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ENERGY STORAGE DEVICES FOR SONAR APPLICATIONS

Eugene R. Stroup

SOUND DIVISION

March 3, 1960

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⑥ ENERGY STORAGE DEVICES FOR SONAR APPLICATIONS.

By

⑩ Eugene R./Stroup

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⑭ NRL-MR-1038

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ABSTRACT

Several energy storage systems including inertial flywheels, storage batteries, electrical capacitors and hydraulic accumulators have been considered for sonar applications. Flywheels and capacitors appear to be somewhat larger in size and weight than batteries. Hydraulic systems were found to be not feasible at this state of the art. An experimental study has been commenced to explore storage battery possibilities.

Sintered-plate, nickel cadmium, rechargeable storage batteries of the sealed and vented varities have been cycled for sonar applications. Each cycle consisted of a one-second discharge in amperes equal to twenty times the nominal cell rating followed by a ten-second charge in amperes equal to approximately two times the nominal cell rating.

A one-half ampere-hour, stainless steel encased sealed cell endured four hundred ninety-four days, or over 3.8 million sonar-type cycles before failure. The failure was attributed to loss of electrolyte through vaporization and escape through inadequate seals. Vented varieties which are encased in plastics may crack with age causing loss of electrolyte. Polystyrene cases have not developed cracks or other deformity in use. Vented cells have endured more than two years under sonar-type cycling.

PROBLEM AUTHORIZATION

NRL Problem No. 55SO5-15
Bureau Project No. NE 050 962

PROBLEM STATUS

This is an interim report on one phase of the problem; work on other phases is continuing.

INTRODUCTION

Sonar applications require intermittent pulsating power and are thereby particularly suited for energy storage power adaptations. Energy storage systems provide higher power-to-weight ratios, lower initial cost, and economy in operation.

Current trends are toward longer pulse lengths and higher peak powers establishing requirements for energy storage systems. Such systems offer savings in size and weight important in development of units for small ships and helicopters. Capacitor storage systems have been employed almost exclusively until recent years when the Naval Research Laboratory introduced the inertial (flywheel) storage system.

The best known energy storage devices in use today are storage batteries, capacitors, flywheels, compressed air, steam and hydraulic accumulators. Of these, capacitors and flywheels have been utilized in sonar systems. Energy storage systems considered in this report for sonar systems are represented by the flow diagrams illustrated in Figure 1.

This report contains a discussion of each of several hypothetical energy storage applications to sonar along with experimental results obtained from laboratory work with sintered-plate, nickel-cadmium storage batteries.

FOUR ENERGY STORAGE DEVICES

The four energy storage systems; namely, capacitor, battery, inertia, and hydraulic, which are illustrated in Figure 1, were compared for three specific sonar requirements. In arriving at the results the following assumptions were made:

(1) Transducer inputs of 2.5, 15, and 50 KVA.

(2) One-second pulse length.

(3) Electronic amplfifier efficiency = 50%.

(4) Transformer/rectifier efficiency = 90%.

(5) Electric generator efficiency = 85%.

(6) Hydraulic pump and motor efficiency = 90%.

The results of the comparison of these four systems are presented in Table I. Energy levels at the transducers were considered at comparable levels for size, weight, and cost comparisons. See notes at bottom of Table I for other considerations incorporated.

With reference to Table I, it may be noted that size, cost, and weight estimates do not include some associated components peculiar to specific systems. For example, the cost, size, and weights of the charger for capacitors or batteries, a motor-generator for the flywheel, and an electric motor and generator for the hydraulic system may be added to the estimates in Table I in order to arrive at a more exact comparison. It is most probable that the difference between the chargers and motor-generators are small enough to be ignored in general comparisons.

Rechargeable Storage Batteries

There are numerous types of rechargeable batteries that were considered for energy storage. These included lead-acid, nickel-cadmium pocket types, nickel-iron, nickel-cadmium sintered-plate types, and silver-zinc. The characteristics considered important to pulse operations of these cells are tabulated in Table II. Additional information on these types of batteries are noted as follows.

The Lead Acid Battery

The lead acid battery is the lowest priced rechargeable storage battery available. It can deliver relatively high discharge currents and accept relatively high charge currents repeatedly over a period of time second only to the alkaline batteries. If cost is secondary and the maximum life and current characteristics are mandatory, another type of battery can be selected.

The Silver Zinc Battery

The silver zinc alkaline battery offers maximum discharge rates per unit size and weight along with the highest price. Short life and low charge rate characteristics make this battery unsuitable for certain cyclic applications. The life expectancy is generally stated as one year, but no more than 10 to 100 cycles depending upon the care and type of use. Manufacturers indicate that complete discharge in seven to eight minutes will not damage the battery and that more than ten hours will be required for recharging. Low charge rates drastically reduce repetition rates in cyclic applications. See Figure 2 for typical voltage curves.

The Sintered-Plate, Nickel-Cadmium Battery

The nickel-cadmium, alkaline battery has been known since about 1900. It has been developed in the United States since World War II, being spurred along by military requirements. Scarcity and high costs of raw materials were partially responsible for slow development. The original nickel-cadmium battery was reported capable of service up to twenty-five years. The development of the sintered-plate has reduced the size of this battery to approximately that of the lead acid battery for power and weight considerations. Sealed, sintered-plate cells are used today in flashlights, hearing aids, and missiles among other things. The popularity of the cell is primarily due to long life characteristics and the sealed configurations.

The sintered-plate, nickel-cadmium storage battery of recent development is currently being studied for various applications in research laboratories throughout the country. It offers long life characteristics and high charge and discharge rates. The sealed variety operates without replenishment of electrolyte. This battery is highly versatile and rugged. However, large weight and size factors may be objectionable for some applications.

Complete and comprehensive usage data not being available, it was necessary to conduct laboratory experiments to determine capabilities for pulse applications. A program is underway to determine the performance of this battery on cyclic operation. The battery test cycle selected for these tests consists of a one-second discharge period equal in amperes to twenty times the ampere-hour rating followed by a ten-second charge. Laboratory results show that the cell can be repeatedly charged and discharged at relatively high currents. For example, a one-half ampere hour sealed cell has been cycled over four million times through a cycle consisting of a one-second, ten ampere discharge followed by a ten-second charge. Periodic test discharge curves indicate a gradual loss in capacity. A summary of test data is contained in Table III.

The Nickel-Cadmium, Pocket-Type Battery

The nickel-cadmium, pocket-type battery differs from the sintered-plate principally in plate structure and current density capabilities. Porous pockets containing nickel are formed into plate structures whereas in the latter case powdered nickel is "sintered" onto a nickel screen presenting a greater active surface exposure to the electrolyte. The sintered-plate, therefore, permits greater current flow making it more suitable for the high current pulse operations peculiar to sonar.

The Nickel-Iron Battery

This is another alkaline (potassium hydroxide) battery suitable where long life is desirable. It is constructed similar to the nickel-cadmium pocket-type. The sintered-plate battery permits substantially larger currents for a given size and weight.

Capacitors

In selecting capacitors for a storage system, one must consider the voltage level to be employed, the quantity of capacitance necessary and the availability of suitably rated storage units. In the remainder of this section the voltage requirements were established from 5 to 15 kilovolts because high-power vacuum tubes are so rated. Also, it will be noted that paper dielectric oil-filled capacitors were used as a basis of estimates made because they are readily available in the proper ratings. The more common dielectrics include mica, glass, paper, air, gas, oil, and electrolytics (aluminum oxides). Capacitors are conventionally classed in accordance with the type of dielectric employed. Electrolytic types provide more capacity per unit size and weight, but are not available at one kilovolt and higher potentials. The high power requirements of sonar indicate the need for high voltage tubes. A survey of vacuum tubes, see Figure 3, reveals that one to three-hundred KVA sonar applications may be expected to employ two to fifteen kilovolt vacuum tubes.

Figure 4 was derived from the relation

$$W = 1/2\, C V^2 .$$

This curve may be used to estimate capacity for a given kilowatt-seconds and voltage. The X's indicate the existence of compatible vacuum tubes of current manufacture. Figure 5 may be used to determine the approximate total weight for a given capacitance. The weights in this table were based on a cross-sectional average of capacitors stocked at NRL. Also, it is assumed that oil-filled paper dielectric capacitors of about 25 cubic inches per pound would be used. An approximate cost may be obtained by multiplying the weight by dollars per pound factor obtainable from the following:

Ratings in Kilovolts	Dollars Per Pound
Under 5	5
5	5
9	4
12	3
15	2
Over 15	2

The above is an average estimate based on paper dielectric oil-filled capacitors.

A capacitor energy storage system listed in Table I is based on these data. Size, weight, and cost are based on capacitors available. The formulation employed to determine capacitance is as follows:

$$W = (1/2)\, C\, V^2 \qquad (1)$$

Where:

W = watt seconds
C = farads
V = volts.

Considering an application with a twenty per cent voltage drop we let:

V_1 = maximum voltage - beginning of pulse load.
V_2 = minimum voltage - end of pulse.
W_1 = watt-seconds potential prior to pulse load.
W_2 = watt-seconds remaining in the capacitor after pulse.
W_L = watt-seconds delivered during the pulse.

And write:

$$W_L = W_1 - W_2 \qquad (2)$$

Substituting, we get:

$$W_L = (1/2) C V_1^2 - (1/2) C V_2^2 \qquad (3)$$

Solving for C, we get:

$$C = 2 W_L / (V_1^2 - V_2^2) \text{ farads.} \qquad (4)$$

Inertia

A relatively new approach to solving sonar power problems - the inertial flywheel system - was introduced by NRL in the 1950's. A study of flywheel characteristics will reveal a system of reasonable cost for many applications. Figure 6 illustrates that flywheel sizes increase exponentially with voltage-speed regulation requirements, which fact is most important wherein size and weight factors have primary significance. See Figures 6 and 7 for a graphical representation of flywheel characteristics of length, weight, energy, speed, and outside diameter. Figure 7 is based on a hollow cylinder with inside to outside diameter ratio equal to 0.8, which value is assumed as an optimum among flywheels. Instructions for using the figures, derivation formulas, etc., are included alongside the respective curves.

Figure 7 was derived from the following considerations: A hollow cylindrical cast iron flywheel with inside divided by outside diameter = 0.8 was selected as a basis for these computations after observing that conventional flywheels currently in use are generally so designed and that the size increases exponentially with this ratio. The formulation employed is as follows.

$$KE = 2 \pi^2 N^2 I \qquad (5)$$

$$I = (W/64)(R_1^2 + R_2^2) \qquad (6)$$

$$W = \pi L \rho (R_1^2 - R_2^2) \qquad (7)$$

$$S = V^2/10 \qquad (8)$$

$$V = 2 \pi N R_1 \qquad (9)$$

Where:

KE = Kinetic energy in foot-pounds/second.
N = Speed in revolutions/second.
I = Inertia in foot-pounds.
W = Weight in pounds.
R_1 = One-half of the outside diameter in feet.
R_2 = One-half of the inside diameter in feet.
L = Length of cylinder in feet.
ρ = Cast iron density factor (450 pounds/cubic foot).
V = Rim velocity in feet/second.
S = Stress in pounds/square inch (15,000 psi - cast iron with 100% safety factor).

Conversion factor for foot-pounds/second = 0.7378 watt-seconds.

Example for using Figures 6 and 7.

First, assume:
Megawatt-seconds requirement = 1
Maximum speed (voltage) droop = 10%
Revolutions per minute = 3600

Second, Enter Figure 6 and find that 10% speed droop yields a multiplication factor (f) = 5.

Third, compute:
System requirement = (megawatt requirement) (factor)
= (1) (5) = 5 megawatt seconds.

Last, enter Figure 7: Find where 5 megawatts intersects with the edge of the inclined plane at a point corresponding with 1900 pounds weight. Find intersection of lines from 3600 rpm and 5 megawatts and follow a vertical line to a point in the inclined plane and interpolate for length which equals approximately 3.5 feet. The outside diameter is found beside the rpm scale and is equal to two feet.

An interesting characteristic of the flywheel, which is illustrated in Figure 7, is that for a given quantity of energy the weight is independent of speed. This results from the application of cast iron stress limits of 15,000 psi imposed. The data at three energy levels in Table I are based on these curves using a 20 per cent speed droop, 0.8 inside diameter/outside diameter ratio and a hollow cylindrical cast-iron flywheel. A small reduction in size and weight over these quantities is possible through consideration of the number of arms or spokes to be used. A conventional flywheel, with ten arms may concentrate up to 30 per cent of the total weight in the arms and hub.

In general, flywheels are reliable and free from complicated maintenance problems. They may be considered too large in size and weight for applications where a high degree of speed regulation is mandatory. The following illustrates the regulation to weight relationship as developed from Figure 6.

Required Megawatt-second Output	Minimum Speed Droop	Multiplication Factor From Figure 6	System Megawatt-Second Requirement	Approximate Weight-Pounds Figure 7
1	10%	5	5	1,900
1	1.0%	50	50	19,000
1	0.1%	500	500	190,000

Hydraulics

Hydraulic systems consist of varied arrangements of hydraulic pumps, hydraulic motors, hydraulic accumulators, expansion tanks, pressure reduction valves, check valves, pressure regulating valves, reflief valves, by-pass valves, associated piping, and equipments. Hydraulic systems are generally recognized as reliable, efficient, powerful, and relatively simple to maintain.

Literature research reveals numerous types of hydraulic systems. Among these the hydraulic ram and press systems utilizing hydraulic accumulators constitute most energy storage, hydraulic-type machines at this state of the art. A proposed system, Figure 8, was considered and found to be too inefficient. Pressure reduction valves located schematically between the accumulator and solenoid valve in Figure 8, would be the source of energy losses in the form of heat in an amount approximately equal to the energy delivered to the load. These losses were based on an assumption of hydraulic pressure reduction from 3,000 to 2,000 psi. This is a strictly hypothetical system presented to stimulate thought along lines, which, it is believed, may yield a plausible solution to a difficult problem.

The operation of the system in Figure 8 is as follows. The hydraulic fluid is initially drawn from the reservoir (which also serves as an expansion tank and oil filter) by two independent pumps. The high pressure/low capacity pump delivers oil to the accumulator until the pressure reaches a nominal 3,000 psi, at which time an unloading valve opens and allows the oil to return to the reservoir and a check valve keeps the accumulator charged. The low pressure/high capacity pump delivers oil to the hydraulic motor between pulse loading. A pulse actuated solenoid valve allows oil under high pressure from the accumulator to drive the motor-generator during the load.

Because of the heat losses in reduction valves, a slightly modified system is suggested in the form of Figure 9. The principal difference lies in the connection of the air side of the hydraulic accumulator to the ship's service high pressure air banks in order to provide minimum change in pressure during accumulator discharge thereby eliminating the necessity for the inefficient pressure reduction valve. The volume of air would serve as a pressure stabilizer in that the variation would be equal to the ratio of the accumulator to air flask capacities. The larger the volume of air in the air banks, the higher the degree of regulation obtainable.

Based on these systems and the flow diagrams in Figure 1, representative hydraulic pumps, motors, and accumulators were listed and data compiled for comparative purposes. See Table I for the results of this data, which includes weights, size, and estimated cost.

EXPERIMENTAL PROGRAM

Apparatus

Figure 10 is a photograph of one of two battery cyclers designed and developed for testing storage batteries through a sonar compatible experimental duty cycle. Figures 11 and 12 illustrate the experimental cycle employed. Each cycler accommodates four batteries simultaneously. Mercury relays are employed in the high current discharge circuits to eliminate test interruptions due to burned relay contacts. Each load circuit is closed and opened over seven thousand times daily. Some of these relays have operated more than four million times without failure. Panel meters are incorporated to provide circuit monitoring.

Experimental Cells

High current density capabilities along with long life characteristics make the rechargeable, sintered-plate, nickel-cadmium, storage battery the best suited for pulse-type applications. These batteries are available in sealed and vented cases. See Figure 13 for sample test units. The electrolyte, potassium hydroxide, does not reveal the charge state through changes in specific gravity. This is determined by noting the reaction of the battery to application of a charge potential or application of a nominal load and noting the voltage. The plates are made of nickel and cadmium. The ampere-hour rating assigned to the battery is based on the five-hour discharge rate. The general condition of the battery can be determined by conducting a test discharge of the battery, noting the ampere-hour yield. To illustrate the results of overcharging sealed cells Figures 14 and 15 are included. This two ampere-hour cell was being discharged at 40 amperes for one second followed by a 4.4 ampere charge for ten seconds to 1.65 final volts.

Voltage Characteristics

Nickel cadmium batteries may deliver currents in amperes equal to twenty times the nominal cell rating in ampere-hours and yet maintain a satisfactory load voltage. See Figures 11 and 12. Some varieties of these batteries may be voltage limited to load currents in amperes equal to ten times the ampere-hour rating. Plate areas and plate separation are important factors in battery performance.

An interesting comparison of "D" cells (standard flashlight - size 1-1/4" x 2-1/4") which emphasizes the influence of voltage characteristics may be made as follows:

Type of Cell	Open Circuit Voltage	Approx. Ampere Hours	Maximum Amperes	Weight Grams	Cost
Nickel-Cadmium	1.3	2	30.0	150	$5.00
Zinc-Carbon	1.5	4	0.5	95	.20
Mercury	1.3	14	1.0	160	2.50

Charging

There are two general methods of charging which may be employed and they include constant current and constant potential. A modified constant potential method is preferred because of simplicity and freedom from the necessity of manual control. This latter method is employed in our equipment.

Cell voltage during charge is illustrated in Figure 11. It must be stated here that if the charge voltage is allowed to rise above 1.45 volt there will be visible evidence of this voltage in the form of bubbling in the electrolyte. A vented cell was charged until the electrolyte had disappeared in the form of vapor and the cell was dry. The cell has been restored with new electrolyte without indication of any damage having been sustained. If the charge voltage should get out of control, all is not lost, providing one is charging vented, nickel-cadmium batteries and that one follows instructions for rejuvenation.

Life

The nickel-cadmium battery has experienced up to twenty-five years in service in Europe. The sintered plate variety has not been in existence long enough to have an established life. We have pulse cycled vented cells like those shown in Figure 13 over two years utilizing a discharge rate in amperes equal to twenty times the ampere-hour rating. As yet we cannot estimate how many years the vented cells will last as no failures have been experienced of a chemical nature. Four cells were encased in an acetate composition which deteriorated within six months of use. The case of one of these cells has been replaced with polystyrene and the cell continues to operate satisfactorily - see item 3AH1VC in Table III. However, despite satisfactory operation, there is evidence of plate failure in the form of minute nickel particles which are gradually collecting in the bottom of the cell. Should these particles ever fall in sufficient quantity to short-out the plates - surely a failure would be experienced. Vented cells exist which do not display plate deterioration or other weaknesses.

CONCLUSIONS AND DISCUSSION

In view of the fact that the hydraulic system in Table I and illustrated in Figure 8 is not presently accepted as being within the "state of the art", it appears that inertial systems might offer the best solution when one compares the factors of weight, size, and cost. Inertial systems are the best all-around choice except in those cases wherein very high degrees of voltage regulation are required. For example, a one per cent speed regulated flywheel system will be fifty times as large and heavy as one embodying one-hundred per cent speed droop characteristics - See Figure 6. At some point storage batteries would be the better solution, all factors considered, including a requirement for a high degree of voltage regulation.

Certain vented nickel-cadmium, rechargeable, sintered-plate storage batteries can be operated on a sonar applicable cycle for periods in excess of two years while delivering one-second pulse loads in amperes equal to twenty times the ampere-hour rating every ten seconds. Vented cells were successfully operated with two in series at a discharge rate in amperes equal to thirty times the ampere-hour rating of the cell for a period in excess of six months. The one-second voltage drop in this latter case amounts to about twelve per cent from beginning to the end of the pulse. This high discharge rate is not being had without its problems. It is necessary to place a twelve-ohm resistor across one of the cells which is in series to allow the other cell to receive a charge comparable with that being received by the shunted cell. Cells of this type tested in series at lower rates, twenty times the ampere-hour rating, have not required the use of such a balancing technique. The sealed variety is attractive from the standpoint that the tedious job of adding distilled water to the electrolyte of numerous cells is eliminated; however, this feature must be given judicious consideration since the sealed cell will explode if not used in conjunction with a well-regulated charger. The nickel-cadmium cells tested were stock items designed and manufactured for general uses.

In view of this fact, it is reasonable to assume that the battery can perform considerably better if designed and developed to deliver the extremely high, short-cycle currents required in sonar applications.

Discussion

Comparisons of energy storage systems are difficult when based on generalities. Each application involves variables which evolve from the consideration of significant factors including simplicity, reliability, availability of proven components, weight, space, voltage regulation, available power (electrical, mechanical, etc.). The relative merits of these systems might be summarized as follows:

SYSTEMS

Quality	Flywheel	Battery	Hydraulic	Capacitors
Simplicity	1	2	3	2
Reliability	1	2	1	2
Availability	1	1	2	1
Weight	1	2	3	4
Size	1	2	3	4
Regulation	3	2	1	3
Totals	8	11	13	16

These totals indicate that the flywheel might be the better choice. Close observation reveals that regulation requirements might best be considered as very high regulation requirements can result in enormous size and weight.

Recommendation

It is recommended that efforts be made to develop the current density capabilities of the nickel-cadmium, rechargeable, storage battery to the maximum within the present state of the art. Such development would improve the size, weight, and regulation factors of this system. The "shallow" discharge that occurs during a one-second sonar pulse constitutes less than one per cent of the ampere-hour capacity of the battery. This should be improved upon and calls for the construction of batteries of greater active plate surface area and lower internal resistance.

WORK IN PROGRESS

Nickel-cadmium battery tests have indicated the suitability of this cell to sonar applications so far as a single cell operated singly is concerned. Some of the limitations of operations with two cells in series have been determined and tests continue. It is expected that it will be possible to operate two or more cells in series without resistance equalization so long as the pulse discharge rate does not exceed approximately one-half the successful rate established for a single cell. The next phase in this study involves the operation of a 30-volt battery at a pulse discharge rate in amperes equal to ten times the ampere-hour rating.

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TABLE I

Comparative Data on Energy Storage Systems For Sonar Applications

System	Transducer Input KW	Amplifier Input KW	Size Feet^3	Weight Lbs.	Estimated Cost Thousands $
Capacitors(1, 3)	2.5	5	14	1,200	6
	15	30	92	6,700	13
	50	100	230	22,000	110
Batteries(1, 3)	2.5	5	1	100	5
	15	30	5	900	16
	50	100	9	1,500	27
Inertia (2, 3)	2.5	5	0.05	7	0.2
	15	30	0.3	40	0.3
	50	100	1.0	135	0.4
Hydraulics(1, 4)	2.5	5	1	150	0.5
	15	30	2.5	450	1.3

Notes:

(1) 20% Voltage droop incorporated in calculations.

(2) Two-foot outside diameter flywheel with 1.6 foot hole in center rotating at 3600 rpm with 20% speed droop incorporated.

(3) Weight, size, and cost includes energy storage devices only.

(4) Weight, size, and cost includes hydraulic pump, motor, and accumulator only.

TABLE II

Rechargeable Storage Battery Characteristics

Type	Watt-Hrs/Lb.	Battery Life		Watt-Hours Efficiency (Percent)	Relative Charge[1] Rate Capability Between Types	Voltage[2] Characteristics
		Years	Cycles			
Lead Acid	7 - 20	4-14 or	10-600	75	Medium	Decreases
Nickel-Cadmium Pocket-Type	8-11	25		65	High	Decreases
Nickel Iron	9-14	25		55-60	High	Decreases
Nickel-Cadmium Sintered-Plate	10	15	1,000$^+$	74-82	High	Decreases
Silver Zinc	48	1 or	10-100	74-82	Low	80% Constant

Notes:

(1) "Relative charge rate capability between types" is an estimate of the ability of the battery to accept a charge in a given length of time. "High" means that the battery can be charged faster than one classed as medium.

(2) "Voltage characteristics" refers to the character of the voltage curve during discharge. "Decreases" means the voltage decreases constantly. "80% constant" means the voltage is "flat" over 80% of the discharge period.

TABLE III

Test Data - Sintered-Plate Nickel-Cadmium Rechargeable Storage Batteries
(Data through 15 February 1960)

Cell Designation[1]	Weight Ounces	Length Inches	Diam. Inches	Width Inches	Height[2] Inches	Unit Cost	1-Sec. Discharge Amps.	10-Sec. Charge Amps.	Total Days Cycled	Water Added cc.	Status
3AH 1 V C	5.6	0.67		2.15	4.00	$4.	60	6.6	325	45	On cycle
3AH 2 V C	5.6	0.67		2.15	4.00	$4.	60	6.6	446	42	Cracked case
3AH 3 V C (2)	5.6	0.67		2.15	4.00	$4.	60	6.6	131	39	Cracked case
2AH 1 V B	4.0	0.73		1.50	3.38	$6.	40	4.4	362	19	On cycle
2AH 2 V B	4.0	0.73		1.50	3.38	$6.	40	4.4	666	22	On cycle
2AH 1 S A	5.7	2.5	1.25			$5.	40	4.4	3		Exploded
2AH 2 S A	5.7	2.5	1.25			$5.	30	3.3	14		Exploded
2AH 3 S A	5.7	2.5	1.25			$5.	30	3.3	226		Exploded
2AH 4 S A (2)	5.7	2.5	1.25			$5.	50	5.5	7		Cell dry
2AH 5 S A	5.7	2.5	1.25			$5.	40	4.4	46		Cell dry
2AH 6 S A	5.7	2.5	1.25			$5.	20	2.2	289		Cell dry
1AH 1 V A	1.7	0.67		1.15	2.30	$8.	20	2.2	331	4	On cycle
1AH 2 V A (2)	1.7	0.67		1.15	2.30	$8.	20	2.2	191	4	On cycle
1AH 3 V A (2)	1.7	0.67		1.15	2.30	$8.	30	3.3	177	8	On cycle
0.5 AH 1 S A	1.54	1.0	1.0			$3.	10	1.1	494		Cell dry
0.5 AH 2 S A (2)	1.54	1.0	1.0			$3.	12.5	1.4	128		Cell dry

(1) This is a summary of data taken from experiments with sealed and vented nickel-cadmium sintered-plate rechargeable storage batteries. Cell designations may be interpreted as follows: Example: 0.5AH 1 S A (2)

0.5AH	The ampere-hour rating assigned to the cell by the manufacturer.
1	The first cell of this type used in the tests.
S	Indicates the cell is sealed. Vented cell are designated with a "V".
A	Code letter for manufacturer.
(2)	Indicates number of cells in series.

(2) Height includes battery posts.

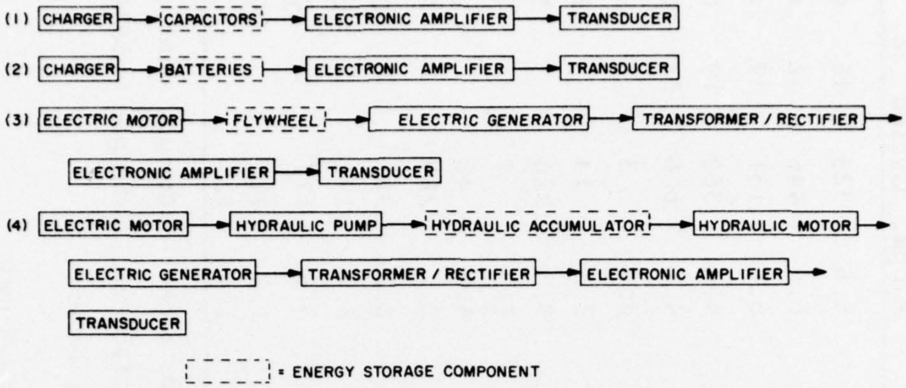
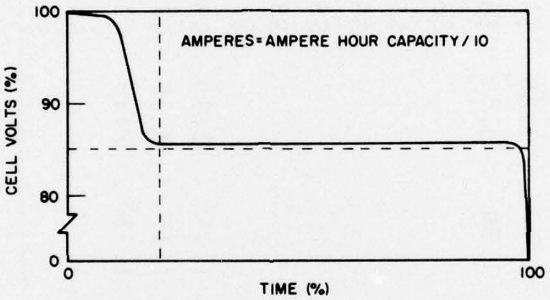
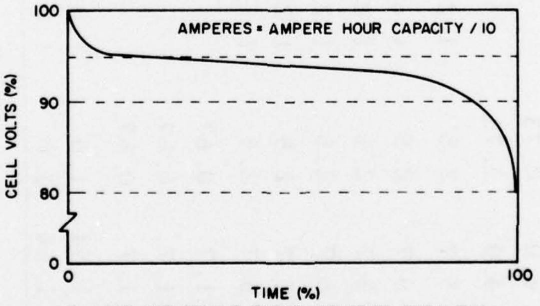


Figure 1 - Energy Storage Applications in Sonar Systems



A. SILVER ZINC



B. LEAD AND NICKLE TYPES INCLUDING NiCd, PbCa, PbSb, NiFe, etc.

Figure 2 - Typical Storage Battery Discharge Curves

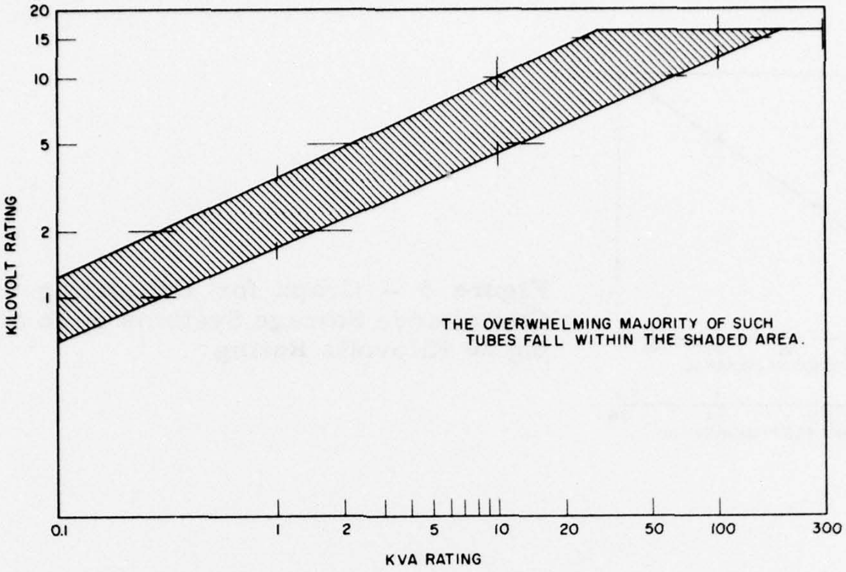


Figure 3 - Vacuum Tubes of Current Manufacture - Class "B" Operation Triodes and Tetrodes

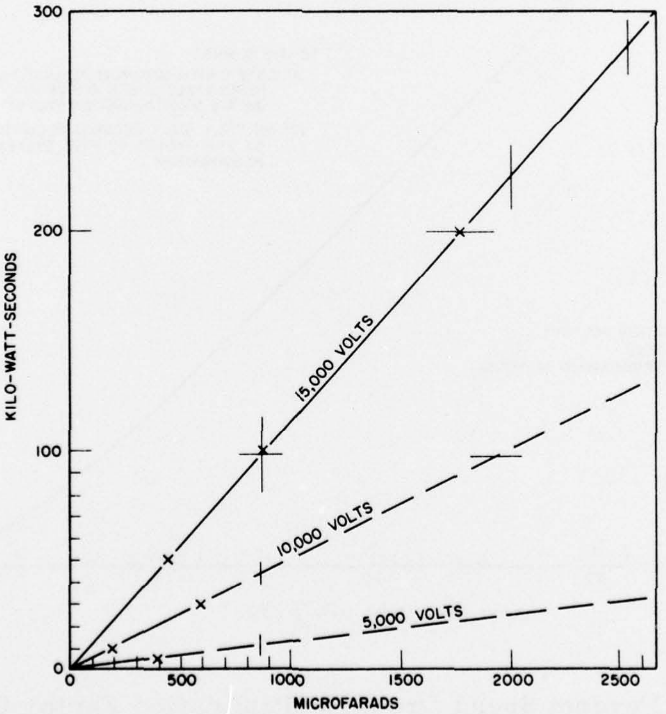


Figure 4 - Graph for Determining Capacitance in Microfarads for Storage Systems to 300 Kilowatt-seconds

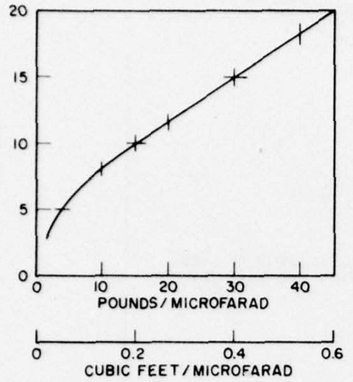
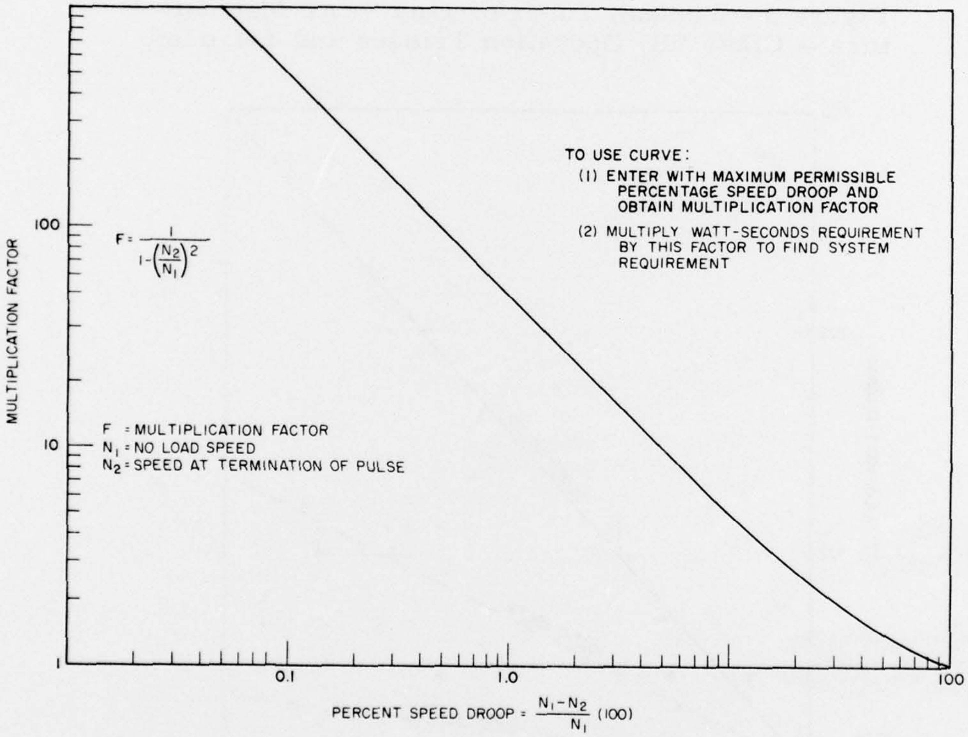


Figure 5 – Graph for Estimating the Size of Capacitance Storage Systems up to and Including 20 Kilovolts Rating



TO USE CURVE:

(1) ENTER WITH MAXIMUM PERMISSIBLE PERCENTAGE SPEED DROOP AND OBTAIN MULTIPLICATION FACTOR

(2) MULTIPLY WATT-SECONDS REQUIREMENT BY THIS FACTOR TO FIND SYSTEM REQUIREMENT

Figure 6 - Percent Speed Droop/Multiplication Factor Curve

How to use curves:

(1) Find system requirement from figure 6

(2) Find weight of cast iron flywheel from figure 7

(3) Select suitable combination of length, speed, outside diameter - figure 7

Derivation of curves:

Inside diameter/Outside diameter = 0.8

Formulation used to derive curves:

(1) $KE = 2\pi^2 N^2 I$

(2) $I = W/64\ (R_1^2 + R_2^2)$

(3) $W = \pi L \rho (R_1^2 - R_2^2)$

(4) $S = V^2/10$

(5) $V = 2\pi N R_1$

KE = Kinetic energy in Ft.Lbs./second.
N = Speed in revolutions/second.
I = Inertia in Ft.Lbs.
W = Weight in Pounds.
R_1 = One-half of the outside diameter.
R_2 = One-half of the inside diameter.
L = Length of cylinder in feet.
ρ = Cast Iron density factor 450 lbs./ft.^{3}.
V = Rim velocity in feet/second.
S = Stress in pounds/inch^2 (15,000 psi-cast iron with 100% safety factor).

Conversion factor: Ft.Lbs./sec. = 0.7378 watt secs.

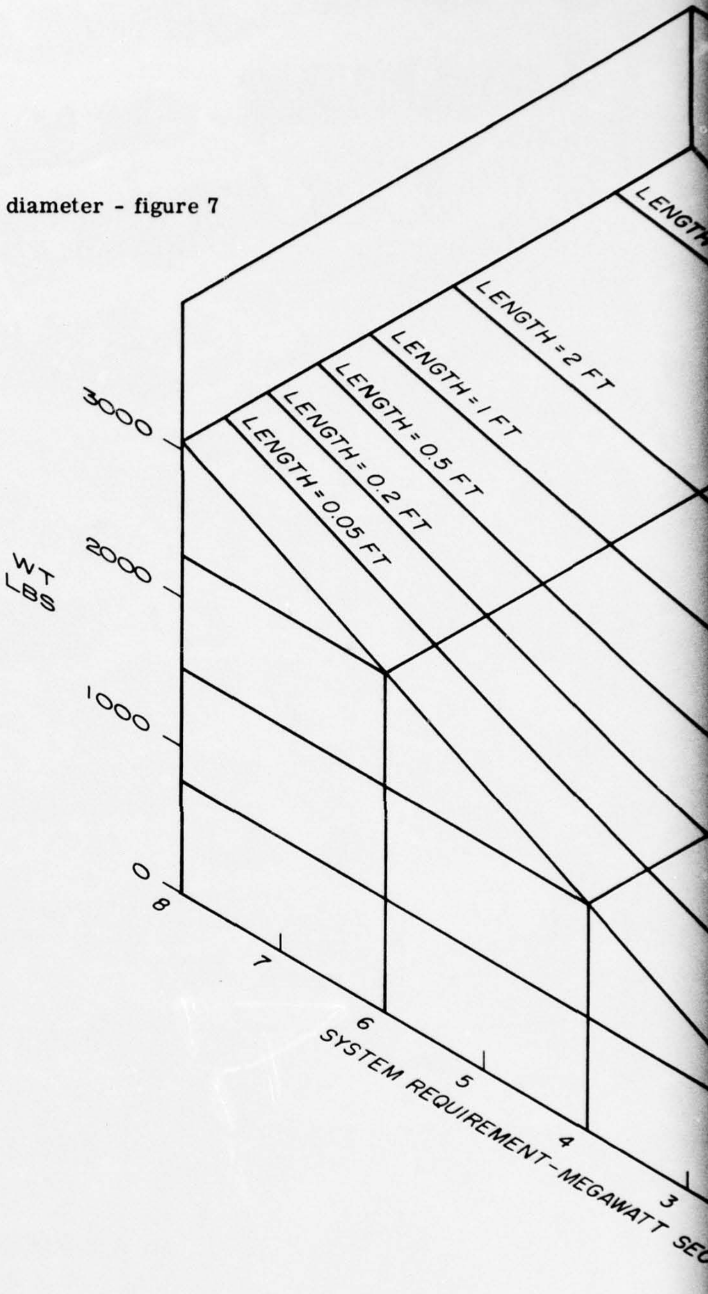
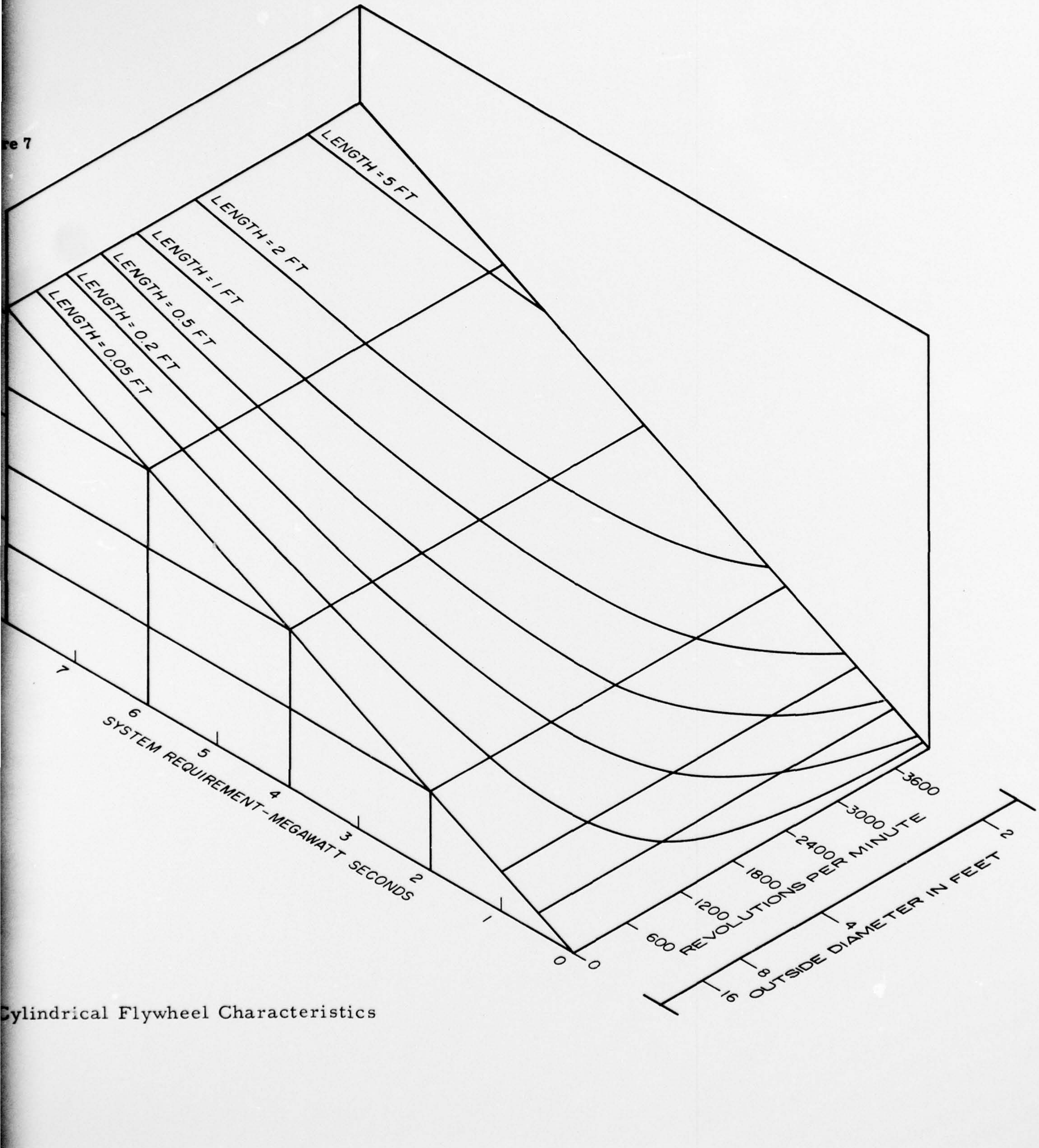


Figure 7 - Hollow Cylindrical Flywheel Characteristics

1

2

re 7



Cylindrical Flywheel Characteristics

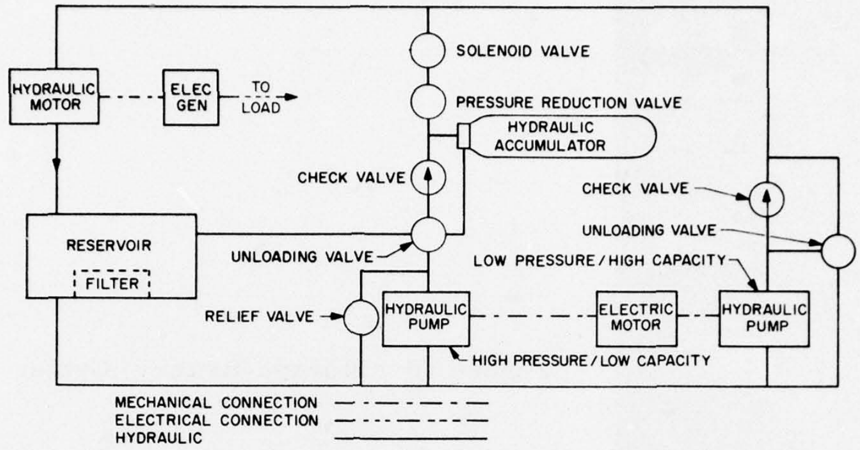


Figure 8 - Suggested Hydraulic Energy Storage System for Constant-Speed Intermittent Duty Generator

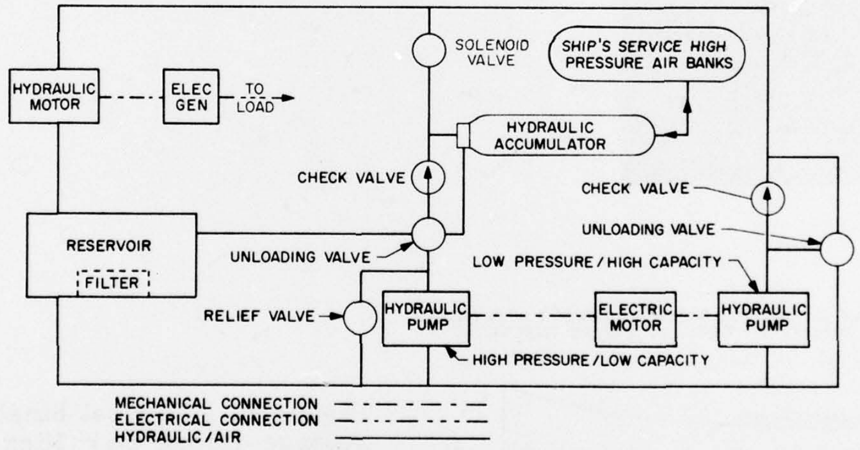


Figure 9 - Suggested Hydraulic Energy Storage System for Constant-Speed Intermittent Duty Generator Utilizing Ship's Service High Pressure Air Banks

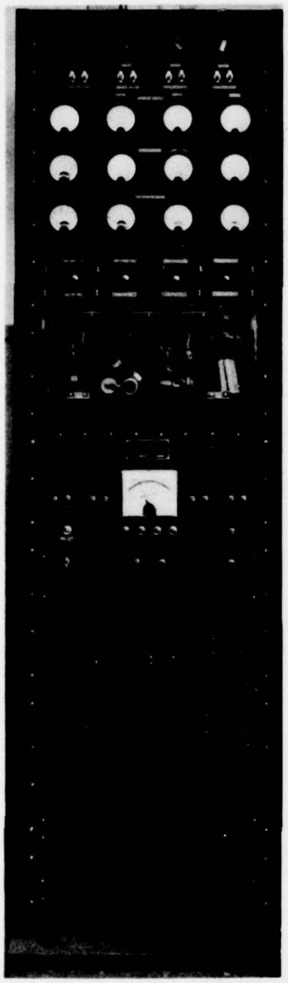


Figure 10 - Storage Battery Cycler

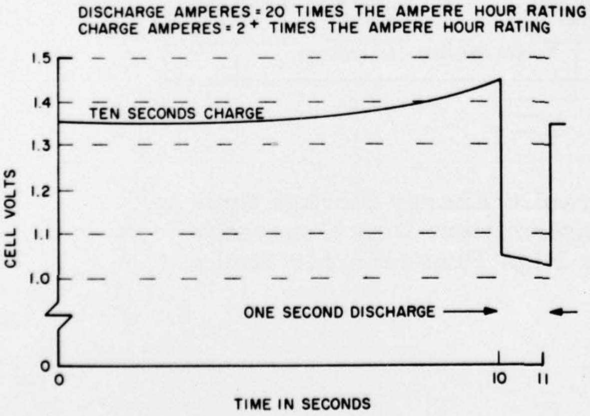


Figure 11 - Typical Single Cycle Voltage Curve for Nickel Cadmium Rechargeable Storage Batteries Being Charged and Discharged Through a Sonar Suitable Cycle

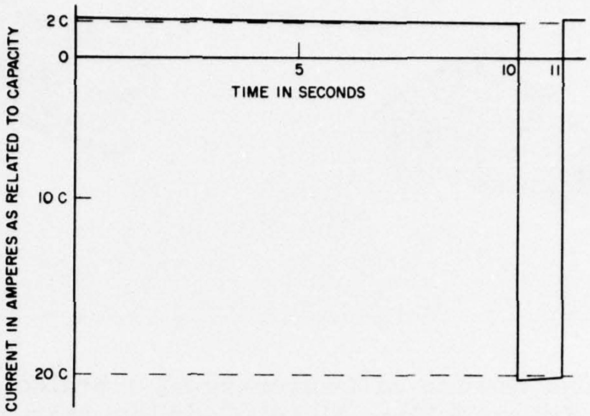


Figure 12 - Nickel Cadmium Storage Battery Current Characteristics for a Single Sonar Type Cycle

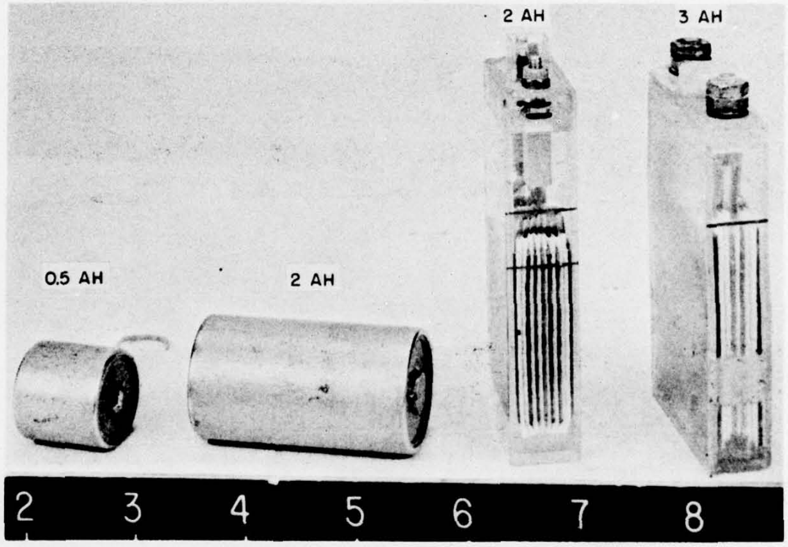


Figure 13 - Nickel Cadmium Rechargeable Storage Battery Test Cells

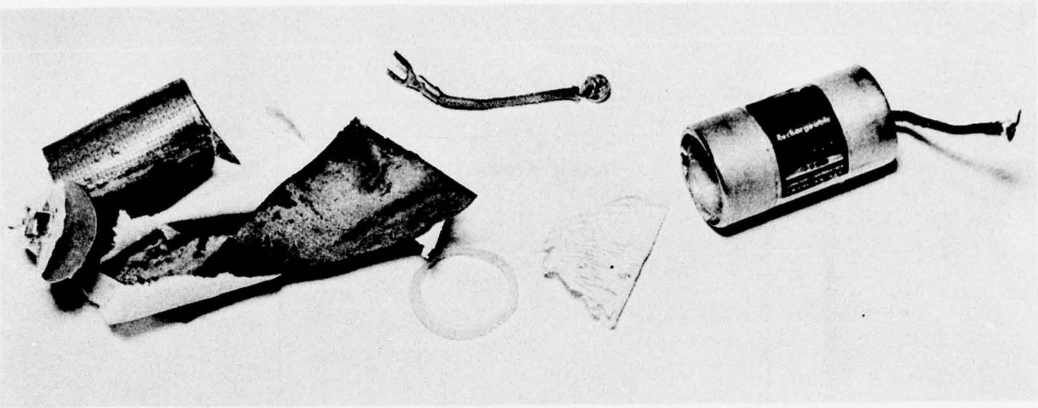


Figure 14 - The Results of Overcharging a Sealed Type "D" Rechargeable Sintered-Plate Nickel-Cadmium Storage Battery

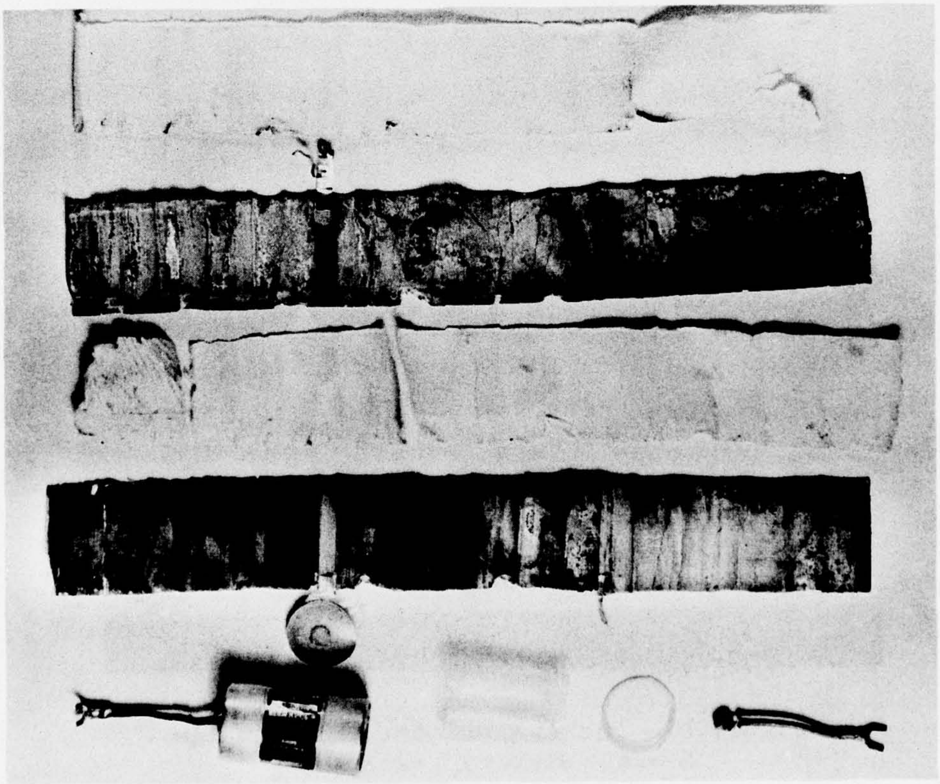


Figure 15 - The Plates, Insulation, Case and Terminal Connections of a Type "D" Rechargeable Sintered-Plate Sealed Nickel-Cadmium Storage Battery