FINAL REPORT

STREAM POWERED GENERATOR

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CONTENTS

SECTION 1

INTRODUCTION

The objective of the program is to develop a prototype lightweight stream powered generator suitable for operation in a shallow low velocity stream of water. The output of the unit is to be regulated and suitable for charging batteries, operating low powered communications equipment and/or other similar devices.

The development of the Stream Powered Generator resulted from Aeronutronic's unsolicited proposal, P24054(U) originally submitted to the Advanced Research Projects Agency, Washington, D.C. The unsolicited proposal was presented for this power unit to fill a void in the area of small, lightweight, silent power units of which the military had an immediate interest. Other type units which fit this category are the;

(1) Hand-crank and/or foot powered generator,

(2) Wind powered generator

(3) Turbine or reciprocating engine powered generator and

(4) Thermoelectric and/or thermionic generators.

Aeronutronic has been actively interested in the area of silent, dynamic power generation for several years. Prior to the completion of the Stream Powered Generator, Aeronutronic delivered to ARPA a prototype charcoal fired 100-watt turbine driven generator for tentative use in areas such as Vit Nam. The turbine powered unit utilizes a closed rankine operating cycle in conjunction with a low vapor pressure organic working fluid, monoisopropylbiphenyl. The advantage of this approach is the low system pressure levels involved leading to an extremely light-weight power unit.

At present Aeronutronic also has a contract with the A.E.C. to evaluate the suitability of this same organic working fluid for silent power generation applications to 10 KW output.

SECTION 2

DESIGN SPECIFICATION

2.1 ELECTRICAL

The unit is to deliver 50 watts of D.C. power at 24 volts when operating in water two feet in deptn flowing at a rate of four knots (originally three knots). The unit will be equipped with a 50-foot electric cable.

2.2 MECHANICAL

The maximum weight will be 15 pounds including weight of mounting stake and 50 foot cable.

Mounting shall insure freedom of movement permitting the unit to be self aligning in the direction of flow.

The unit will be designed to maximize environmental protection in brackish or salt water with a projected life of at least one year.

The unit will be designed to minimize the effect of drifting vegatation.

SECTION 3

GENERAL DESCRIPTION OF THE PROTOTYPE UNIT

The ~~prototype~~ Stream Powered Generator is shown in Figure 3.0-1. ~~The~~ unit consists of a propeller driven housing which contains a directly driven permanent magnet alternator, voltage regulator, bearings and shaft seals, and oil supply for lubrication and heat transfer. The rotating assembly is attached to the mounting stake via the stationary shaft through which the electric cable is routed. The mounting stake is equipped with a swivel joint allowing the unit to be self aligning with the direction of the stream flow.

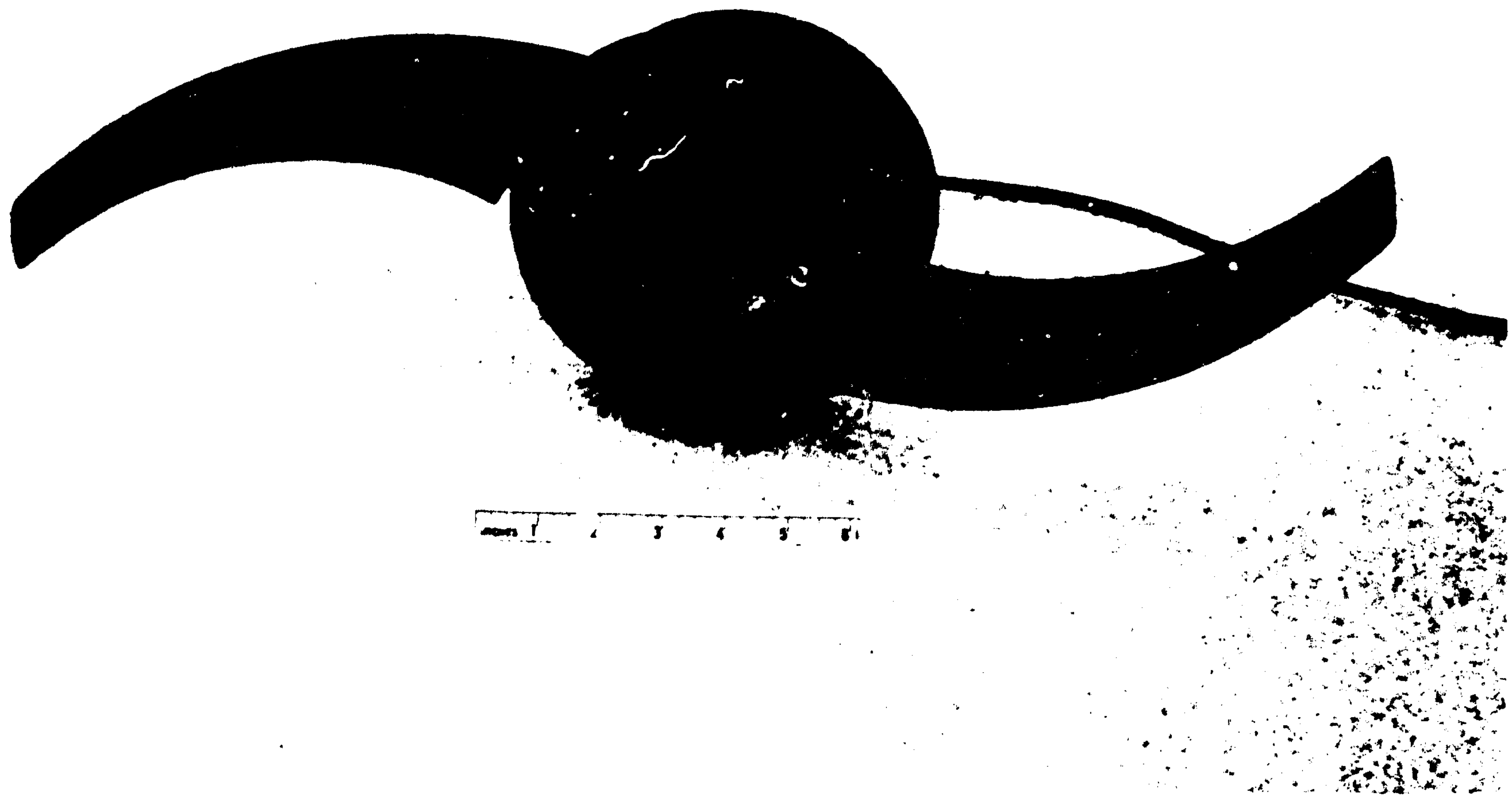
The unit will deliver 50 watts at 24 volts ±1% when driven by a 4.0 knot stream of water. The unit weighs 14.5 pounds and has a maximum propeller diameter of 22.5 inches which is suitable for operation in the maximum 2-foot stream depth specified. The high speed propeller blades are swept back in the plane of rotation and also slightly in the direction of the free stream to minimize the effect of drifting vegetation.

The material used in the construction of the generator housing, propeller blades and mounting stake is 6061-T6 aluminum. The aluminum parts have been hard black anodized to provide mechanical abrasion resistance, increase atmospheric corrosion resistance and also minimize the effect of galvanic action due to the incorporation of dissimilar materials. The materials exposed to the outside atmosphere have been limited to aluminum as referenced, 300 series stainless steel for all screws used in the assembly, titanium for the shaft and a brass case for the shaft seal. The anodized aluminum surfaces and assembly techniques applied reduce the galvanic action due to these dissimilar materials to an acceptable level.

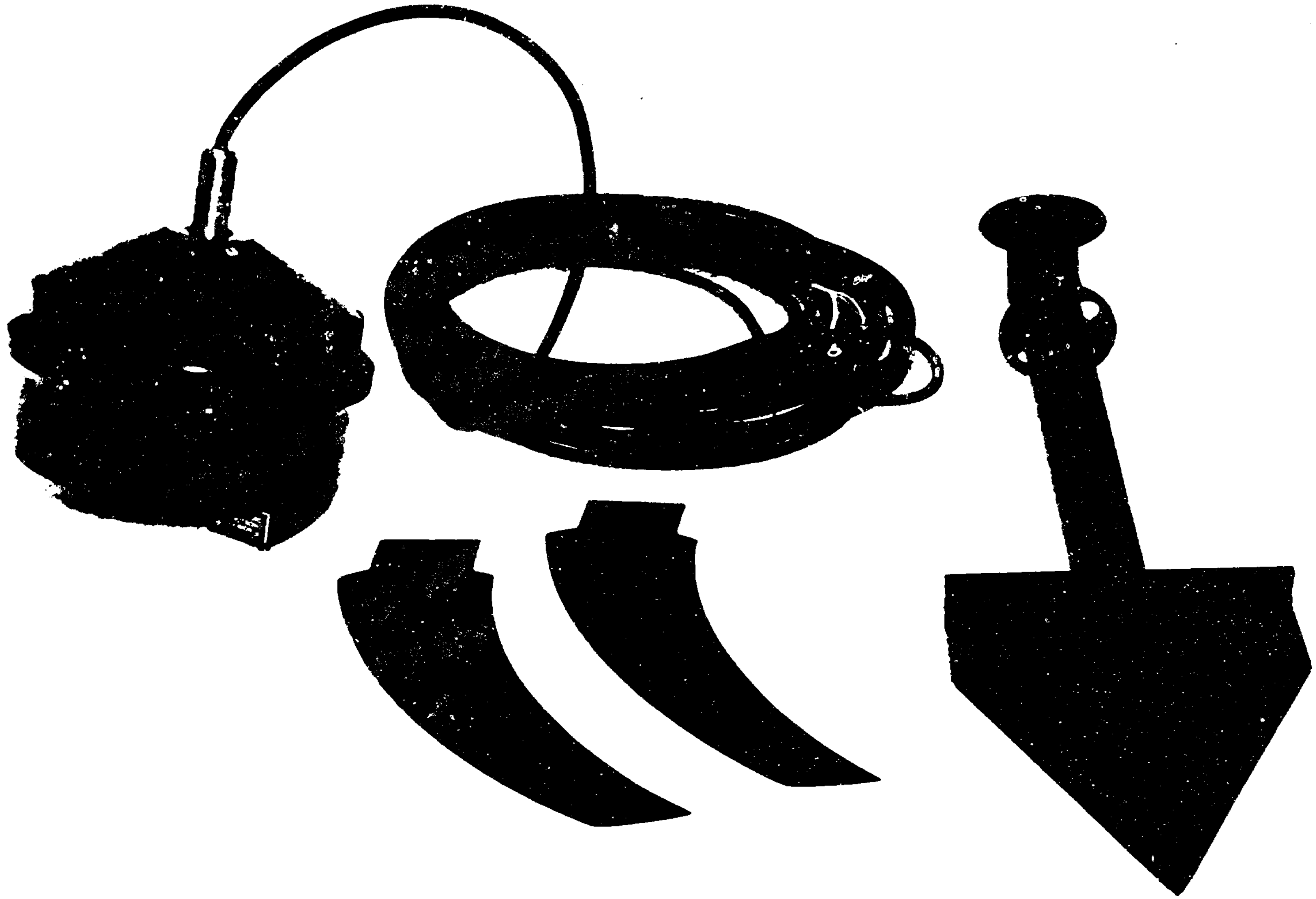
The unit incorporates a solid state series voltage regulator to provide a closely regulated D.C. output 24 volts ±1%. The regulator will provide this regulation from no load to full load. The solid state regulator is also equipped with a current limiting feature to prevent damage of the unit due to accidental short circuits and/or overloads. The regulator is designed to provide protection and regulation for stream velocities of at least 200% of the rated 4.0 knots.

The unit design incorporates the use of two back to back shaft seals, one to keep the salt water out of the unit and the other to keep the oil, used for lubrication and heat transfer from the voltage regulator, inside the unit. The quantity of oil used is only 400 cc and is centrifuged to the outside hub area when in normal operation. The oil is fed to the bearing through the use of stationary pitot tubes. The heat generated in the series voltage regulator is transferred to the oil through a copper fin, which is immersed in the centrifuged annulus of oil, and on out through the housing to the water. The details of the unit described can be seen on the layout drawing.

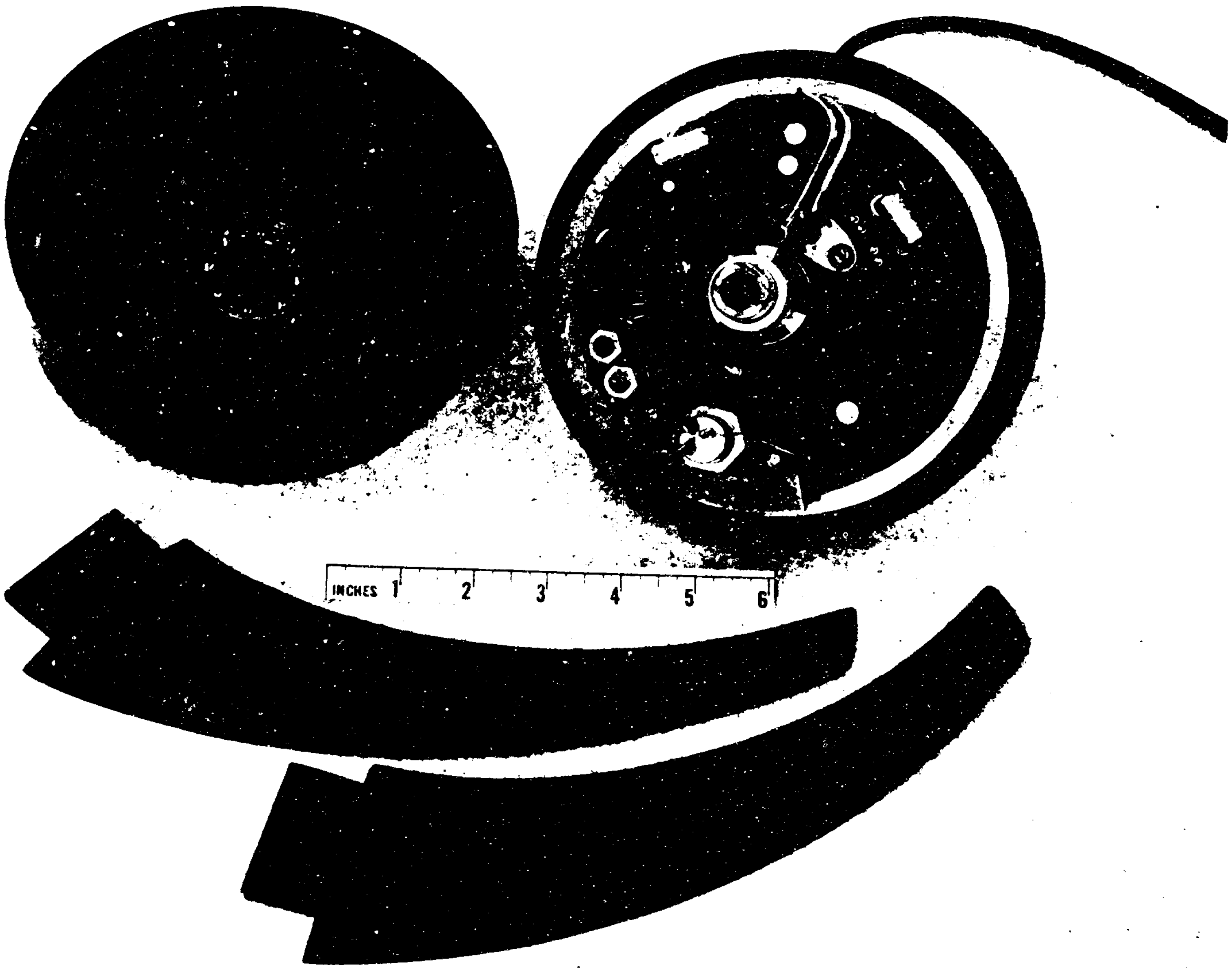
Figure 3.0-1 through 3.0-3 are pictures from various views of the Stream Powered Generator. Figure 3.0-4 is a picture of the unit with the propeller hub removed and showing the inside assembly. Figures 3.0-4, 3.0-5 and 3.0-6 show the unit in various stages of disassembly and indicate the simplicity of construction. The only parts which cannot be seen in the picture shown on Figure 3.0-6 are the shaft seals and their associated O-rings. These are contained in the housing section which also supports the permanent magnet rotor. The details of the unit described can be seen on the layout drawing, Figure 3.0-7.



[illegible] STREAM POWERED GENERATOR DOWNSTREAM VIEW



STREAM POWER GENERATOR



STREAM POWERED GENERATOR

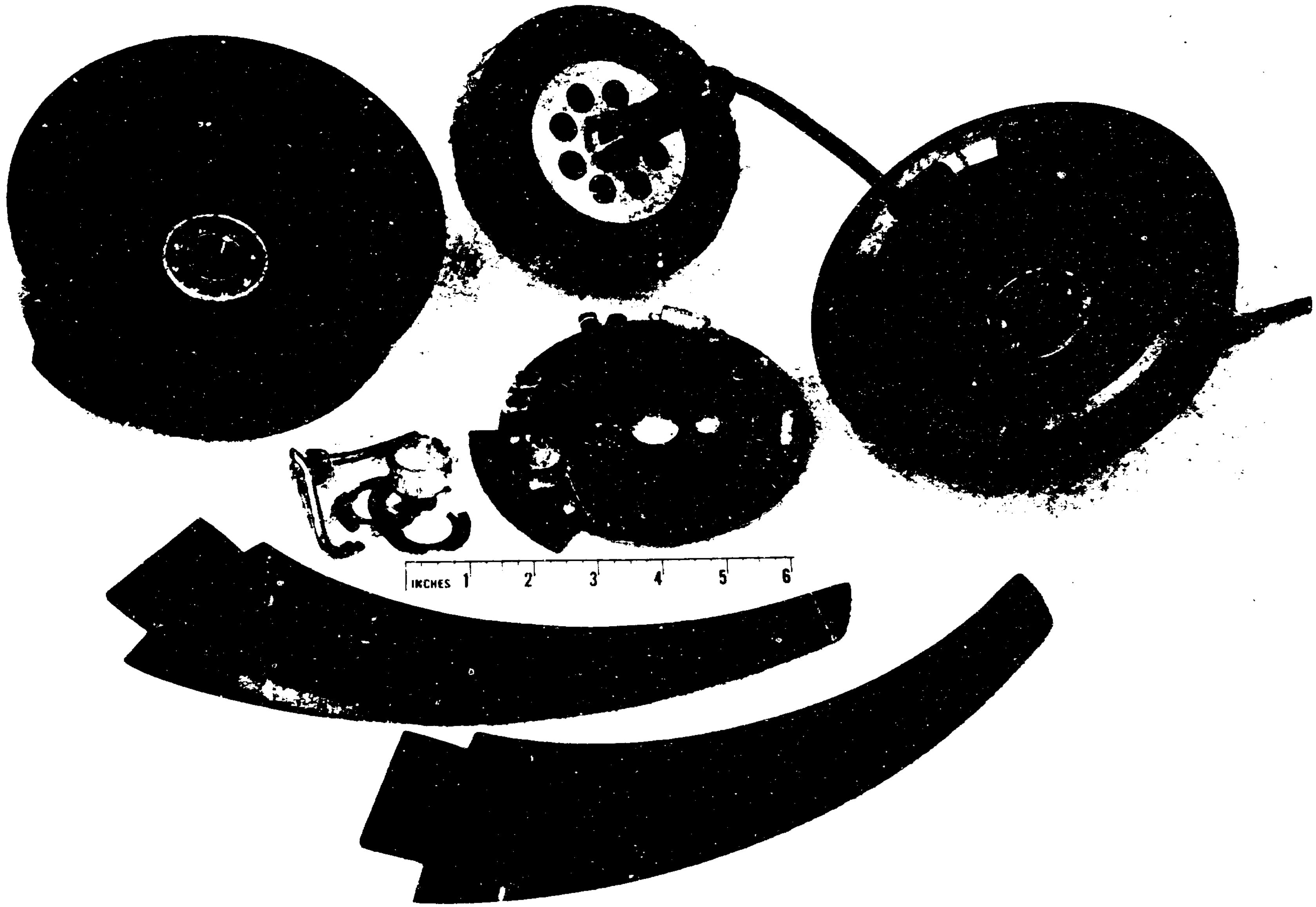
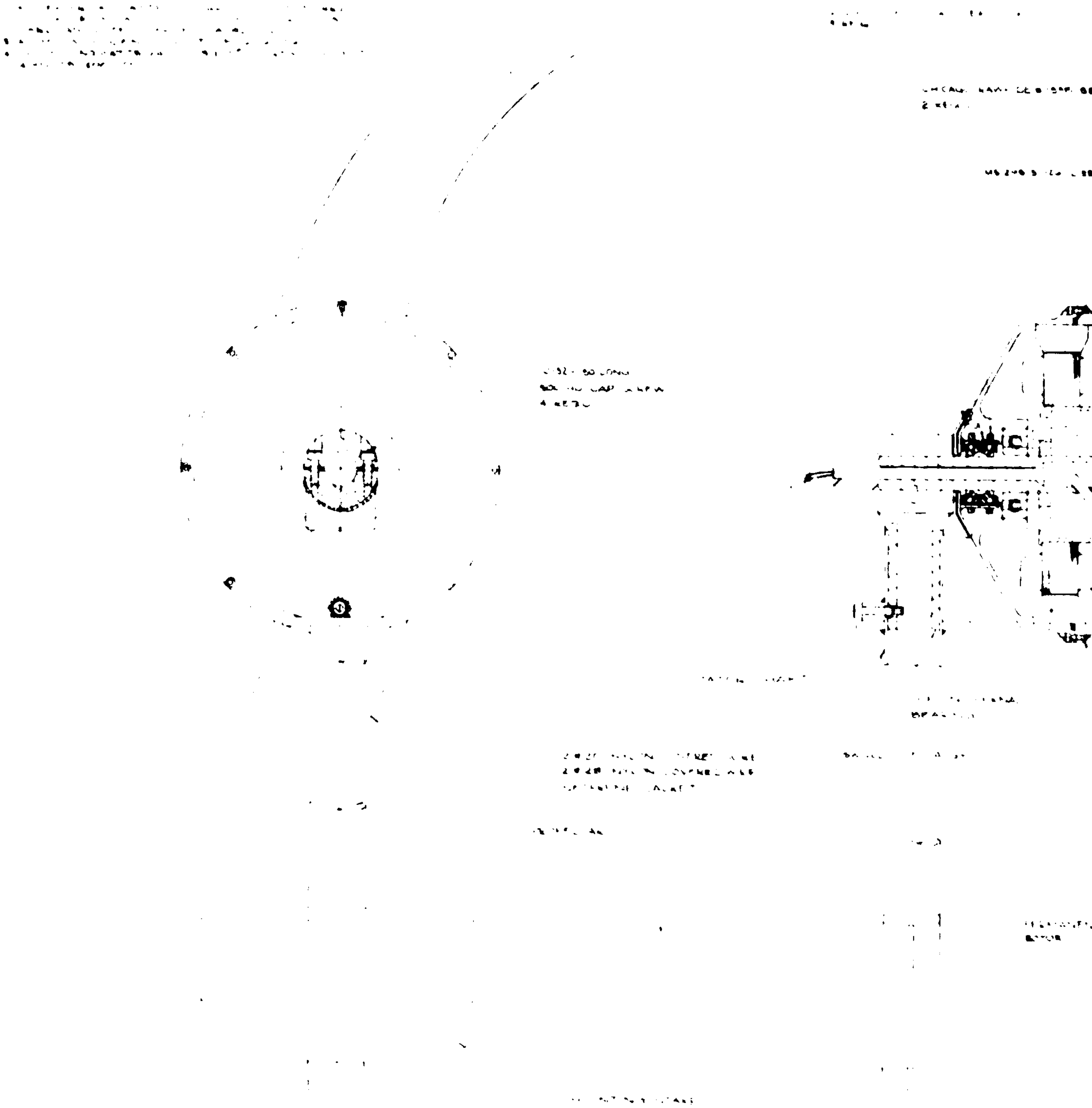
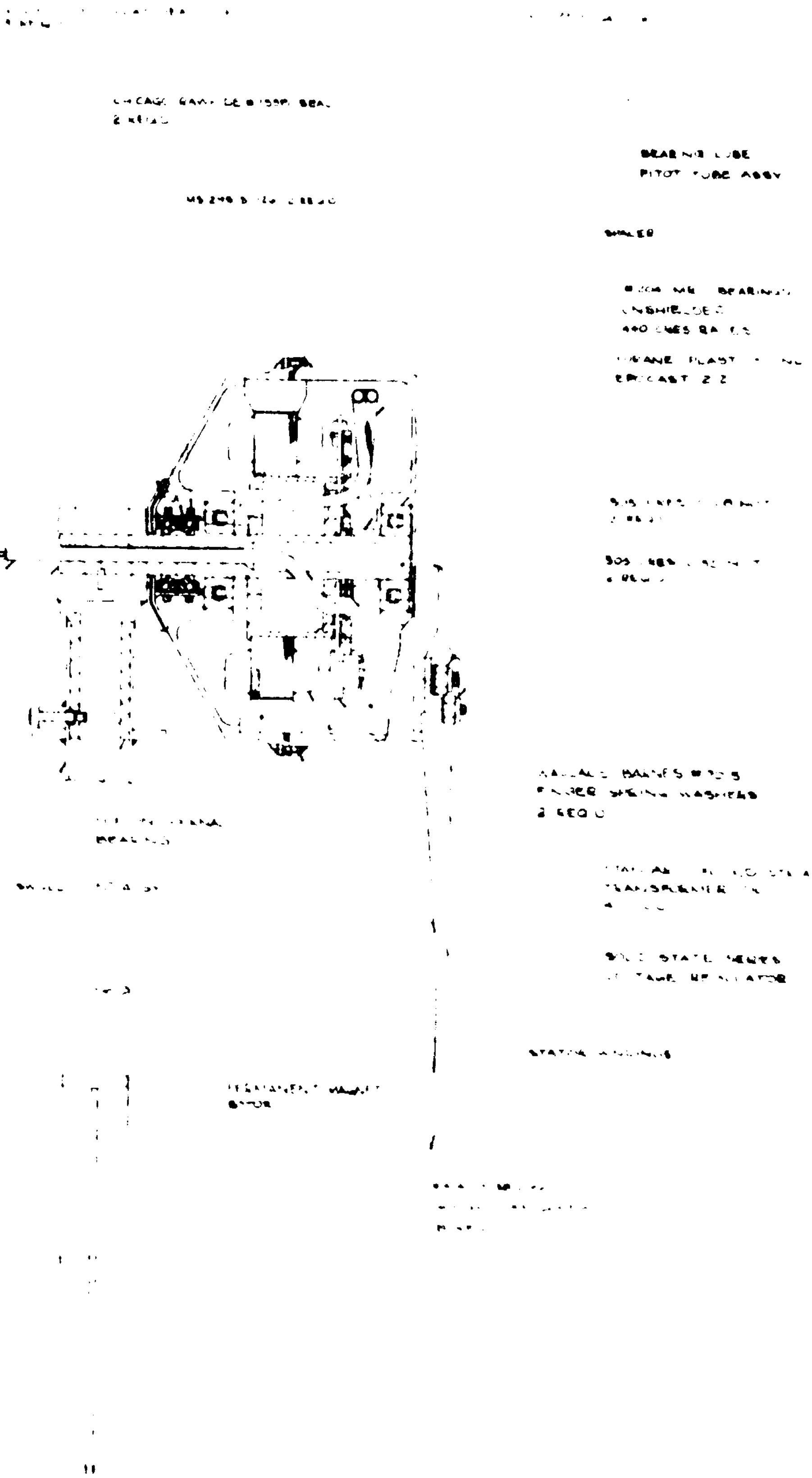


FIGURE 3.9-6. STREAM POWERED GENERATOR




PITOT TUBE ASSY

SECTION 4

COMPONENT DESIGN

4.1 GENERATOR

The detailed engineering analysis indicated the most suitable generator in regards to weight is the permanent magnet Lundell generator. Other types of brushless generators such as the electromagnetic Lundell, homopolar inductor and heteropolar machines are considerably heavier than the permanent magnet machine selected. Types such as the induction generator and flux switch generator are unsuitable. The induction generator, due to the low frequencies involved, requires a large bank of capacitors for excitation and the flux switch generator is primarily ruled out because it is basically a single phase machine requiring considerably more conversion and filtering to produce an acceptable D.C. output.

The configuration utilized is an inside-out design where the rotor is on the outside. This approach is the reverse of a conventional design and allows the housing to rotate which will aid in minimizing the fouling effect of drifting vegetation. The inside-out configuration also makes it easier to produce a rotor with many poles. It is necessary to provide a machine with a large number of poles in order to minimize the stator yoke thickness and also to achieve a design with a short winding span to obtain the least weight.

The lightest generator is one designed to utilize the most exotic materials available resulting from our space age technology; however, the detailed analysis of the generator indicated that it could be designed to meet the performance requirements specified using conventional and readily available materials.

The generator is designed to produce 50 watts at 24 volts DC when driven at 420 rpm. The overall full load efficiency of the unit, including rectifier, regulator and cable losses is approximately 50%. While this efficiency appears to be abnormally low, it is consistent in regards to the power available from the moving stream and in meeting the weight requirement for the unit.

The generator is designed around an off-the-shelf 30-slot lamination. The rotor has 16 poles, which provides 0.625 slots per pole per phase. This combination, 30 stator slots and 16 rotor poles, required the use of a fractional-slot winding design with a slightly reduced winding factor as compared to an integral-slot design. Ten poles is the maximum number of rotor poles which can be used for an integral-slot design with the 30-slot lamination, and would have required a longer coil span which would have in turn increased the internal impedance of the unit. Analysis indicated that the series impedance is critical in regards to the weight allowance and must be maintained at a low enough value to be able to deliver the power at the required voltage. While the power necessary could be developed within the generator, an abnormally high impedance would cause excessive internal losses and thus the output power required could not be delivered.

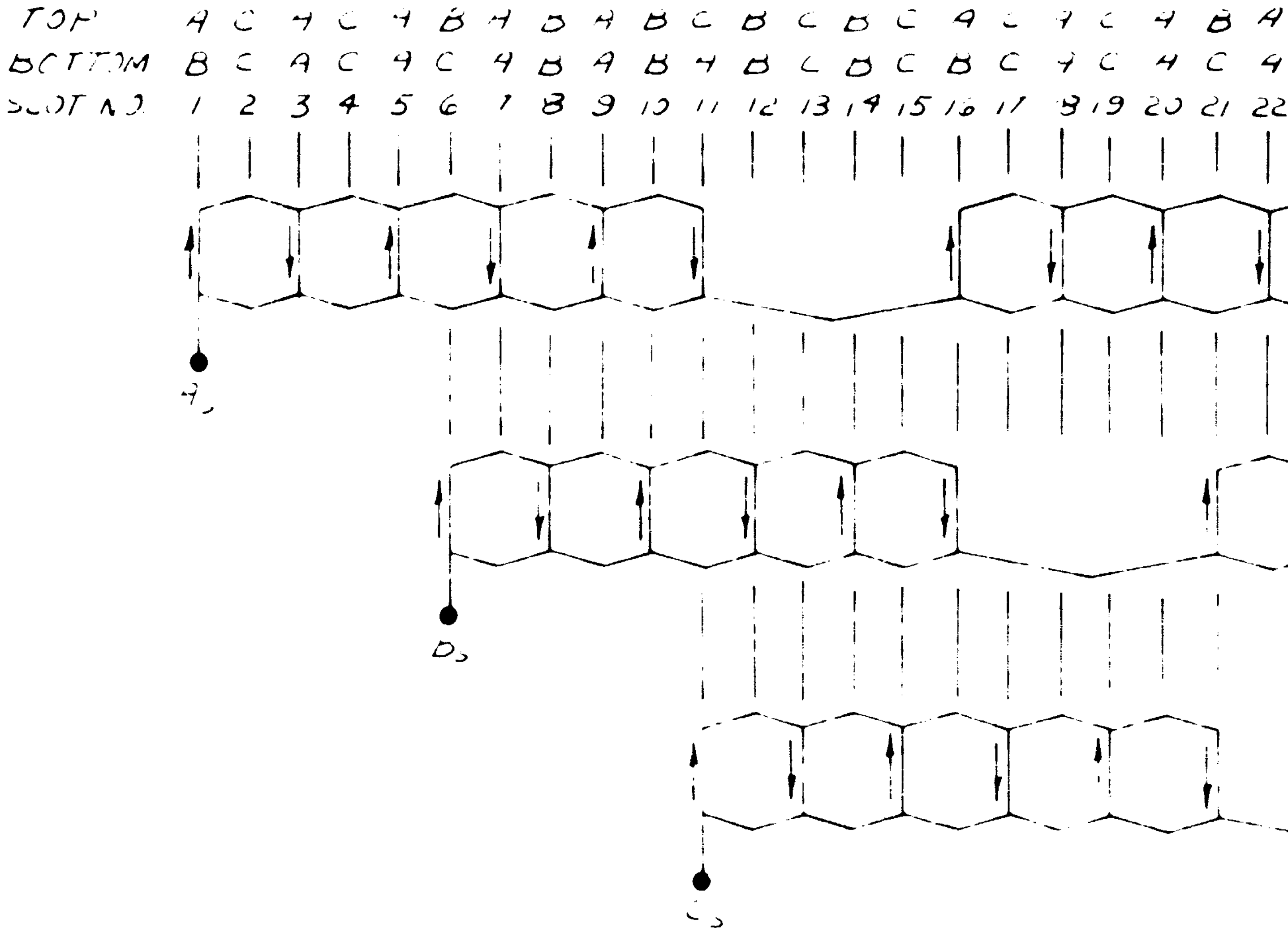
The generator is wound for 3-phase 16-pole operation with 60° phase belts. A winding span of two slots is used, resulting in a winding-distribution factor of 0.955 and a pitch factor of 0.992. The rotor is constructed with an 80% pole span. This pole span coupled with a small radial air gap of .010 inches results in a field-form distribution factor of approximately .80 and a field-form factor of 1.05. The total winding factor is the product of the winding factors and rotor field-form factors resulting in a total winding factor of 0.795. Neither the stator or rotor is skewed; thus no skew factor is applied. Figure 4.1-1 indicates the stator winding layout used.

The generated voltage must be sufficiently high to provide the 24-volt output required plus account for internal voltage drops in the generator due to the winding-impedance and to the armature-reactance effects caused by the rectified load. Also, the generated voltage must be high enough to account for the voltage drops across the output rectifies, the series voltage regulator and the 50-foot output cable. Table 4.1-1 indicates the magnitude of the impedance, currents and voltages involved in the electrical system.

The final design parameters such as winding configuration, densities, impedances, etc. are the result of several iterations of the design. The impedances and voltage drops indicated in Table 4.1-1 reflect a stator winding with 35 turns per slot-phase coil which provides a total of 700 series conductors per phase. The windings are connected in wye to produce the generated 28.01 volts line-to-line, required at full load to meet the 24 volt D.C. output requirement. The AC generated voltage indicated is a result of the arithmetic summation of all of the DC voltage drops involved which is then reduced to its AC compliment using a rectification factor of 1.25. The AC generated voltage derived is the vectorial summation of the terminal voltage required and the internal impedance drops in the generator. Figure 4.1-2 indicates the size and shape of the laminated stator stack and the envelope dimensions of the wound stator assembly. Figure 4.1-3 is a picture of the fabricated hardware.

The air gap density necessary to produce the required line-to-line generated voltage of 28 volts is 36,700 lines per square inch at a design speed of 420 rpm. The air gap density requires a magnetizing force of 127 ampere turns per pole. The armature reaction effect of the rectified

STATOR WINDING DIAGRAM



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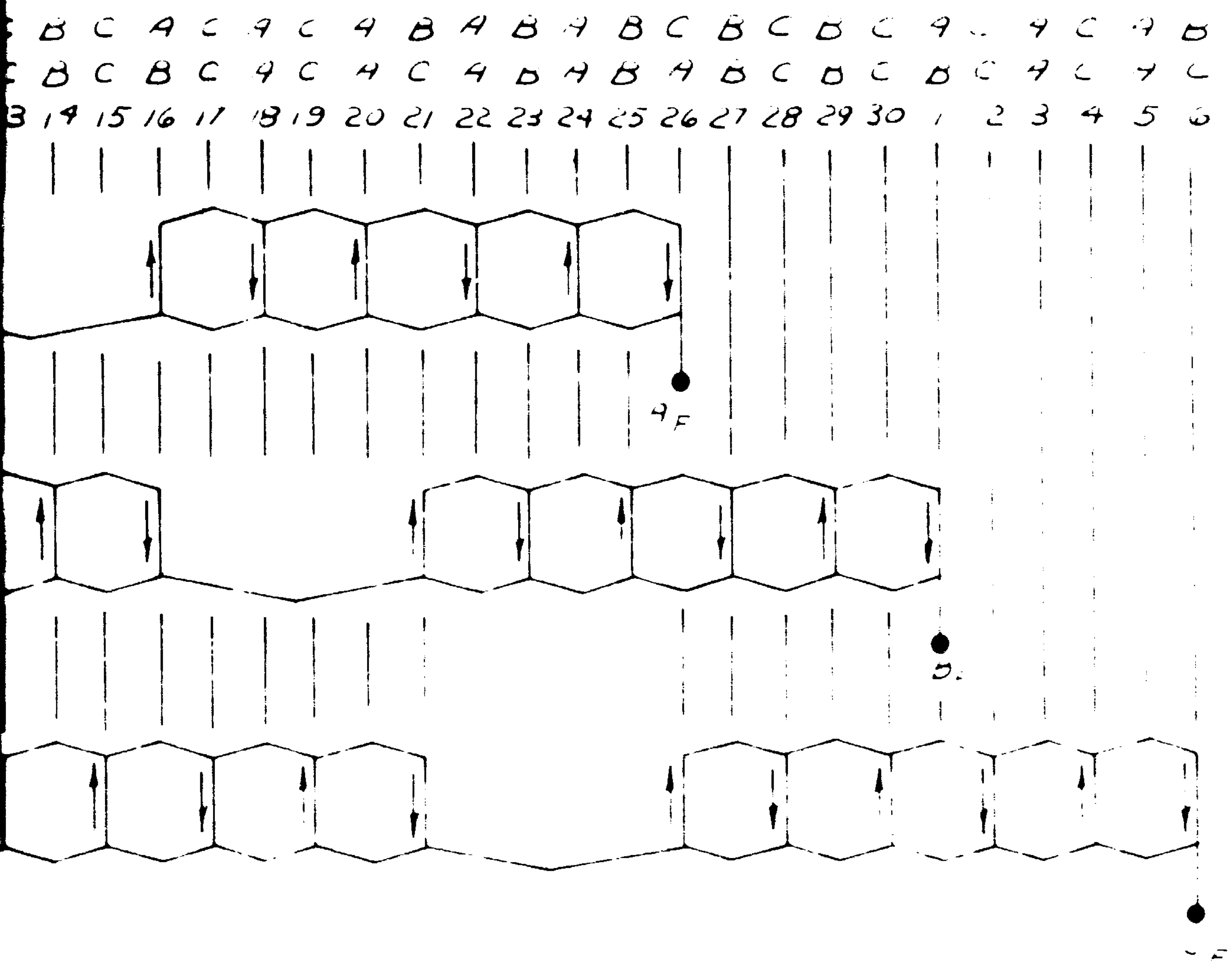
STATOR WINDING DIAGRAM



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B

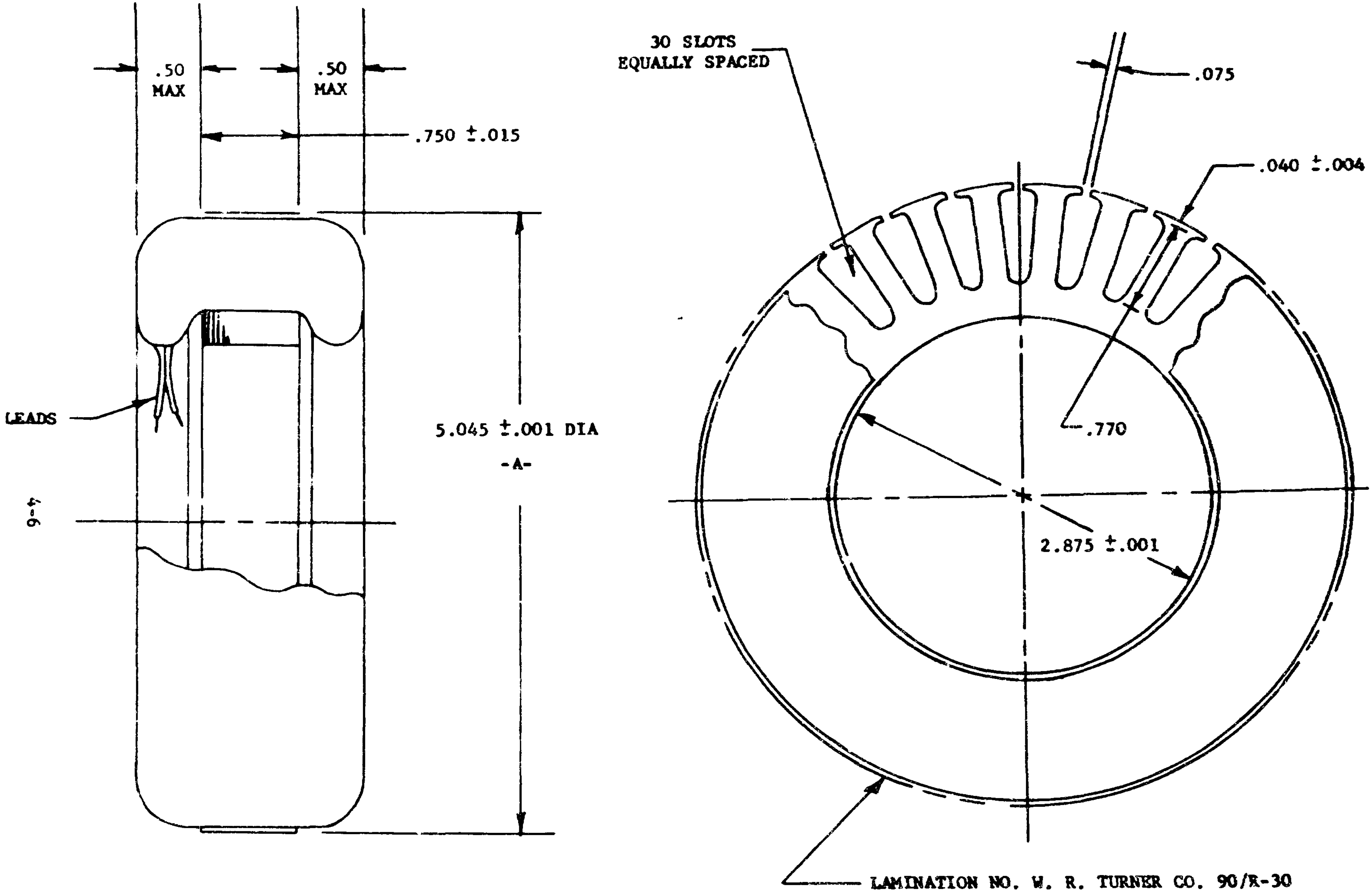
FULL LOAD ELECTRIC SYSTEM

IMPEDANCES AND VOLTAGE DROPS

Power Output	watts	50
Output Voltage	volts	24
Full Load Current	amps	2.083
Cable Resistance	*ohms	1.095
Cable Voltage Drop	volts	2.280
Regulator Impedance	ohms	.250
Regulator Saturated Voltage Drop	volts	.500
Total Regulator Voltage Drop	volts	1.520
Rectifier Voltage Drop	volts	1.500
Total D.C. Voltage Required	volts	29.300
Bridge Rectification Factor (3 Phase)		1.250
Stator Terminal (AC) Voltage Required (L-L)	volts	23.440
Stator Winding AC Current	amps	1.699
Stator Winding Resistance (Calc)	*ohms	1.171
Stator Winding Reactance (Calc)	ohms	1.087
Stator (LL) Generated Voltage Req.	volts	28.01

*Resistance at 77°F.

TABLE 4.1-1



GENERATOR STATOR ASSEMBLY

FIGURE 4.1 - 2

load has a demagnetizing effect of 28 ampere turns per pole. In the Lundell configuration selected the North and South Poles are in series thus requiring at full load a total magnet force of 310 ampere turns.

Alnico V is the permanent magnetic material utilized in the rotor with a length of .75 inches. This length provides a useful 750 ampere turn magnetizing force for stabilization. The rotor is both air stabilized and short circuit stabilized. The rotor magnet dimensions are .25 x .25 x .75 inches. 'Approximately 75 magnets are placed side by side to form a toroid on the outside diameter of the rotor. The magnets lay between two steel rings which are an integral part of the cantilevered pole pieces. Each ring contains eight poles which when nested form the 16-pole rotor. Figure 4.1-4 is a picture of the unassembled rotor parts. Figure 4.1-5 is a picture of a partially assembled rotor. A ring of copper is placed between the pole pieces and the magnets. This ring is a damper circuit and prevents the rotor from being demagnetized when the generator is short circuited, thus providing the short circuit stabilization previously referenced.

The normal interpole leakage area is insufficient to allow air stabilization of the magnet at a level high enough to provide the required operating flux. Actually the air gap flux which must be present at no load is 44,400 lines per square inch. This is because there are no demagnetization ampere turns and the full 310-ampere-turn magnet force is acting on the air gap unless saturation occurs.

The calculated interpolar leakage flux at zero load is approximately 75% of that required for full stabilization. The additional leakage required is supplied by the installation of a magnetic shunt ring around the outside of the magnet ring. The aluminum ring installed between the magnet and the shunt provides a non-magnetic gap of .110 inches to control the amount of leakage.

FIGURE 4.1-3. GENERATOR STATOR STACK AND WOUND STATOR

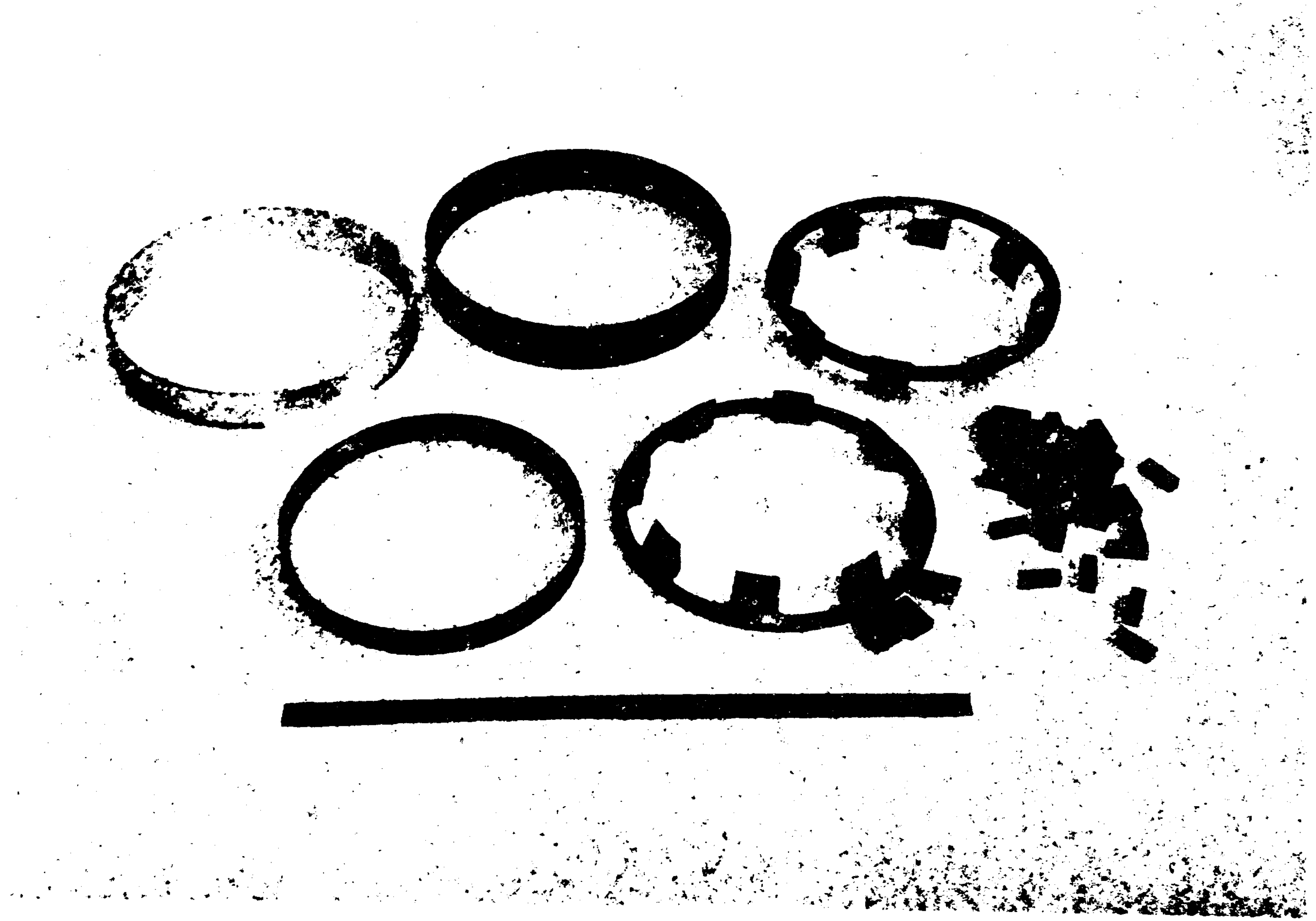


FIGURE 4.1-4. GENERATOR ROTOR PARTS

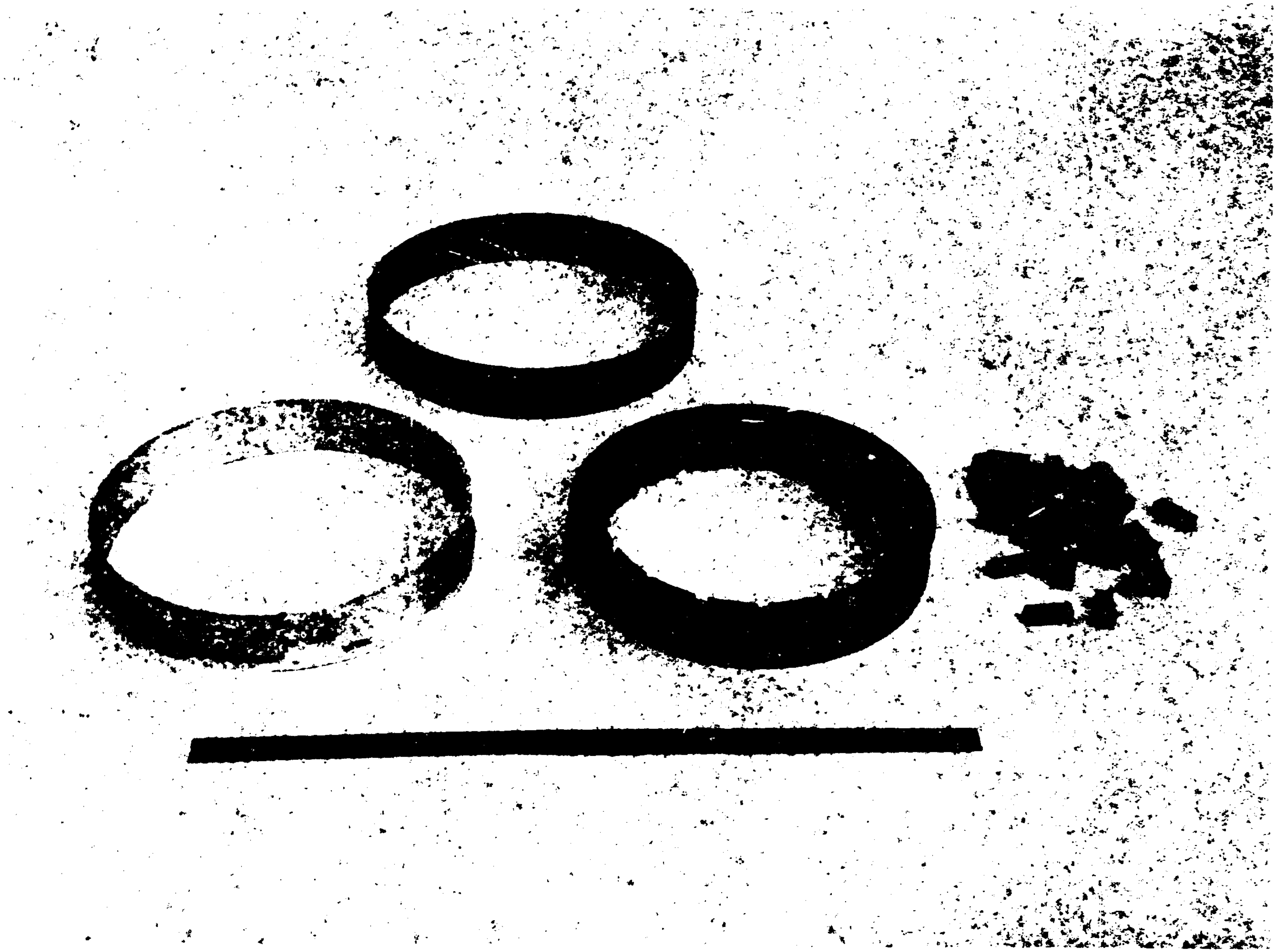


FIGURE 4.3-[illegible]. GENERATOR ROTOR IN ASSEMBLY

The field density in the magnet is approximately 57,000 lines per square inch. The material used, Alnico V, is capable of supporting 64,500 lines per square inch at the peak energy point. A picture of the final rotor assembly can be seen in Figure 3.0-6. The rotor is installed in the generator housing.

4.2 VOLTAGE REGULATOR

The voltage regulator is required to provide a regulated output over the full load range and also compensate for changes in stream velocity. The design is based on the practicle aspects of the possible utilization and/or handling of the stream generator unit. The regulator is designed to provide a regulated output of ±1% of the normal 24-volt output over the full load and with stream velocities ranging from 4.0 to 8.0 knots. The regulator design also incorporates a current limiting feature to prevent over loads and/or a short circuit from damaging the rectifiers or regulator itself.

The generator when driven at rated speed, 420 rpm, has a short circuit current limitation of approximately 5.0 amps. While this is only 250% of the rated design current it would require the use of larger electronic components for rectification and regulation. The regulator current limit point is set at 2.4 amps when driven at rated speed. This limit increases to approximately 2.7 amps when the generator is driven at higher speeds. This is due to the large increase in generator voltage which effects the drive in the current limiting stage.

The output of the generator is rectified using a full wave bridge. The silicon rectifiers are rated 1.5 amp average per diode allowing a peak DC rating of 3.6 amps when derated for the free air power dissipation involved. The DC output is slightly filtered using 25 microfarads of capacity which is then delivered to the series regulator.

The voltage regulator as designed is an all solid state unit. The output of the regulator is sensed and then controlled to provide a 24-volt output. Figure 4.2-1 is a circuit diagram of the regulator.

SOLID STATE SERIES VOLTAGE R

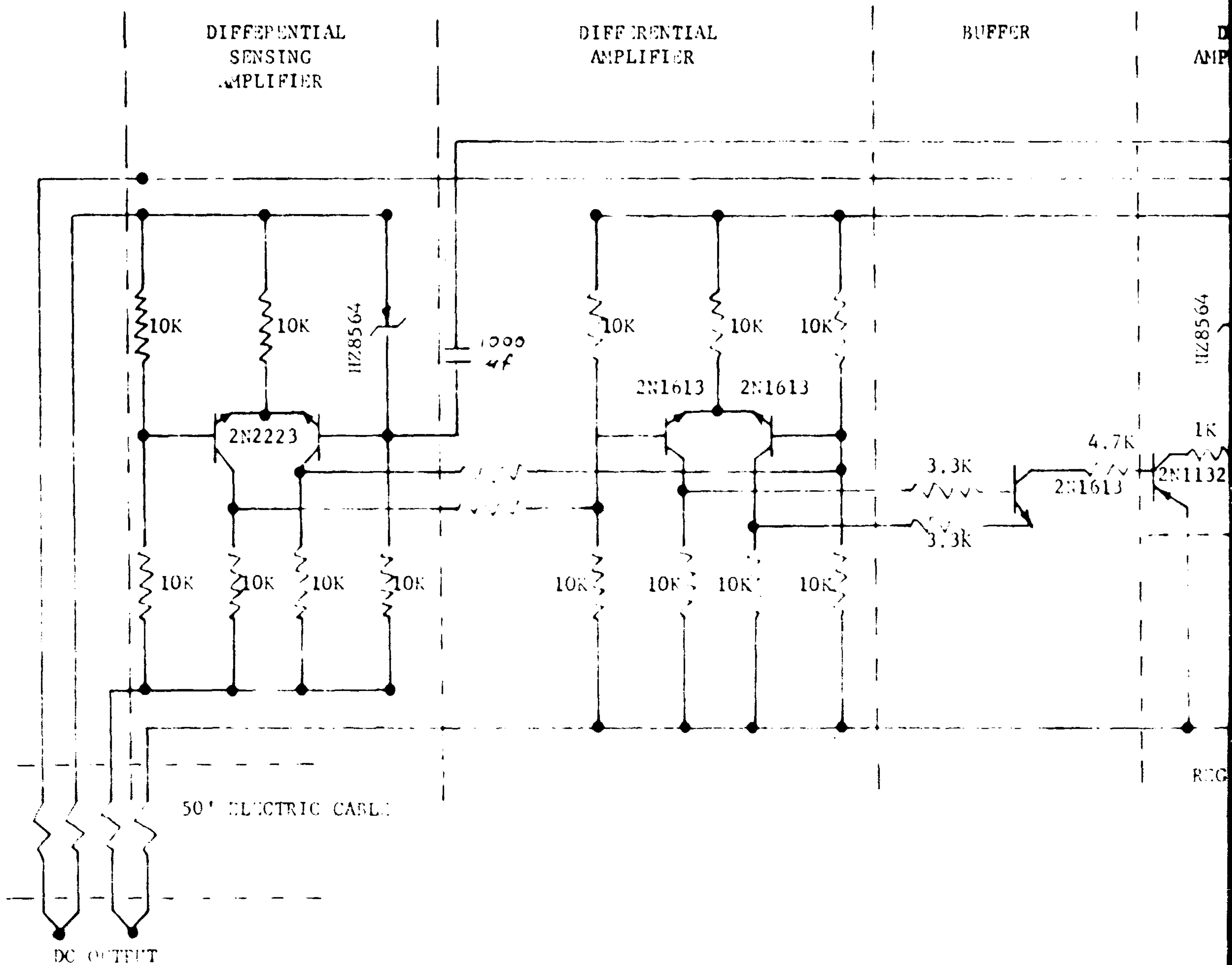


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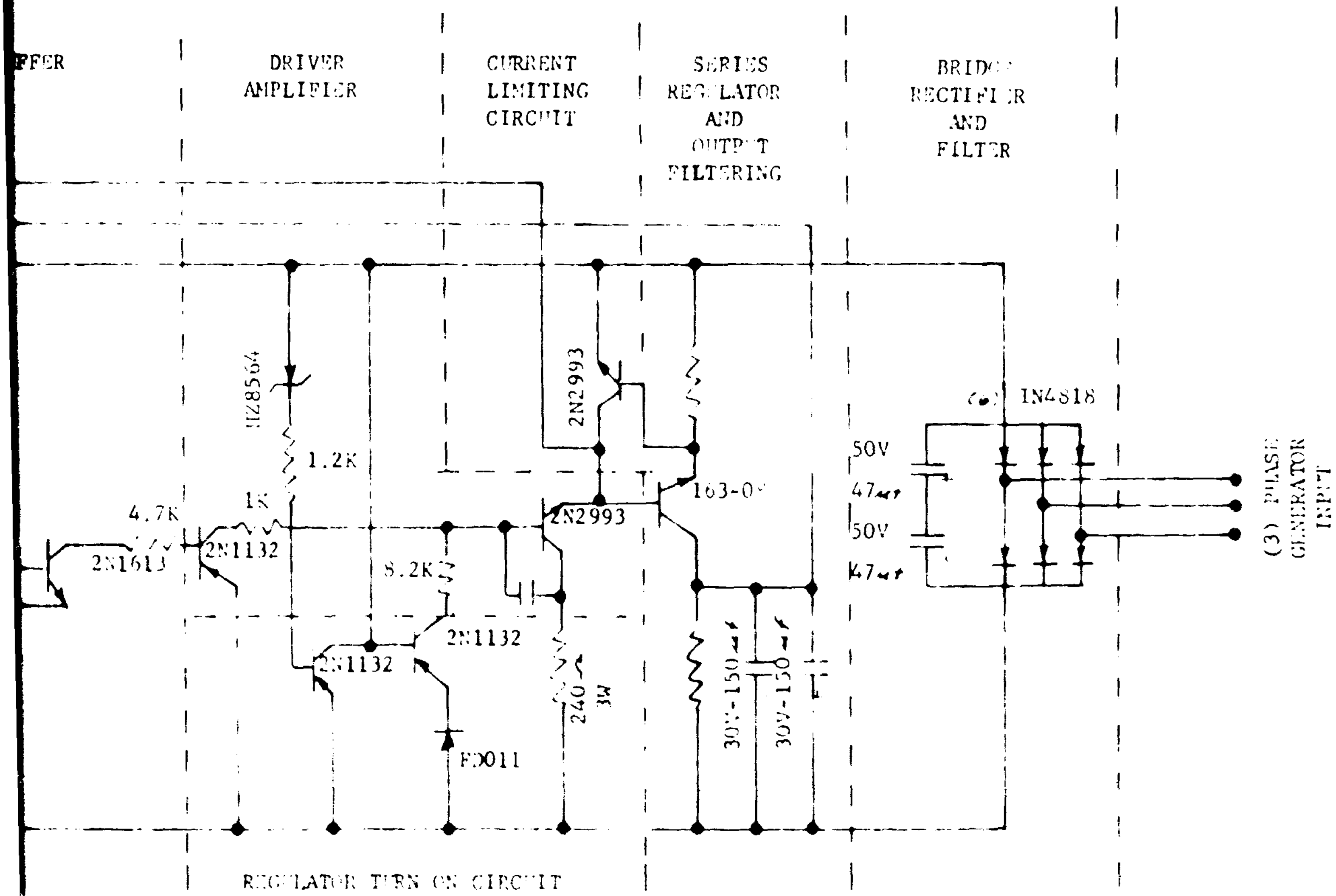
FIGURE .2 - 1

ATE SERIES VOLTAGE REGULATOR



ALL RESISTORS 1/2 WATT UNLESS MARKED OTHERWISE

FIGURE ..2 - 1

B

The DC voltage that is sensed is the output at the end of the 50-foot cable. The electric cable consists of two number 20 conductors to carry the load current and two number 28 conductors to carry the sensing signal. There is approximately a 2.0 volt drop in the cable at full load which is compensated for by sensing the voltage at the load end of the cable.

The voltage sensing stage consists of a differential amplifier which has one side clamped with a zener reference diode. The differential amplifier has a high gain thus only a slight input voltage change when compared to the zener reference will cause the amplifiers to switch. The output of the sensing differential amplifier is coupled to a second differential amplifier with a higher current handling capability. The output of the second differential amplifier is then coupled to the output driver amplifier through a buffer stage. The drive stage controls the series regulating power transistor. This element must dissipate the energy which must be handled. The energy involved is the product of the load current being delivered and the difference between the generated voltage and voltage at the load; 24 volts.

The voltage regulator is also an active filter providing a well filtered output. The output ripple is reduced to approximately .4 volts peak to peak with the incorporation of only 300 microfarads of filter capacitor across the output and no series inductance. This of course eliminates the need for the normal large filter which would be required due to the low generated frequency involved.

The driver amplifier stage also incorporates a turn on circuit to turn the output stage on at low voltages. This is necessary since no comparing signal is available until the series output stage is operating.

The current limiting feature is incorporated into the output stage. The current magnitude is proportional to the voltage dropped across a .25 ohm resistor in series with the load current. This voltage is sensed and used to turn on a transistor which drives the base of the series regulating transitor negative. This in effect partially turns the output transistor off limiting the load current. This circuit has a threshold point which is due to the normal base to emitter voltage drop. This feature allows the load current to rise to a set value, dependent on the size of the series sensing resistor, before any current limiting is initiated.

The power dissipated in the output stage is transferred through a fin to the oil centrifuged to the outside of the generator housing. The output stage design is adequate to handle 75 watts of power which would be equivalent to operating at full load with a 250% of rated stream velocity. Figure 4.2-2 is a picture of the regulator assembly. Figure 3.0-5 is a picture of the regulator mounted inside the generator housing.

4.3 PROPELLER

The objective of the hydrodynamic analysis was to design a lightweight propeller which was capable of producing adequate shaft power to achieve the required 50-watt electrical output when operating at a stream velocity, c_o, of 3 knots (5.066 ft/sec)(later changed to 4 knots) and the design-point generator speed, N, of 420 rpm. The basic propeller theory and analysis employed to meet this objective, as well as the actual propeller fabrication, are described in the following paragraphs.

The performance of various propeller configurations is characterized by the speed parameter, λ_o, and the power coefficient, π_p. The speed parameter is defined by the following equation.

$$\lambda_o = \frac{\pi N}{30} \frac{R_T}{c_o} \tag{1}$$

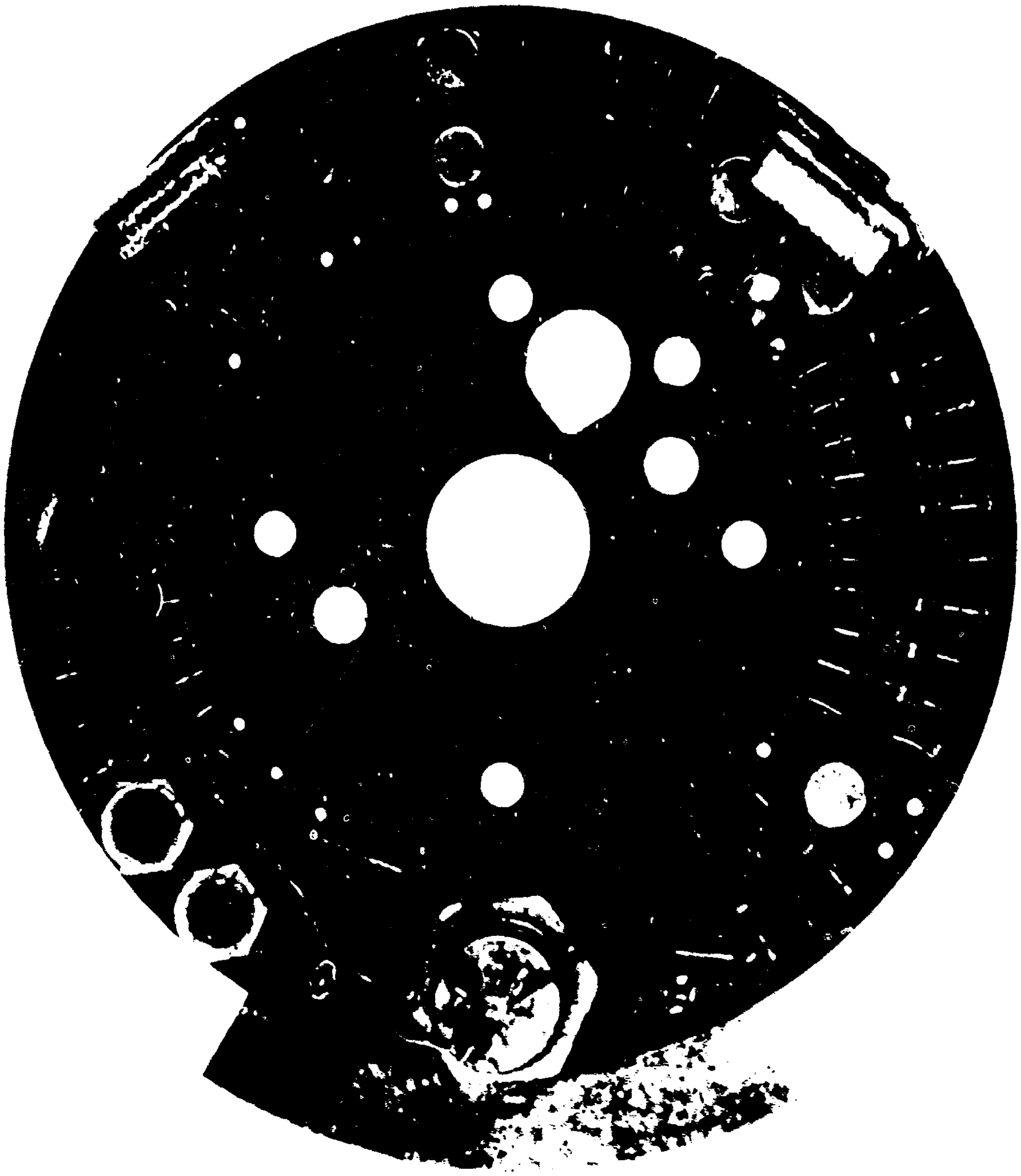
where R_T - rotor tip radius (feet)

N - shaft speed (rpm)

C_o - stream velocity (ft/sec)

The power coefficient π_p is given by the following relation:

$$\pi_p = \frac{C_1 W_{SH}}{\gamma \frac{c_o^3}{2g} \frac{\pi}{4} D_T^2 (1 - r^2)} \tag{2}$$



where W_{SH} - shaft power (watts)

D_T - tip diameter (feet)

v - specific weight of stream (pound/cubic foot)

r - hub ratio of rotor

C_1 - 0.737 $\left(\frac{\text{foot - pound}}{\text{second - watt}} \right)$

Figure 4.3-1 presents the performance of both low and high-speed propellers as a function of λ_p and λ_o. It represents a summary of the theoretical and experimental investigations of References (1), (2), and (3).

For the maximum allowable propeller diameter of 24 inches, the design-point value of λ_o is 8.67 and thus, from Figure 4.3-1, the high-speed, two-bladed propeller was chosen for use in the stream generator. The indicated design-point power coefficient for this configuration is $\lambda_p = 0.34$ which, when substituted into Equation (2) along with the hub (generator) diameter of 7 inches, yields a value for the shaft power of $W_{SH} = 172$ watts. This value represents the shaft power to be expected from a two-bladed propeller of optimum design when operating at the design conditions for the stream generator.

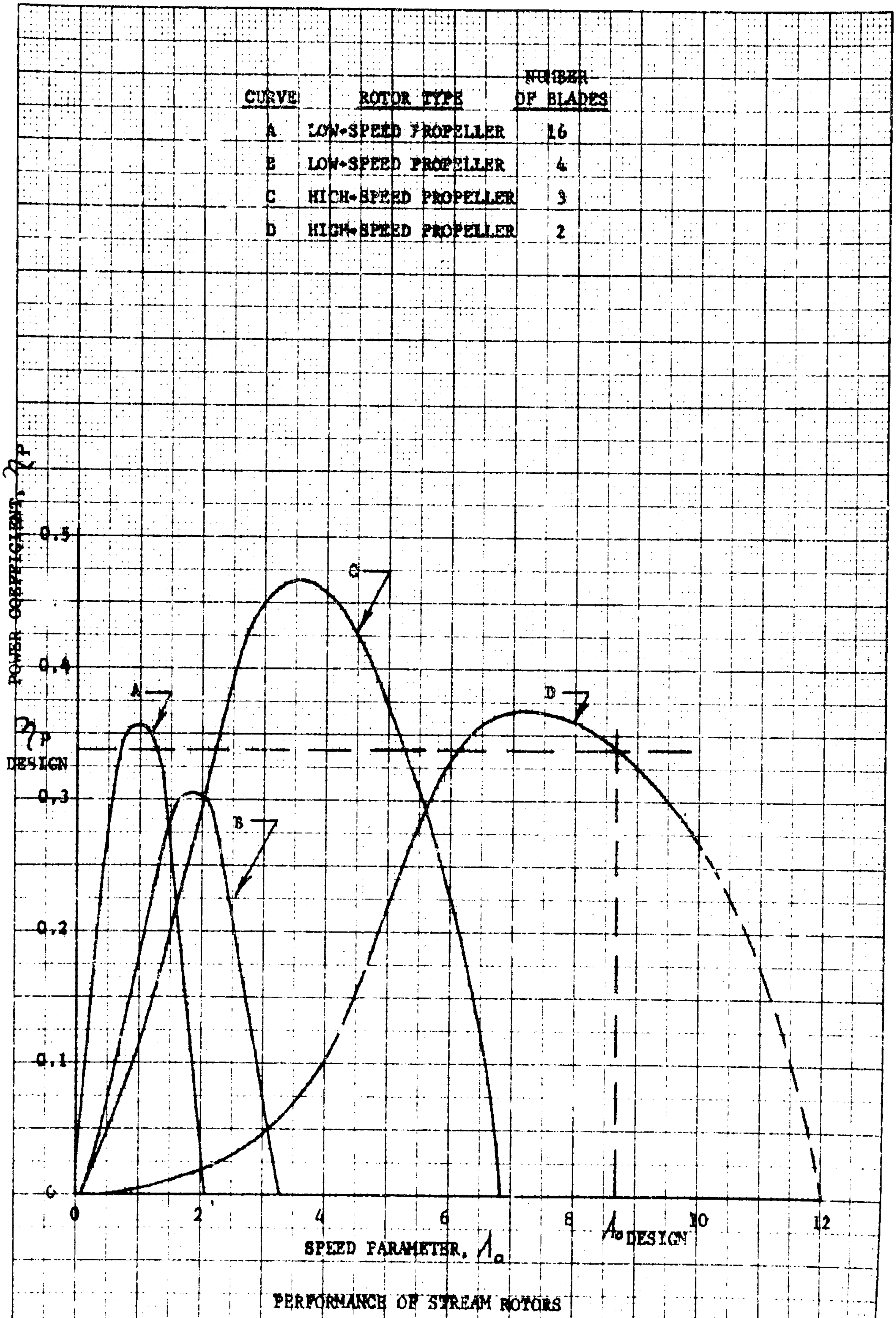
The hydrodynamic design of the rotor blade sections was based upon airfoil theory. For this purpose, the loading factor ($C_L\sigma$), defined as the product of section lift coefficient and section solidity (σ = chord length/blade spacing) was determined for each radius according to the following equation:

---

(1) Prandt, L., Betz, A., Test results of the Aerodynamic Institute of Goettingen, Oldenburg 1932/1935, Berlin.

(2) Huetter, U., Design Rules for Wind Power Plants, Ph.D. thesis, Weimar 1942, also Hutte, 28 edition, Pages 1030-1044, Ernst & Son, Berlin 1954.

(3) Fateew, Windpower Plants, Moscow 1948.



PERFORMANCE OF STREAM ROTORS

FIGURE 4.3 - 1

$$(C_L\sigma)_R = \frac{2\left(\frac{\Psi_T}{x^2}\right)}{\left(\frac{\varphi}{x}\right)^2 + \left(1 + \frac{1}{2}\frac{\Psi_T}{x^2}\right)^2} \tag{3}$$

Where Ψ_T denotes the tip pressure coefficient, φ is the flow coefficient and x denotes the dimensionless radius ratio $x = {}^{R}/R_{tip}$. Ψ_t is determined by the following relation:

$$\Psi_T \triangleq \frac{\Delta H}{U_T^2/g} = \frac{C_2 W_{SH}}{\left(\frac{\gamma}{g}\right) N^2 c_m D_T^4 (1 - r^2)} \tag{4}$$

where ΔH = change in dynamic head (ft-#/lb)

U_T = rotational velocity at the blade tip (ft/sec)

$C_2 = 343 \left(\frac{\text{ft-\#}}{\text{watt sec}}\right)\left(\frac{\text{rpm}}{\text{rad/sec}}\right)^2$

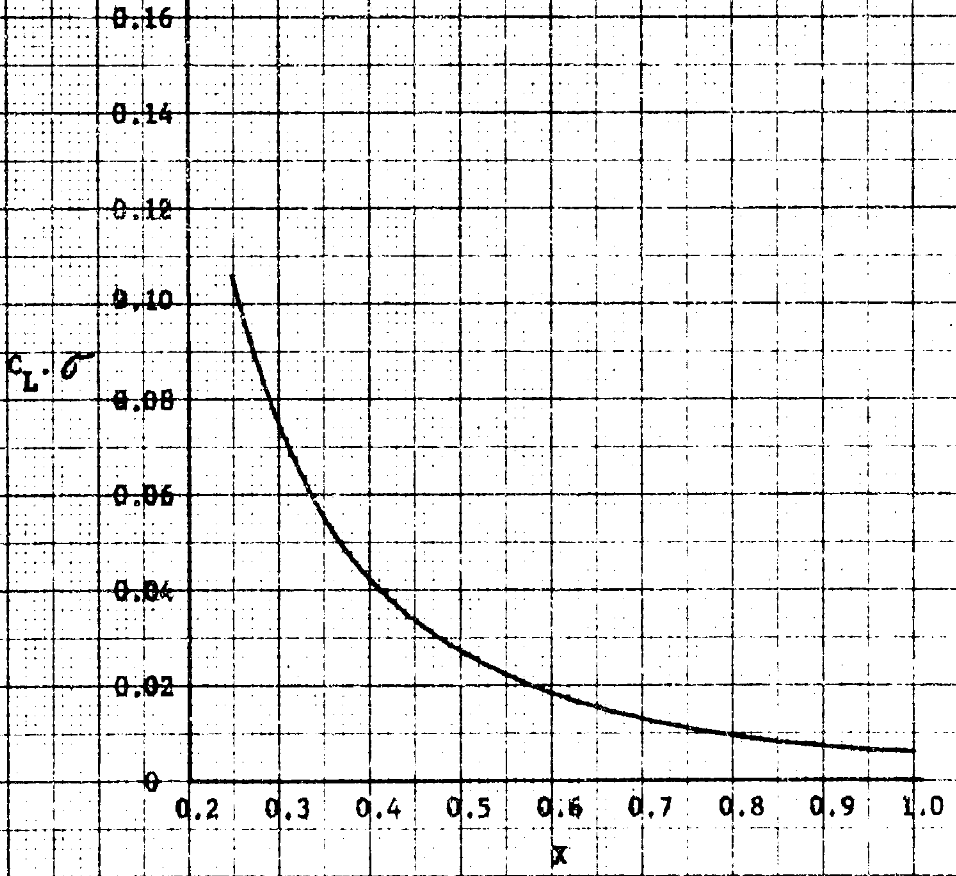
The effective through-flow velocity in the rotor plane, c_m, is given according to actuator disc theory by the following relation from Reference (2):

$$c_m = c_o(1 + \xi)/2 \tag{5}$$

where ξ denotes the deceleration coefficient, which is a function of the speed parameter, λ_o, and the power coefficient, η_p. For the present lightly loaded design, $\lambda_o = 0.33$. Finally, the flow coefficient, φ, is defined as the ratio of the through-flow velocity, effective in the rotor plane, to the rotor tip velocity, i.e.:

$$\varphi \triangleq \frac{c_m}{U_T} = \frac{30\, c_o\, (1 + \xi)}{\pi\, N D_T} \tag{6}$$

Substitution of the appropriate values into Equations (4), (5) and (6) yields the design-point values for c_m, Ψ_T, and φ of 3.38 ft/sec, 0.00340 and 0.0769, respectively. Figure 4.3-2 presents the calculated $(C_L\sigma)$ distribution as function of the dimensionless radius ratio.



BLADE LOADING FACTOR, $(C_L \cdot \sigma)$ VS. RADIUS RATIO, $X = {}^{R}/R_{tip}$

FIGURE 4.3 - 2

A linear chord distribution, varying from 0.75 in. at the blade tip to 3.00 in. at the hub, was selected. This distribution resulted in required section lift coefficients, C_L, in the range from 0.21 to 0.34. The next step was to select a blade profile having low drag characteristics in the above range of C_L which could be easily manufactured. The Goettingen Profile 610, consisting of a simple segment of a circle, was found to meet these requirements quite well, as shown in Figure 4.3-3, which depicts both the profile geometry and the lift and drag coefficients as a function of the angle of attack, δ. The selection of the 610 profile results in values of the drag coefficient, c_d, between .008 and .013 for the specified range of C_L. The resultant distributions of chord length, lift coefficient and drag coefficient are shown in Figure 4.3-4 as a function of the dimensionless radius ratio.

While the blade profiles at all radii were kept geometrically similar, both the chord length (and thus thickness distribution) and blade angle vary from hub to tip. The blade angle, β_s, is defined as the angle between the circumferential direction and the chord of the blade and is determined by the following equation:

$$\beta_s = 90 - \beta_\infty - \delta \tag{7}$$

Where β_∞ denotes the angle of the vector mean relative velocity, W_∞, with the axial direction, as determined from the equation:

$$\beta_\infty = \tan^{-1}\left[\frac{x}{\varphi}\left(1 + \tfrac{1}{2}\frac{\Psi_T}{x^2}\right)\right] \tag{8}$$

The angle of attack, δ, is defined as the angle measured from W_∞ to the chord and is determined from Figure 4.3-3 for the specified lift coefficients. The variation of β_s, β_∞, and δ as a function of the dimensionless radius ratio are shown in Figure 4.3-5.

The preceding analysis determines the optimum blade configuration for the "ideal" propeller having zero drag which results in a change in dynamic

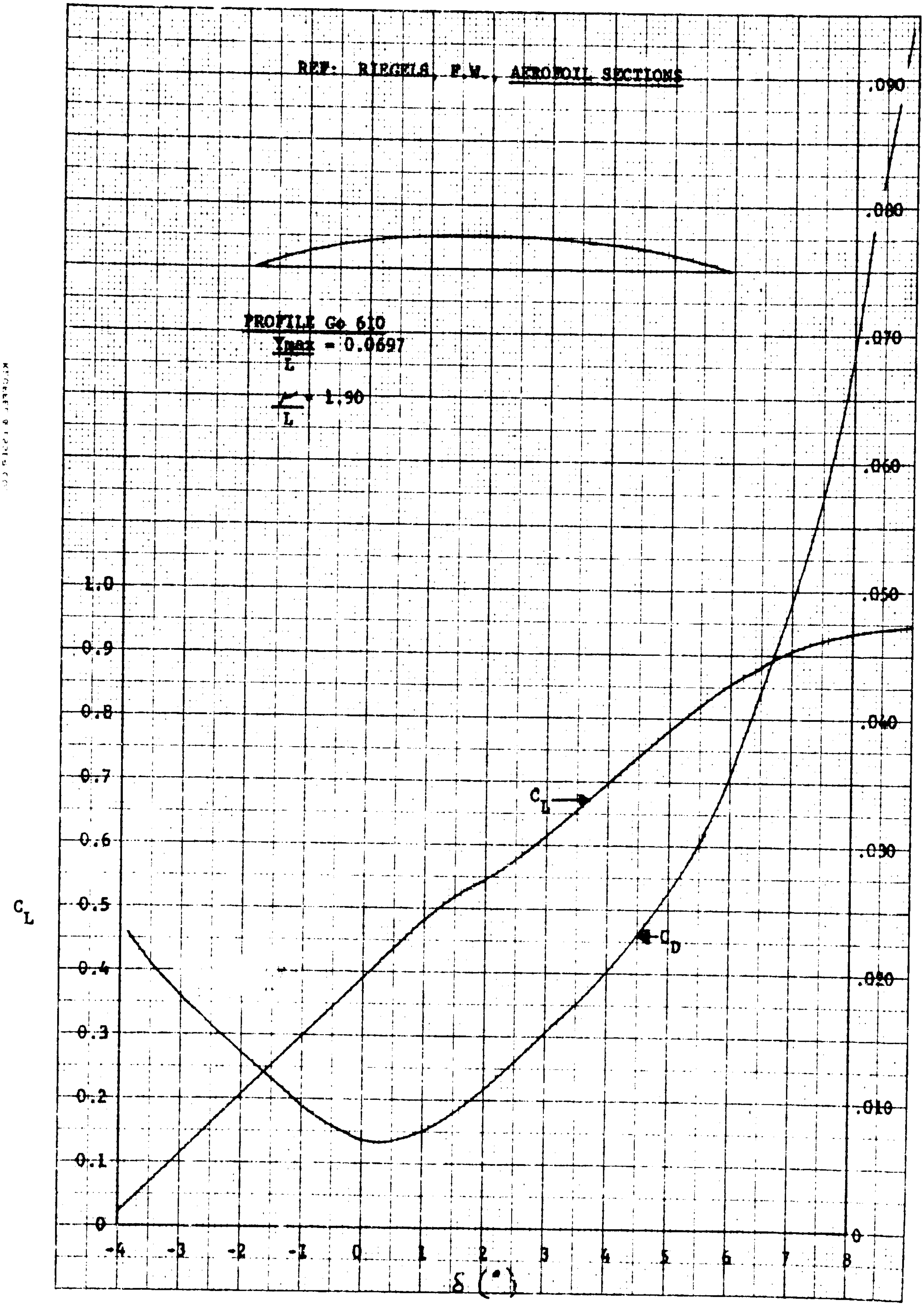


FIGURE 4.3-3 BLADE PROFILE LIFT AND DRAG COEFFICIENTS VS. ANGLE OF ATTACK

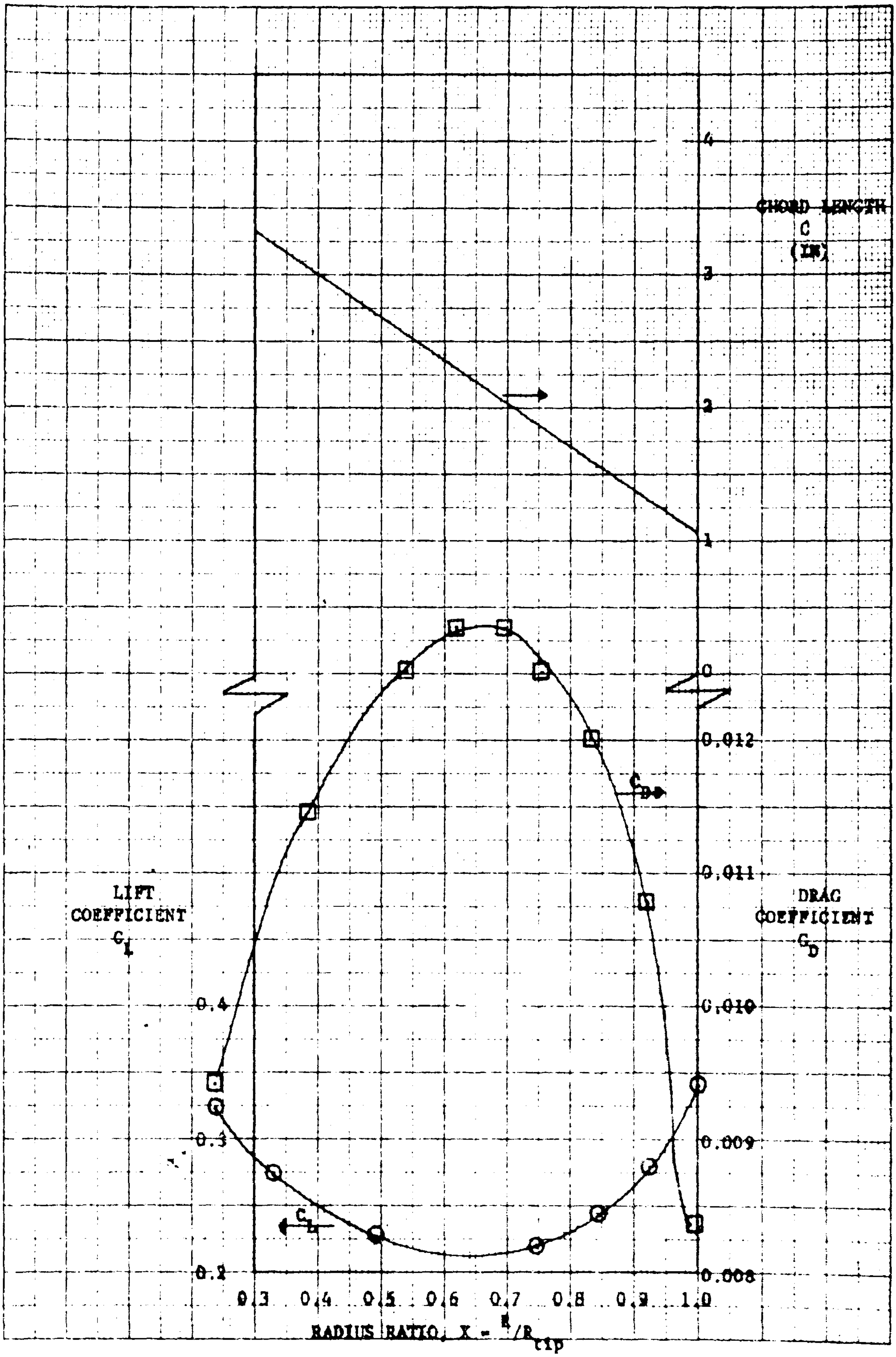
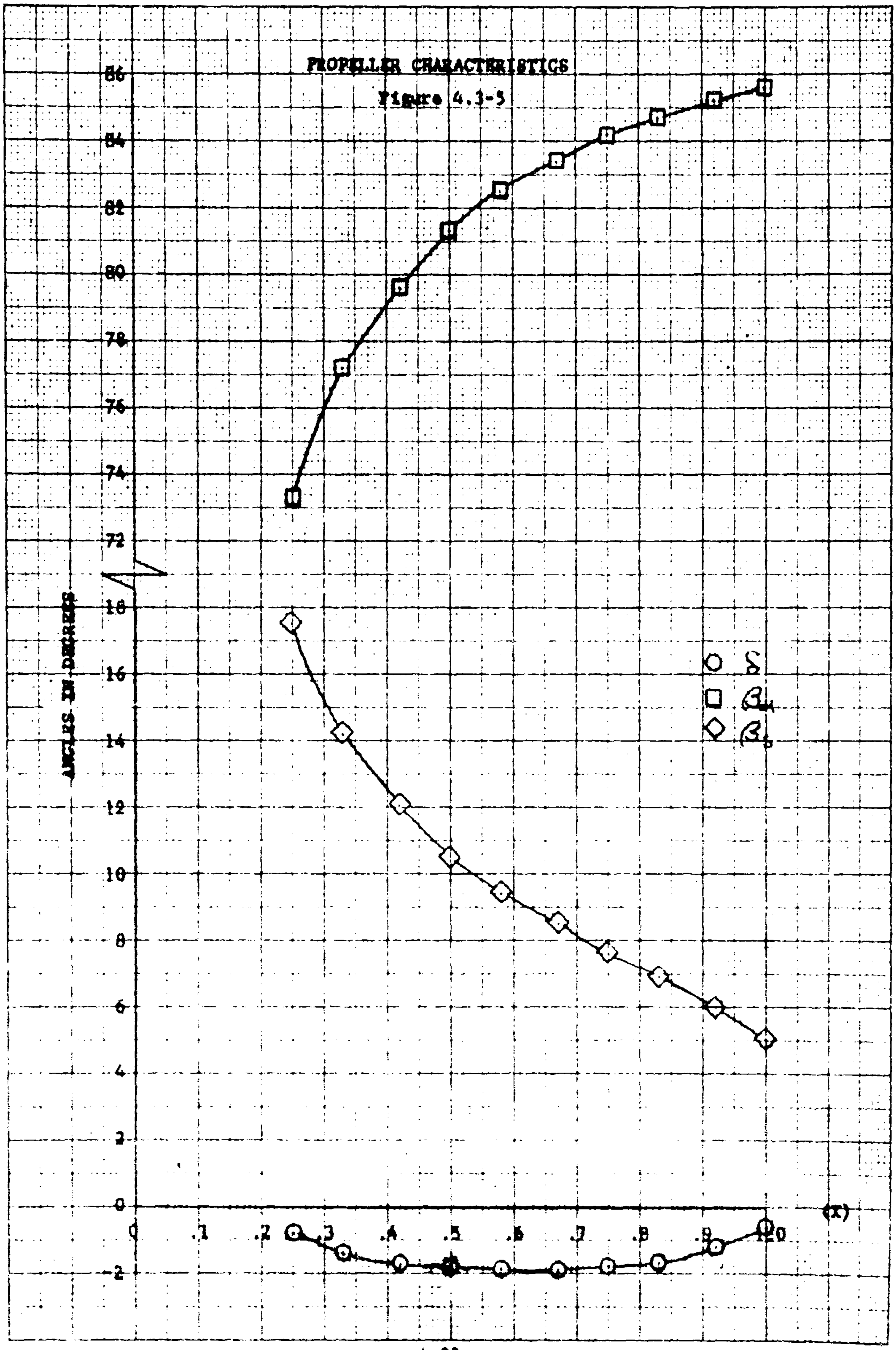


FIGURE 4.3-4 PROPELLER BLADE CHARACTERISTICS


PROPELLER CHARACTERISTICS
Figure 4.3-5
ANGLES IN DEGREES
86
84
82
80
78
76
74
72
18
16
14
12
10
8
6
4
2
0
-2
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
(x)

head (ΔH) which is constant as a function of radius. Consequently, the shaft power developed will be less than 172 watts at design-point conditions due to the finite values of c_d noted above. The actual predicted performance of the propeller may be determined from the following finite-difference equation:

$$W_{SH_{actual}} = \sum_{R_{Hub}}^{R_{Tip}} C_3 \mu_B \left(\frac{\pi N}{30}\right)\left(\frac{\gamma W_\infty^2}{2g}\right)(C_T C R) \Delta R \qquad (9)$$

where $W_\infty = \left[\left(\frac{\pi N}{30}\right)^2 R^2 + c_m^2\right]^{\frac{1}{2}}$

$C_T = C_L \cos \beta_\infty - c_d \sin \beta_\infty$

= blade-section torque coefficient

μ_B = number of blades

$C_3 = 1.357 \frac{\text{watt sec}}{\text{ft-\#}}$

The actual predicted propeller performance is shown as a function of shaft speed and free-stream velocity in Figure 4.3-6.

Finally, it is necessary to check the cavitation performance of the proposed propeller turbine. For this purpose, the suction specific speed is calculated according to the following equation:

$$S = \frac{N \quad Q}{(NPSH)^{3/4}} \qquad (10)$$

when

N = RPM of rotor

Q = volume flow through propeller (GPM)

NPSH - Net positive suction head

$$NPSH = \frac{P_a}{\gamma} + H + \frac{c_o^2}{2g} - \frac{P_v}{\gamma}$$

P_a - ambient pressure (pound/foot^2)

H - submergence of propeller center line (feet)

C_o - free stream velocity (feet/second)

P_v - vapor pressure of cold water (pound/foot^2)

γ - specific weight of water (pound/cubic foot)

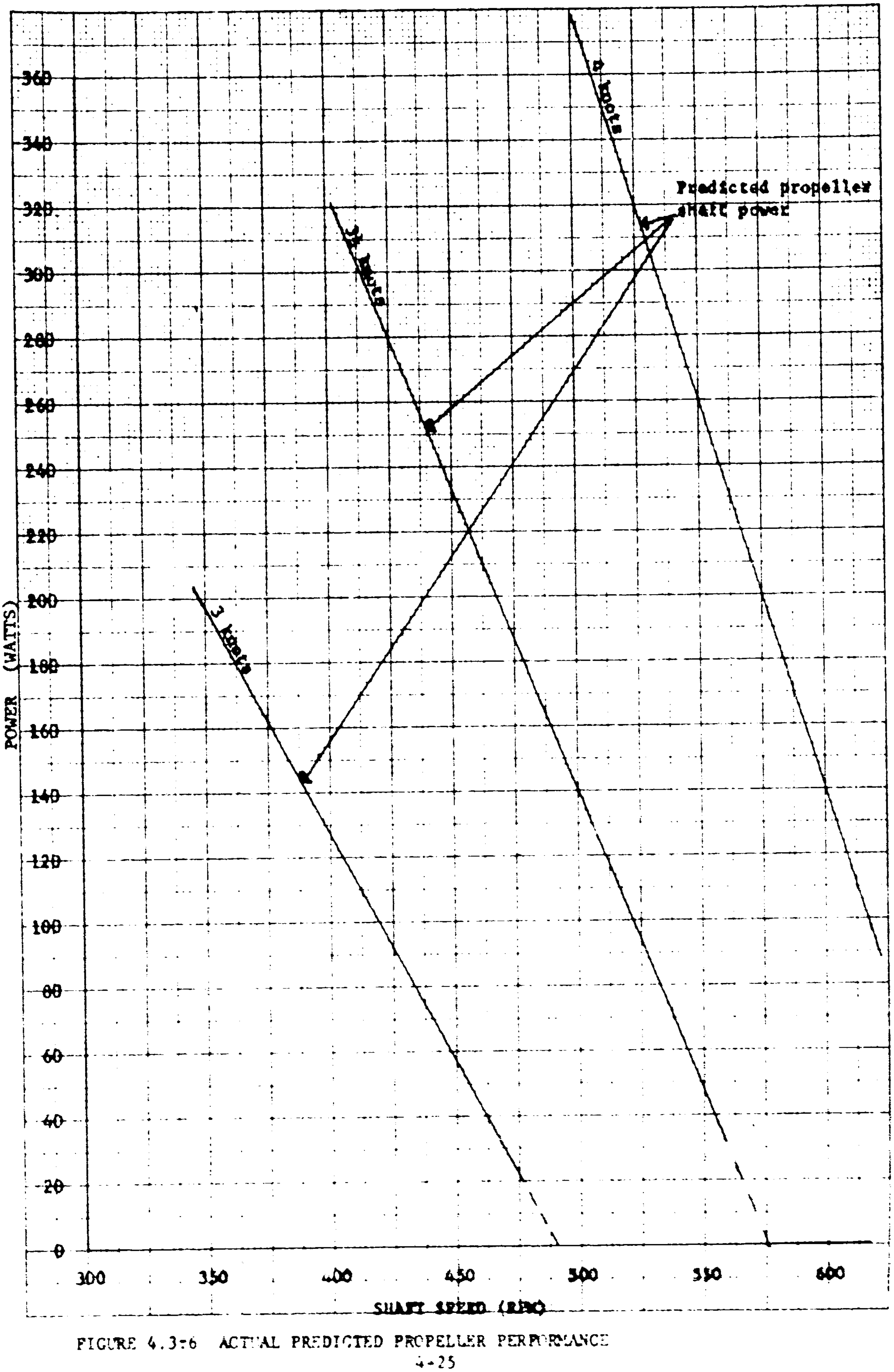


FIGURE 4.3-6 ACTUAL PREDICTED PROPELLER PERFORMANCE

The calculated suction specific speed is S = 2265 at the design point, which is far less than the critical value of S_{crit} = 10,000; thus, the proposed propeller will operate free from any cavitation effects.

In order to achieve weed-free propeller operation, the blade centerline describes a spiral path in the frontal view as shown in Figure 3.0-1. The net effect of this configuration is that any weeds hitting the blades are centrifuged out to the tip, resulting in essentially weed-free operation.

The propeller blades were fabricated from ¼-in.-thick 6061-T6 aluminum plate. The curved propeller blank was first cut from the plate and twisted to obtain the desired values of B_s. Next, the required blade contours were accomplished by hand filing and polishing. Finally, the mounting holes were machined and the finished blades were hard black anodized per specification MIL-A-8625B Type 3.

4.4 MECHANICAL DESIGN

The basic requirements to be met by the mechanical design are the selection of materials compatible with both the brackish or salt water environment and the 15-pound weight goal. Also, the design must minimize the fouling effects of drifting vegetation, provide adequate rigidity to overcome magnetic side loads imposed by the generator and provide a sealed protective atmosphere for the voltage regulator, generator and bearing system.

The selection of an inside-out generator design contributed greatly to the simplification of the overall mechanical design. The inside-out rotor configuration allowed the whole unit housing to rotate which aids in minimizing the fouling effect of drifting vegetation.

The selected component mounting arrangement provides the rigidity necessary to overcome themagnetic side loads imposed by the generator. The housing half which holds the rotor could have been constructed with a cantilevered bearing support to improve the concentricity of the generator rotor and stator. However, the cantilevered approach requires considerably heavier construction and thus was not utilized.

The electric cable is routed through the c nter of the stationary shaft and out through the side of the shaft under the hollow support for the stator winding assembly. The cable is potted in place with an epoxy.

The solid state voltage regulator circuit board also holds the bridge rectifier and filter capacitors required. The circuit board is mounted directly to tha hub supporting the stator. The only external connections in the unit are the connection of the (3) phase leads from the generator and the (4) leads from the electric cable.

Sise 204, single row, deep grove, light series bearings are used. Catalog information presented by the Marlin-Rockwell Corporation indicates one such bearing is adequate to meet the one year life requirement with a 100-pound axial thrust at the 420 rpm design speed. The calculated total axial load is approximately 55 pounds. Possibly a smaller bearing could be utilised thrust-wise; however, the bore diameter must be adequate to allow the passage of the cable as well as have the strength necessary to support a relatively large bending load.

The upstream bearing carries all of the thrust developed plus the force developed by the preload spring acting on the downstream bearing. The preload force is approximately 10 pounds and is necessary to insure that the downstream bearing is not unloaded which would cause skidding and premature wear. The preload spring is installed between the shaft and the electronic circuit board and loads the inner race of the bearing. The thrust is transferred across the bearing to the housing. A slip fit between both bearings and the shaft is used. A slight interference fit is used between the bearing outer races and the housing.

The bearings are lubricated by the oil contained in the housing. This oil, approximately 400cc, is centrifugred to the outside housing wall during operation, and thus would normally be unavailable for lubrication. Consequently, two stationary pitot tubes are installed to deliver lubricant to the bearings. The tube openings face into the direction of the moving fluid. The fluid is ducted through the tubes to the bearings after which gravity returns the oil to the bottom of the housing.

The internal construction of the unit is such that it is desirable to prevent the entrance of water and/or dirt into the housing. Most of the materials utilized are compatible in themselves with salt water; however, galvanic action between dissimilar metals and contamination by dirt could have a serious effect on the bearing life expectancy. Two lip type rubbing shaft seals are utilized to prevent leakage in this area. The seals are mounted back to back, one to prevent the entrance of water and the other to prevent the leakage of oil out of the unit. The shaft seals are lightly loaded thus limiting the pressure capability. However, normal installation of the unit precludes operation at an uncompatible pressure.

O-ring seals are used to prevent leakage across the back of the shaft seal. A large diameter O-ring is also used to seal the interface between the two halves of the housing.

The electric cable is routed through the center of the shaft and into the housing. The clearance around the cable is potted or sealed using a low temperature semirigid epoxy. The end of the cable is also sealed with epoxy to prevent leakage of water into the unit through the cable jacket. The amount of oil contained in the unit is small enough that the cable is not immersed in the oil in any position.

The voltage regulator can be required to dissipate up to 75 watts under abnormal operating conditions. This heat must be removed from the area of the series-regulating transistor with a fairly low thermal drop. Transistor design data indicate that the maximum allowable transistor case temperature is 270°F. Analysis indicates that 75 watts of power can be transferred to the oil heat transfer medium with a minimum of complexity.

The heat generated is transferred to the oil centrifuged to the outside housing wall via a small fin which is submerged in the annulus of oil. Analysis indicates the total temperature gradient from the housing to the transistor case will be approximately 75°F when a fin area of 3.0 square inches is used. This provides a conservative maximum operating temperature of 155°F if operating in an 80°F ambient stream.

The oil contained in the housing centrifuges to the housing wall at a housing speed of 110 rpm. At this speed, or lower, very little power can be generated thus no damage can result to the regulating transistor.

The mounting stake supplied will provide the swivel action necessary to allow the unit to align itself with the direction of the stream flow. The sleeve bearing that allows the swivel action is made of teflon. The mounting stake assembly is made of 6061-T6 and is also hard anodized.

The mounting stake, shown on Figure 3.0-1, will be normally insufficient to support the stream forces acting on the unit in operations. Approximately 45 pounds of force is acting on the unit at full load. The mounting stake is equipped with a mounting ring, just under the swivel joint, to anchor any guy wires, etc., required to fully support the unit.

4.5 MATERIAL SELECTION

The unit housing, mounting stake, propellers and all other parts, where possible, are made from 6061-T6 aluminum. Aluminum is used because of its light weight and environmental compatibility. *Material compatibility information gathered indicated that uncoated 6061-T6 aluminum is very compatible with sea water resulting in long term exposure attack to depth of only a few mils. Other parts made from aluminum, mounted internally, are the stator mounting hub and preload spring washers. All screws used in the external assembly are made from 300 series stainless. The shaft is made from titanium. Titanium is selected because of its compatibility with salt water and also because of its light weight but high modulus.

*Corrosion Resistance of Metals and Alloys. 2nd Edition 1963
Edited by F. L. LaQue & H. R. Copson.

An aluminum shaft would be desirable; however, because of the lower modulus of aluminum, an abnormally large shaft would have been required to carry the possible bending loads.

The bearings selected are stainless steel to insure a minimum of degration in the event a small amount of water does seep past the seals. The oil lub pitot tubes are also made from thin wall 300 series stainless steel tubing and are silver brazed to a mounting bracket.

The stator stack is constructed with .014-inch silicon iron laminations which are epoxy bonded to form a rigid stack. The stator is wound with polyimide-insulated copper conductors. The slot insulation is .010-in. Nomex (Du Pon nylon). The interphase insulation is .002-inch-thick "H"film" which is the Du Pont trademark for a polyimide film insulation. The stator windings are tied with a glass fiber cord and terminated with stranded, teflon-covered lead wire. The stator assembly is impregnated with Class H, Dow Corning GP77 varnish. This combination of materials is compatible with the selected transformer oil to which they are exposed.

The electronic circuit board is an epoxy-bonded micarta laminate. The board is drilled and connecting pins installed in an evenly-spaced radial pattern. The components are for the most part installed between inline radial pins. The bulk of the interconnecting wiring is on the back of the circuit board.

The final regulator assembly has been dip coated with a low temperature, semirigid epoxy. The epoxy coating is to seal the sensitive, high-gain circuits from inadvertent exposure to moisture and also to increase the mechanical integrity of the regulator. Small amounts of moisture between elements in the high gain circuits could cause the regulator to drift if not sealed. The connections made from the stator and cable on the board are insensitive to moisture and are not sealed after installation.

The electric cable is constructed of stranded, tinned copper conductor with a nylon jacket over each lead. The four leads are jacketed in neoprene which is compatible with salt water and long-term exposure to the sun.

The materials used in the construction of the unit are all highly compatible with the required salt water environment. However, because of some material dissimilarities, galvanic action can cause serious corrosive action. The materials used and exposed to the water are 6061-T6 aluminum for all structural items, 300 series stainless steel for all fasteners, a titanium shaft and a brass case on the shaft seal. In general, galvanic corrosion can exist between all of these items. To reduce this potential corrosion problem to an acceptable rate, the aluminum parts are hard black anodized per MIL-A-8625B Type III. The anodized coating is a good insulator thus preventing or reducing the galvanic currents that would normally flow. All galvanic currents that could be generated have to go through the insulating anodized coating. There is no surface that is exposed to the water environment that can see bare aluminum.

Material combinations with other than the anodized aluminum which can result in a couple will cause very little galvanic corrosion due to their placement. Titanium develops a protective oxide coating when immersed in salt water. After a few minutes in sea water a noble potential is developed which is close to the potential of stainless steel. The couple formed by the brass case on the shaft seal and the titanium shaft is weak because direct-couple currents have to pass through the oxide coating on the aluminum housing. The uncoupled galvanic action between these two materials is relatively mild.

SECTION 5

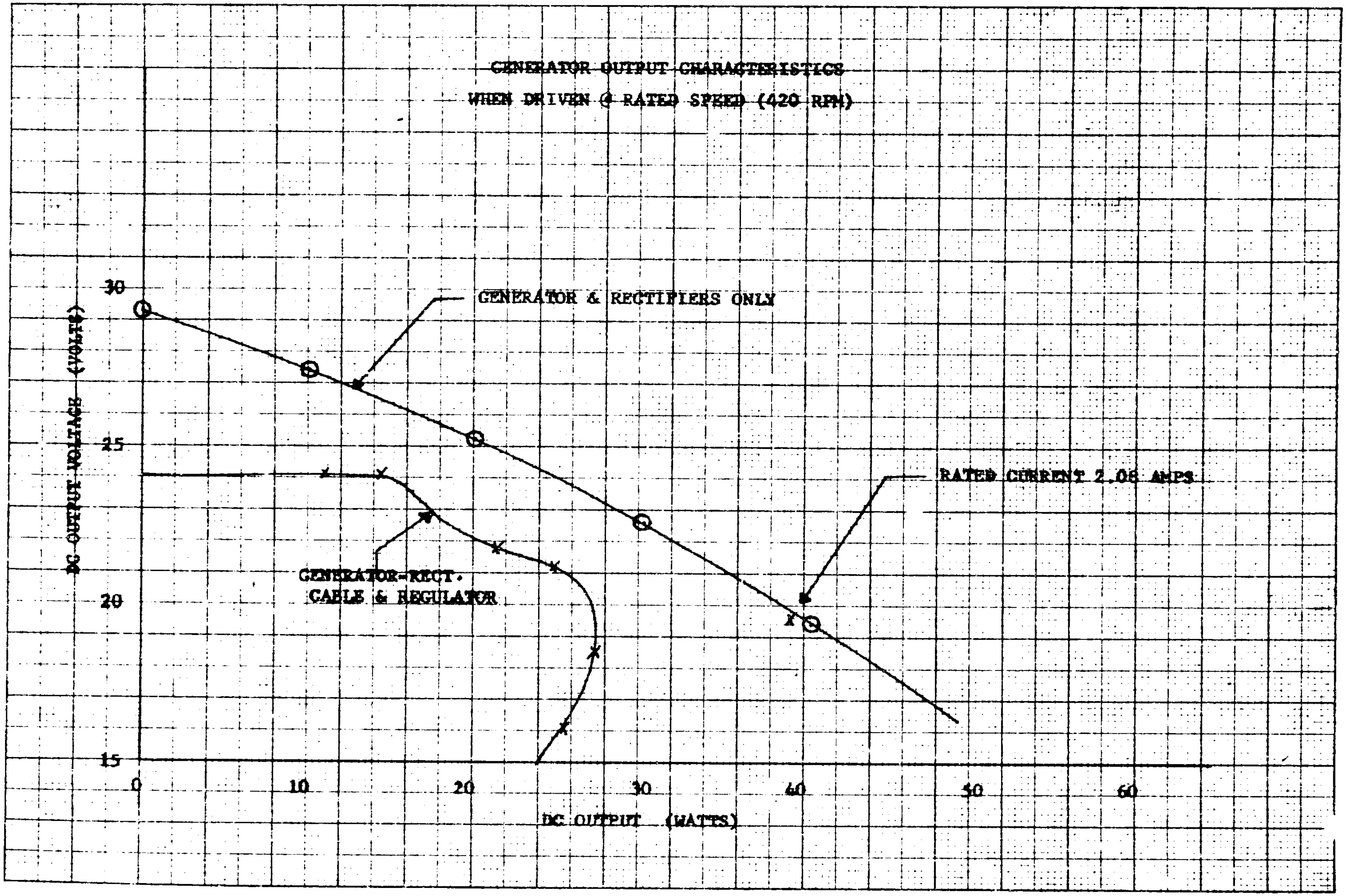
DEVELOPMENT TESTING & EVALUATION

5.1 GENERATOR

The generator was fabricated as described in Section 4.1 and then tested on a dynamometer. Immediately it was found that the generator could not deliver the required 50 watts of power at 24 volts DC at 420 rpm. Figure 5.1-1 indicates the output characteristics of the generator with and without the voltage regulator.

Ensuing investigations indicated that the no-load flux was only about 83% of that necessary at full load to provide an output of 24 volts DC. When full load is applied to the machine, the armature reaction currents buck out some of the magnet ampere turns available, further reducing the available flux at the air gap. The calculated demagnetization ampere turns with rated load current is approximately 28 ampere turns per pole.

The measured light load AC voltage, 22.0 volts line to line, indicates an air gap flux level of 30,300 lines per square inch. This air gap density requires a total magnet force of 218 ampere turns. When the rated load current demagnetization force is present, the air gap ampere turns are reduced and the air gap density is only 26,845 lines per square inch. This reduces the generated voltage to 19.5 volts L-L which is considerably lower than required to produce 24.0 volts DC. Further



GENERATOR OUTPUT CHARACTERISTICS
WHEN DRIVEN @ RATED SPEED (420 RPM)
GENERATOR & RECTIFIERS ONLY
RATED CURRENT 2.08 AMPS
GENERATOR-RECT.
CABLE & REGULATOR
DC OUTPUT VOLTAGE (VOLTS)
DC OUTPUT (WATTS)
30
25
20
15
0
10
20
30
40
50
60

FIGURE 5.1-1

investigation also indicated that the rectification conversion factor at the rated load current point is only 1.15 versus a normal factor of 1.25. Wave form pictures indicate that the generated waveform is severely distorted. This is greatly due to the rectified load applied. In the Lundell configuration the North and South Poles are in a series, thus the total demagnetization force on the magnet is 56 ampere turns. Figure 5.1-2 indicates the load regulation characteristics of the generator.

The major item which accounts for the deficiency in power output is the low air-gap flux density. An investigation into the reason for this low density indicated that the poles of the rotor are operating in a highly saturated condition. This was determined by successively machining segments off of the magnetic shunt installed on the outside of the rotor. It was noted that there was no decrease in generated voltage until the shunt was completely removed. At this time the decrease was only 3.4%. As the shunt was being removed, the measured flux density in the shunt area remained fairly constant. This indicated that this flux, for the most part, was not required for the air-stabilized condition that the magnetic assembly was in. The measured density in the shunt area required a magnetizing force of approximately 470 ampere turns. The air gap required only 210 ampere turns for the voltage generated. Thus the difference, approximately 260 ampere turns, was dropped across the rotor pole pieces. Figure 5.1-3 indicates the load-speed characteristics of the fully assembled unit. The unit was driven on the bench with a DC motor at a speed that would produce an output slightly less than 24.0 volts. This was done for various loads. Figure 5.1-4 is a picture of the unit under test.

Up to this point all the testing accomplished was done in the laboratory. Since the type of propeller proposed for the design is not conventional, it was decided to integrate and test the propeller-generator combination before contemplating any modifications. The results of the tests of the integrated unit are discussed in Section 5.3.

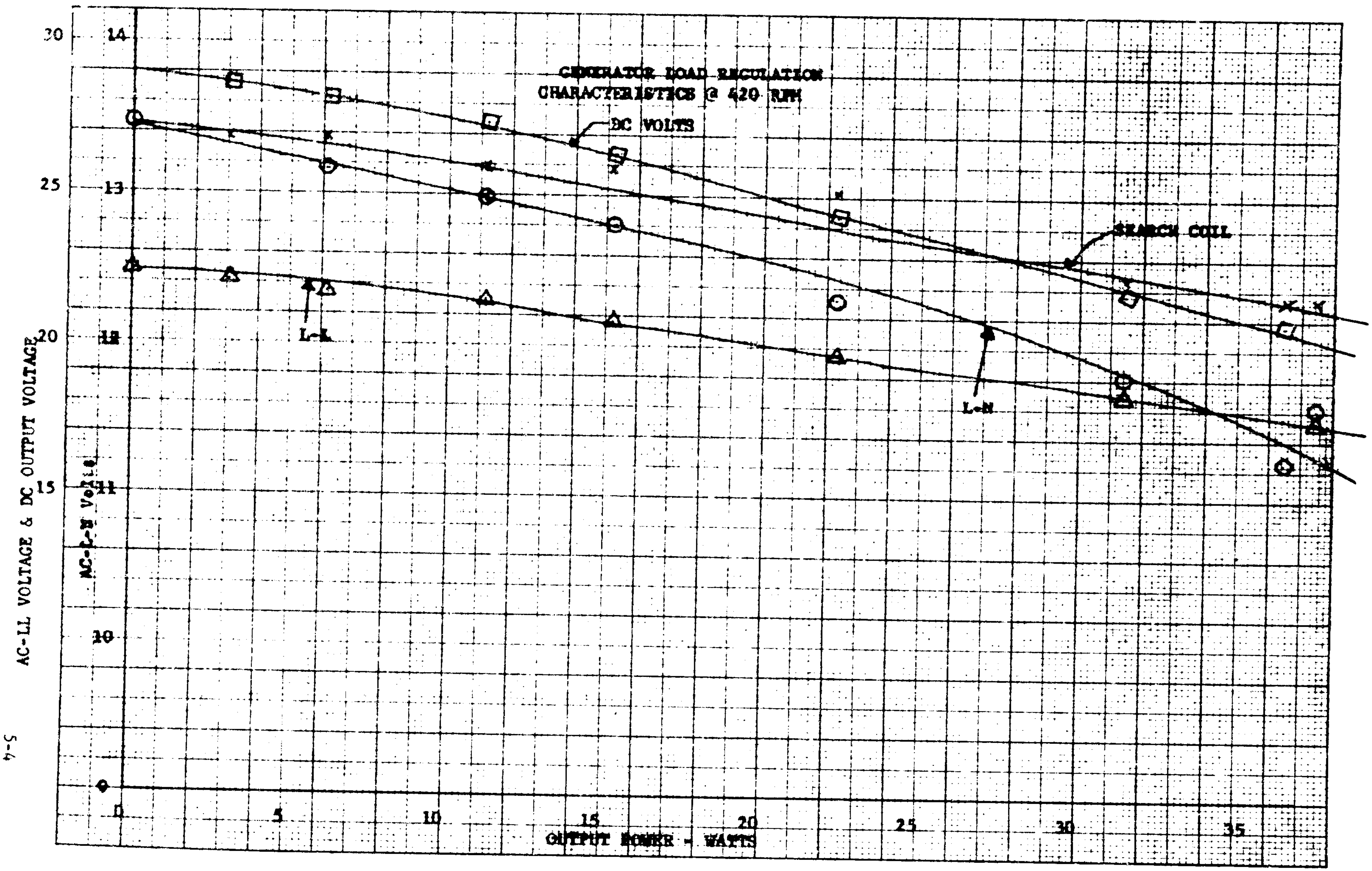

GENERATOR LOAD REGULATION
CHARACTERISTICS @ 420 RPM
DC VOLTS
SEARCH COIL
L-L
L-N
AC-LL VOLTAGE & DC OUTPUT VOLTAGE
AC-L-N Volts
OUTPUT POWER - WATTS
30
25
20
15
14
13
12
11
10
0
5
10
15
20
25
30
35

FIGURE 5.1-2

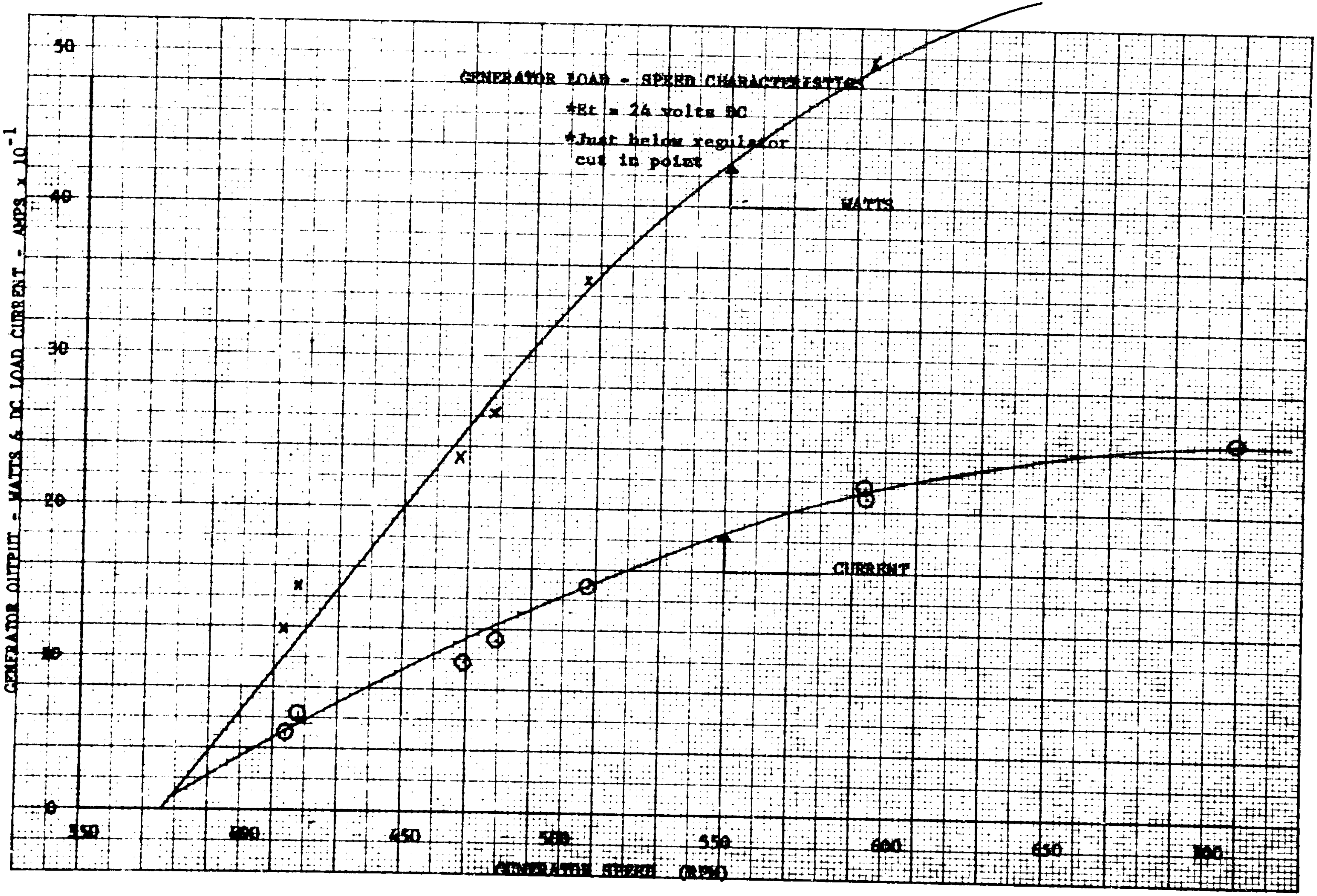
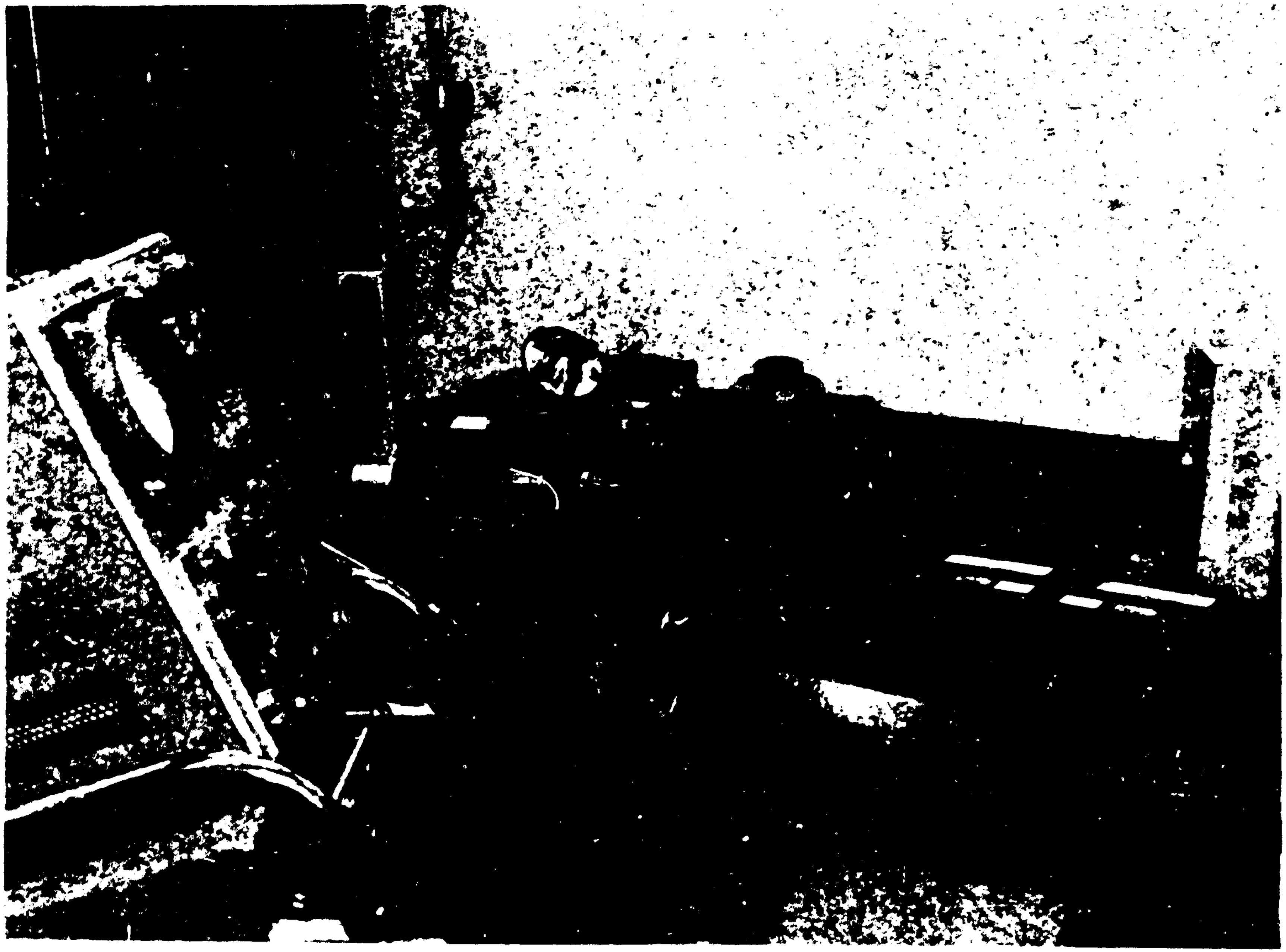

GENERATOR LOAD - SPEED CHARACTERISTICS
*Et = 24 volts DC
*Just below regulator
cut in point
WATTS
CURRENT
GENERATOR OUTPUT - WATTS & DC LOAD CURRENT - AMPS x 10^{-1}
0
10
20
30
40
50
350
400
450
500
550
600
650
700

FIGURE 5.1-3



[illegible]

5.2 VOLTAGE REGULATOR

The voltage regulator was first breadboarded and tested on the bench over the full design load range. The initial breadboard tests used commercial (3) phase power, 60 cps as the source of energy. Modifications were made as required to provide a regulated output considered acceptable. The breadboard regulator was then tested with the stream generator. Since the generator is not a stiff power source, several modifications were required to reduce a tendency to become unstable. Primarily these changes were a metter of providing a small amount of filtering of the raw DC output from the rectifiers and incorporating some feedback from the driver amplifier to the input differential sensing amplifier.

The prototype voltage regulator was then fabricated, installed inside the housing and tested as an integrated assembly. The regulator provides a regulated output of ±1% of the nominal 24-volt output over the full load and speed range required. The design also provides a well filtered output. The normal ripple level from an unfiltered DC output would be approximately 5.0%. The ripple output of the voltage regulator is less than .5 volts peak to peak under the worst load condition.

The unit was run at twice rated speed and operated at full load when tested in the lab. This required the voltage regulator to dissipate 50 watts of power. The unit was operated continuously in normal 75°F ambient air with only a slight increase in housing temperature. The thermal design appears to be more than sufficient to handle reasonable inadvertent overloads.

5.3 PROPELLER

Two sets of propeller blades were fabricated as described in Section 4.3. One of these sets had the spiral sweepback described previously. However, the second set consisted of straight radial blades, having the same blade profile and chord distribution, in order to evaluate the effects of sweepback on propeller performance.

Prior to their installation on the generator both sets of propellers were tested, using a specially-developed, adjustable Prony-brake apparatus, while suspended in front of a small power boat moving through the calm water of Newport Bay, California. A commercial rotor-driven marine speedometer, of the type used in racing sailboats, was used to determine free-stream velocity, and a speed pickup from a second such unit was employed to determine propeller speed. These tests confirmed that the performance of the curved propeller was approximately as predicted by the previously-presented analysis; the effects of the spiral sweepback appear to be negligible and no cavitation was detected during the tests, although some aeration of the propeller tips was observed while testing at blade angles significantly above the design values. The propellers were then repitched in an attempt to raise their operating speed to the 600-rpm range at three knots in order to meet the design requirements with the present generator. This attempt appeared to be successful and, consequently, the propellers were assembled to the generator for a final series of system tests of the complete propeller-generator combination.

The integrated unit was tested in the same manner as the propellers, i.e., while suspended in front of the power boat. The first series of tests quickly established that the unit could not deliver the required output at three knots, primarily because adequate shaft speed could not be developed by the propellers at this value of free-stream velocity. Only a slight gain in performance was obtained through further repitching of the propeller blades. In retrospect these results are as expected, since operation at 600 rpm and three knots results in a value of the propeller speed coefficient, $\lambda_o = 12.4$ and Figure 4.3-1 confirms that operation at this point is not possible, even with a completely optimized propeller design. The disparity between these results and those obtained during the propeller tests is attributed to erroneous readings of free-stream velocity during the propeller test series. Although the marine speedometer was calibrated several times during these tests, it was later discovered that severe hysteresis and non-linearity were caused by marine fouling of this unit which apparently led to the erroneous readings.

For the above reasons, no quantitative test data are presented from the propeller test series; however, for comparison with the final test results, it is possible to predict the performance of the integrated unit using the results from the propeller analysis and the generator bench tests. This prediction is accomplished as shown in Figure 5.3-1, where the total estimated generator power requirements and the calculated propeller performance are plotted as a function of shaft speed. The interceptions of the former curve with the propeller performance curves determine the predicted shaft speed, and thus power output, as a function of free-stream velocity.

The results from the above calculations, as well as the final test results for the integrated stream generator, are plotted in Figure 5.3-2. The agreement between the test results and predicted performance is excellent; the output is seen to be about 35 watts at three knots, while the desired 50-watt output is achieved at approximately 3.6 knots. In order to obtain more accurate performance data, these tests were conducted without the voltage regulator; the previously-discussed bench tests of the generator/regulator combination indicate that the required 24-volt, 50-watt output is achieved by the stream generator at a free stream velocity of about 4.0 knots. In a final attempt to increase propeller speed (and thus power output), the propeller diameter was reduced to 22.4 inches; however, as shown in Figure 5.3-2, no significant increase in performance was achieved. The reduced propeller diameter of 22.4 in. was retained in the final configuration to provide increased clearance within the allowable 24-inch stream depth.

The results are considered to verify the analytically-predicted propelle performance. Furthermore, it is concluded that the failure to achieve the required 50-watt power output at the original 3-knot stream velocity was due to the inability of the generator to load the propellers and/or the inability of the propellers to provide the increased shaft speed required by the generator.

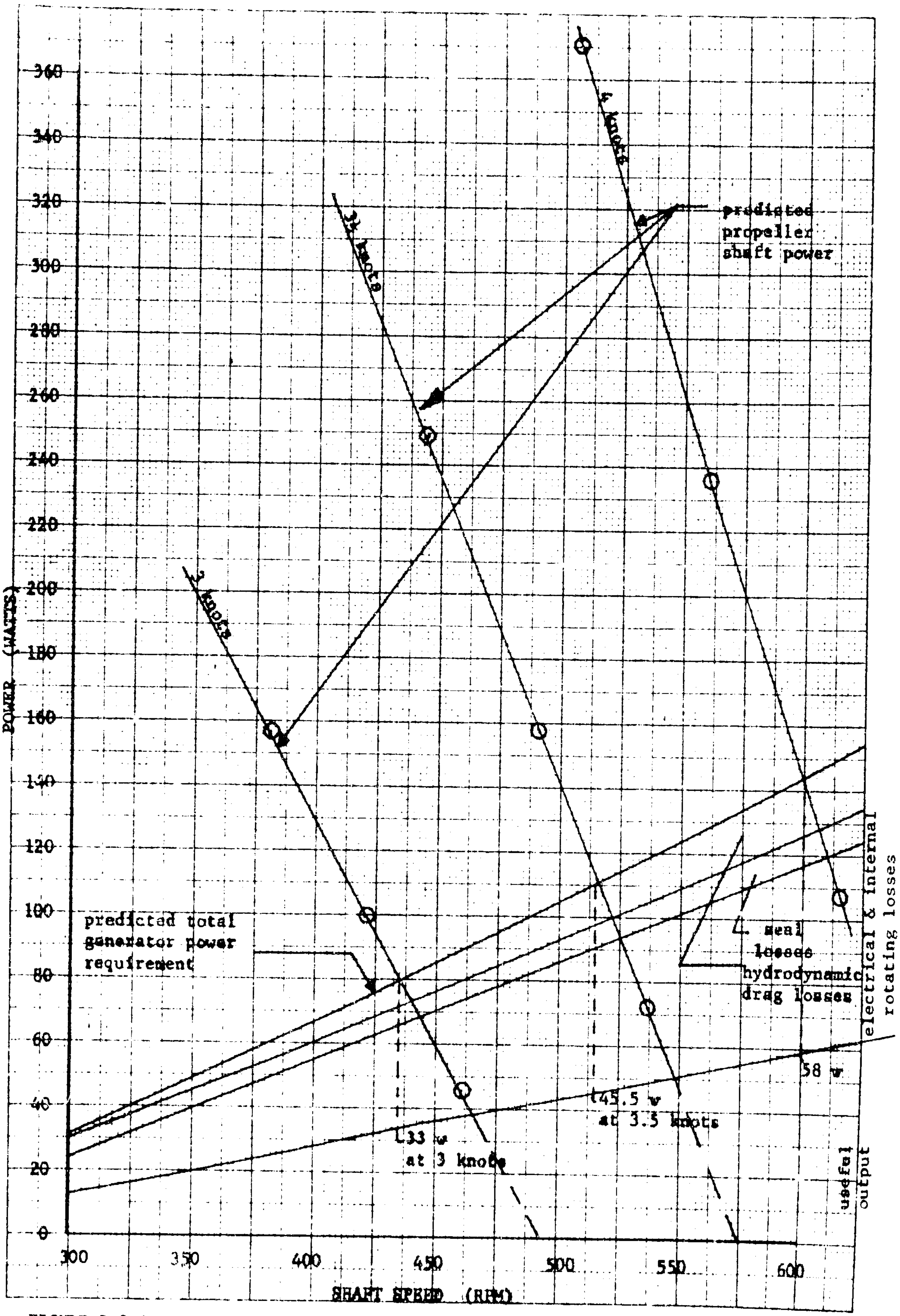


FIGURE 5.3-1 DETERMINATION OF PREDICTED STREAM POWERED GENERATOR PERFORMANCE

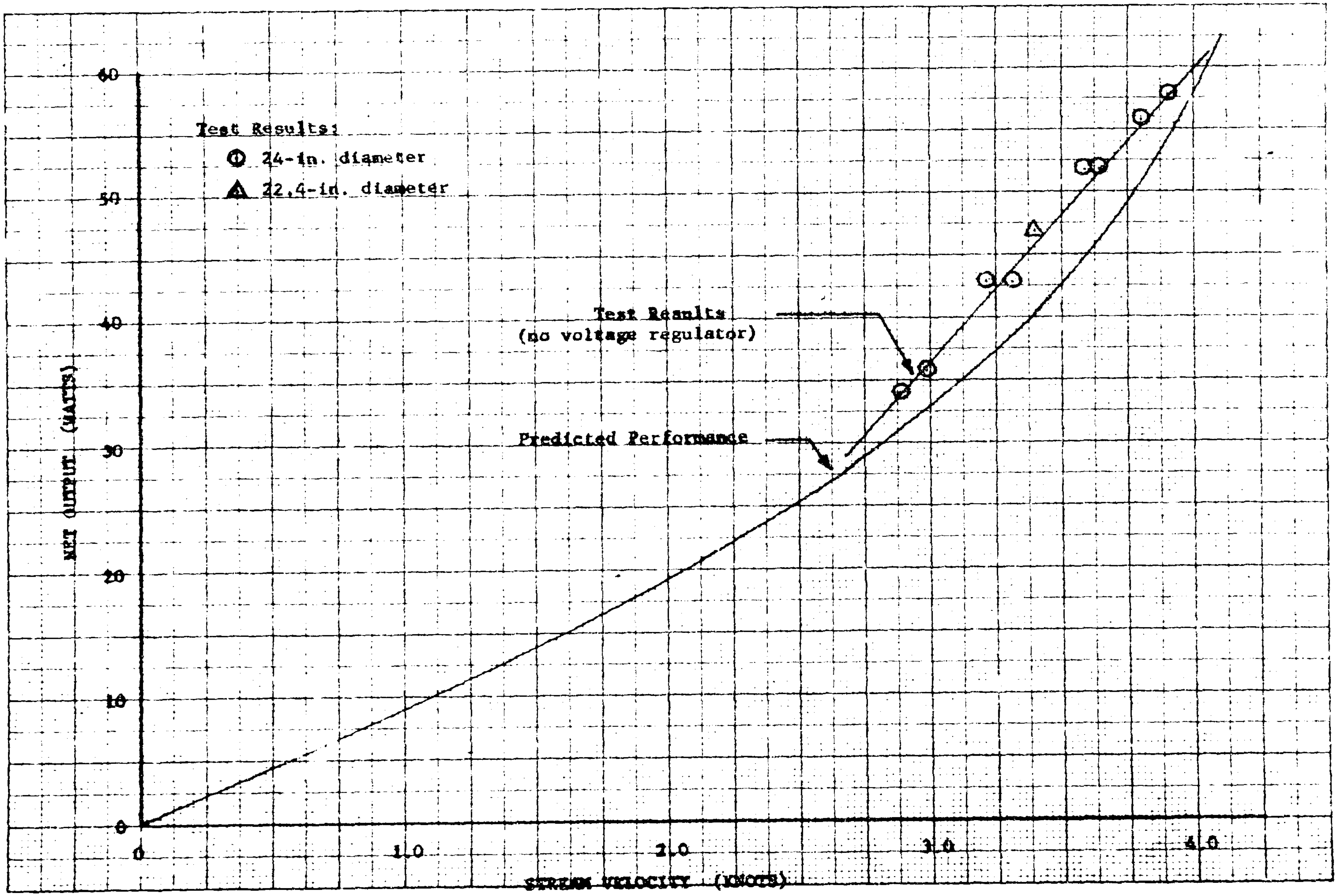


FIGURE 5.3-2 STREAM POWERED GENERATOR PERFORMANCE (UNREGULATED)

5.4 MECHANICAL DESIGN

The unit as designed appears to be adequate in all respects. The unit was operated for approximately 20 hours in salt water during development testing of the unit. No degradation due to corrosion is evident on the unit. The bearing system and shaft seal arrangement appears very satisfactory. No leakage of water into the unit nor oil out of the unit has been noted. The shaft seal losses are quite acceptable, approximately 10 watts at 600 rpm. The breakaway torque is only slightly higher than the running torque and the unit starts easily at low water velocity.

The materials inside the unit appear to be compatible with the transformer oil. The insulation material used in the construction of the unit appears to be completely compatible. However, the neoprene cable jacket swells slightly after a short period of immersion. Immersion of the cable material in the oil for a period of several months indicated no degradation of the cable. When the cable sample was removed and air dried, the swelling soon abated and the sample returned to its original condition.

The anodized aluminum parts of the power unit withstood all handling throughout the development testing. The mounting stake and swivel joints were not used in the development. The unit was mounted in front of a boat when tested, using development support hardware.

SECTION 6

RECOMMENDATIONS

The performance of the present stream generator has indicated the basic soundness of the concepts employed in its design. However, it is felt that the power output of this unit can be significantly improved through further modifications to the generator and propeller. A discussion of the necessary modifications is presented in the following sections.

6.1 GENERATOR

The development test data obtained on the generator indicate the basic design approach is adequate. The major modifications necessary to produce the required 50-watt output at a 420 rpm design speed with the same configurations are;

(1) The utilization of better magnetic materials in the construction of the rotor.

(2) The selection of a different combination of rotor poles and stator slots.

The rotor pole pieces are in a highly saturated magnetic condition. The material used at present is 1020 cold rolled steel. This material, after an annealing cycle, has a saturation density of less than 90,000 lines per square inch with a magnetization force of 20 ampere turns per inch.

A material such as Supermendur has a density capability of over 130,000 lines per square inch with the same magnetizing force level providing the capability required. This material is not usually readily available, nor is it the only material usable; however, it is quite apparent that the utilization of a better magnetic material is necessary.

The selection of a 30-stator-slot, 16-pole combination resulted in a short winding span which provided a winding with high pitch and distribution factors and a relatively low impedance. The necessity of using a fractional slot winding resulted in an abnormal amount of waveform distortion and concurrently a lower AC to DC conversion factor. An alternate selection, 30 stator slots and 20 rotor poles, would have a lower pitch factor, .866 versus .992, but a greatly reduced internal impedance. Also this combination would result in an even number of phase coils per pole and thus would produce less waveform distortion. The 30-stator-slot, 20-rotor-pole combination still requires a fractional slot winding, however, this winding is unique in that only 120° phase belts can be used which provides a uniform winding of one coil per pole per phase.

The highest winding conversion factor can be obtained from an integral-slot design of 1 slot per pole per phase, but to keep the span within a reasonable limit requires an abnormally narrow stator tooth width. While this approach is not completely impractical, it is a more expensive approach.

The unit can be made smaller if weight is of primary importance, but only at increased expense or complexity. Alnico V-7 is the only permanent magnet material with a higher saturation level than the Alnico V used. Other materials may have higher energy products, but for this application, weight is more a function of total flux capability per unit area. A decrease in weight can be expected using Alnico V-7, but will be limited to 10 or 20%.

A major weight savings can be obtained by running the generator at a much higher speed. The alternator at present is approximately 40% of the total unit weight and, in addition, some of the housing weight can be attributed to the size of the generator. Primarily, it is a matter of the increased complexity of a gear box to drive the generator at a higher speed to obtain a unit with minimum weight.

6.2 PROPELLERS

During the development tests, it was established that the propeller performance was essentially as predicted by the design analysis. However, it is apparent that the power output of the stream generator can be significantly increased by modifications to improve the matching of the propeller and generator performance characteristics and/or by gaining further increases in the propeller power capability. Three basic methods of approach appear to be worthy of discussion:

(1) Modify the genrator to produce 50-watts at 420 rpm (as described in Section 6.1), and redesign the propellers for maximum power at this speed.

(2) Redesign the propellers to achieve the maximum possible speed while still producing shaft power which is compatible with the speed-power characteristics of the present generator.

(3) Employ a lower-speed, three-bladed propeller in conjunction with a gearbox and high-speed generator.

From the analysis of Section 4.3 it may be seen that at 420 rpm the present propellers are not operating at the minimum-drag point due to the selected chord distribution. Consequently, the actual calculated shaft power delivered by the propeller at 420 rpm was found to be only about 99 watts, compared to the theoretically possible value of 172 watts, which was obtained from Equation 4.3-(2). The present chord distribution was required to provide adequate rigidity in the aluminum blades and thus prevent excessive bending. By making the blades of titanium, smaller chord lengths become allowable, and it would then be possible to design the propellers to operate at the maximum value of lift-to-drag ratio, C_L/C_d, and thus maximum torque coefficient C_T. Based on a value of $(C_L/C_d)_{max} = 63.5$ for the present blade-section profile (from Figure 4.3-3 at $\delta = 0°45'$), the new propeller would develop approximately 145 watts shaft power at 420 rpm and 3 knots. When coupled to a modified generator, having the same efficiency as the present unit but capable of utilizing this power at 420 rpm, a net output of about 72 watts could be achieved. It should be noted that, in order to fully realize this potential, the effects of bending due to hydrodynamic forces acting on the blades would have to be determined by computer analysis and compensated for in the manufacturing stage, and the machining process would have to be more accurate.

For use with th present generator, the theory presented in this report indicates that a 20-inch-diameter propeller, designed for maximum lift-to-drag ratio as described above, would result in a maximum power output at 3 knots of about 43.5 watts at 360 rpm. Some further improvement might be achieved by using a differnt blade profile having a higher lift-to-drag ratio; however, Figure 4.3-1 indicates that, with the present generator, the maximum possible output is only about 47 watts at three knots.

It appears that the maximum possible power output for the specified 2-foot stream depth and 3-knot stream velocity could be achieved by using a 24-in. diameter three-bladed propeller operating at 175 rpm to drive a high-speed generator through a gearbox. When designed for maximum lift-to-drag ratio, such a propeller would deliver about 196 watts shaft power to the gearbox. Assuming gearbox and electrical efficiencies of 95 and 75%, respectively, a net power output of 140 watts is estimated at 3 knots. Admittedly, this design is more complex and possibly somewhat heavier than the present unit; however, much of the added weight due to the gearbox would be regained through the reduction in generator weight. Using an estimated overall weight of 18 pounds, this unit would deliver about 7.78 watts per pound compared to 3.33 watts per pound required in the present stream generator.