise of bow propeller
s novel electric propulsion system ate same as geared drive turbine system	Same as novel electric propulsion system	Same as novel electric propulsion system, except hydrodynamics
s novel electric propulsion system numerical blade rate g detection due to multiple external sources	Same as novel electric propulsion system	Same as novel electric propulsion system, except hydrodynamics Propeller frequency radiation from pods Multiple source detectability
s controllable pod motor system numerical blade rate also forward	Same as novel electric propulsion system Revert to controllable pod motor system	Same as controllable pod motor system Forward pod influence on self-noise
s novel electric propulsion system also forward dal mechanism noise ation due to pitch variation during rotation	Same as novel electric propulsion system Eliminate sail motors; replace with sail planes If necessary	Same as novel electric propulsion system, except hydrodynamics Multiple source detectability Forward propeller influence on self-noise

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## APPENDIX A

### SHAFTLESS MOTORS

In the inboard/outboard turboelectric systems, the propulsion motor rotors are supported by separate journal and thrust bearings, generally located near the ends of the electromagnetic parts. Since the bearings are both large and water lubricated, it is appropriate to consider using the motor air gap directly as a journal bearing. The thrust bearings are indirectly affected by this change, but the effects are not great and are not discussed.

For background, this approach was considered (but not reported) in the original design of the novel electric propulsion system propulsion motors, using a stave type of bearing in the air gap. In addition, the Naval Engineering Experiment Station has investigated this approach for small integral horsepower motors, using smooth epoxy surfaces on both rotor and stator.

Using the air gap as a journal bearing offers a reduction in both size and weight by eliminating separate journal bearings and associated structure. It also locates the bearing surfaces directly at the critical dimension to be held--the air gap radial thickness. The unit loading is smaller than for the separate bearings, since the area is somewhat larger.

The major factor preventing use of the air gap as a bearing in flooded propulsion motors is the environment. It does not appear feasible to assure an ideal environment around the bearings at all times, thus, they must be capable of operation in the presence of particles such as sand. The bearings shown in this report are intended to withstand considerable abuse without serious degradation of performance. Conversely, while scoring of an air gap bearing does not seriously affect bearing operation, it does affect the primary function of the epoxy coating, which is environmental protection for the magnetic material.

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Any sleeve bearing requires some clearance, and the smooth surfaces of rotor and stator trap any particles entering the clearance and carry them around through the rubbing parts of the bearing. The stave type bearing previously mentioned was intended to allow particles to be flushed out axially, but this required enlarging the air gap to accommodate the staves and introduced the possibility of catastrophic failure if any of the many small staves should break loose.

Since the air gap bearing also operates in the boundary-lubricated regime, wear occurs and adversely affects the epoxy environmental protection function. In addition, the rubbing surfaces are similar-- epoxy on epoxy--which leads to high coefficients of friction, particularly after standing idle. Furthermore, the close clearance required for a bearing obstructs the flow of cooling water through the air gap, where a large part of the electrical losses are dissipated.

Thus, while using the air gap for a bearing is an intriguing idea in principle, there are serious practical obstacles to its accomplishment in this application.

While the Naval Engineering Experiment Station investigations are mentioned for background information, those results do not directly apply to this study, nor do the foregoing remarks directly apply to the experiment station work. The latter concerns small machines with more favorable weight-to-area ratios, a controlled environment, and vertical shafts, all of which offer much improved opportunity for successful operation.

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## APPENDIX B

### EXCITING FORCES DUE TO UNBALANCE

Figure 39 is a comparison of the relative force unbalance of major contributing propulsion machinery in each plant when operating at maximum rpm. It is based on the assumption that each machine can be balanced to a degree equal to:

$$U = \frac{4w}{N}$$

where: U = unbalance in in.-oz  
w = wt of rotor in lb weight  
N = rpm

The expression used to compute unbalance force  $F = 1.77 \times 10^{-6} UN^2$  is a measure of the  $M\omega^2 r$  centrifugal force of the rotor. This concept is for rigid rotors and does not account for the complexity of thermal instability often found in micro-balancing of large rotors. The bar graph of Figure 39 is a relative db plot for the different systems, using the lowest calculated force, that found the acyclic propulsion generator as the reference or 0 db level in the force ratio relationship.

$$db = 20 \log \frac{F}{F_{ref}}$$

$$\text{Example: } db = 20 \log \left[ \frac{(56000 \times 3600)}{(2500 \times 3600)} \right] \quad \begin{array}{l} \text{AC-DC Prop. gen.} \\ \text{Acyclic Prop. gen.} \end{array}$$

$$= 20 \log \left( \frac{560}{25} \right) = 27 \text{ db.}$$

In other words, the propulsion generator of the AC-DC system produces 27 db more fundamental noise than the lowest unbalanced force generator, the acyclic propulsion generator.

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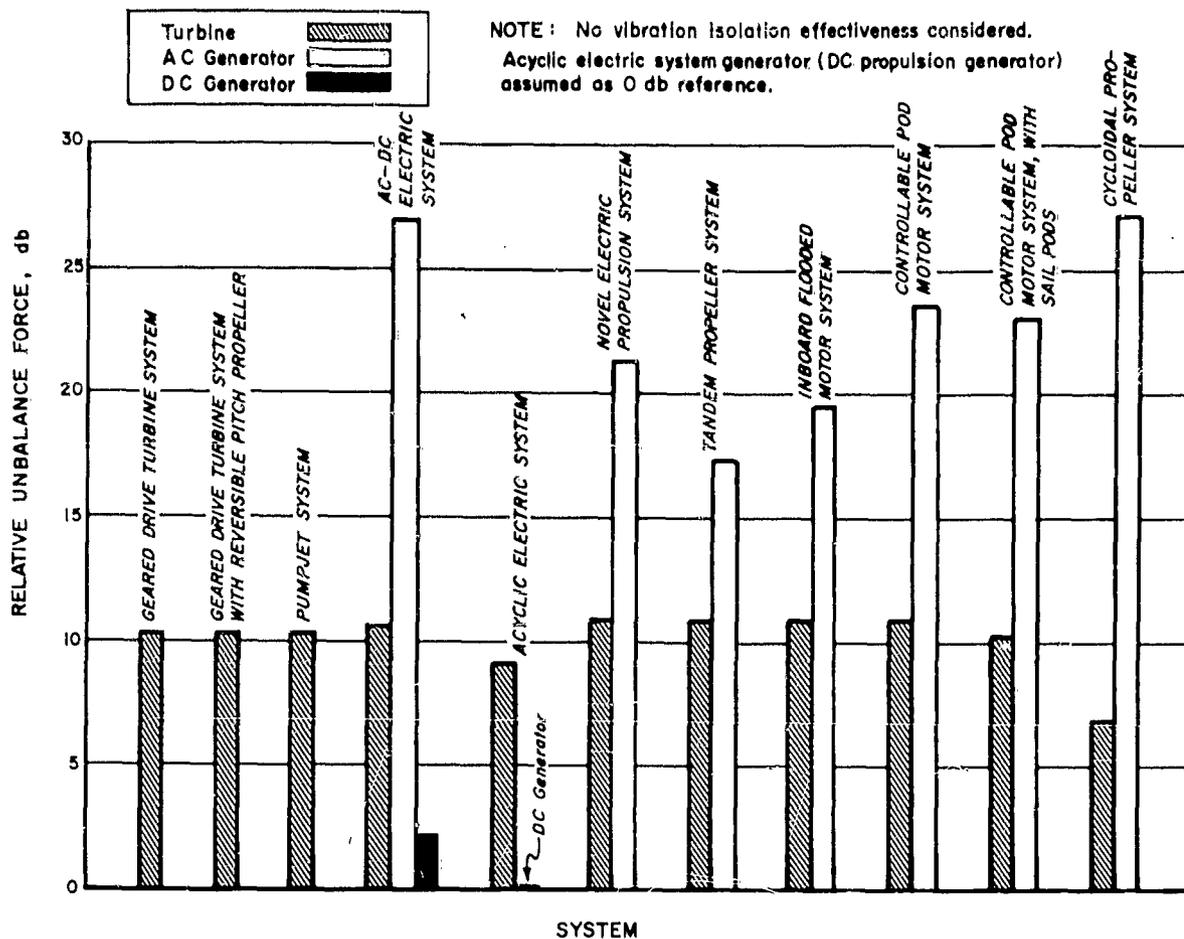


Figure 39 Relative Unbalance of Turbines and Generators at Maximum Speed

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It is interesting to note that all the turbines produce approximately the same force level. It is clearly evident from the force (F) expression and bar graph that mass of the rotor is the important parameter in unbalance, varying over 20/1 through the designs, whereas speed only varies 3.3/1, i.e., 6000/1800 for full power conditions.

Recent experience of generator manufacturers has shown that it is very difficult to micro-balance large rotors over a broad temperature range the unbalance varying as much as 5/1. This gives added emphasis to the acoustical advantage of small light weight rotors.

<p>GENERAL DYNAMICS/Electric Boat C413-63-043 A Survey of Conventional and Unconventional Submarine Propulsion Systems (U) T. J. Gerken, April 30, 1963 174 pages, 39 illustrations</p> <p>A survey is made of conventional and unconventional submarine propulsion systems. This survey included three all-mechanical systems, two inboard turboelectric systems, and six inboard/outboard turboelectric systems incorporating free-flooding propulsion rotors. A current FBX snip is used as a reference design and only the propulsion systems are varied. The eleven systems are described and compared, and four are indicated as offering potential improvements over the current propulsion system.</p>	<p>GENERAL DYNAMICS/Electric Boat C413-63-043 A Survey of Conventional and Unconventional Submarine Propulsion Systems (U) T. J. Gerken, April 30, 1963 174 pages, 39 illustrations</p> <p>A survey is made of conventional and unconventional submarine propulsion systems. This survey included three all-mechanical systems, two inboard turboelectric systems, and six inboard/outboard turboelectric systems incorporating free-flooding propulsion rotors. A current FBX snip is used as a reference design and only the propulsion systems are varied. The eleven systems are described and compared, and four are indicated as offering potential improvements over the current propulsion system.</p>	
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