FINAL REPORT

20 KW BATTERY STUDY PROGRAM

30 JULY 1971

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Goddard Space Flight Center
Greenbelt, Maryland

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TRW
SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278

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CONTENTS

CONTENTS (Continued)

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

TABLES

1. INTRODUCTION

1.1 OBJECTIVES

The purpose of the 20 kw battery system study is to define the technology required for the development of such systems and to provide parametric data and methods for preliminary configuration selection, optimization, and estimation of weight, cost, and reliability of modular batteries and power controls for systems in the 20 to 25 kw range.

To this end and to limit the study to a reasonable size and scope, a set of task definitions was formulated and coordinated with NASA. These task definitions are set forth in Appendix A.

The study is intended as a tool for the comparison of different general types of power system configurations and to expose the deficiencies in power system technology or data availability for power system analysis.

Six configurations were selected for detailed study from a large group of candidates. These are described in Section 2.5. A computer program was modified for use in estimation of the weights, costs, and reliabilities of each of the six configurations, as a function of several important independent variables, such as system voltage, battery voltage ratio (battery voltage/bus voltage), and a number of parallel units into which each of the components of the power subsystem was divided. Battery voltage ratios differing significantly from 1.0 are typical "boost" configurations in which a low battery voltage is boosted to the bus voltage.

The computer program was used to develop the relationship between the independent variables alone and in combination, and the dependent variables; weight, cost, and availability. Parametric data, including power loss curves, are given in the Addendum at the end of this report.

1.2 CONCLUSIONS

The following paragraphs present the conclusions regarding the relationships between the independent variables of power level, system voltage, battery voltage ratio, and number of units and the dependent variables of mass, cost, and availability.

1.2.1 Mass

Significant factors affecting the mass of the power subsystem in all configurations are the power level and the bus voltage. The observed manner of variation, described in general terms, is as follows:

Mass tends to increase proportionally with power.

For all cabling and electronic equipment, the mass decreases with increasing bus voltage rapidly between 30 and 100 volts and more slowly from 100 to 300 volts. Heat dissipation of cabling and electronic equipment also decreases with increasing bus voltage in much the same manner, leading to a significant decrease in solar array mass with increasing bus voltage due to the lower losses.

Total battery mass, including spare cells and replacement batteries, is relatively unaffected by cell size alone within the range studied in that five 20 ampere-hour batteries are not greatly different in mass than one 100 ampere-hour battery. However, the use of a smaller number of high-capacity batteries can lead to higher weights than the use of lower capacity batteries in larger numbers. This is due to the necessity for addition of larger increments of weight when high capacity batteries are used. If, for example, 10 batteries of 100 ampere-hour capacity just fall short of the required capacity, the addition of an eleventh requires the addition of 10 percent of the battery mass. If 50 batteries of 20 ampere-hour capactiy were being used, and a fifty-first added, this represents only a 2 percent addition.

Battery mass tends to increase slightly with increasing voltage, the increase being more pronounced when larger capacity cells are used due to the stepwise addition of large blocks of weight.

In the range of 5 to 15 units, division of the electronic equipment into different numbers of units has no significant effect upon its weight, since in this power range the equipment must be designed with many parallel power stages. Subdivision into several units results in replication of the logic and low-level circuit stages, which represent a negligible part of the equipment weight.

1.2.2 Cost

The major factors affecting the cost of power subsystem elements are battery cell size and power. Except for the solar array, system voltage has only a random effect, varying as the number of units required for the task are increased or decreased in a stepwise fashion. In actual program development, these variations should be smoothed out, leaving the costs essentially independent of voltage.

Battery costs increase significantly with decreasing cell size. This is due primarily to the increased testing and handling costs resulting from the increasing number of cells as cell size is reduced. In the cost model used, the testing costs per unit cell for large cells is not significantly greater than that for small cells. Battery unit tests costs do not increase proportionately with the size of the battery.

Solar array costs are not computed but should be proportional to the number of cells, and hence should show a significant decrease with increasing voltage, due to the low system losses at high voltages.

Cost is proportional to power requirement.

1.2.3 Availability

Because this study was conducted on a maintainable system, the measure of the safety of the system was taken to be the availability rather than the reliability, where reliability is defined as the probability that no debilitating failure will occur during the life of the system, and availability is defined as the probability that the required power levels will be available when called for regardless of the number of failures occurring. The time interval between a component failure and its replacement with a good component becomes a significant factor in availability calculation.

1.2.3.1 Battery Availability

In the case of the battery, the availability model was used to calculate the number of spare cells which would have to be carried in addition to the launched battery complement, assuming that battery maintenance would occur by replacement of defective cells as soon as they were discovered, and that the battery would be off-line during the replacement period. The results of the analysis showed that during the 3.33-year battery life, approximately 70 to 90 percent of the cells would have to be replaced before the battery itself was replaced at the end of its life. A detailed analysis of this conclusion is shown in Section 2. 4. 4. 1 along with the assumptions inherent in its development. While the results are not entirely consistent with the history of relatively good performance of batteries in orbit, the assumptions appear to be reasonable, and the data derived directly from a NASA test source after 2 years of testing. It is concluded that further work is required in determination of battery reliability, power availability, and cell replacement requirements.

Those factors found to have a major impact upon power availability from the battery are cell size and power requirement (peak or nominal). System voltage affacts availability only in the third decimal place. In those systems where more than one module is used per battery, the number of modules has no significant impact upon availability. Availability decreases significantly with decreasing cell size and is significantly lower at peak than at nominal power levels. Availability also decreases slightly with increasing nominal power requirement.

1. 2. 3. 2 Electronic Equipment Availability

The model of reliability used for all electronic equipment is as follows: Where units are operated in parallel, it was assumed that if "n" units are required, n + 1 units are installed, and all units are operating simultaneously. The failure of a single unit would still permit complete operation. However, failure of another unit before the first could be replaced would result in performance degradation. The following conclusions were reached based upon the above assumptions:

In most of the electronic elements of the power subsystem such as converters, inverters, etc., availability tends to decrease slightly with increasing system voltage above 100 volts and with increasing power requirement. Where electronic equipment is required to carry peak powers, the probability of peak power availability is significantly less than that of nominal power.

In every case, and in all configurations, the availability of the various subsystem elements designed for nominal power is essentially 1. 0 for emergency powers, leading to the conclusion that no backup power system is needed.

The behavior of electronic black box availability as a function of the number of units into which the black box element is divided is fairly complex. The following general conclusions may be reached:

If a subsystem element must be designed to carry the peak power of the system, dividing the box into many separate elements and adding one additional spare was found to have no significant impact upon the availability of peak power. The probability of having nominal power (50 percent of peak) available, increases as a function of the number of units into which the element is divided, until, in a system whose probability of having a peak power is only 60 percent, the probability of nominal power is greater than 0.99999999 using 10 units, and the probability of emergency power is greater than 0.99999999 with seven or more units (see Figure 1-1).

Similarly, if a subsystem element is required to carry only nominal power (such as a charging circuit) then division into larger numbers of smaller units was found to have little impact upon the normal power levels but increases the probability of availability of emergency power significantly (see Figure 1-2). In general, the gains to be achieved by division of electronic boxes into several elements lose their significance when more than 10 packages are used, although other factors, such as handling ease, etc., may result in a decision to subdivide further.

1.2.4 Optimum Battery Depth of Discharge

A mathematical analysis of the battery depth of discharge-cycle life relationship shown in Section 2.3.2, and further detailed in Appendix C, leads to the conclusion that the optimum depth of discharge at which to operate a nickel cadmium battery in low earth-orbits is a constant equal to the reciprocal of the slope of the log cycle-life versus depth of discharge curve. In the case of the data used here, this is approximately 20 percent. This conclusion is independent of the orbit period.

It should be emphasized that this conclusion is valid only when:

- The system is a maintained system
- The required lifetime of the system is far in excess of the lifetime of the battery under the conditions of use, so that battery replacements are required.

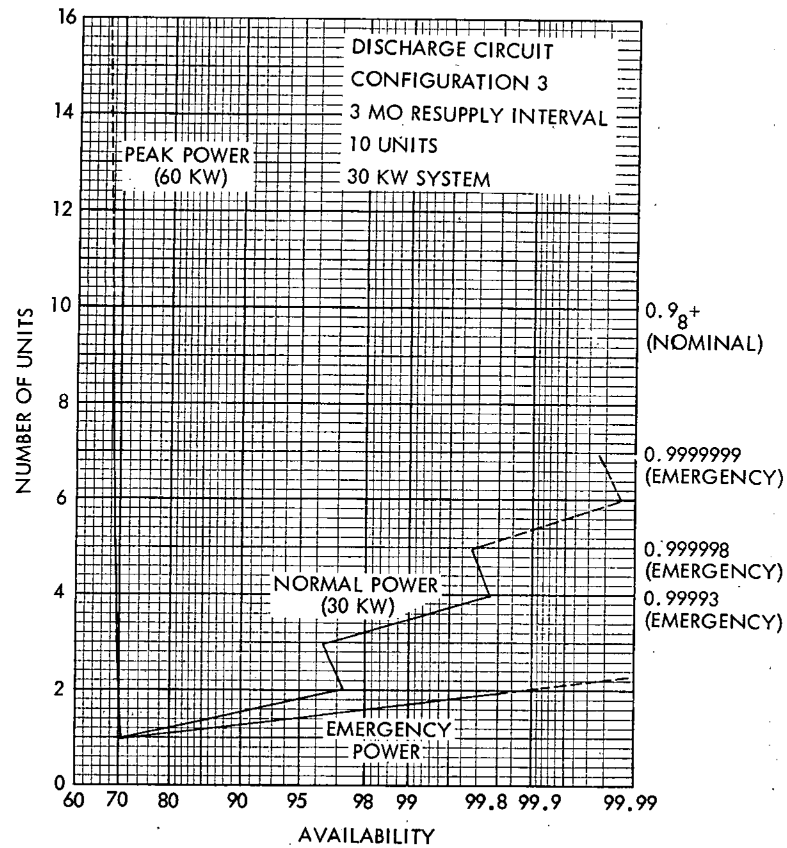

Figure 1-1. Discharge Circuit - Configuration 3

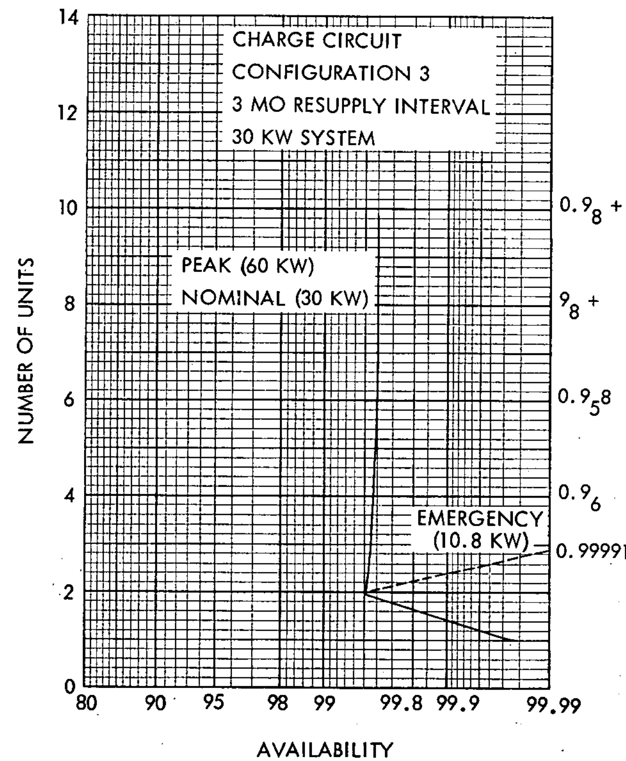

Figure 1-2. Charge Circuit - Configuration 3

Because of the above restrictions, the fact that batteries are being used at far greater depths of discharge in some long-life synchronous orbit applications is not inconsistent with the conclusion reached.

1.3 CONFIGURATION COMPARISON

Six configurations are defined in Section 2.5. A comparison of the relative merits of the six configurations is summarized in Figures 1-3 through 1-9. Configuration 1 is the simplest and the lightest. Configuration 6 is the heaviest. Configurations 2, 3, and 5 are closely grouped at approximately 5 percent heavier than configuration 1. Configuration 4 is about 10 percent heavier. The rates of change of weight with voltage vary significantly so that the relative weights of the configurations are different at 300 volts.

When the battery voltage ratio is changed in Configurations 2, 3, and 6 (i. e., a boost system is used to increase a low battery voltage to a high bus voltage), the weight at 100 volts are slightly greater than the low boost configuration but decrease significantly at 300 volts leading to the conclusion that there is a significant advantage to the use of high boost systems as compared to a nonboost system only at very high voltages. A significant weight penalty is paid for the use of a boosting system at 30 volts.

Costs of the several configurations (excluding the cost of the solar array and power control unit) generally follow the weight patterns very closely, the relationships changing with voltage as do the weights.

Availability (probability of having nominal power) assuming a 3 month resupply interval shows little sensitivity to system voltage, although a slight peaking in availability does appear to occur at 100 volts in five of the six configurations. Configuration 6 has the lowest availability, and the greatest loss in the interval between 100 and 300 volts. Configurations 1 and 4 are highest and are virtually equal in availability.

1.4 RECOMMENDATIONS

1.4.1 Battery Operating Depth of Discharge

A tentative value of operating depth of discharge should be established at 20 percent, pending further evaluation of nickel cadmium cycle life data.

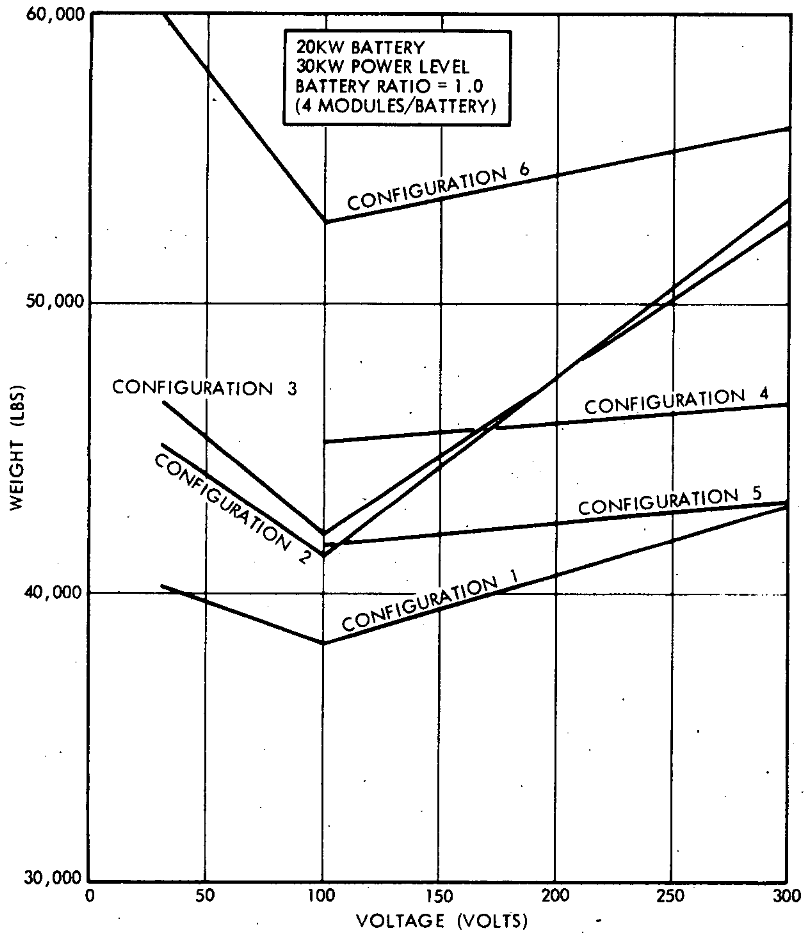

Figure 1-3. Configuration Comparison - Weight

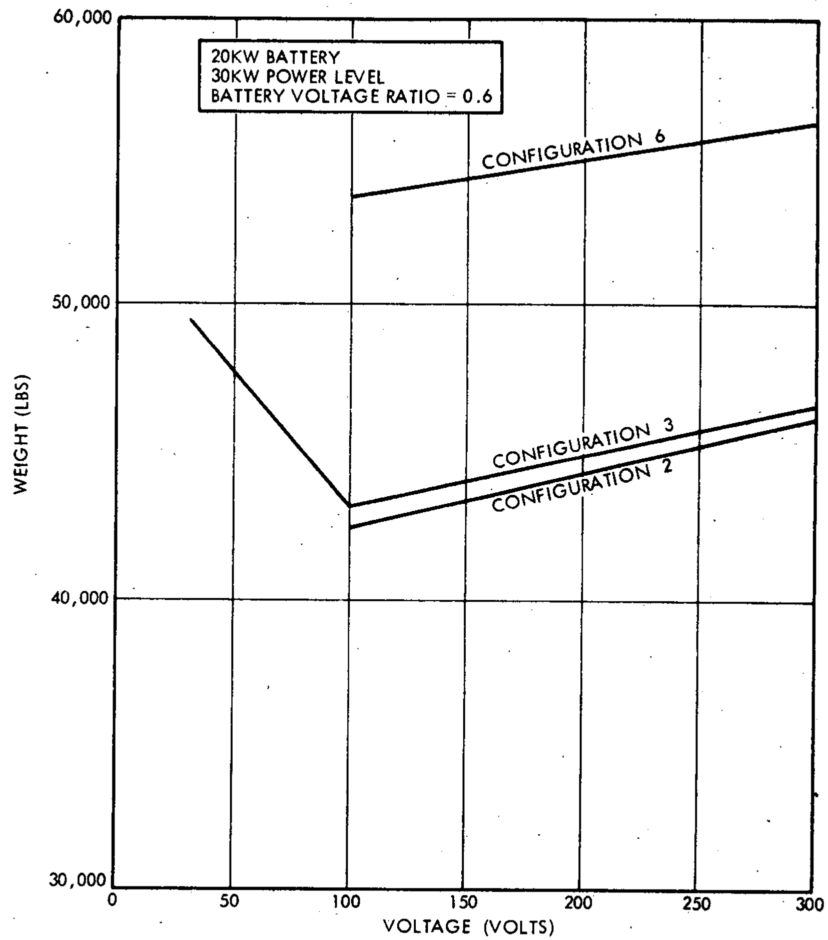

Figure 1-4. Configuration Comparison - Weight

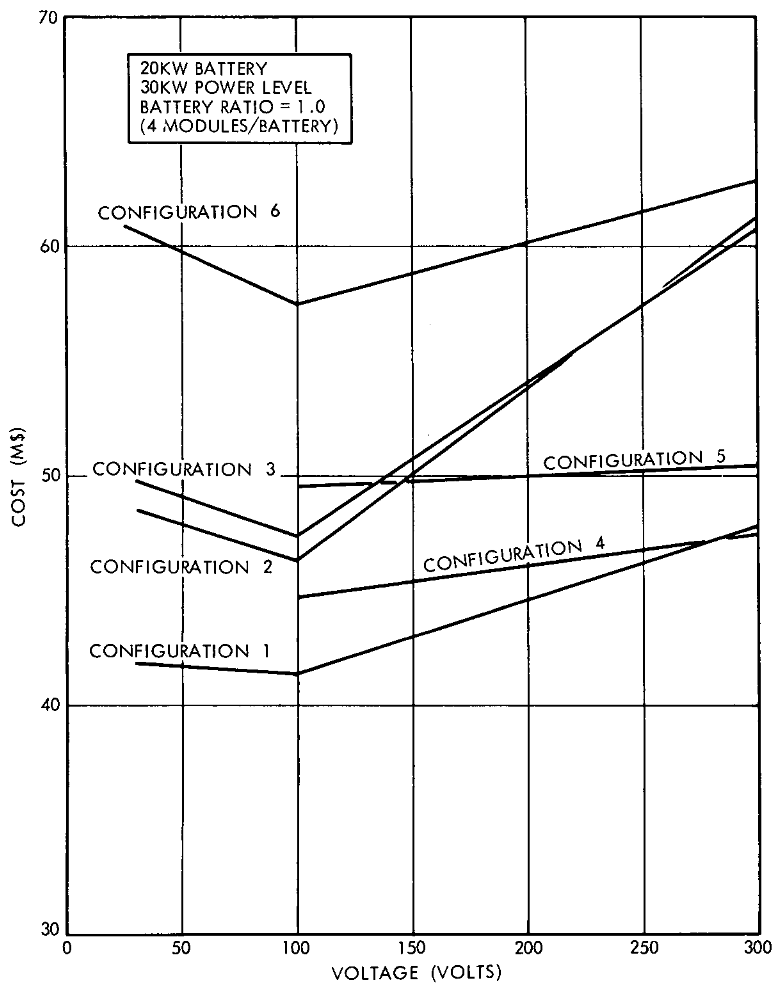

Figure 1-5. Configuration Comparison - Cost

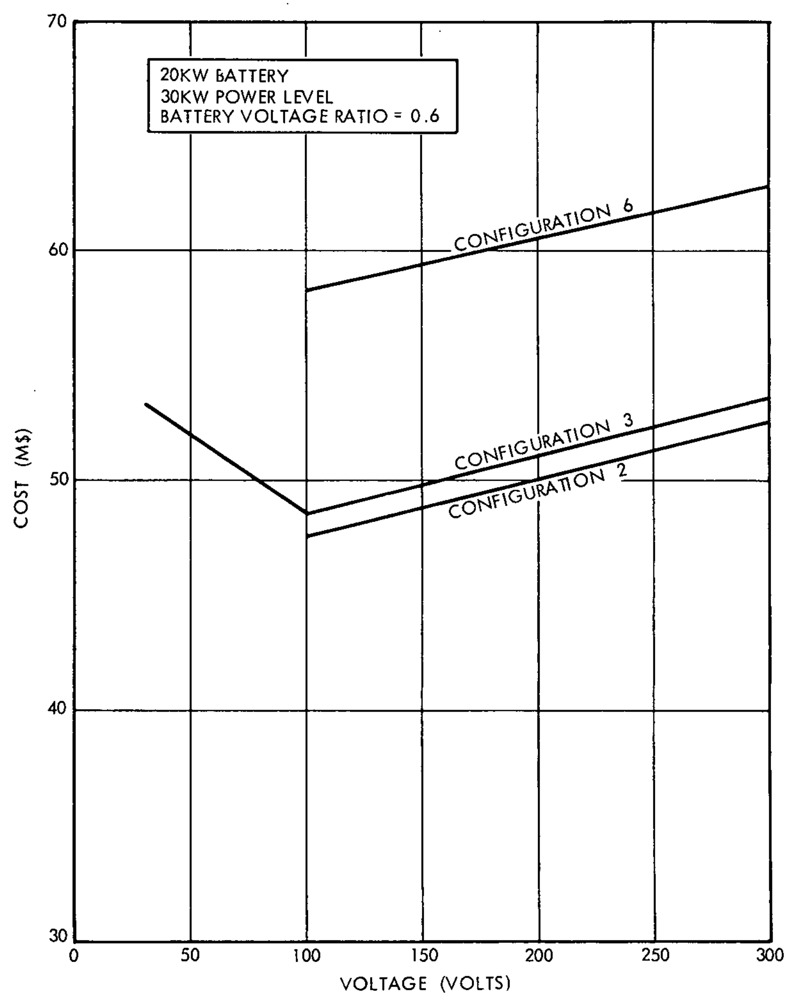

Figure 1-6. Configuration Comparison - Cost

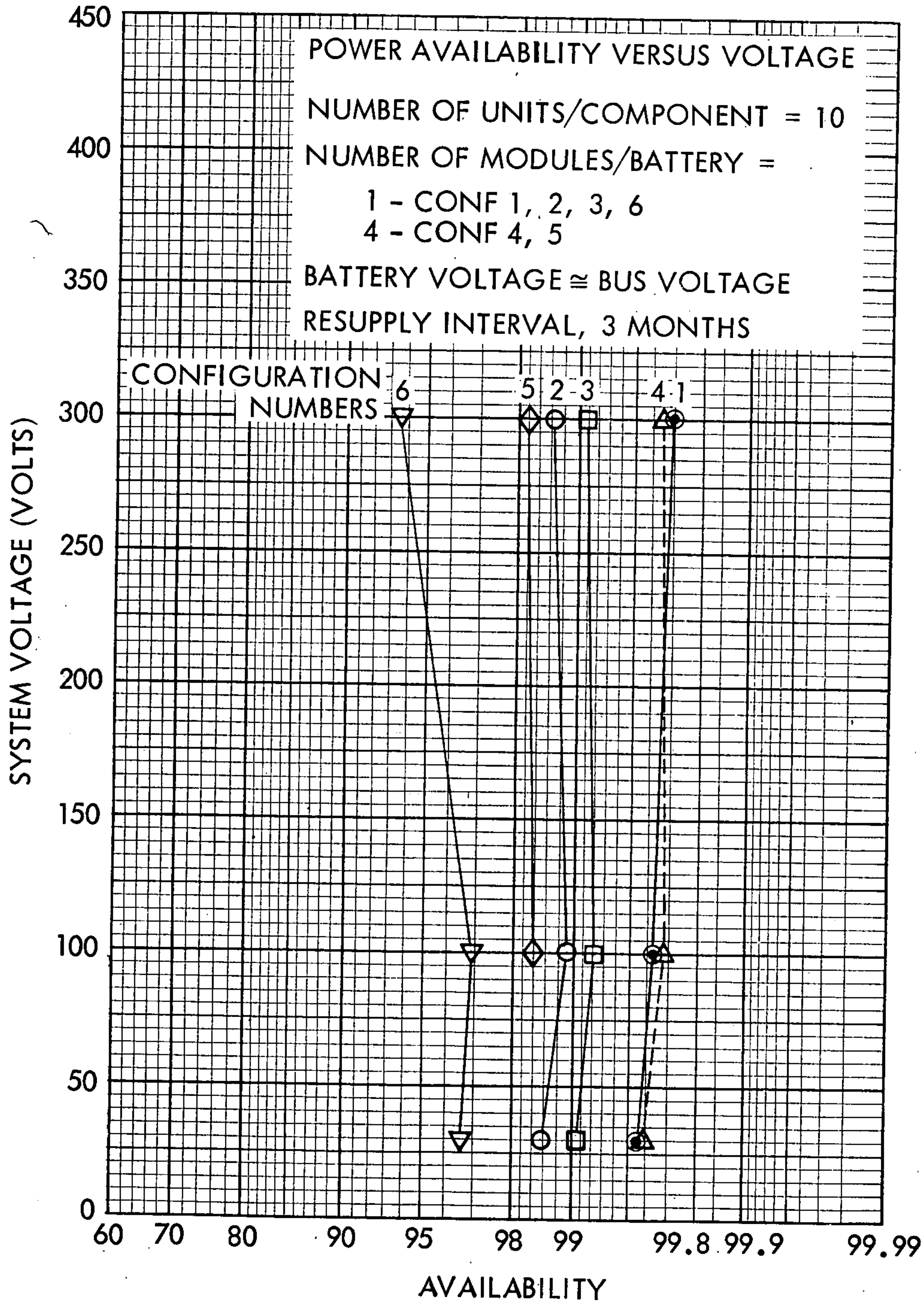

Figure 1-7. Configuration Comparison - Availability

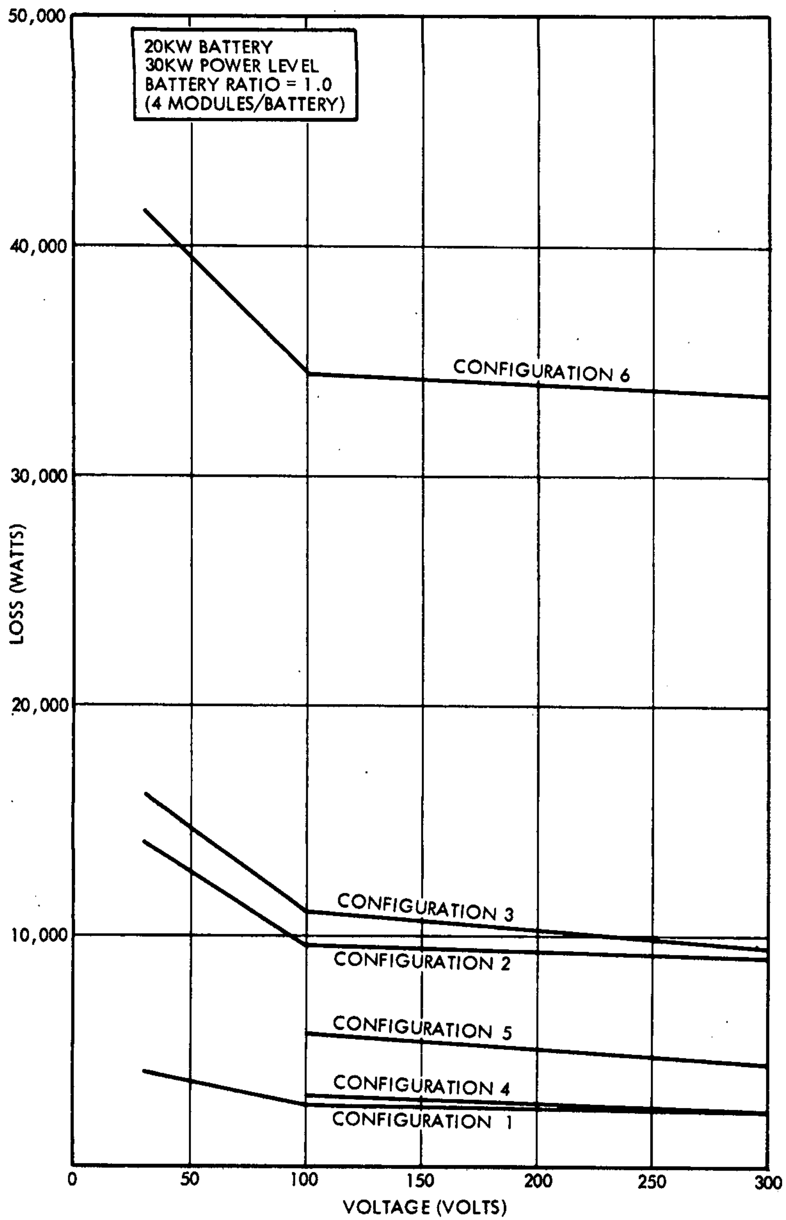

Figure 1-8. Configuration Comparison - Losses

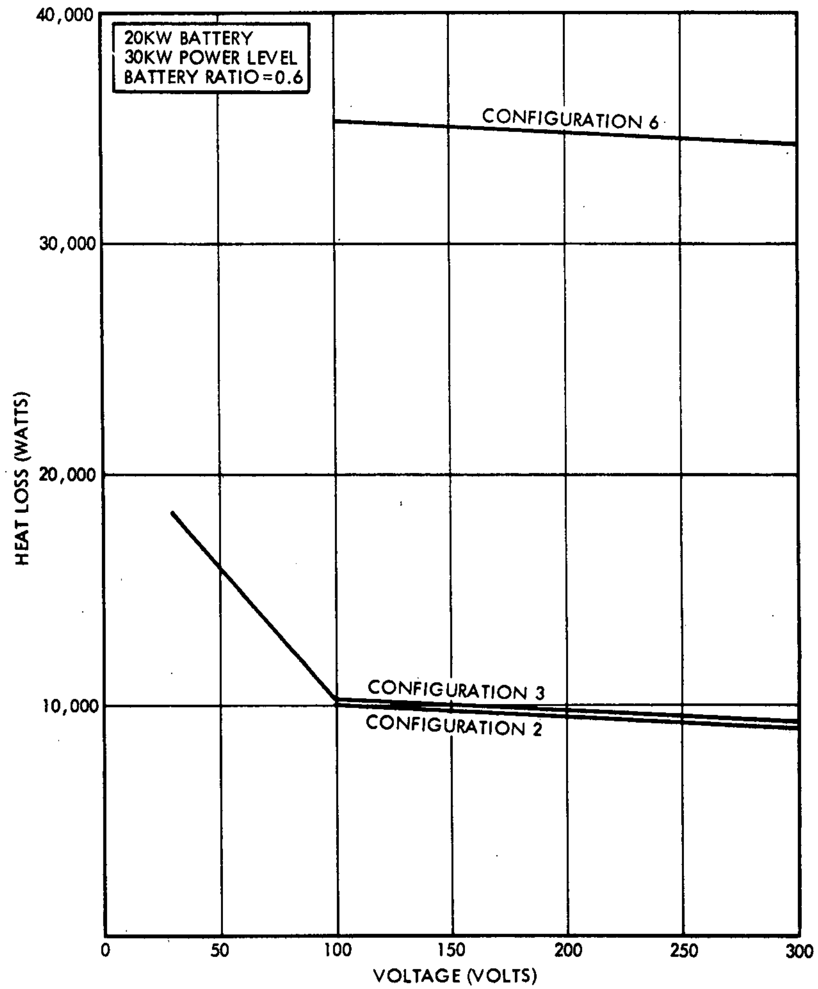

Figure 1-9. Configuration Comparison - Losses

As further test data become available, operating depth of discharge should be revised to approximate the value of 1/B, where B is the slope of the cycle life versus DOD curve. See Appendix C for calculations.

1.4.2 Battery Replacement Interval

A tentative value of battery replacement factor should be established at 3. (A total of three battery complements are flown during the 10-year life of the space station.) This value should be re-examined in the light of any new battery cycle life data which may become available.

1.4.3 Battery Type and Cell Size

Effort should be directed toward the development and qualification of larger cells, having capacities of at least 100 ampere-hours. The study did not develop data on the optimum cell size for minimum weight and cost, but it was clearly shown that the larger cell sizes led to overall lower program costs than the use of smaller cells.

1.4.4 Battery and Cell Reliability Data

The relatively large number of expected cell failures calculated from available cell cycle life and capacity dispersion data, and assuming the model of cell degradation shown in Section 2.4.4, suggests that battery cell replacement could represent a significant cost in terms of spare cells and crew effort if the results of the analysis are at all representative of the true manner of failure. It is recommended that an effort be made to determine more accurately the expected cell failure rate in orbit, to verify the accuracy of the cell degradation model assumed in calculation of cell failure rates, and to develop battery designs which are compatible with rapid and effortless cell replacement.

1.4.5 Emergency Backup/Power Supplies

If adequate provisions are made to prevent propagation of failures between parallel electronic units or parallel batteries, no independent backup power supply is recommended to assure a high probability of maintaining sufficient power for crew survival, based upon a survival power requirement of approximately 30 percent of normal loads.

1.4.6 Modularization of Power Subsystem Components

Where central power processing equipment is used, such equipment should be divided into between five and ten units for optimum system weight and cost. No significant improvement can be achieved by using a larger number of smaller units unless other factors not considered in this study (such as convenience, mass distribution, etc.) are of overriding importance.

1.4.7 System Voltage

All configurations show a definite minimum in weight and cost at approximately 100 volts and a possible slight advantage in availability in spite of decreasing losses with increasing voltage. This relationship holds regardless of the use of lower voltage batteries in those configurations which will permit boosting from a lower battery voltage to a higher bus voltage. Consequently, a system voltage near 100 V is recommended.

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2. STUDY RESULTS

The results of the study are presented in this section. The discussion is arranged according to the tasks outlined in Appendix A.

2.1 CONSTRAINTS DEFINITION

2.1.1 Mission Constraints

2.1.1.1 Power Level

A brief survey of the field has disclosed no specific, well defined nonmilitary application of unmanned spacecraft in the 20 kw range.

Manned spacecraft have a definite application for power systems in the 25 to 35 kw range during the next decade. The manned space station, characterized as having a crew of 12 and a power level of 25 kw, has been the subject of considerable study over the past few years; consequently, the objectives of the study were altered to center about the nominal power level of 30 kw.

2.1.1.2 Service Life

A power system of 10 year capability is desirable for design because of the high cost of construction and injection into orbit.

At the present time, by use of optimized redundancy techniques, (generally binomial circuit redundancy for low-level circuits and batteries, quad redundancy for high power analog circuits, and standby redundancy for high power switching circuits) the calculated reliable life of a satellite electric power system can be extended to approximately 5 years. By use of modular power systems, which are binomially redundant, reliable operation may be extended beyond 5 years (Ref 1).

Complete redundancy of power system components has been examined in a general way by Gould and Canetti (Ref. 2) for a 10-year mission. Their analysis would be somewhat overoptimistic for batteries, since it assumes a constant component failure rate over the total time interval. They conclude that for a 10-year reliability of a single system, a MTBF of 100 years is required, which is not readily achievable. Three standby backups would be required to achieve a reliability of 0.98, more than quadrupling power system weight. They conclude that for a 10-year service life in a manned mission, on-board redundancy is not an acceptable approach.

Because of the increasing failure rate of battery cells with time, it is not clear at the present that a 10-year mission with high probability of success is a parctically achievable goal without in-orbit battery replacement. Optimization studies indicate that the minimum total weight occurs at a depth of discharge of 0.2, with complete replacement of the battery twice during the 10-year mission.

2.1.1.3 Orbital Characteristics

Nonmilitary applications of unmanned satellites at the high power levels appear generally to occur at two altitudes: low oribts from 100 to 300 nautical miles and a high altitude of synchronous equatorial orbit. Of these, the synchronous applications appear to be preponderant, relating to high power communications and direct broadcast of radio, television, and telephony.

Manned applications to date appear to be only at the low altitudes, from 230 to 270 n mi, except for an advanced space port, vintage 1990; one version of which periodically dives to a 20 n mi altitude. Of these, the only application in the 20 to 25 kw level is the initial space station.

2.1.1.4 Gravitational Forces

Projected plans for the 12-man, 20 to 25 kw space station require that the systems be designed for operation in zero gravity; however, plans for subsequent expansion involve rotation of portions of the original space station, so that, should electric power components be mounted in the rotated portions, the mountings for such components would be structurally designed to support some gravitational force.

2.1.1.5 Variation in Power Level and Type

Estimated variation in power levels (12-man station) (Ref. 3) include:

Nominal	Peak	Emergency Minimum
25	50	9

The distribution of power between alternating and direct current use is from 1/3 to 2/3 ac.

2.1.1.6 Utilization of Power

Manned Space Station. Typical power requirements for a space station are given in Table 2-1.

Table 2-1. Space Station/Space Baseload Requirements
Average Power - kw

		Station	Base
Define	EC/LS (including thermal)	9	35.0
Define	SCS	0.9	1.5
Define	P/RCS	1.3-5.0	5.0
	Communication and data	1.6	4.0
	Lighting	2.0	8.0
	Crew	0.5	2.0
	Logistic support	1.0	1.5
	Experiments	3.4	20.0
	Pilot production	-	10.0
	Subtotal	19.7	87.0
	Growth contingency	5.3	13.0
	Total	25.0	100.0

Unmanned Satellite. No possible prediction can be made without a mission definition. In the communication-type of mission, the power is delivered at relatively low levels to housekeeping and low level communications gear. The major block of power is reserved for the output stages of the transmitting equipment.

The impact of the variations in power level and the uses of power suggest that the study be made for an unmanned satellite using distribution of dc to most, or all of the equipment, and power conditioning equipment, as a part of the larger user equipment.

In the manned space station, because of the diversity of uses to which power is being applied and the relatively large proportion of direct utilization of ac, serious consideration should be given the use of a hybrid power system, in which some specialized loads, such as lighting, are supplied with unregulated dc at minimum power transfer loss. The remainder of the power is distributed as ac and conditioned by Transformer-Rectified-Filter units in the user equipment.

2.1.2 Human Factors

The primary impact of human factors upon power system design is the availability or unavailability of astronauts as a maintenance crew. In unmanned satellites designed for long life, the achievement of a service life at full power beyond 3 to 5 years requires the addition of redundancy of either the circuit, standby, or binomial power module-type. The achievement of 10-year reliability carries enormous penalties in weight, although no direct information has been found on a tradeoff of the total weight and cost of manned versus unmanned missions to accomplish the same tasks.

The following are some of the human factors which have an impact upon power system design with a brief summary of the approximate limitations and advantages imposed by the human presence.

2.1.2.1 Component Location

For batteries and related control components to be maintained they must be mounted within the climate-controlled compartment of the spacecraft or satellite. This results in an increase in the required con-controlled-environment volume and specifically, in an increase in the requirement for heat rejection from the controlled compartment. Note that the total heat rejection requirements do not change and that the temperature control requirements of the battery are similar to those of the human.

2.1.2.2 Component Mass

Initial plans call for a zero-gravity environment. While it has been demonstrated possible for a man to handle up to 1000-pound mass by slow and deliberate movements, a 20 kilowatt battery would weigh considerably in excess of a ton and would have to be broken down into more readily handled packages. It seems logical at this point to assume that the battery is broken down into modules from 1 to 3 series-connected cells of 100 to 200 ampere-hour capacity, each module having a mass less than 60 pounds. These could be quite readily handled and replaced conveniently should one of the cells in a module be found to be defective.

Similarly electronic power control equipment could be broken down into modules of convenient size. Any larger sections would have to be designed for part or subassembly replacement in situ.

2.1.2.3 Availability of Humans for Repair and Replacement Activities

Current plans for the manned space station do not yet indicate the number of men available for the crew which could be dedicated to maintenance and repair. However, crew listings (Ref. 4) disclose the presence on board of mechanical and electrical-electronic competence which could be diverted to essential repairs.

Howard and Orrok (Ref. 5) define the optimum use of man in space as unusual, infrequent, and unexpected occurrences and suggest that any routing operations can be performed by machine, thus relieving the astronaut of the task.

In accordance with the above generalizations, it is assumed that few, if any, routine monitoring tasks be required of the astronaut. The electric power equipment will be designed with a large safety factor for crew survival and should contain performance monitoring equipment and sensors necessary for diagnosis of impending battery and power system failures. If necessary, on-board or ground computational facilities should be made available for processing of sensor information for diagnostic failure prediction and warning. Periodic human review of the diagnostic information may be of help; some of which may be performed on the ground.

2.1.2.4 Crew Safety Factor

Gervais and Kirkland (Ref. 3) call for an emergency backup power supply of approximately 40 percent of the nominal average power, however, by modular design of the power system and by employing appropriate fault isolation equipment to prevent propagation of faults and overloads between modules, failure of a single nonredundant element in any one module will not compromise crew safety. In a system consisting of 10 2.5-kw modules, it would require the simultaneous failure of six of the 10 modules to compromise crew survival. In this way, extremely high reliability for providing sufficient power for crew survival can be achieved at relatively small or negligible weight penalty, without use of an independent backup power supply.

Failure of components other than the batteries and associated charge/discharge controls presents different problems which are not considered as a part of this study.

2.1.2.5 Crew Maintenance Capabilities

The capabilities of the space station crew for maintenance of batteries and power control equipment are limited by the following factors.

- Ability to apply translational forces and torques in zero-G environments. If the man is required to apply forces with one hand, maintaining a grip on a handhold with the other, his ability to apply steady forces for appreciable periods of time is limited.

  If the man can anchor himself with a tether or by other means, he is capable of performing virtually any task normally required for repair or replacement of a module weighing 50 pounds or less (on earth) with relatively small time penalties.

- Ability to carry spare equipment throughout the spacecraft. Considered in an earlier part. Responsible for the arbitrary limit of approximately 50 pounds. An additional factor requires that the center of mass of the object be not more than 20 inches from the body of the man.

- Ability to handle small parts and components. The man's ability to handle small parts is essentially unimpaired; however, he does not have the luxury of a convenient bench top for temporary storage. The presence of large numbers of small parts is a nuisance factor rather than any real limitation. Good design practice would use captive fasteners in hinged equipment lids. In general, it is suggested that repair of electronic equipment take the following form.

  Low level components and components and circuits would be packaged in modular subassembly form and would plug into sockets or receptacles, or would be wired to terminal strips.

  High power components would be individually, permanently mounted on dismountable heat sinks. Connections would be made by lugs and terminal strips.

No repairs would be made by soldering, welding, etc. because of the problems of splatter of molten metal and because of the possibility of release into the atmosphere of toxic vapors from the flux.

2.1.2.6 Thermal Interface Problems.

The battery and associated control equipment are nonlinear heat dissipators. This heat will have to be rejected to the spacecraft or station radiators. Several alternatives exist:

1) The components may be designed with internal liquid cooling loops which are coupled to a forced convection liquid cooling system. The major maintenance problem encountered with this kind of system is that of breaking the liquid loop connections without spilling droplets of coolant into the environment.

2) The components may be directly coupled to thermally controlled baseplates, relying upon the interfacial atmospheric film to establish good conductivity. This may be further enhanced by use of a soft conductive filler, such as silicone grease spread over the interface. The adhesive qualities of the grease would make it practical to use with minimal danger of spillage, but it would be less convenient than surface-to-surface contact.

3) The components may be cooled by a circulating gas loop using atmostpheric gas. Special precautions would have to be taken in the construction of the electronic equipment to eliminate all materials which might outgas toxic or malodorous vapors.

2.1.2.7 Toxicity Problems.

Toxicity problems specifically related to batteries can occur only in the event of rupture of one of the cells or as a result of use of materials external to the cell which outgas toxic vapors.

In case of cell rupture, the only materials which can emerge are oxygen gas, hydrogen gas, water vapor, and a small amount of a concentrated solution of potassium hydroxide in the form of a fine spray. The quantity of potassium hydroxide solution is limited, since little or no free liquid is present in the cells.

Most of the liquid is held absorbed in the porous electrodes and separator. The danger of free potassium hydroxide spray being injected into the atmosphere may be obviated by enclosure of the cell terminals (which are the weakest part of the cell and are the first to rupture) in a small cap containing an absorbent. Free liquid on surfaces is improbable and will remain on surfaces due to surface adhesion, which is extremely high in alkaline solutions. If allowed to remain, the material will absorb carbon dioxide from the surrounding atmosphere and be converted to nontoxic potassium carbonate.

Hydrogen gas is nontoxic but can form explosive mixtures with oxygen in the proper proportions. Direct rupture of a single cell will not emit sufficient gas to form an explosive mixture. The absence of gravity prevents the gas from concentrating in pockets to form potentially explosive mixtures due to its lower density. Technology exists for detection and removal of hydrogen from air and oxygen mixtures.

Oxygen gas and water vapor in the appropriate quantities need not be considered.

It is concluded that there is no significant toxicity penalty associated with enclosure of the batteries within the controlled environment compartment.

2.1.2.8 Voltage.

There is an established requirement for protection of personnel from accidental contact with voltages above 30 volts. Most equipment being repaired can be turned off; on the other hand batteries cannot. Batteries above 30 volts would be so connected that they can be electrically subdivided into series-connected sections of 30 volts or less during repair operations.

2.1.3 Summary of Assumptions for 20 kw Battery System

Mission

- 12-man space station
- Zero-G environment
- Power levels

Nominal	25 kw
Peak	50 kw
Minimum	9 kw

- 270 n mi orbit, 55 degrees inclination

- Load power characteristics, 1/3 to 2/3 ac, remainder dc
- 10-year service life, flight in 1975.

Power system design characteristics:

- Modular power system battery and controls design module sizes range from 2.5 kw to 10 kw.
- All power system components are mounted in the controlled-environment compartment.
- All power system black boxes or subassemblies of black boxes are limited in mass to 65 pounds.
- Batteries and battery controls are internally nonredundant, i.e., use no component-redundant circuits such as quad-connected transistors.
- Fault isolation and power system protection devices are assumed to prevent failure propagation between modules.
- A limited number of spare battery cells are carried on board and are replaced by logistic supply as used.

2.2 BATTERY CELL TYPE SELECTION

A preliminary comparison was made between various types of chemical systems potentially useful as secondary batteries. Table 2-2 shows a qualitative tradeoff of the various systems.

Table 2-2. Comparison of Battery Systems

Characteristic	Nickel Cadmium	Silver Cadmium	Silver Zinc
Flight proven	+	+	-
Hermetically sealed	+	+	0
Data available	+	0	0
Good manufacturing control	+	0	0
High rate discharge	+	+	+
High rate charge	+	-	-
Overcharge capability	+	-	-
Energy density	-	0	+
Memory effects	-	-	0
Maintenance needs (trickle charge)	0	+	+
Electrode stability	+	-	-
Life	+	0	-
Voltage control	+	-	-
Toxicity of components	0	0	0
Simplicity of construction	+	0	0
Pressure in normal operation	+	0	0
Heat generation and rejection	-	0	0

+ Advantage (good)
- Disadvantage (poor)
U Data unavailable for comparison
0 neither + nor -

For use in a near earth 100-minute orbit, the most important characteristics are rapid recharge capability, cycle life, and high rate discharge capability. The only available system which has these three characteristics is the nickel-cadmium system. The silver-cadmium system cannot be recharged in the short time period allowed for charge in a 100-minute orbit and thus cannot be considered.

With additional work, the regenerative fuel cell system may show promise. Most of the other systems available are not sealed, presenting a safety hazard, or do not have cycle/life capabilities compatible with a 10-year mission.

Thus, a hermetically sealed nickel-cadmium battery is recommended for the 25-35 kw battery system for 1975 to 1979 flight.

2.2.1 Battery Weight Analysis

In an unmanned spacecraft, the vehicle is launched with a complement of batteries and a certain proportion of these must survive for the full mission. However, with the introduction of resupply capability, a new optimization tradeoff becomes available.

Qualitatively, a battery may be considered to wear out after a finite number of cycles of operation. The symptoms of such wear-out take the form of a slow degradation of output voltage on discharge, until the battery no longer delivers the minimum acceptable output voltage at the end of the the discharge period. Upon use of a reconditioning cycle in which the battery is fully discharged and subsequently recharged, the battery recovers and returns to a form of behavior approximating that of a new battery and, upon further cycling, the degradation in voltage begins again. It is able however to sustain fewer cycles after each successive reconditioning operation before its voltage degrades unacceptably. While the acceptable degradation level will vary from program to program, a good compromise value is a minimum end of discharge voltage of 1.05 volts/cell, which will permit optimum use of the battery. The end of wear-out life may then be defined as occurring when the interval between reconditioning cycles becomes unacceptably short. The batteries have undergone no catastrophic failure, are still in operation, but require replacement.

The number of cycles of operation which a battery will deliver is a function of the depth of discharge at which it is operated. Most studies performed at constant depth of discharge cycling show a semilogarithmic relationship between cycle life and depth of discharge (Figure 2-1). The impact of reconditioning upon this relationship, other than its increasing the total number of available cycles, is largely unknown, and an accurate estimate of the variation of number of cycles with depth of discharge with periodic reconditioning is unavailable. The results of this study are therefore limited by the accuracy of the best available engineering estimate of this function, which was derived after an examination of OAO data, OGO data, and NAD CRANE reports, and NASA SP-172.

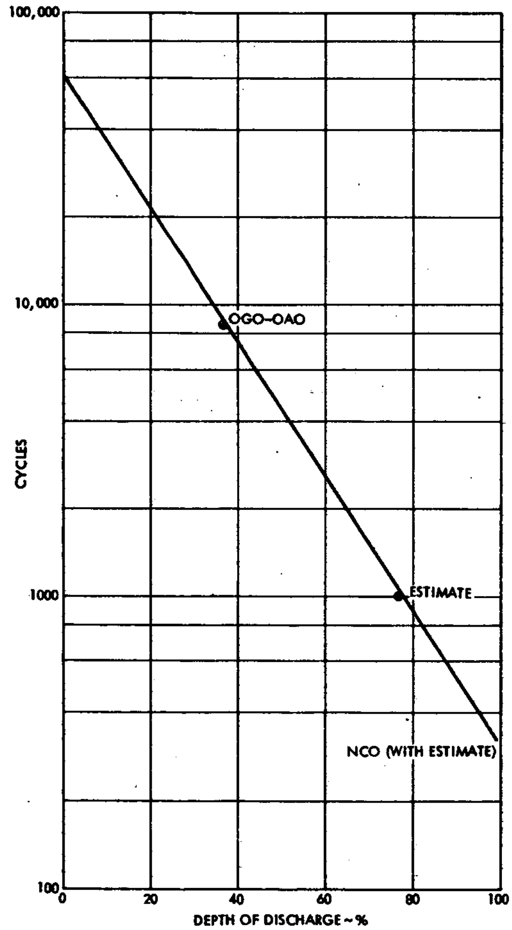

Figure 2-1. Estimated Cycle Life, Nominal 75°F Environment

In any specific application, as the battery depth of discharge is increased, the original launched weight of the battery required to perform the task decreases, but the number of cycles which it will support also decreases; the replacement interval becomes shorter, requiring more frequent replacement for an increase in total weight. The all-up weight of the battery (launched weight plus resupply weight) may be expected to go through a minimum. A study was conducted to determine the minimum total weight and the depth of discharge at which it occurred as a function of the wear-out cycle life of the cells. A simple computer program is shown at the end of Appendix C with total weight as a function of depth of discharge.

The results of this study are predicted upon the following assumptions:

1) The service life of the cell is independent of age and dependent upon the number of cycles.

2) Wear-out failures alone are considered. Random failures are assumed to be eliminated by detection and replacement of individual cells.

2.3 OPTIMIZATION METHOD ANALYSIS

It was clear from the start that the number of independent variables having a significant impact upon the power system weight, cost, and reliability was too great for a repetitive calculation and search for an optimum among all possible alternatives within the scope of the program. Consequently, it was decided to design a method to allow the user to specify the desired system and all of the significant variables, and to perform a rapid evaluation of the weight, cost, and reliability of the specified system. Repeated calculations would then show the impact of variables upon the overall system properties. The calculation method is illustrated in Appendix .

Certain simplifications were made in the calculation process. Among these was the use of a pre-estimate of the power subsystem specific weight. The pre-estimate is used in analysis and optimization of cabling weight to avoid the need for iterative calculation and precalculation of the optimum battery depth of discharge. The battery depth of discharge is a constant, dependent upon the slope of the battery cycle life versus depth of discharge curve and is independent of other factors.

2.3.1 Cabling

The power loss in cabling must be selected on the basis of a tradeoff between a heavy cable needed for an extremely low power loss and excessive amounts of weight needed by the power source for a high cable loss.

The discussion below outlines a method for approximating cable losses for a minimum weight power system based on this tradeoff. Appendix B contains the derivations and assumptions used in making the tradeoff.

The optimum cable power loss can be expressed as:

$$\hat{D}_{LC} = K_P \left[-1 + \sqrt{1 + (1/K_P)} \right] \qquad (1)$$

$$\hat{D}_{LC} = 0.5 \qquad (2)$$

when

$$K_P = \infty$$

where

$$\hat{D}_{LC} = \text{optimum cable loss}$$

$$K_P = \text{power system coefficient}$$

$$K_P = K_C/(\nu_{PS} - K_C) \tag{3}$$

where

K_C = cable coefficient ~ lb/watt

ν_{PS} = power source specific weight ~ lb/watt

$$K_C = \frac{4\rho_C \delta_C L_C^2}{V_L^2} \tag{4}$$

where

ρ_C = cable material density ~ lb/ft^3

δ_C = cable specific resistance ~ ohm-ft

L_C = cable length ~ feet

V_L = user load voltage drop ~ volts

Using the above set of equations a set of optimum cable loss data for cable runs of 100 feet and 500 feet are shown in Figure 2-2. Note that the optimum cable power loss is relatively insensitive to power source specific weight above the level of 0.6 lb/watt.

Since the expected weight of 25 kwe solar cell/battery power systems (for the space station) is 25,000 pounds (see computed weights) or more (1.0 lb/watt), a relatively coarse approximation of the specific weight should yield a fairly good approximation of the optimum cable loss.

2.3.2 Battery Depth of Discharge

To determine the optimum battery depth of discharge a brief examination of the effect of battery depth of discharge on total battery weight was made. The results are discussed in Section 2.6.1 and indicate that for a nickel-cadmium battery, minimum weight is attained when the battery depth of discharge is approximately 20 percent. It was further shown that this optimum value is apparently independent of the space vehicle orbital period.

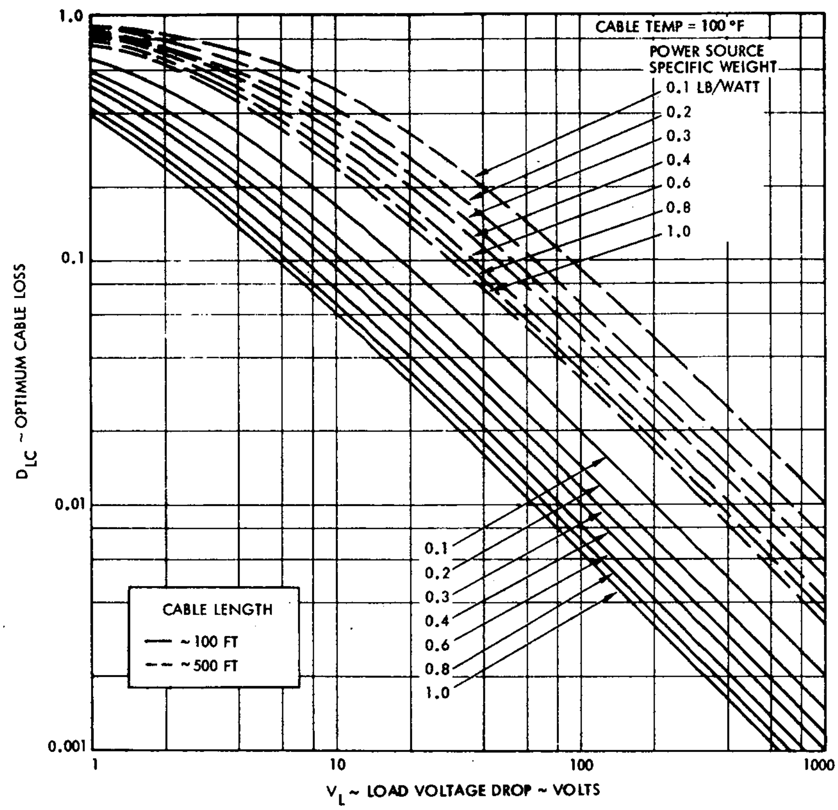

Figure 2-2. Optimum Power Loss in Copper Cable

A more detailed examination of the parameters affecting the optimum battery depth of discharge was made and reported in Appendix C. A simple computer program for calculating battery weight and DOD is also shown in Appendix C. Briefly, the results obtained in this examination indicate that if the battery cell cycle life can be expressed in the form of a semi-log plot:

$$C_{CD} = \alpha_D e^{-\beta D_D} \tag{5}$$

where

C_{CD} = design cycle life of battery cells

α_D = intercept of chosen design line

β = slope of cycle life versus depth of discharge design line

D_D = battery depth of discharge

then the optimum battery depth of discharge for a minimum total battery weight including replacements is given by:

$$\hat{D}_D = 1/\beta \tag{6}$$

The results of this analysis, shown in Section 2.6, further indicate that this optimum is independent of:

- Battery discharge power requirement
- Duration of battery discharge (related to orbital period)
- Total battery cycles for the mission
- Battery specific weight.

Typical cycle life data shown below can be used to obtain the required slope of the cycle life design line.

Table 2-3. Cycle Life of Nickel Cadmium Batteries

Depth of Discharge	Cycle Life
1% intercept	63,000
80%	800

The slope is then:

$$\beta = \frac{\ln(63,000) - \ln(800)}{(0.8) - (0.0)} = 5.455 \tag{7}$$

From which the optimum depth of discharge is

$$\hat{D}_D = 1/5.455 = 0.183 \equiv 18.3\% \tag{8}$$

This value confirms the value of the 20 percent depth of discharge discussed above. Hence, a value of 20 percent depth of discharge was used in design calculations.

2.4 DATA REQUIREMENTS DEFINITION

2.4.1 Electronic Equipment

Equipment characteristics data is needed for the power conditioning units indicated in the selected configurations (Section 2.5). These power conditioners include:

- Filter - unregulated dc bus
- Boost regulator - PWM
- Buck regulator - PWM
- Inverter - unregulated
- Converter - unregulated
- Converter - regulated, transistor-type
- Converter - regulated, SCR-type
- Transformer/rectifier, unregulated
- Shunt - dissipative
- Shunt - sequential
- Series regulator - dissipative
- Voltage control limit logic
- On/Off control logic

The analytical model of power conditioning equipment was developed by dividing each electronic box into a set of basic functions. Thus, a backing regulator consists of an output filter (including inductor), a switching stage, an input filter, and an oscillator and control stage. Parametric data for weight, losses, and cumulative failure rate were generated for each of the "functions" as a function of voltage at a fixed frequency of 10 kHz.* The functions are "assembled" in the computer to indicate the total weight, failure rate, and losses for a black box.

*Earlier studies (Ref. 12) have confirmed that a good compromise between reliability and the optimum weight of power systems is achieved when switching power processing equipment is operated at a frequency of approximately 10 KHz; furthermore, that modest variation in frequency about this value does not have a significant impact upon the overall power subsystem weights.

Packaging factor data were also generated.

For configuration 6, the appropriate data were altered to express function properties at 400 Hz.

Functional design data have been assembled and presented in Section 2.6.2.

2.4.2 Battery

Battery data have been acquired on two different types of nickel-cadmium cells, the commonly used prismatic cell, and the pile-structure battery using bipolar electrode cells. A review was made of the relative merits of the two types of cell for use in typical spacecraft systems.

The prismatic cell structure consists of a set of interleaved positive and negative electrodes immersed in an electrolyte and connected in parallel. This type of structure is a convenient method of packaging a large surface area into a convenient, compact storage. The disadvantage of the prismatic structure is that the current flow pattern in the electrode is parallel to the surface of the electrode, and consequently the electrode thickness and width forms the cross sectional area of the current conductor. As a result, the resistance and inductance of the electrode matrix and of the internal and external leads are added to the internal impedance of the cell itself. This, in turn causes an uneven distribution of current flow at the surface of the electrodes, reducing the effective area of the electrodes and degrading cell performance further.

Heat is removed from the cell relatively easily, since the outermost electrodes are parallel and in contact with the largest cell face.

A bipolar electrode pile reduces the internal impedance contribution of the cell electrode structure to an irreducible minimum. The conductor cross sectional area is increased to the projected area of the electrode surface, and its length is reduced to the sum of the thickness of the electrodes; thus, reducing both resistance and inductance to a minimum. Current distribution is more uniform, preventing further performance degradation. In this way, the cell may be expected to and does deliver high currents with less IR losses than the equivalent electrode area prismatic cell. Total capacities per unit electrode weight may be approximately equivalent to that of the prismatic cell. In their current state of development, bipolar electrode cells are operated with relatively large quantities of electrolyte (flooded) and have a negligible oxygen recombination capability.

The bipolar electrode pile has several significant disadvantages relative to the prismatic cell:

1) The only available control of the size and shape of a battery of any specific voltage and capacity is the electrode thickness which also has an effect upon the maximum current capability. Only one electrode pair may be used in each cell and no bipolar designs are available for parallel connection of cells.

2) Current designs of bipolar cells use an elastic compression seal backed up by a cured potted seal. The total sealing area is expanded to encompass the entire periphery of the cell and may contribute significantly to the weight of the cell. At the present time, no seal designs have been investigated which would materially reduce the overall cell weight. Because of the compression characteristic of the seal, rigid battery end-plates are necessary to maintain compression, also contributing to the battery weight.

3) Heat is most readily conducted from both types of cells in a direction normal to the surface of the electrodes. In the prismatic cell, the number of electrodes stacked in the direction of heat flow can be controlled by the specific cell design and within reasonable limits, can be varied to produce cells with a greater or lesser heat rejection capability. In the bipolar electrode battery, however, the number of electrodes is determined by the battery voltage. The heat rejection capability of a 19-plate prismatic cell is approximately equivalent to a bipolar electrode battery of nine series-connected cells with a discharge voltage of 11 to 11.5 volts. This may be somewhat alleviated by the reduction in IR losses in the bipolar cell but these are a relatively small proportion of the total heat generated.

4) At the power levels required for normal constant-power satellite operations, the power voltage drop (and consequent higher output voltage) is not significant enough to offset the increased weight, decreased recombination capability, higher development cost, and poorer heat rejection capability. At very high power densities, the bipolar designs show significant merits.

A listing of the required data for each type of cell includes:

- Optimum depth of discharge as a function of the number of cycles required. This is defined as the depth of discharge which results in the lowest total battery weight including both launch and resupply

- Cell average discharge voltage as a function of depth of discharge and current

- Resupply factor as a function of the optimum depth of discharge. Resupply factor is defined as the number by which the originally launched battery weight must be multiplied to obtain the total battery weight

- Average battery ampere-hour efficiency as a function of the charge period and depth of discharge. If the charge period is in excess of 4 hours, sequential charging will be used to fix the charging rate at a level equal to or above C/4

- Average value of reversible potential and an average value of entropy change to be used in calculation of heat dissipation

- Average value of charging voltage to be used in calculating charge power

- Cell weight as a function of capacity in AH

- Battery packaging factor as a function of cell block weight*

- Maximum allowable cell capacity

- Minimum allowable charge rate

2.4.3 Thermal Data

From a thermal standpoint, the simplest and most reliable method of cooling electronic equipment and batteries, with a minimum weight expenditure, would be to couple the equipment by direct contact to a space radiator of the proper size. This method, however, limits the possible locations for the equipment to areas on or just beneath the spacecraft

*Packaging weight includes all items required to hold the battery together, and any heat sinks designed to be integral to and inseparable from the cells or replaceable cell modules. This weight does not include that weight associated with thermal control which can be separated from the cell modules and serviced independently.

surface. Analyses were made of three different heat coupling systems to establish preliminary design estimates of the weight penalty incurred by placing a battery inboard from the surface. The results are also applicable to other heat producing equipment.

One of the systems uses a fluid-loop to transport heat from the battery baseplate to a space radiator. The second system utilizes a heat pipe in place of the fluid-loop. A standard of comparison is provided by the third system which uses a direct contact coupling between the battery baseplate and the radiator.

Since the radiator will represent a significant fraction of the total weight of any of the three systems and since the amount of radiator area required is dependent on the conduction coupling of the system, the radiator was included in the comparative weight calculations. This was done by setting the radiation resistance (a known function of radiator area) equal to the difference between the required overall resistance and the sum of the calculated conductive-type resistances and then solving for radiator area. The results of the analysis are shown in Table 2-4 below and are representative of nonoptimized but practical cooling systems.

Table 2-4. Comparison of Battery Cooling Systems

System	Total Weight (lbs)	Electrical Power (watts)	Radiator Area (ft^2)
Direct contact	3	0	7
Fluid-loop	13	60	7
Heat pipe	10	0	12

For the above systems an active control ratio of only 2 to 1 on the overall resistance would suffice to maintain the battery within a 30 to $100^{\circ}F$ temperature envelope. The fluid-loop can provide this and greater ratios with little or no increase in weight by throttling or bypassing the flow. Either of the other two systems would probably have to rely on louvered radiators for active control. Inward-facing louvered systems which can operate under direct solar radiation currently weigh about 1 lb/ft^2 and consequently would add to the weights of the direct contact and heat pipe systems shown above. For these reasons, a fluid-loop cooling system was selected for this study. Data requirements for this system were correlated, subject to the following directions:

- Based upon normal battery and electronic black box operating internal temperatures, characterize a liquid loop cooling system capable of satisfying the requirements.
- Provide curves, data tables, or algebraic functions from which the weight of that portion of the thermal control subsystem associated with the power subsystem may be estimated.
- Provide curves, data tables, or algebraic functions from which the heat dissipating baseplate weight may be estimated for both electronic boxes and batteries, as a function of the heat dissipation.
- Where adequate data are unavailable, provide engineering estimates of such data identifying them as such.
- Indicate the source and validity of the data and the range over which they may be expected to remain valid.

Preliminary thermal control data is discussed in Section 2. 6. 3.

2. 4. 4 Reliability Data and Functions

The power requirements for the space station (Section 2. 1. 3) indicate the following levels of operation:

Maximum power - 50 kwe

Nominal power - 25 kwe

Emergency power - 9 kwe

These relative values hold throughout the power system. Hence, at any point within the system, the following relationships hold:

$$\frac{\text{Maximum power}}{\text{Nominal power}} = 2.0$$

$$\frac{\text{Emergency power}}{\text{Nominal power}} = 0.36$$

2.4.4.1 Component Reliability Analysis

The philosophy used in the design of the power system is that any of the components listed in Section 2. 4. 1 (with the exception of logic elements) are required to carry the maximum power requirement at their particular location in the system. Since any component is made up of a number of equivalent units installed in parallel, the design load for any one unit is:

$$P_U = P_{max}/N_I \tag{1}$$

where

P_U = unit design requirement ~ watts

P_{max} = component maximum power requirement ~ watts

N_I = number of parallel installed units per component

Turning the situation around, at any given point in the system, the number of units required to reach the various operational power levels is given by:

$$(N_R)_{MAX} = N_I \tag{2}$$

$$(N_R)_{NOM} \geq (N_I/2.0) \qquad N_R = \text{number of required units} \tag{3}$$

$$(N_R)_{EMR} \geq (0.36/2.0)\, N_I \tag{4}$$

The above functions are graphically illustrated in Figure 2-3. The number of units at the nominal emergency power levels are step functions since only integral units are allowable.

Assuming that failure of a unit results in the equivalent of the unit being removed from the circuit, the reliability of a component at any of the power levels is given by the binomial distribution (Reference 6). Thus:

$$R_C\begin{pmatrix} N_I \\ N_R \end{pmatrix} = \sum_{k=N_R}^{N_I} \left[\frac{N_I!}{(N_I - k)!\, k!}\right] R_U^{\,k} (1 - R_U)^{(N_I - k)} \tag{5}$$

where

$R_C\begin{pmatrix} N_I \\ N_R \end{pmatrix}$ = probability of having N_R operational units out of N_I installed units

R_U = individual unit reliability

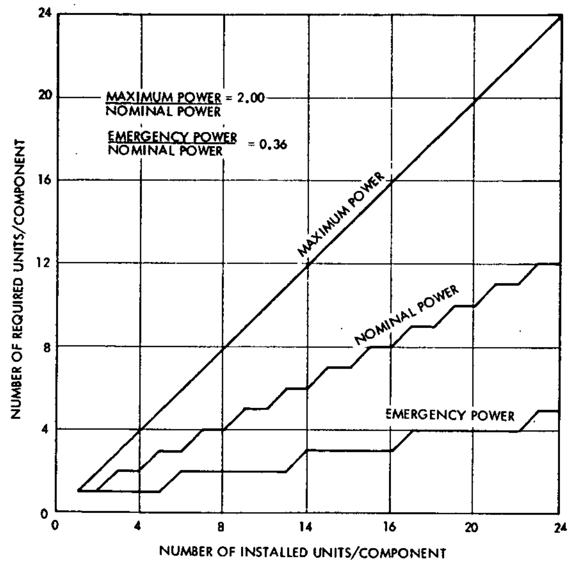

Figure 2-3. Number of Units Needed to Meet Power Level Requirements

Unit reliability (for random failure) as a function of time is:

$$R_U = e^{-\lambda_u T_{RSE}} \tag{6}$$

where

λ_u = unit failure rate ~ failures/hour

T_{RSE} = equipment resupply interval ~ hours

Assuming the same unit reliability for all power levels, component reliability as a function of installed units is shown in Figure 2-4. Component reliability for both the normal and emergency power levels are "sawtooth" functions, again reflecting the integral nature of the allowable number of units.

Battery reliability analysis on the other hand, is based upon the following assumptions:

1) Battery failures are of two different kinds:

- Wearout failures, in which the capacity of the battery falls slowly in spite of reconditioning until the interval between reconditioning steps becomes unacceptably small, and the battery must be replaced. No catastrophic failure has occurred.
- Random failures.

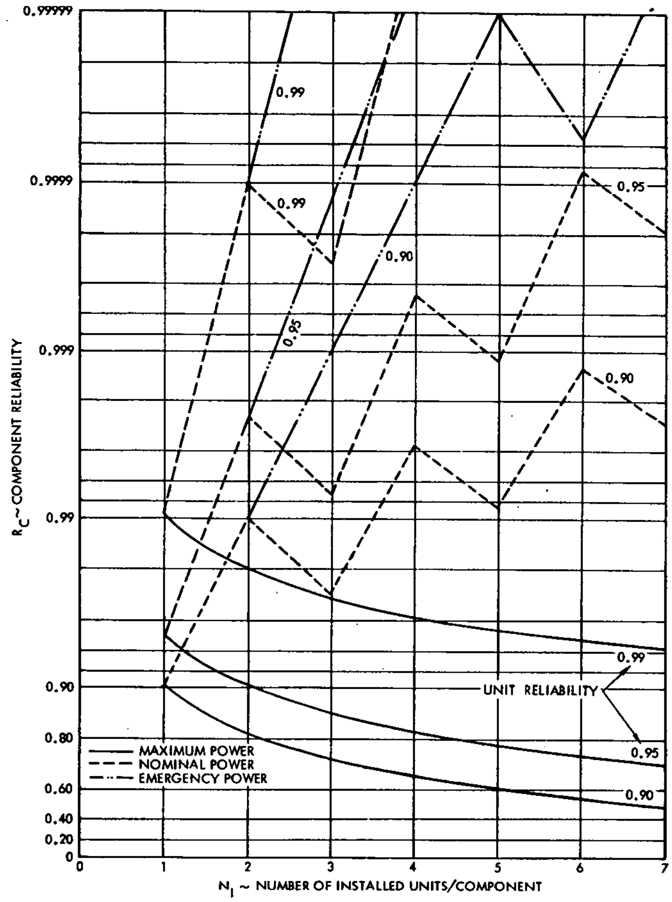

Figure 2-4. Component Reliability

2) The consequence of a wearout failure is replacement of the entire battery or complete set of batteries.

3) The consequence of a random failure occurring early in the life of the battery is replacement of the individual failed cell; such replacement occurring in time to prevent propagation of the failure to other cells of the battery.

4) During the replacement time interval, the battery is out of service.

5) The power subsystem contains a number of batteries, each of which is independently controlled in charge and capable of being independently disconnected from the power line.

6) The power subsystem contains at least one more battery than is required for delivery of full power. This battery is considered to be in reconditioning while the remainder are carrying the load and is unavailable for power delivery.

An analysis was conducted on the reliability of batteries, assuming that the distribution of cell failures was represented by a two-parameter Weibull model. The "A" parameter was derived from the zero depth of discharge intercept of the cycle-life vs depth of discharge curve. The beta or "B" parameter derivation was studied at considerable length.

In an initial attempt, the "B" parameter was derived from failure data selected from the NAD Crane reports on battery testing. The resulting values of B varied significantly from one another, and gave a B parameter averaging approximately 1.3, indicating a relatively high failure rate between random and gaussian distribution. This led to relatively high cell replacement rates.

Because of the difficulties encountered in using these data, a further attempt was made to refine the battery cell data as follows:

It was assumed that the cells had a failure characteristic similar to that of Figure 2-5, a linear relationship between log of cycle life and depth of discharge. It was further assumed that the cause of this kind of failure characteristic is a loss of capacity of the cell until it reaches a value equal to or less than the minimum allowable capacity of the cell (that capacity which will just meet normal load requirements).

The assumptions lead to the characteristic of Figure 2-6, in which the natural variation in capacity from cell to cell results in some cells failing earlier than others. This distribution curve of capacity moves to the left in time as the cells are cycled, until some part of the curve intersects the minimum allowable capacity line.

A brief study of data provided by NASA on pre- and post-cycling of nickel-cadmium cells led to the conclusion that there was no significant difference in the distribution of capacities about the mean (see Table 2-5), although there was a significant reduction in the mean capacity level after cycling. This conclusion permitted the use of capacity variation data on new cells, providing validity to the assumption that it would remain essentially unchanged with extended cycling.

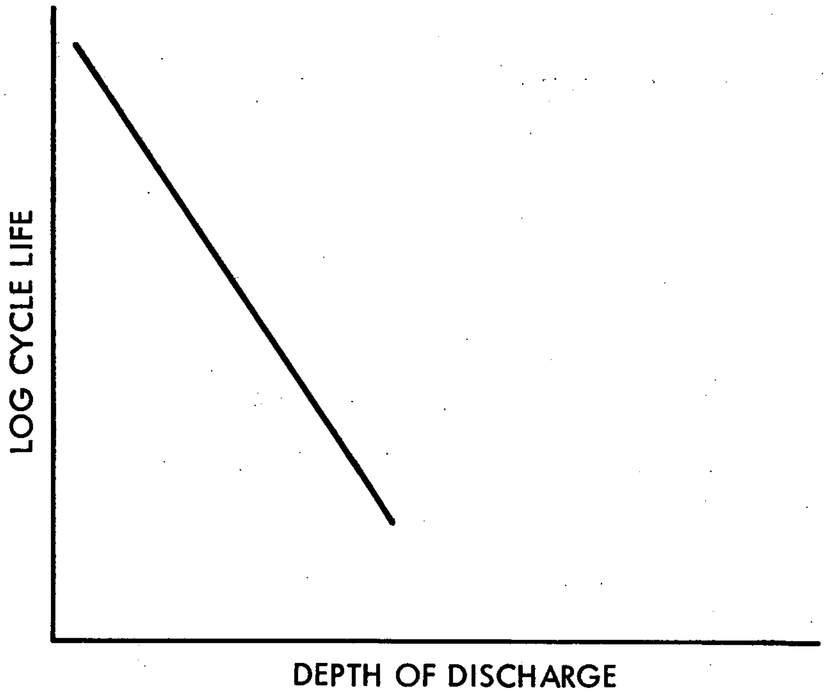

Figure 2-5. Log of Cycle Life versus Depth of Discharge

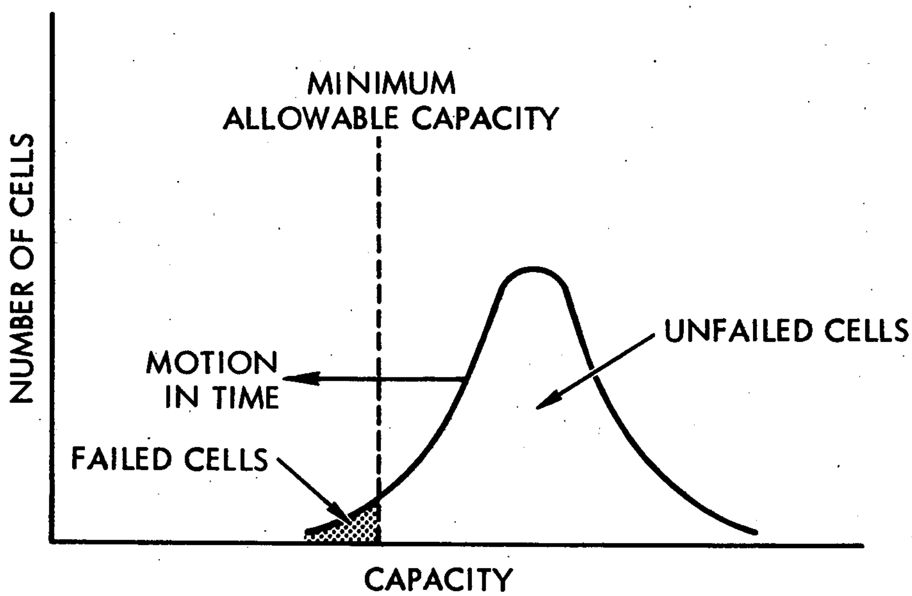

Figure 2-6. Variation in Capacity versus Number of Cells

Table 2-5. Variance Comparisons (Minutes of Discharge)

	Volt Level	Pre	Post	F-Ratio
36D	1.0	3.74	12.61	0.0878*
	0.5	6.4	13.94	0.2108
	0.0	7.2	16.30	0.1953
58D	1.0	9.4	10.2	0.8348
	0.5	11.5	11.1	1.075
	0.0	11.3	11.2	1.016

*Significant difference with 90% confidence

When this assumption was made, and the data from capacity measurements on new cells in the 50 ampere-hour and 100 ampere-hour capacity range used, a weibull "B" parameter between 2.5 and 6 resulted, and a compromise value of 3.5 was used in all subsequent calculations.

In spite of the larger value of the "B" parameter, the resulting calculations of the number of spare cells still leads to the conclusion that during the 3.33 year period of life of any one of the battery complements, the number of spare or replacement cells required is approximately 70 to 90% of the basic cell complement of the original battery in order to achieve the power availability figures reported.

This is not consistent with the relatively reliable performance of nickel-cadmium cells hitherto experienced in spacecraft.

The model of battery availability is described in appendix E.

2.4.5 Cost Data

A method for determining power system cost has been developed, based on summation of the labor and material costs for each component of the system. The method contains the following assumptions:

- That during any specific phase of the program, both recurring and nonrecurring labor have an equal and constant proportionality factor with power
- That management labor is a constant proportion of engineering labor

- That all material costs are recurrent
- That with a varying program duration, the relative schedule of each phase of the program (and consequently the sustaining engineering labor rates) remains constant with respect to the other phases. For example, it assumes that if the electrical design phase occurs over 30 percent of a 3-year program, it will also occupy 30 percent of a 5-year program.

Cost data for use in the calculation are divided into two two-dimensional matrices: one for labor and one for materials. (Table 2-6).

Table 2-6. Cost Data Matrix Vectors

Vector	Definition
I	Design phase
J	Cost data per function

The "J" dimension of the labor array is arranged as follows:

1) Power multiplier
2) Nonrecurring labor (hours)
3) Recurring labor (with each piece of deliverable hardware) (hours)
4) Sustaining labor (hours/year of effort)
5) Management

While the "J" dimension of the materials array is arranged as:

1) Materials whose costs are not a function of power level ($)
2) Materials whose costs are a linear function of power level ($ watt)
3) Other direct costs

Additional data required for the cost estimates include:

- Attrition factors (a vector having a J dimension)
- Phase (an array from 0 to 1 with I and J dimensions expressing the proportion of the total program duration from the Ith to the (I + 1th) phase for the Jth equipment item

- Rate 1 (labor rates as a function of time for general engineering)
- Rate 2 (labor rates as a function of time for management)
- Rate 3 (overhead rates as a function of time)
- Rate 4 (G and A rates as a function of time)

Table 2-7. I^{th} Vector, Design Phase List

Location	Design Phase
1	Design
2	Fabrication
3	Test
4	Launch Support

Costs of electronic equipment, such as converters, regulators, and controls were estimated on the basis of a base price per function, regardless of the nature of the function. This appears to be a reasonable estimating method, since the lower power functions have fewer parts, but more expensive ones. Spot tests against equipment of known cost have shown a reasonable correspondence.

Battery cost data are the results of estimates made by TRW, and are based upon extensive cell acceptance testing.

Solar array costs are not reported.

2.5 SUBYSTEM CONFIGURATION DEVELOPMENT

2.5.1 System Configuration Analysis and Selection

A number of system configurations were studied in an attempt to develop a rationale for selection of six configurations of interest. These are expressed in the form of a matrix, showing combinations of bus voltage (or solar array) control and battery charge-discharge power processing, and encompass both ac and dc systems.

Many of these configuration candidates may be eliminated as general classes, for example:

Dissipative linear regulators, both shunt and series, were eliminated on the grounds that heat dissipation is excessive in at least one significant operating mode of the system.

Switching series regulators in the main power bus were eliminated as a class, due primarily to the power loss.

Figure 2-7 shows the various types of configurations considered and some of the reasons for eliminating them from consideration for further effort. In many cases, the listed reasons may not in themselves provide sufficient justification for elimination of the configuration. In these cases, the configuration possesses the listed disadvantage and no specific advantages.

In the final analysis, it is not possible to justify selection between similar and closely related configurations, other than by detailed analysis beyond the capabilities of a preliminary screening operation of this kind. In this case, elimination of one and selection of the other is arbitrary, but the resulting conclusions regarding weight, reliability, and cost will not be significantly affected.

2.5.2 Subsystem Configuration and Description

2.5.2.1 Configuration 1

This is a typical power system design (Figure 2-8) similar to that used by TRW on a large number of spacecraft programs.

Bus voltage is limited but not regulated by the partial shunt regulator, which may be of the dissipative- or sequential-type. Battery control is independent of the bus voltage control and is accomplished by decreasing

ARRAY CONTROL → / BATTERY POWER PROCESSOR ↓	NO CONTROL	ACTIVE PARTIAL SHUNT VOLTAGE LIMITER	SEQUENTIAL PARTIAL SHUNT VOLTAGE LIMITER	ZENER DIODE SHUNT VOLTAGE LIMITER	SERIES SWITCHING LINE REGULATOR (BUCK, BOOST, BUCK-BOOST)	SERIES INVERTER	MAXIMUM POWER TRACKER	SERIES DISSIPATIVE LINE REGULATOR
DISCHARGE BOOSTER (REGULATOR)	WIDE VOLTAGE VARIATION		(INCOMPATIBLE)					
DISSIPATIVE CHARGER	EXCESSIVE HEAT		EXCESSIVE HEAT					
DISSIPATIVE CHARGER AND DISCHARGE BOOSTER	EXCESSIVE HEAT		EXCESSIVE HEAT					
CHARGE AND DISCHARGE CONVERTERS (UNREGULATED)	SELECTED (CONFIGURATION 2)		NOT COMPATIBLE	EXCESSIVE HEAT	EXCESSIVE POWER LOSSES		EXCESSIVE POWER LOSSES	EXCESSIVE HEAT
MODIFIED MESAC	NOT CONSISTENT (UNREGULATED).		SELECTED (CONFIGURATION 3)					
SEPARATE LOW VOLTAGE ARRAYS FOR BATTERY CHARGE	EXCESSIVE VOLTAGE RANGE	EXCESSIVE HEAT	SELECTED (CONFIGURATION 4)					
INVERTER BATTERY CHARGE SUPPLY + LOW-V TRF'S	EXCESSIVE VOLTAGE RANGE		SELECTED (CONFIGURATION 5)					
NO POWER PROCESSING	EXCESSIVE VOLTAGE VARIATION		SELECTED (CONFIGURATION 1)					
TRF CHARGER UNREGULATED INVERTER DISCHARGER			X			UNREGULATED AC		
TRF CHARGER + REGULATED INVERTER DISCHARGER			X			UNREGULATED UNLESS V LIMIT USED		
MODIFIED AC MESAC	NOT COMPATIBLE		X			SELECTED (CONFIGURATION 6)		
			X					

Figure 2-7. Combinations of Power Conditioning Equipment

the battery current to a constant trickle charge value in response to a signal from the state-of-charge sensor, which is assumed to be an auxiliary electrode.

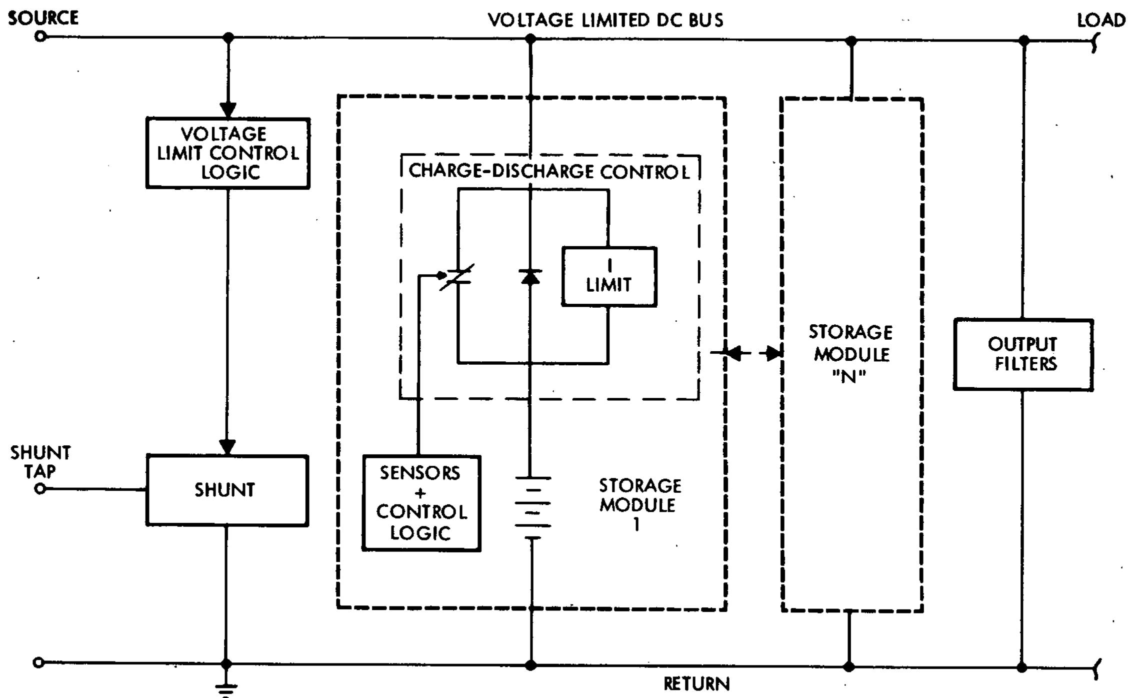

Figure 2-8. Configuration 1

When the available source power exceeds load power plus charge power, the bus assumes the regulated voltage determined by the shunt voltage limiter.

When the batteries are charging, the bus voltage is determined by the battery charging voltage.

When the batteries are discharging, the bus voltage is determined by the battery discharge voltage.

Bus regulation is approximately ±12 percent.

Advantages

High efficiency
Simplicity
Minimum design risk

Disadvantages

This configuration is less attractive than other high bus voltage systems, because of the limitation in the number of series-connected cells which may conveniently be used in a battery without compromising the adequacy of charge control.

2.5.2.2 Configuration 2

In this configuration (Figure 2-9) bus voltage is unregulated. When the main dc bus is being supplied by the batteries, the voltage is also unregulated. It reflects the battery discharge voltage adjusted by a fixed ratio applied by the uplink converters.

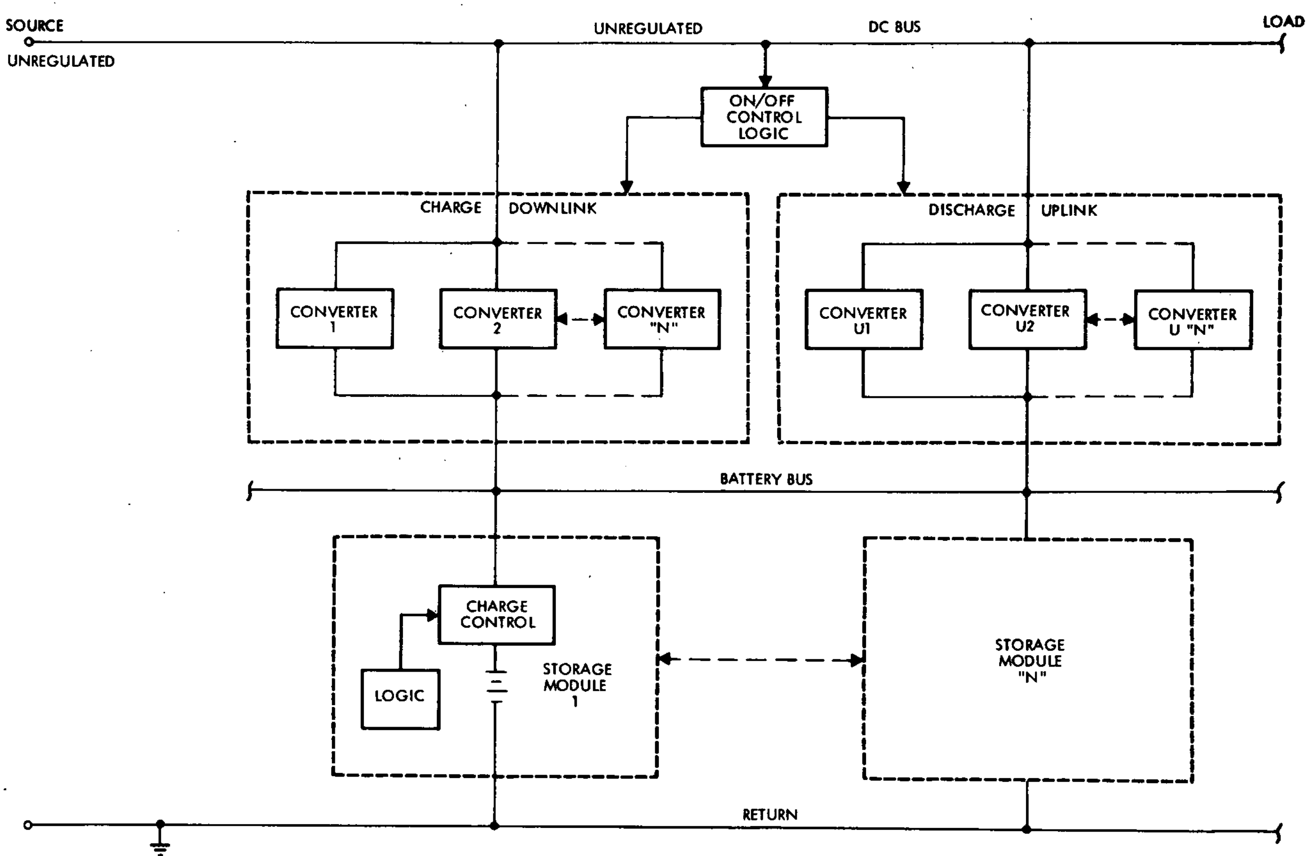

Figure 2-9. Configuration 2

The downlink battery charge converters are regulated. This allows comparatively low voltage batteries to be used with a high voltage bus.

Advantages

High efficiency of power transfer from solar array to matched load

Compatibility of low voltage batteries with a high voltage bus

Disadvantages

Main bus voltage range reflects battery charge and discharge characteristics and may be wide for deep discharge.

Lowered efficiency of stored energy utilization

2.5.2.3 Configuration 3

This is a modified MESAC configuration (Figure 2-10). Its function is identical to that of the configuration developed in the MESAC program, except that both the up and down conversion links are cross-strapped in parallel, providing charge and discharge paths between the regulated dc load bus and the unregulated battery bus. A sequential shunt is used to minimize heat.

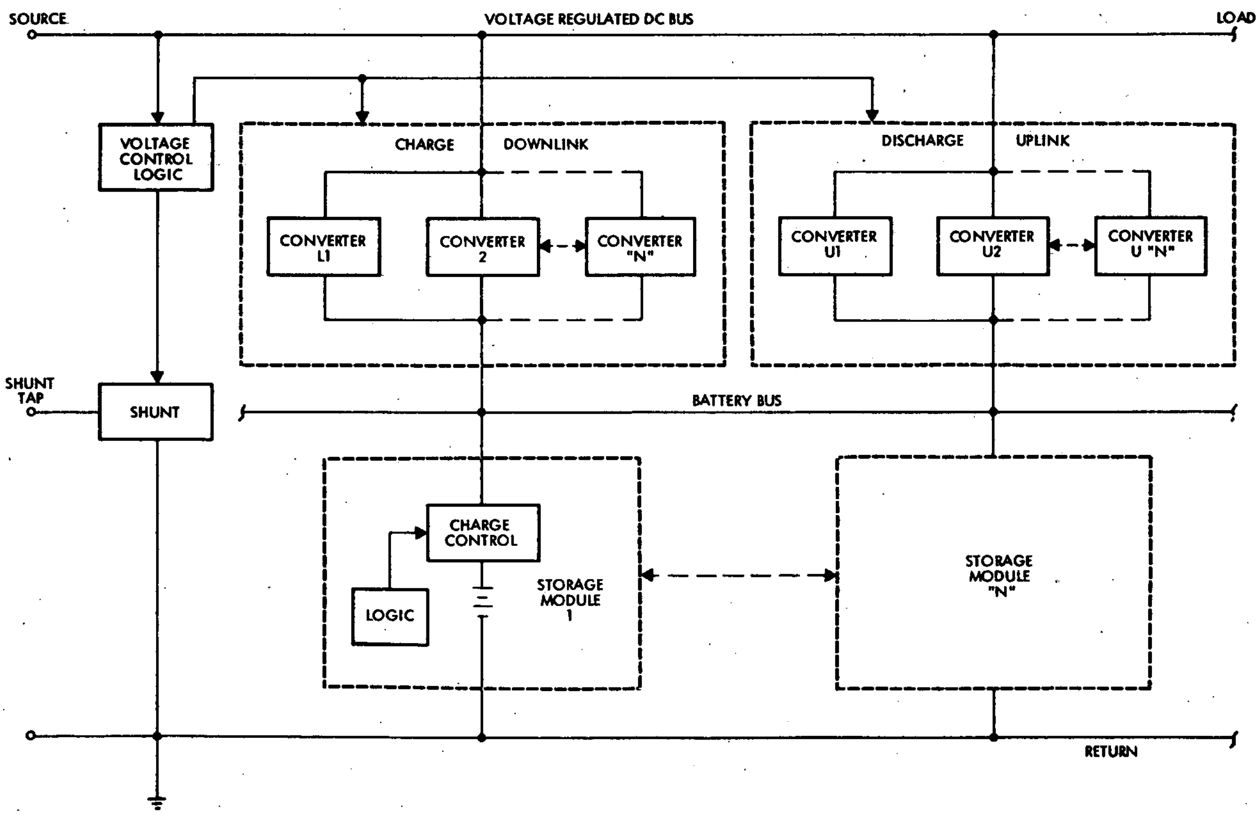

Figure 2-10. Configuration 3

Battery charge control is entirely independent of the up and down conversion operations and is associated with the individual batteries. The advantage of this approach over the MESAC approach is to provide additional flexibility in optimization of the system with essentially no penalties.

Charge control is similar to that of configuration 1, involving insertion of a current limiter into the battery bus - battery line when the auxiliary electrode signals charge completion.

Advantages

High efficiency of source utilization

Regulated dc with no loss limits in the direct source-load line

Good utilization of excess energy at the beginning of life, if desired

Compatibility of low voltage battery with high voltage line

Minimum heat dissipation

Disadvantages

Decreased efficiency of stored energy utilization because of the loss elements in the charge and discharge lines

Relative complexity of control circuitry, difficulty of diagnosis, and detection of component failure.

2.5.2.4 Configuration 4

This configuration (Figure 2-11) utilizes high voltage batteries which are discharged in series and charged in parallel by means of separate sections of solar array.

The entire power system is divided into several parallel modules, each module containing as many independent solar array charging sections as there are battery modules in series. Thus, if each battery consists of five series connected blocks of 20 series-connected cells, the bus voltage will be approximately 125 volts, each battery contributing 25 volts (on discharge) and each of the five solar array sections operating at approximately 30 volts. The individual 20-cell battery submodules are decoupled from one another on charge by series-connected diodes.

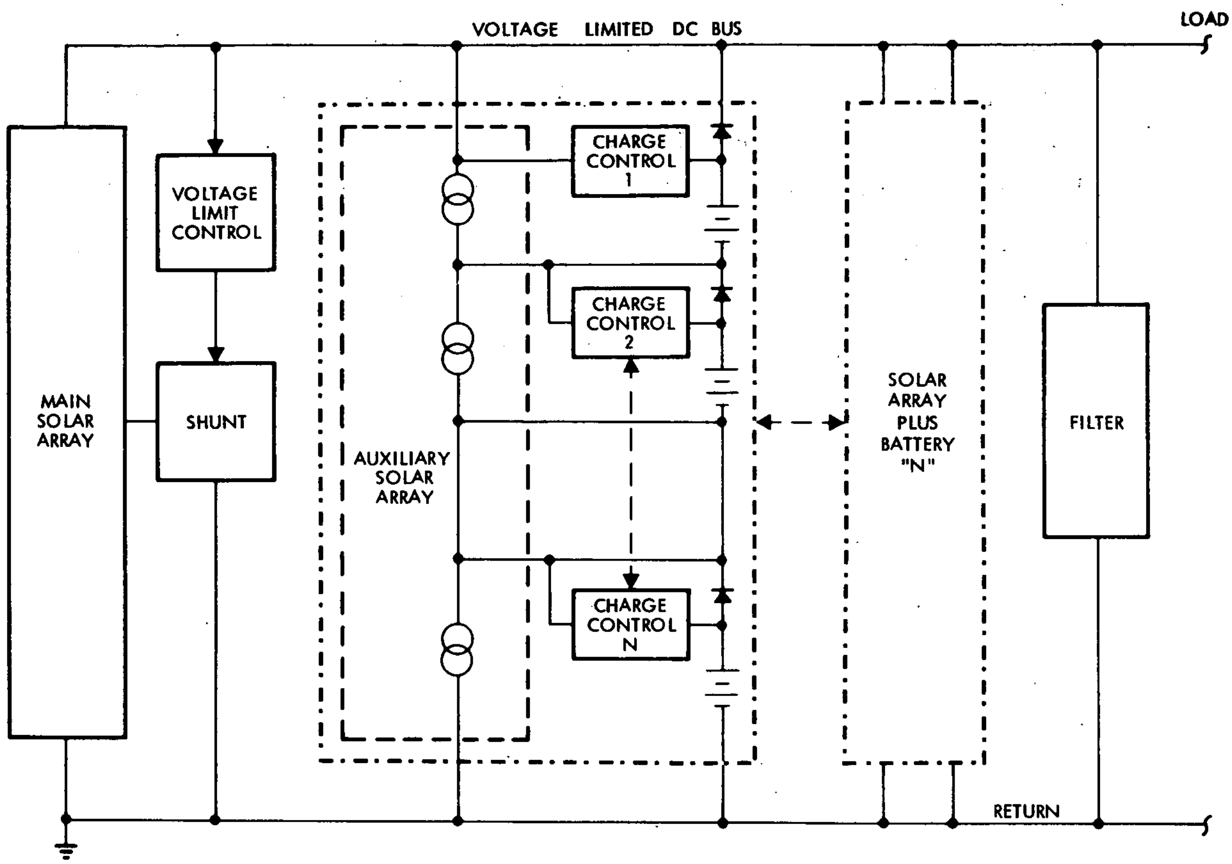

Figure 2-11. Configuration 4

The main load bus is limited but not regulated in voltage by a shunt limiter, either of the sequential- or dissipative-type.

Each 20-cell battery section is charged independently through its allocated charging section; the charge current being limited only by the solar array section current capability. Charge is terminated by introduction of a current limiter into the charging line in response to a state-of-charge signal from an auziliary electrode.

Energy management in this system is relatively automatic without the use of complex controls. When the battery is discharging, the power from the charging sections of the solar array becomes immediately available at the main bus (except for trickle charge power).

If any one of the batteries has not completed its charge, none of the power from the battery charging sections of the solar array is available at the main bus until the bus voltage has fallen to the level equivalent to the reversible potential of the battery; at which point charging stops and the total charge power becomes available at the bus.

Advantages

Permits operation of high voltage batteries without the corollary problems of charging high voltage batteries

Relatively simple electronics

Relatively high efficiency of energy utilization from source to load

Disadvantages

Significant increase in complexity of solar array design, harness design, and slip ring design

Modest loss in efficiency for stored energy due to diode losses

Decrease or loss of charging power of the charging section of the solar array associated with any one of the battery submodules (20-cell sections) will result in a comparable decrease or loss of capability of the entire battery loaded in the submodule.

2.5.2.5 Configuration 5

This is a second configuration (Figure 2-12) which utilizes high voltage batteries charged in parallel and discharged in series. However, it uses electronic means to accomplish this rather than complicating the configuration of the solar array.

The load bus is limited but not regulated by a shunt limiter, either of the sequential- or dissipative-type. The high voltage battery is divided into several series-connected sections, each of which is charged by a transformer-rectifier unit driven by a central inverter which is powered from the main dc bus.

Each battery section is controlled by a switching charge controller which inserts a current limiter into the charging line in response to a signal from an auxiliary electrode.

No special electronics is required to induce load sharing between batteries and loads during the charging process, since the unregulated inverter output is opposed by the battery charge voltage through the TR unit. However, in the event of a battery failure of the type which might lower the battery section charge voltage, a current limiter is required to prevent the deffective battery section from overloading the entire charging system.

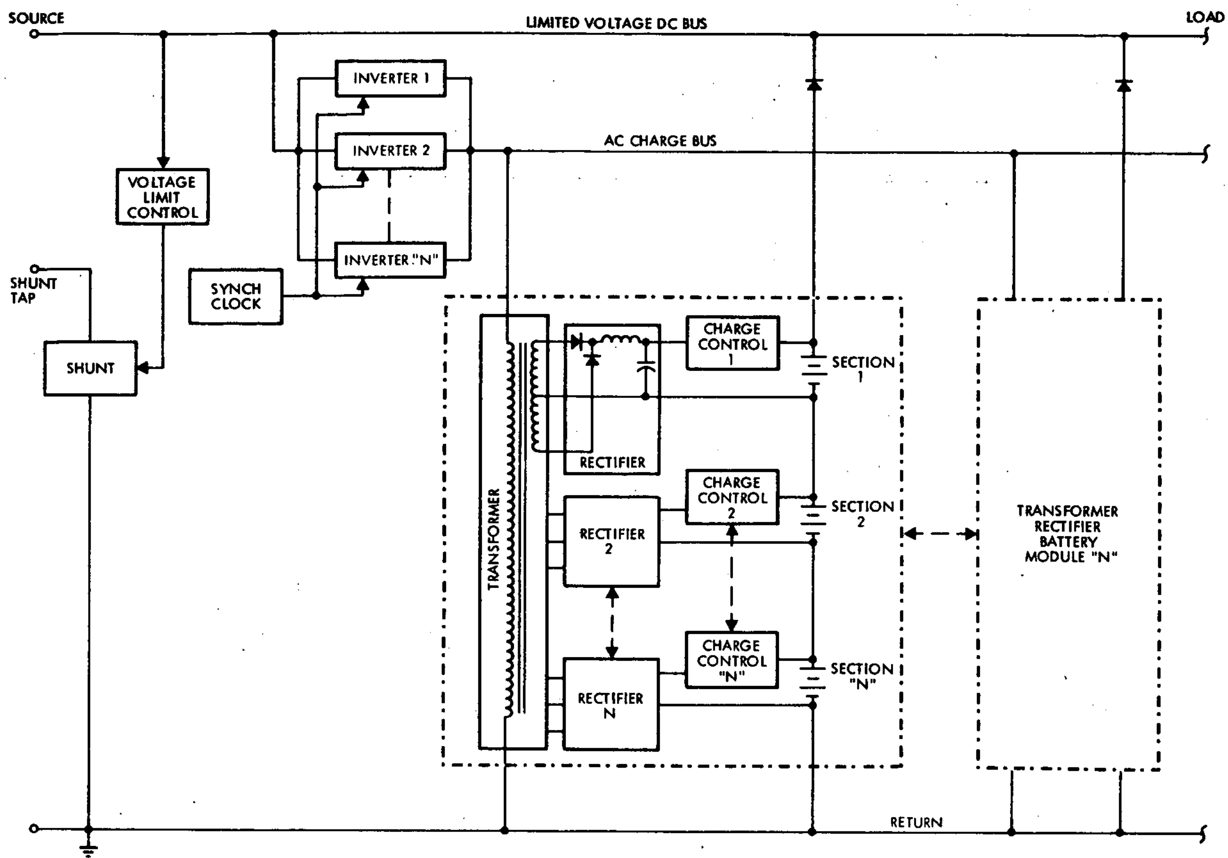

Figure 2-12. Configuration 5

Advantages

High efficiency of power transfer between the solar array and loads at all times

Permits discharge operation of high voltage batteries without the attendant difficulties in controlling charge of high voltage batteries

Relatively simple electronics

Relatively simple design of solar array and cabling, including slip rings

Disadvantages

Significant loss in efficiency of utilization of stored energy

Necessity for distribution of both ac and dc within the electrical power system

20

2.5.2.6 Configuration 6

This is the only ac distribution configuration considered (Figure 2-13). It is an alternating current version of the MESAC configuration and is expected to have an efficiency approximately equivalent to that of the dc MESAC system. As in Configuration 3, the down transformation and up inversion are disassociated from any particular battery to provide additional flexibility in optimization.

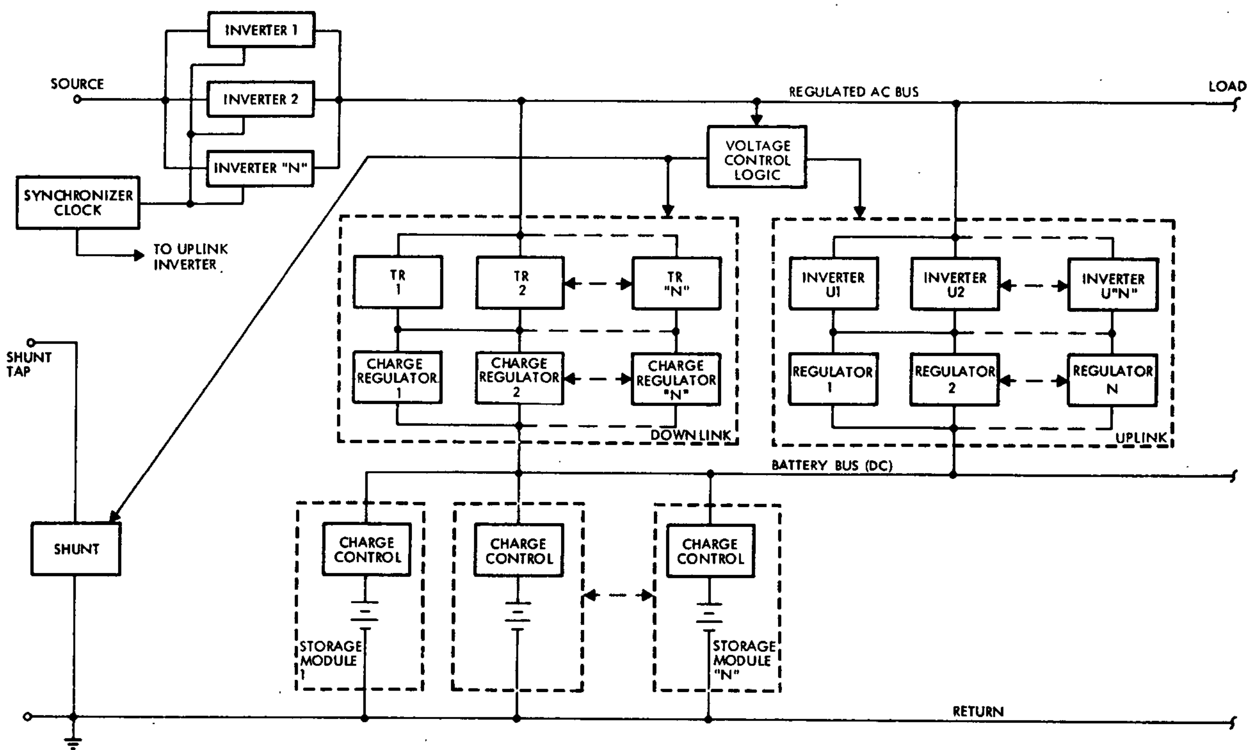

Figure 2-13. Configuration 6

The ac distribution bus voltage is controlled during periods when the solar array output exceeds the load requirements by adjustment of the shunt loads on the system. Thwn the batteries are charging, and the solar array power is equal to or less than the load power plus charge power, a signal from the central voltage control logic unit adjusts the impedance of the charge regulators such that the ac bus voltage is held constant.

Should the solar array power increase further or the demand lessen, the shunt voltage limiter is added to the shunt load, again maintaining the bus voltage constant. Should the load exceed the solar array power requirement, the charge regulators and shunts are turned off and the regulated inverter supplies ac to the main bus. System voltage is controlled by the multiple-function logic section identical in basic function to the MESAC logic.

Advantages

Delivers, regulated, conditioned, isolated power at assorted voltages to each load with only a single unmodulated conditioning step between solar array and loads. Minimum postregulation is required. This leads to high efficiency of power transfer between source and load.

Disadvantages

Decreased efficiency of source utilization because of the loss elements in the charge and discharge lines

Relative complexity of the control circuitry, difficulty of diagnosis, and detection of component failure.

2.6 DATA DEVELOPMENT

2.6.1 Battery Data

The battery data are based upon the following assumptions:

1) A 10-year mission life is required and will be achieved by replacement of batteries as frequently as required to maintain the total launched battery weight at a minimum.

2) The batteries are assembled in modules of a limited number of series-connected cells, each module weighing less than 65 pounds, and are formed of several series-connected modules.

Plots of optimum depth of discharge as a function of orbit period (Figure 2-14) and resupply factor as a function of optimum depth of discharge (Figure 2-15), are derived by calculation from an original data plot of cycle life versus depth of discharge. Calculations were performed using a simple computer program described in Appendix C. These cycle life data are in turn derived from a review of OGO life test and orbital operations data and from OAO life test data. They were also correlated with cycle data taken by NAD Crane, Indiana. These data are believed to be relatively conservative, since they do not take into account the possibility of replacement of defective cells and the interaction between failures which causes failure of additional cells when a battery with a defective cell continues to operate. Energy density data for the above calculation was assumed to be 11 watt-hours/lb, that value readily attainable in cells of 9 to 20 ampere-hour capacity. The conclusion of constant optimum depth of discharge of 0.2 does not depend upon this value.

Average discharge voltage (Figure 2-16) and charge voltage plots (Figure 2-17) as a function of depth of discharge were made with current (or rate) as a parameter. These data are based upon information which are stored in battery characteristics simulation computer programs developed for general use at TRW. The data are a compromise estimate resulting from an extensive examination of a variety of data including OGO, OAO, and others.

Average efficiency data (Figure 2-18) are based upon measurements taken on nine ampere-hour cells but which are believed to be representative of a relatively wide range of sizes. In calculation of efficiency the assumption was made that the shape of the efficiency curve is the same regardless of the depth of discharge.

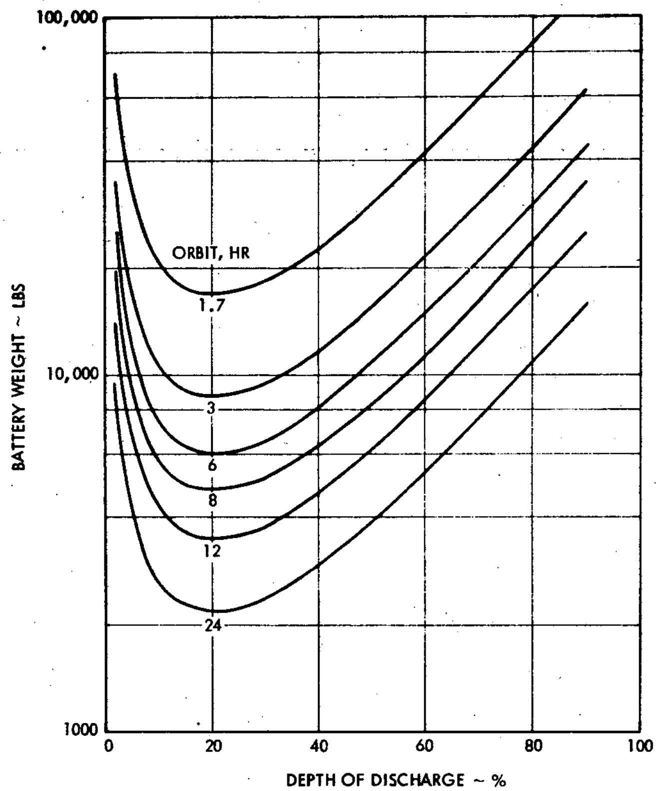

Figure 2-14. Battery Weight Versus Depth of Discharge with Orbital Period as Parameter

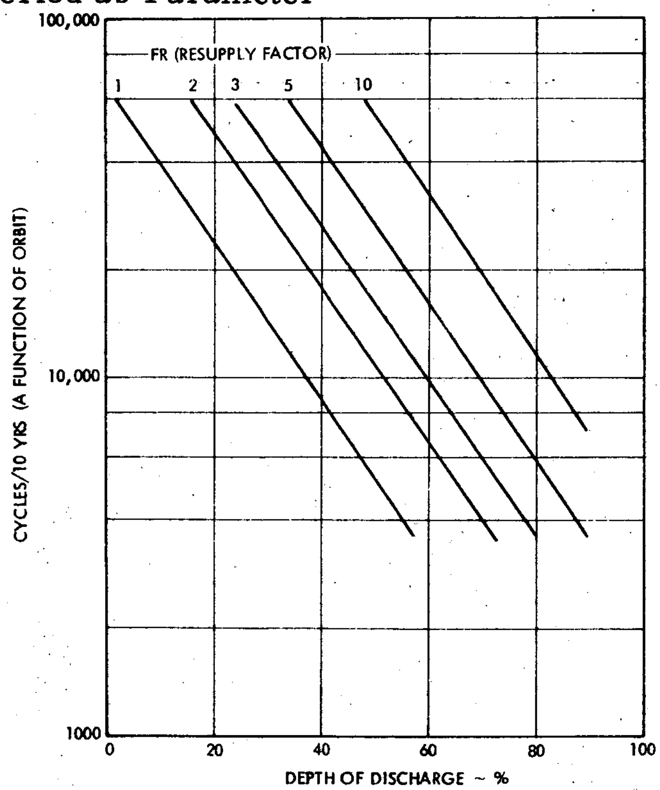

Figure 2-15. Cycles During a 10-Year Mission Versus Depth of Discharge with Resupply Factor as Parameter

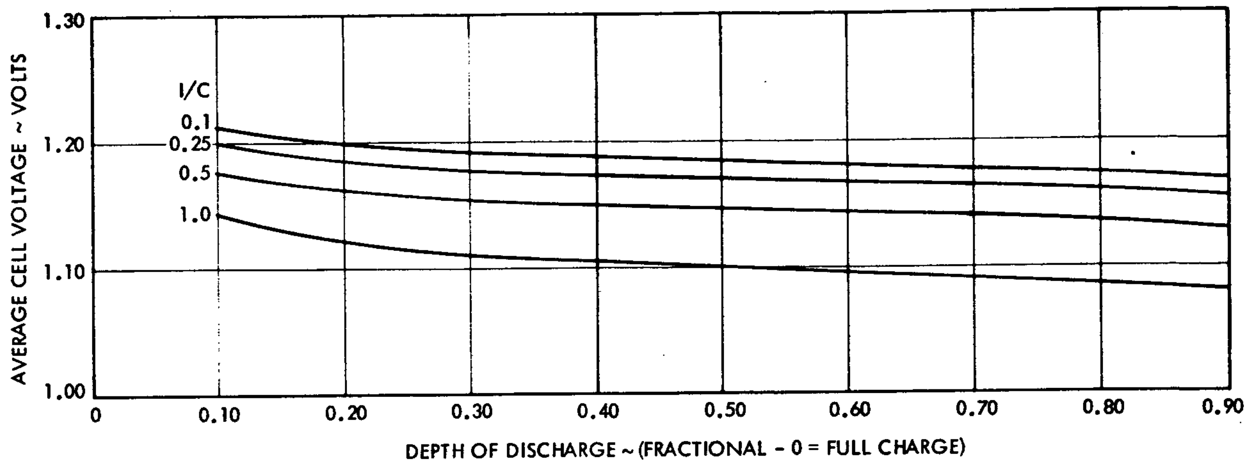

Figure 2-16. Average Cell Voltage on Constant Current Discharge Versus Depth of Discharge; Normalized Current as Parameter, 70°F Ambient~Fresh Cells

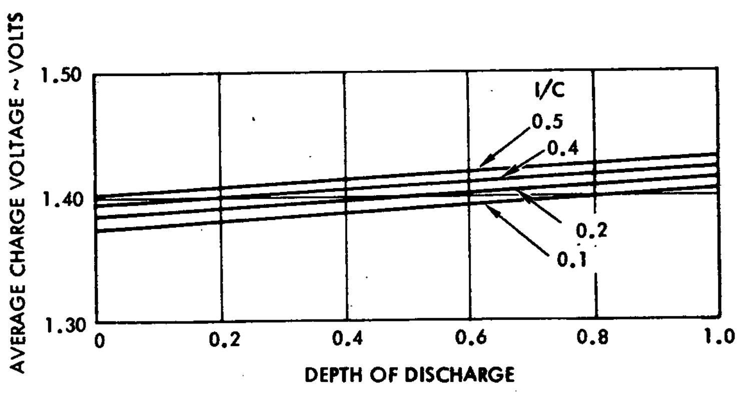

Figure 2-17. **Average Charge Voltage Versus Depth of Discharge, 70°F Constant Current Charge to a 1.46 Volt Limit**

This results in a proportionality in efficiency between partial and full depth of discharge, which results in a family of lines with zero slope. This assumption is, to the best of our knowledge, the best available approximation of actual efficiency performance of the Ni-Cd system.

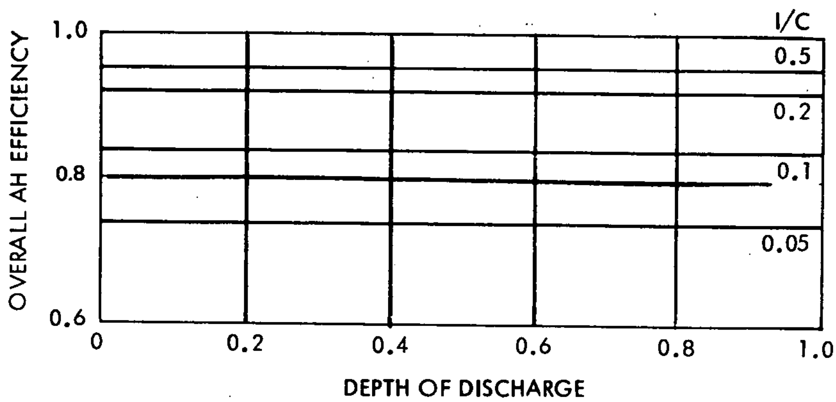

Figure 2-18. Depth of Discharge Versus Overall AH Efficiency with Normalized Charge Rate A Parameter - 70°F Data

Cell weight data (Figure 2-19) are based upon actual measured cell capacities and weights on purchased experimental and flight cells to capacities of 50 ampere-hour. Weights of 100 ampere-hour cells are based upon predicted and measured data obtained from vendors. The cells in question are all of standard prismatic construction and are not representative of more advanced cell types.

Packaging factor data (Figure 2-20) are based upon the results of a computer program designed for detailed design of batteries for Air Force programs, assuming modules of five series-connected cells. It is felt that these data require additional work before they can be considered representative.

All the data are based upon standard prismatic cells, varying from 6 to 20 ampere-hours in capacity. It is expected that all these data are in error by not more than 5 percent except for the cell weight which is believed to be within 1 percent.

2.6.2 Power Control Data

A simplified method for the development of parametric data for selected power conditioners and discussion of the method is given in

Appendix D. Briefly, design information on a series of electronic functions, such as switching, transformation, rectification, etc., has been collected. The functions are merged in a specific order (Appendix D) to obtain various types of power processing and control equipment. This section contains design data for the various electronic functions.

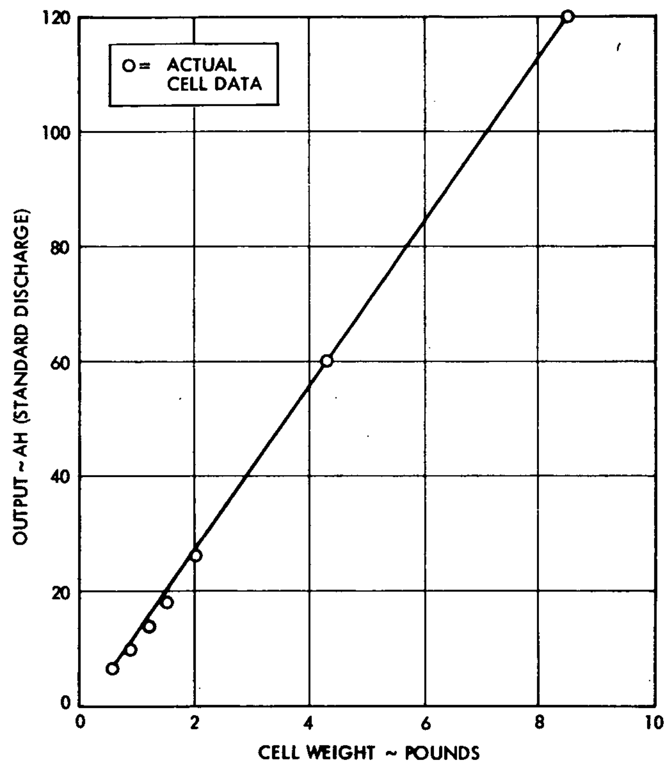

Figure 2-19. Nickel-Cadmium Cell Weight Versus Output

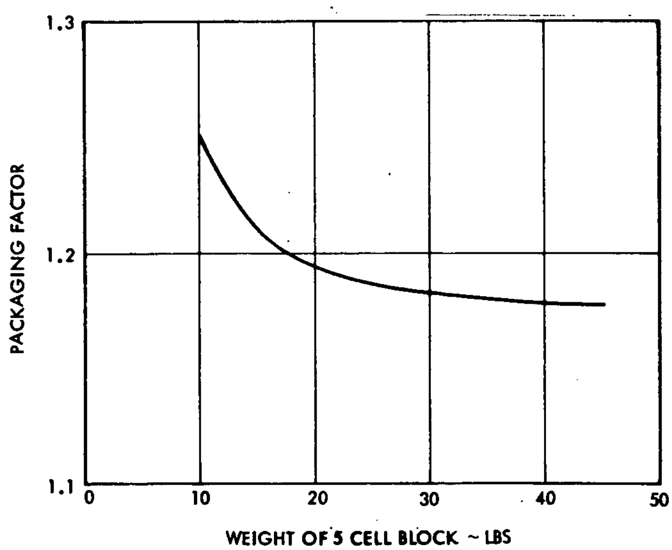

Figure 2-20. **Packaging Factor Versus Cell Block Weight**

Parametric data on losses, weights, and failure rates have been computed for these functions over a voltage range of 30 to 300 volts. The specified power and voltage ranges have been rearranged into a set of discrete function design points that effectively cover the desired ranges. These are:

Output voltage	30, 100, and 300 Vdc
Switching frequency	10 kHz
Power	1 kw , 3 kw, and 10 kw

The parametric data, as developed from the models generated, is illustrated graphically, for most functions by four to six curves. These are:

- Percentage loss versus operating voltage at a fixed power level
- Weight versus operating voltage at a fixed power level
- Failure rate versus operating voltage at a fixed power level
- Scaling constant curves for percentage loss, weight, and failure rate versus output power level at constant voltage and frequency.

The percentage loss, weight, and failure rate are plotted as a function of operating voltages for a selected switching frequency at the 1 kw power level. These three curves of percentage loss, weight, and failure rate are modified as a function of output power level by multiplying the values given by the 1 kw curves by the multiplying factors given by the scaling curves at any power level.

Curves of design data for the various electronic functions are indicated in Table 2-8.

Table 2-8. Electronic Functions

Function	Figure
Passive (dc) filter - LC (no ac requirement)	2-21
Passive (dc) filter - LC (high ac current requirement)	2-21
Passive (dc) filter - LC (high ac voltage requirement)	2-21
Passive (dc) filter - LC (high ac voltage and current requirement)	2-21
Passive (dc) filter - C (no ac requirement)	2-22
Passive (dc) filter - C (high ac current, low frequency)	2-22
Passive (ac) filter - LC (high ac voltage and current)	2-23
Power modulation, switching - PM buck	2-24
Power modulation, switching - PM boost	2-24
Power modulation, switching - PM inversion	2-24
Rectification - PWM square wave	2-25
Rectification - sine wave	2-25
Rectification - square wave	2-25
Transformation	2-26
Inversion - sine wave	2-27
Inversion - square wave	2-27
Power modulation, dissipative - linear series	2-28
Power modulation, dissipative - linear shunt	2-28
Power modulation, dissipative - sequential shunt	2-28
Error amplifier	2-29
Driver circuit - linear series	2-30
Driver circuit - linear shunt	2-30
Driver circuit - sequential shunt	2-30
Driver circuit - switching PWM, buck, and boost	2-30
Driver circuit - switching PWM, inversion	2-30
Driver circuit - inversion SCR, series resonant	2-30
Driver circuit - inversion SCR, square wave	2-30

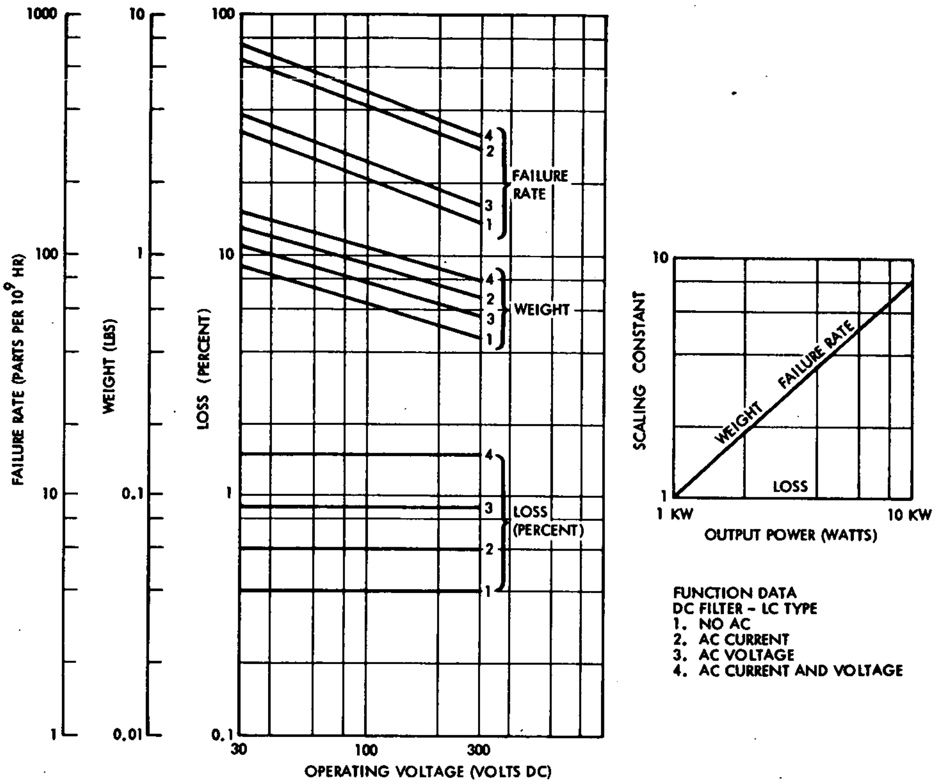

Figure 2-21. Function Data, DC Filter - LC Type

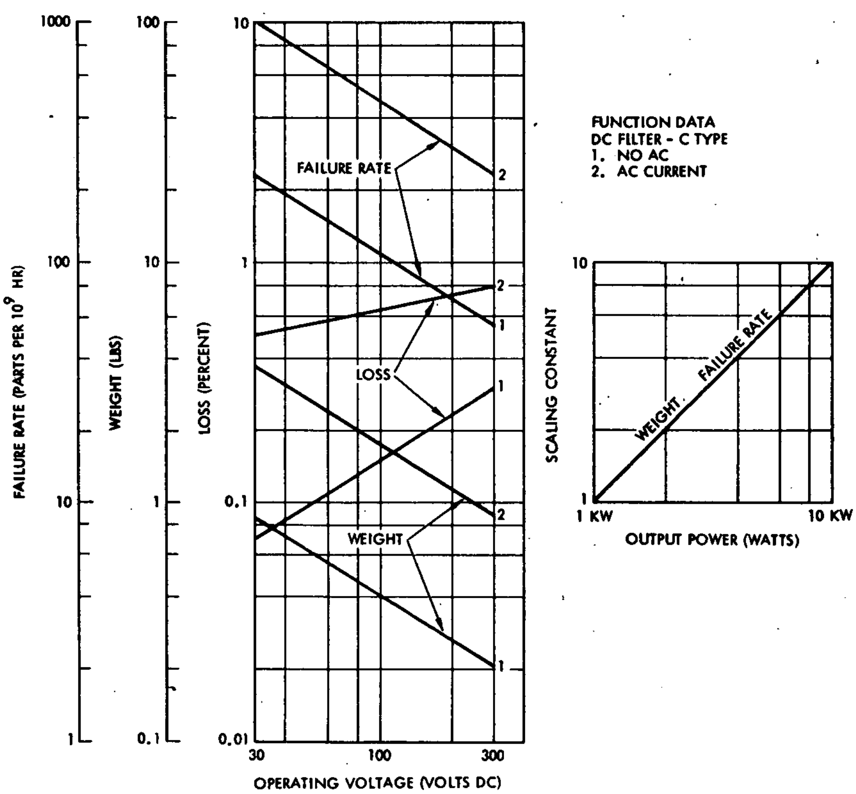

Figure 2-22. Function Data, DC Filter - C Type

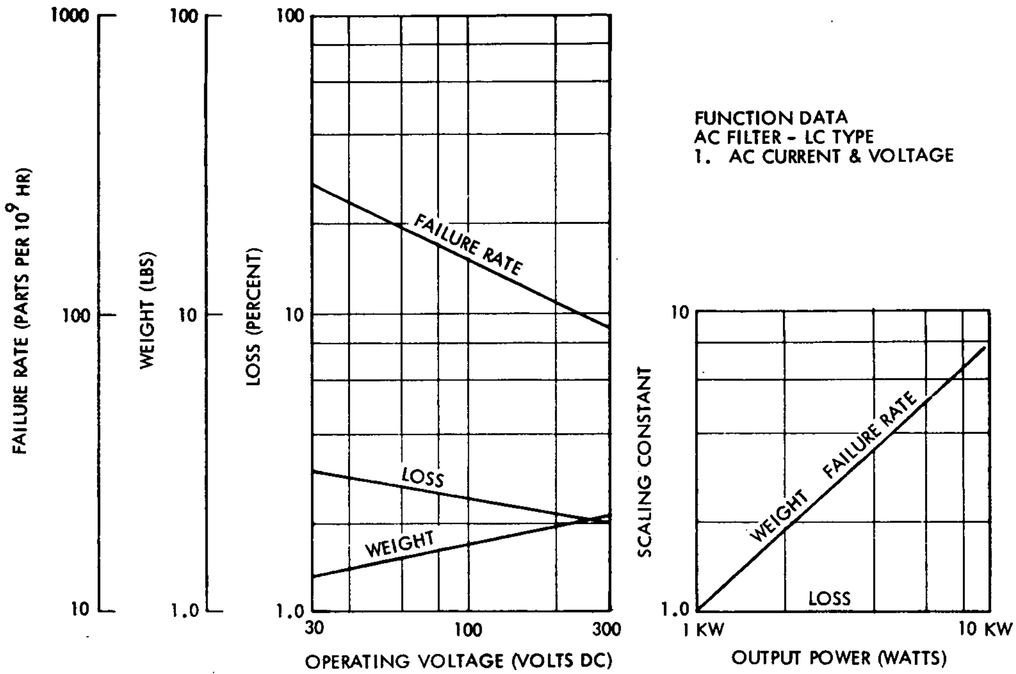

Figure 2-23. Function Data, AC Filter - LC Type

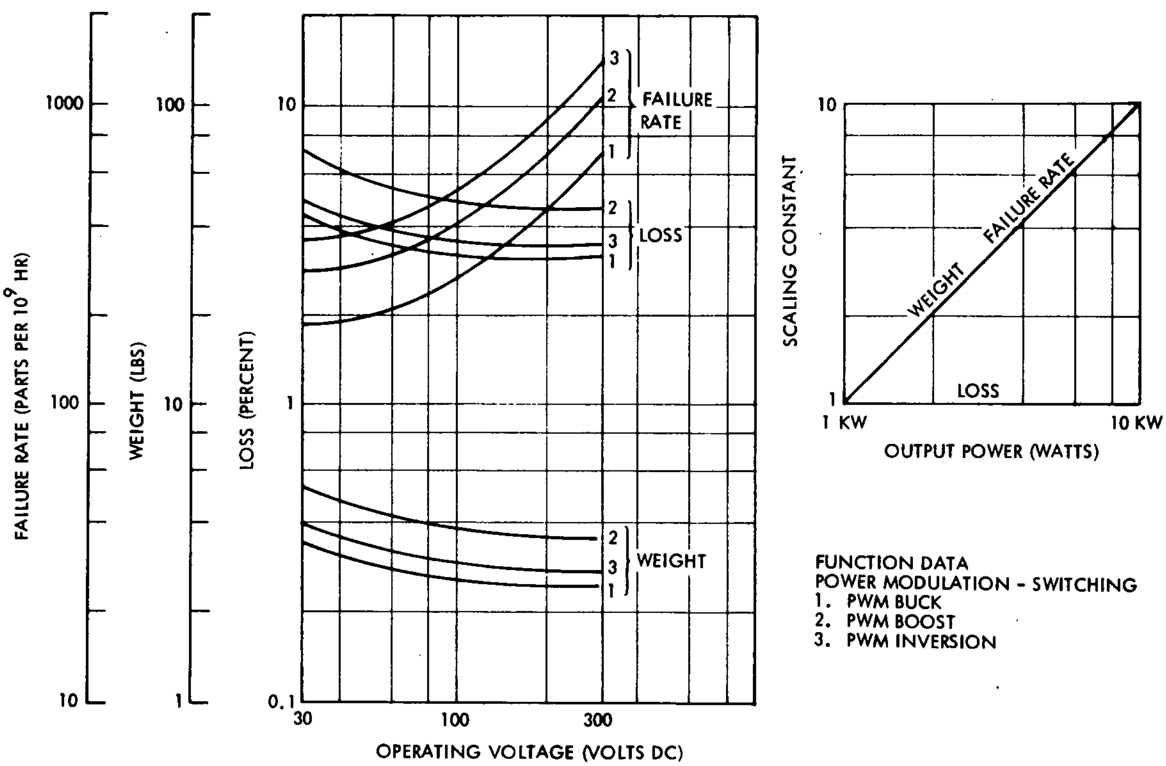

Figure 2-24. Function Data, Power Modulation - Switching

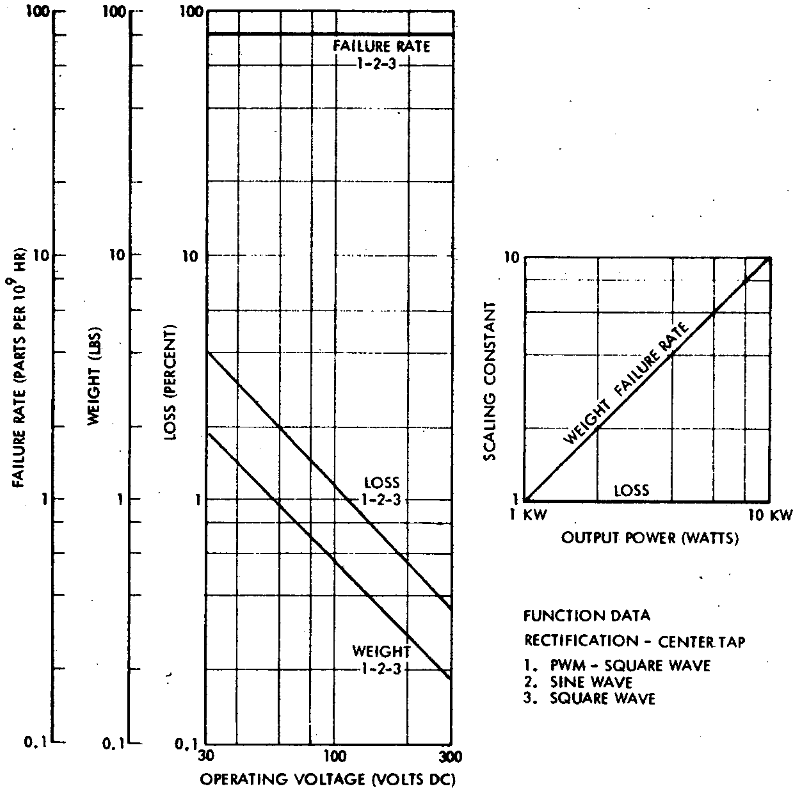

Figure 2-25. Function Data, Rectification - Center Tap

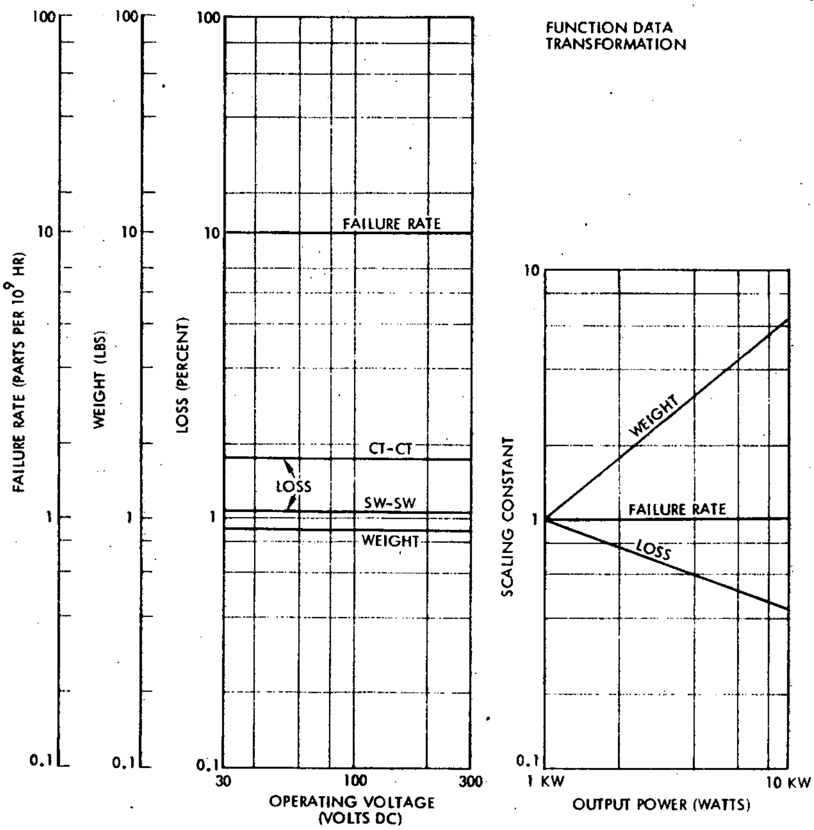

Figure 2-26. Function Data, Transformation

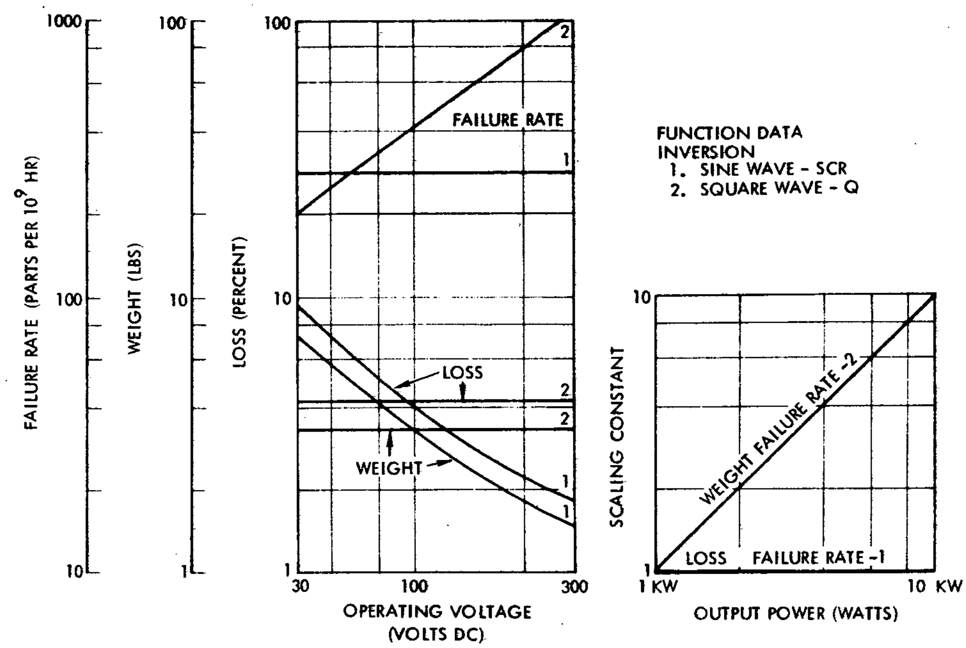

Figure 2-27. Function Data, Inversion

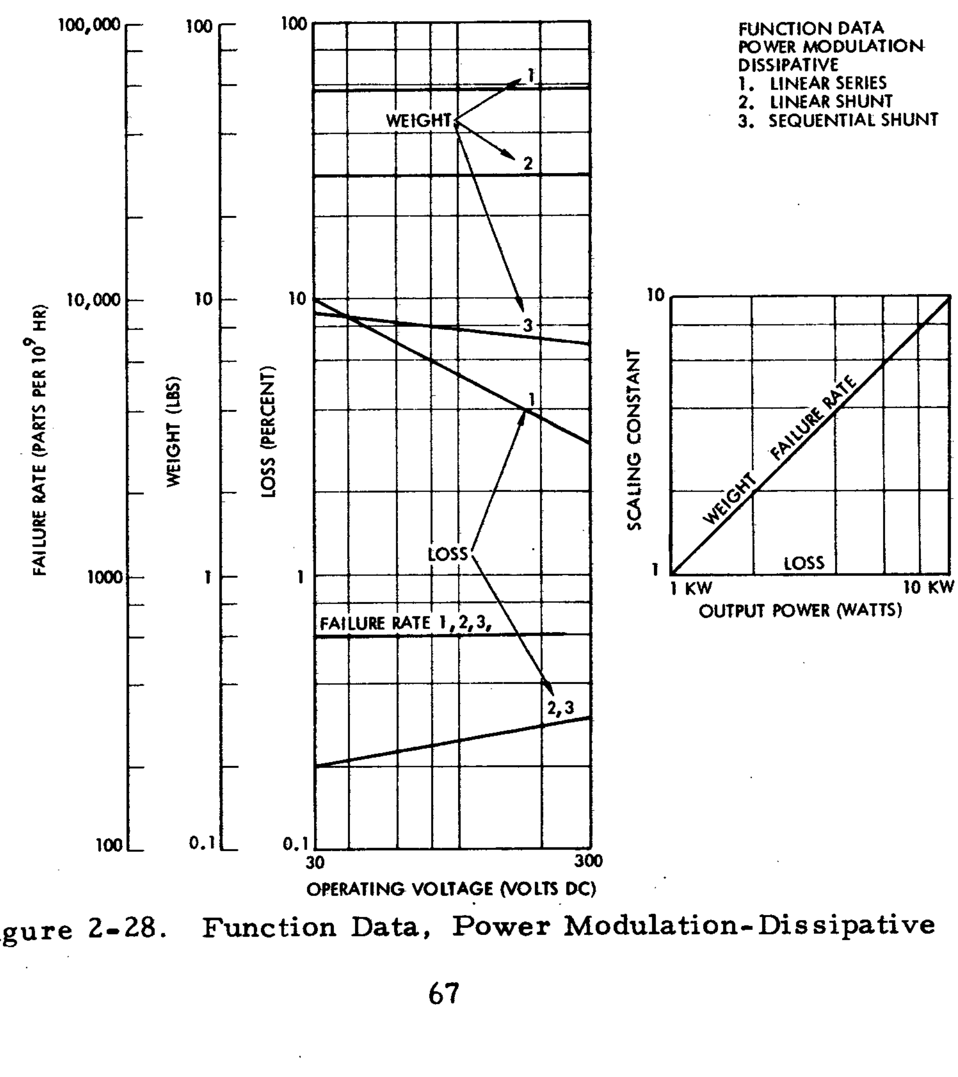

Figure 2-28. Function Data, Power Modulation-Dissipative

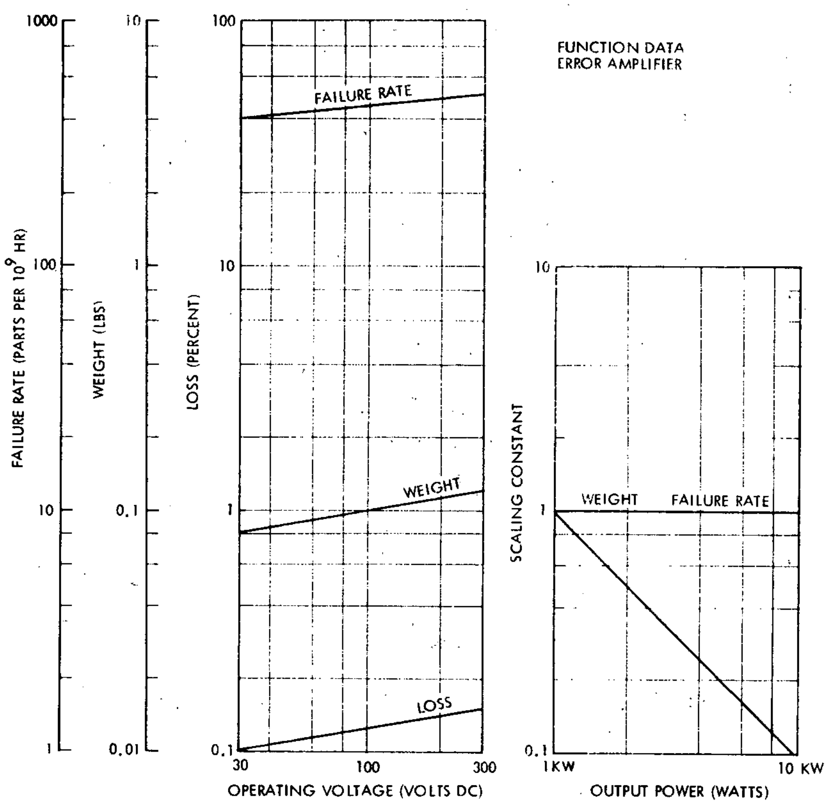

Figure 2-29. Function Data, Error Amplifier.

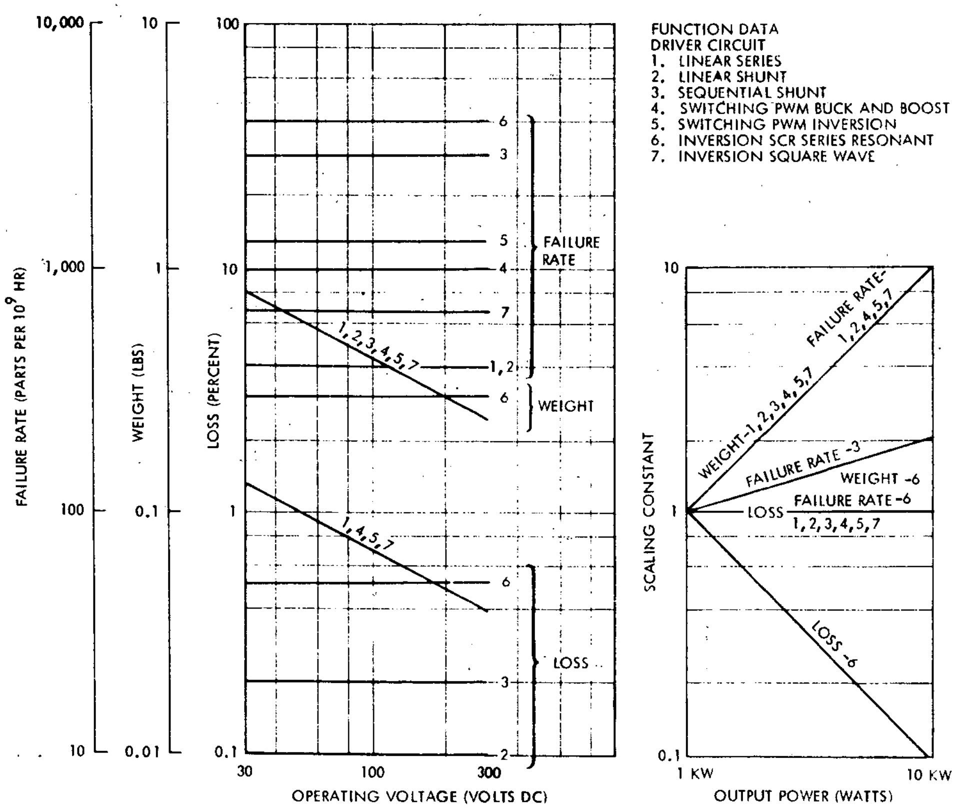

Figure 2-30. Function Data, Driver Circuit

The packaging weight factor curve is shown in Figure 2-31. The packaged weight factor changes as a function of output power. The weight of all the functions of the power conditioner are summed and are then multiplied by the package weight factor to determine the actual unit weight.

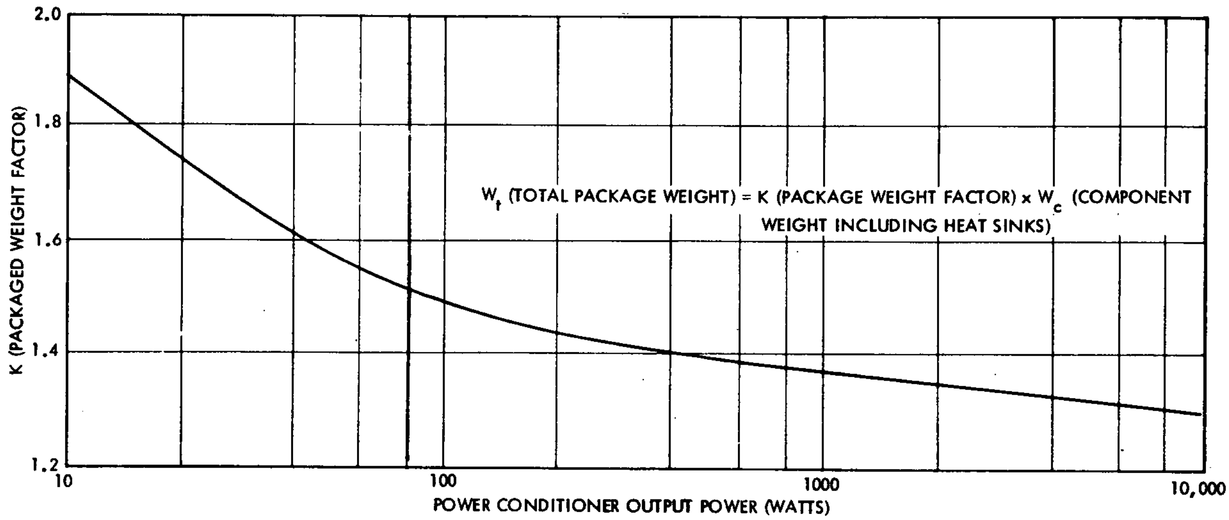

Figure 2-31. Packaging Weight Factor Curve

2.6.3 Thermal Control Data

Generalized weight estimate equations were formulated for a fluid-loop type thermal control subsystem to be used with a 20 kw nickel-cadmium battery. The following simplified equations for estimating the weights of thermal control components were developed.

Component	Approximate Weight (lbs)
Radiator (if facing the sun)	$W_{rad} \approx 0.10\ Q_{rad}$
Radiator (if facing cold space)	$W_{rad} \approx 0.04\ Q_{rad}$
Pump/motor unit	$W_p \approx 0.00362\ Q_{rad}$
Battery baseplate*	$W_p \approx 1.69\ KW_{elec}$
Vertical intercell fins*	$W_f \approx 8.65\ KW_{elec}$
Black box heat sink brackets	$W_h \approx 0.008\ L\ Q_{rad}{}^{3/2}$
Black box baseplate	$W_{bb} \approx 0.022\ Q_{BB}$

*Based on an existing 2 kw battery design.

Q_{rad} = the rate of heat radiation from the radiator in watts

Q_{BB} = the rate of heat dissipation from a given black box in watts

KW_{elec} = battery electrical capacity in kilowatt hours

L = the length of the heat transfer path from a black body heat source to the black box baseplate in inches

2.6.4 Reliability Data

The latest generic part failure rates for spacecraft applications and failure mode percentage distributions for these components are shown in Tables 2-9 and 2-10(Ref. 7). These data are based primarily on an accumulation of orbital part operating hours and failure information from Vela, Pioneer, and OGO spacecraft data contained in the TRW Systems Group orbital reliability data bank. Where such data were not available (primarily on low usage part types), failure rates are based upon industry sources such as FARADA (Ref. 8), military handbooks and specifications, manufacturers' test data, and industry surveys.

The nominal environment for which these data apply is $30^{\circ}C$ ambient temperature and operation at 25 percent of the critical rated stress. Other environmental factors, such as vibration and shock peculiar to launch conditions, induce a higher failure rate. To account for this, the listed failure rates should be multiplied by appropriate application factors. For example, a factor of 10 may be used for the time period to which components are exposed to a launch environment.

These part failure rates have been used in determining the failure rates of the electronic functions discussed in a prior section (Section 2.6.2) of this report.

Table 2-9. Generic Part Type Failure Mode Distribution

Part Type	In Orbit		Boost	
	% Short	% Open	% Short	% Open
Capacitors				
Ceramic fixed	50	50	50	50
Paper-plastic, plastic fixed	60	40	60	40
Fixed tantalum (foil)	60	40	60	40
Fixed tantalum (solid)	85	15	70	30
Fixed tantalum (sintered slug)	60	40	60	40
Glass	60	40	60	40
Mica	60	40	60	40
Resistors				
Metal film	--	100	--	100
Carbon	--	100	--	100
Carbon composition	--	100	--	100
Wirewound fixed	10	90	10	90
Variable {composition, wirewound}	25	75	10	90
Inductive Devices				
Coils	20	80	20	80
Transformers (< 0.5 w)	40	60	40	60
(0.5 - 1 w)	50	50	50	50
(10 - 1000 w)	60	40	60	40
Diodes				
Silicon (alloy and diffused)	60	40	60	40
Germanium (alloy and diffused)	60	40	60	40
Zener (silicon)	75	25	75	25
SCR	80	20	80	20
Transistors				
Silicon (≤ - 1 w)	60	40	25	75
(1 - 10 w)	60	40	60	40
(> 10 w)	65	35	65	35
Germanium (≤ 1 w)	70	30	70	30
Integrated Circuits	60	40	40	60

Table 2-10. Generic Part Failure Rates for Spacecraft Applications

Part Type	Failure Rate (Failures/10^9 hrs) at 25 Percent Rated Stress and 30°C Amb. Temp.
Capacitors	
Ceramic	6*
Ceramic, feed-thru filter	10
Glass	3*
MICA	4*
Mylar	20*
Polystyrene	1
Tantalum, solid	9*
Tantalum, foil	20
Variable	40
Connectors	
General	40*
Coaxial	10*
Connector pins (active)	0.1*
Diodes	
Silicon, general purpose	2*
Silicon, power rectifier	44*
Tunnel	100
Varactor	40
Zener	23
4-level device (SCR, etc.)	136*
Inductive Devices	
Inductors (per coil)	10*
Transformers	
(<0.5 w)	14*
(0.5-1 w)	14*
(10-1000 w)	14*
Integrated Circuits	
Analog amplifier	150
RTL	35
DTL	25
TTL	50
MOS	100
Hybrid (Nonmicrowave)	65

Part Type	Failure Rate (Failures/10^9 hrs) at 25 Percent Rated Stress and 30°C Amb. Temp.
Resistors	
Compsition, carbon	2*
Metal film	1*
Wirewound allurate	10
Wirewound power	10
Wirewound variable	50*
Relays	
Magnetic latching	64*
General purpose	106*
Microwave Components	
Diplexer	131
Filters (low pass)	5
Omnimode transducer	3
Hybrid	23
Coupler	13
Variable attenuator	80
Waveguide	1
Waveguide tuning screw	0.5
Ferrite junction	5
Microwave diode	50
Stripline structure	1
Transistors	
Silicon (high power > 10 w)	40*
Silicon (low power <10 w)	10*
Field effect	60
Mechanical Components	
Squib pin puller	300,000/cyc.
Separation nut, explosive	48,000/cyc.
Hold down spring	110
Hold down arm	100
Hold down latch	100
Torsional spring	220
Compression spring	110
Pin puller device	48,000/cyc.
Shear pin	6
Hinge joint	100
Ratchet latch	100
Paddle hinge assembly	662
Boom hinge assembly	600,000/cyc.

Part Type	Failure Rate (Failures/10^9 hrs) at 25 Percent Rated Stress and 30°C Amb. Temp.
Other Components	
Antenna	90
Azimuth motor	200
Bearings	11
Bolometer	620
Compression spring	110
Crystals, quartz	20
Fill	70
Fuse	200
Heater, blanket	14
Heater, strip, flexible	10
Holding latch mechanism	100
Hydraulic damper, viscous	500
Interconnections	
Solar array	1
Soldered	0.5
Welded	0.5
Magnetic amplifier	14
Nozzle, hot gas	166/cyc.
Cold gas	16/cyc.
Pressure transducer	540
Pressure switch	320/hr + 80/cycle
Resolver	100
Slip rings and brushes	860 per brush per slip ring contact
Shuttle or mechanical switch	461
Solar cell	1
Solenoid	347
Squib	300,000/cyc.
Tank (per inch of weld)	0.6
Tanks (propellant)	120
Tank bladder	330
Thermistor	35
Thermostat	70
Thermostat switch	9
TWT (0-5 w)	500
(5-20 w)	2500
(>20 w)	7250

*Based entirely on orbital operating data

2.7 COMPUTER PROGRAM DEVELOPMENT

2.7.1 Computer Program Description

This section contains a description of the computer program which will be used in the subsystem analysis and tradeoff studies of the 20 KWE power system. Schematics of the analysis method at the topmost levels used in the program, are shown in Figures 2-32 and 2-33. The process of analysis is broken down into the levels indicated below:

- Subsystem performance and characteristics
- Element performance and characteristics
- Component performance and characteristics
- Function performance and characteristics
- Auxiliary calculations

The procedural order of subsystem calculations in also shown in these figures. (Note that analysis locations 100-111 in Figure 2-32 match those in Figure 2-33.) Symbols shown in each element represent the weight, cost, and reliability for each of them.

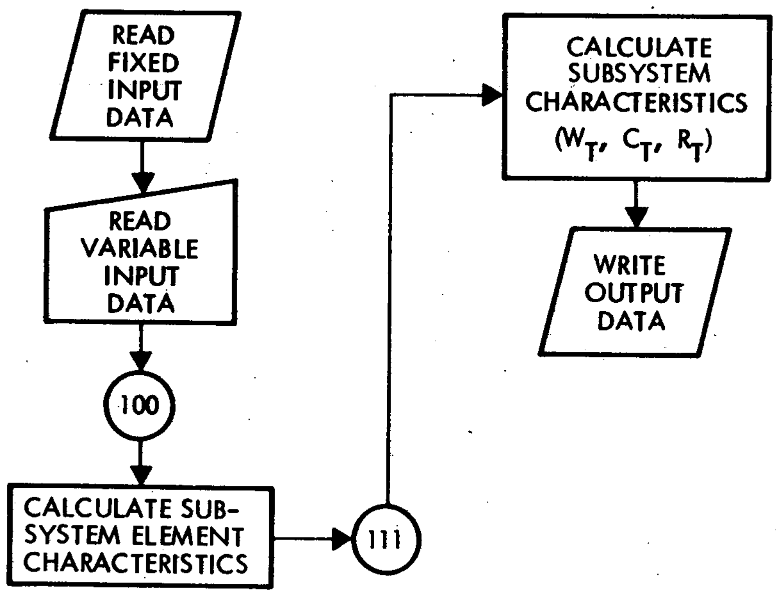

Figure 2-32. Power Subsystem Analysis

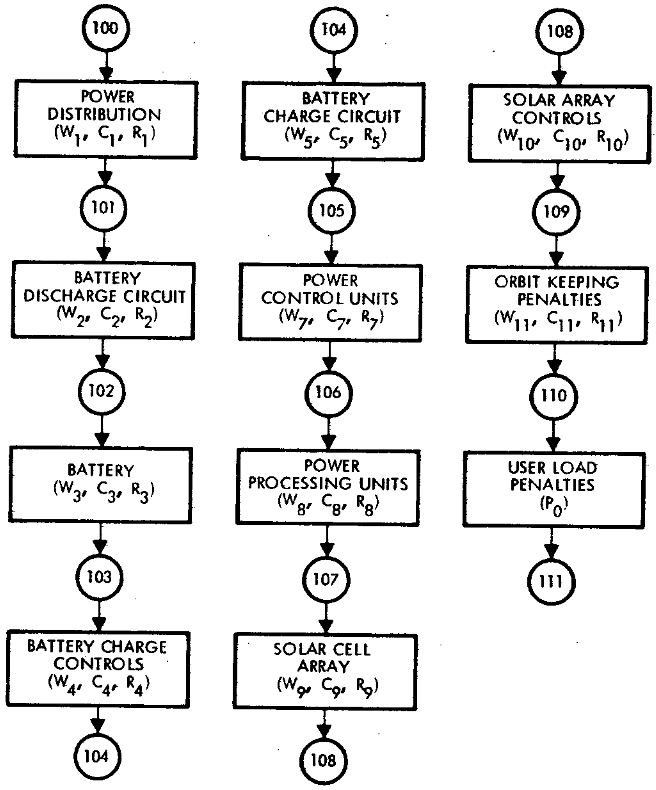

Figure 2-33. Subsystem Element Analysis

2.7.1.1 Program Arrangement

The general arrangement of the computer program is shown in Figure 2-34. The program operational method is discussed below.

Determination of overall subsystem performance is accomplished at the primary level by the main program-termed the master control block. Functions performed by the master control block were shown in Figure 2-32 and include:

- Reading input data into the program
- Calling design routines in correct order
- Summing up element characteristics into overall system performance
- Writing output data onto desired formats

While provision is made for user load penalties, orbit-keeping penalties, and distribution losses, these were considered to be outside the program scope and were not implemented.

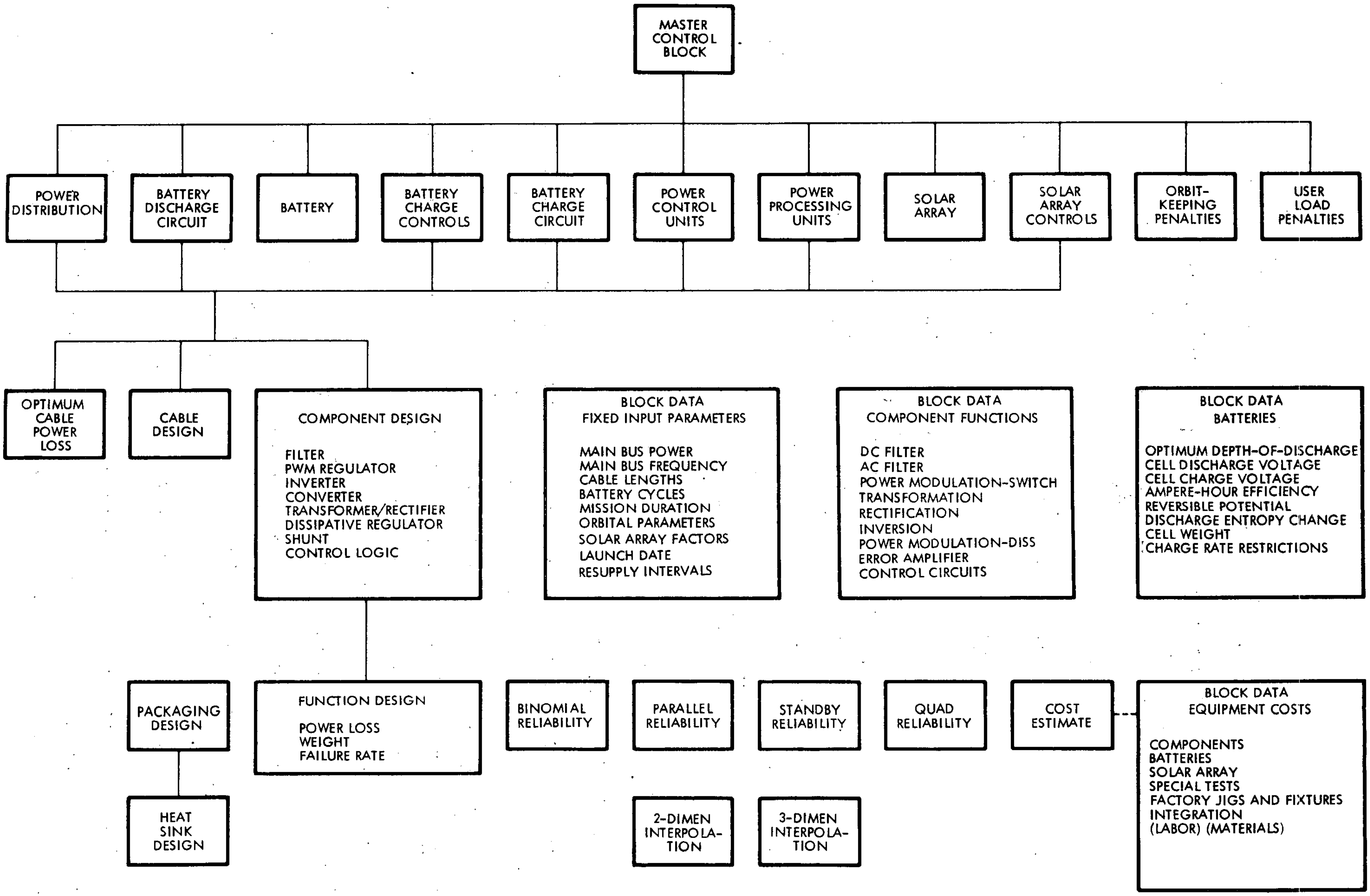

Figure 2-34. 20 KWE Battery Study, Computer Program

Input data are of two types. Fixed input data (information needed by all designs) is maintained permanently in the form of a block data subprogram. Typical fixed data includes:

- Main bus power levels
- Main bus frequency
- Cable lengths
- Total battery cycles
- Mission duration and launch date
- Orbital parameters
- Solar array factors
- Resupply intervals

The rationale behind the selection of values for the fixed input data are discussed in Section 2.7.2.

Variable input data are read in separately for each design case. These data include:

- Power subsystem configuration number
- Main bus voltage
- Battery cell capacity
- Battery voltage ratios
- Component redundancies

Major subsystem characteristics printed out by the master control block include:

- Subsystem weight (W_T)
- Subsystem cost (C_T)
- Subsystem reliability (R_T)
- Effective power level (P_O)

The master control block also prints out these same characteristics for each of the elements of the subsystem.

Element characteristics obtained by the program include (see Figure 2-33)

- Weight (W_i) $(i = 1, 11)$
- Cost (C_i)
- Reliability (R_i)

2.8 PARAMETRIC SENSITIVITY STUDIES

To obtain data useful in assessing the weight, cost, and reliability of the six configurations, the computer program was used to produce parametric data showing the variations of the weight, cost, losses, and reliability of each of the elements of the power subsystem as a function of those variables which have a significant impact upon the results. Depth of discharge of the battery was held constant at 20 percent, based upon the study shown in Appendix C, eclipse length was held constant at 0.6 Hr, and subsystem specific power was held constant at an assumed 1.45 watts/lb. (This last figure is used only in estimation of cabling weight, and any error introduced by an error in the estimate of specific power is small.)

For estimation of weight and cost, plots are shown of the weight, cost, and losses of each power subsystem element as a function of the output voltage of the element at each of three output power levels. A separate correction factor plot is provided for weight, cost, and losses as a function of the number of units into which the subsystem element is divided.

Starting with the battery discharge circuit, and the required bus voltage, and power output, the weight of the battery is determined from the original curve. A multiplier factor is read from the correction factor curve, and the weight is multiplied by this number. Similarly, losses and costs are also determined.

The losses are added to the output power to determine the output power required of the next subsystem element upstream, i.e., the battery. In this fashion, one progresses backward through the power subsystem summing weights and power losses until an estimate is reached for the total power subsystem. A detailed procedure is shown in Appendix F for calculation of the total weight, cost, and reliability for one case.

The resultant subsystem data comparisons shown in the following section were calculated by this process in the computer during the process of developing the parametric data.

The following simplifications were made in all parametric data shown:

a) Where data vary from one configuration to another only as a function of power, these data were combined into a single graph and are shown as being valid for all the related configurations, since they are parametric in power, and can be retrieved by interpolation.

b) Where the impact of a variable such as voltage, number of units, battery voltage ratio, etc., have an impact only in the fourth significant figure in weight, cost, and reliability, such variation is neglected, and the data combined.

c) Reliabilities greater than 0.9999 are not plotted, however, in the combined system data, as shown in Section 1, precision of reliability calculation is at least as good as 0.99999999. (0.9_8). The reason for this limitation was the need to protect one of the subroutines from a mode error which occurred at very high reliabilities. Therefore, it is assumed that any reliability greater than 0.99999999 was equal to 1.0.

d) Mass of the power control unit is not computed or shown in this study due to the wide variety of possible power configurations. A simple power control unit would be negligible in mass relative to the total system mass; the assumption of more complex ones could be misleading.

e) Power consumption of the power control unit is assumed to be 0.2 percent of the total power output of the unit.

f) Mass of the solar array is estimated, however solar array costs are not, nor are solar array reliabilities. Heat loss of the cable connecting the solar array to the main bus is reported.

g) In configuration 6, the 400 Hz inductive reactance was not considered, nor was the effect of non-unity load power factors upon cable losses.

2.9 STUDY LIMITATIONS

The limited scope of this study did not permit the treatment of a number of significant areas of interest, some of which are essential to the design of reliable high power satellite systems. Among these are the following:

- <u>Failure propagation avoidance in modular power systems</u>

  One of the fundamental assumptions in the aforegoing study was the assumption that means would be provided to prevent a failure in any one module of a power system from inducing a failure in another module of the power subsystem serving either the same or a different function. If, for example, several inverters or converters are working at peak load in parallel, and one fails, the load on the remaining devices will increase, possibly to the point of overload, thus failing all of the parallel boxes.

  Similarly, a direct short-circuit in any component or unit of the power subsystem or in any subsystem load could simultaneously overload all parallel devices which supply power to the bus from which it draws power, thus causing a total failure of the system. Means of implementing the protection of parallel boxes were assumed, but were not studied.

- <u>Common-point failure in power systems</u>

  Any automatically controlled modular power subsystem may eventually converge to some single point of vulnerability to failure. Examples of these are a common distribution bus which can short-circuit or open-circuit, a common control system or portions thereof, such as frequency control and voltage control references or a central control computer or data bus. While the modularity of the power subsystem tends to be self-protecting against catastrophic failure of the basic power storage, generation, and processing functions, considerable care must be exercised to assure that the control and distribution functions are either self-protecting against failure, or can be decoupled and the system manually controlled until repair is effected. While these basic concepts were considered, means of implementing such protection were not considered in this study.

- <u>Highly advanced system and equipment concepts</u>

No highly advanced concepts of equipment or subsystem design were considered. Such concepts, including the SCR inversion schemes under development at TRW, and use of very high frequency equipment, etc. were felt to be inapplicable to the study if the premise of a 1975 flight is to be used. In the light of possible delays in the program, however, further study of more advanced concepts may produce useful results.

APPENDIX A

TASK DEFINITIONS

1. CONSTRAINTS DEFINITION

1.1 Mission Constraints

Form a set of preliminary assumptions regarding the range of missions and spacecraft configuration to be studied. Missions and configurations of maximum interest to NASA will be considered. Place a minimum number of constraints upon the study. Orbital altitude will remain variable between 200 nautical miles and synchronous altitude.

1.2 Human Factors Constraints

Form a set of preliminary assumptions regarding the availability of humans for control, maintenance, and repair of the electric power system in space and in the launch area, and regarding the impact of such human availability upon the design criteria for the power system.

2. BATTERY CELL-TYPE SELECTION

Study the major types of batteries for their applicability to long-life orbiting spacecraft in a solar-array-battery power system, and perform a brief tradeoff study leading to the selection of a single battery type for further study.

3. OPTIMIZATION METHOD ANALYSIS

Perform an analysis of the method to be used in optimizing the spacecraft electric power system, battery, and battery controls, and define the parametric data requirements for implementation of the optimization analysis method. This is a prerequisite for the definition of the basic data on batteries, battery controls, and thermal interface controls to be developed as a part of the study.

4. DATA REQUIREMENT DEFINITION

Define the data required on battery, battery controls, and thermal controls necessary for the development of the parametric data on the several power subsystem configurations.

5. SUBSYSTEM CONFIGURATION DEVELOPMENT

Study the various electric power subsystem configuration concepts and select a minimum of six configurations compatible with the mission and spacecraft configuration originally assumed under the constraints definition task. Develop mathematical models of each of the six configurations capable of calculating the relationship between electric power system weight, cost, and reliability as a function of the important subsystem variables including but not limited to system voltage, orbital altitude, battery service and cycle life, cell and electronic component failure rates, and degree of redundnacy used in the various subsystem components.

6. DATA DEVELOPMENT

6.1 Battery Data Development

Develop the battery data whose requirements are defined in task 5, data requirement definition, for both conventional battery structures using prismatic, multiple electrode cells and for pile-structure batteries using bipolar electrode cell modules.

6.2 Power Control Data Development

Develop the data on power controls and thermal controls whose requirements are defined in task 5, data requirements definition. Analyze and discuss the limitations imposed upon such equipment by the available components, point out potentially fruitful areas of component improvement which may result in significant cost and weight savings, or in reliability improvements.

7. ANALYTICAL TOOL DEVELOPMENT

Develop and/or modify existing computer programs to implement the mathematical models defined in task 5, subsystem configuration development.

8. PARAMETRIC SENSITIVITY STUDIES

Using the computer models and the data derived from tasks 6 and 7, perform sensitivity studies on each of the six selected configurations over a range of system variables so defined as to include most probable designs.

9. DATA PREPARATION AND OPTIMIZATION

9.1 Data Preparation and Optimization

Arrange the parametric data for use with the optimization method defined under task 3, optimization method analysis, and perform an optimization study and comparison of subsystems for two missions to be selected and coordinated with NASA.

9.2 Technology Definition

Collect and summarize the results of the technology definition studies conducted under task 6 and provide a set of recommendations for development of improved power system components and circuitry.

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APPENDIX B

OPTIMUM CABLE LOSSES (TWO-WIRE SYSTEM)

A schematic of a power system is shown below in Figure B-1:

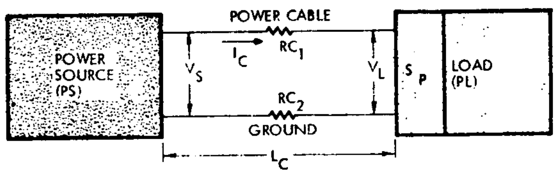

Figure B-1. Power System

To optimize the cable power loss for minimum power system weight, the following information is needed:

- Power source specific weight
- Load power dissipation
- Cable length
- Cable material density and specific resistance
- Load voltage drop or power source voltage

The set of equations below derives an expression for optimum cable loss when the load voltage drop is known. Similar equations can be used when power source voltage is known.

Total power system weight is given by:

$$W_{TP} = W_{PS} + W_{C1} + W_{C2} \tag{1}$$

where

W_{TP} = total power system weight ~ lbs

W_{PS} = power source weight ~ lbs

W_{C1} = power cable weight ~ lbs

W_{C2} = power cable ground weight ~ lbs

Power source weight can be given in the form:

$$W_{PS} = \nu_{PS}\, P_S \tag{2}$$

where

P_S = power source output ~ watts

ν_{PS} = power source specific weight ~ lbs/watt

The weight of the power cable is:

$$W_{C1} = \rho_C L_C A_{CT1} \tag{3}$$

where

ρ_C = cable material density ~ lb/ft^3

L_C = cable length ~ ft

A_{CT1} = total crossectional area of power cable ~ ft^2

While the weight of the power cable ground is:

$$W_{C2} = \rho_C L_C A_{CT2} \tag{4}$$

Combining equations (1) to (4):

$$W_{TP} = \nu_{PS}\, P_S + \rho_C L_C\, (A_{CT1} + A_{CT2}) \tag{5}$$

The resistance of each cable wire is:

$$R_{C1} = \delta_C\, L_C/A_{CT1}\ ;\ R_{C2} = \delta_C\, L_C/A_{CT2} \qquad \text{(6 and 7)}$$

where

δ_C = specific cable resistance ~ ohm-ft

R_{C1} = power cable resistance ~ ohms

R_{C2} = power cable ground resistance ~ ohms

Substitution of equations (6) and (7) into equation (5) yields:

$$W_{TP} = \nu_{PS}\, P_S + (\rho_C\, \delta_C\, L_C^{\,2})\left(\frac{1}{R_{C1}} + \frac{1}{R_{C2}}\right) \tag{8}$$

Assuming that the resistance of the power cable and power cable ground are the same:

$$R_C = R_{C1} = R_{C2} \tag{9}$$

where

R_C = power cable or power cable ground resistance ~ ohms

Equation (8) then becomes:

$$W_{TP} = \nu_{PS} P_S + \left(\frac{2 \rho_C \delta_C L_C^2}{R_C}\right) \tag{10}$$

The total power loss in the cables and cable ground is:

$$P_C = 2I_C^2 R_C \tag{11}$$

where

I_C = cable current ~ amperes

P_C = cable power loss ~ watts

Combining (10) and (11):

$$W_{TP} = \nu_{PS} P_S + \left(\frac{4 \rho_C \delta_C L_C^2 I_C^2}{P_C}\right) \tag{12}$$

The cable loss is then defined as:

$$D_{LC} = P_C/P_S \tag{13}$$

where

D_{LC} = cable loss

Combining Equations (12) and (13):

$$W_{TP} = \nu_{PS} P_S + \left(\frac{4 \rho_C \delta_C L_C^2 I_C^2}{D_{LC} P_S}\right) \tag{14}$$

The load power dissipation is related to the power source output by:

$$P_S = P_L/(1 - D_{LC}) \tag{15}$$

where

P_L = load power dissipation ~ watts

Substitution of Equation (15) into (14) yields:

$$W_{TP} = \frac{\nu_{PS} P_L}{(1 - D_{LC})} + \left(\frac{4\,\rho_C \delta_C L_C^{\,2}\, I_C^{\,2}}{P_L}\right)\left(\frac{1 - D_{LC}}{D_{LC}}\right) \tag{16}$$

The voltage drop across the load is defined as:

$$V_L = P_L/I_C \tag{17}$$

where

V_L = load voltage drop ~ volts

Combining Equations (16) and (17):

$$W_{TP} = P_L \left\{\left(\frac{\nu_{PS}}{1 - D_{LC}}\right) + \left(\frac{4\,\rho_C \delta_C L_C^{\,2}}{V_L^{\,2}}\right)\left(\frac{1 - D_{LC}}{D_{LC}}\right)\right\} \tag{18}$$

Defining:

$$S_{TP} = W_{TP}/P_L \tag{19}$$

where

S_{TP} = power system specific weight ~ lb/watt

and

$$K_C = \left(\frac{4\,\rho_C \delta_C L_C^{\,2}}{V_L^{\,2}}\right) \tag{20}$$

where

K_C = cable coefficient ~ lb/watt

and substituting Equations (18) and (19) into (20)

$$S_{TP} = \left(\frac{\nu_{PS}}{1 - D_{LC}}\right) + K_C \left(\frac{1 - D_{LC}}{D_{LC}}\right) \tag{21}$$

Taking successive derivatives of Equation (21):

$$\frac{\partial S_{TP}}{\partial D_{LC}} = \frac{\nu_{PS}}{(1 - D_{LC})^2} - K_C \left[\frac{1}{D_{LC}} + \left(\frac{1 - D_{LC}}{D_{LC}^{\ 2}}\right)\right] \tag{22}$$

$$\frac{\partial^2 S_{TP}}{\partial D_{LC}^{\ 2}} = \left[\frac{2\nu_{PS}}{(1 - D_{LC})^3}\right] + 2K_C \left[\frac{1}{D_{LC}^{\ 2}} + \frac{(1 - D_{LC})}{D_{LC}^{\ 3}}\right] \tag{23}$$

Since:

$$(0 \leq D_{LC} \leq 1) \tag{24}$$

and all other quantities are positive, then:

$$\frac{\partial^2 S_{TP}}{\partial D_{LC}^{\ 2}} > 0 \tag{25}$$

Equation (25) is a sufficient condition for a minimum specific weight of power system when:

$$(\partial S_{TP}/\partial D_{LC}) = 0 \tag{26}$$

Combining Equations (22) and (26):

$$\frac{\nu_{PS}}{(1 - \hat{D}_{LC})^2} = K_C \left[\frac{1}{\hat{D}_{LC}} + \left(\frac{1 - \hat{D}_{LC}}{\hat{D}_{LC}^{\ 2}}\right)\right] \tag{27}$$

where

$\hat{D}_{LC}$ = optimum cable loss for a minimum weight power system

Rearranging Equation (27):

$$(\nu_{PS} - K_C)\,\hat{D}_{LC}^{\ 2} + 2K_C\,\hat{D}_{LC} - K_C = 0 \tag{28}$$

Defining

$$K_P = K_C/(\nu_{PS} - K_C) \tag{29}$$

where

K_P = power system coefficient

Combining (28) and (29):

$$\hat{D}_{LC}{}^2 + 2K_P \hat{D}_{LC} - K_P = 0 \tag{30}$$

The real solution to the quadratic (30) is:

$$\hat{D}_{LC} = K_P \left[-1 + \sqrt{1 + (1/K_P)}\right] \tag{31}$$

In the limit, when (K_P) is very small, then Equation (31) becomes:

$$\hat{D}_{LC} \approx \sqrt{K_P} \tag{32}$$

In another limit, when the power source specific weight and the cable coefficient are equal, the optimum cable loss is indeterminate. Hence defining:

$$X = 1/K_P \tag{33}$$

Equation (31) becomes:

$$\hat{D}_{LC} = \left(\frac{-1 + \sqrt{1 + X}}{X}\right) \tag{34}$$

and

$$\left\{ \lim_{X \to 0} \hat{D}_{LC} = \frac{0}{0} \right\}$$

Using De L' Hospital' s rule:

$$\left|\underset{x \to o}{\text{LIM}\ \hat{D}_{LC}}\right| = \left\{\frac{d/dx\,[- + \sqrt{1 + x}]}{dx/dx}\right\}_{x \to o} = \left\{\frac{1}{2\sqrt{1 + x}}\right\}_{x \to o} = \frac{1}{2} \qquad (35)$$

Hence:

$$\hat{D}_{LC} = 0.5 \qquad (36)$$

when:

$$(\nu_{PS} = K_C)$$

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APPENDIX C

OPTIMUM BATTERY DEPTH OF DISCHARGE

The total weight of battery required for the mission duration is:

$$W_{BT} = W_{BRQ} N_{RF} \tag{1}$$

where:

W_{BT} = total battery weight for the mission ~ lbs

W_{BRQ} = battery weight required for the battery discharge requirements ~ lbs

N_{RF} = resupply factor to ensure the required battery life for the mission

The resupply factor can be expressed as:

$$N_{RF} = C_{MS}/C_{CD} \tag{2}$$

where:

C_{MS} = battery cycles required for the complete mission

C_{CD} = design cycle life of the battery cells.

While the battery needed to meet power system requirement is:

$$W_{BRQ} = \frac{P_d T_d}{D_d} \cdot \frac{\partial W_B}{\partial E_B} \tag{3}$$

where:

P_d = battery discharge power requirement ~ watts

T_d = duration of battery discharge ~ hours

D_d = battery depth of discharge

$\frac{\partial W_B}{\partial E_B}$ = battery specific weight ~ lbs/watt-hour

Combining Equations (1) through (3):

$$W_{BT} = \left(\frac{P_d T_d}{D_D}\right)\left(\frac{C_{MS}}{C_{CD}}\right)\left(\frac{\partial W_B}{\partial E_B}\right) \tag{4}$$

Battery cell cycle life data are usually given in the format shown in Figure C-1.

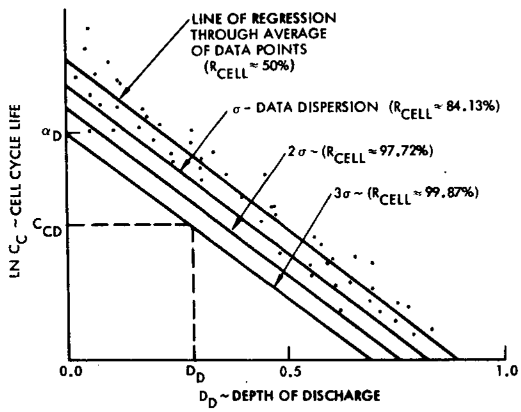

Figure C-1. Battery Cell Cycle Life Data

From the above figure, it can be seen that for any line through the data points, representing any reliability level for a given cell:

$$C_{CD} = \alpha_D e^{-\beta D_D} \tag{5}$$

where:

α_D = intercept of chosen design line

β = slope of cycle life versus depth of discharge design line

Equation (5) may be rewritten as:

$$D_D = \left(-\frac{1}{\beta}\right) \ln\left(\frac{C_{CD}}{\alpha_D}\right) \tag{6}$$

Combining Equations (4) and (6):

$$W_{BT} = (P_d T_d C_{MS})\left(\frac{\partial W_B}{\partial E_B}\right) \frac{(-\beta/\alpha_D)}{(C_{CD}/\alpha_D) \ln (C_{CD}/\alpha_D)} \tag{7}$$

Defining:

$$K_B = (P_d T_d C_{MS})\left(\frac{\partial W_B}{\partial E_B}\right) \tag{8}$$

where:

K_B = battery weight coefficient ~ lbs and combining Equations (7) and (8):

$$W_{BT} = \frac{-(\beta K_B/\alpha_D)}{(C_{CD}/\alpha_D)\ln(C_{CD}/\alpha_D)} \tag{9}$$

Taking successive derivations of Equation (9):

$$\left(\frac{\alpha_D^{\,2}}{\beta K_B}\right)\left(\frac{dW_{BT}}{dC_{CD}}\right) = \frac{1}{(C_{CD}/\alpha_D)^2 \ln(C_{CD}/\alpha_D)} \left[1 + \frac{1}{\ln(C_{CD}/\alpha_D)}\right] \tag{10}$$

$$\left(\frac{-\alpha_D^{\,3}}{\beta K_B}\right)\left(\frac{d^2W_{BT}}{dC_{CD}^{\,2}}\right) = \frac{1}{(C_{CD}/\alpha_D)^3\left[\ln(C_{CD}/\alpha_D)\right]^3} + $$

$$\cdots + \left[1 + \frac{1}{\ln(C_{CD}/\alpha_D)}\right]\left\{\frac{1}{(C_{CD}/\alpha_D)^3\left[\ln(C_{CD}/\alpha_D)\right]^2}\right.$$

$$\left. + \frac{2}{(C_{CD}/\alpha_C)^3\left[\ln(C_{CD}/\alpha_D)\right]}\right\} \tag{11}$$

For an extremum to occur:

$$\frac{dW_{BT}}{dC_{CD}} = 0 \tag{12}$$

Hence, from combining Equations (10) and (12):

$$\left[1 + \frac{1}{\ln(\hat{C}_{CD}/\alpha_D)}\right] = 0 \tag{13}$$

or

$$\hat{C}_{CD} = \alpha_D e^{-1.0} \tag{14}$$

where:

$\hat{C}_{CD}$ = extremum value of cell design cycle life

Substitution of Equations (13) and (14) into Equation (11) yields:

$$\left(\frac{d^2W_{BT}}{dC_{CD}^2}\right)_{\hat{C}_{CD}} = -\frac{\beta K_B e^3}{\alpha_D^3} < 0 \tag{15}$$

Hence at $C_{CD} = \hat{C}_{CD}$ a minimum total battery weight is found.

Comparing Equations (5) and (14):

$$-1.0 = -\beta\hat{D}_D \tag{16}$$

From which the optimum cell depth of discharge is:

$$\hat{D}_D = (1/\beta) \tag{17}$$

Computer Program and Printout to Calculate Total Battery Weight of 10-Year Mission, 5850 Cycles/Yr

```
      DISPLAY "TYPE IN Y2,Y1,X2,X1,PWR"
      ACCEPT Y2,Y1,X2,X1,PWR
10    FORMAT (1H,6X,F8.4,3X,F15.2)
      K1=ALOG[Y2/Y1]/(X2-X1)
      A=EXP[K1]
      B=Y2/(A**X2)
      DISPLAY "POWER =",PWR,"WATTS"
      DO 100 I=2,90,2
      X=.01*I
      Y=B*(A**X)
      NCYCL=Y
      YR=FLOAT[NCYCL]/5850.
      WT=PWR*4./6.*1./X*1./11.*10./YR
100   WRITE (1,10) X,WT
      END
```

Where

X = Depth of Discharge

Y = Cycle life of one battery at depth of discharge, X

Ncycl = Cycle life in integral numbers of cycles

YR = Life in years of a battery at depth of discharge, X

$$WT = \frac{\text{t(eclipse) x (mission life in years)}}{\text{t(orbit) x DOD x (battery watt-hr/lb) x (battery life, yr)}}$$

(Depth of Discharge) X	(Total Weight) WT	(Depth of Discharge) X	(Total Weight) WT
0.0200	77745.74	0.4800	32311.30
0.0400	42960.63	0.5000	34282.10
0.0600	31652.90	0.5200	36429.70
0.0800	26236.20	0.5400	38776.62
0.1000	23196.56	0.5600	41315.38
0.1200	21363.31	0.5800	44091.55
0.1400	20237.72	0.6000	47106.91
0.1600	19570.33	0.6200	50374.16
0.1800	19225.56	0.6400	53930.81
0.2000*	19122.45*	0.6600	57812.11
0.2200	19212.81	0.6800	62011.22
0.2400	19463.41	0.7000	66573.80
0.2600	19856.08	0.7200	71531.70
0.2800	20377.11	0.7400	76929.27
0.3000	21018.32	0.7600	82772.74

*MINIMUM WEIGHT

(Depth of Discharge) X	(Total Weight) WT	(Depth of Discharge) X	(Total Weight) WT
0.3200	21777.55	0.7800	89126.56
0.3400	22651.42	0.8000	96093.20
0.3600	23644.69	0.8200	103537.48
0.3800	24756.27	0.8400	111779.11
0.4000	25990.02	0.8600	120685.64
0.4200	27357.92	0.8800	130301.60
0.4400	28860.50	0.9000	140893.92
0.4600	30507.88		

APPENDIX D

POWER CONTROL DATA DEFINITION

Parametric data on power conditioner efficiency, weight, and reliability is necessary for the proper evaluation of various power system configurations in the 20 kw battery program. A basic technique for generating this data as well as some of the desired data itself, was developed in a study of component limitations conducted for NASA GSFC (Ref. 12). The method involves the establishment of analytical models of the various subcircuit functions which comprise the building blocks of typical power conditioners used in spacecraft systems. Utilizing these models, designs were created based on the use of space-qualified parts to obtain parametric data on function power loss, weight, and failure rate and to establish scaling factors for estimating the variation of these dependent variables as a function of power level. The function designs were performed over the operating ranges and conditions pertinent to the requirements of the present study. The data for those functions common to a particular power conditioner can then be combined to yield overall power conditioner parametric data.

Data have been generated for power circuit functions which, in varying number and combinations, compose the power-level portions of the following equipment: switching, buck-type dc voltage regulator, dc-dc converter, power control equipment, sequentially switched and linear shunt regulators, transformer-rectifier units square wave inverter and other power control and processing equipment.

Further data have been generated for an SCR series-resonant inverter circuit under development in conjunction with NASA-ERC under Contract NAS 12-2183, "Multikilowatt Ion Thruster Power Processor." Preliminary study of the series resonant circuit using silicon controlled rectifiers has shown the feasibility of a low weight, high efficiency, and low part count power conditioners operation at high power and high input voltage.

Data are available over an operating voltage range of 30 to 300 Vdc and a power range of 1 to 10 kw. Normally used design constraints and component derating factors are imposed in performing the function designs.

In the following paragraphs are presented the operating ranges and requirements for the power conditioners of concern in this study, the defintion of power conditioner subcircuit functions, the power conditioner block diagrams, the parametric data for the function circuit design, and general notes on the presentation and use of function parametric data. Function circuit design, including analytical models utilized, special function design assumptions, and constraints are also discussed.

1. POWER CONDITIONING CIRCUIT FUNCTIONS

The formulation of analytical power conditioner models and the determination of their adaptability to other than the specified requirements and ranges can be greatly enhanced by standardizing various subcircuit functions because of the commonality displayed by such functions in power conditioning. After careful review, the various subcircuit functions have been formulated and are shown in Table D-1. The functions are divided into power level and signal level categories. The efforts in this study have been concentrated on power level functions only. The definitions of these functions are given in Table D-2.

1.1 Basic Power Functions

Most of the basic power functions are characterized by differing design constraints on the critical components, depending on the particular type of power conditioner involved. These variations are classes, as determined in this study, are indicated in Table D-3. Further explanation of these classes is deferred to the discussions on function design.

1.2 Auxiliary Power Functions

The following auxiliary functions, while not identified in the power conditioners under study, are necessary in actual system design:

- RFI filtering—the process of suppressing or minimizing the above-audio range frequency components in power lines with passive components.
- Transmission—the means of distributing power (includes connectors and cabling).
- Power control—the means of connecting or disconnecting power (includes relays, contactors, and static devices).

Table D-1. Circuit Functions

Power	Signal
Basic	Basic
Power modulation (7 classes)	Sensing
Inversion (5 classes)	Voltage
	Current
Transformation	References
Rectification (3 classes)	Frequency standard
Passive filtering (11 classes)	Pulse generator
Auxiliary	Operational amplifier
RFI filtering	Voltage gain
	Current gain
Transmission	Auxiliary
Power control	Time delay
Overcurrent protection	Logic
Overvoltage protection	OR gate
	AND gate
	Digital
	Flip-flop
	Multivibrator
	Schmitt trigger
	Relay driver
	Telemetry conditioning

Table D-2. Power Function Definitions

Power Modulation

- Switching. The process of controlling power from a source such that the output is maintained within desired limits. The control is accomplished by varying the ON/OFF time ratio of a power switch either by pulse width modulation (PWM) or by pulse rate modulation (PRM). Either process, herein, is referred to as pulse modulation (PM).

- Dissipative. The process of controlling power from a source such that the output is maintained within desired limits. The control involves dissipation of excess energy.

Inversion

The process of converting dc voltage to ac voltage.

Transformation

The process of converting ac voltage from one level to another, either step-up or step-down, and working as an isolation transformer or as an auto-transformer.

Rectification

The process of converting ac voltage to an unfiltered dc voltage.

Passive Filtering

The process of suppressing or minimizing frequency components in power lines with passive components. The two types considered in this study are the dc filter (those used in either dc power lines, input, or output) and the ac-type (used primarily for harmonic filtering in ac output power lines or waveshaping of currents drawn from the power source).

Active Filtering

The process of suppressing or minimizing frequency components in power lines with active elements. This process is effectively equivalent to the dissipative power modulation process.

Table D-3. Power Function Classes

- Power Modulation
  - Switching
    - PWM - inversion
    - PWM - rectification
    - PM - buck
    - PM - boost
  - Dissipative
    - Series
    - Shunt
- Inversion
  - Square wave
    - Resistive load
    - Rectifier - LC filter load
    - Rectifier - C filter load
  - Square wave with fixed dwell
  - Sine wave
- Rectification
  - Square
  - PWM - square wave
  - Sine wave
- Passive Filtering
  - dc filters
    - LC - no ac requirement
    - LC - high ac current
    - LC - high ac voltage
    - LC - high ac voltage and current
    - LC - high ac voltage with transformation
    - LC - high ac voltage and current with transformation
    - C - no ac requirement
    - C - high ac current, low frequency
    - C - high ac current, high frequency
  - ac filters
    - LC - high ac voltage and current
    - C - high ac current

- Overcurrent protection—the process of providing protection in the event of fault conditions, either by current interruption or by current limiting.

- Overvoltage protection—the process of protecting load equipment against overvoltages during a power conditioner fault.

1.3 Basic Signal Functions

The basic signal functions used in the selected power conditioners are defined below. Auxiliary signal functions, not defined, are listed in Table D-1.

- Reference—a voltage or current level established as a standard of comparison for feedback control purposes.

- Frequency standard—a self-oscillating source used to develop power conditioner operating frequency and required low-level timing signals.

- Pulse generator—an active network for converting variable analog signal levels to a pulse-type digital signal having either variable pulsewidth or variable pulse frequency.

- Operational amplifier—an active network for obtaining a controlled voltage (or current) gain versus frequency characteristic.

2. POWER CONDITIONER BLOCK DIAGRAMS

Block diagrams of the selected power conditioners indicated in Section 3, utilizing the functions listed in Table D-3, are illustrated in Figures D-1 through D-4. Each block diagram, showing the division between power and signal functions, is discussed in the paragraphs that follow.

2.1 Dc Voltage Regulator - Switching Type

The block diagram shown in Figure D-1 typifies the functional breakdown of a switching-type dc voltage regulator and applies to either the buck or boost configuration. In the former case, the power functions from input to output consist of an input passive LC filter (high ac current type), a PM buck-type switching power modulator, and an output passive LC filter (high ac voltage type). Output voltage is sensed and compared with a voltage reference in an operational amplifier which, in turn, controls the modulator stage via the pulse generator.

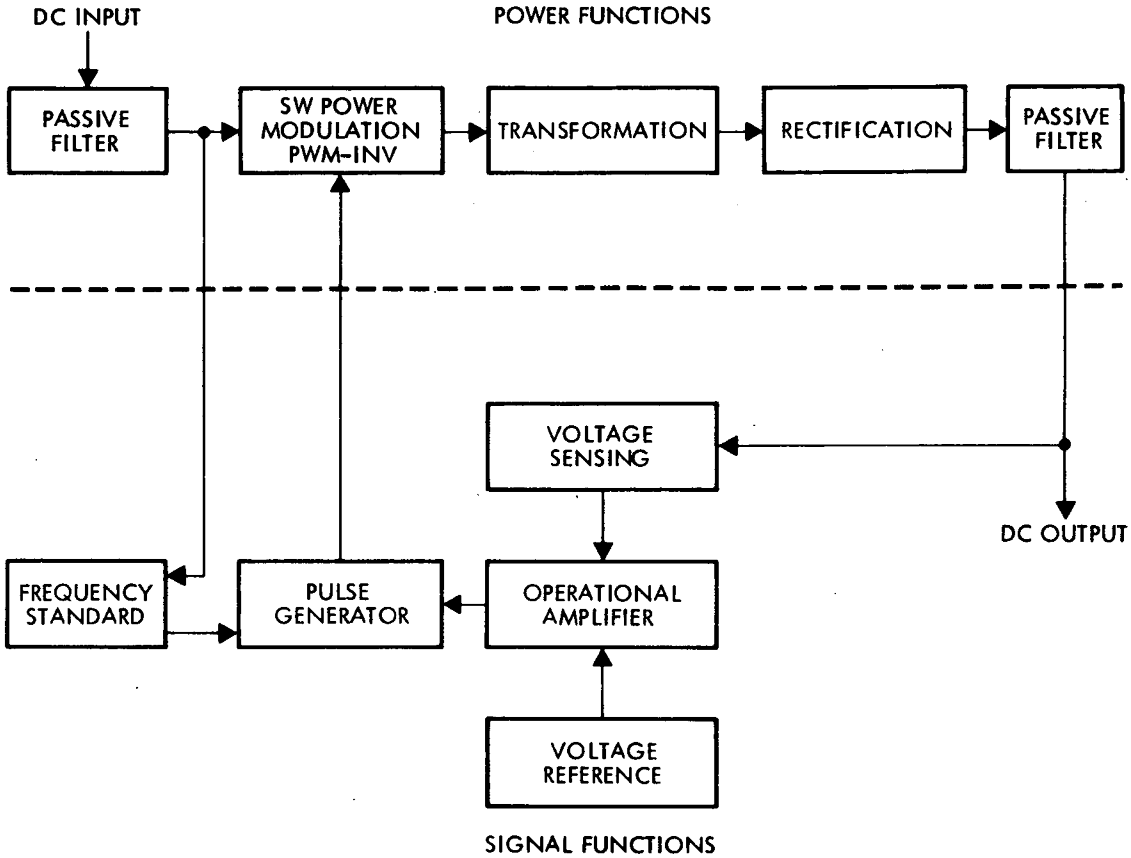

Figure D-1. Dc Voltage Regulator - Switching

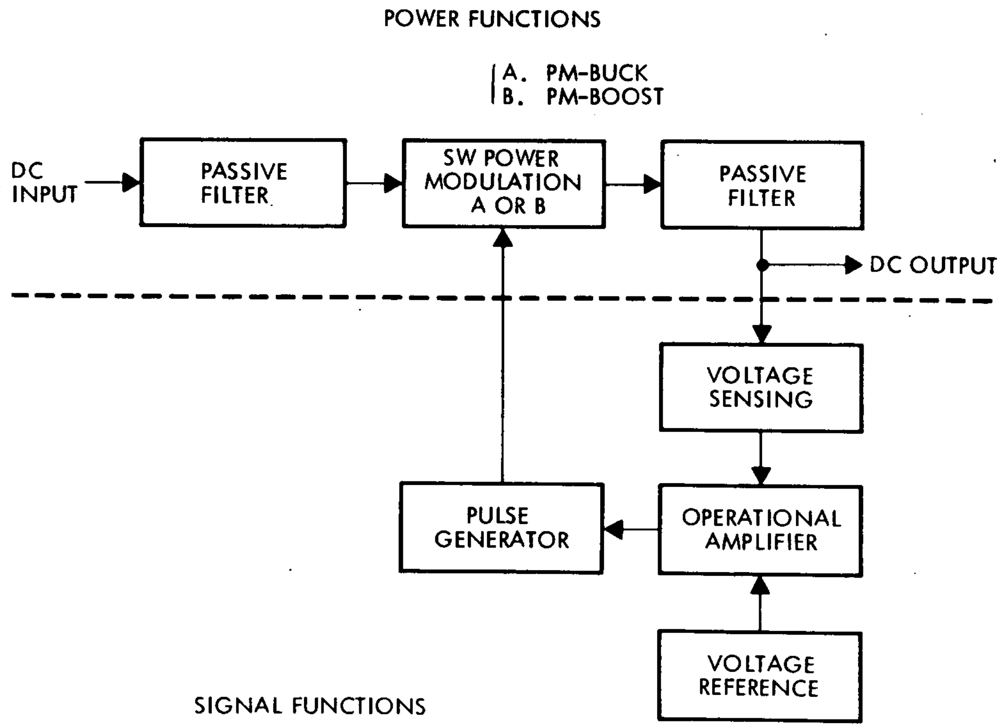

Figure D-2. Dc-dc Converter Pulsewidth Inversion

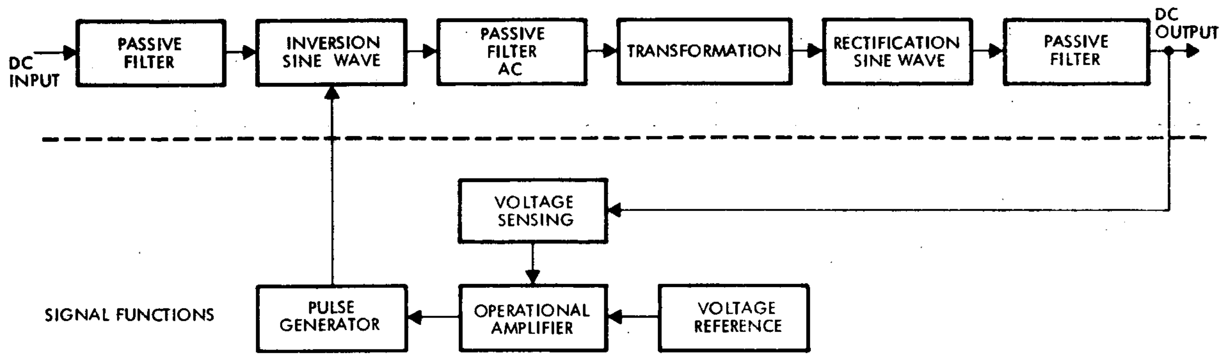

Figure D-3. Dc-dc Converter Series Resonant Inversion

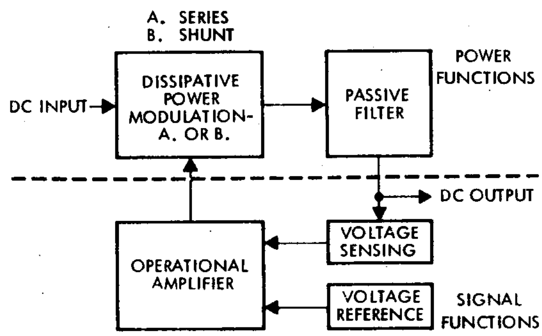

Figure D-4. Dc Voltage Regulator - Dissipative

In the boost configuration, the power functions from input to output consist of an input passive LC filter (low ac current type), a PM boost-type switching power modulator, an output passive LC filter (high ac voltage and ac current-type). Output voltage is sensed and compared with a voltage reference in an operational amplifier which, in turn, controls the modulator stage via the pulse generator.

2.2 Dc-dc Converter - Pulsewidth Inversion

The power functions of this converter, shown in Figure D-2, consist of a passive input filter (high ac current), a switching power modulator of the PWM inversion-type, a transformer, a rectifier (PWM square wave type), and a passive output filter (high ac voltage). It is characterized by high efficiency and low weight due to the combination of regulation and inversion functions within one power switching stage. The signal functions are implemented in a manner similar to that described in Paragraph 5.1.

2.3 Dc-dc Converter - Series Resonant Inversion

The power functions of this converter, shown in Figure D-3, consist of a passive input filter (high ac current), a switching inversion stage passing sine wave current, a passive ac filter (high ac voltage and current) which forces the current in the power switch to be a sine function, a transformer, a rectifier (sine wave current-type) and a passive output filter (high ac current).

This converter is characterized by its use of SCR's which are turned off by the resonant circuit (ac filter). The high current and high voltage components are available for high power designs.

3. PARAMETRIC DATA

In seeking a simplified method for the development of parametric data for the selected power conditioners, an attempt has been made to utilize results from previous studies.

The function classes examined below are identified and the basic procedure and ground rules utilized in function circuit design are outlined.

General notes regarding the presentation and use of the function parametric data are also given.

3.1 Circuit Design of Functions

The following function classes have been examined:

Passive (dc) filter - LC (no ac requirement)

Passive (dc) filter - LC (high ac current requirement)

Passive (dc) filter - LC (high ac voltage requirement)

Passive (dc) filter - LC (high ac voltage and current requirement)

Passive (dc) filter - C (no ac requirement)

Passive (dc) filter - C (high ac current - low frequency)

Passive (ac) filter - LC (high ac voltage and current)

Power modulation, switching - PM buck

Power modulation, switching - PM boost

Power modulation, switching - PM inversion

Rectification - PWM square wave

Rectification - sine wave

Rectification - square wave

Transformation

Inversion - sine wave

Inversion - square wave

Power modulation, dissipative - linear series

Power modulation, dissipative - linear shunt

Power modulation, dissipative - sequential shunt

Error amplifier

Driver circuit - linear series

Driver circuit - linear shunt

Driver circuit - sequential shunt

Driver circuit - switching PWM, buck and boost

Driver circuit - switching PWM, inversion

Driver circuit - inversion SCR, series resonant

Driver circuit - inversion SCR, square wave

Parametric data on losses and weights have been computed for these functions over a voltage range of 30 to 300 volts. The specified power and voltage ranges have been rearranged into a set of discrete function design points that effectively cover the desired ranges. These are:

- Output voltage - 30, 100, and 300 Vdc
- Switching frequency - 10 kHz
- Power - 1 kw, 3 kw, and 10 kw

The design procedure entails the selection of one set of voltage design points and the performance of a design at several of the design point power levels. This procedure is then completely repeated at other voltage design points.

The general design constraints applicable to all functions, as established for this study, are listed below:

- Thermal vacuum environment is assumed. Maximum allowable component temperatures are as follows:

Silicon semiconductors	100^{o}C case temperature
Magnetics	30^{o}C rise to hot spot
All others	85^{o}C case temperature
Minimum temperature	-35^{o}C.

- Capacitor derating factors are 60 percent on dc voltage at 85^{o}C case temperature and 50 percent or less on ac current rating. Ceramic capacitor ac current ratings are based on simplified thermal calculations.

- Resistor derating is 25 percent on power at 85^{o}C case temperature.

- Diode derating factors are 50 percent at 85^{o}C case temperature for both forward current and peak reverse voltage. When paralleling of fast-recovery rectifiers is required, units matched for both recovery time and forward drop are selected. When a series is required, shunt-connected zener diodes are used across each diode to protect against the effects of unequal diode switching times and unequal voltages.

- Transistor derating factors are 80 percent on V_{CEO} and 50 percent on I_c both at 100^{o}C case temperature. These are applied, as follows, in the selection of a particular device for switching application. The forward bias "safe area" curve, which requires inputs for pulsewidth, duty cycle, and collector-emitter voltage, is utilized. As an approximation, the transistor switching time intervals can be converted to an equivalent single pulsewidth and the duty cycle determined. This approximation is used because available safe area data is is very limited. (A more valid approximation would entail the use of both forward and reverse bias safe area curves.) The peak collector-emitter voltage during the switching interval (with the above 80 percent derating factor applied) is used to enter the safe area curve along with the pulse-width and duty cycle factors. The collector current capability, applying the given 50 percent current derating factor, is thus determined. Devices are placed in series or parallel, if required.

In paralleling power transistors, beta matched units are assumed with individual drive resistances (R_B). In connecting transistors in series, collector-base connected, zener diodes are used to protect against the effects of unequal switching times and unequal voltage across the transistors.

- It is assumed that semiconductors are mounted directly to an aluminum heat sink, which is insulated from a baseplate having a maximum temperature of 71°C. Heat transfer is by conduction only. Heat sink weight is added to component weight in computing total function weight. It is determined by multiplying semiconductors losses by a factor equal to 0.05 lb/w loss. This figure is based on an assumed heat conduction of 0.5 w/in^2 to the baseplate.

- In magnetic design, the following general considerations apply.

Peak core-flux density is limited as follows:

Oriented silicon steel	10,000 gauss
Powdered permalloy	4,000 gauss
Ferrite	3,000 gauss
Grain oriented 50 percent NiFe	11,000 gauss
Grain oriented 80 percent NiFe	5,000 gauss

Current density is initially set at 500 circular mils per ampere in "filled window" designs.

Gapped cores for inductor designs are limited to a gap length, one-tenth or less, of the smallest cross sectional dimension.

To account for potting or hardware in magnetic designs, the following weight-scaling factors are used:

Conformally coated units

Toroids	1.15 x (core weight + copper weight)
Pot cores	1.2 x (core weight + copper weight)
Gapped tape-wound cores (less than 1 lb)	1.25 x (core weight + copper weight)
Gapped tape-wound cores (1 to 10 lb)	1.2 x (core weight + copper weight)

3.2 Function Parametric Data

The parametric data, as developed from the models generated, will be illustrated graphically for most functions by four curves. These are:

- Percentage loss versus operating voltage at a fixed power level
- Weight versus operating voltage at a fixed power level
- Failure rate versus operating voltage at a fixed power level
- Scaling constant for percentage loss, weight, and failure rate versus output power level at constant voltage and frequency.

The percentage loss, weight, and failure rate are plotted as a function of operating voltages for a selected switching frequency and output level. The scaling constant curve allows the three curves of percentage loss, weight, and failure rate to be modified as a function of output power level. To use the scaling constants, the percentage loss, weight, and failure rate for a selected operating voltage and frequency are determined from the first three curves, which are plotted for a 1 kw design operating at 10 kHz. The scaling constant curves give the multiplying factors that are used to change the original data to the data at another power level.

Percentage loss here is defined as the ratio of the losses to the sum of losses and output power. This is selected rather than efficiency because it simplifies the analysis of relationships of individual functional losses to total power conditioner loss. Efficiency can be determined as one minus the percentage loss.

4. EVALUATION OF PARAMETRIC DATA

The parametric data in most cases is based on paper designs. Presently designed power conditioning spacecraft hardware operate at 200 watts maximum and 80 volt input voltage and cannot be used to check the validity of the paper design.

When using transistors as switching elements, series and parallel configurations have to be used to obtain the necessary voltage and current ratings for the high power equipment. The series-parallel connection requires special attention in forcing both the current and voltage to be shared between the parts.

To overcome the transistor rating problem, silicon control rectifier circuits are now being developed for application in space hardware. Capacitors also share the rating problem because of their limitation on voltage and ac current capability. Attempts to solve the component sharing problem have been included in the paper design, and therefore, it is expected that the parametric data is an accurate evaluation of the functions characteristics. New component and circuit developments could cause a weight, loss, or failure rate reduction.

APPENDIX E

BATTERY RELIABILITY ANALYSIS

1. DEFINITIONS AND FORMULAE

The intent of this study is to model a power supply whose nominal power output is 25,000 watts (25KW). The power source is a number of batteries (NB) in parallel, each battery containing a number of modules (NM), each module consisting of cells (NC), for a total of NM x NC = NCB cells per battery.

The calculations determine the weight, in pounds, of the assembly, the number of failures needing replacement, and the availability of each battery.

Figure E-1 is a first level flow diagram of the computerized model. In support of the model, analysis has been performed on data found in References 1, 2, and 3.

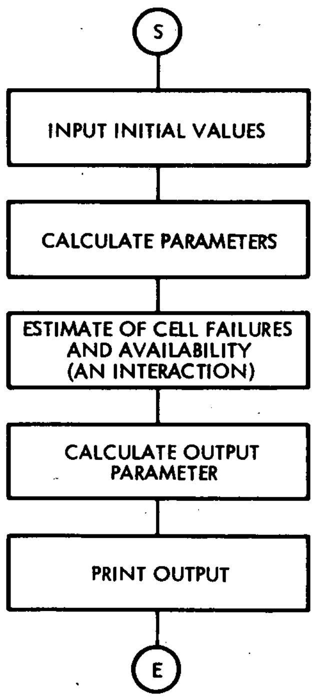

Figure E-1. Level One Flow Diagram

The power supply model, written in FORTRAN IV, assumes that each cell in each battery is independent of both the number of cells in the battery and of every other cell failure. Thus the number of cell failures is calculated for each battery and multiplied by the number of batteries to determine the total number of cell failures.

The input parameters to the model and their acronyms are given in Table E-1. The calculated parameters, their acronyms, and how they are calculated are given in Table E-2.

Table E-1. Input Parameters

Acronym	Description
CA	Battery cell capacity
PEMER	Emergency battery power requirement
WT	Battery cell weight in pounds
PDNOM	Nominal battery power required in watts
NC	Number of cells per module
NM	Number of series modules per battery
TRSI	Spares resupply internal in months
D	Depth of discharge
XNRF	Battery resupply factor
A1	Parameter = 63,000
A2	Parameter = -5.455
E	$= 10^{-10}$ = truncation parameter
TOP	Orbit in hours = 1.555
FRL	Failure rate of logic circuitry = 500 bits
TECL	Percent of time in sunlight = 0.60
CMS	Design goal of power system = 56,260
NSTP	Number of steps in calculation = 25
B	MTBF
RTC	Number of cycles to replace a cell
RTL	Number of cycles to repair the logic circuitry

Table E-2. Calculated Parameters

Acronym	Description	Formula
CURN	--	D/TECL
TN	Number of cycles between complete replacement, i.e., battery design goal	CMS/XNRF
NCB	Number of cells per battery	N M * NC
NB	Number of batteries needed (nominal)	PDNOM * TECL/CA * D * VC * XNCB)
NBE	Number of batteries needed (emergency)	NB*PEMER/PDNOM
TC	Total number of battery cells	NB * NCB
A	Characteristic life	= A1* exp(+A2*D)
CRSI	Number of cycles between spare cell resupply	CMS * TRSI/(12 * TMS)
NSC	Number of Spares resupply trips	TN/CRSI
NCC	Number of cycles at constant failure rate	TN/STP
VT	Nominal battery voltage	VC * XNCB
Alpha	Weilbull parameter	(A/G) ** BE
G	Working variable	T(1 + 1/BE)
BE	Beta, Weilbull parameter	1.2 + 0.3D
HO	Initial failure rate	BE/ALPHA
FR	Constant failure rate of a cell	1/B
WTB	Battery Assembly weight in pounds	WT*TC
F1	Constant failure rate of a cell per orbit	TOP*FR
H2	Failure rate at end of a "constant" period	[1+AN)**(BE-1)*HO]
AN	Number of cycles	NCC*M
M	Calculation number	M = 1, 2, 3, . . . , NSTP
S3	Probability of no cell failure	exp (-NCC*(H2+F1)
S2	Probability of cell failure	1 - S3
P(1)	Probability of no cell failure in a battery	S3*NCB
P(I)	Probability of I^{-1} cell failures per battery	S2* P(I-1)*(NCB-I) [(I-1)*S3]

Table E-2. Calculated Parameters (Continued)

Acronym	Description	Formula
AVV2	Availability of logic circuitry	1/(1+RTL*FRL)
AVV1	Availability of a battery	1/ [1+RTC*NCB*(H1+F1)]
AV1	Availability of Power Segment	AVV1*AVV2
AC	Working variable	
C(I)	Availability of NB-I+1 batteries	Averaged and using binomial distribution
H	Working variable	
S(I)	Probability of I-1 failures per battery through the Mth calculation cycle	CALL TWOCON
CR	Expected number of cell failures	$\sum_{I=1}^{256} (I-1) * S(I)$
NS	95% confidence that number of failures are ≥ NS	$\sum_{I=1}^{NS} \delta\ (I) < 0.95$
WTT	Total mission battery weight, in pounds	WTB*NB+WT*NS

2. ASSUMPTIONS

2.1 Failure Rates

Failure may be of two kinds due to a constant failure rate, FR, and/or a varying failure rate, H2. To shorten the time required for calculations the value of H2 is held constant during the interval (M-1)*NCC to M*NCC. The value of H2 used is the value calculated at M*NCC for M = 1, 2, . . . , NSTP. This is a slightly conservative value as shown in Figure E-2.

2.2 Independence

The assumption of independence of failures is that the failure of a cell does not influence the failure rate of any other cell. Thus the failure of a cell in a module does not induce other failures within this module.

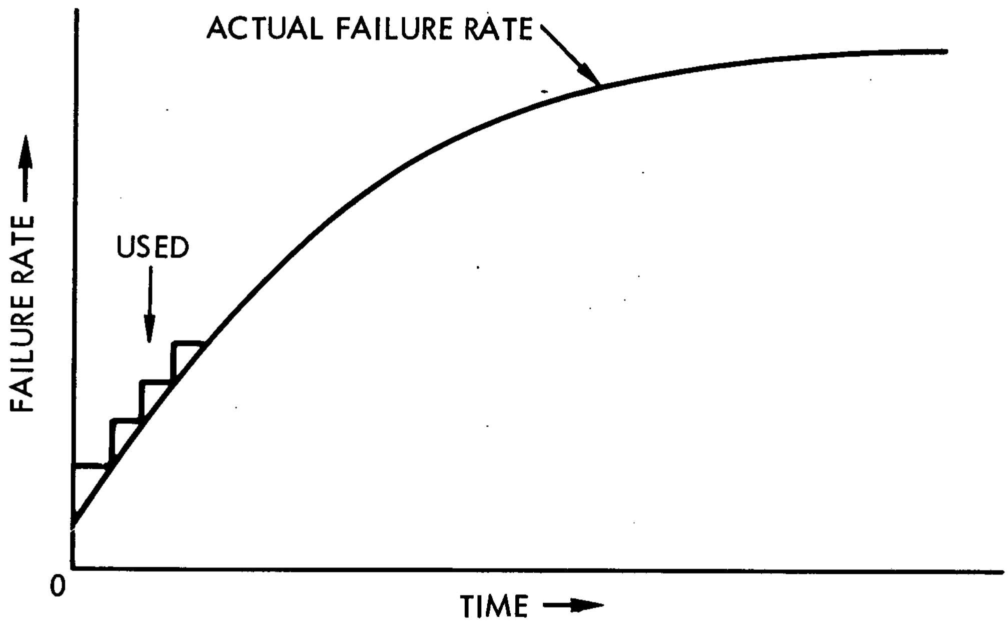

Figure E-2. Illustrations of Failure Rate Assumptions

This is equivalent to assuming that the failed cell is replaced immediately and that the replacement procedure does not degrade the system, i. e., perfect replacement. That checkout and verification are part of the replacement procedure and that the repairman has a vested interest means that this is a reasonable assumption.

2.3 Spares

The failure rate of the inactive cells is conservatively assumed to be the same as that of the operating cells. The number of failures among the spares is not calculated but it is assumed that the resupply planning is such that one always has a spare available for replacement. This is equivalent to an infinite supply source. A refinement of the model would include potential clustering of failures which could exhaust the spares as well as a different failure rate for inactive cells.

3. CALCULATIONS

3.1 Failures

The vector [S = S(1), S(2), ..., S(256)] is the NSTP the convalution of P; that is

$$S = P^{*NSTP}$$

where

$$P^{*2} = P * P$$

and

$$P(N) = \text{Probability that N-1 failures occur in the interval.}$$

The vector S cannot be computed directly from P by convoluting NSTP times.

To accomplish this, one must use a working variable, called H, in the following fashion:

1) $S = P*H$
2) $H = S$
3) Go to step 1) if less than NSTP iterations have been completed; otherwise one is finished.

Again we must use an indirect approach; this time for step 1). We use the subroutine TWOCON in the following manner:

A = P, B = S, then we calculate the vector C as:

$$C(M) = \sum_{I=1}^{M} A\ (M-I+1) * B(I)$$

for

$$M = 1, 2, 3, \ldots$$

then we set

$$S = C.$$

This subroutine is called NSTP times.

Upon completion of this iteration, we have that

S(N) = Probability that N-1 failures have occurred in TN number of cycles (battery design goal)

3.2 Availability

The availability of two subsystems in series is the product of the availabilities of each.

The availability of NB, NB-1, --- batteries (and associated logic circuits) is obtained from the binomial distribution.

This is calculated for each constant period. See Figure E-2.

The final availability is the average of each of the constant periods.

The availability is calculated from

$$AC = \frac{MTBF}{MTBF + MTTR}$$

$$= \frac{1}{1+MTTR * \lambda}$$

which is the steady state availability. With slowly varying failure rates, a constant MTTR, and a large value of TN, this assumption of steady state is adequate. The worst case assumption on the failure rate tends to make the availability estimate conservative.

APPENDIX F

CALCULATION OF WEIGHT, COST, AVAILABILITY AND RELIABILITY

1. PROCEDURE FOR CALCULATION OF OVERALL SYSTEM WEIGHT, COST, AND AVAILABILITY

Weight, cost, and availability may be determined by following the procedure of Table F-1, noting the weights, costs and reliabilities of each of the subsystem elements in order as they are determined.

Should one or more of these elements be absent from any configuration, the weight and cost of the missing element is zero, and its availability is equal to 1.0.

Because of the wide diversity in the weight, cost and reliability of the power control unit, which is greatly dependent upon the logic requirements and upon various human engineering elements, estimates of power control unit weight, cost, and availability have been omitted, and an arbitrary 0.2 percent assigned for its power consumption.

Similarly, because of widely varing manufacturing methods, the cost estimate for the solar array has been omitted, although a basic estimate may be made by multiplying its power output by dollar/watt of power output.

2. PROCEDURE FOR ESTIMATION OF SUBSYSTEM WEIGHT, COST, AND RELIABILITY

Perform the indicated operations in the following order:

a) Discharge Circuit.

b) Battery.

c) Charge Control.

d) Charging Circuit.

e) Power Summation (Note: for configuration 5, the power summation step is performed after the power processing unit step).

f) Power Processing Circuit.

g) Solar Array.

h) Array Controls.

Beginning by making assumptions regarding the required power output of the system (nominal load), the number of units into which the component elements of the system are to be divided, and the bus voltage of the system:

a) <u>Discharge Circuit</u>

The procedures is as follows:

Look up the weight, cost, and losses as a function of the system voltage, interpolating for power level.

Look up the weight, cost, and loss correction factors as a function of the number of units into which the subsystem element is to be divided.

Multiply weight, costs, and losses by the appropriate correction factors to get the weight, cost, and losses of the discharge circuit. Should correction factors not be found in the data, they are equal to 1.

Input power to the discharge circuit is equal to output power plus corrected losses, and is set equal to the output power of the next element upstream.

b) <u>Battery</u>

The procedure for the battery is similar, except that the correction factors are shown as a function of the number of modules per battery, which is equal to 1 except in the case of configurations 4 and 5, in which case a correction factor may be required.

c) <u>Charge Control</u>

Prior to calculation of the charge control, an estimate must be made of charge input power.

$$\text{estimate } I/C_{charge} = \frac{DOD}{t_{eclipse}} \times \frac{P_{out} + \text{Losses}}{P_{out}} \times \frac{t_{eclipse}}{(t_{orbit} - t_{eclipse})}$$

where P_{out} = battery output power

losses = battery losses.

If I/C < 0.1, set I/C = 0.1 look up battery efficiency as a function of I/C.

$$P_{in} \cong \frac{(P_{out} + \text{losses})\, t_{eclipse}}{(t_{orbit} - t_{eclipse})\ \text{efficiency}} = \text{charge control output power}$$

$$\text{Charge Control Voltage} = V_{bus}/\text{No. of modules per battery}$$

Having determined the charge control output power and voltage, the same procedure as was used for the discharge circuit may then be used for the charging circuit. The assumption of one on-line and one standby unit charge control for each battery module is inherent in the data.

d) Charging Circuit

The charging circuit uses the input power to the charge control as its output power, and has an output voltage approximately equal to the voltage of the charge control. Using these data as arguments, perform the calculation in a manner identical to the discharge circuit calculation.

e) Power Summation

For configuration 5, in which the power processing units are actually power supplies for the charging circuits, this step should be delayed until completion of the power processor unit step. In all other configurations, the power processing circuit output power is equal to 1.002 times the sum of the input power of the charging circuit and the output power of the discharge circuit.

$$P_{ppu} = 1.002\,(P_{chg\ ckt\ input} + P_{disch\ ckt\ output})$$

The discharge circuit output is equal to the required system power.

f) Power Processor Unit

Having determined the input power to the Power Processor Unit, for all configurations except configuration 5, its output voltage is set equal to the bus voltage. In configuration 5, its output voltage is indeterminate, but may be conveniently estimated at approximately two volts higher than the charge circuit output voltage.

The power processor unit calculations are performed in the same manner as the discharge circuit calculations.

g) Solar Array

The output power of the solar array is equal to the input power of the power processor, except in the case of configuration 5, in which

$$P_{sa} = 1.002\,(P_{input,\ ppu} + P_{disch\ ckt\ output})$$

The output voltage of the solar array is set equal to the bus voltage and the calculations performed as in the discharge circuit calculations.

h) Solar Array Controls

The power handling requirements of the solar array controls are estimated as follows:

$$P_{a/c} + (P_{sa} - P_{load\ (minimum)})\ /2$$

$$\text{Array control voltage} + \text{Vbus}\ /\ 2$$

The calculations are then performed in a manner similar to the discharge circuit calculations.

Availability estimates are made in a similar fashion, except that, for the different configurations the availability has been determined to be independent of a number of factors.

Consequently, the availabilities have been arranged as a function of system power, and system bus voltage where applicable.

i) <u>Totalling</u>

$$Wt = \sum_{1}^{9} W_i$$

$$Cost = \sum_{1}^{9} C_i$$

$$A = \prod_{1}^{9} A_i$$

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APPENDIX G

PARAMETRIC DATA

The parametric data needed for calculation of the weight, cost, and reliability of the total power subsystem is arranged in the following manner.

Each subsystem element, such as battery, discharge circuit, charge control, etc. forms one major block of data. Within each of these blocks, the data are arranged in the following order:

1) Weight as a function of voltage and power output. As many graphs as are needed to encompass all of the significant variables are provided.

2) Cost as a function of voltage and power. More than one graph may be needed.

3) Losses as a function of voltage and power. More than one graph may be provided.

4) Availability as a function of power and resupply interval. More than one graph may be provided.

Where cell capacities vary, the graphs are arranged in the order 100 A-Hr, 50 A-Hr, 20 A-Hr.

Where battery discharge voltages vary, the graphs are arranged in the order RB + 1.0, 0.6, 0.25.

Where numbers of installed units vary the graphs are arranged in the order 5, 10, 15 installed units.

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1. "Modular Energy Storage and Conditioning (MESAC) Study," TRW Systems Group Interim Report, 10 December 1968.

2. C. L. Gould and G. S. Canetti, "System Lifetime Considerations," AIAA Sixth Annual Meeting and Technical Display, AIAA Paper No. 69-1080, October 1969.

3. R. L. Gervais and V. D. Kirkland, "Space Station Power Systems," AIAA Sixth Annual Meeting and Technical Display, AIAA Paper No. 69-1081, October 1969.

4. C. P. Llewellyn, "Optimization of Experiment Resource Utilization During Manned Space Station Missions," AIAA Sixth Annual Meeting and Technical Display, AIAA Paper No. 69-1065, October 1969.

5. B. Howard and G. T. Orrok, "Use of Man in Space," AIAA Sixth Annual Meeting and Technical Display, AIAA Paper No. 69-1045, October 1969.

6. I. Bazovsky, Reliability Theory and Practice, Prentice-Hall, Inc. New Jersey, 1965.

7. E. L. Jones, "Generic Component Failure Rates for Spacecraft Applications," TRW Systems Group Report No. 990-7175-R0-00, January 1970.

8. Failure Rate Data Hnadbook, Bureau of Naval Weapons, U. S. Naval Ordnance Laboratory, Corona, California.

9. F. C. Runge, "Space Station Operations: Requirement and Interactions," AIAA Sixth Annual Meeting and Technical Display, AIAA Paper No. 69-1062, October 1969.

10. A. Nussberger (North American Rockwell), "1969 Big Meadows Workshop on Large Solar Cell Power Systems Technology," Big Meadows, Virginia, October 1969.

11. J. Boretz, TRW Systems Group, Private Communication, February 1970.

12. "Analysis of Aerospace Power Conditioning Component Limitations," 09024-6001-R0-00, prepared for NASA under Contract No. CR-97000, April 1969.

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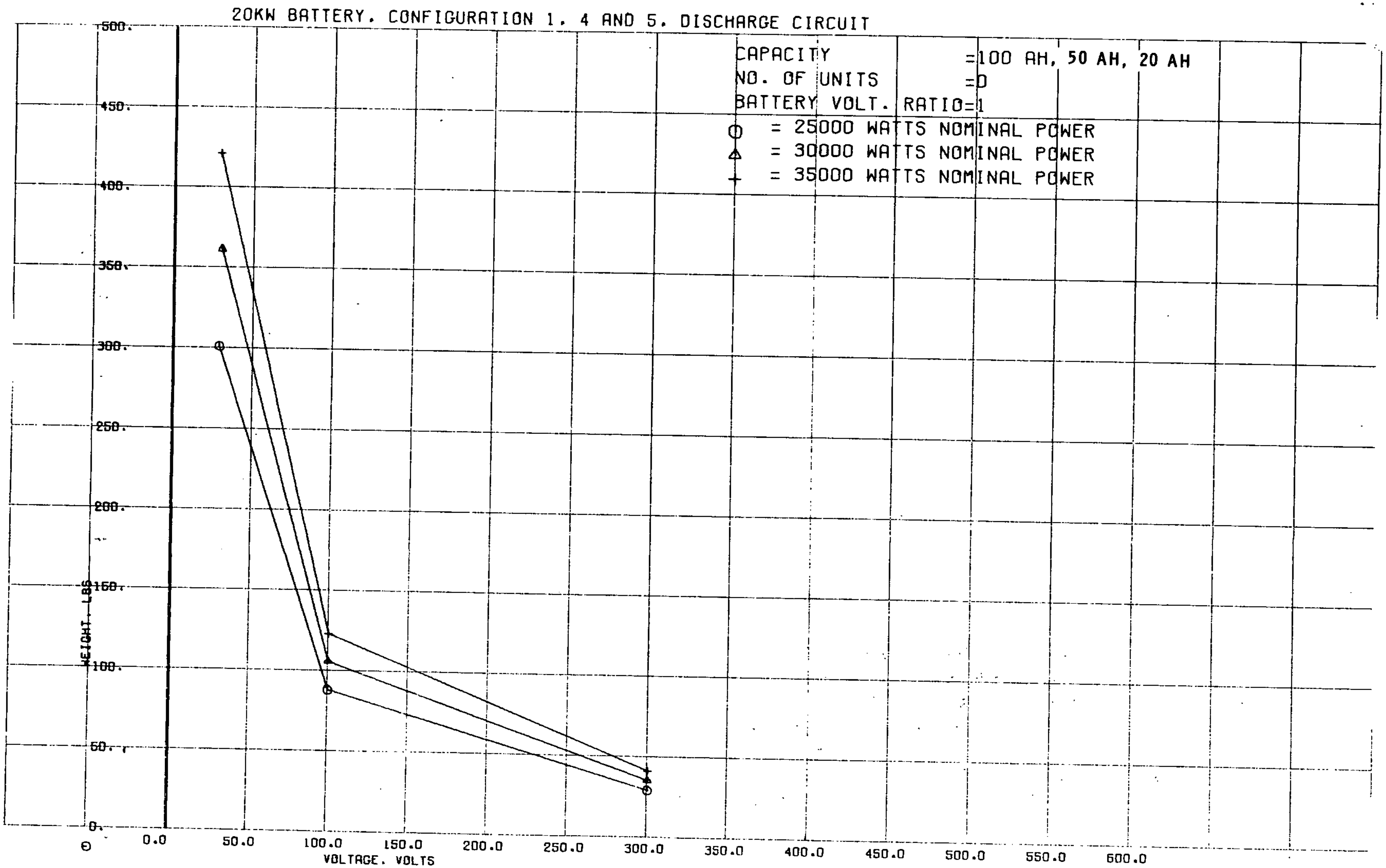
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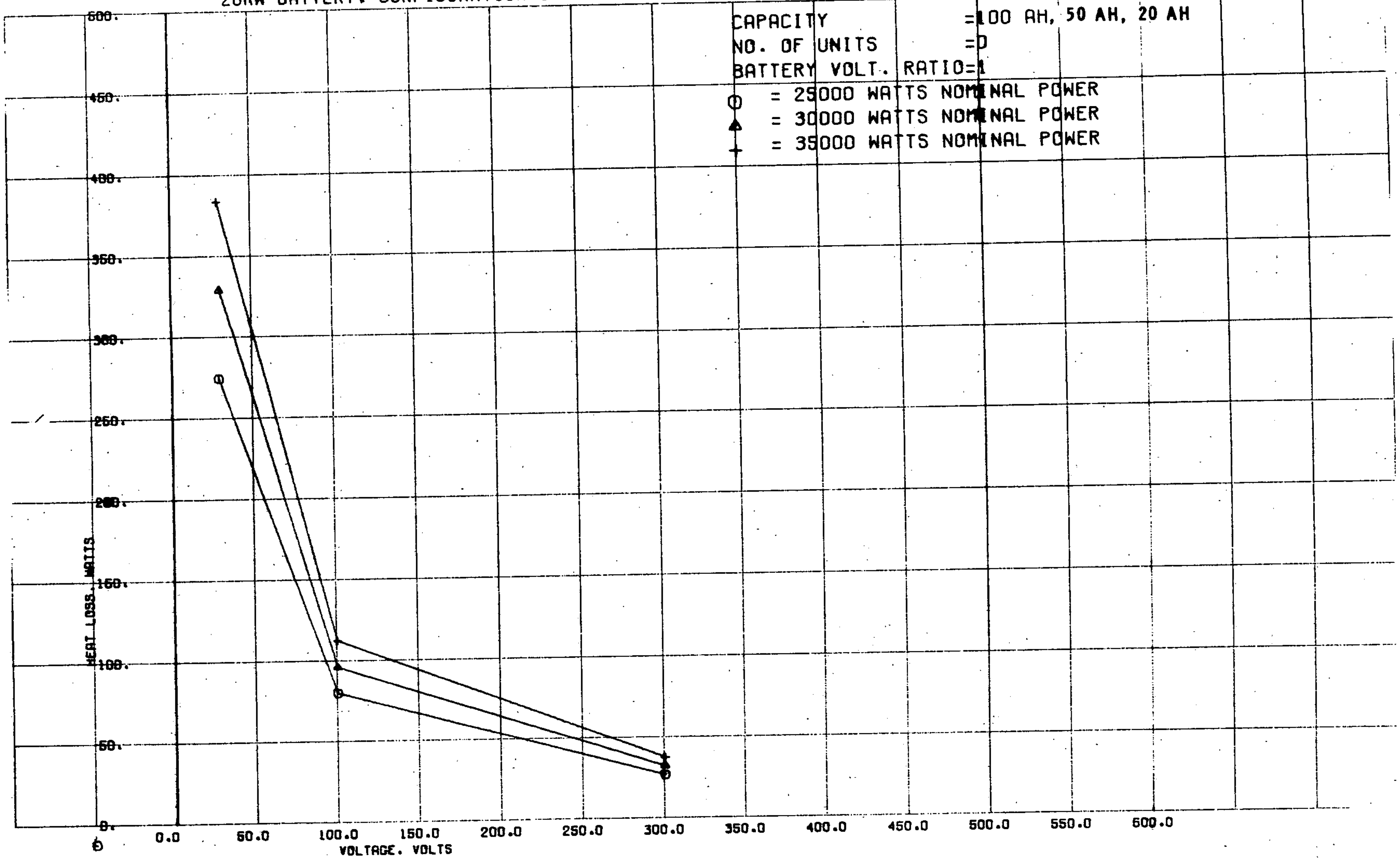
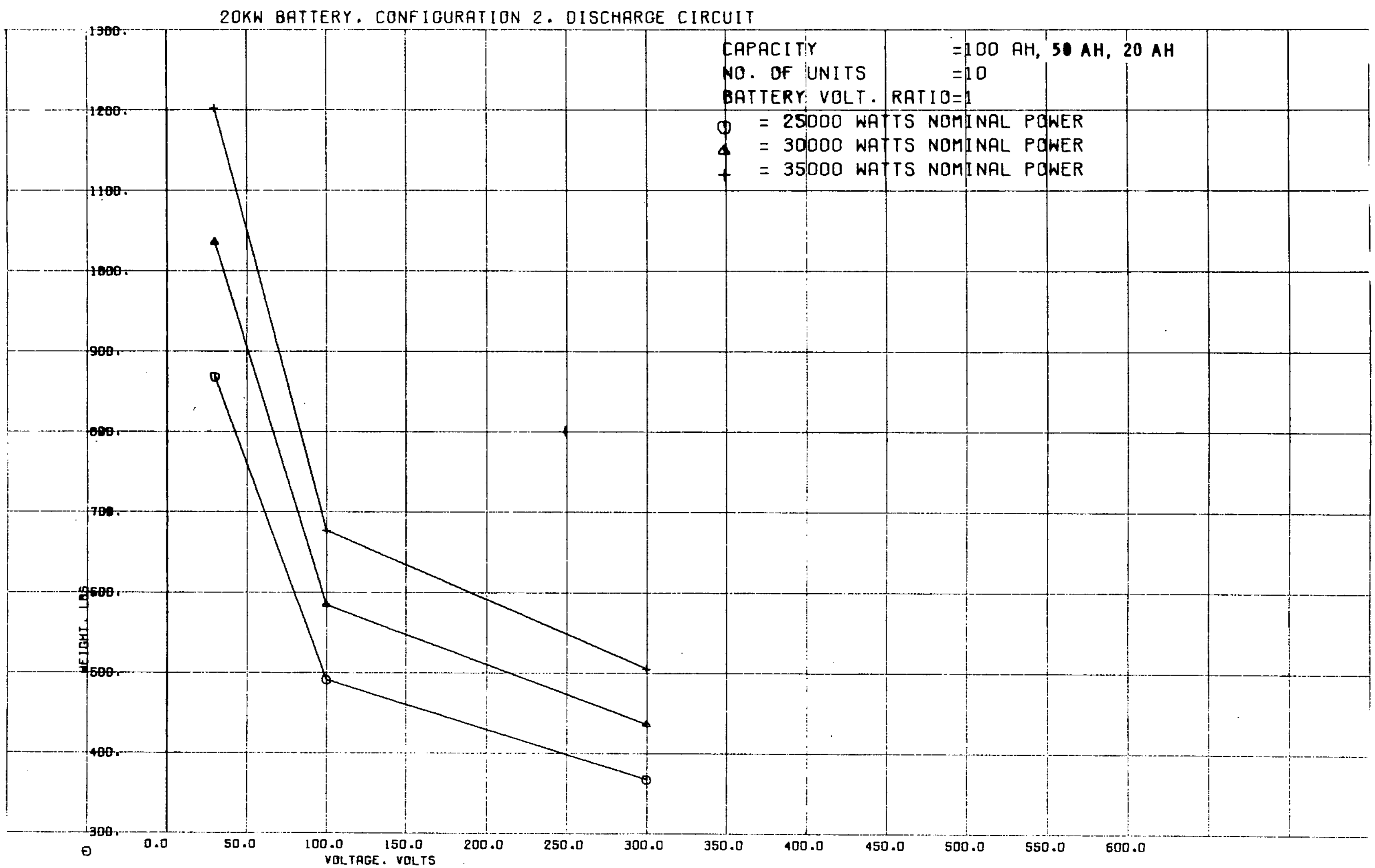
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
○ = 25000 WATTS NOMINAL POWER
△ = 30000 WATTS NOMINAL POWER
+ = 35000 WATTS NOMINAL POWER
WEIGHT. LBS
500.
450.
400.
350.
300.
250.
200.
150.
100.
50.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

20KW BATTERY. CONFIGURATION 1. 4 AND 5. DISCHARGE CIRCUIT

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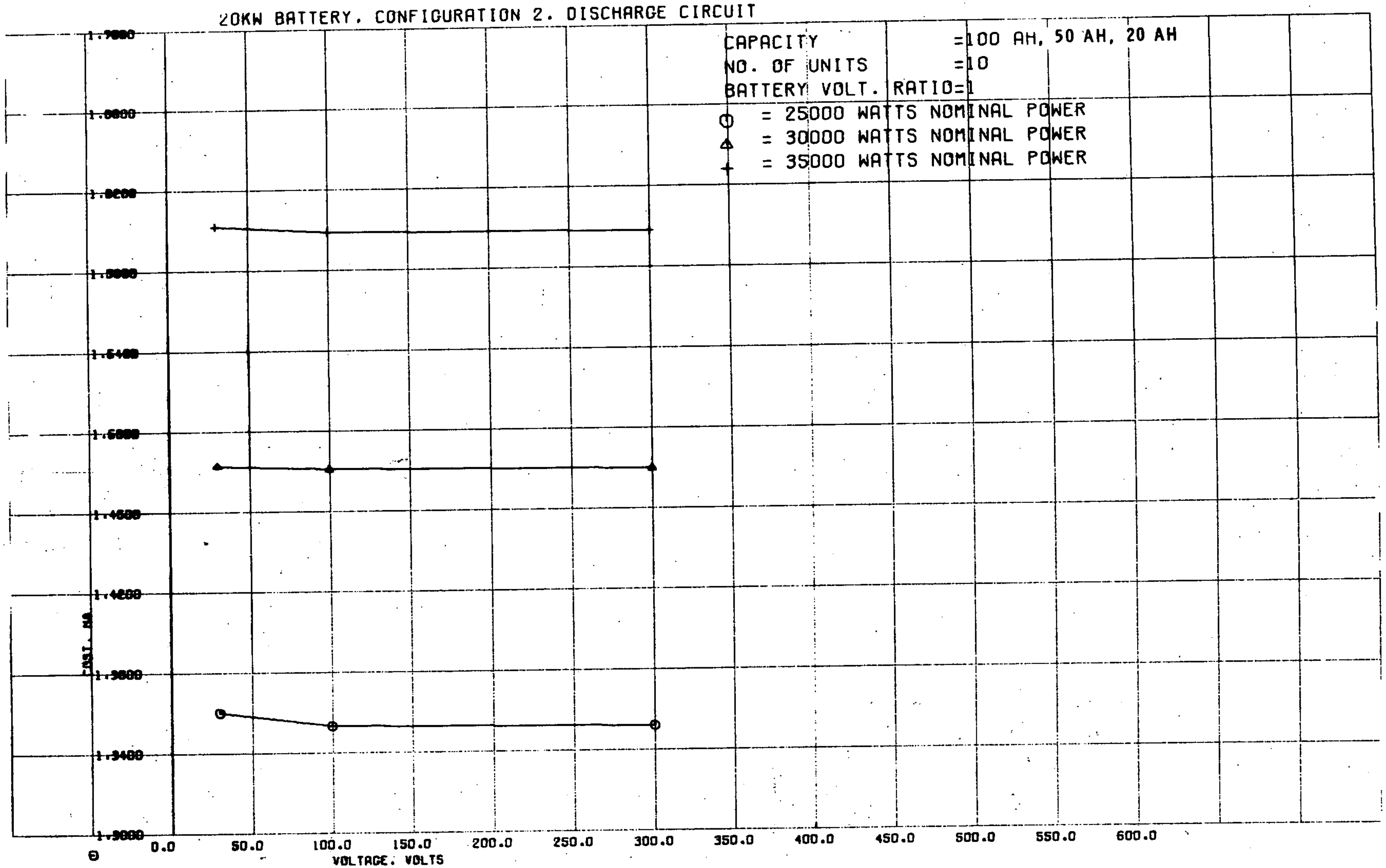
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
400.
300.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 2. DISCHARGE CIRCUIT
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NO. OF UNITS =10
BATTERY VOLT. RATIO=1
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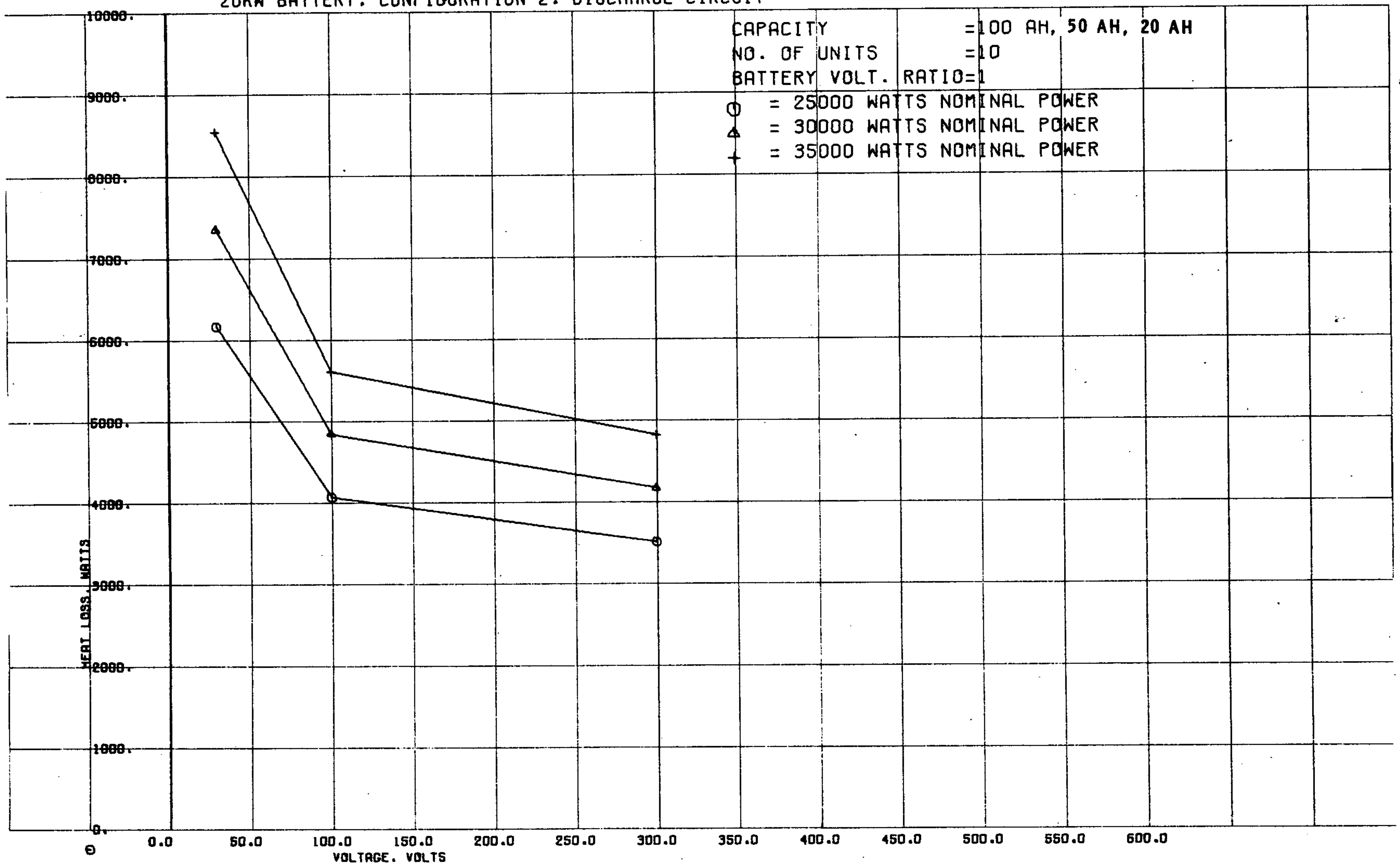
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
COST, NO
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

20KW BATTERY. CONFIGURATION 2. DISCHARGE CIRCUIT



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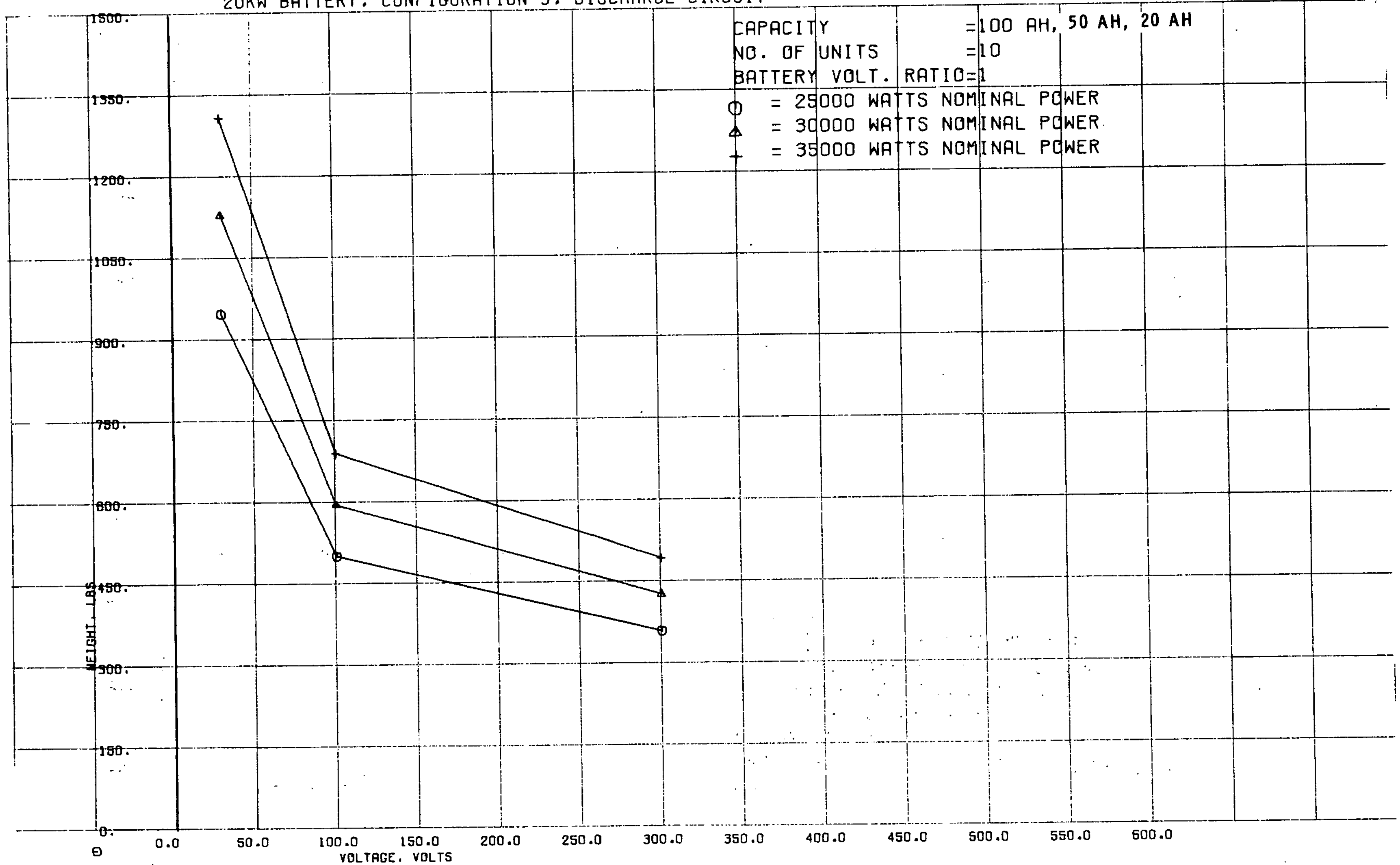
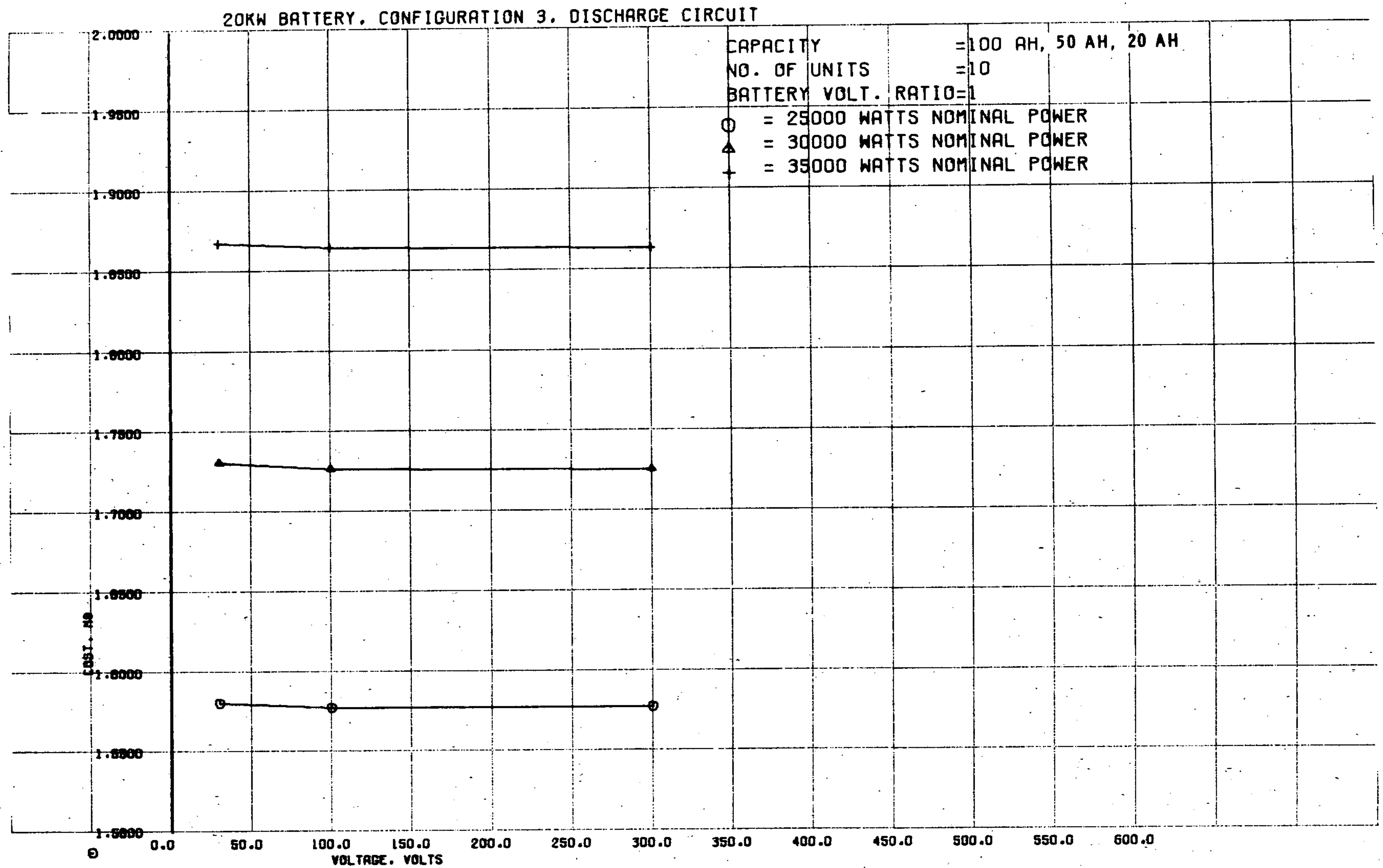
20KW BATTERY, CONFIGURATION 3, DISCHARGE CIRCUIT

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NO. OF UNITS =10
BATTERY VOLT. RATIO=1
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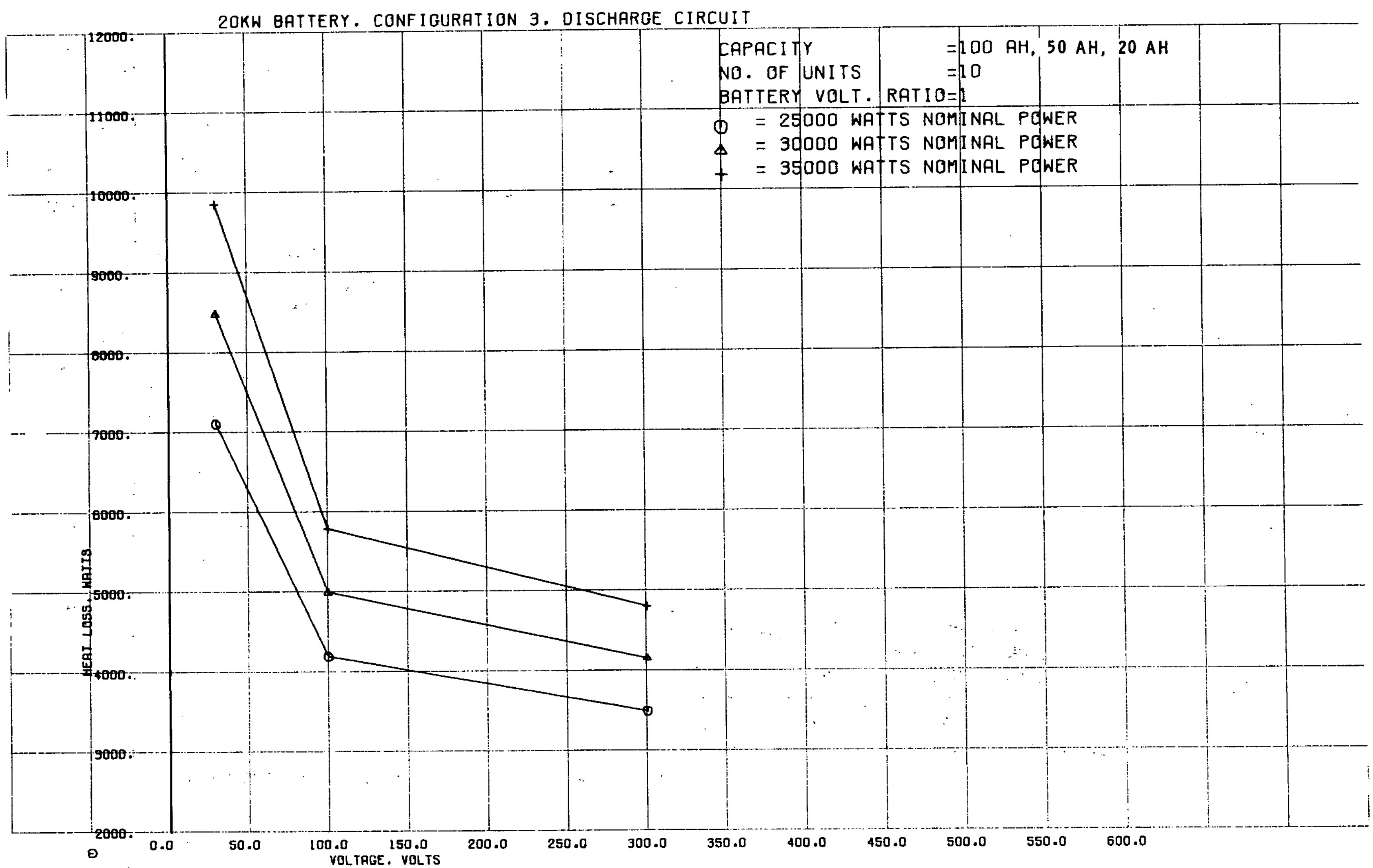
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS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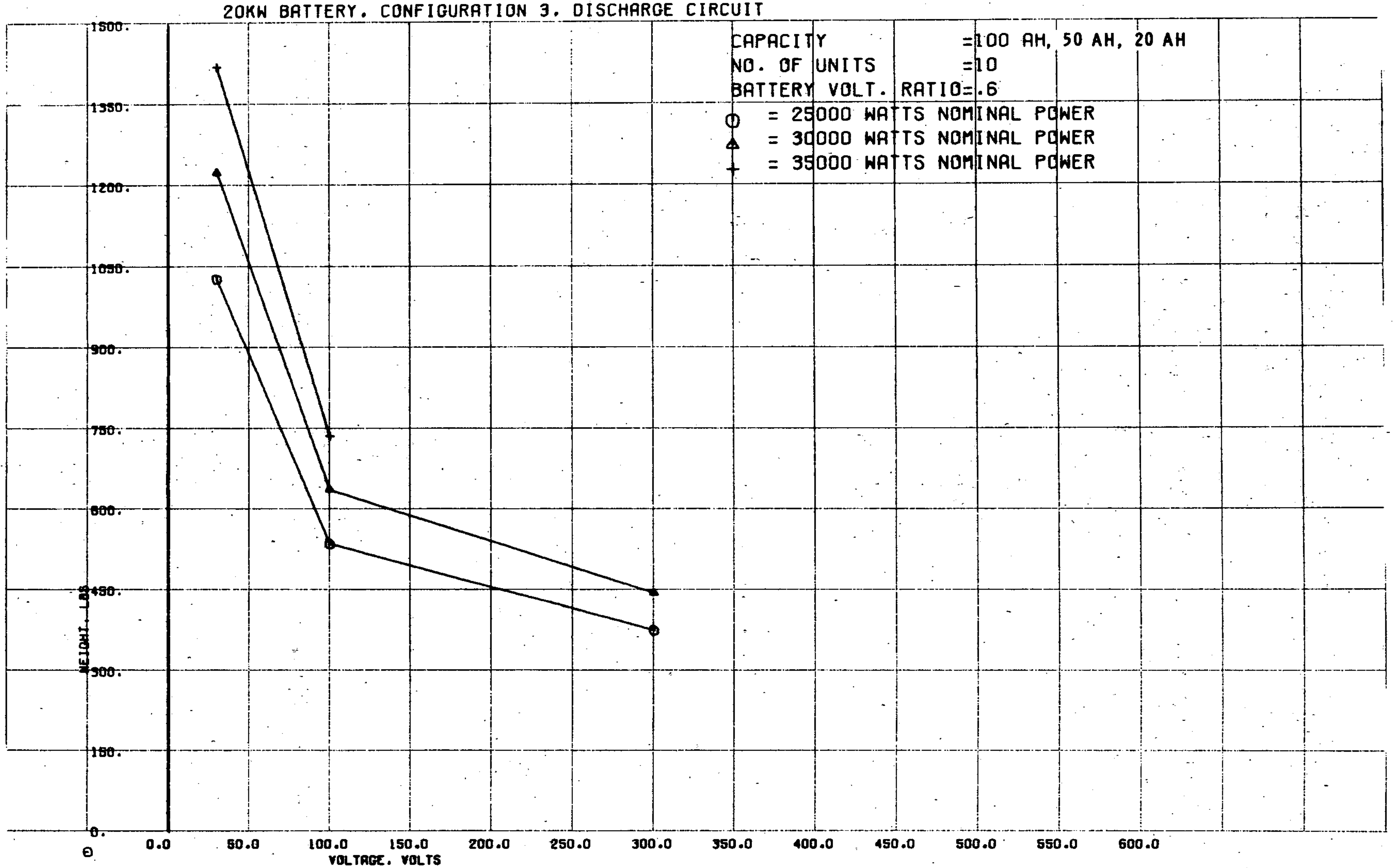
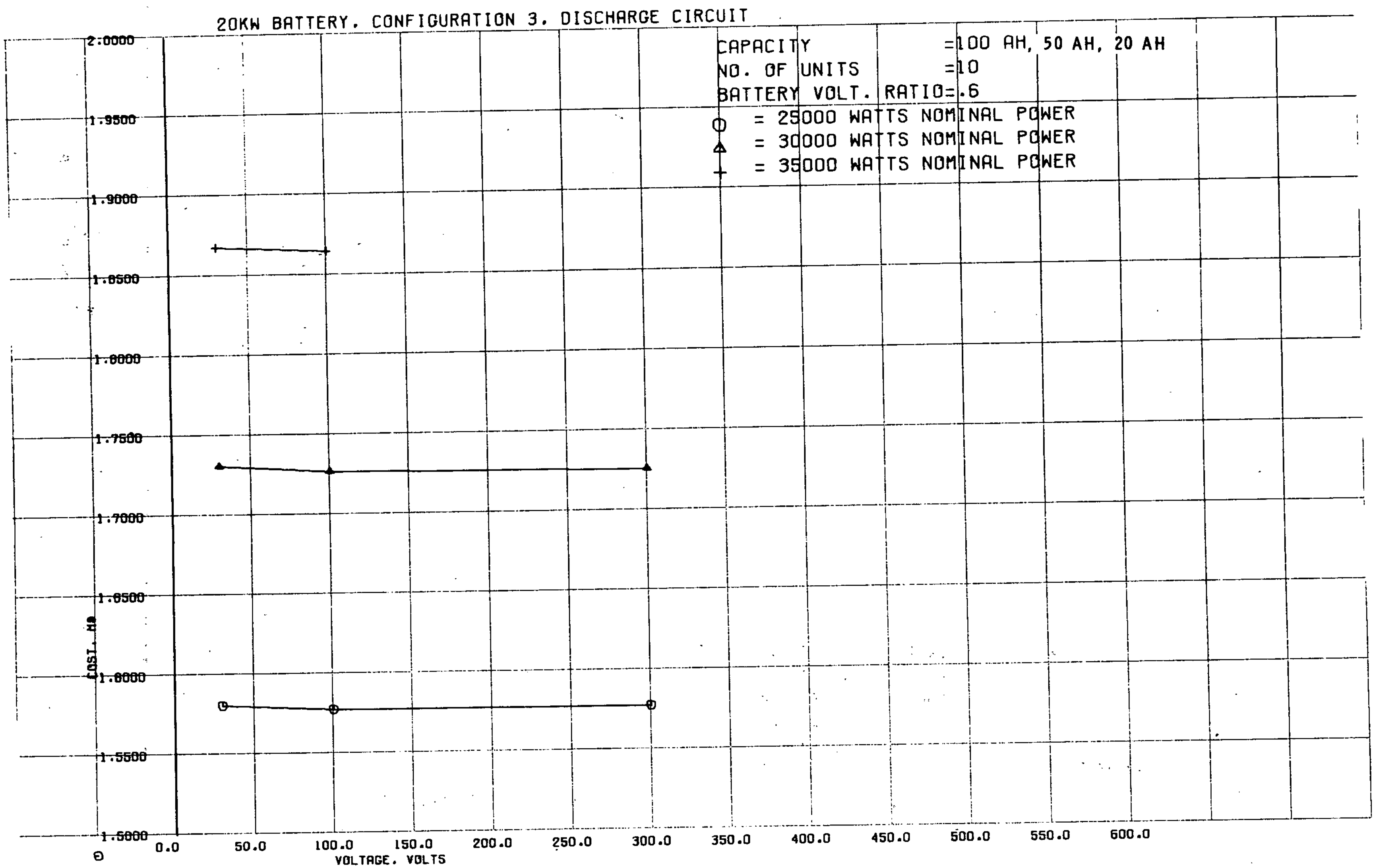
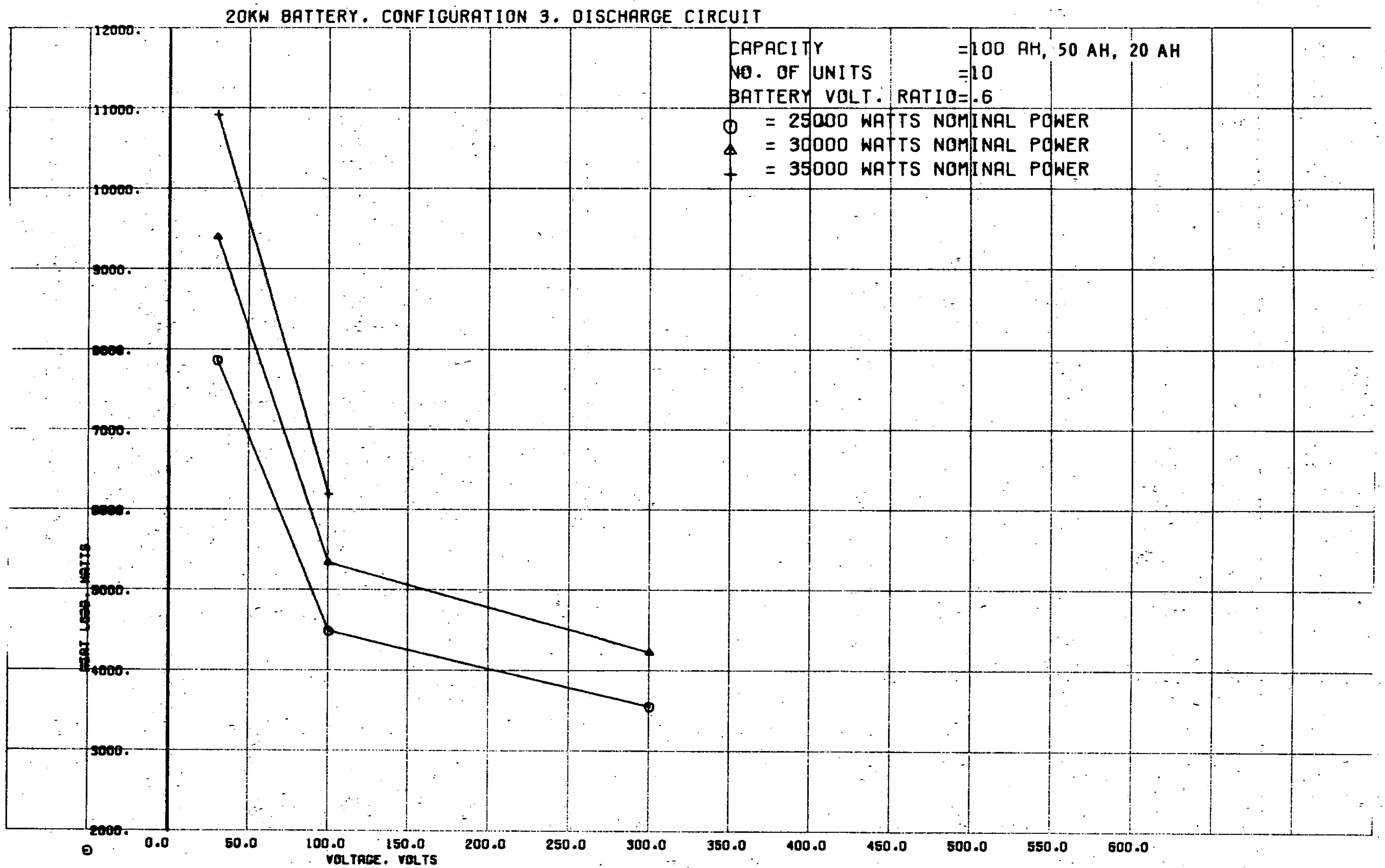
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
HEAT LOSS, WATTS
12000.
11000.
10000.
9000.
8000.
7000.
6000.
5000.
4000.
3000.
2000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

20KW BATTERY. CONFIGURATION 3. DISCHARGE CIRCUIT





20KW BATTERY. CONFIGURATION 3. DISCHARGE CIRCUIT
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
COST, M$
2.0000
1.9500
1.9000
1.8500
1.8000
1.7500
1.7000
1.6500
1.6000
1.5500
1.5000
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 3. DISCHARGE CIRCUIT
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS

SEE CONFIGURATION 1

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SEE CONFIGURATION 1

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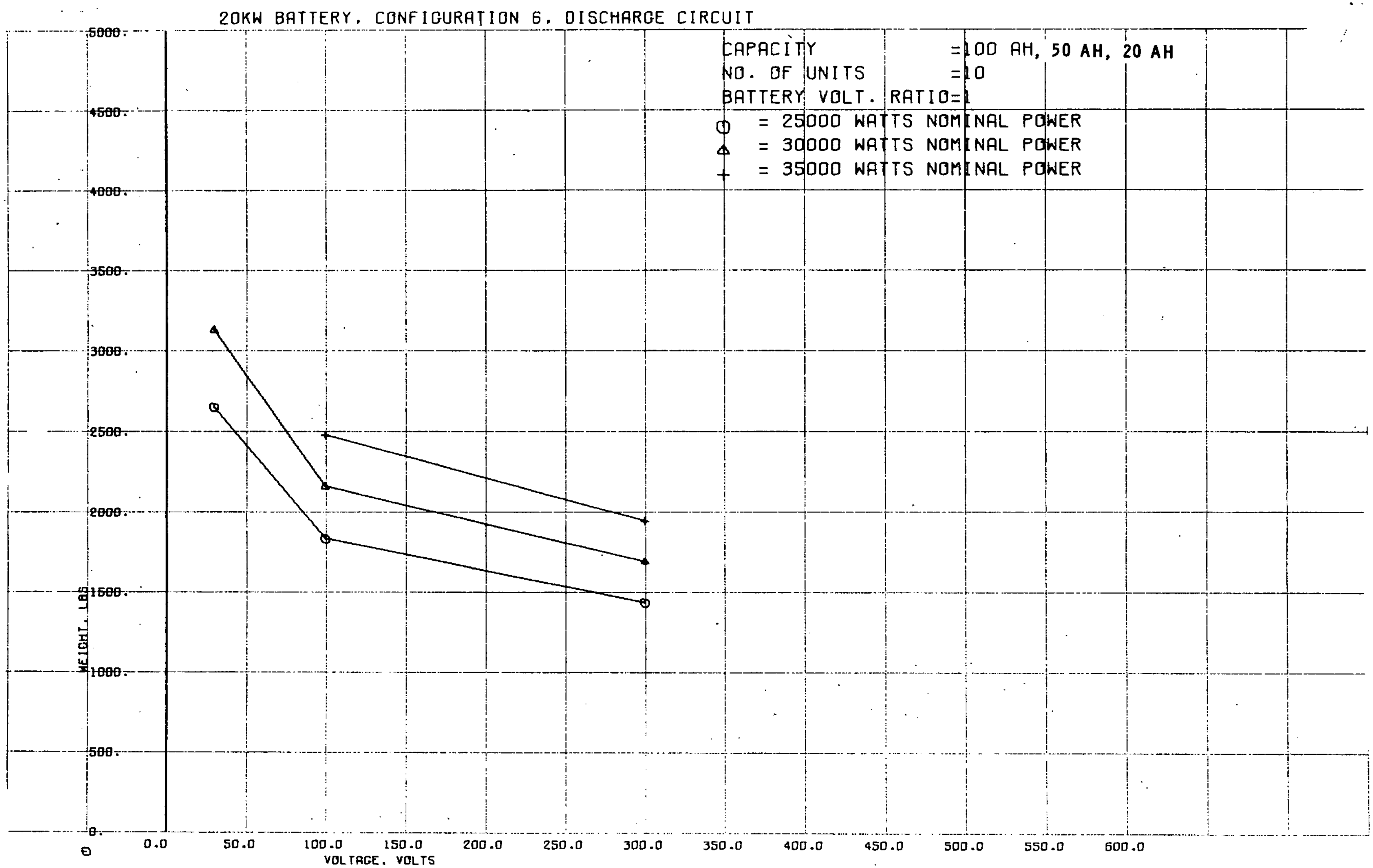

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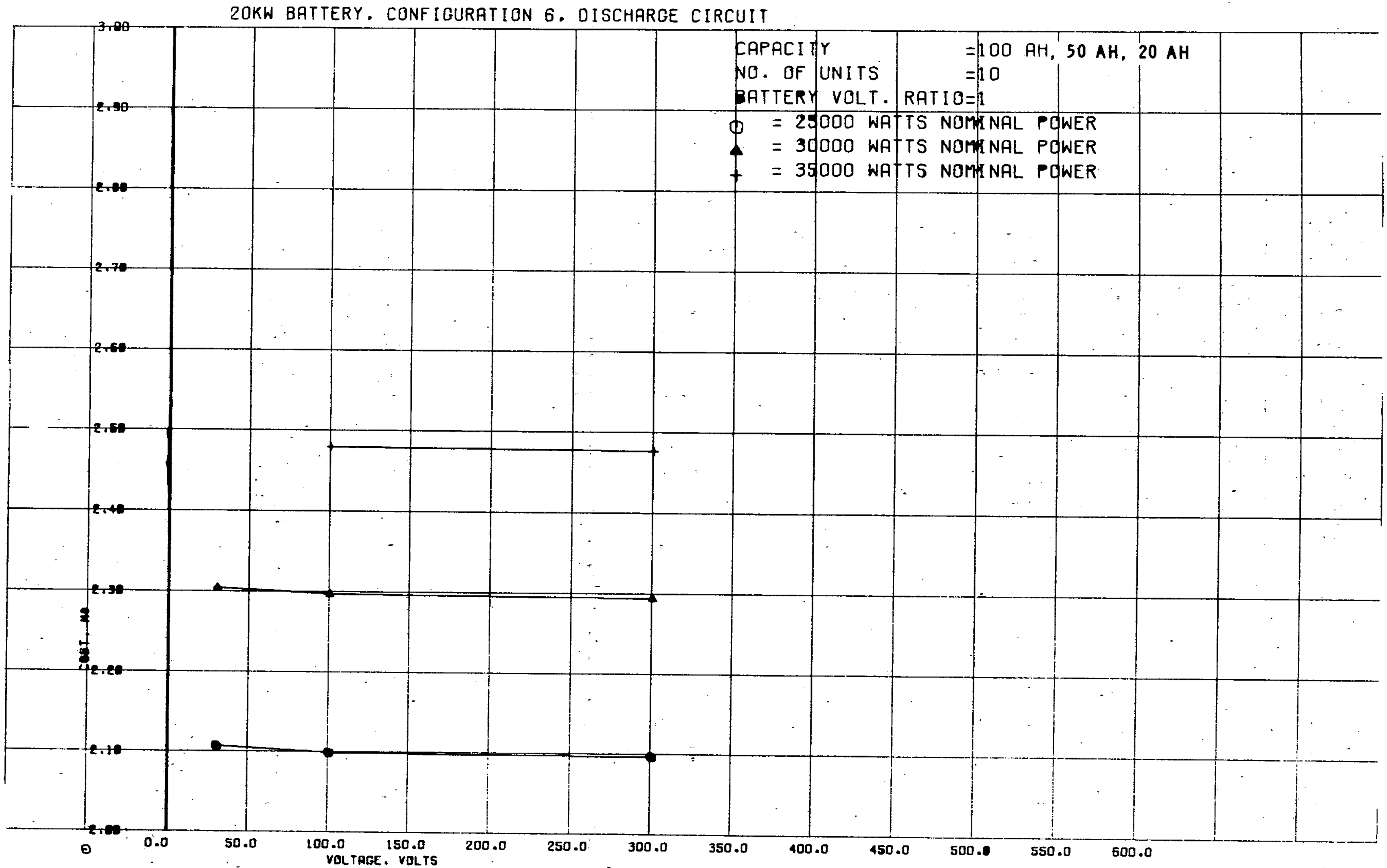
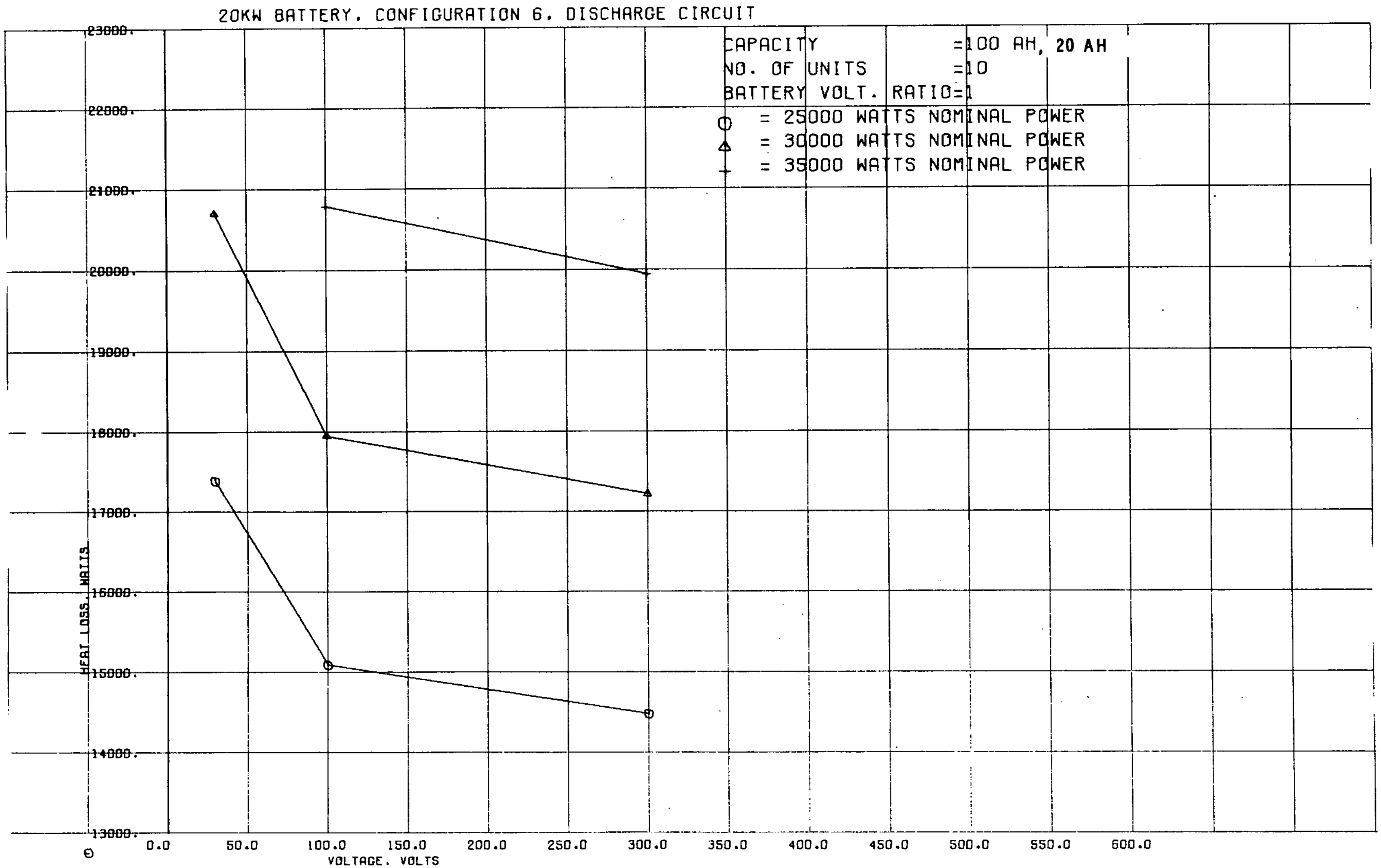
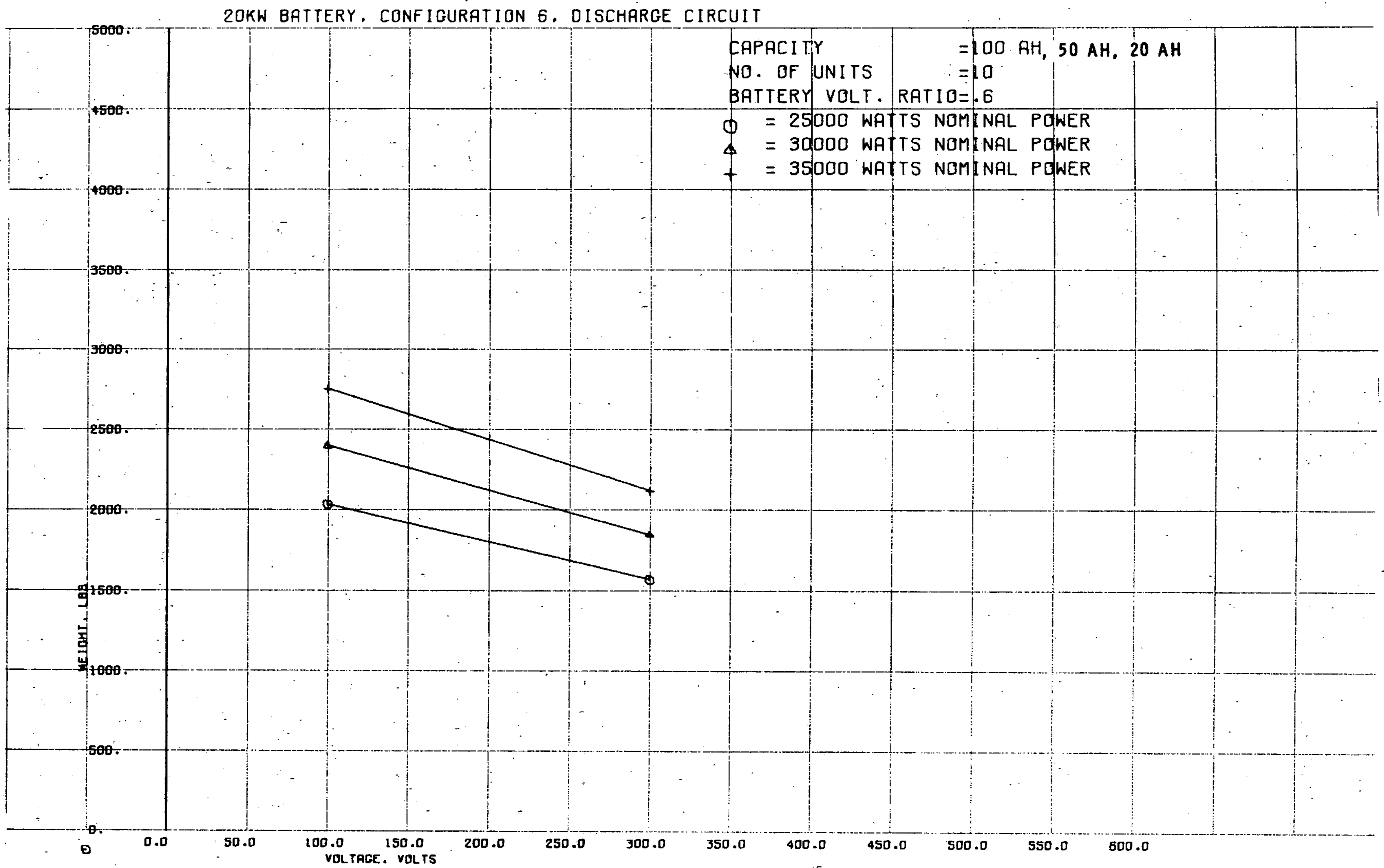
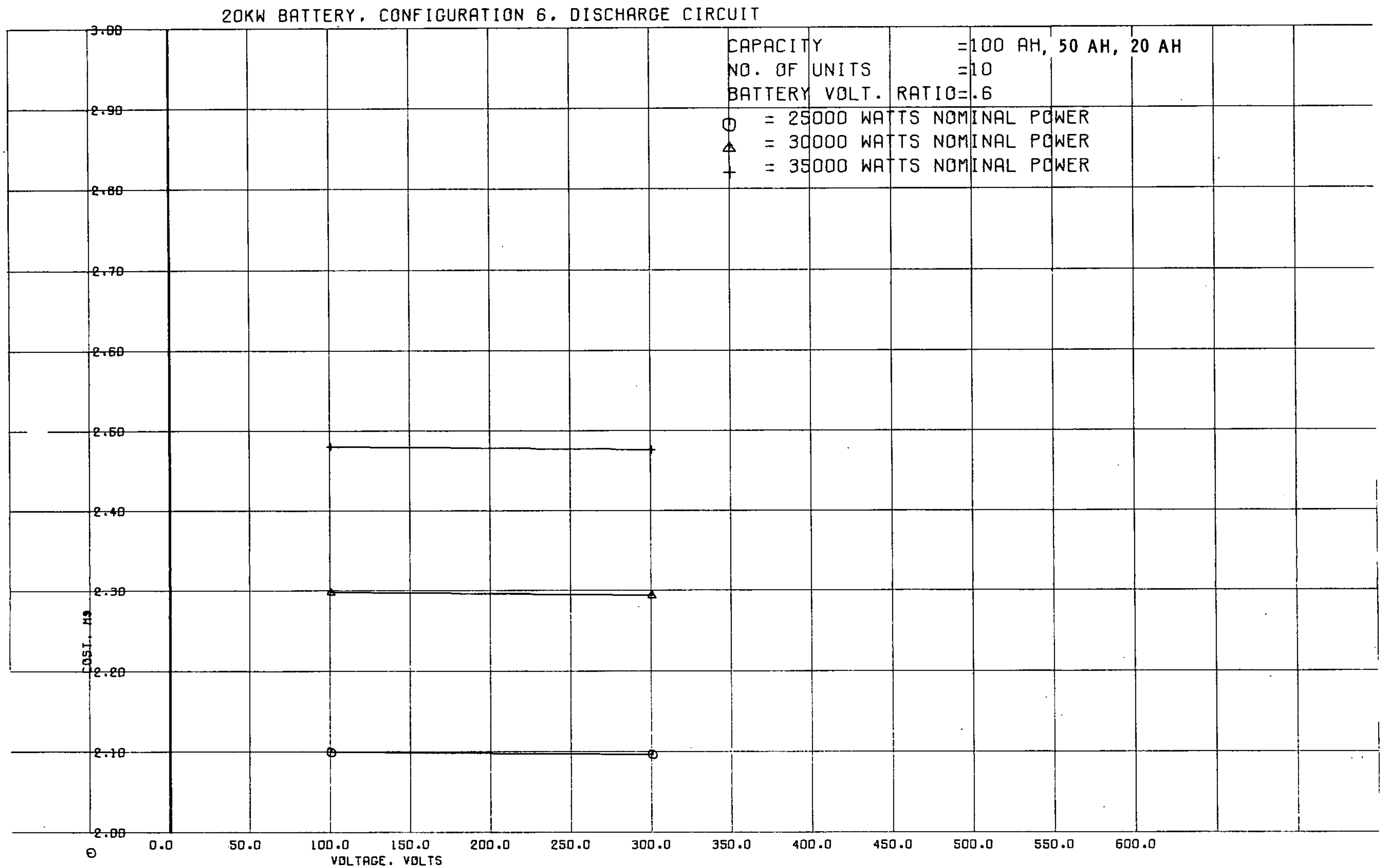


20KW BATTERY, CONFIGURATION 6, DISCHARGE CIRCUIT
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 6. DISCHARGE CIRCUIT
CAPACITY =100 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, DISCHARGE CIRCUIT
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
WEIGHT, LBS
5000.
4500.
4000.
3500.
3000.
2500.
2000.
1500.
1000.
500.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS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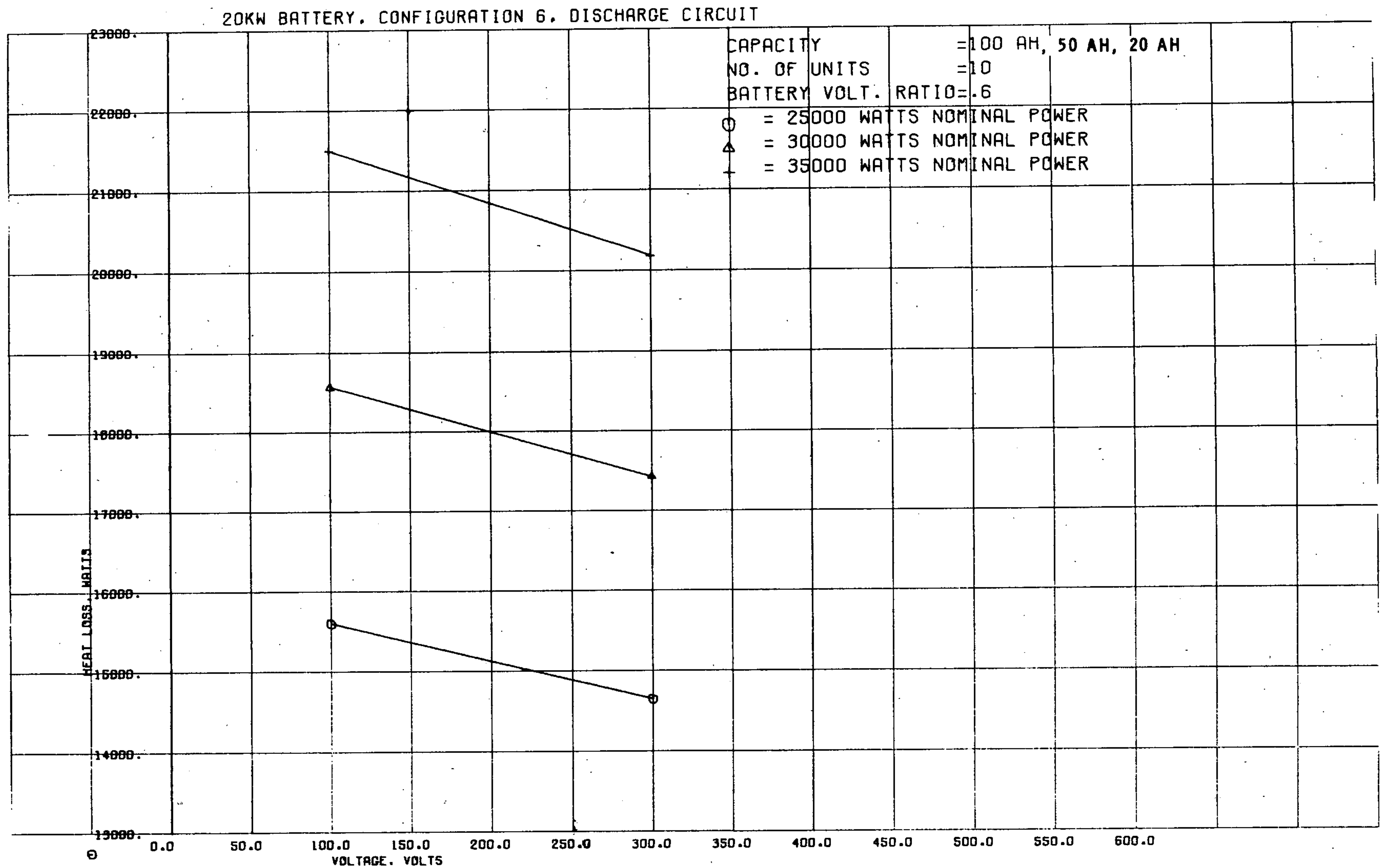
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0



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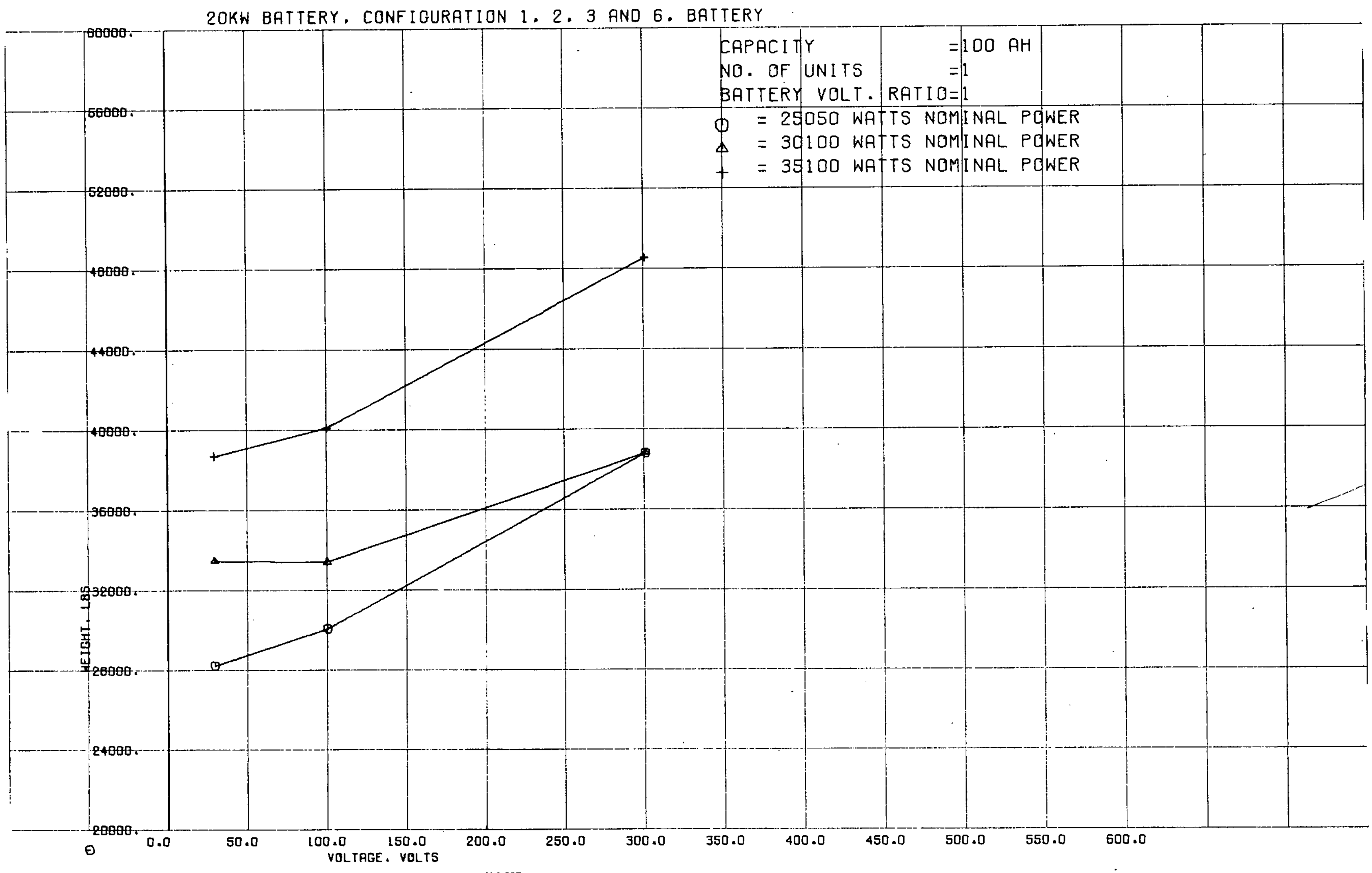
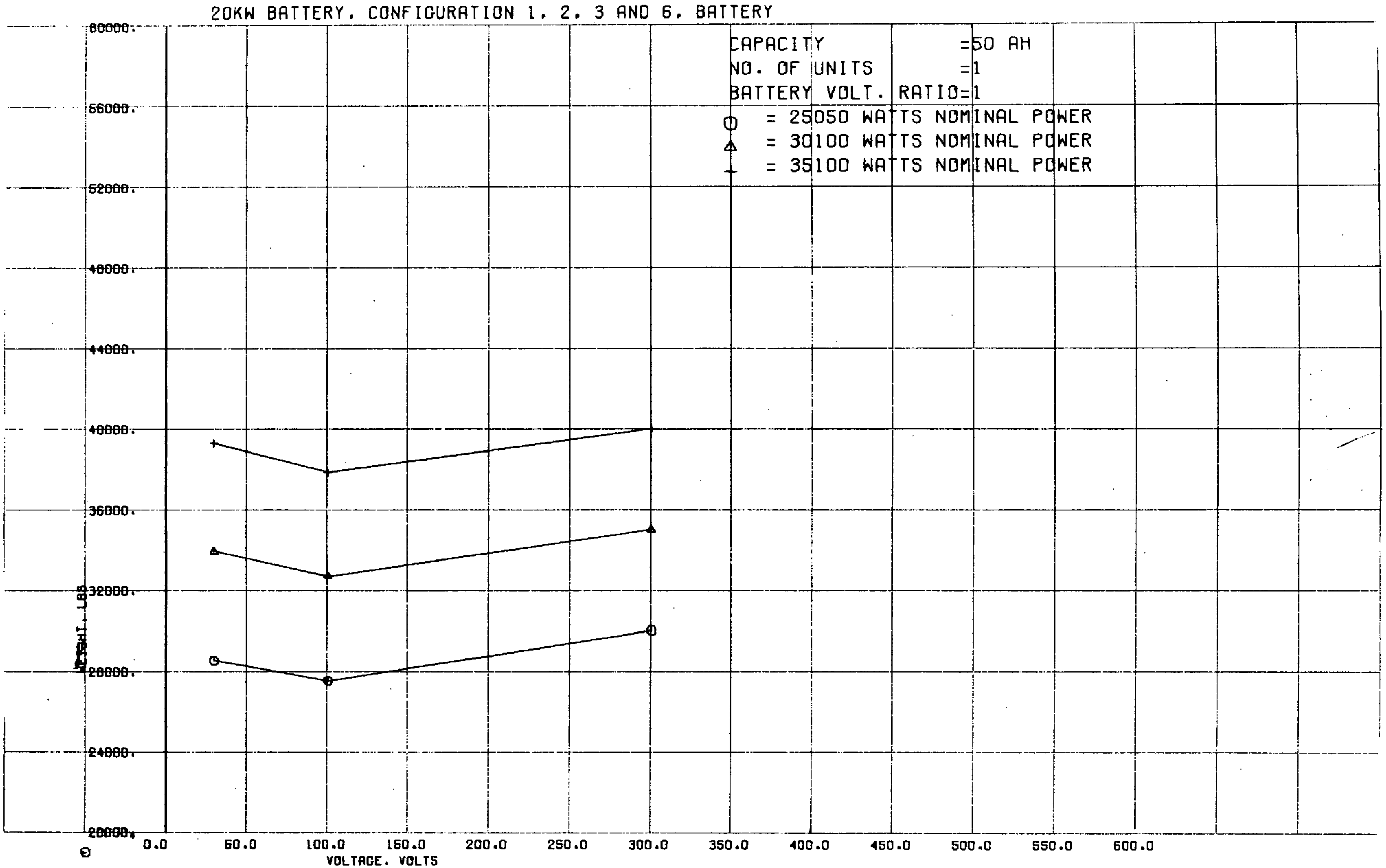
CAPACITY =100 AH, 50 AH, 20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25000 WATTS NOMINAL POWER
= 30000 WATTS NOMINAL POWER
= 35000 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
23000.
22000.
21000.
20000.
19000.
18000.
17000.
16000.
15000.
14000.
13000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0



20KW BATTERY. CONFIGURATION 1. 2. 3 AND 6. BATTERY
CAPACITY =100 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
WEIGHT, LBS
60000.
56000.
52000.
48000.
44000.
40000.
36000.
32000.
28000.
24000.
20000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS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CAPACITY =50 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
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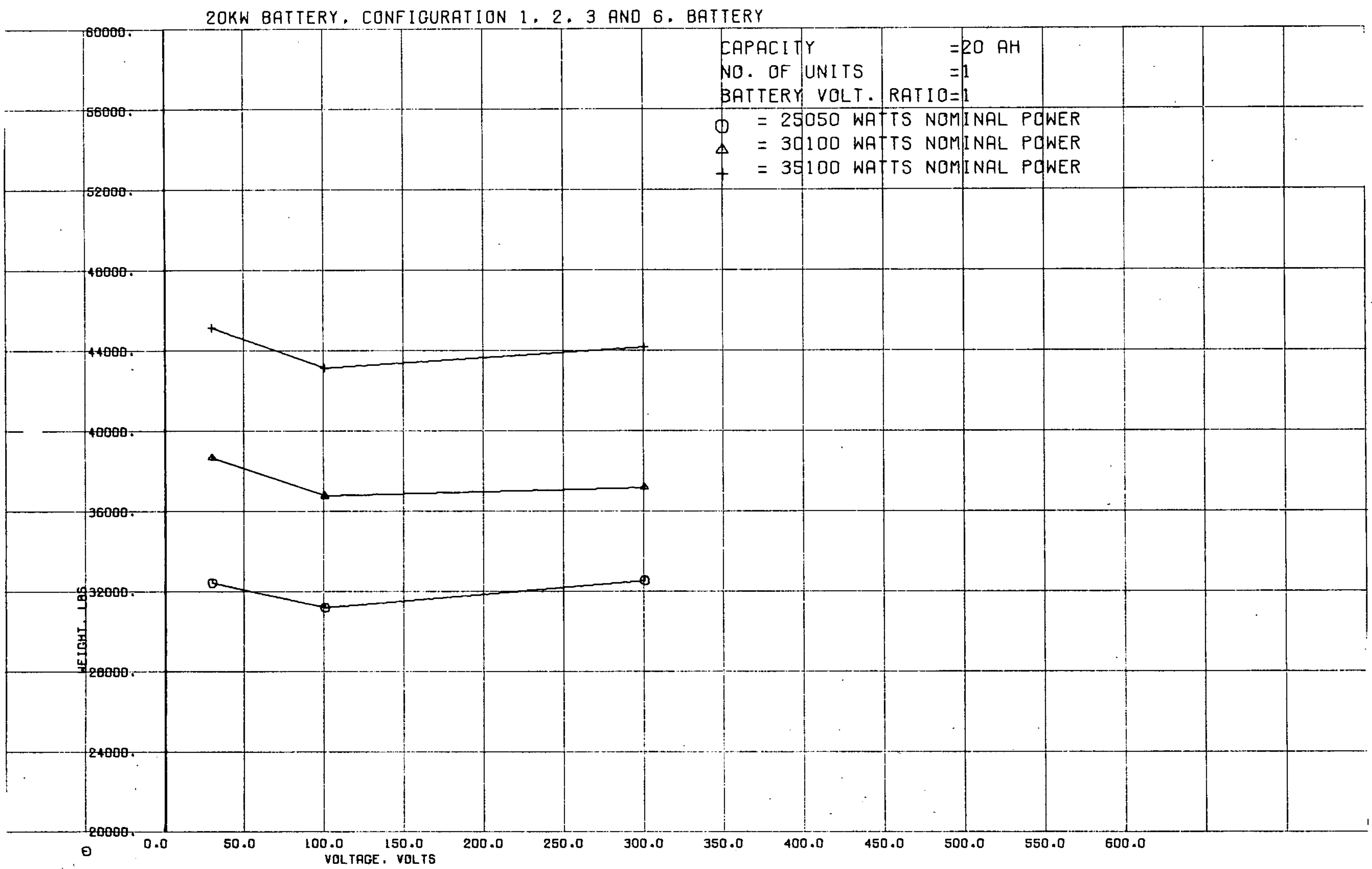
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
60000.
56000.
52000.
48000.
44000.
40000.
36000.
32000.
28000.
24000.
20000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS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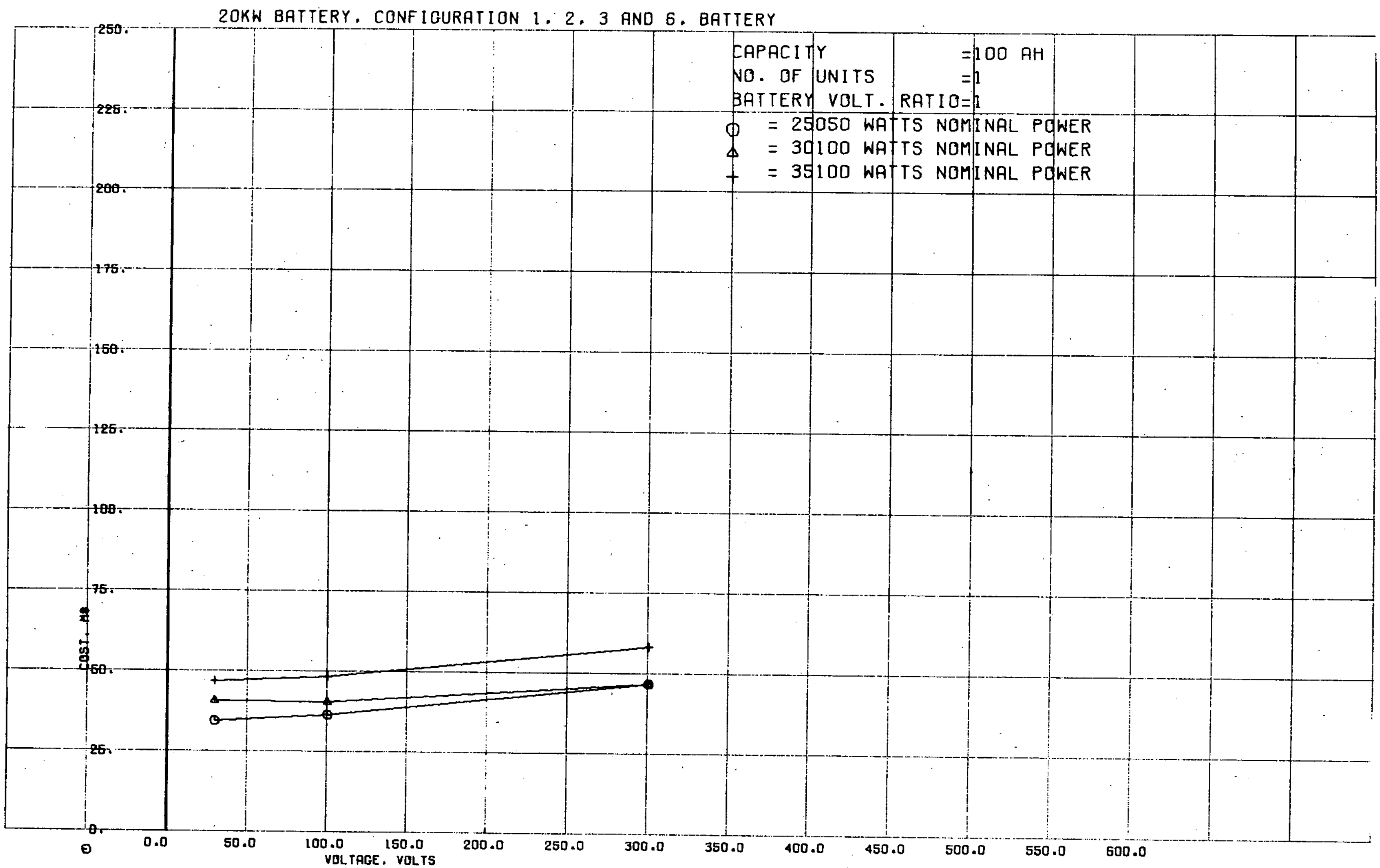
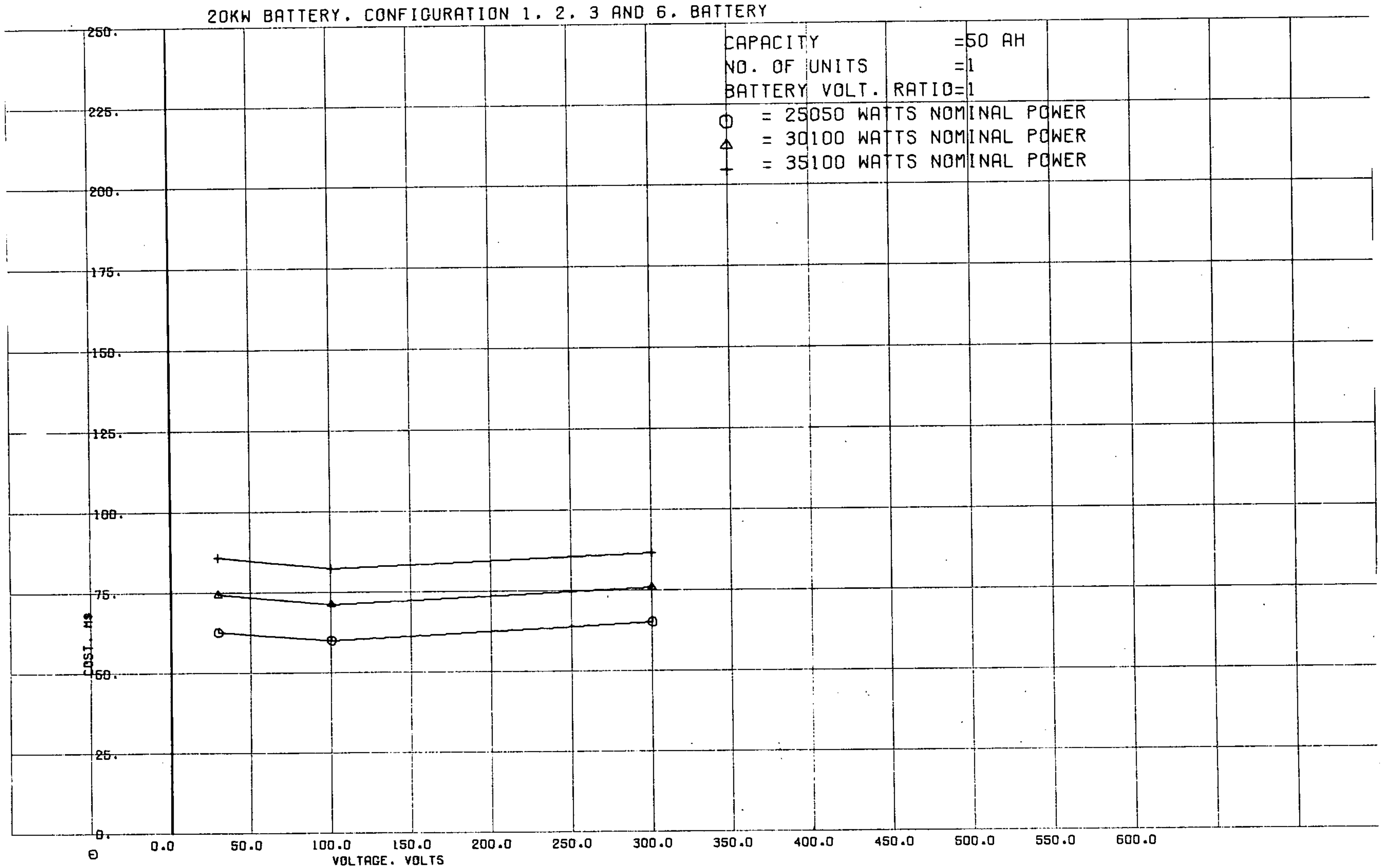
CAPACITY =20 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
○ = 25050 WATTS NOMINAL POWER
△ = 30100 WATTS NOMINAL POWER
+ = 35100 WATTS NOMINAL POWER
WEIGHT, LBS
60000.
56000.
52000.
48000.
44000.
40000.
36000.
32000.
28000.
24000.
20000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY, CONFIGURATION 1, 2, 3 AND 6, BATTERY
CAPACITY =100 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS
0.
25.
50.
75.
100.
125.
150.
175.
200.
225.
250.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0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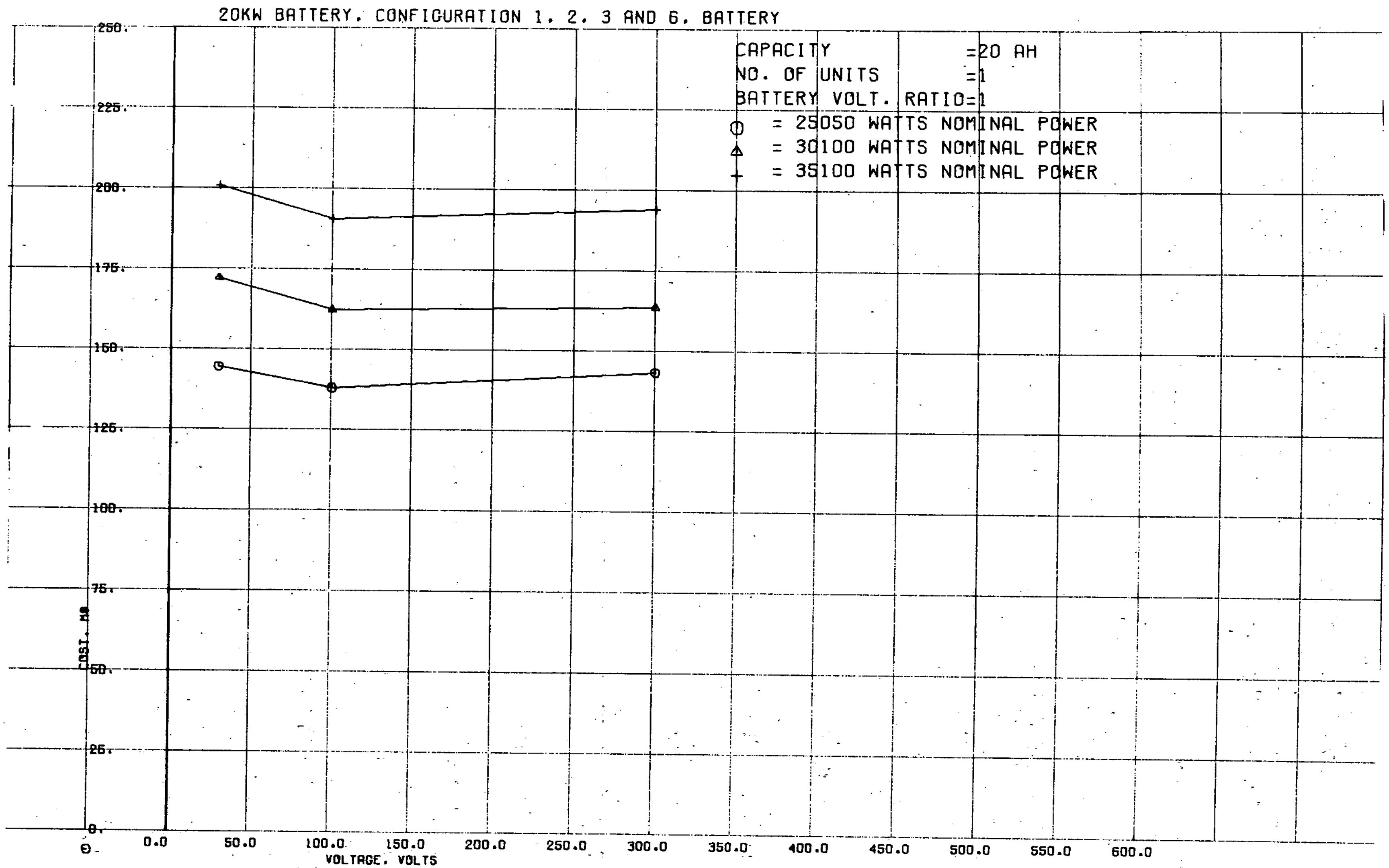
CAPACITY =50 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
250.
225.
200.
175.
150.
125.
100.
75.
50.
25.
0.
COST. M$
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS



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CAPACITY =20 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
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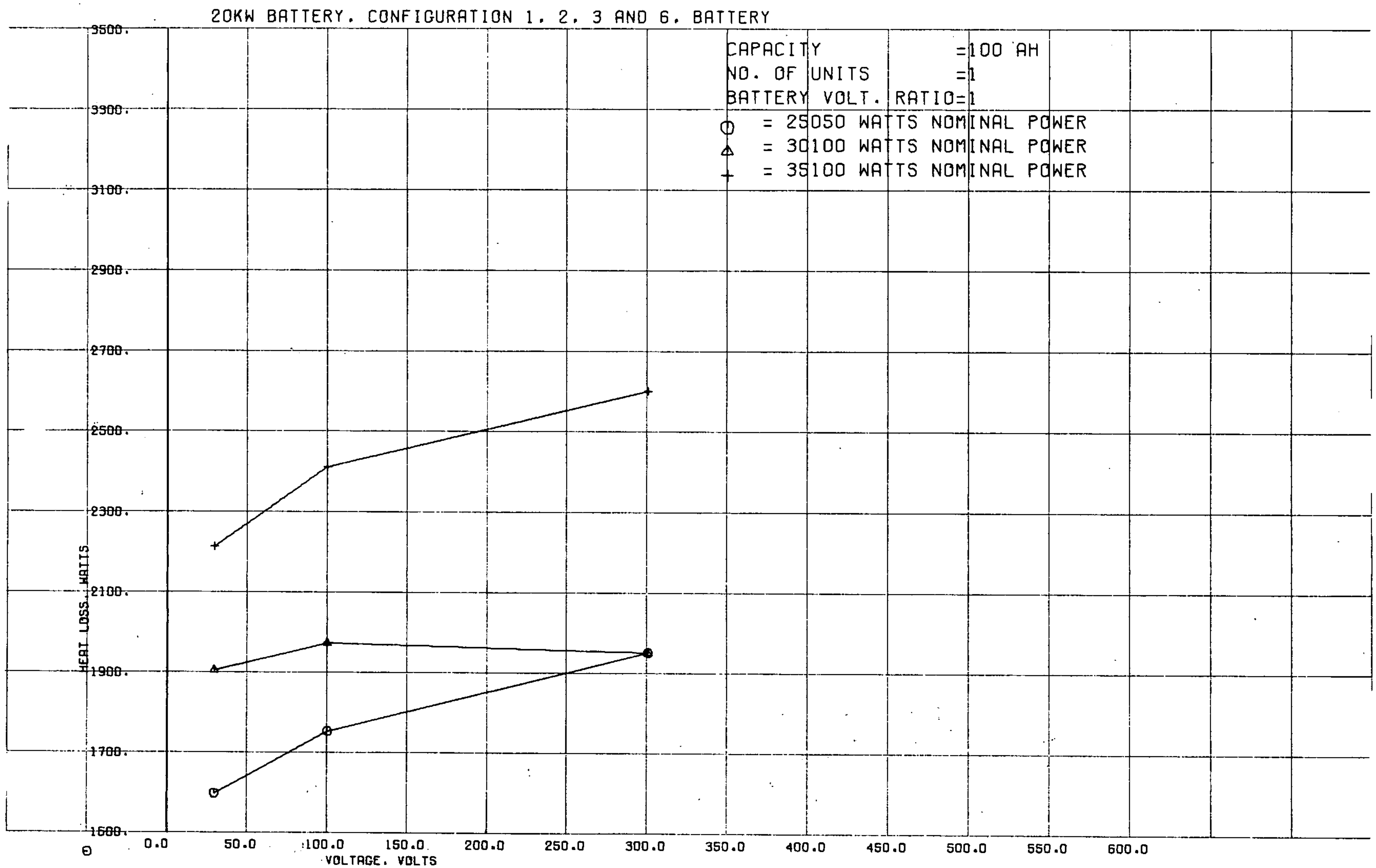
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS



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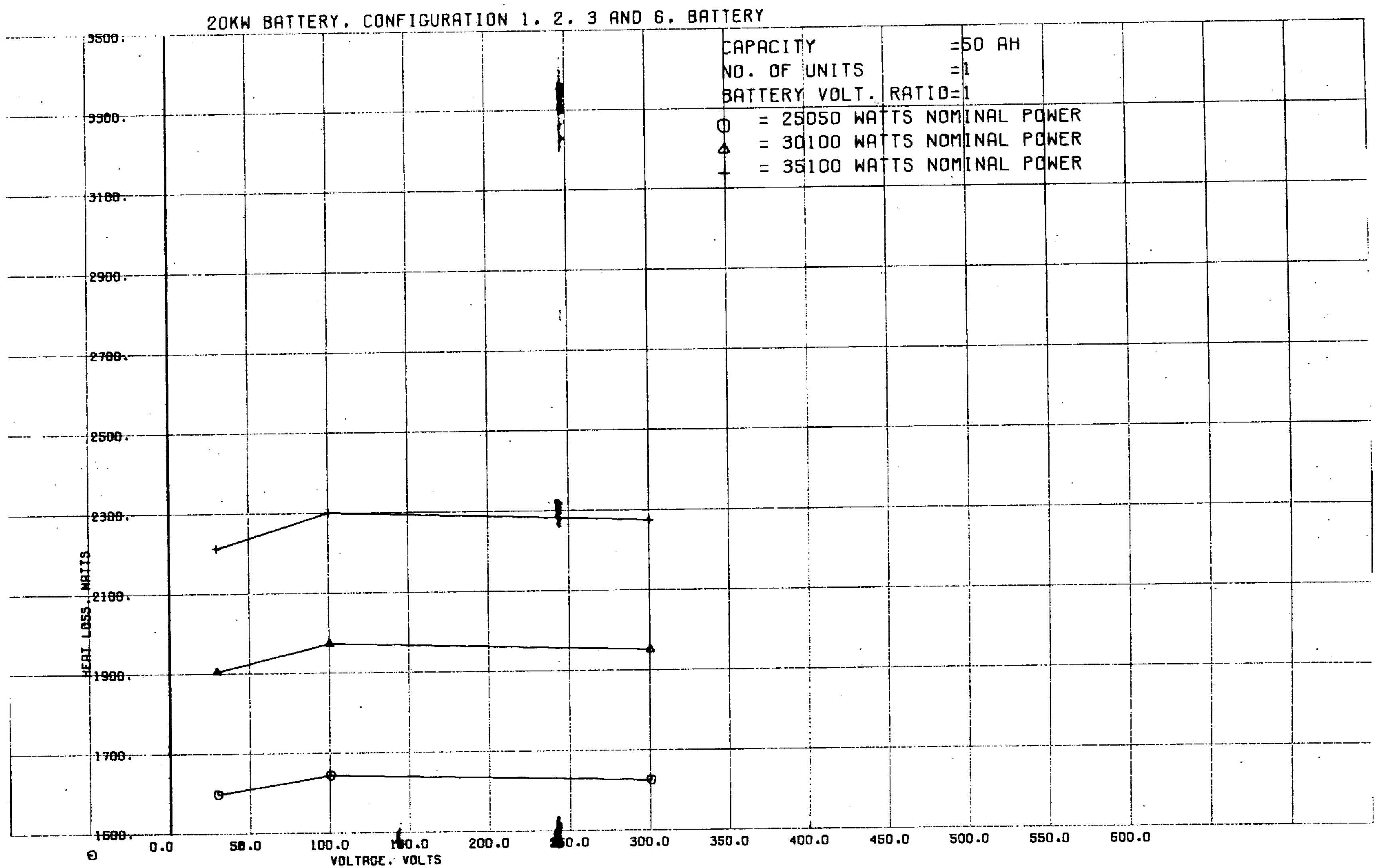
CAPACITY =100 AH
NO. OF UNITS =1
BATTERY VOLT. RATIO=1
O = 25050 WATTS NOMINAL POWER
Δ = 30100 WATTS NOMINAL POWER
+ = 35100 WATTS NOMINAL POWER
HEAT LOSS, WATTS
3500.
3300.
3100.
2900.
2700.
2500.
2300.
2100.
1900.
1700.
1500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



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NO. OF UNITS =1
BATTERY VOLT. RATIO=1
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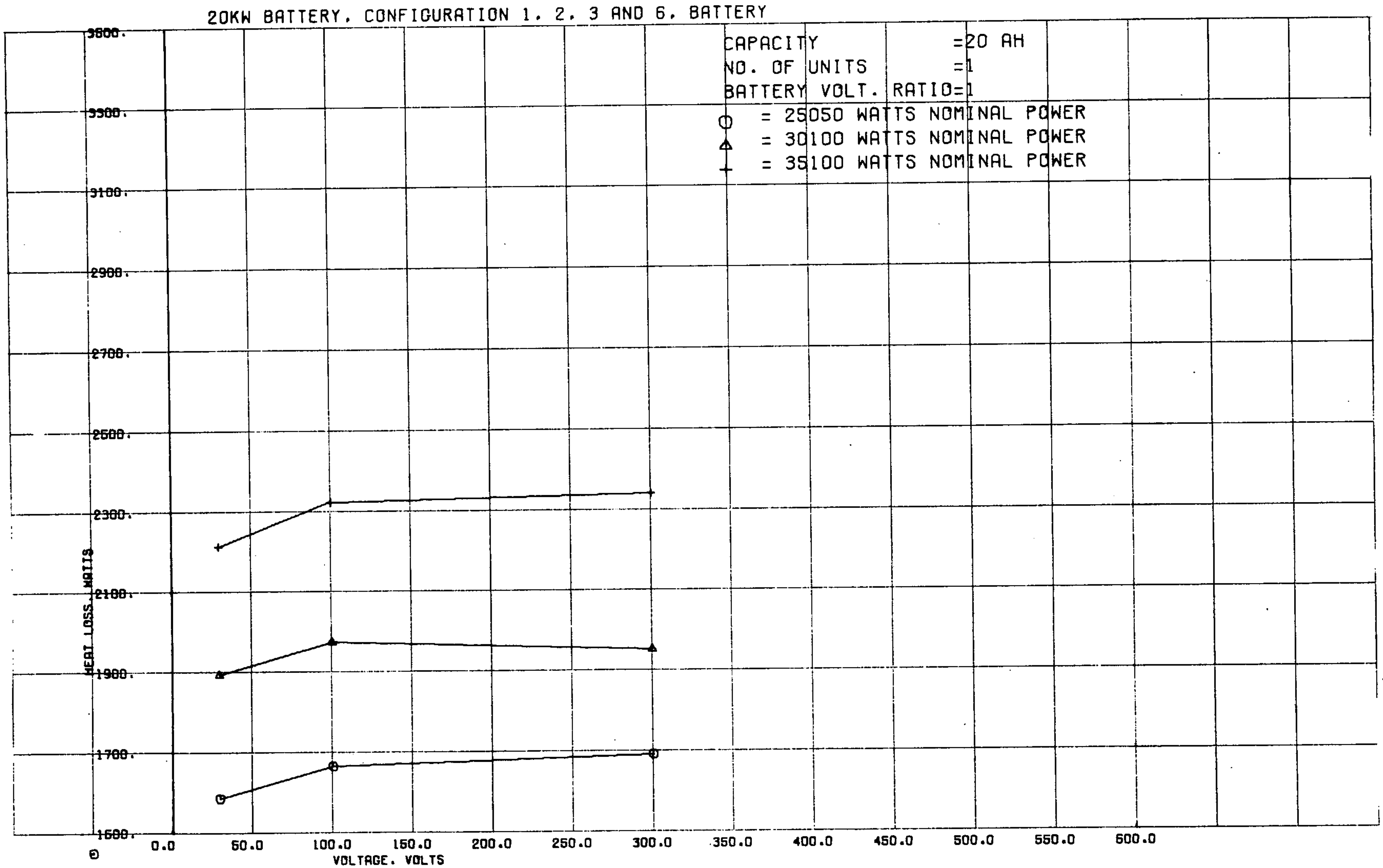
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS



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NO. OF UNITS =1
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30100 WATTS NOMINAL POWER
= 35100 WATTS NOMINAL POWER
HEAT LOSS, WATTS
3500.
3300.
3100.
2900.
2700.
2500.
2300.
2100.
1900.
1700.
1500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

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SEE CONFIGURATION 1

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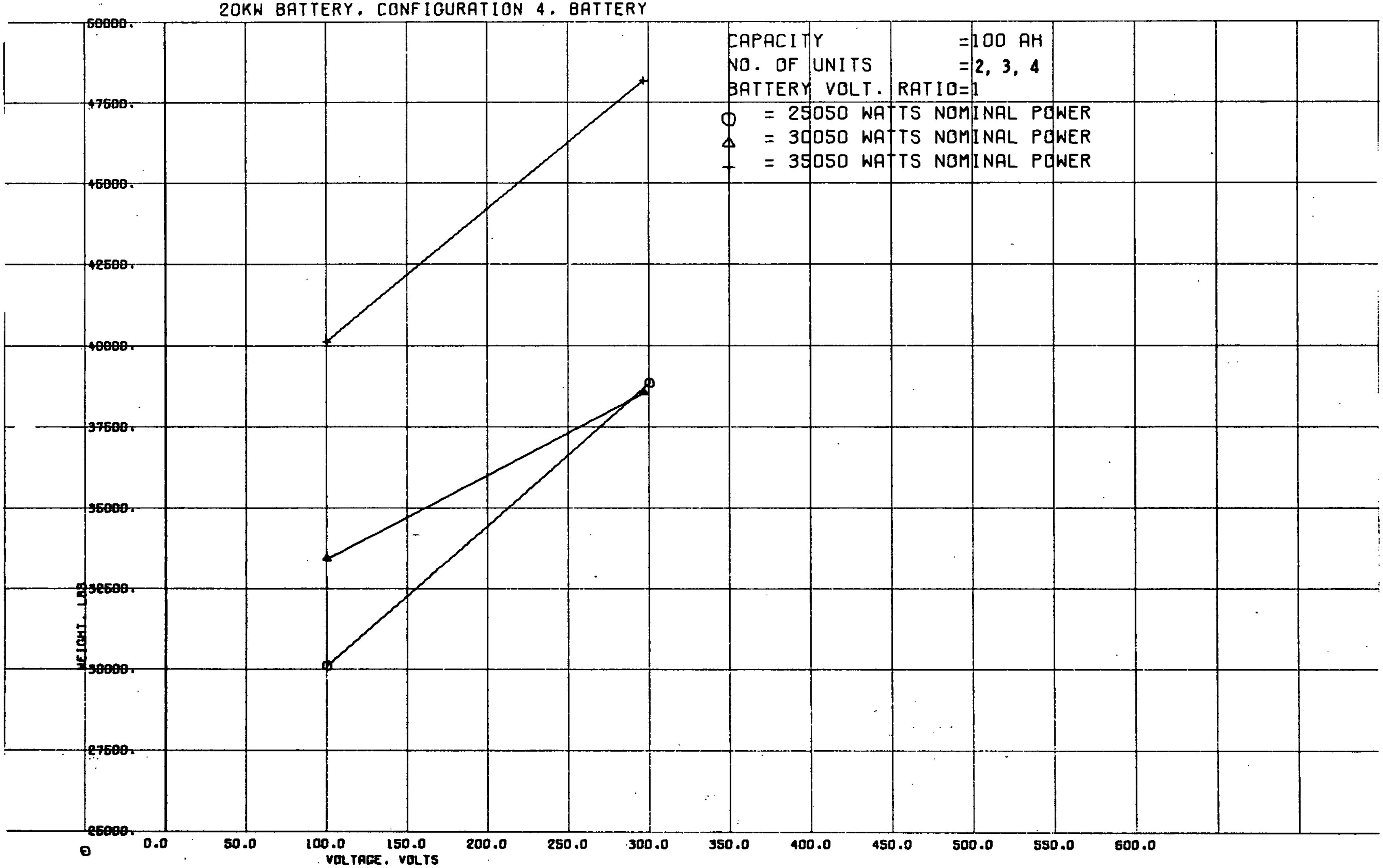
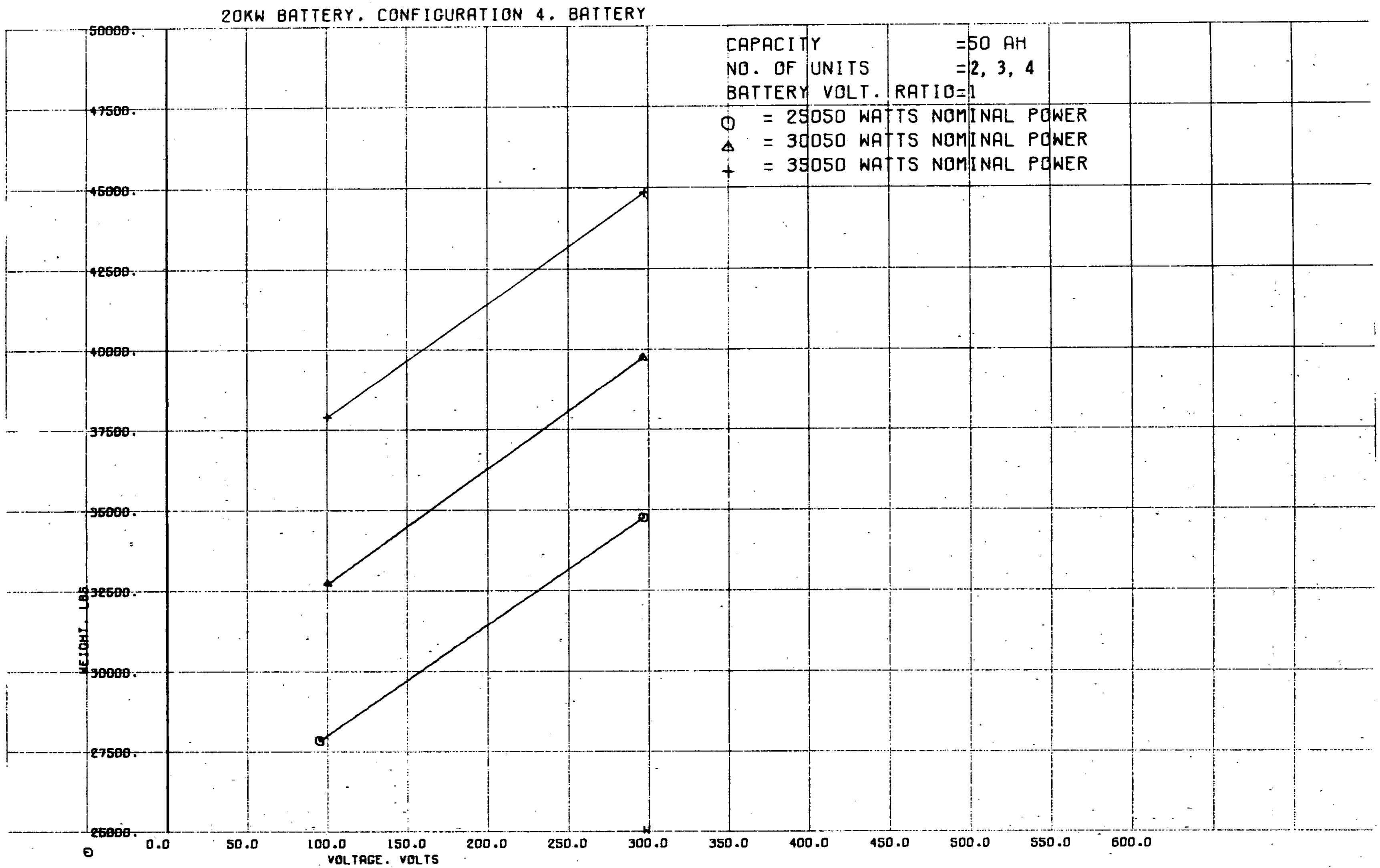
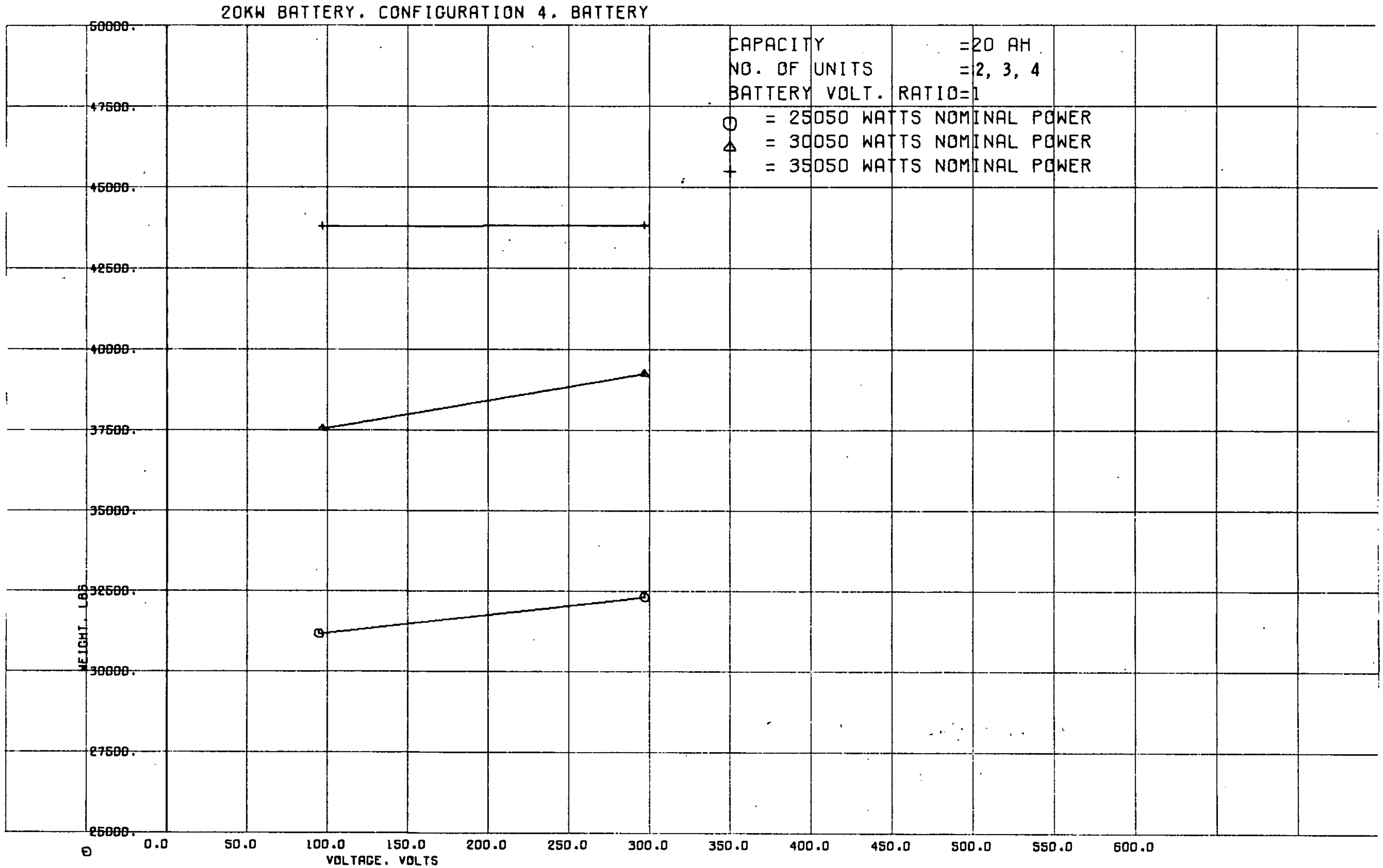
SEE CONFIGURATION 1

20KW BATTERY. CONFIGURATION 4. BATTERY





20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =50 AH
NO. OF UNITS =2, 3, 4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
50000.
47500.
45000.
42500.
40000.
37500.
35000.
32500.
30000.
27500.
25000.
WEIGHT. LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =20 AH
NO. OF UNITS =2, 3, 4
BATTERY VOLT. RATIO=1
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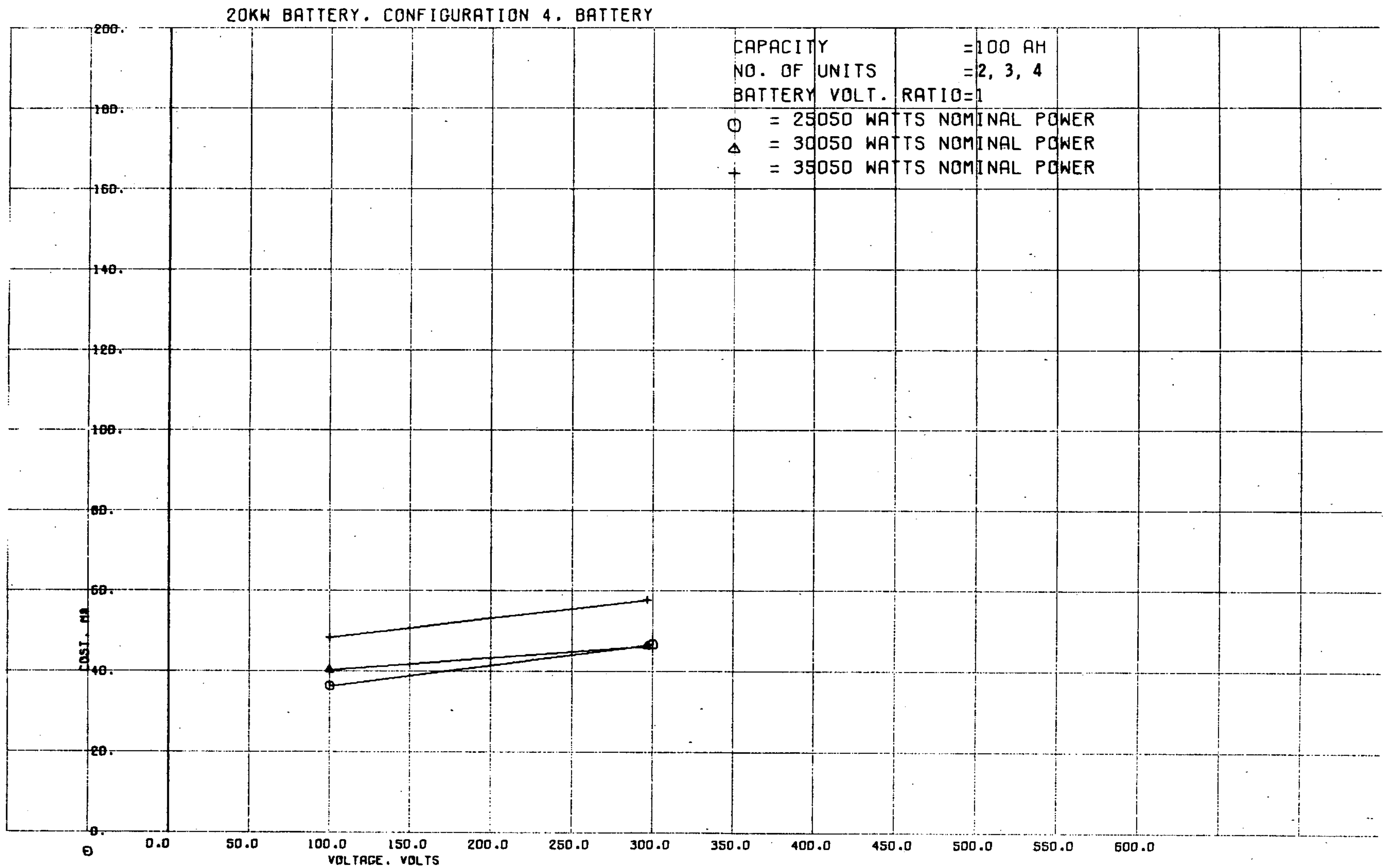
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
50000.
47500.
45000.
42500.
40000.
37500.
35000.
32500.
30000.
27500.
25000.
WEIGHT. LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =100 AH
NO. OF UNITS =2, 3, 4
BATTERY VOLT. RATIO=1
○ = 25050 WATTS NOMINAL POWER
△ = 30050 WATTS NOMINAL POWER
+ = 35050 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
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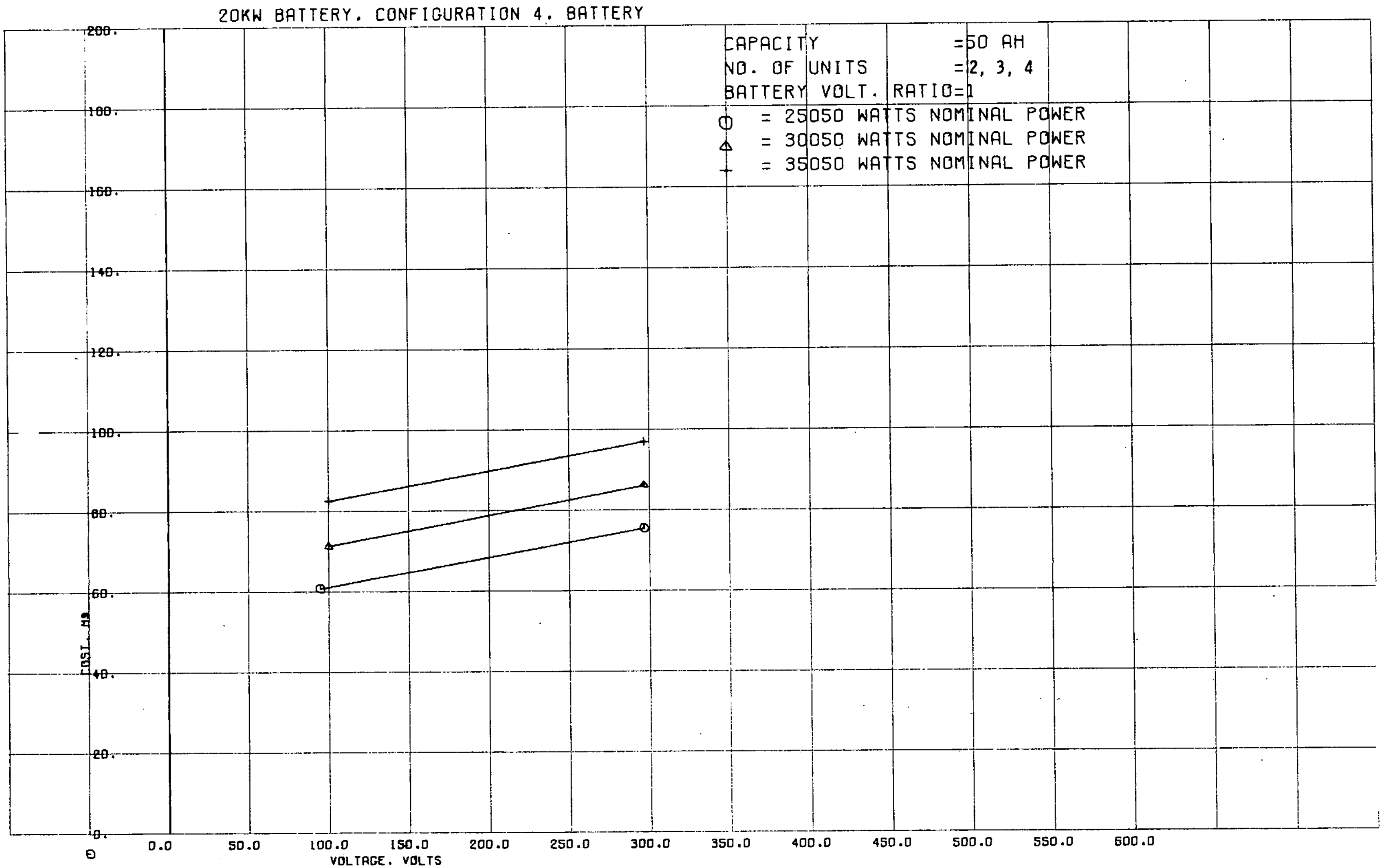
40.
60.
80.
100.
120.
140.
160.
180.
200.


20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =50 AH
NO. OF UNITS =2, 3, 4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
COST. M$
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
0.0
50.0
100.0
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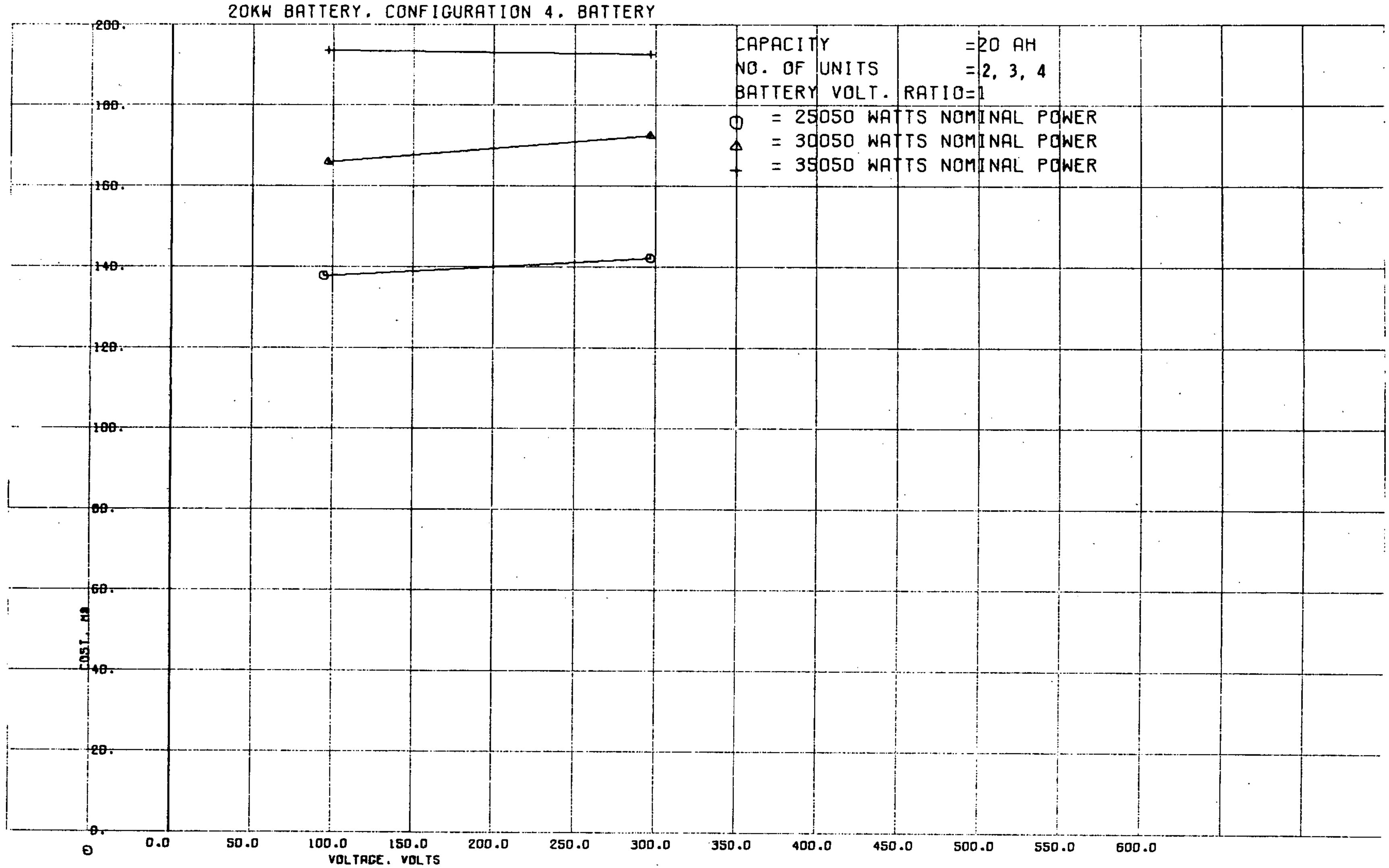
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY, CONFIGURATION 4, BATTERY
CAPACITY =20 AH
NO. OF UNITS =2, 3, 4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS
0.
20.
40.
60.
80.
100.
120.
140.
160.
180.
200.
0.0
50.0
100.0
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200.0
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300.0
350.0
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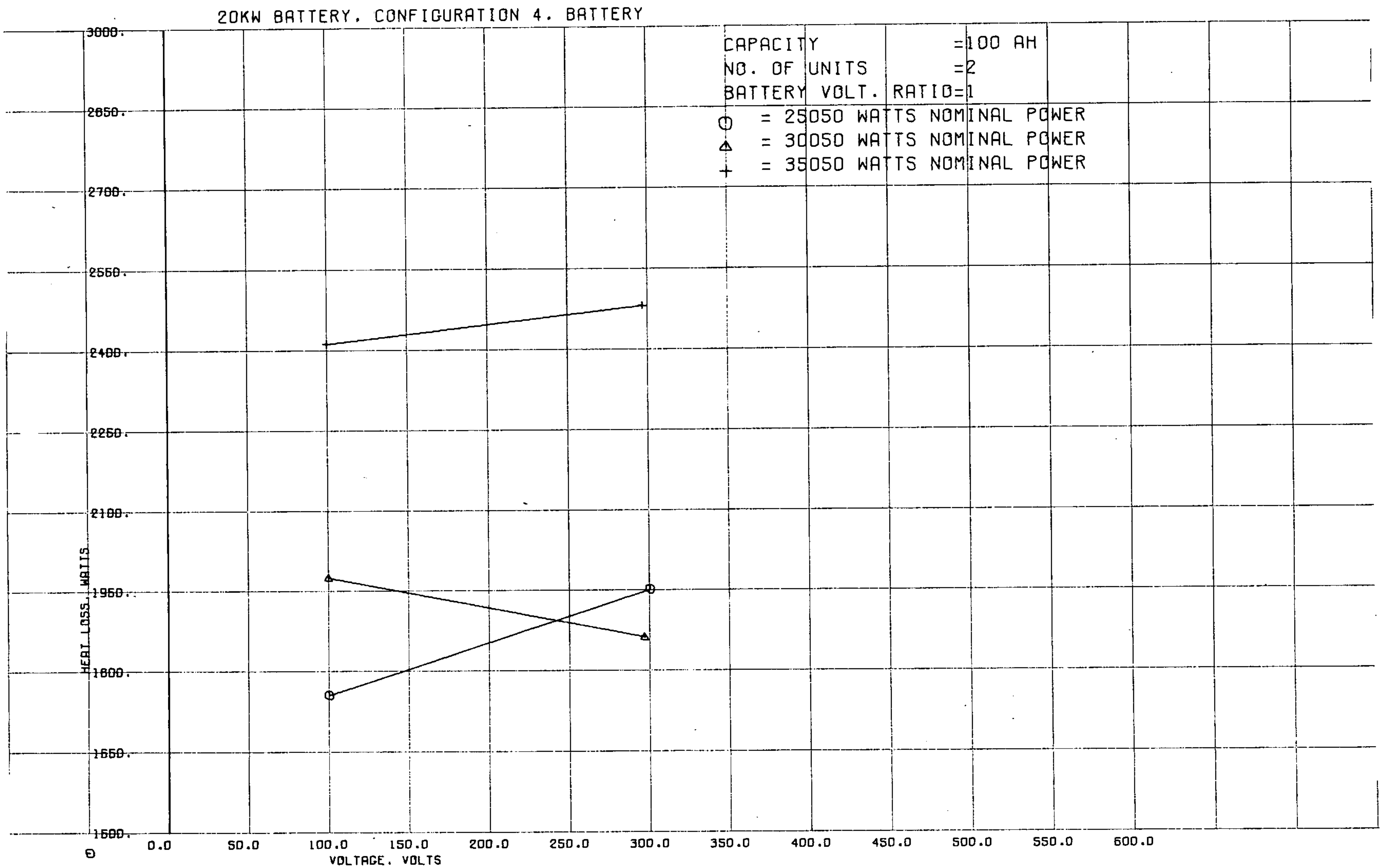
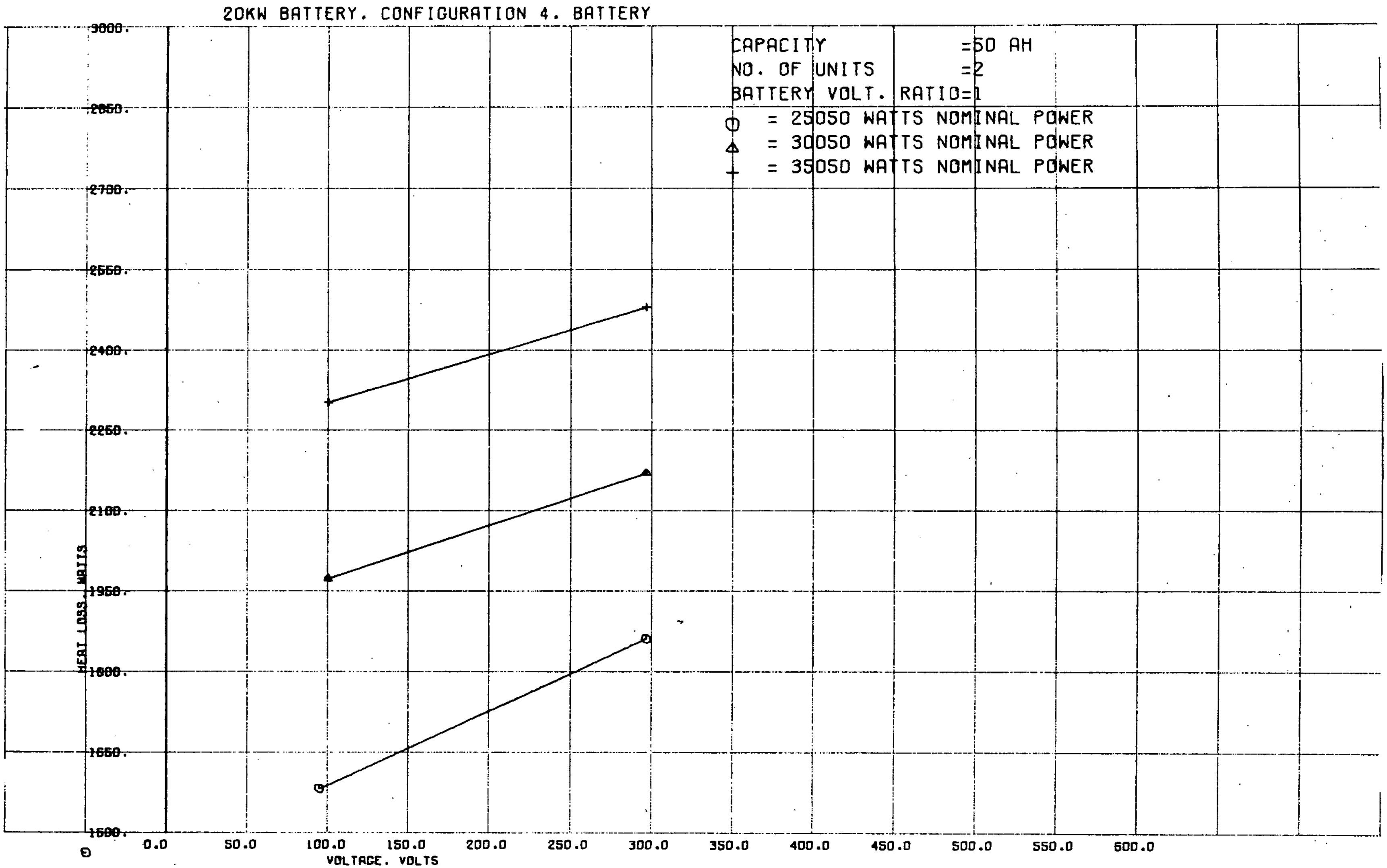
550.0
600.0


20KW BATTERY, CONFIGURATION 4. BATTERY
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
0.0
50.0
100.0
150.0
200.0
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300.0
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450.0
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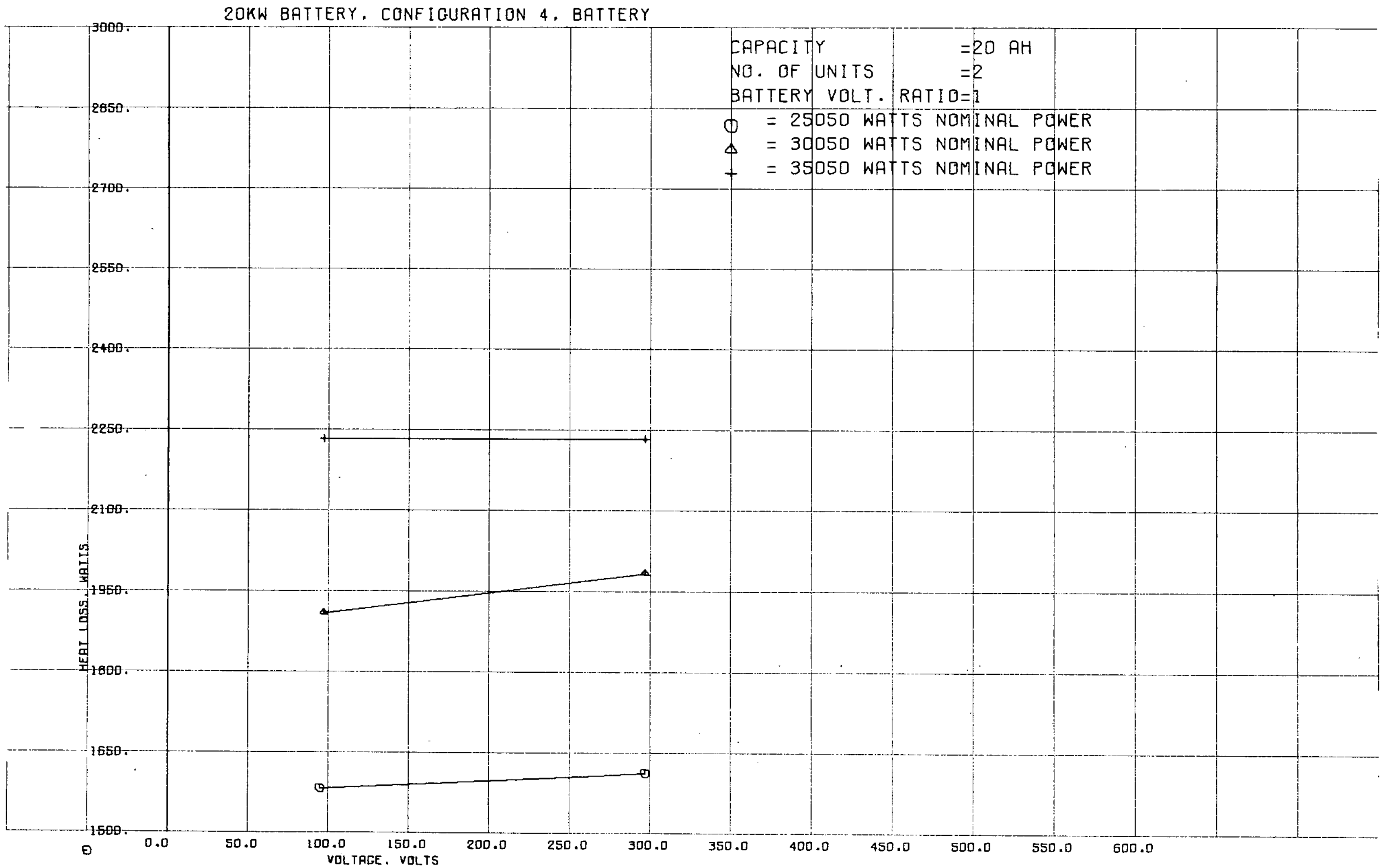
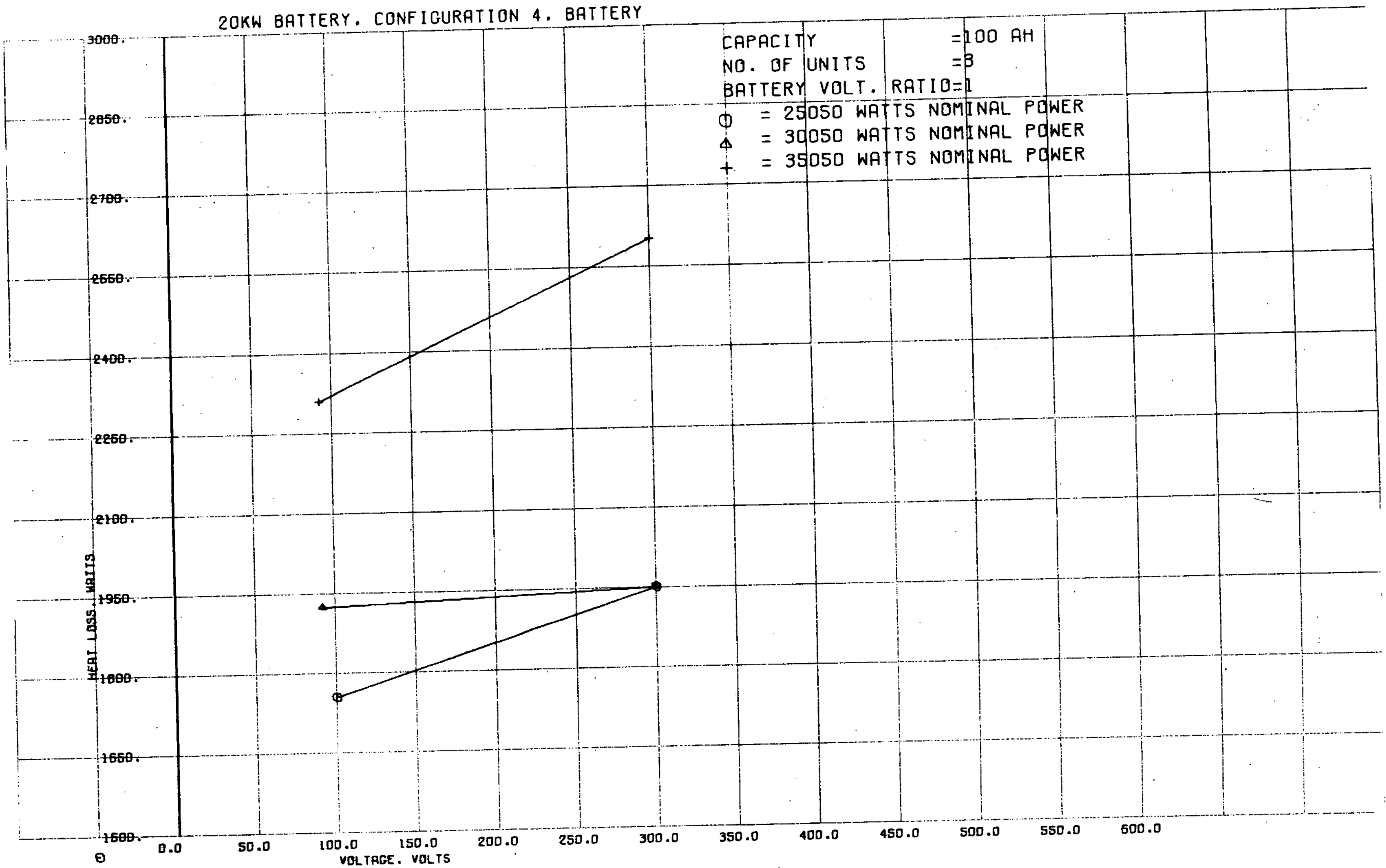
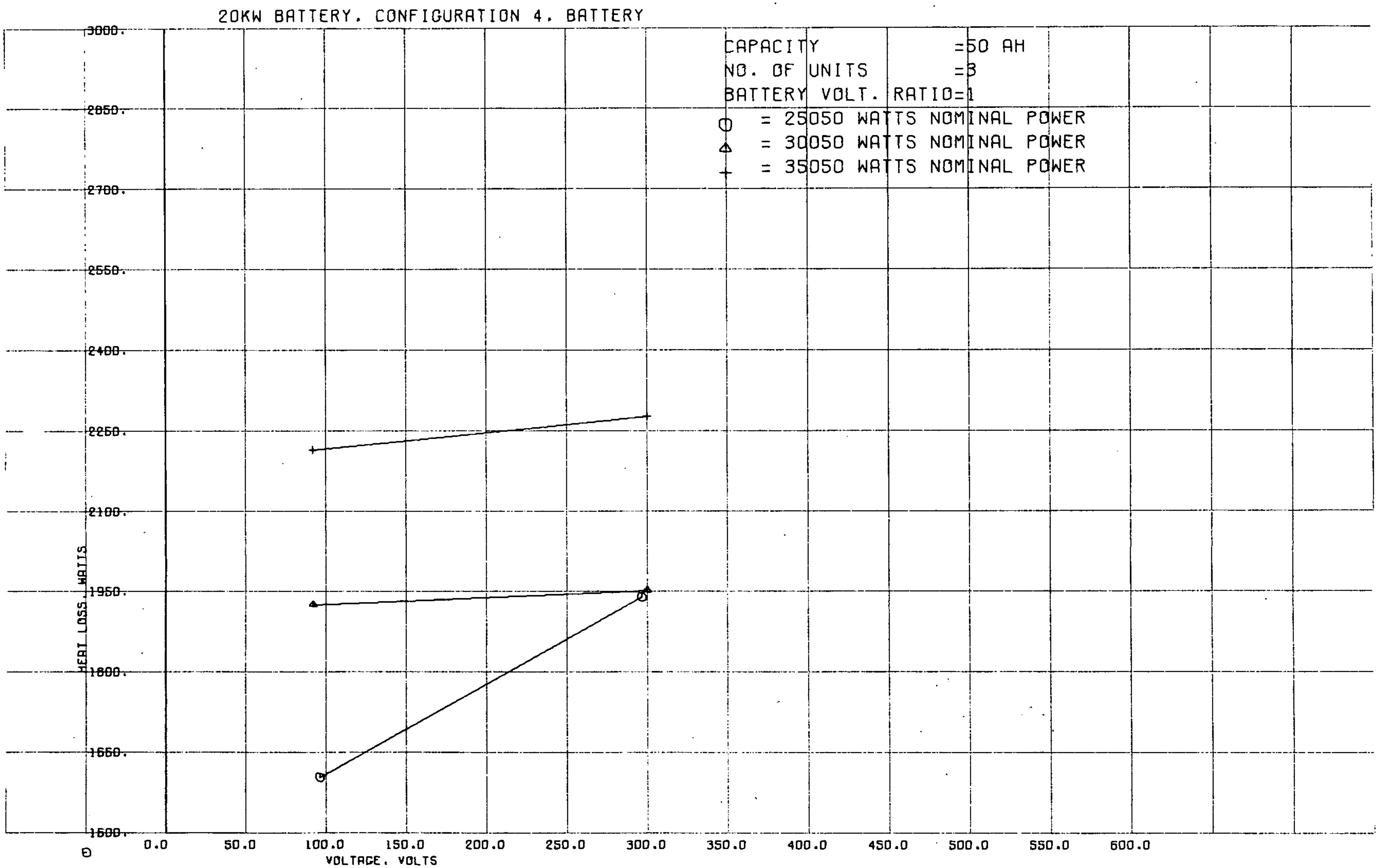
550.0
600.0



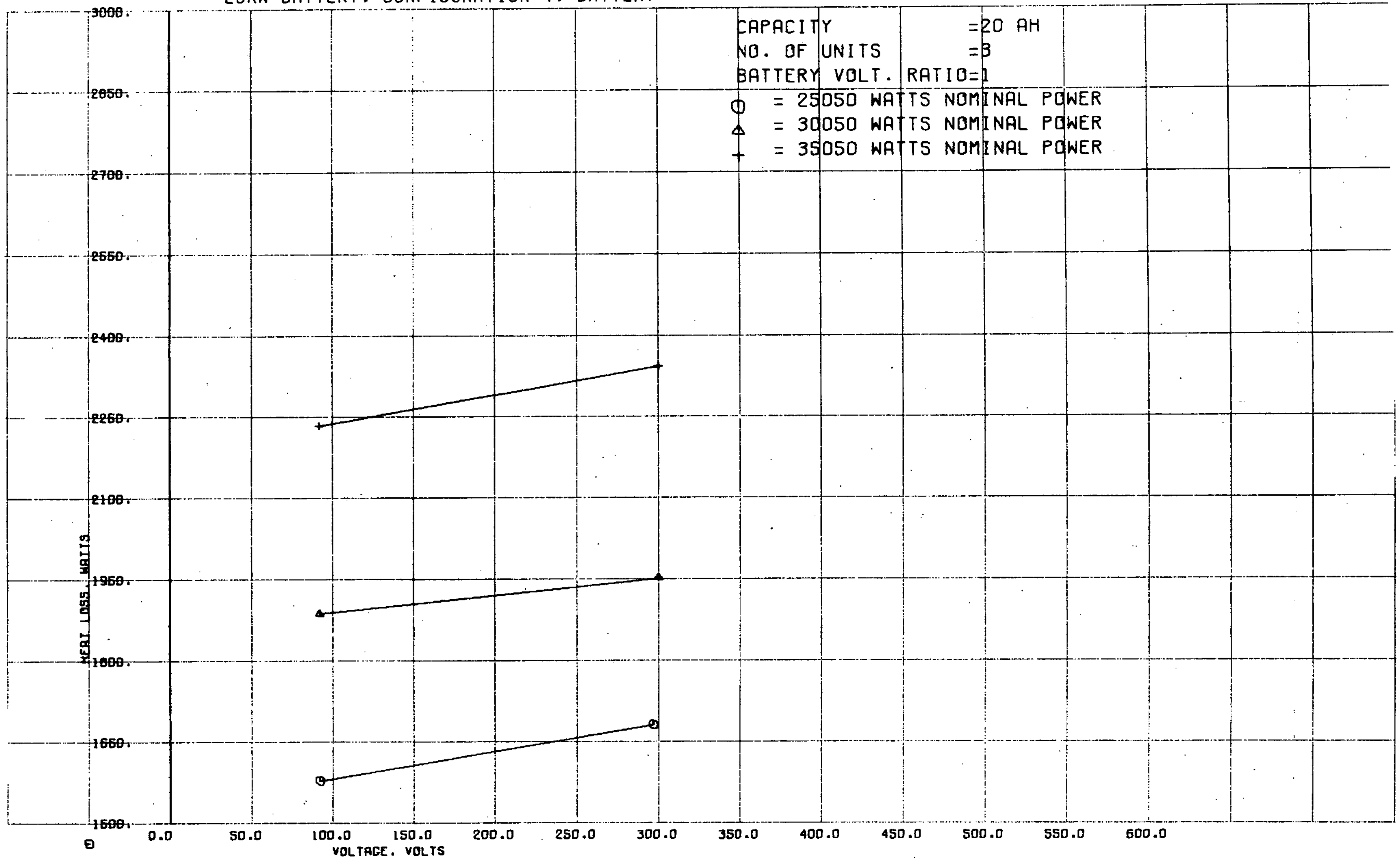
20KW BATTERY, CONFIGURATION 4, BATTERY
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
HEAT LOSS, WATTS
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

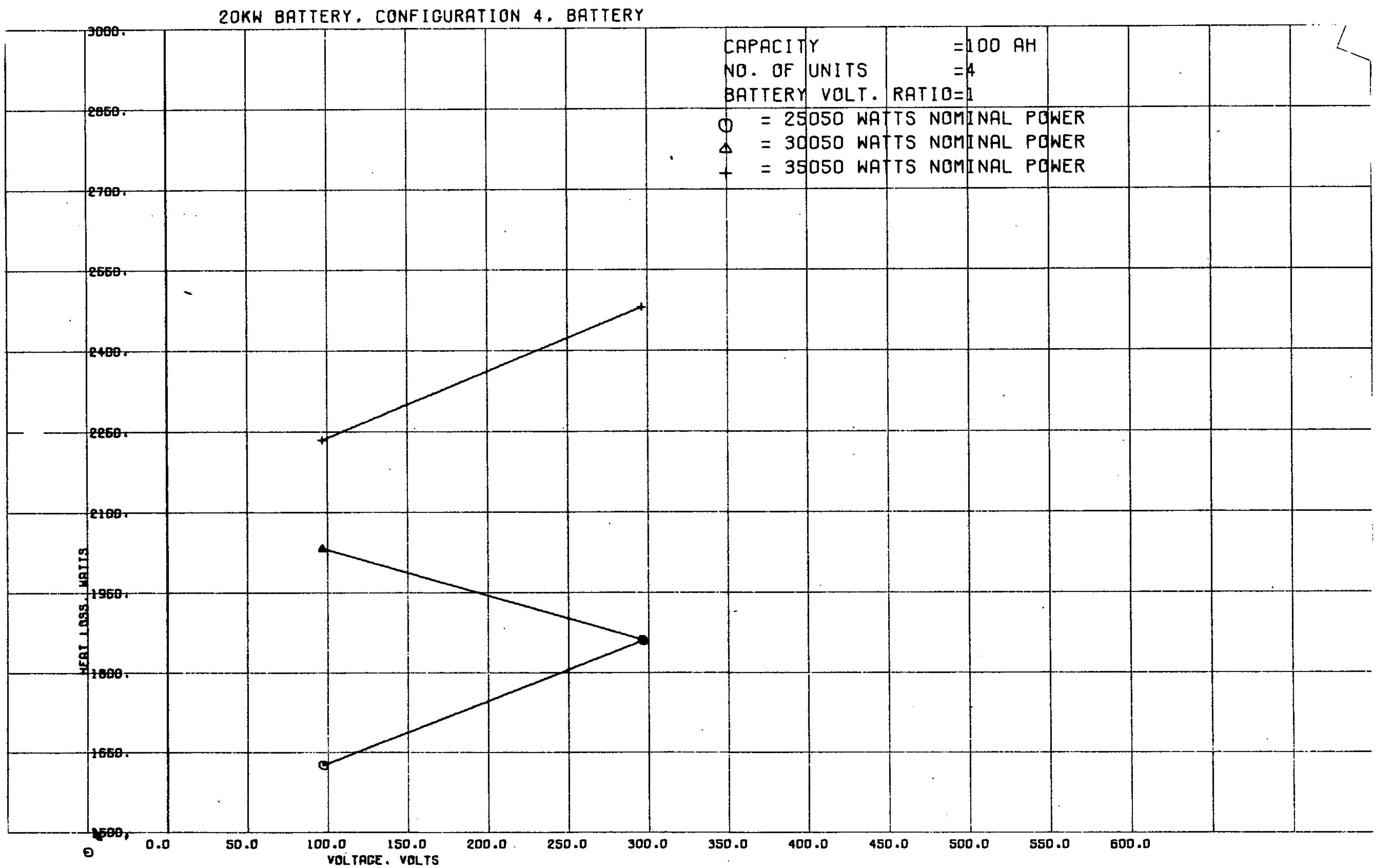


20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =100 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
○ = 25050 WATTS NOMINAL POWER
△ = 30050 WATTS NOMINAL POWER
+ = 35050 WATTS NOMINAL POWER
HEAT LOSS. WATTS
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =50 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

20KW BATTERY. CONFIGURATION 4. BATTERY




20KW BATTERY, CONFIGURATION 4, BATTERY
CAPACITY =100 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
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= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
HEAT LOSS, WATTS
0.0
50.0
100.0
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250.0
300.0
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400.0
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500.0
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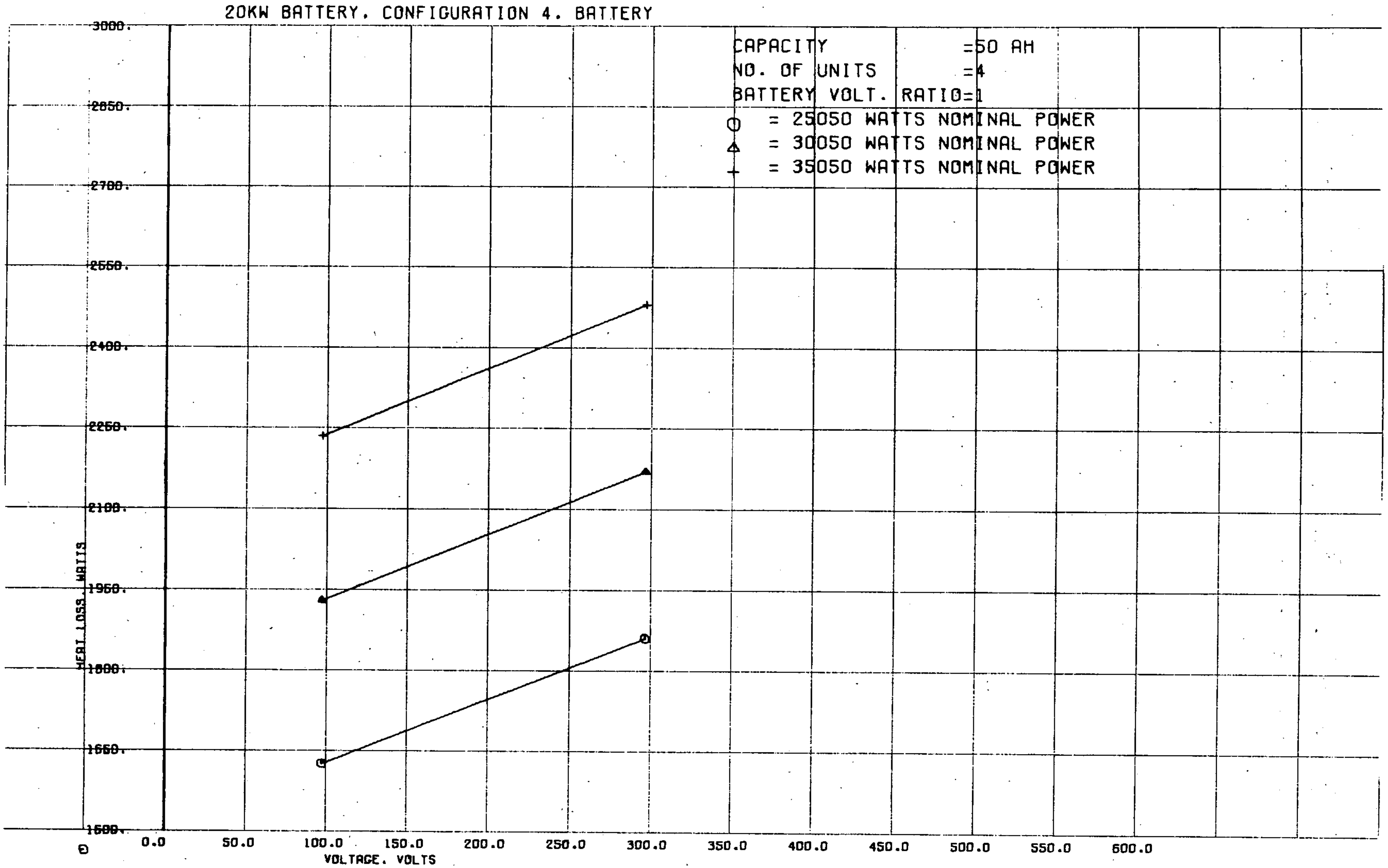
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 4. BATTERY
CAPACITY =50 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
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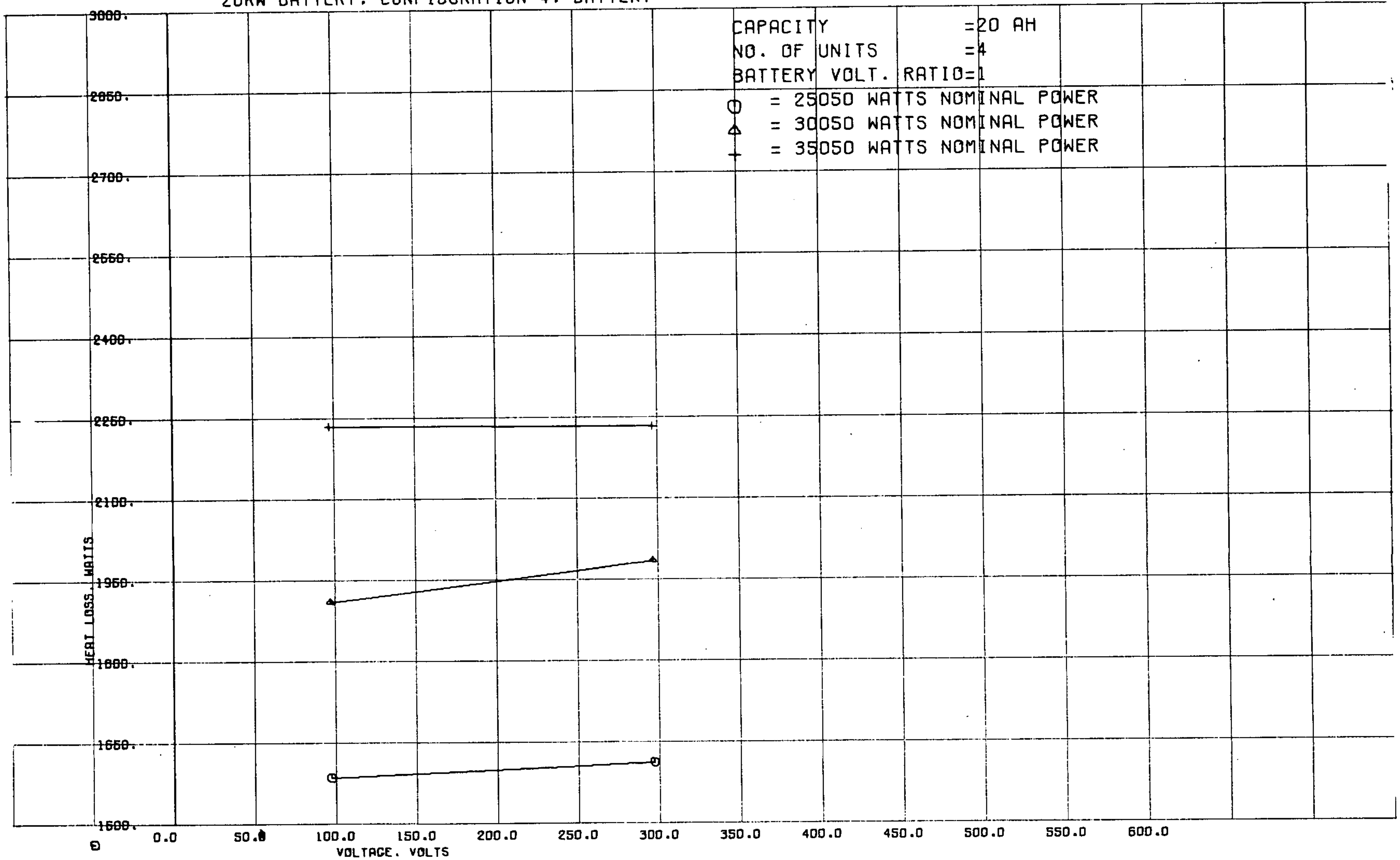
= 35050 WATTS NOMINAL POWER
3000.
2850.
2700.
2550.
2400.
2250.
2100.
1950.
1800.
1650.
1500.
HEAT LOSS. WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

20KW BATTERY, CONFIGURATION 4, BATTERY



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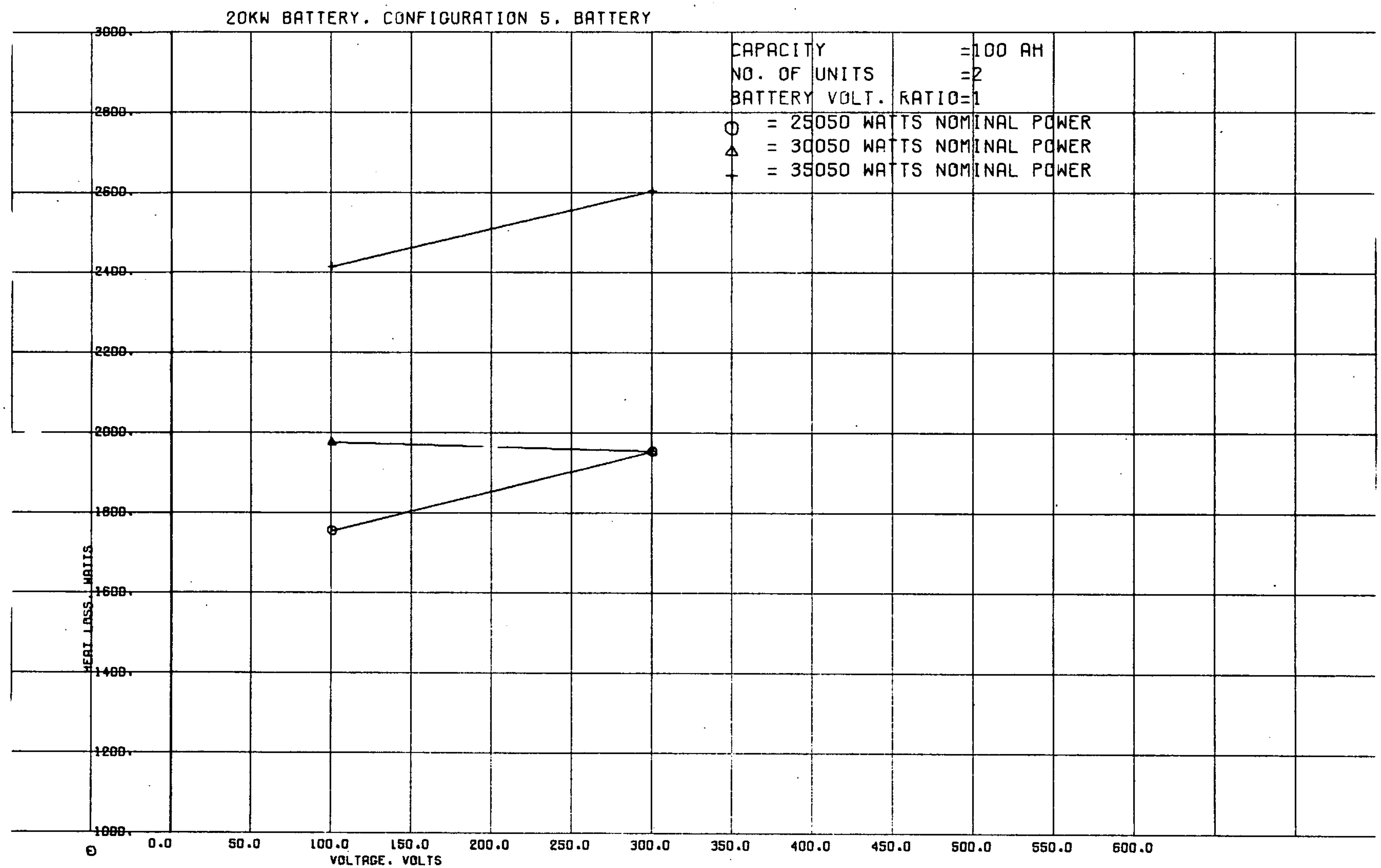

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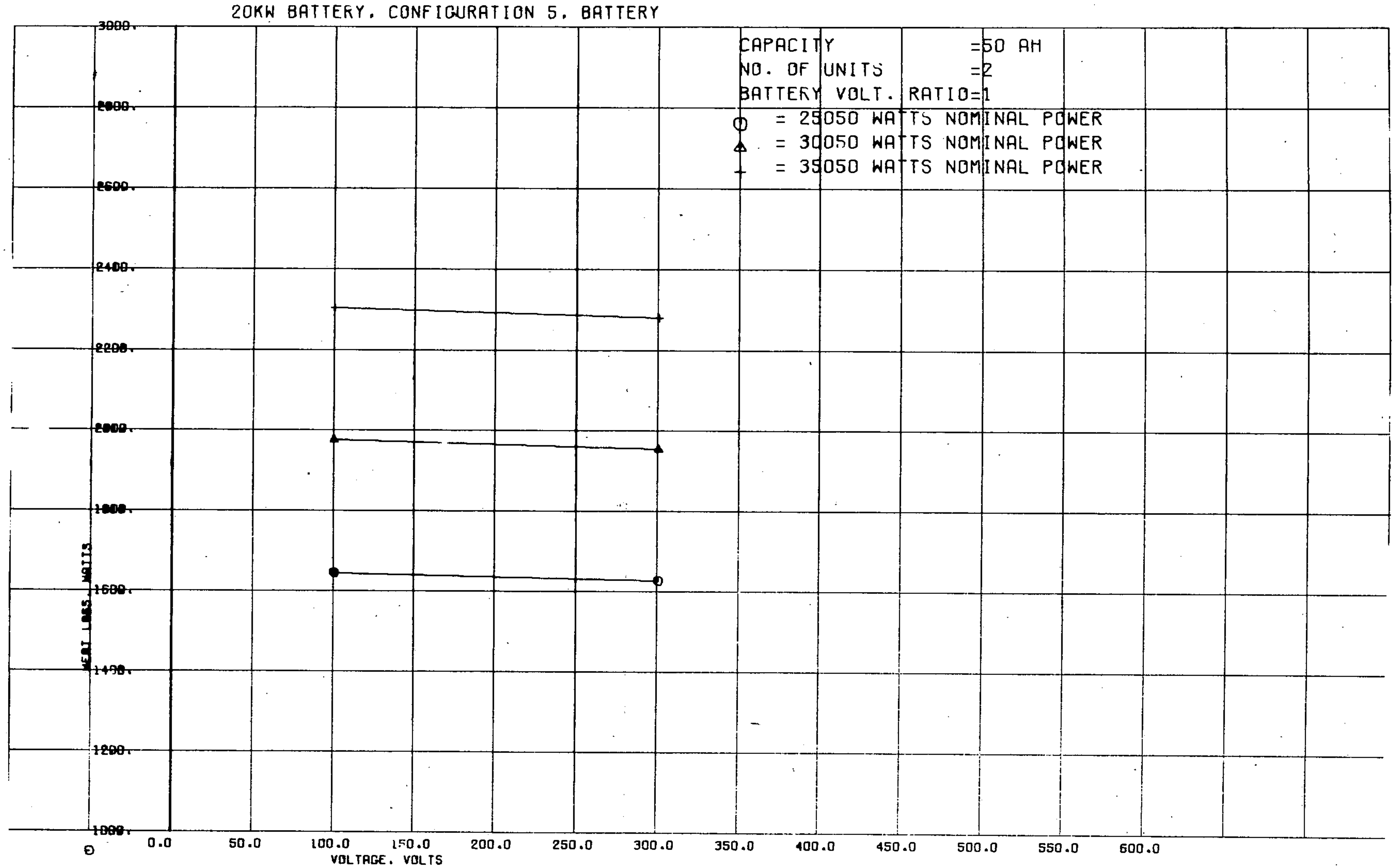
20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =50 AH
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BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
3000.
2800.
2600.
2400.
2200.
2000.
1800.
1600.
1400.
1200.
1000.
0.0
50.0
100.0
150.0
200.0
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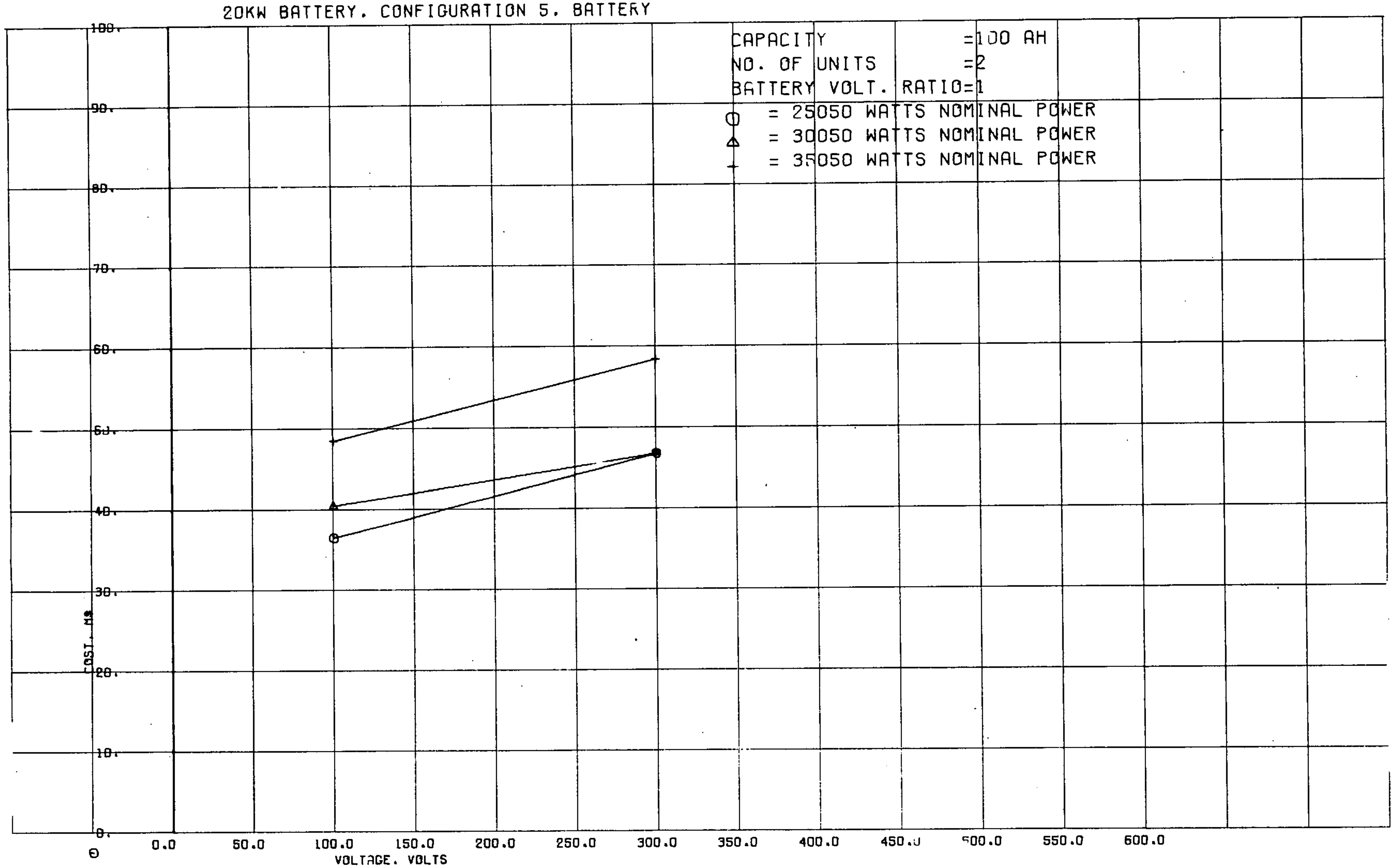
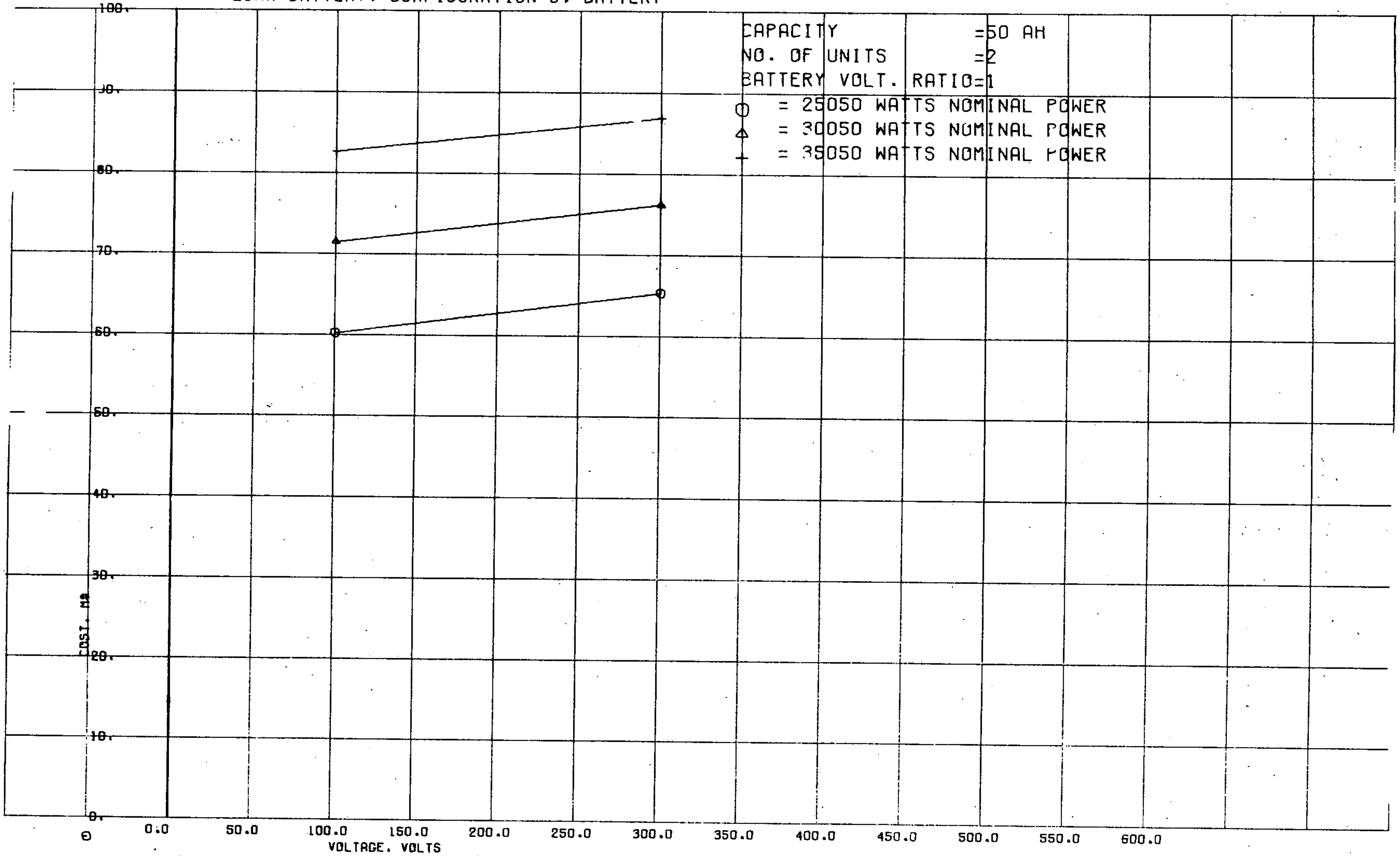
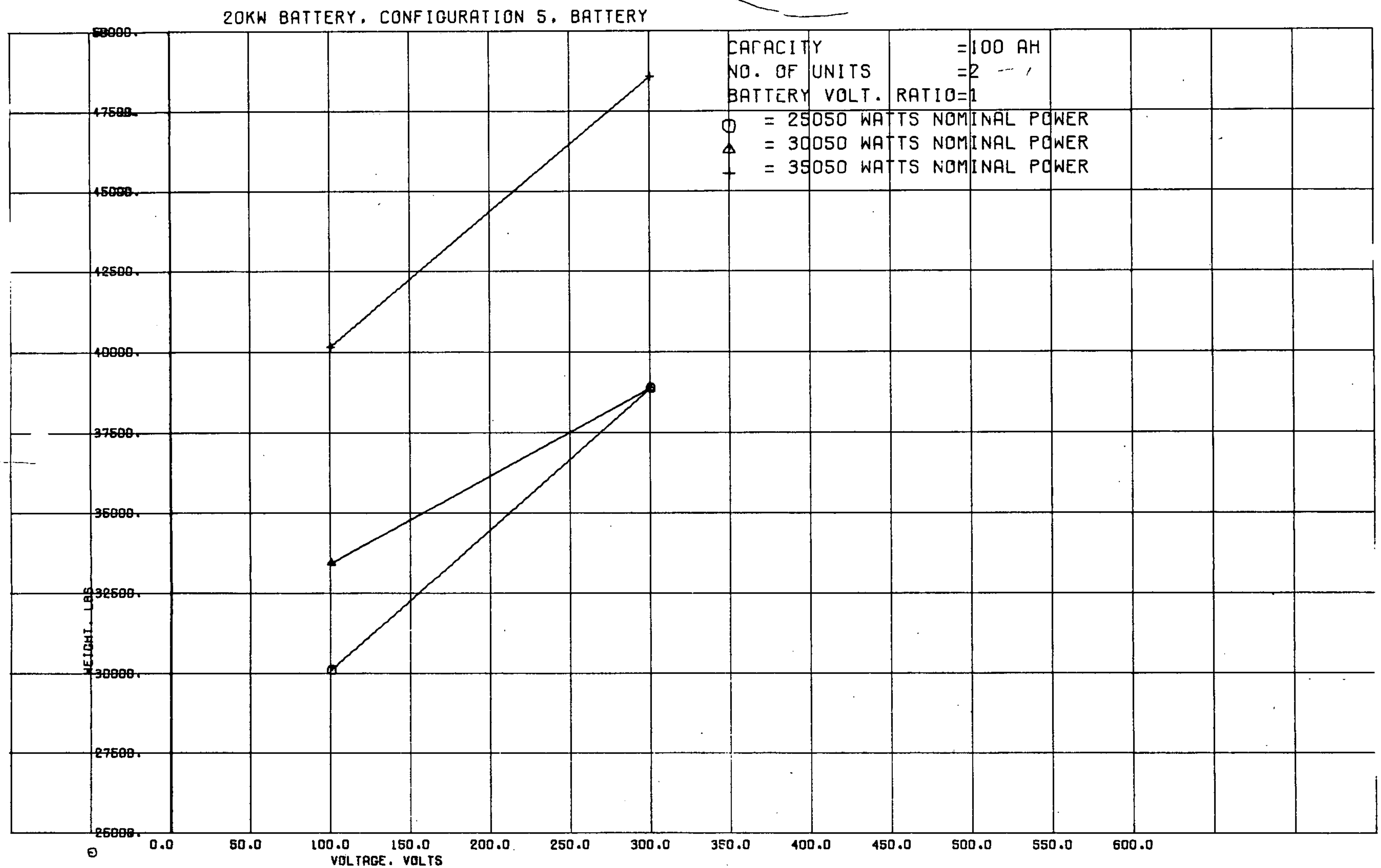
450.0
500.0
550.0
600.0

20KW BATTERY. CONFIGURATION 5. BATTERY



20KW BATTERY. CONFIGURATION 5. BATTERY





20KW BATTERY, CONFIGURATION 5, BATTERY
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NO. OF UNITS =2
BATTERY VOLT. RATIO=1
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= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
50000.
47500.
45000.
42500.
40000.
37500.
35000.
32500.
30000.
27500.
25000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
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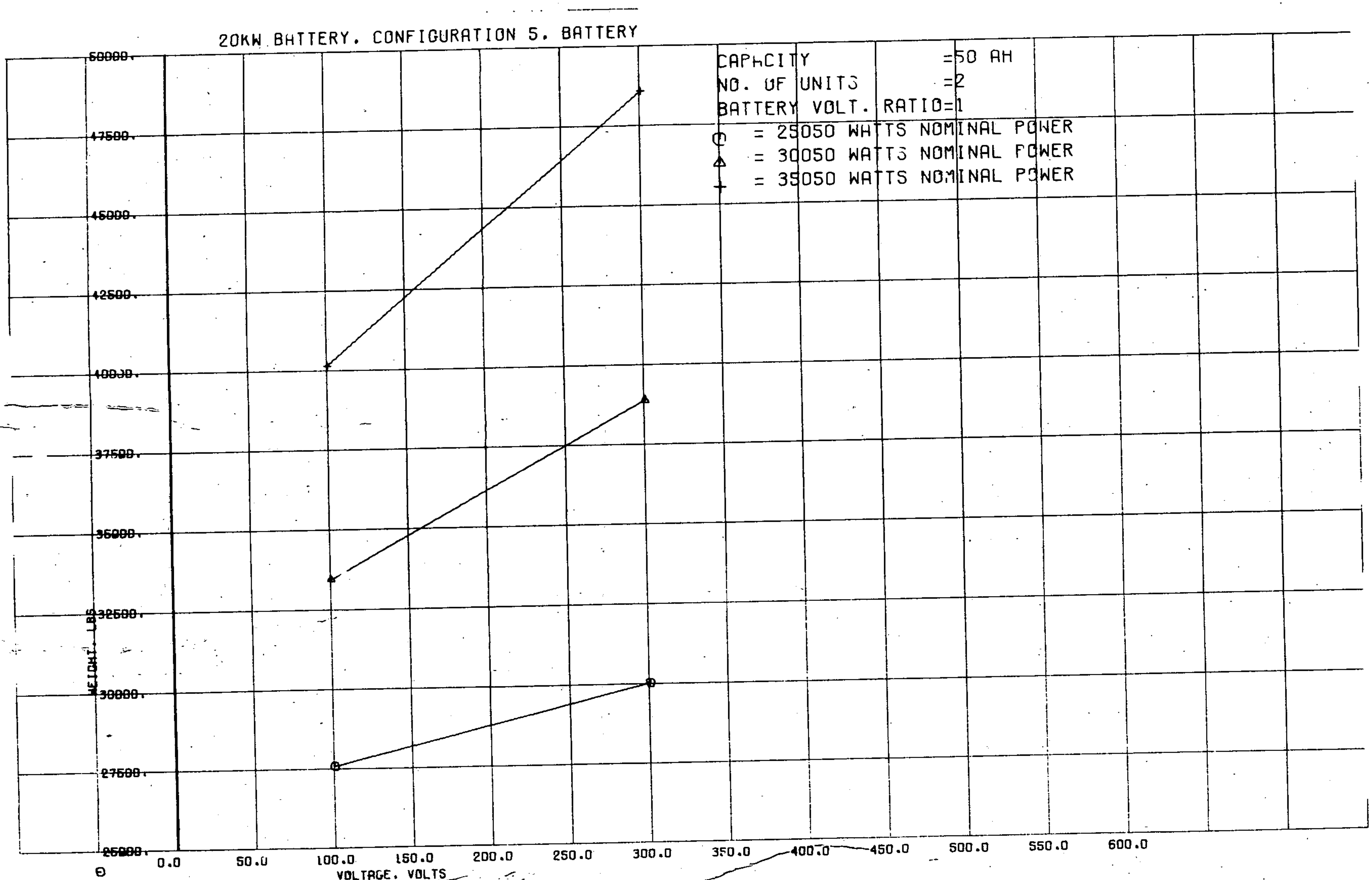
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 5. BATTERY
CAPACITY =50 AH
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BATTERY VOLT. RATIO=1
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= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
50000.
47500.
45000.
42500.
40000.
37500.
35000.
32500.
30000.
27500.
25000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
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250.0
300.0
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400.0
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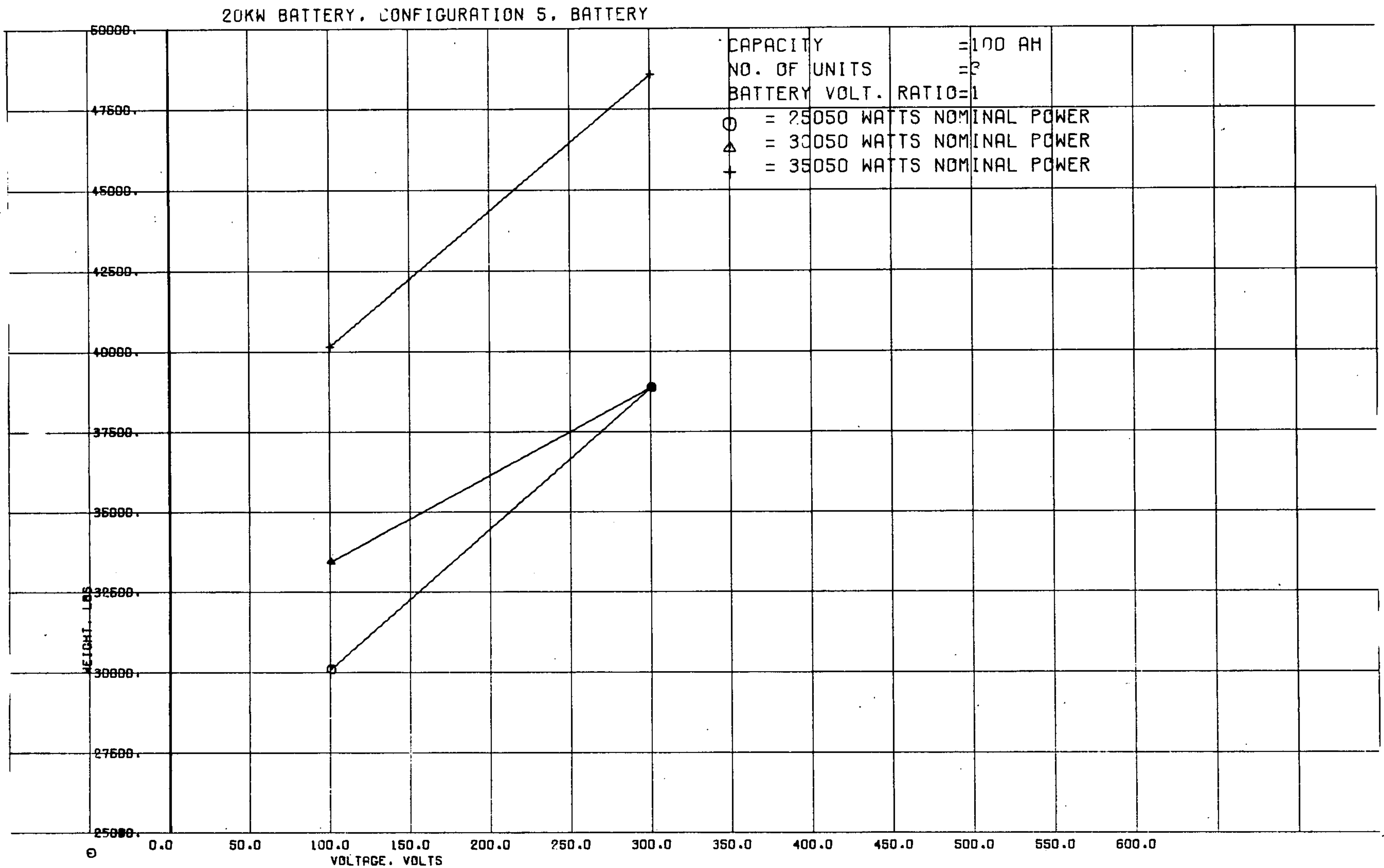
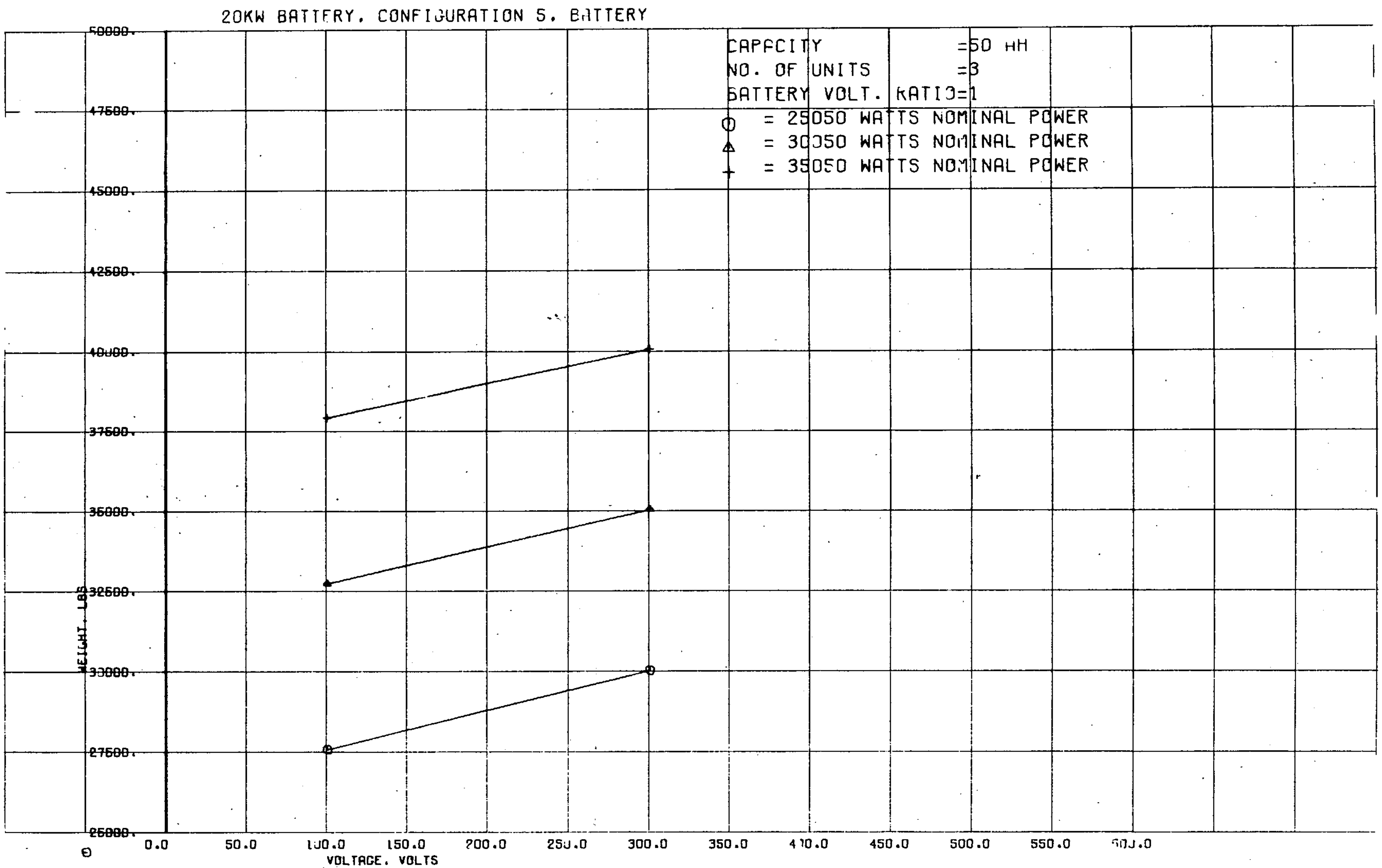
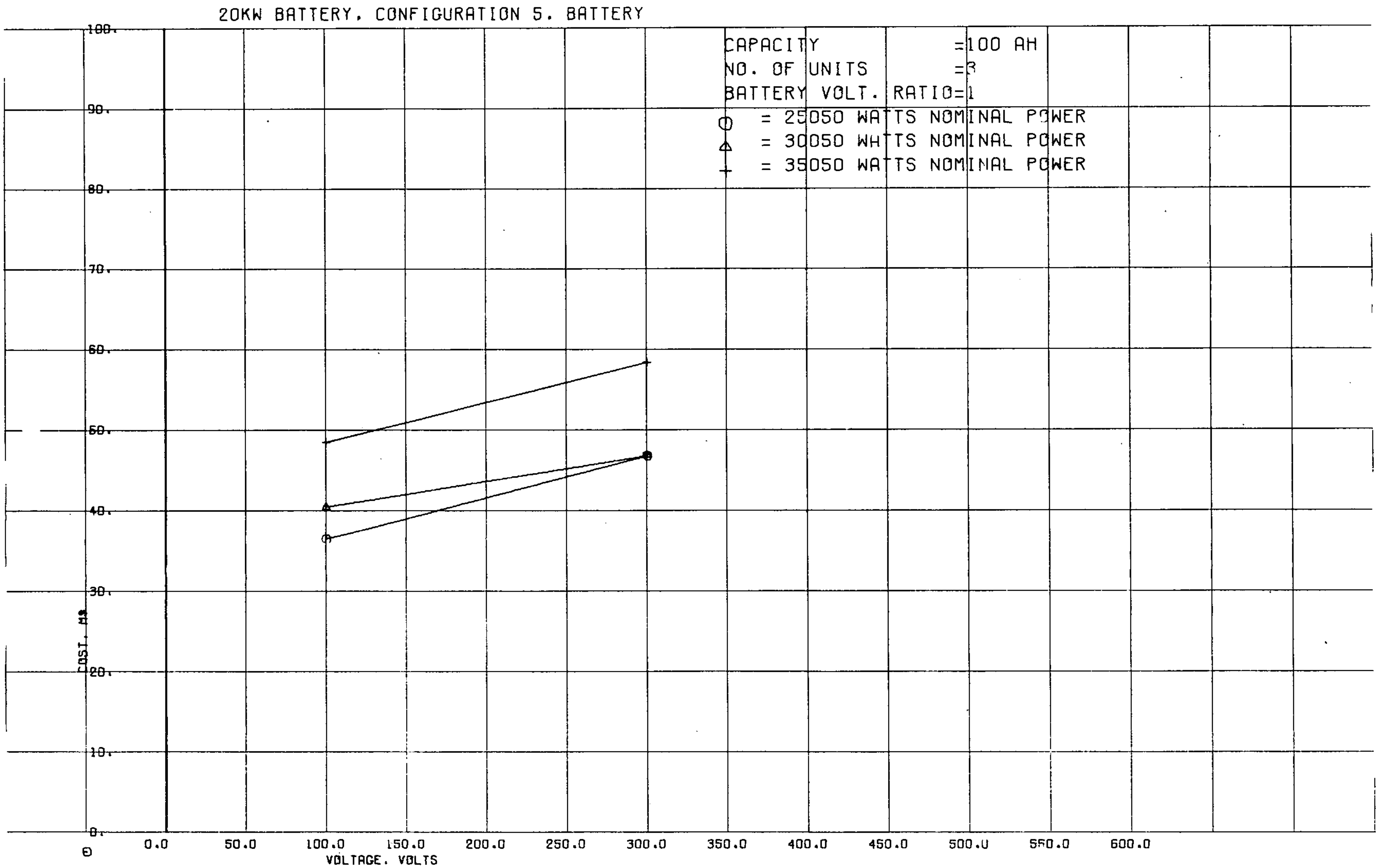
500.0
550.0
600.0
VOLTAGE, VOLTS

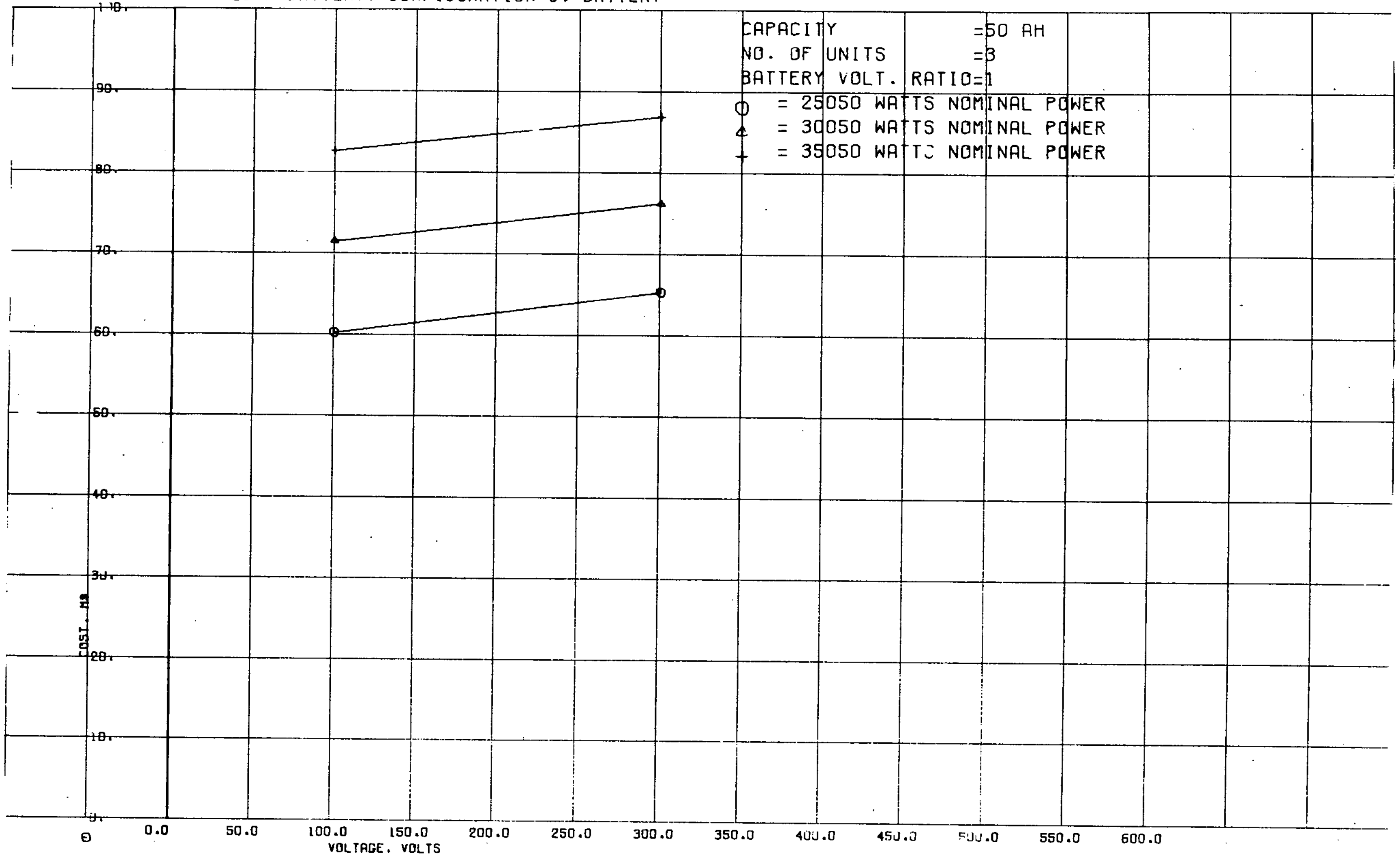

20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =100 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
50000.
47500.
45000.
42500.
40000.
37500.
35000.
32500.
30000.
27500.
25000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

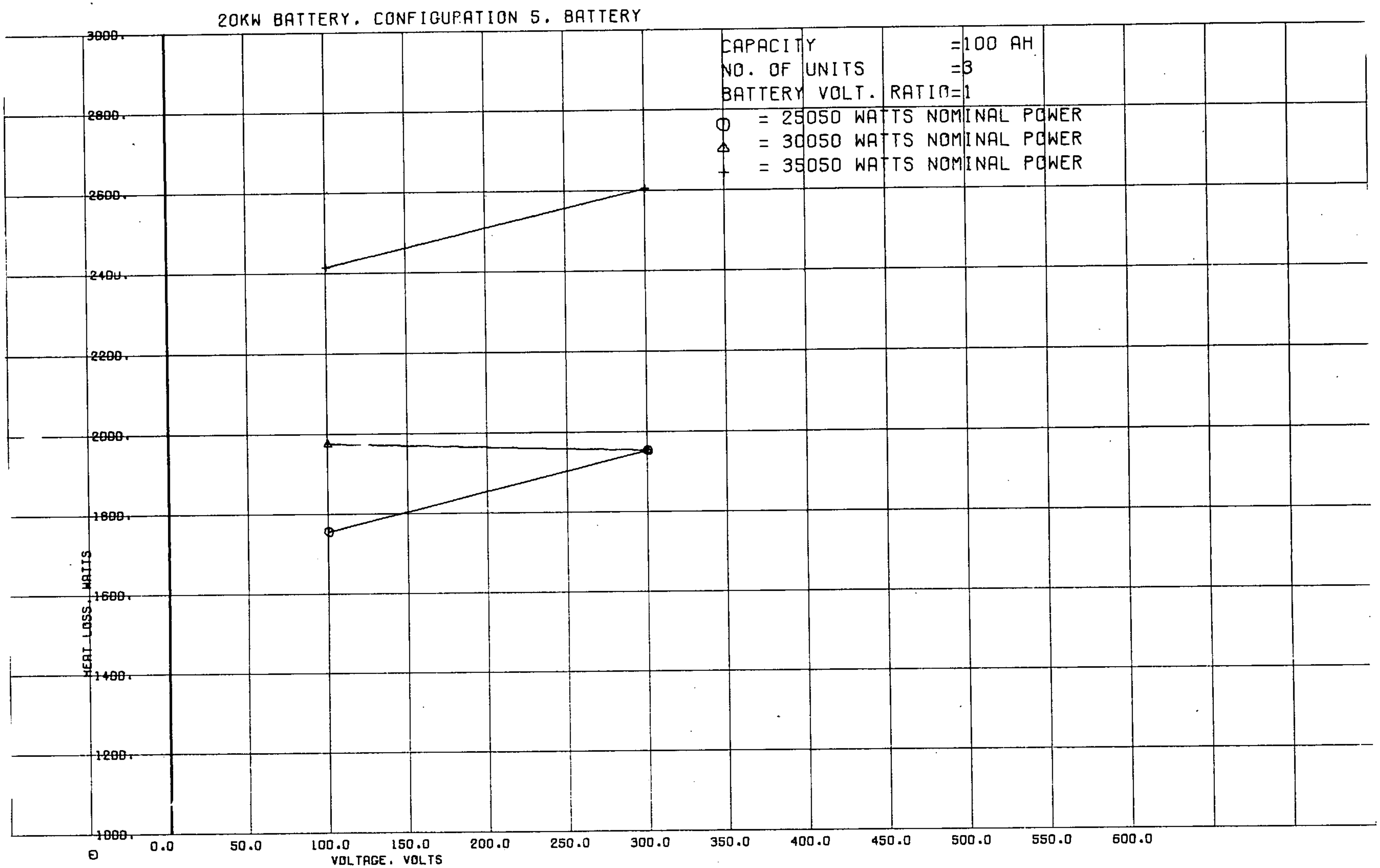


20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =50 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 5. BATTERY
CAPACITY =100 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS

20KW BATTERY. CONFIGURATION 5. BATTERY




20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =100 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
3000.
2800.
2600.
2400.
2200.
2000.
1800.
1600.
1400.
1200.
1000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
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400.0
450.0
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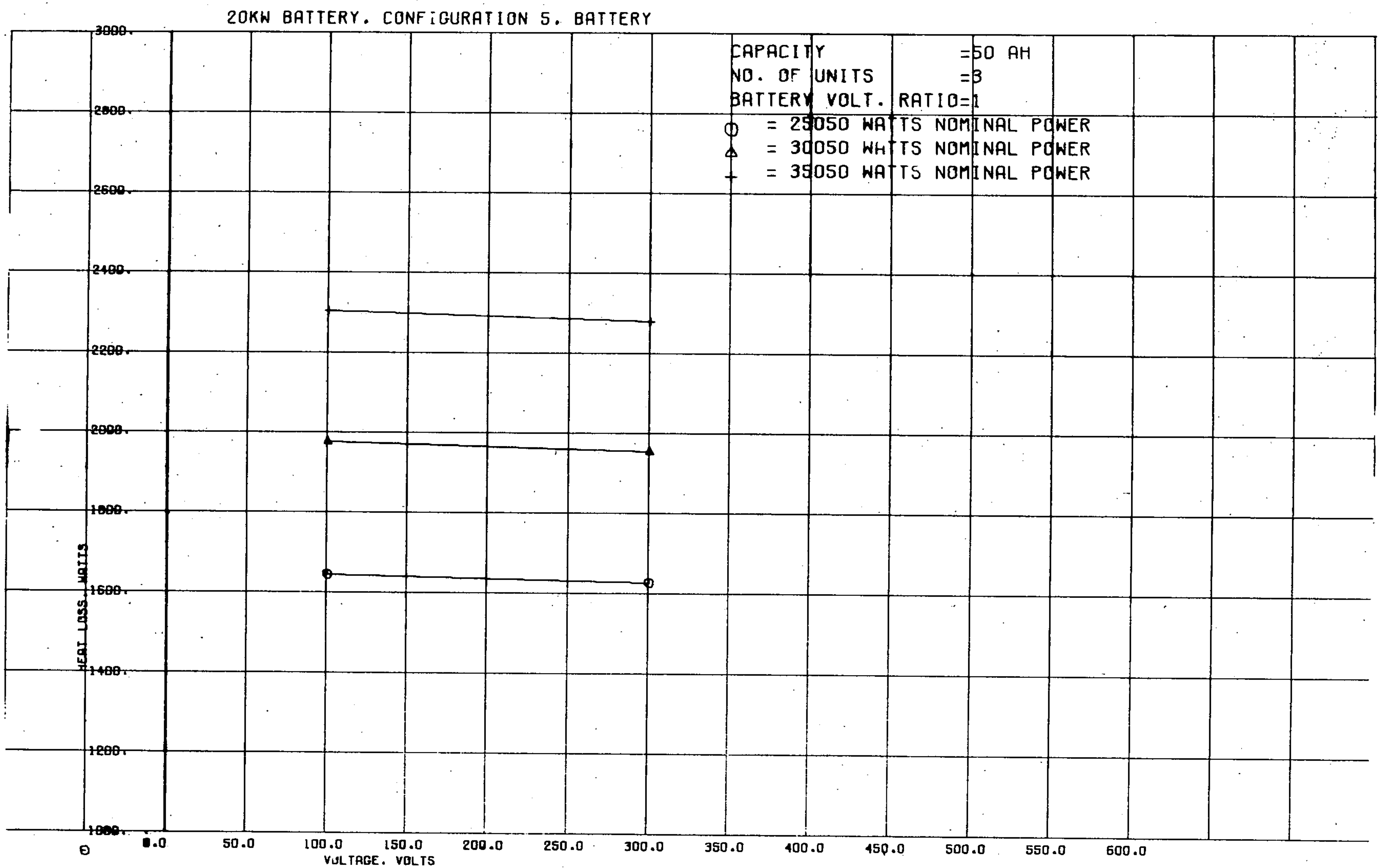
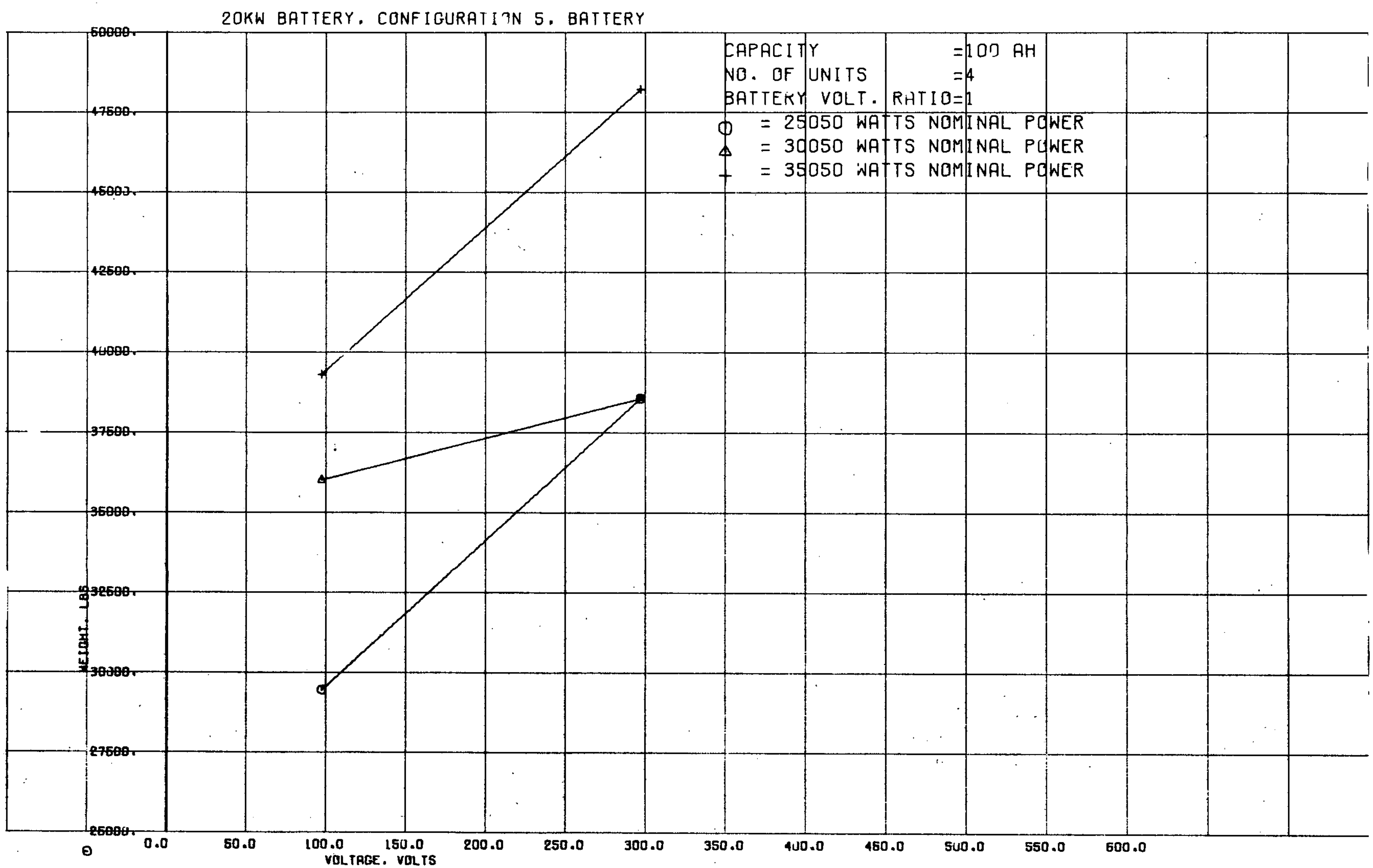
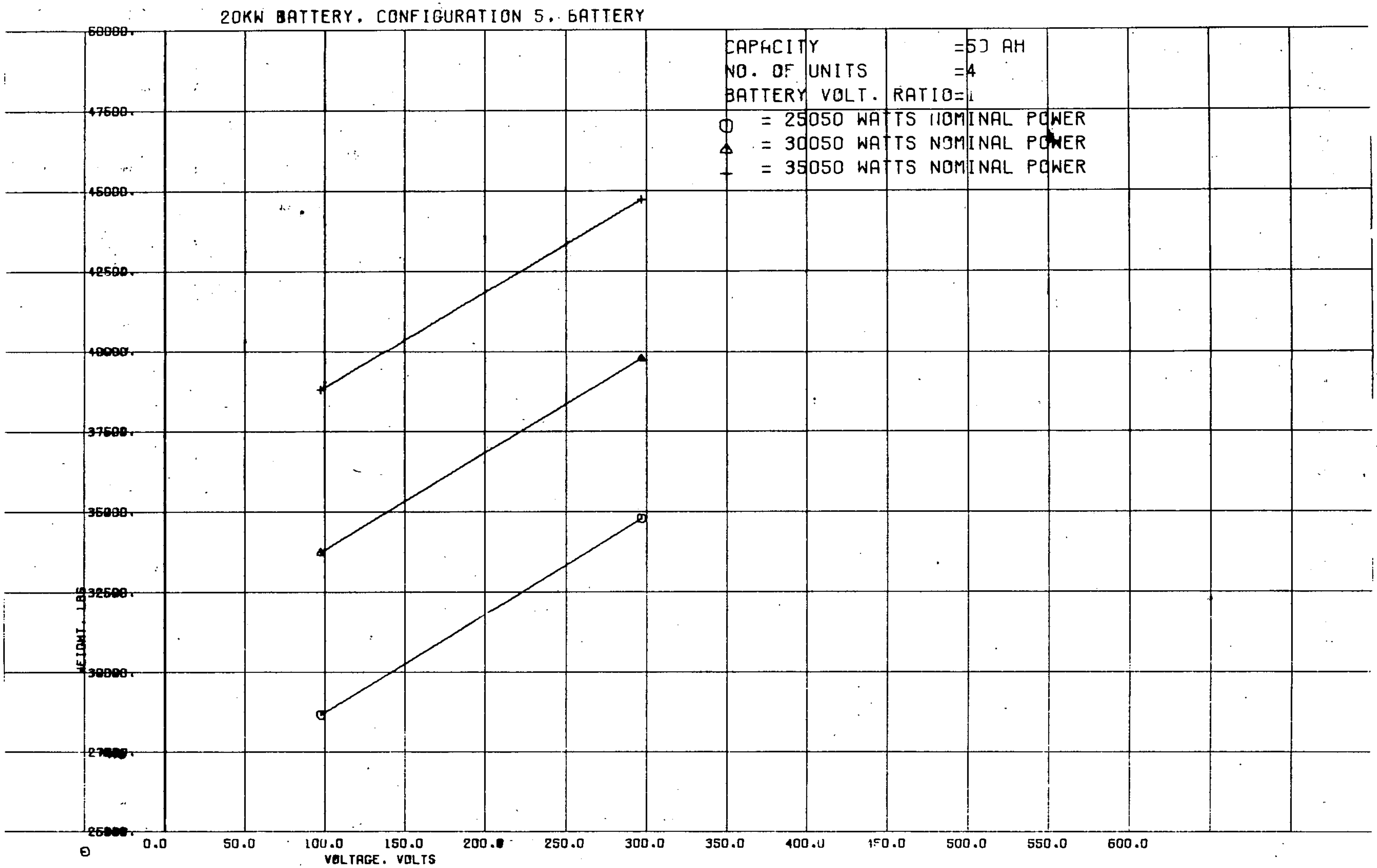
550.0
600.0

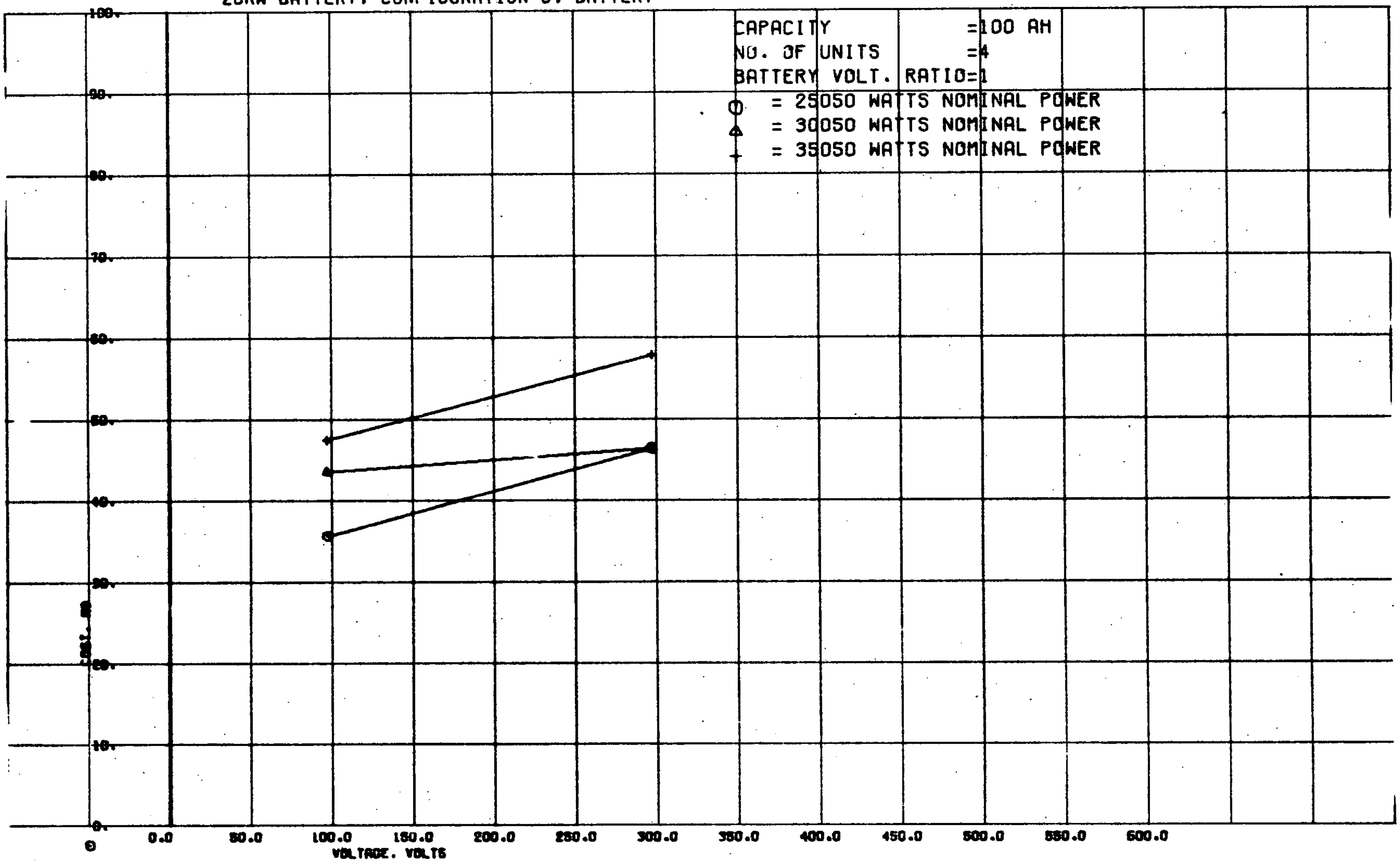

20KW BATTERY. CONFIGURATION 5. BATTERY
CAPACITY =50 AH
NO. OF UNITS =3
BATTERY VOLT. RATIO=1
○ = 25050 WATTS NOMINAL POWER
△ = 30050 WATTS NOMINAL POWER
+ = 35050 WATTS NOMINAL POWER
HEAT LOSS. WATTS
3000.
2800.
2600.
2400.
2200.
2000.
1800.
1600.
1400.
1200.
1000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

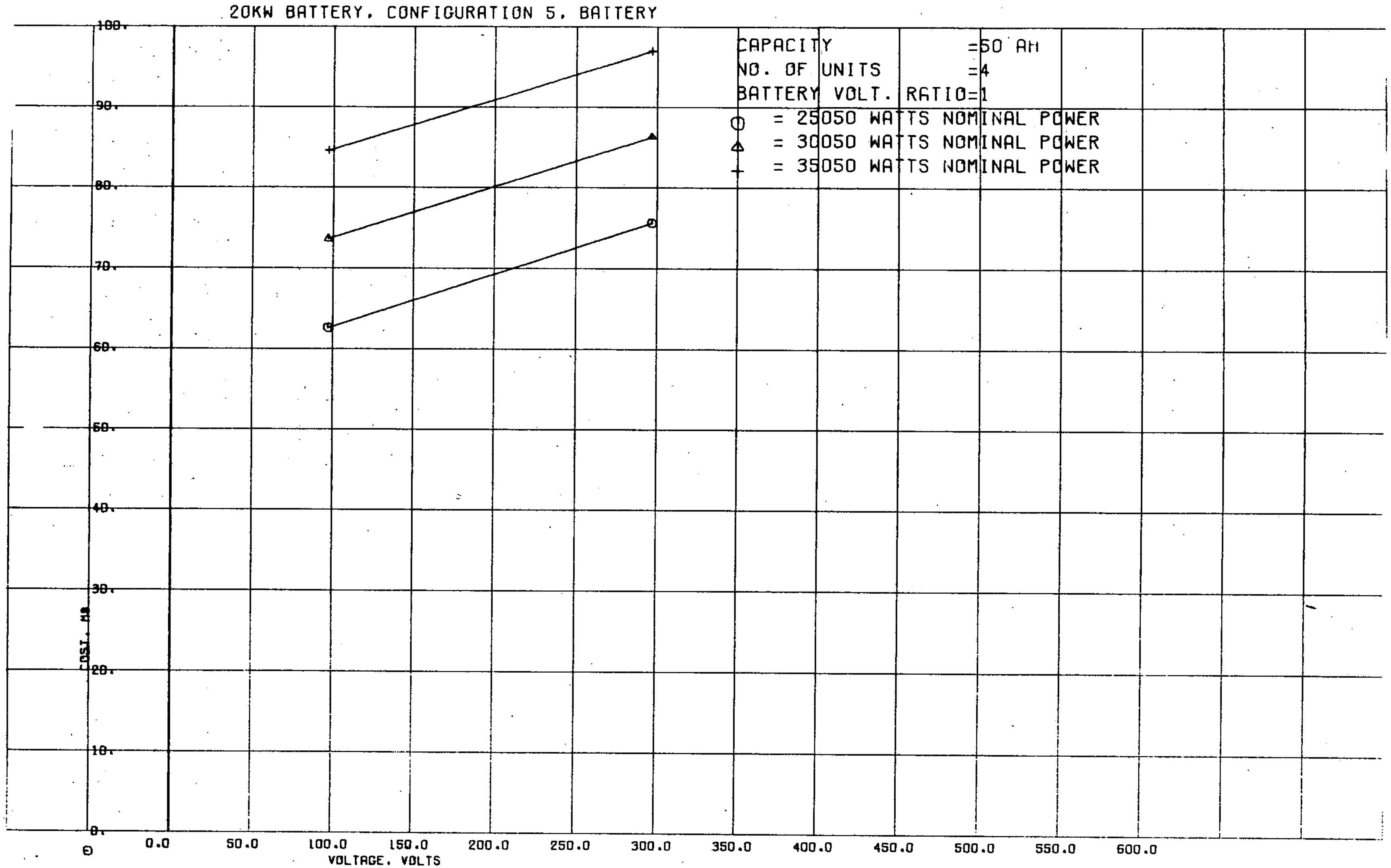

20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =100 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
WEIGHT, LBS
50000.
47500.
45000.
42500.
40000.
37500.
35000.
32500.
30000.
27500.
25000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



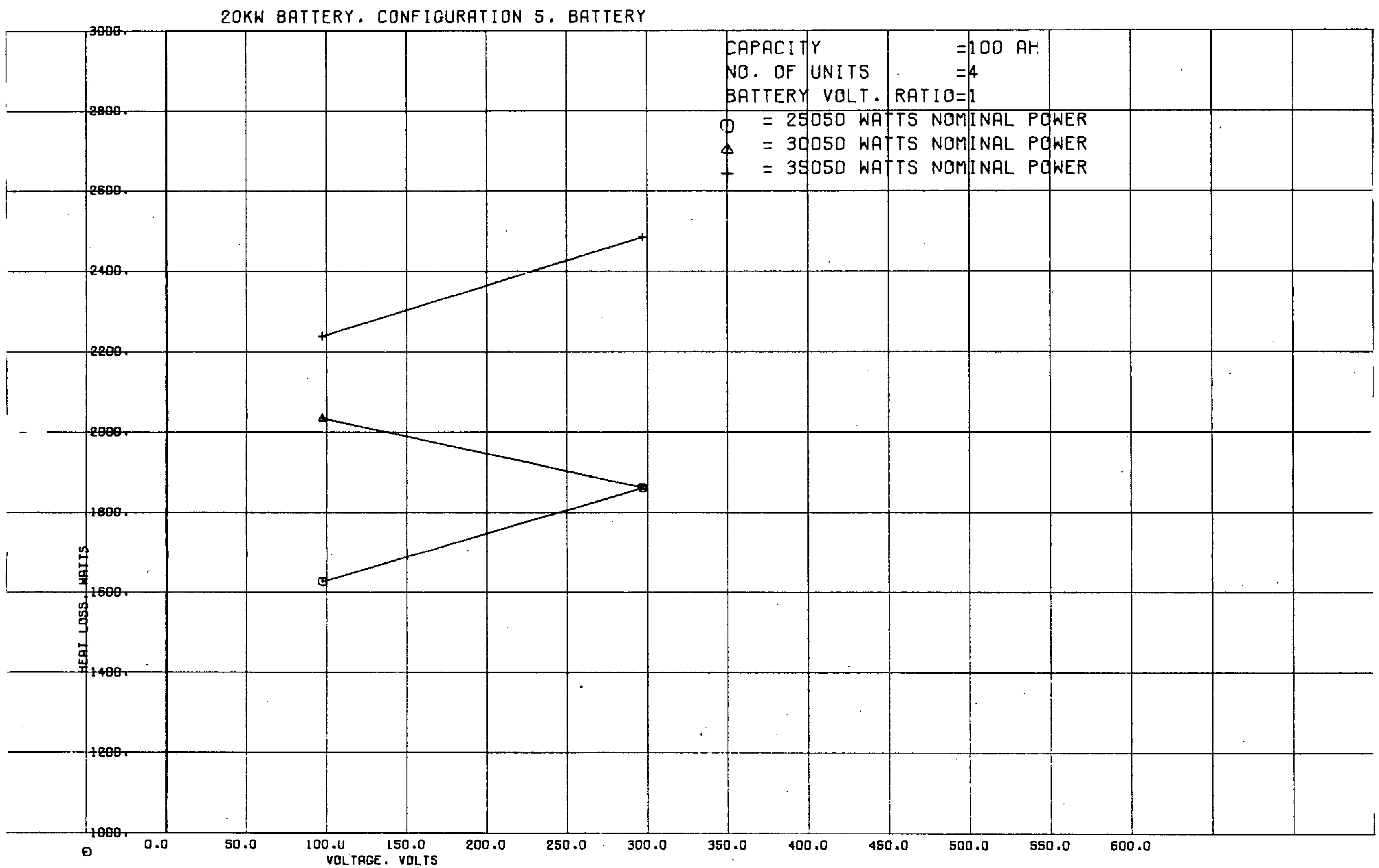
20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =50 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS

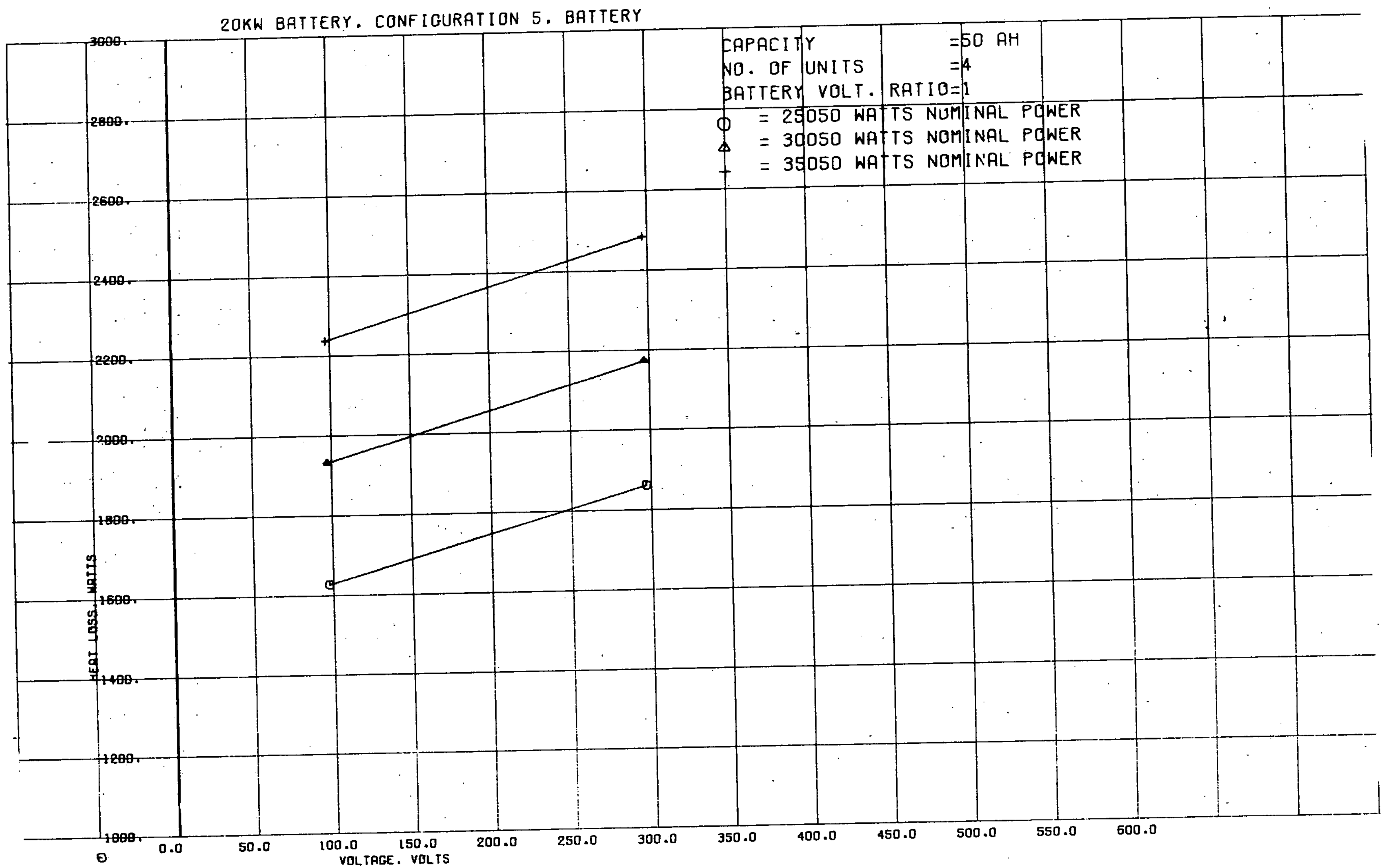
20KW BATTERY, CONFIGURATION 5, BATTERY





20KW BATTERY, CONFIGURATION 5, BATTERY
CAPACITY =50 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
○ = 25050 WATTS NOMINAL POWER
△ = 30050 WATTS NOMINAL POWER
+ = 35050 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 5. BATTERY
CAPACITY =100 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
3000.
2800.
2600.
2400.
2200.
2000.
1800.
1600.
1400.
1200.
1000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0


20KW BATTERY. CONFIGURATION 5. BATTERY
CAPACITY =50 AH
NO. OF UNITS =4
BATTERY VOLT. RATIO=1
= 25050 WATTS NOMINAL POWER
= 30050 WATTS NOMINAL POWER
= 35050 WATTS NOMINAL POWER
3000.
2800.
2600.
2400.
2200.
2000.
1800.
1600.
1400.
1200.
1000.
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

SEE CONFIGURATION 1

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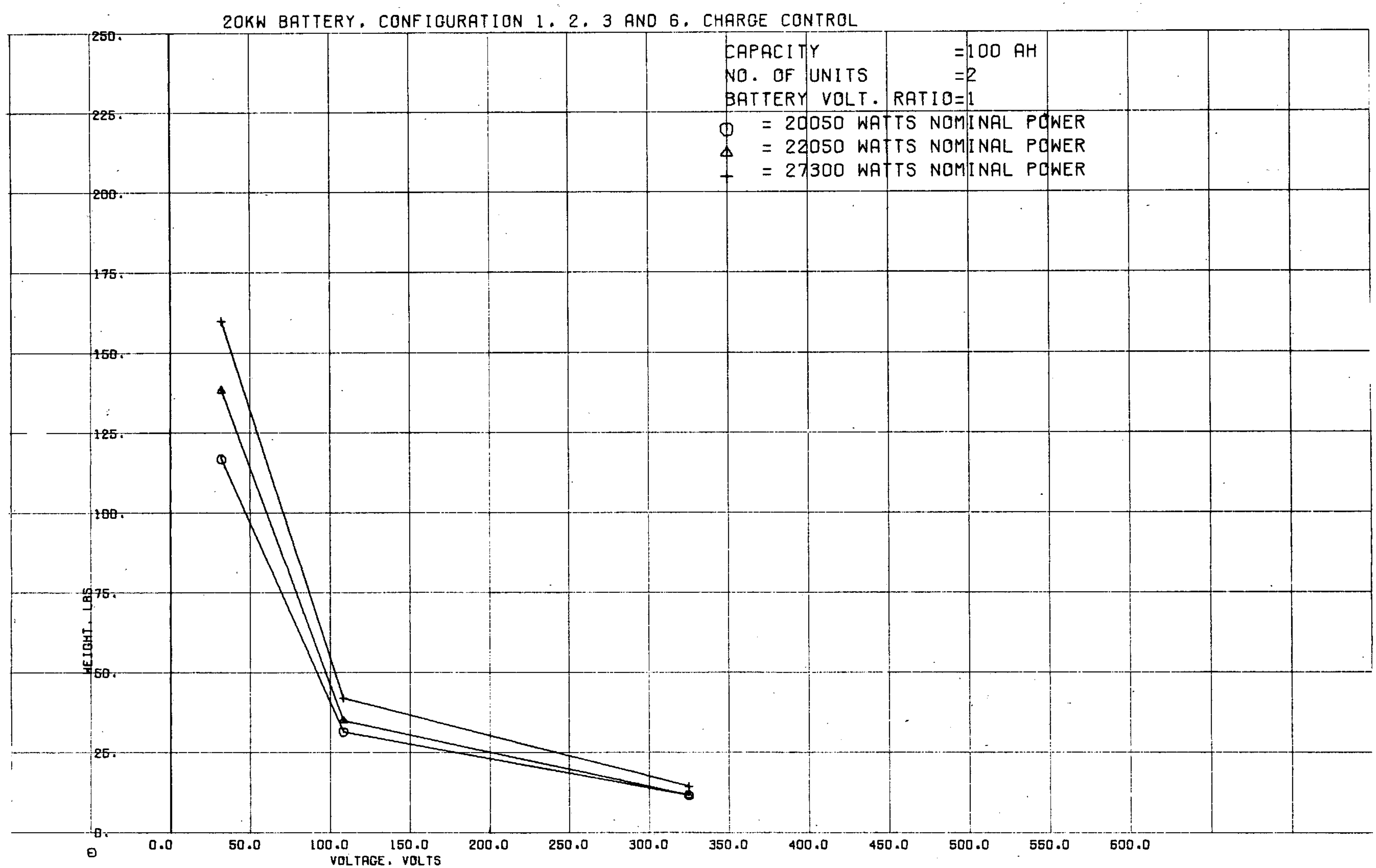

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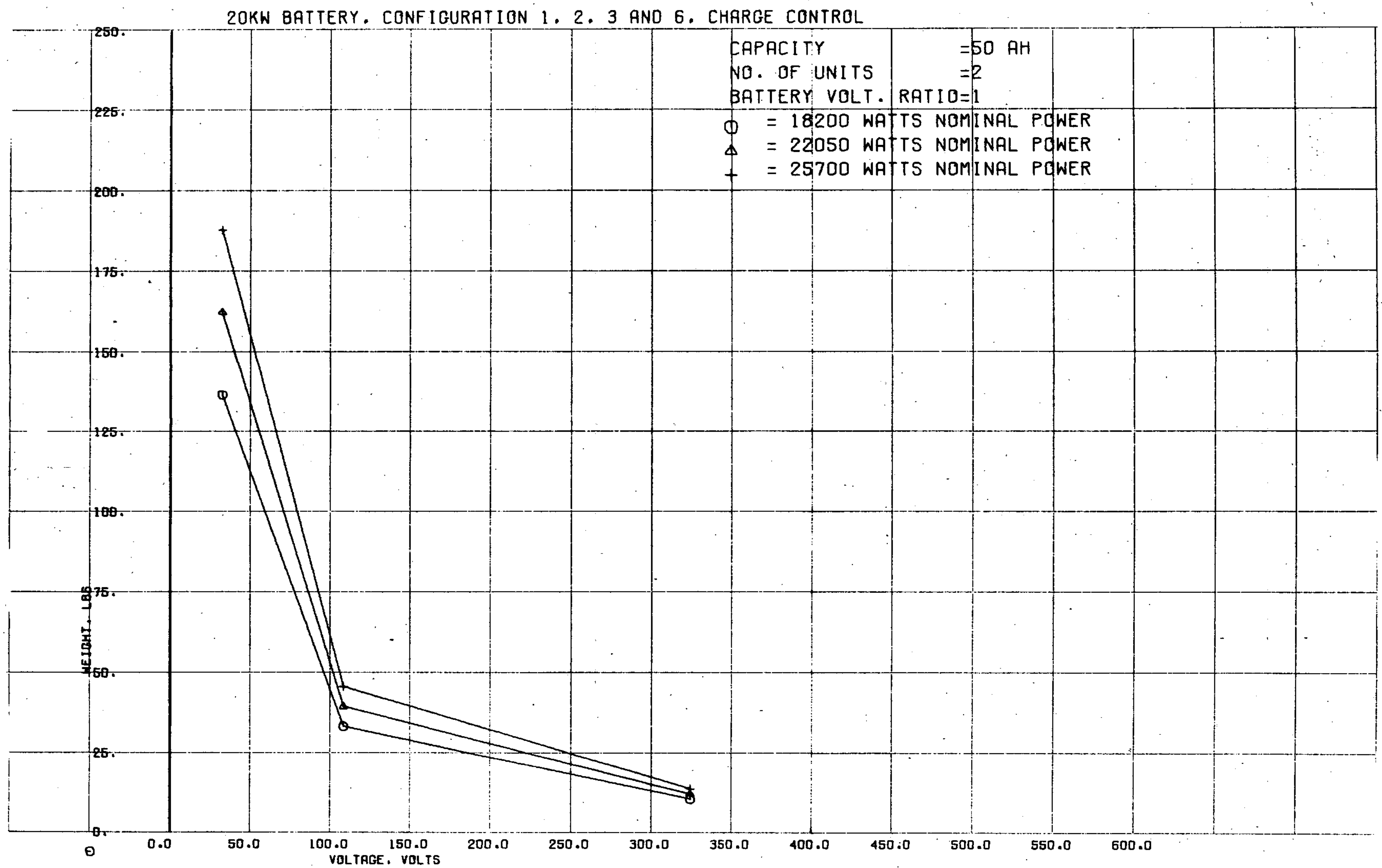
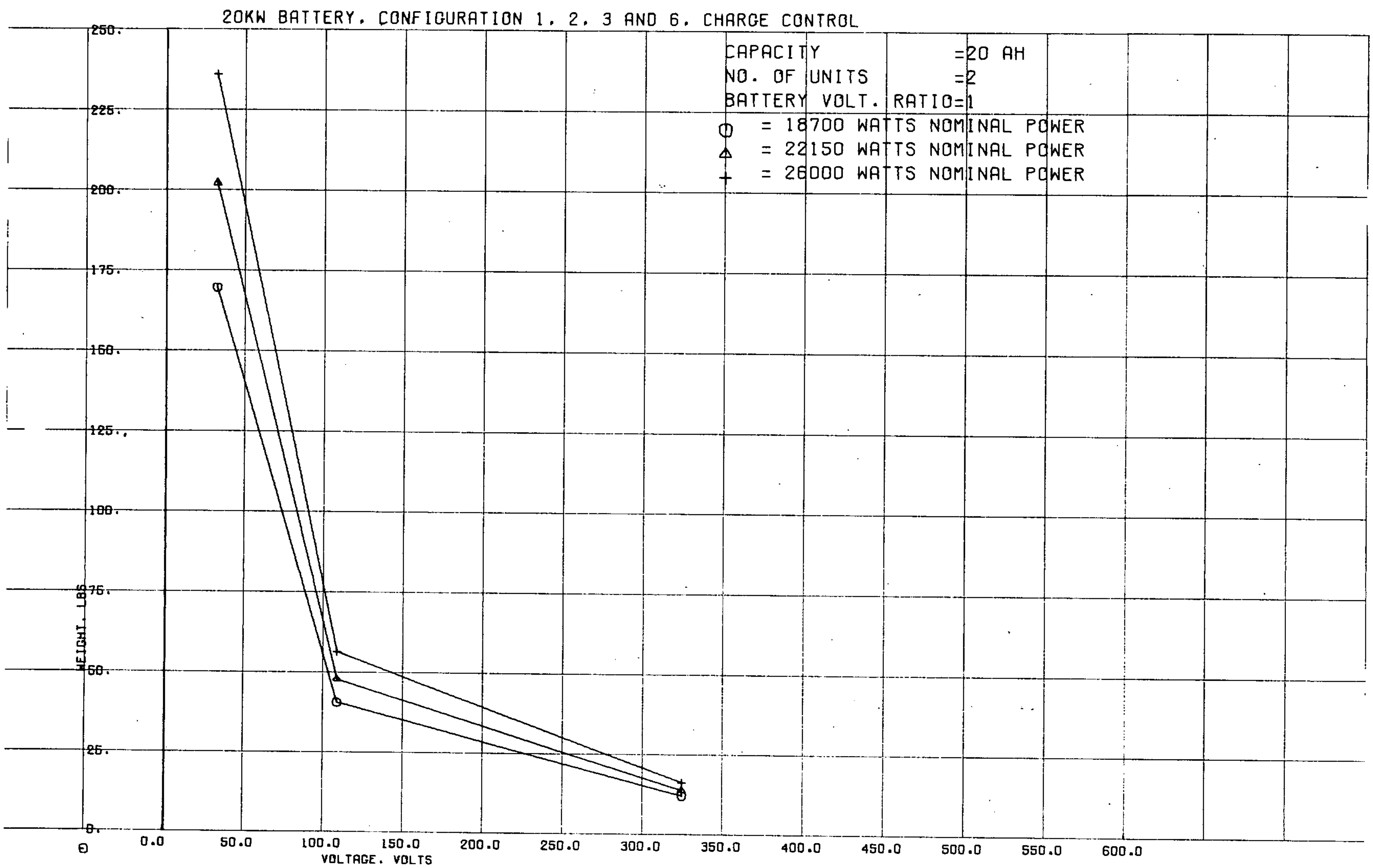
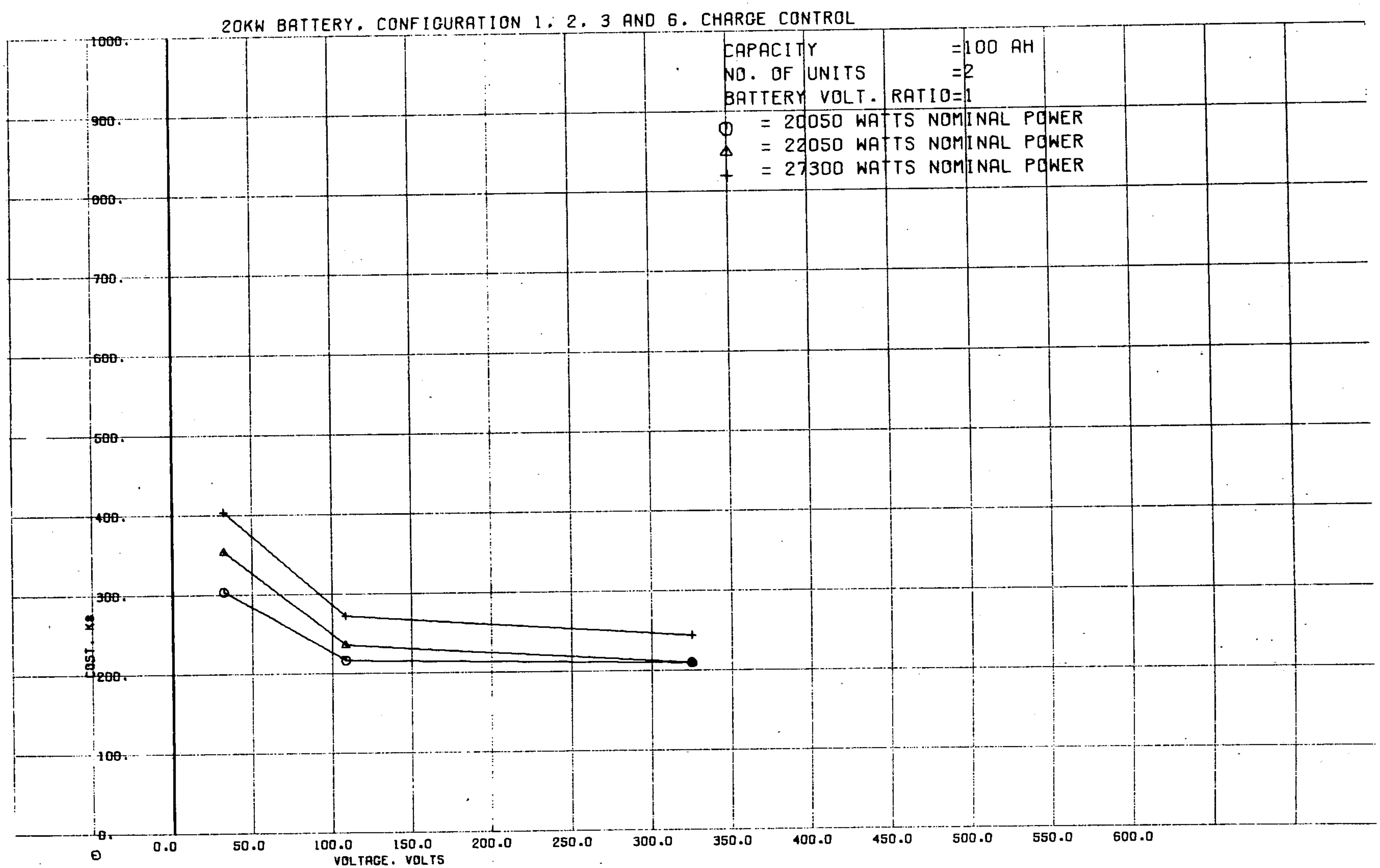
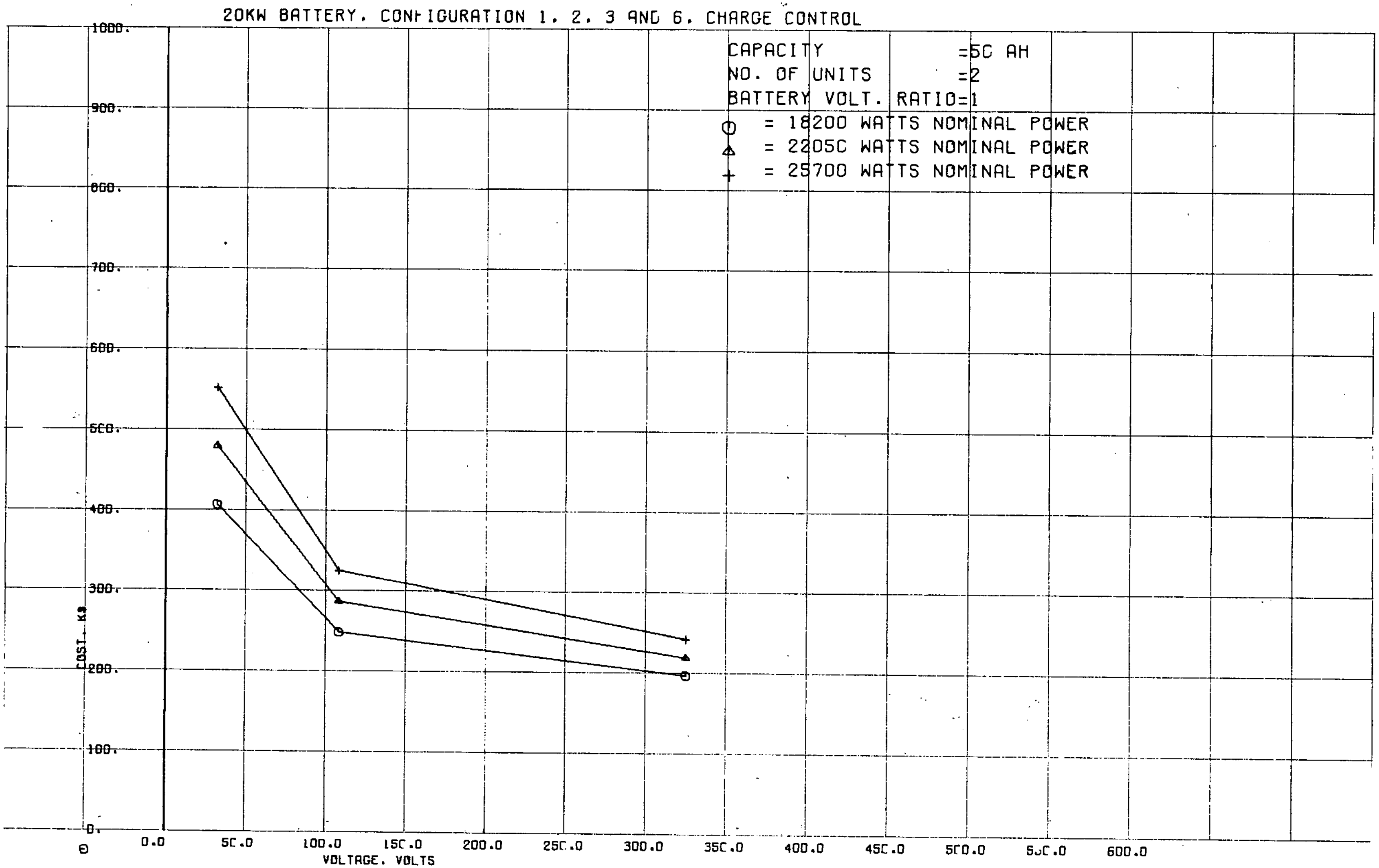


20KW BATTERY. CONFIGURATION 1. 2. 3 AND 6. CHARGE CONTROL
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18200 WATTS NOMINAL POWER
= 22050 WATTS NOMINAL POWER
= 25700 WATTS NOMINAL POWER
WEIGHT. LBS
250.
225.
200.
175.
150.
125.
100.
75.
50.
25.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY, CONFIGURATION 1, 2, 3 AND 6, CHARGE CONTROL
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18700 WATTS NOMINAL POWER
= 22150 WATTS NOMINAL POWER
= 26000 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
250.
225.
200.
175.
150.
125.
100.
75.
50.
25.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

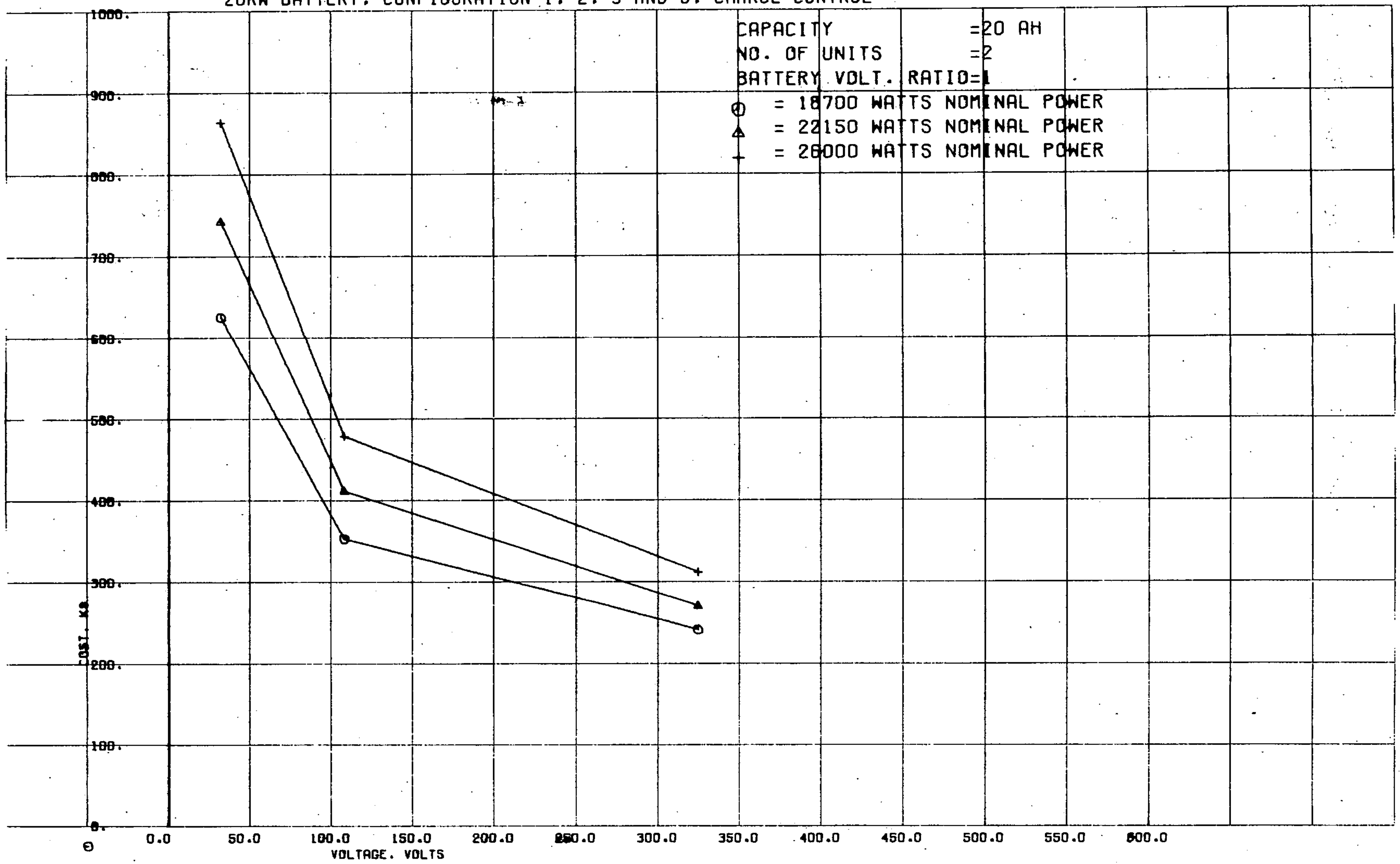


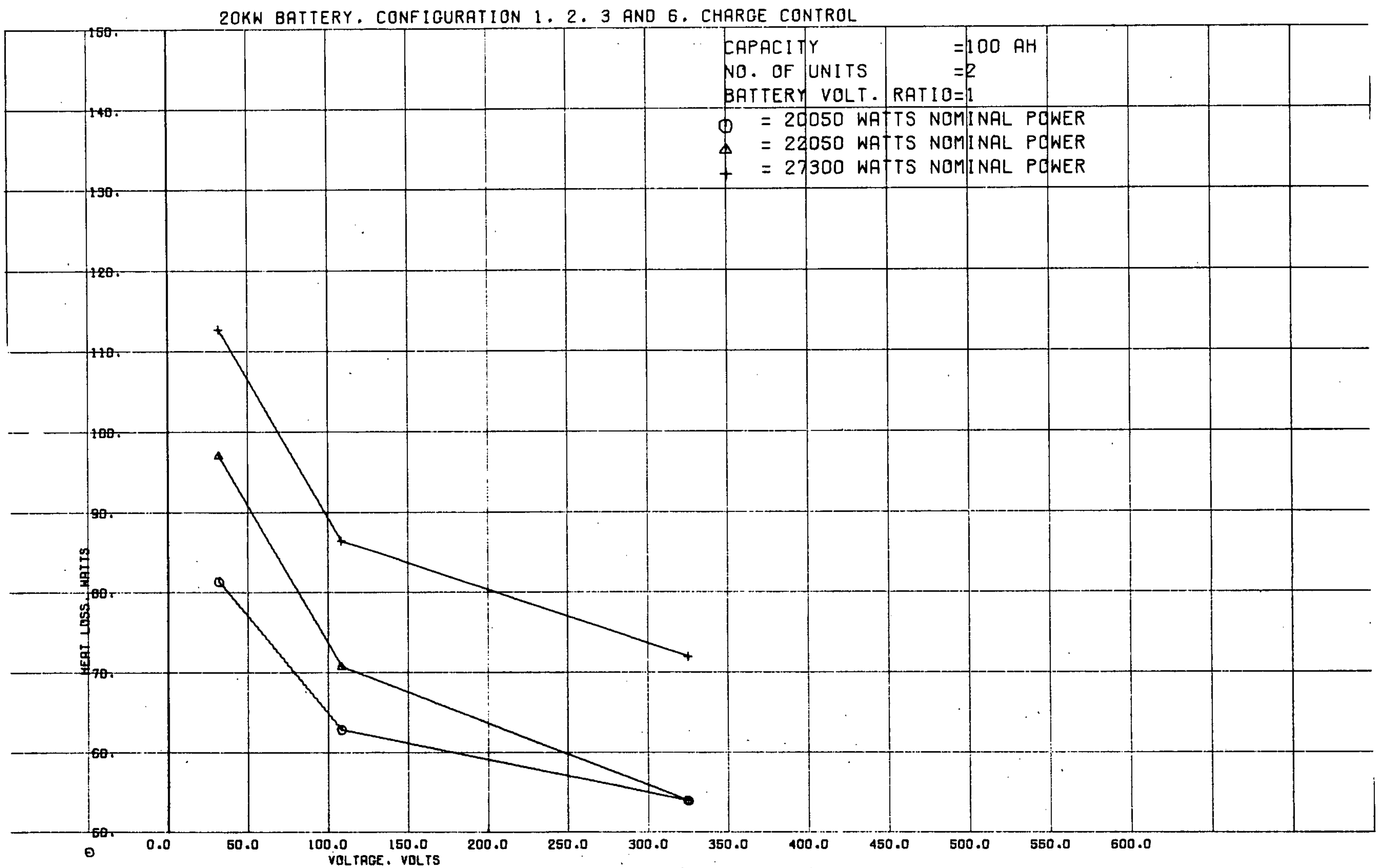
20KW BATTERY. CONFIGURATION 1. 2. 3 AND 6. CHARGE CONTROL
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20050 WATTS NOMINAL POWER
= 22050 WATTS NOMINAL POWER
= 27300 WATTS NOMINAL POWER
COST. K$
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS



20KW BATTERY. CONFIGURATION 1. 2. 3 AND 6. CHARGE CONTROL
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18200 WATTS NOMINAL POWER
= 22050 WATTS NOMINAL POWER
= 25700 WATTS NOMINAL POWER
COST. K$
VOLTAGE. VOLTS

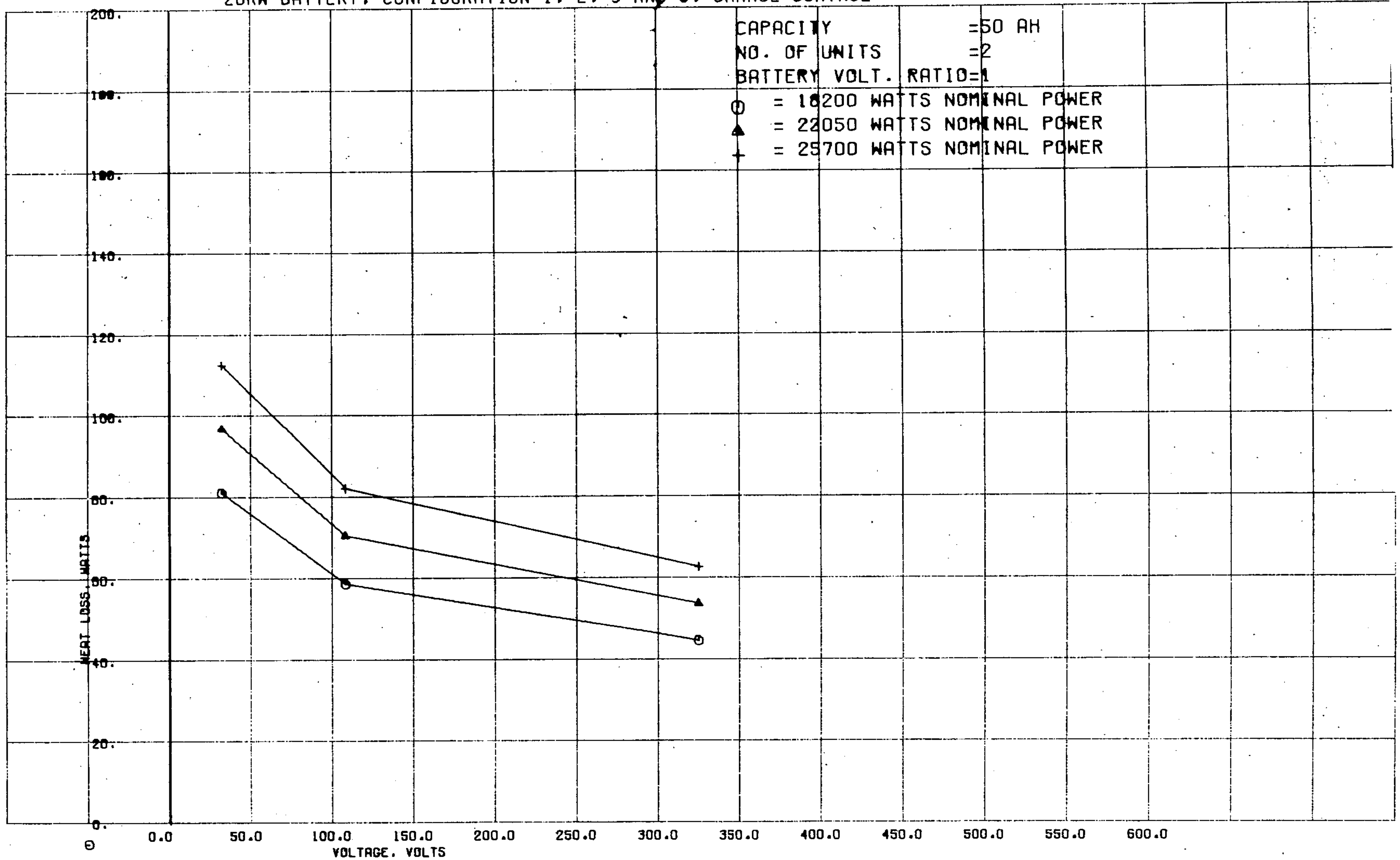
20KW BATTERY, CONFIGURATION 1, 2, 3 AND 6, CHARGE CONTROL

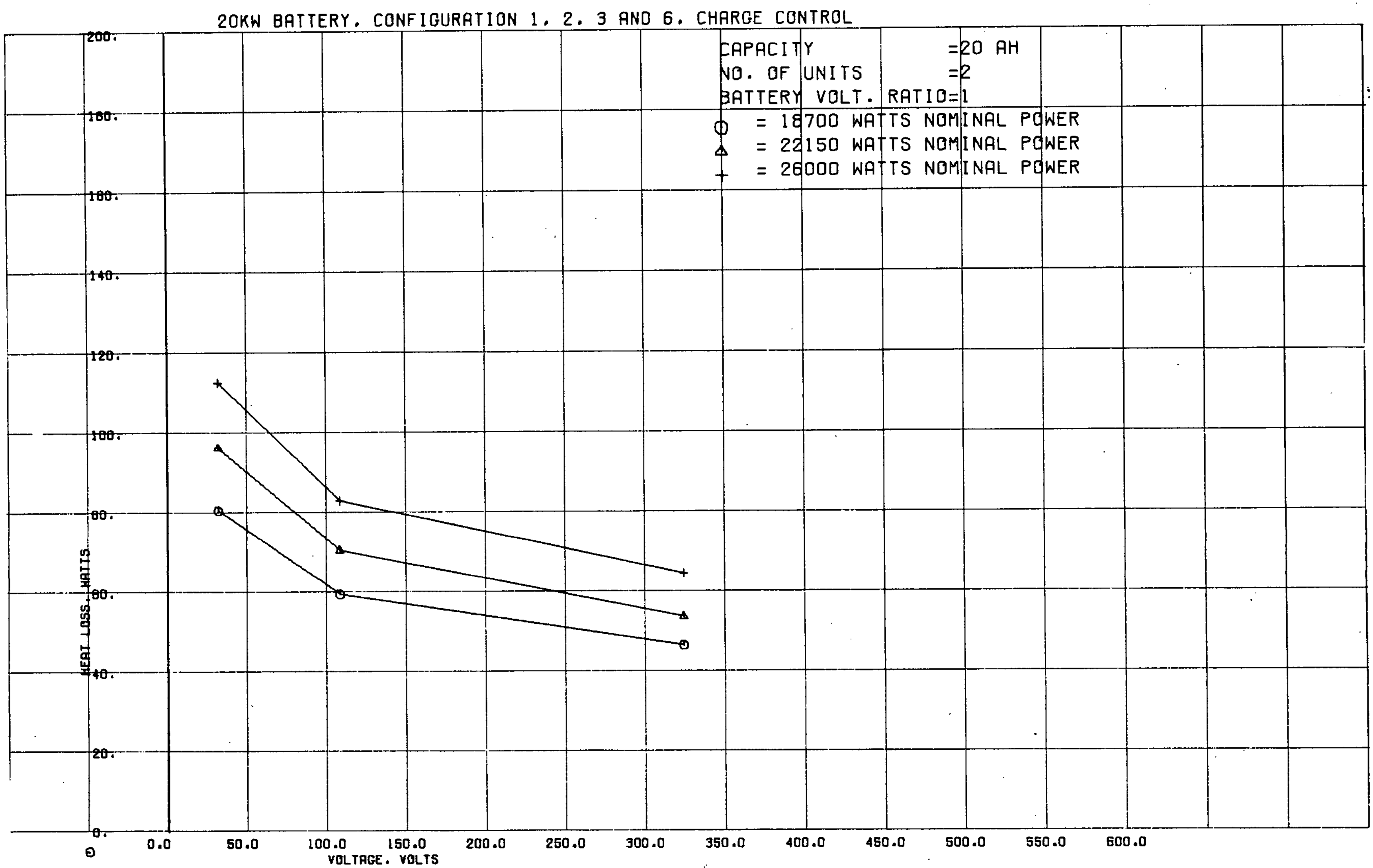




20KW BATTERY, CONFIGURATION 1, 2, 3 AND 6, CHARGE CONTROL
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20050 WATTS NOMINAL POWER
△ = 22050 WATTS NOMINAL POWER
+ = 27300 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
150.
140.
130.
120.
110.
100.
90.
80.
70.
60.
50.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

20KW BATTERY, CONFIGURATION 1, 2, 3 AND 6, CHARGE CONTROL





20KW BATTERY, CONFIGURATION 1, 2, 3 AND 6, CHARGE CONTROL
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18700 WATTS NOMINAL POWER
△ = 22150 WATTS NOMINAL POWER
+ = 26000 WATTS NOMINAL POWER
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

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SEE CONFIGURATION 1

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SEE CONFIGURATION 1

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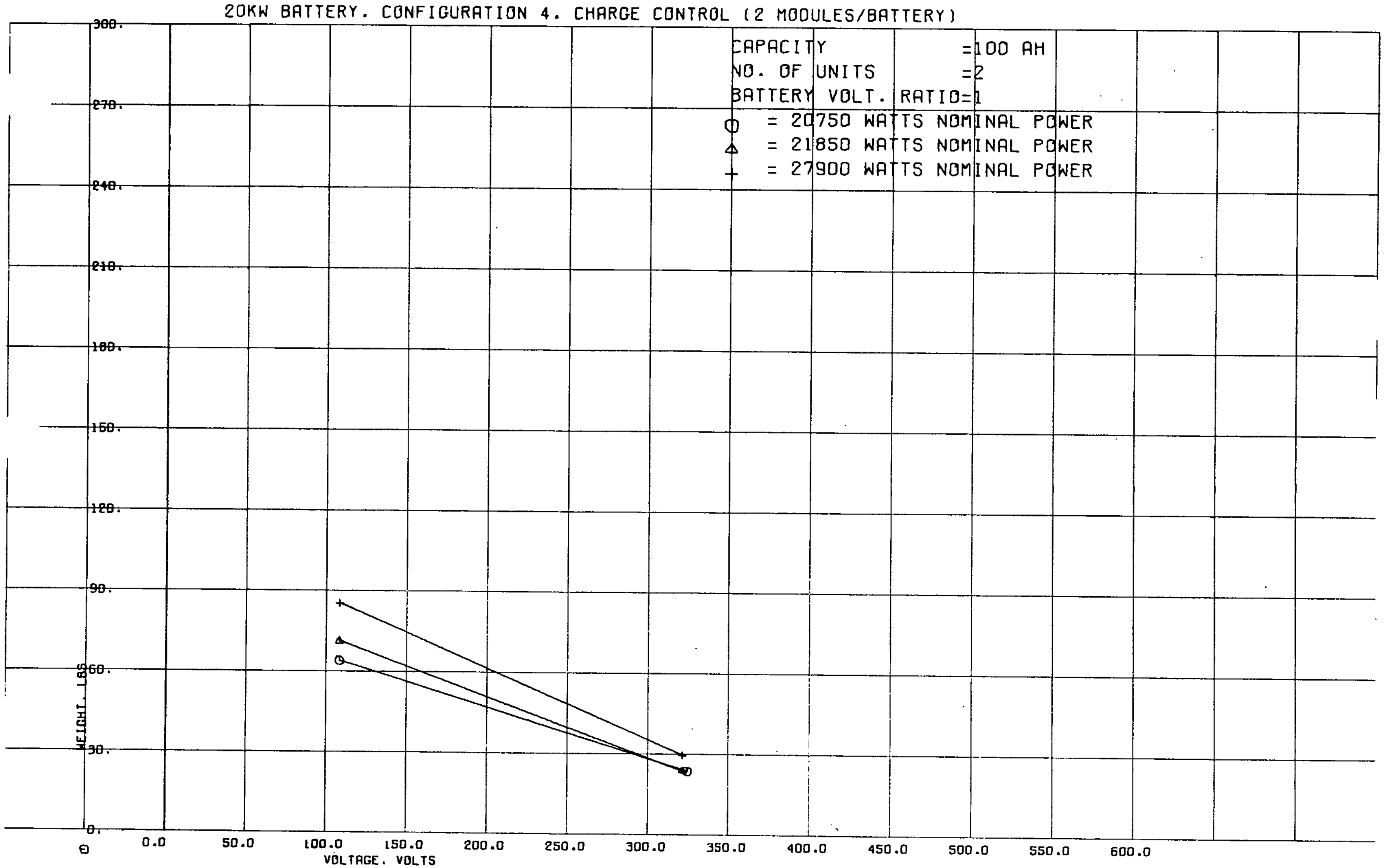

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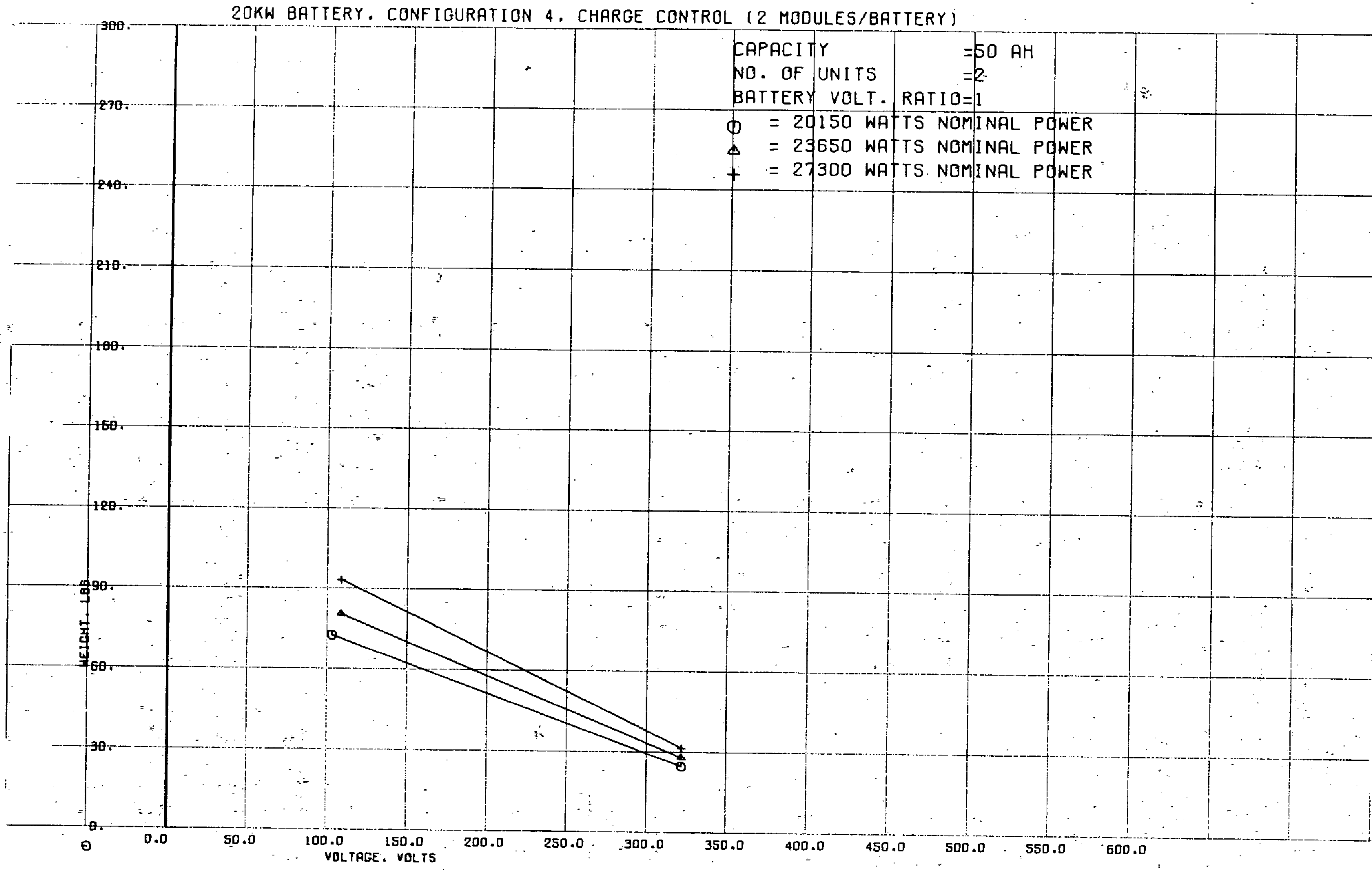
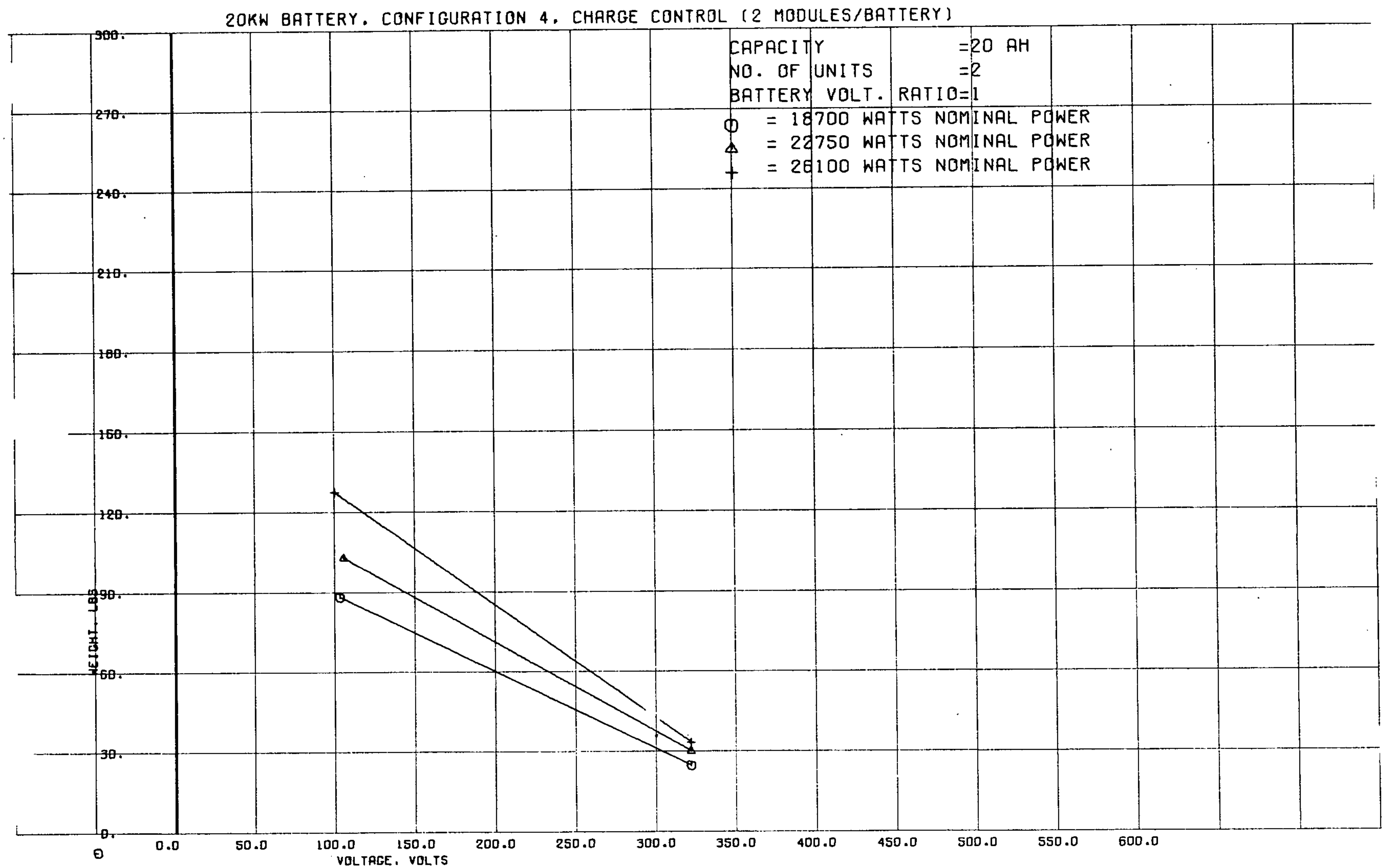
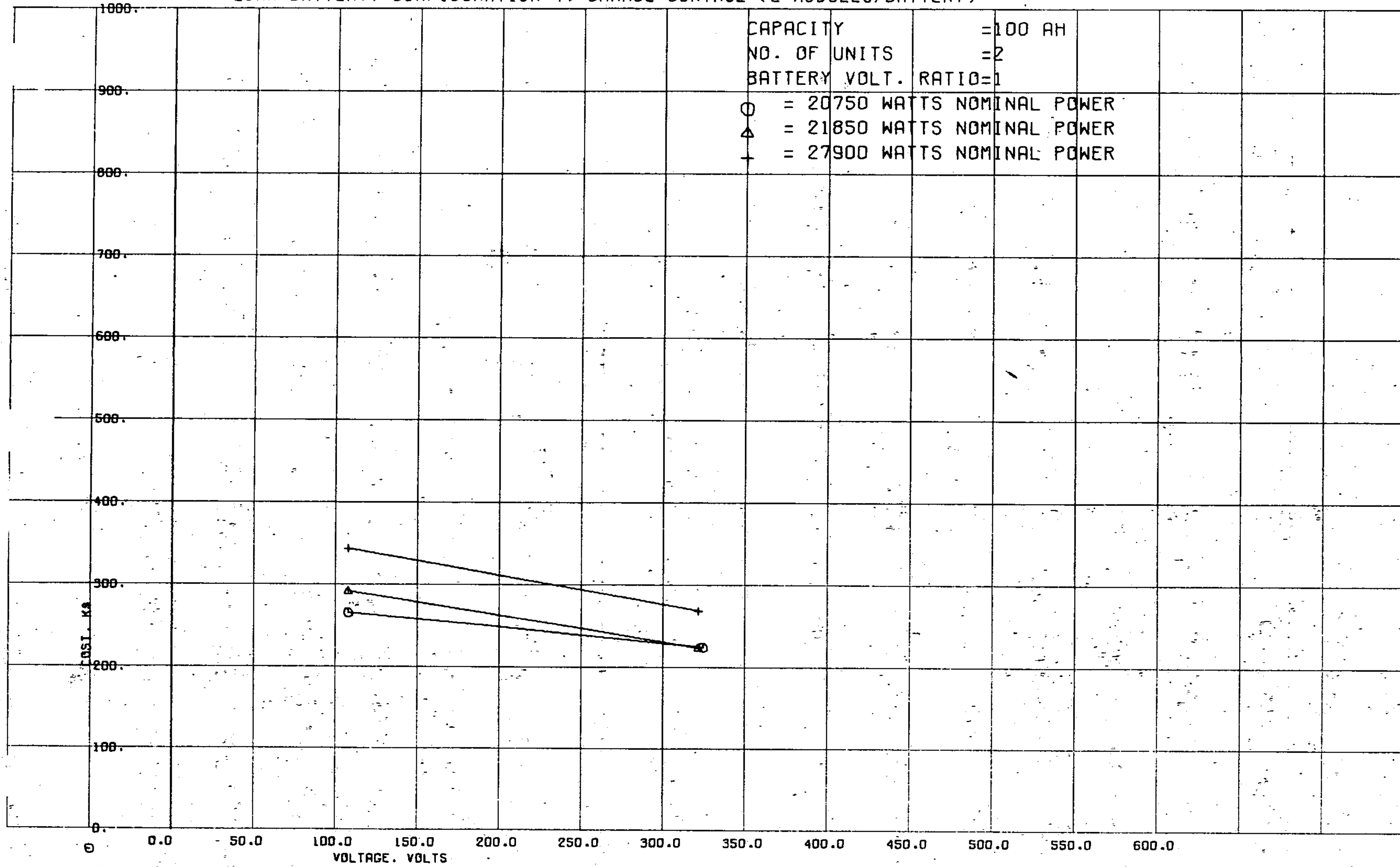


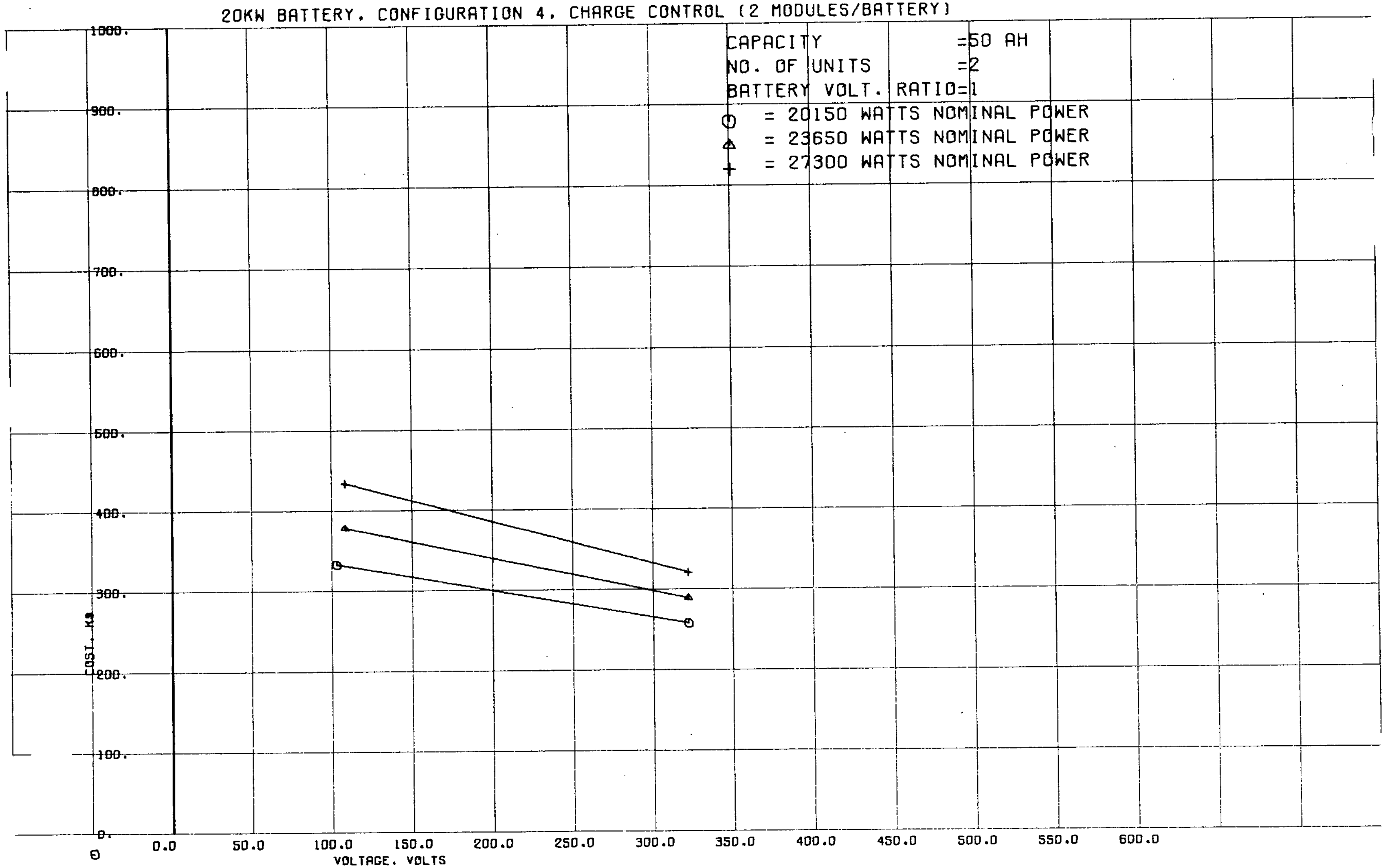
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20150 WATTS NOMINAL POWER
= 23650 WATTS NOMINAL POWER
= 27300 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
30.
60.
90.
120.
150.
180.
210.
240.
270.
300.

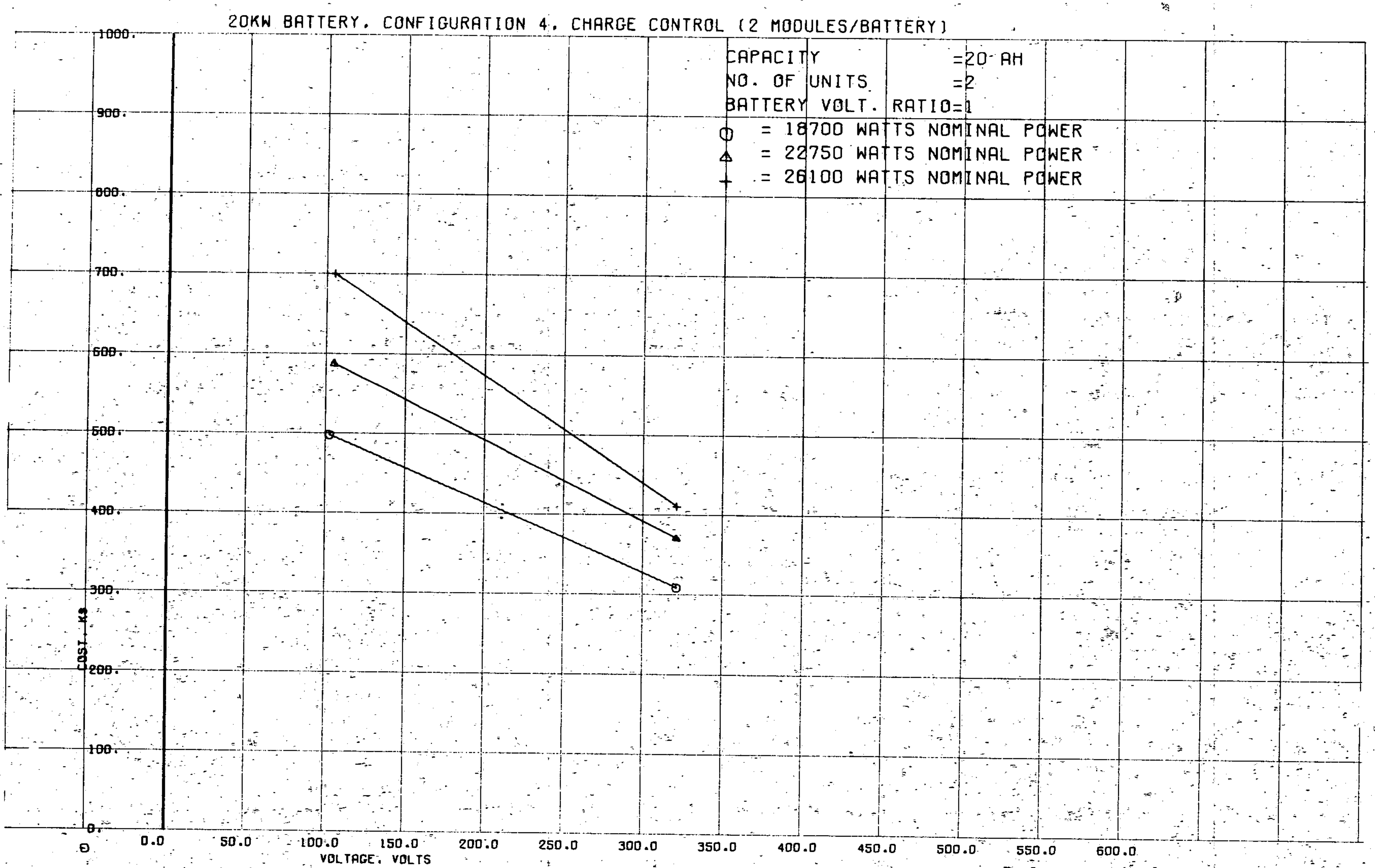

20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18700 WATTS NOMINAL POWER
△ = 22750 WATTS NOMINAL POWER
+ = 26100 WATTS NOMINAL POWER
WEIGHT, LBS
300.
270.
240.
210.
180.
150.
120.
90.
60.
30.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

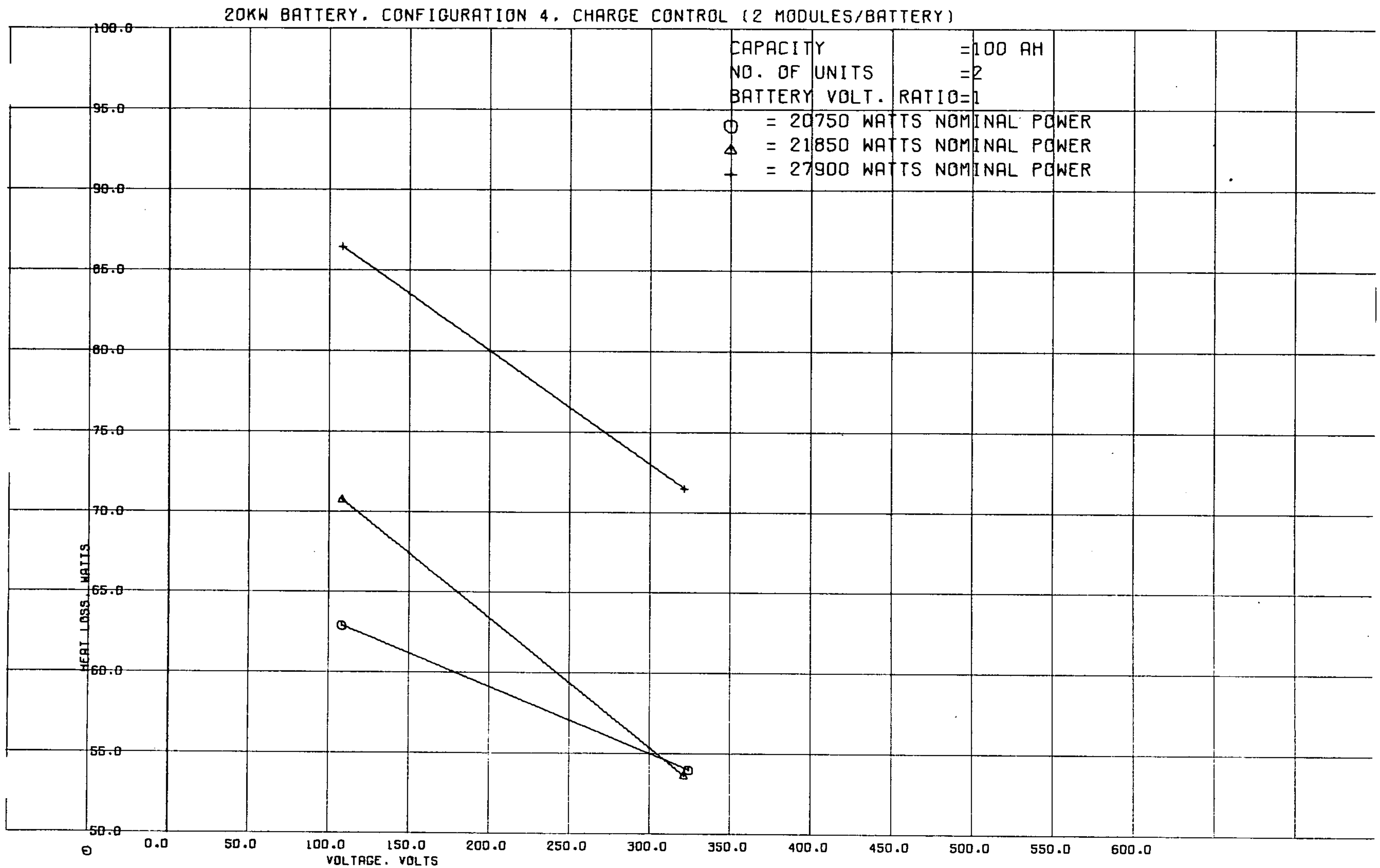
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (2 MODULES/BATTERY)

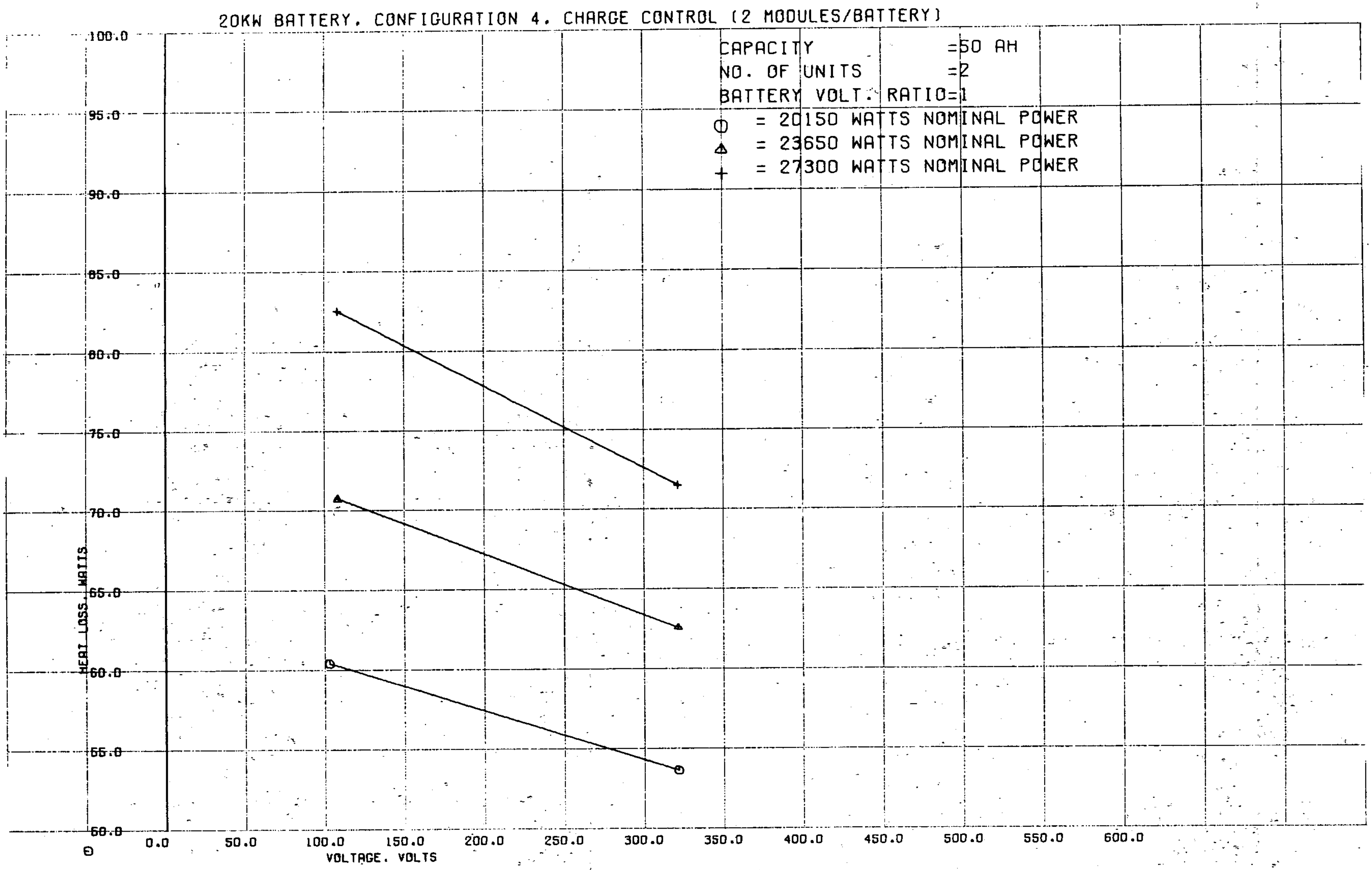


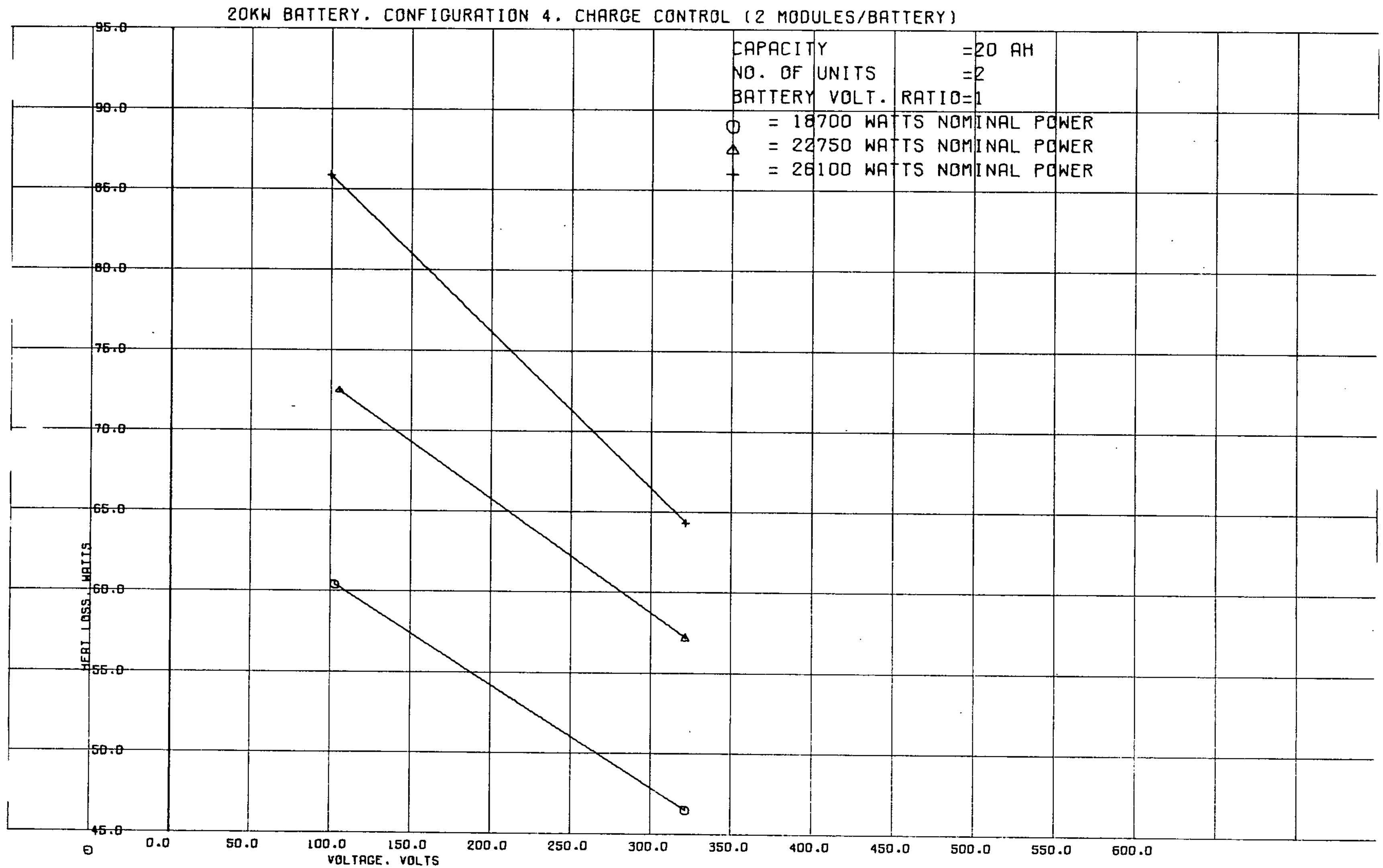
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (2 MODULES/BATTERY)

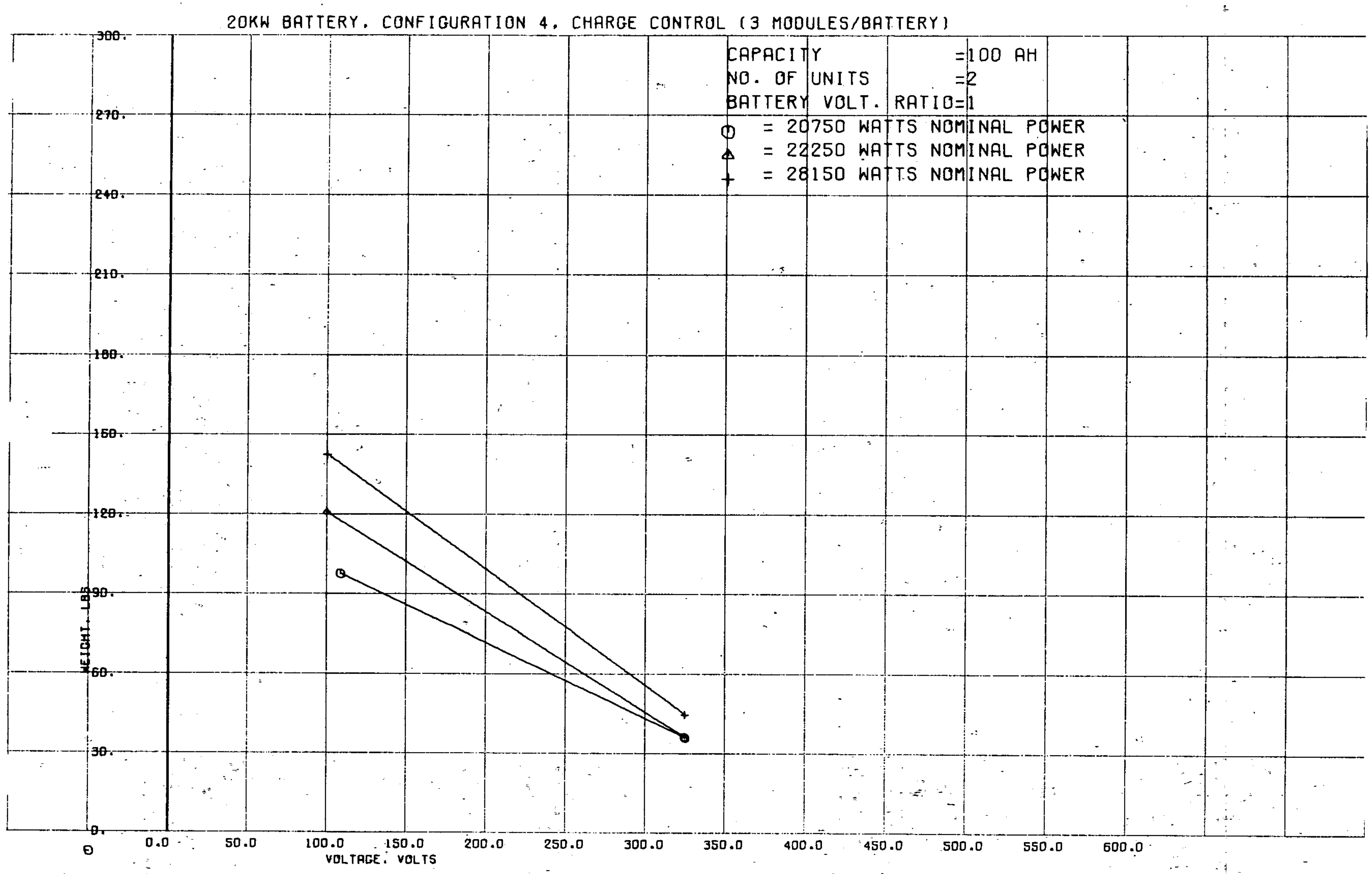


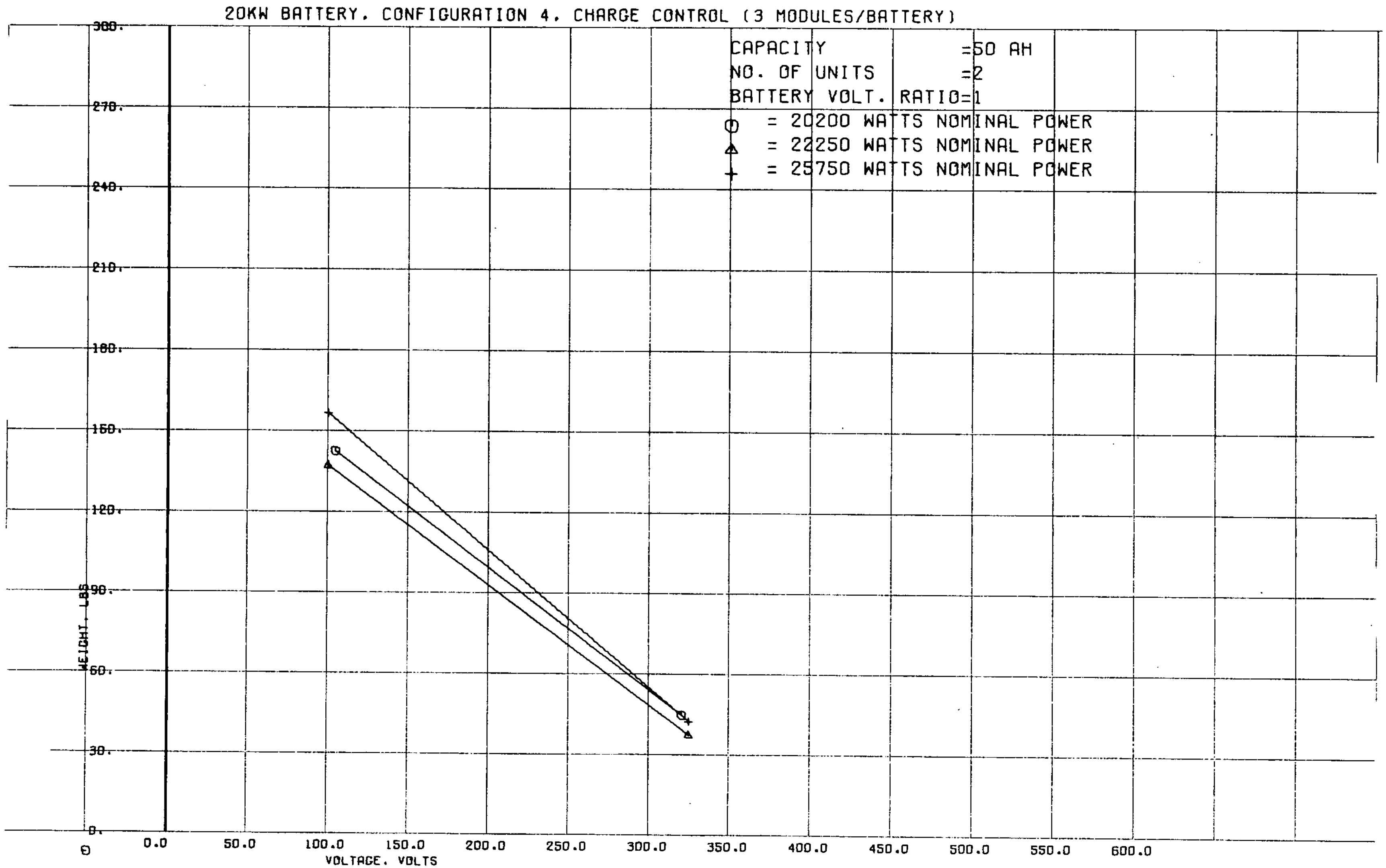

20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18700 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 26100 WATTS NOMINAL POWER
COST, K$
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

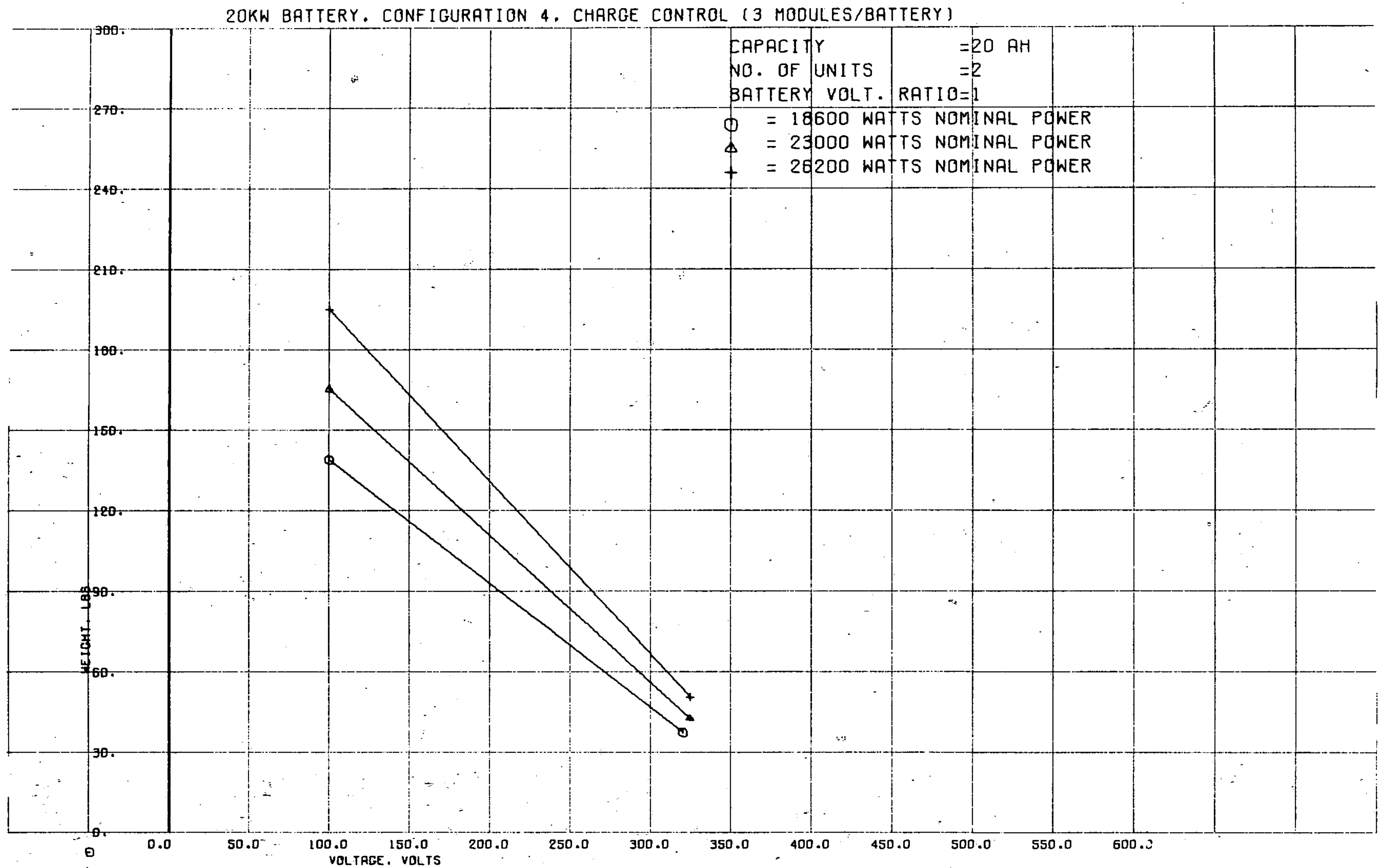

20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20750 WATTS NOMINAL POWER
△ = 21850 WATTS NOMINAL POWER
+ = 27900 WATTS NOMINAL POWER
HEAT LOSS, WATTS
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20150 WATTS NOMINAL POWER
= 23650 WATTS NOMINAL POWER
= 27300 WATTS NOMINAL POWER
HEAT LOSS, WATTS
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18700 WATTS NOMINAL POWER
△ = 22750 WATTS NOMINAL POWER
+ = 26100 WATTS NOMINAL POWER
HEAT LOSS, WATTS
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

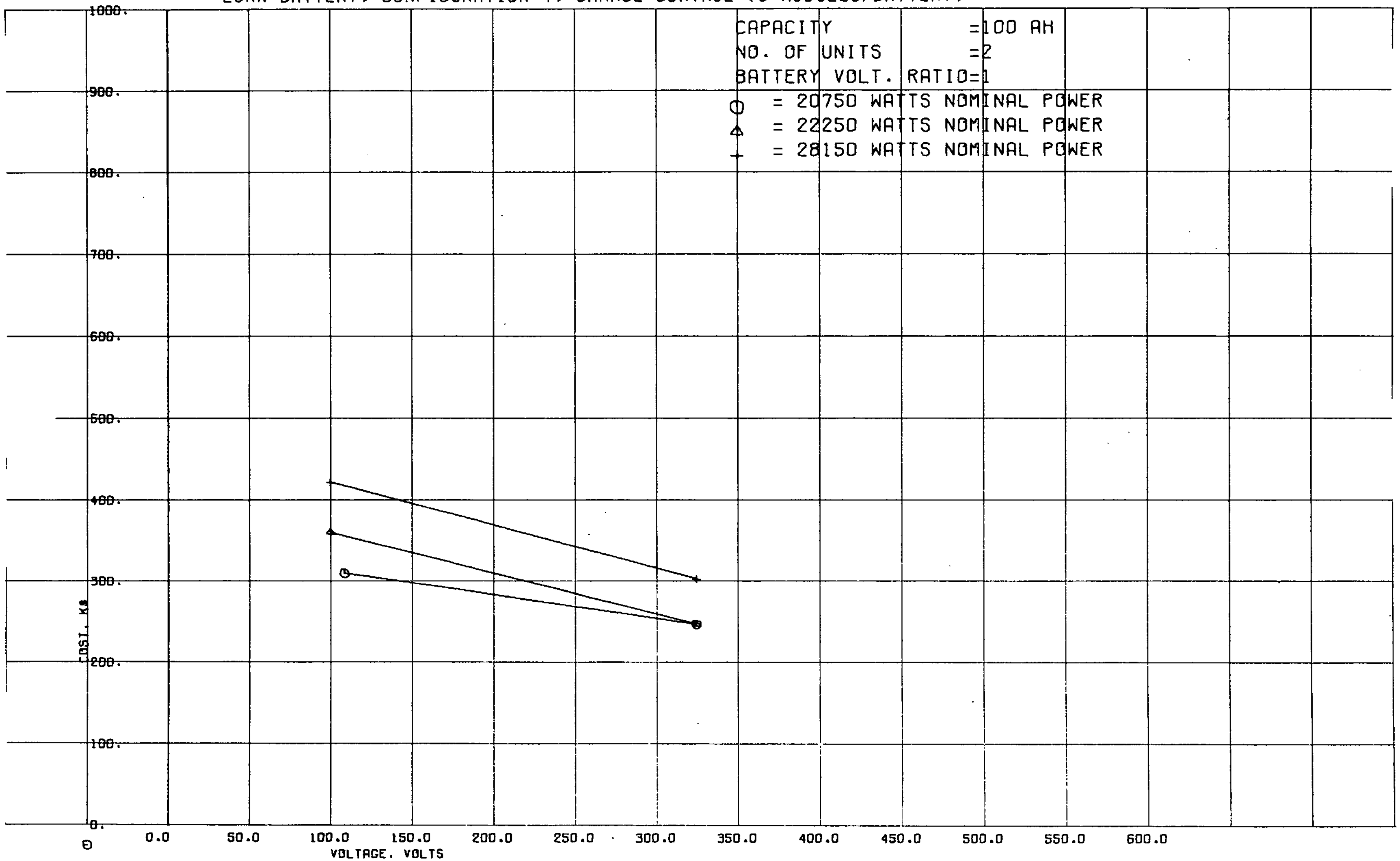

20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 20750 WATTS NOMINAL POWER
Δ = 22250 WATTS NOMINAL POWER
+ = 28150 WATTS NOMINAL POWER
300.
270.
240.
210.
180.
150.
120.
90.
60.
30.
0.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

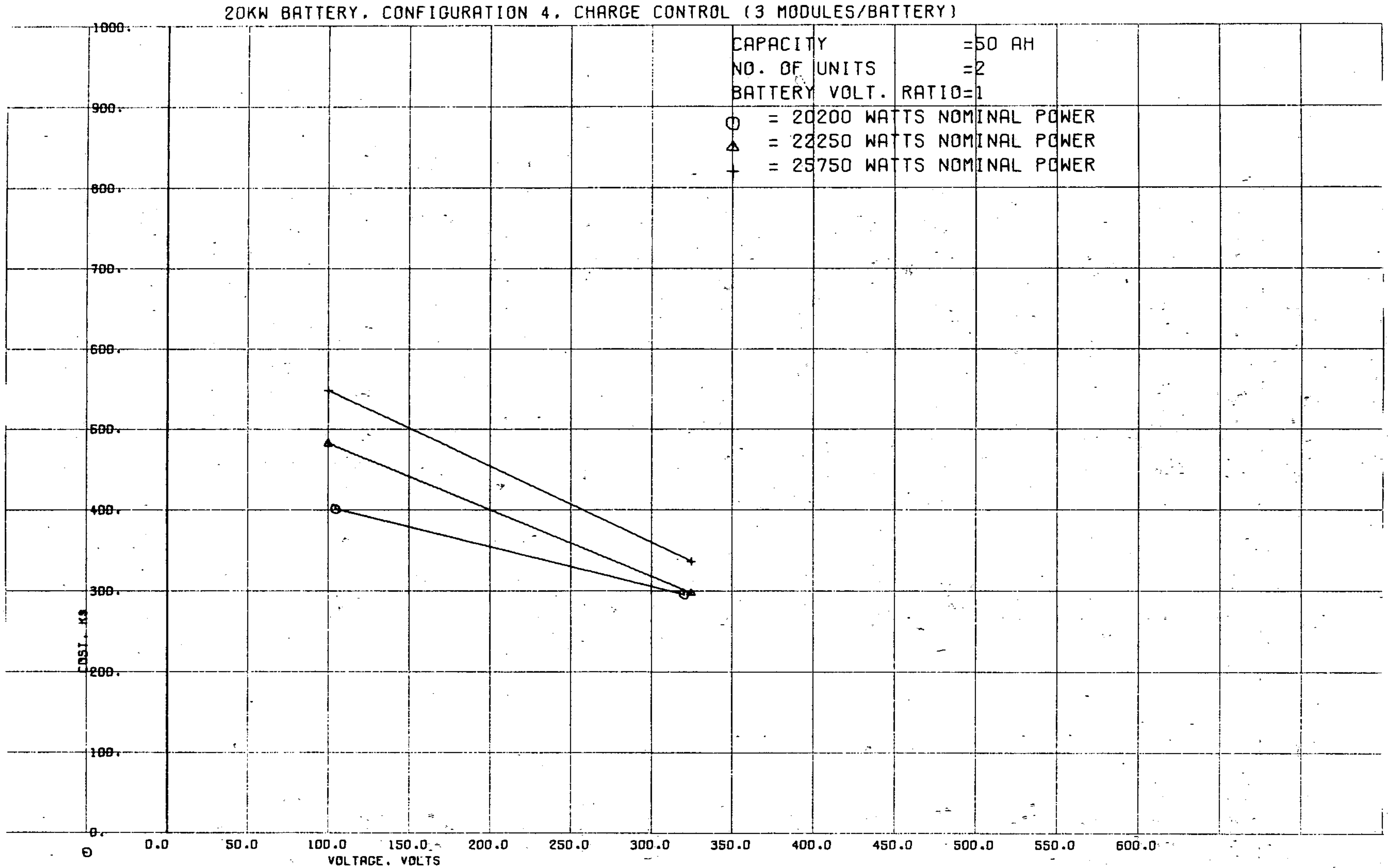

20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20200 WATTS NOMINAL POWER
△ = 22250 WATTS NOMINAL POWER
+ = 25750 WATTS NOMINAL POWER
WEIGHT, LBS
300.
270.
240.
210.
180.
150.
120.
90.
60.
30.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

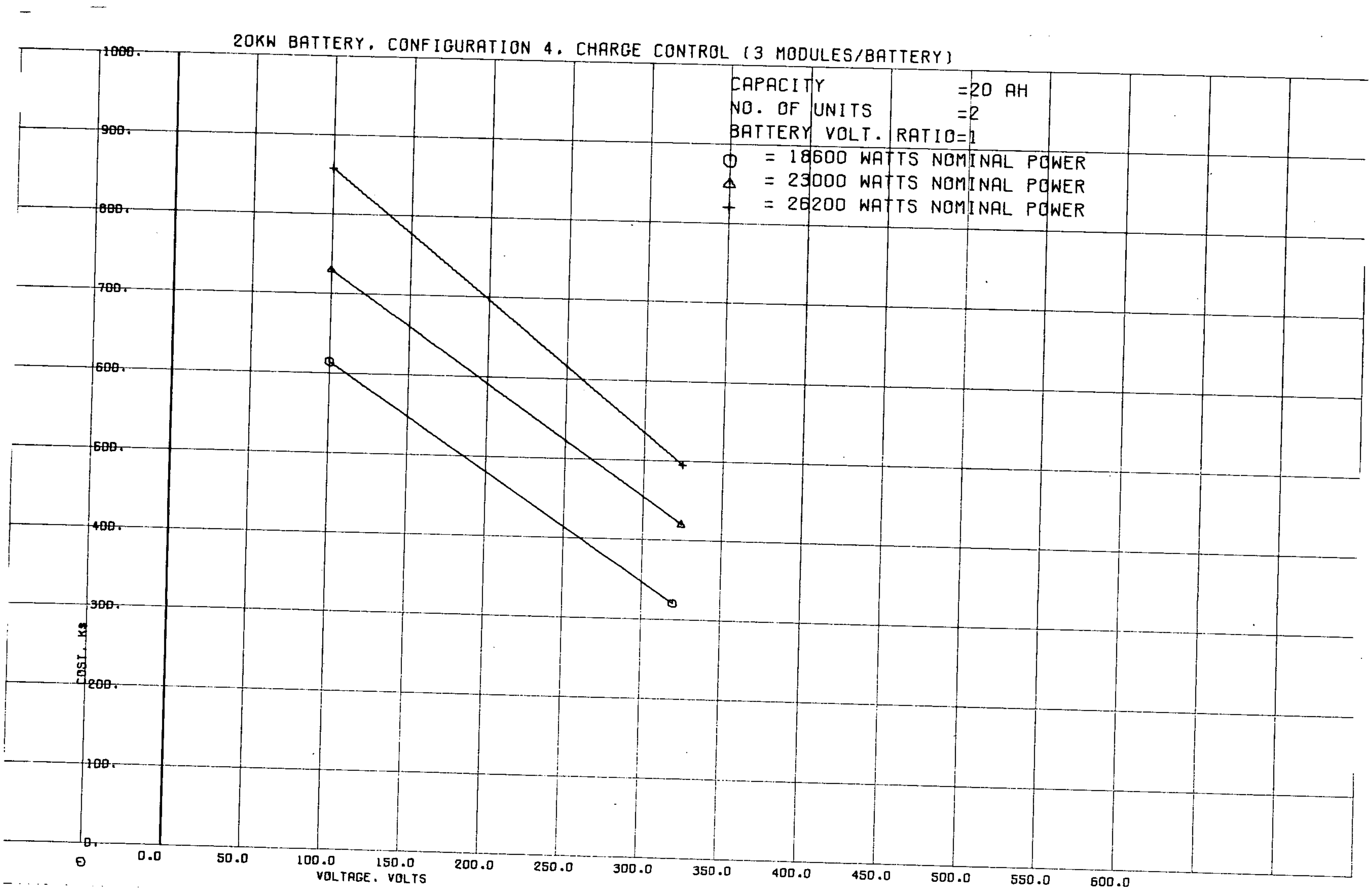


20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18600 WATTS NOMINAL POWER
= 23000 WATTS NOMINAL POWER
= 26200 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS

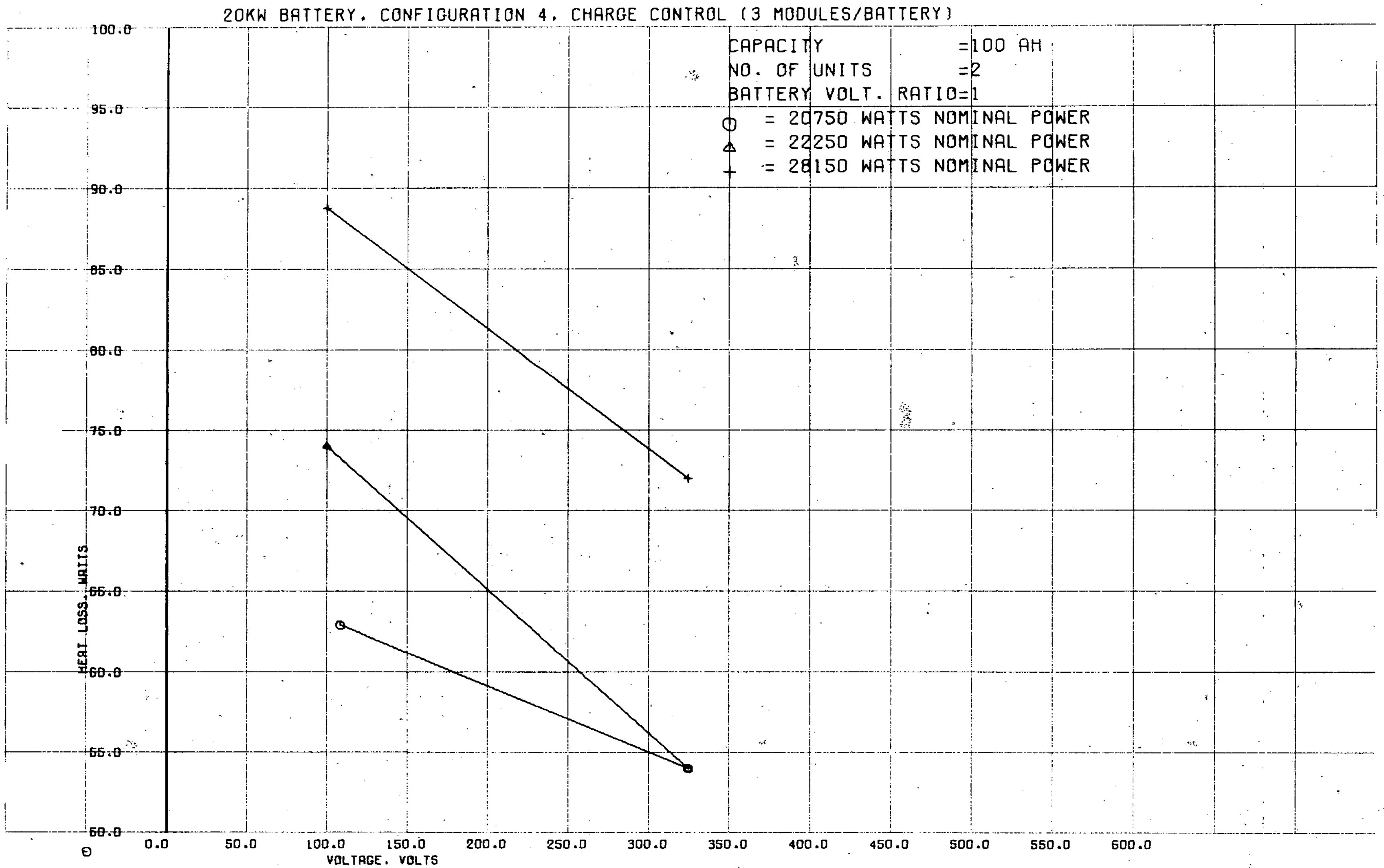
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (3 MODULES/BATTERY)



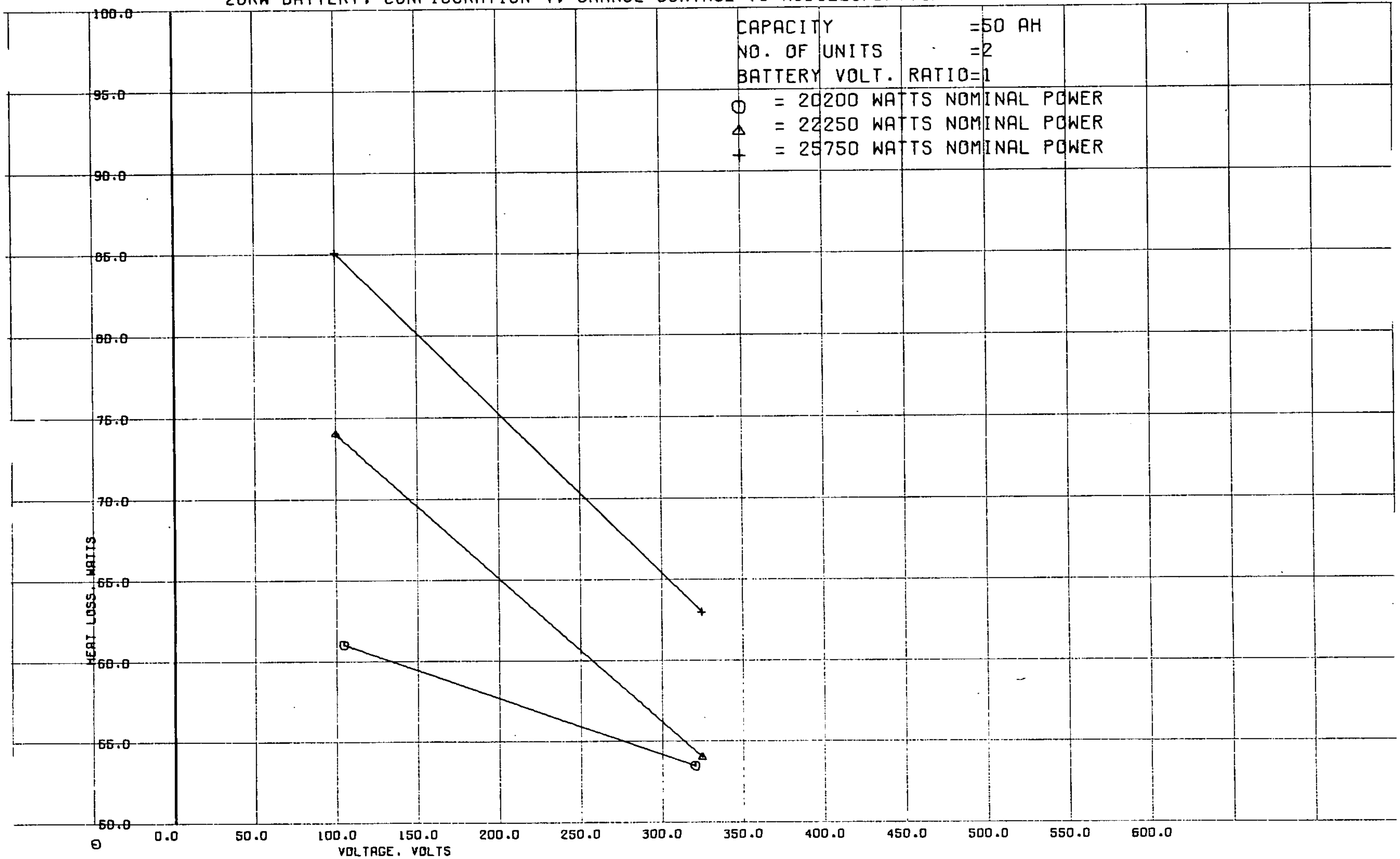

20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20200 WATTS NOMINAL POWER
△ = 22250 WATTS NOMINAL POWER
+ = 25750 WATTS NOMINAL POWER
COST, K$
VOLTAGE, VOLTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
100.
200.
300.
400.
500.
600.
700.
800.
900.
1000.

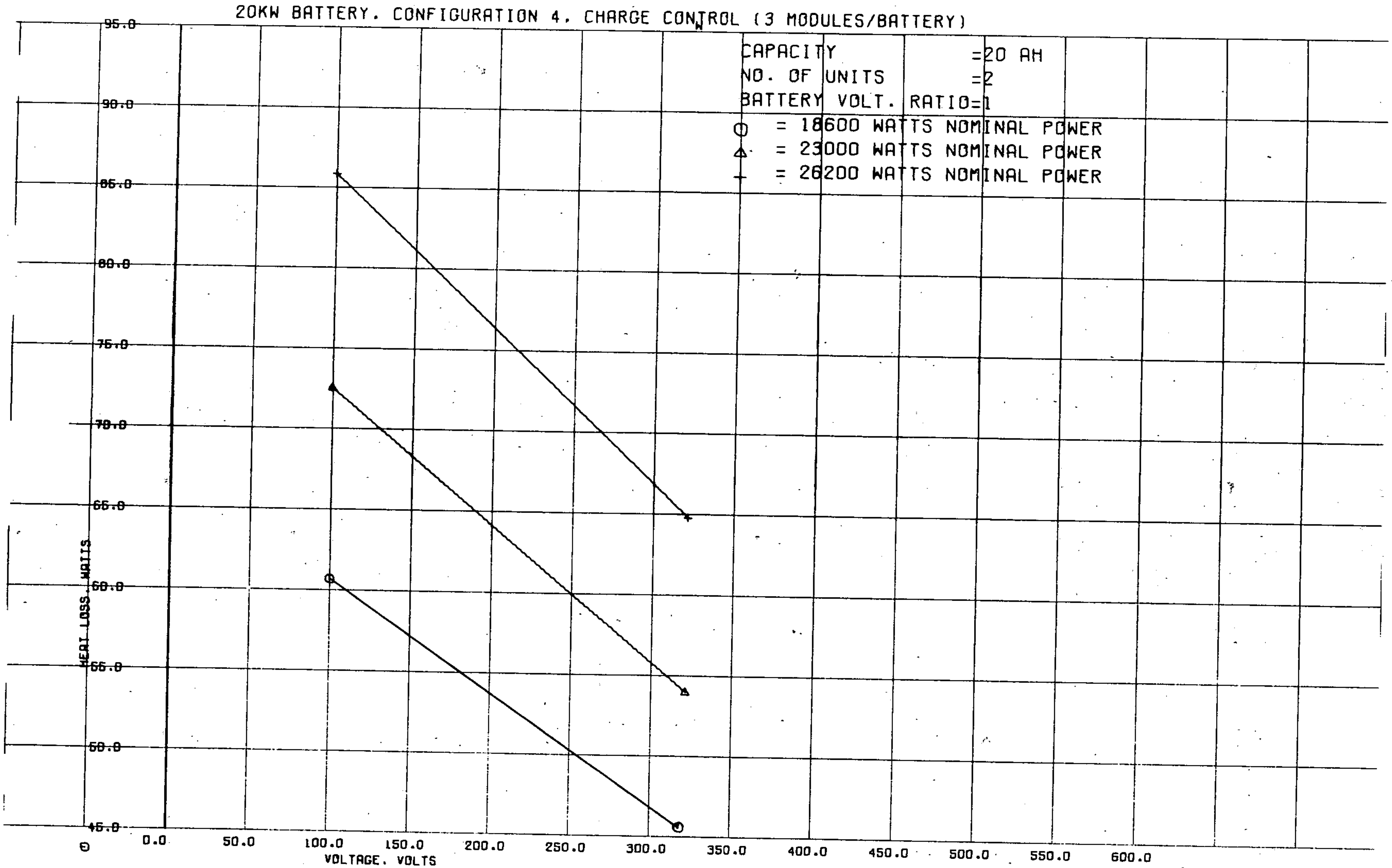


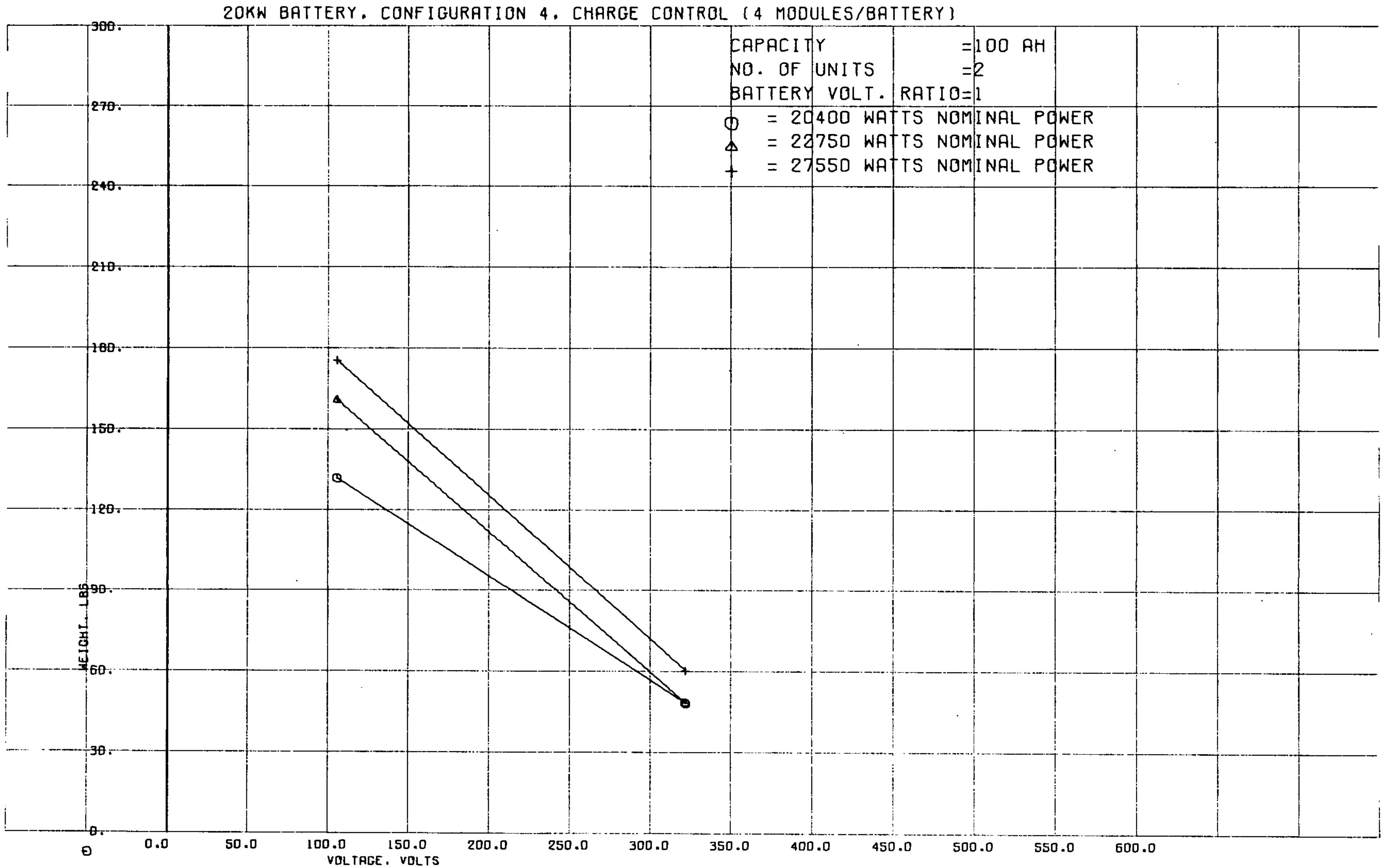
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18600 WATTS NOMINAL POWER
= 23000 WATTS NOMINAL POWER
= 26200 WATTS NOMINAL POWER
COST, K$
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20750 WATTS NOMINAL POWER
△ = 22250 WATTS NOMINAL POWER
+ = 28150 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

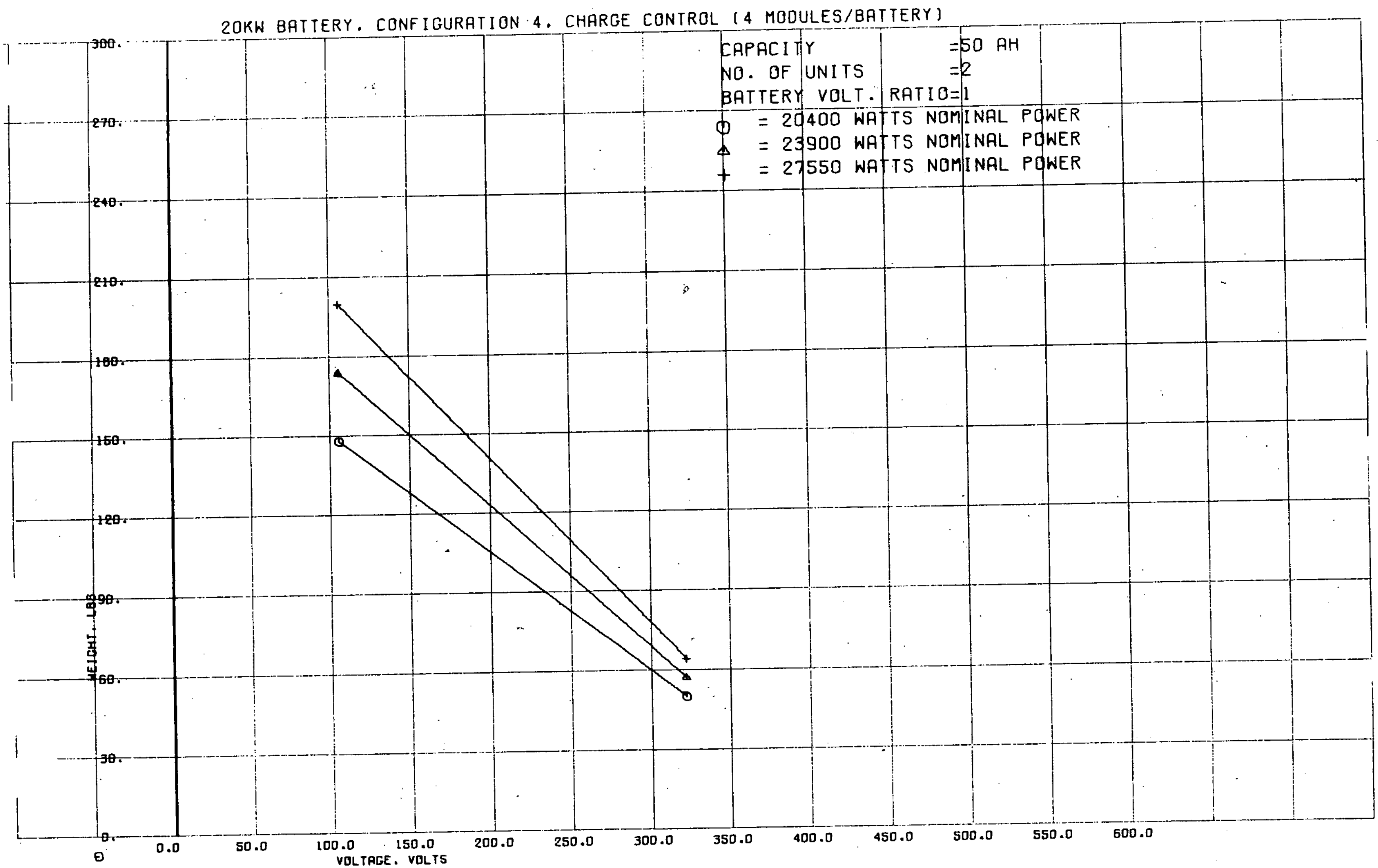
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (3 MODULES/BATTERY)



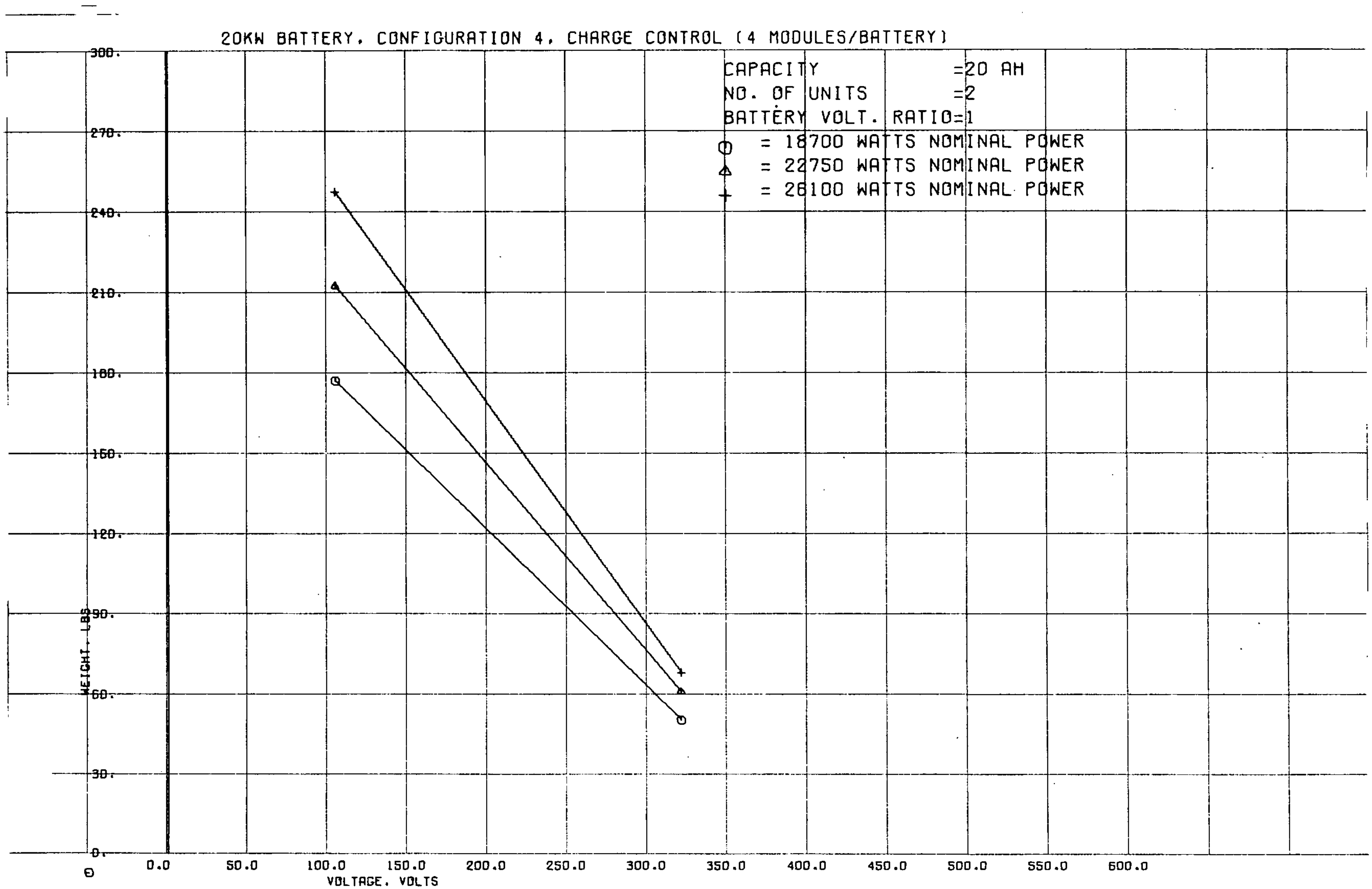

20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 18600 WATTS NOMINAL POWER
△ = 23000 WATTS NOMINAL POWER
+ = 26200 WATTS NOMINAL POWER
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



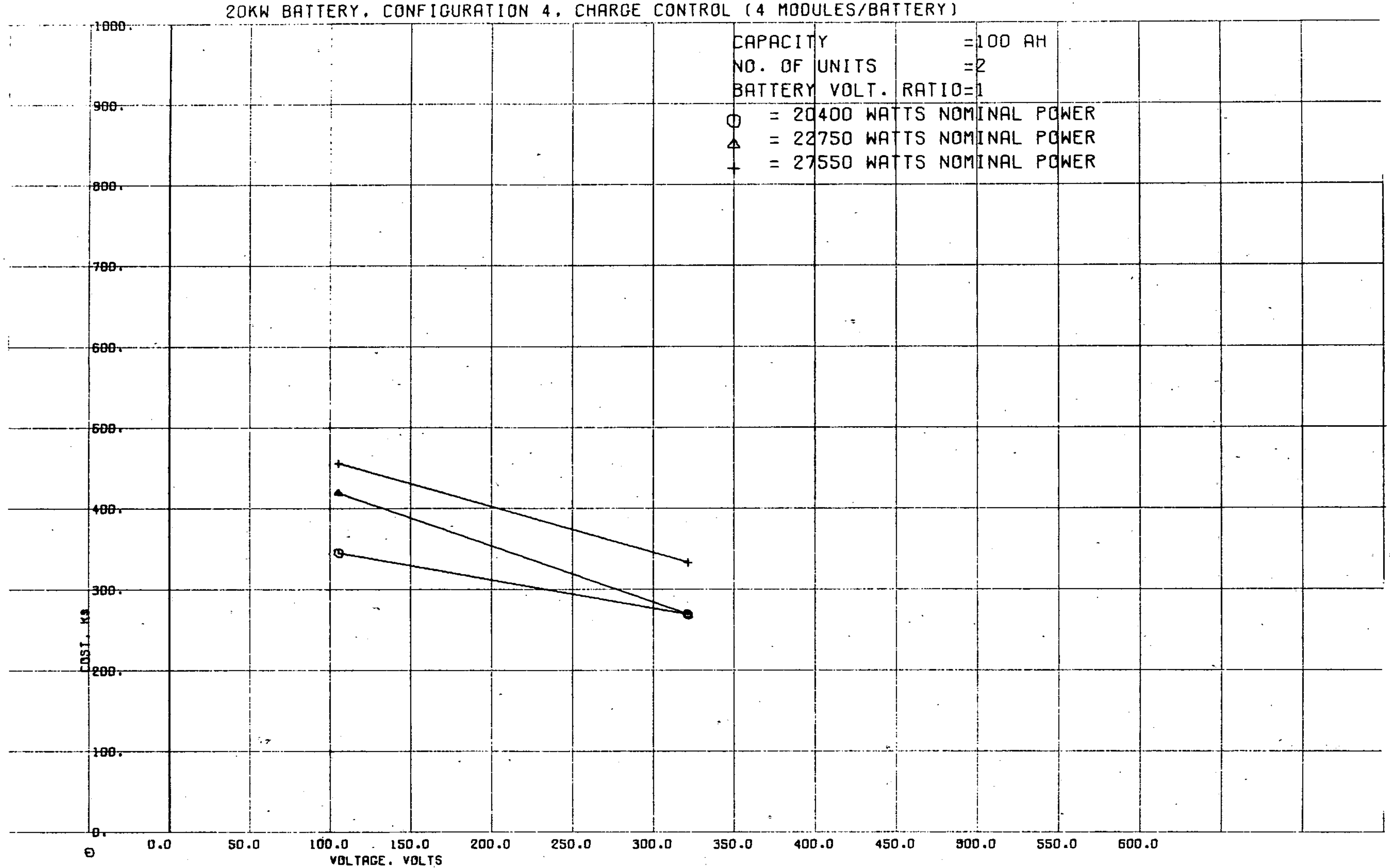
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20400 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 27550 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
300.
270.
240.
210.
180.
150.
120.
90.
60.
30.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

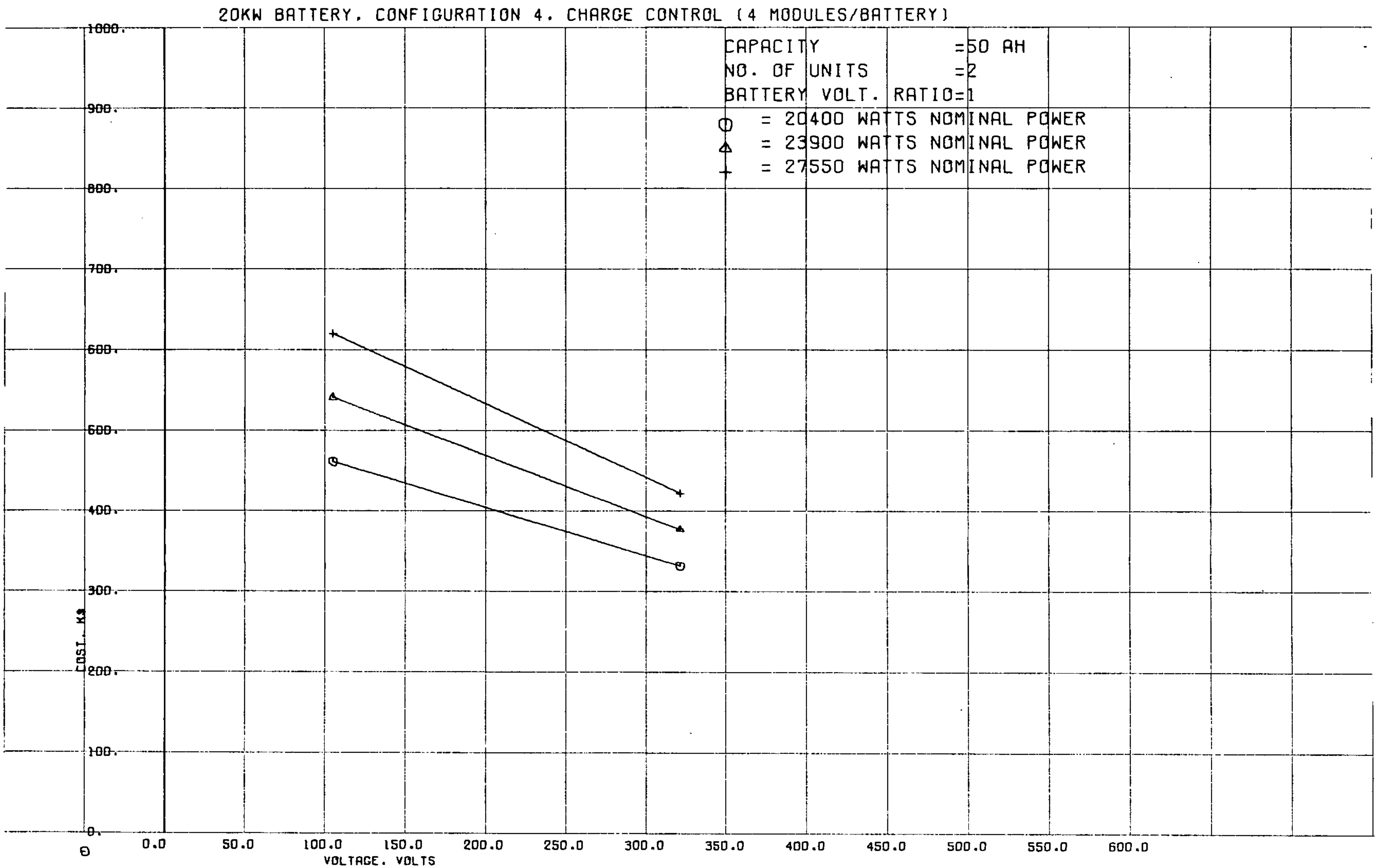


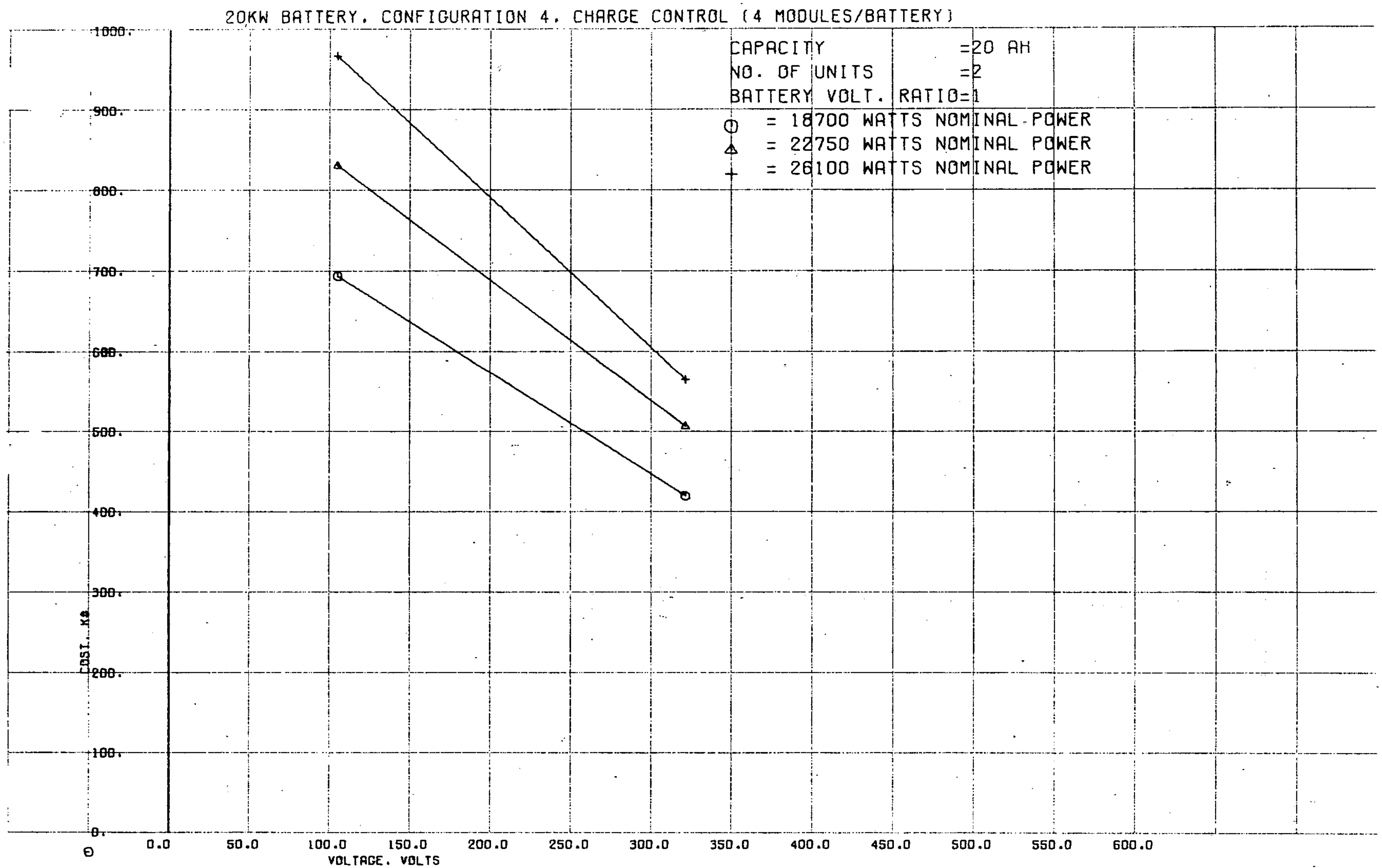
20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 20400 WATTS NOMINAL POWER
Δ = 23900 WATTS NOMINAL POWER
+ = 27550 WATTS NOMINAL POWER
WEIGHT, LBS
0.
30.
60.
90.
120.
150.
180.
210.
240.
270.
300.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18700 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 26100 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
0.
30.
60.
90.
120.
150.
180.
210.
240.
270.
300.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

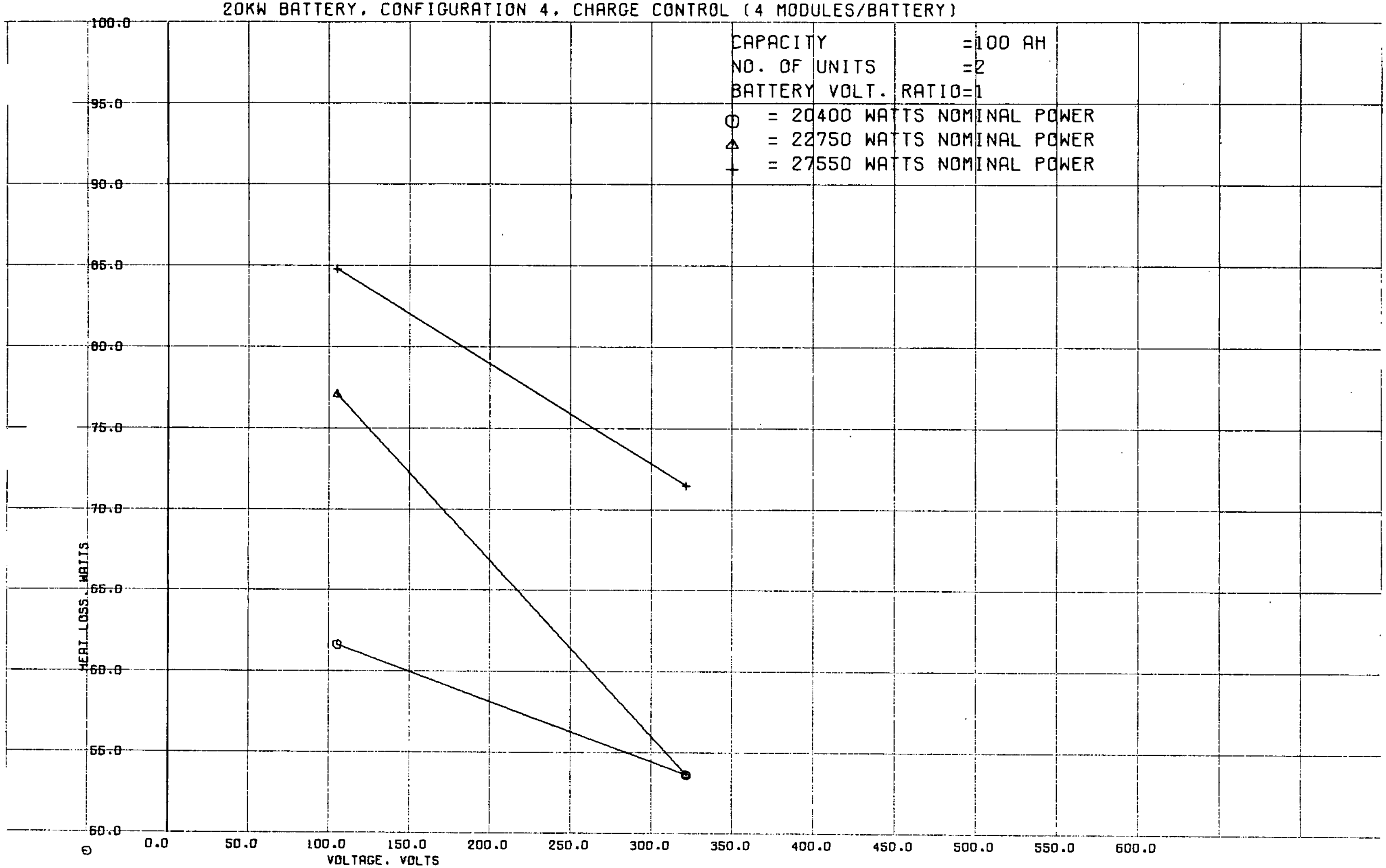
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)

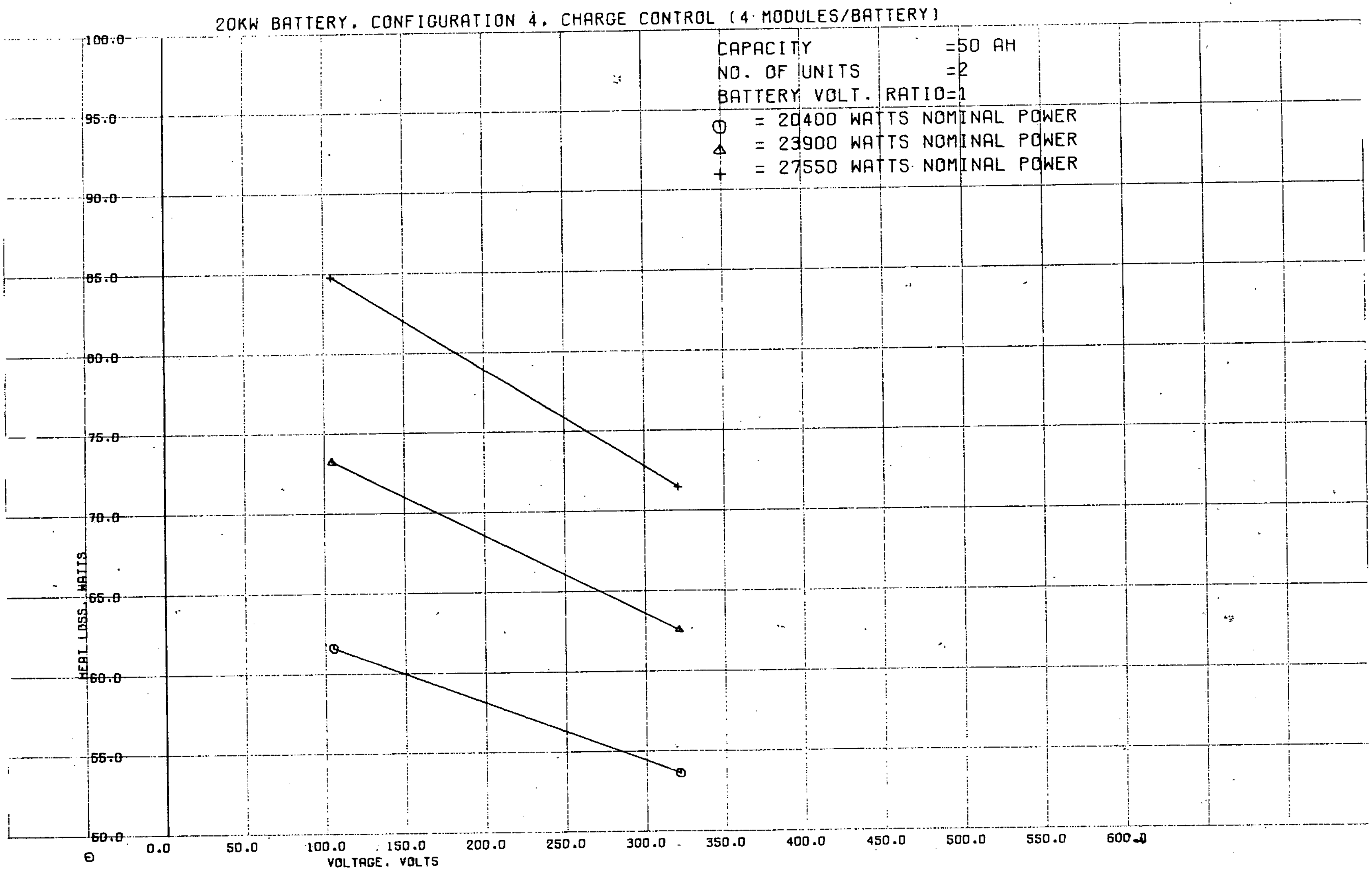


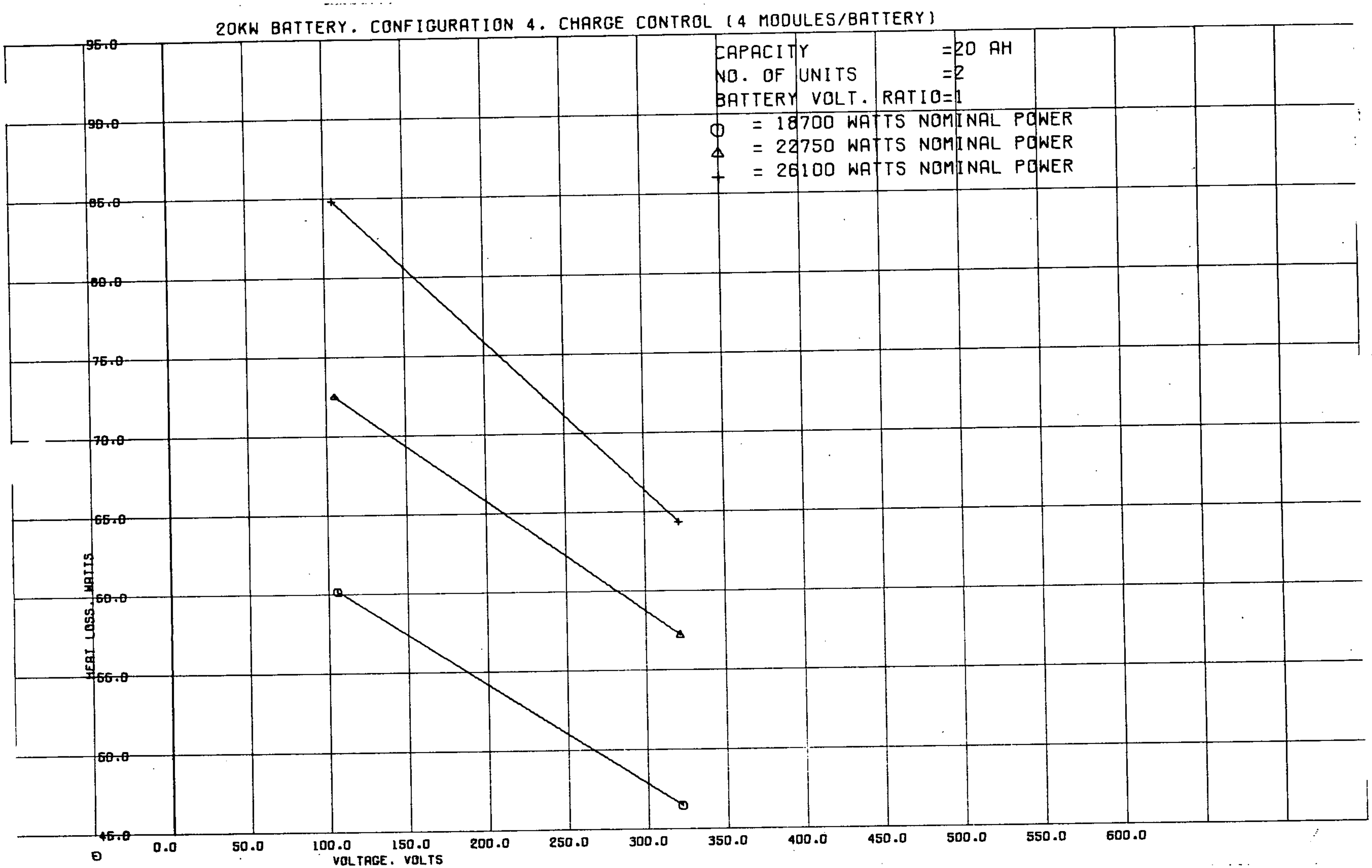

20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 20400 WATTS NOMINAL POWER
Δ = 23900 WATTS NOMINAL POWER
+ = 27550 WATTS NOMINAL POWER
COST, K$
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18700 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 26100 WATTS NOMINAL POWER
COST, K$
0.
100.
200.
300.
400.
500.
600.
700.
800.
900.
1000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

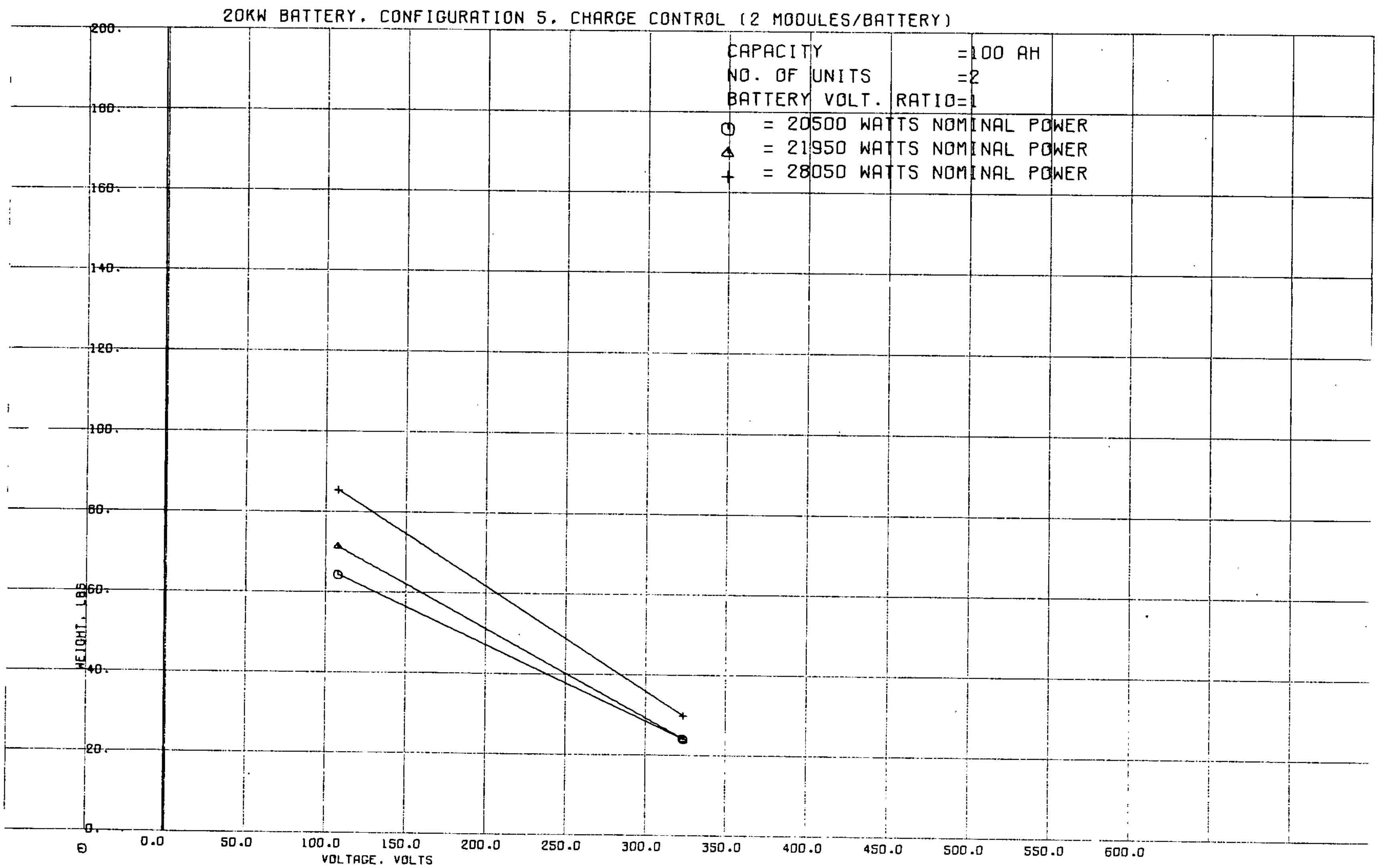
20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)




20KW BATTERY, CONFIGURATION 4, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20400 WATTS NOMINAL POWER
△ = 23900 WATTS NOMINAL POWER
+ = 27550 WATTS NOMINAL POWER
HEAT LOSS, WATTS
100.0
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 4. CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18700 WATTS NOMINAL POWER
△ = 22750 WATTS NOMINAL POWER
+ = 26100 WATTS NOMINAL POWER
95.0
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



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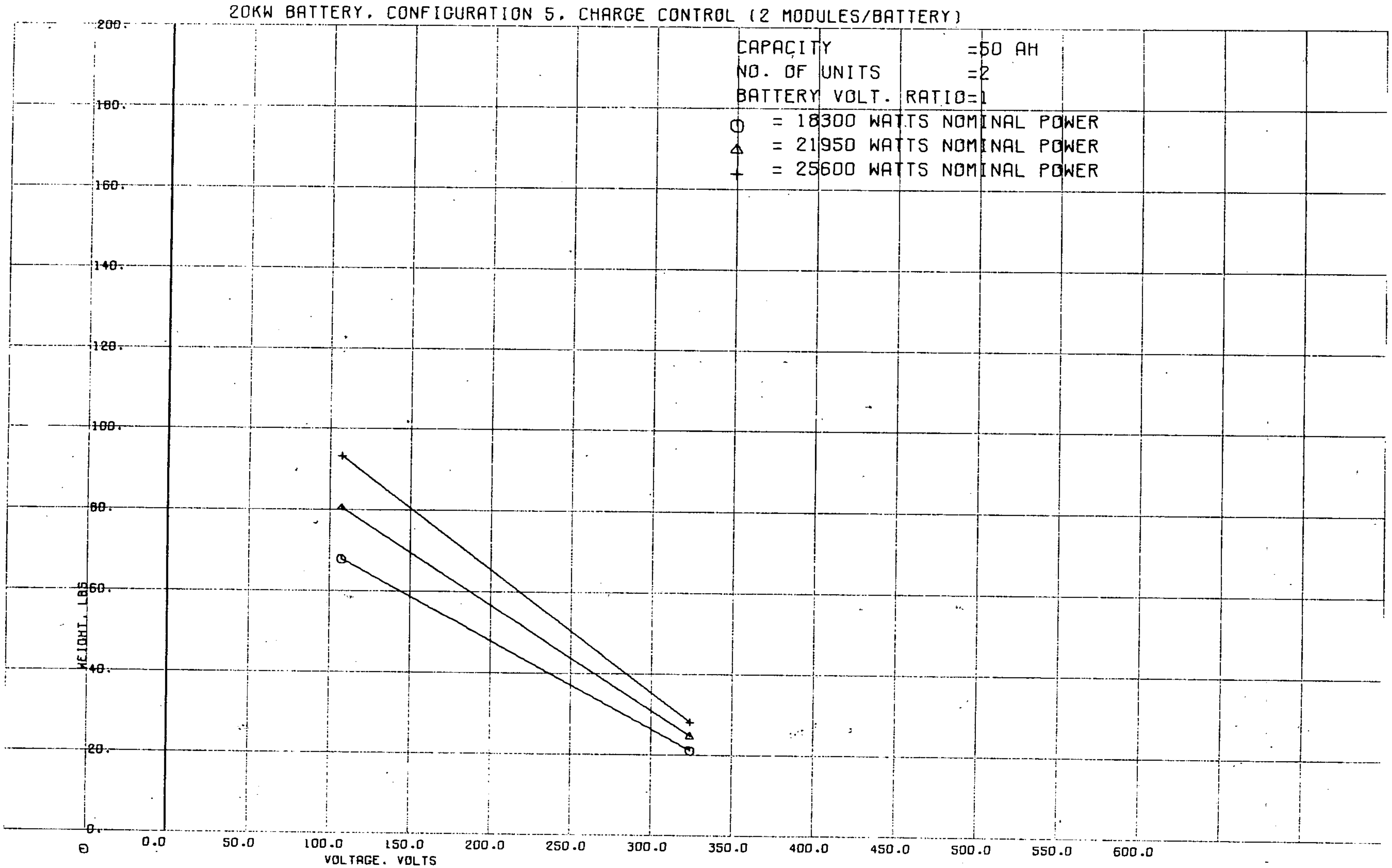
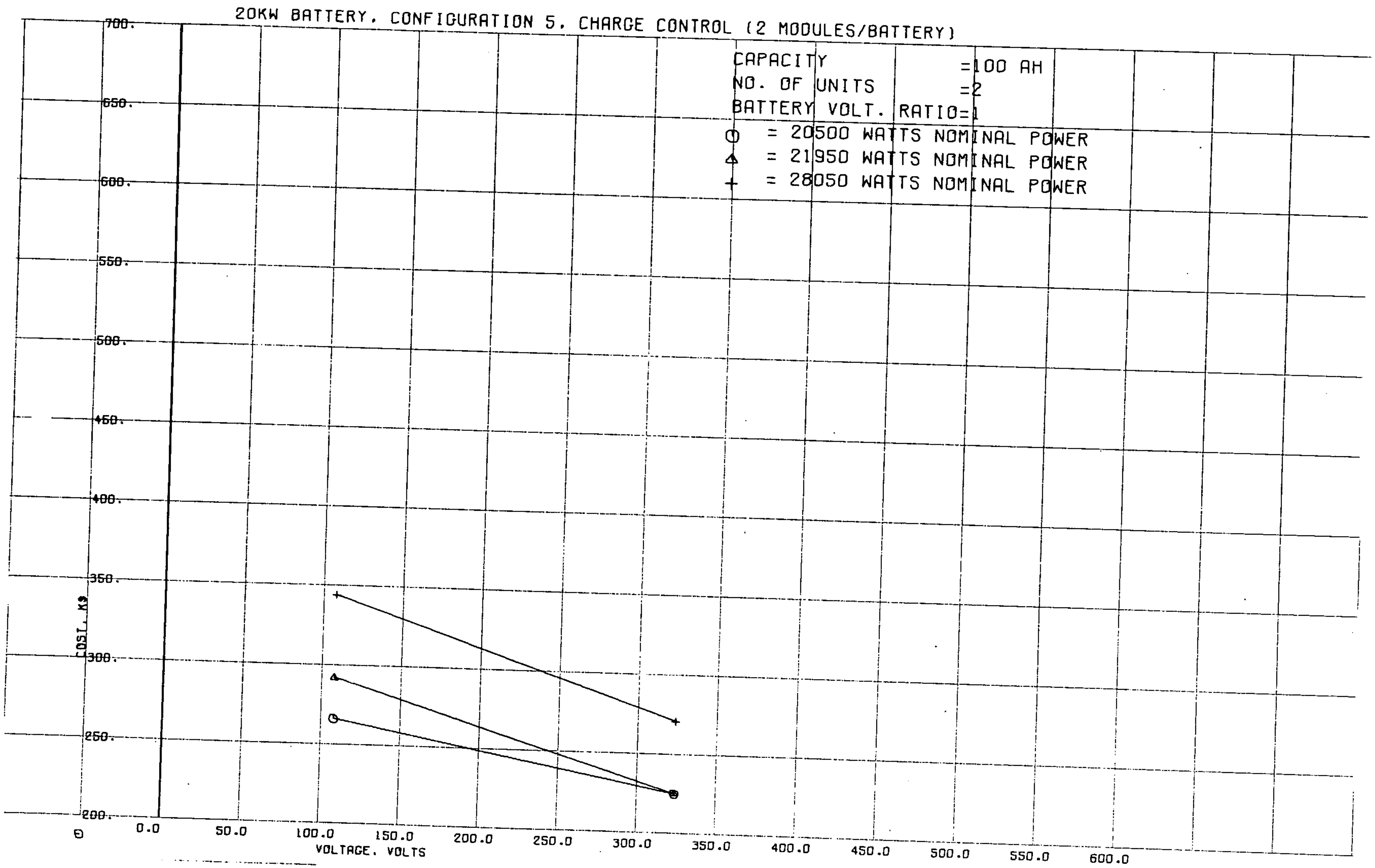


20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18300 WATTS NOMINAL POWER
△ = 21950 WATTS NOMINAL POWER
+ = 25600 WATTS NOMINAL POWER
WEIGHT, LBS
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

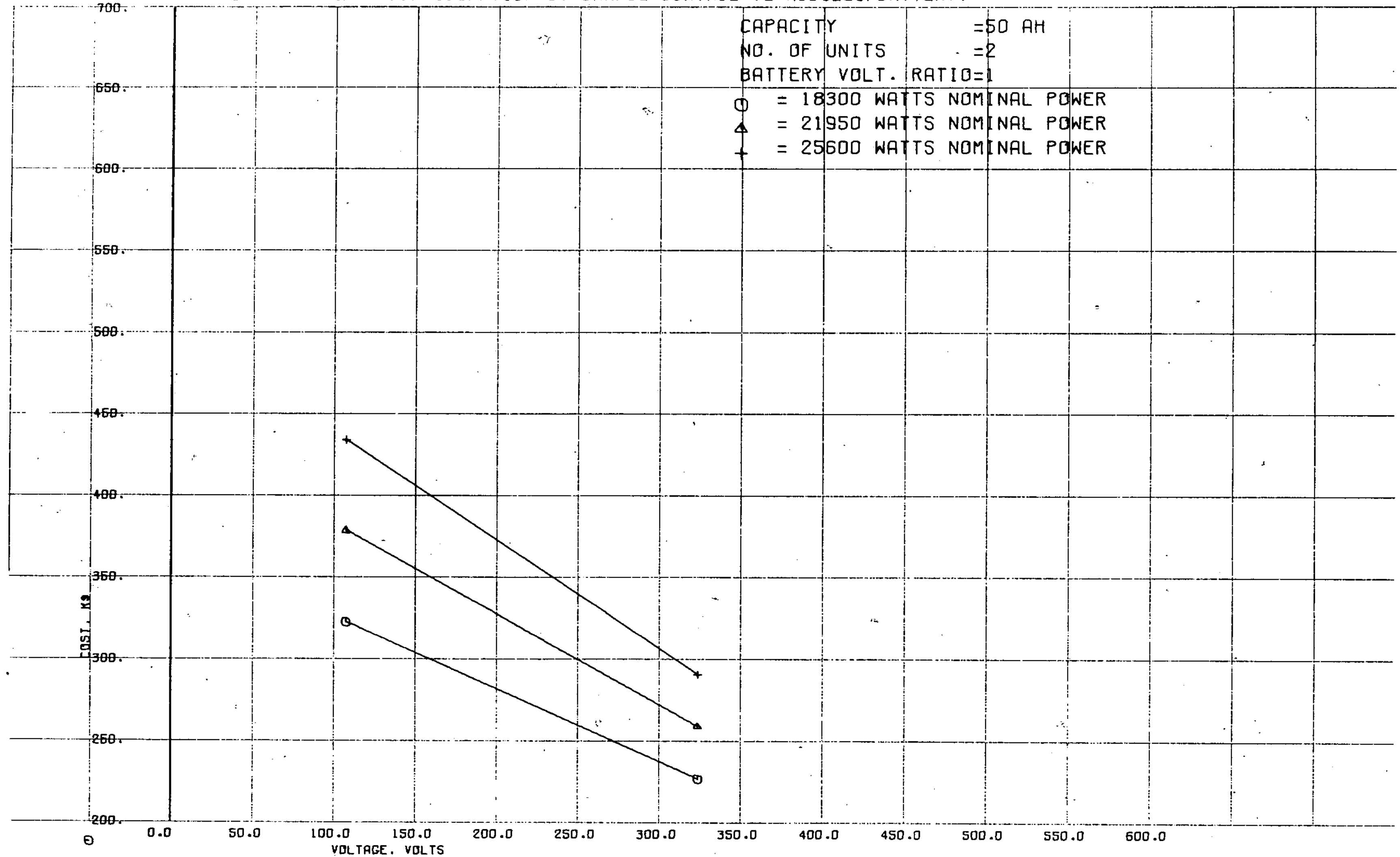
50

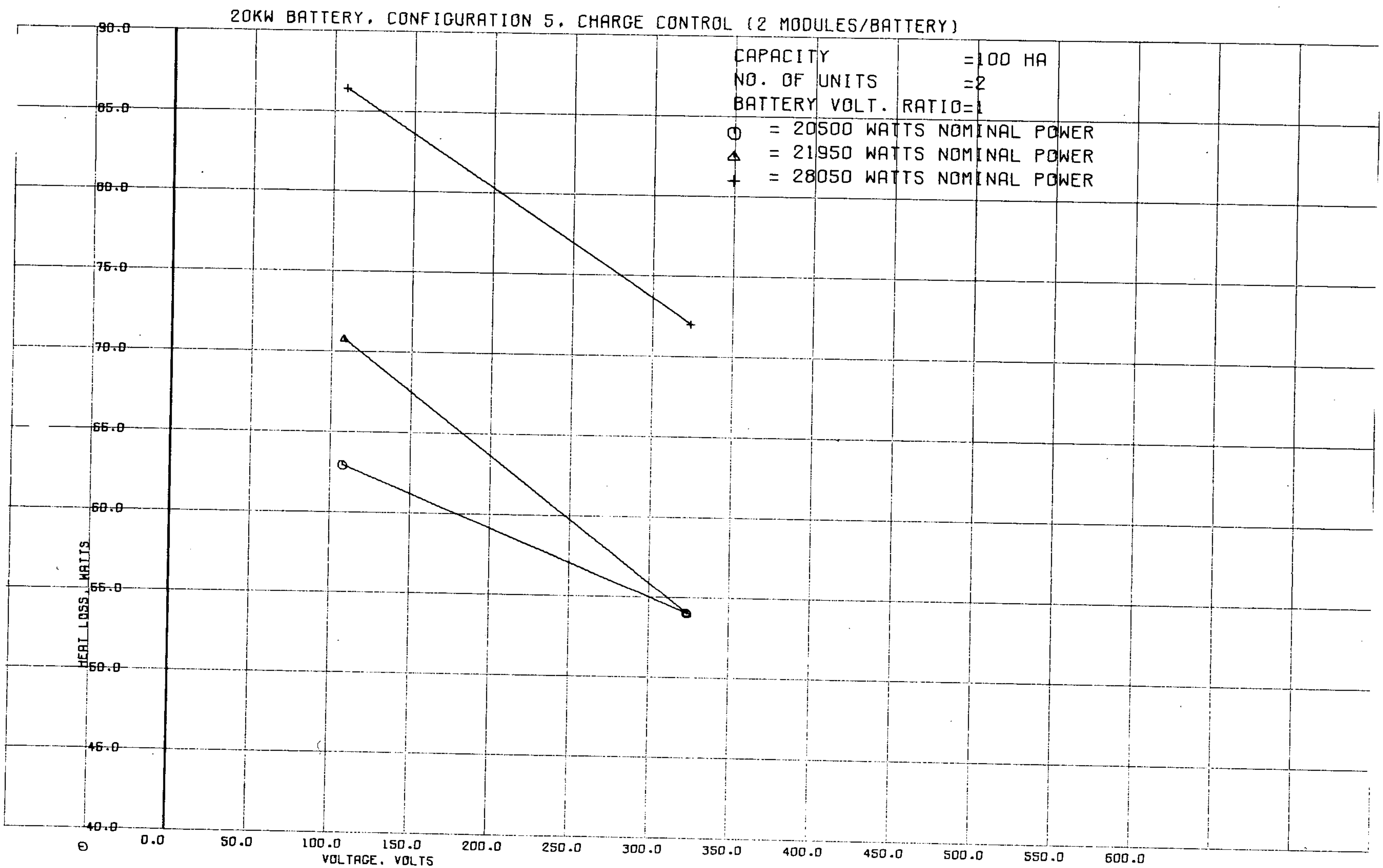


20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20500 WATTS NOMINAL POWER
△ = 21950 WATTS NOMINAL POWER
+ = 28050 WATTS NOMINAL POWER
COST, K$
700.
650.
600.
550.
500.
450.
400.
350.
300.
250.
200.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

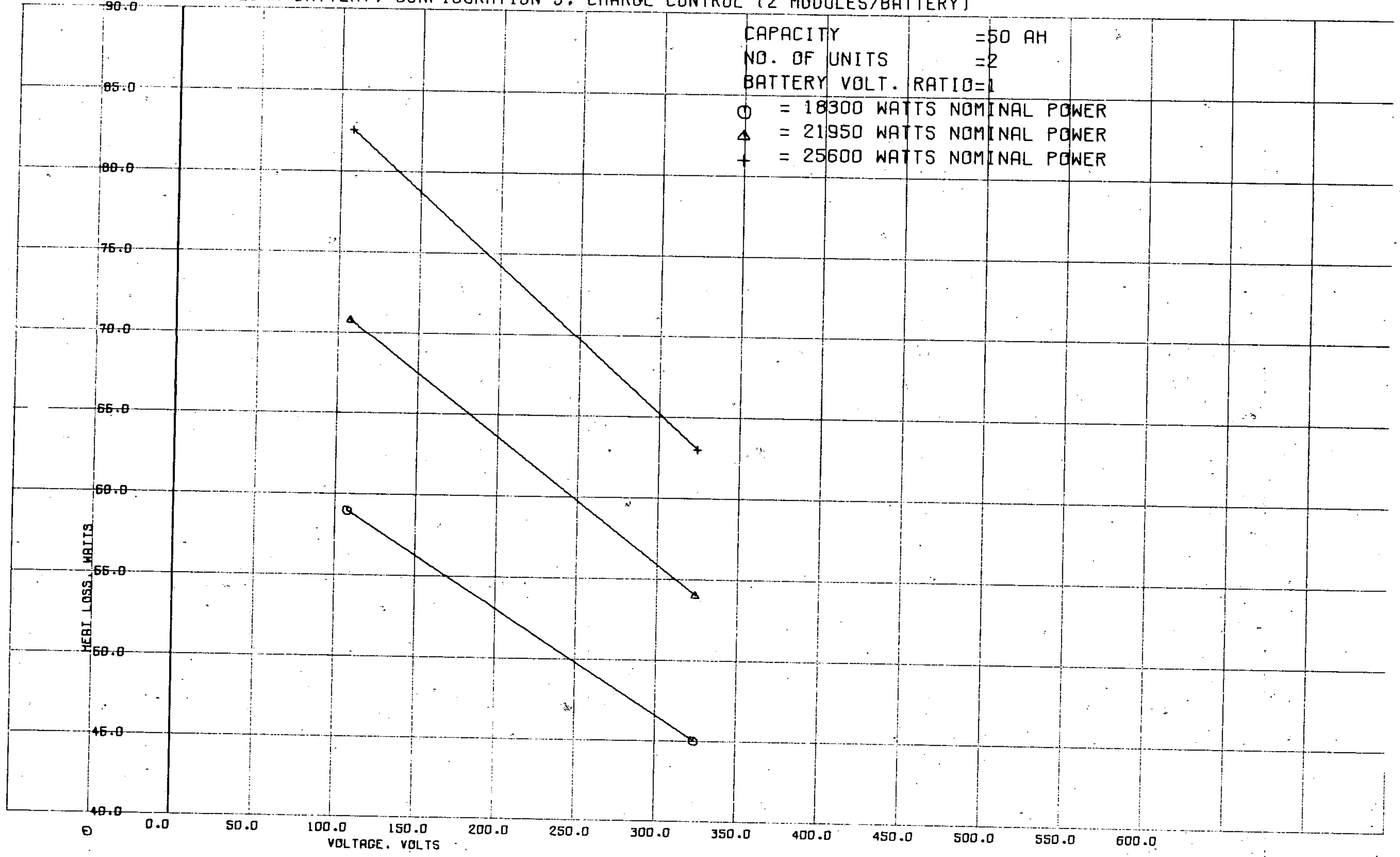
A-117

20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (2 MODULES/BATTERY)

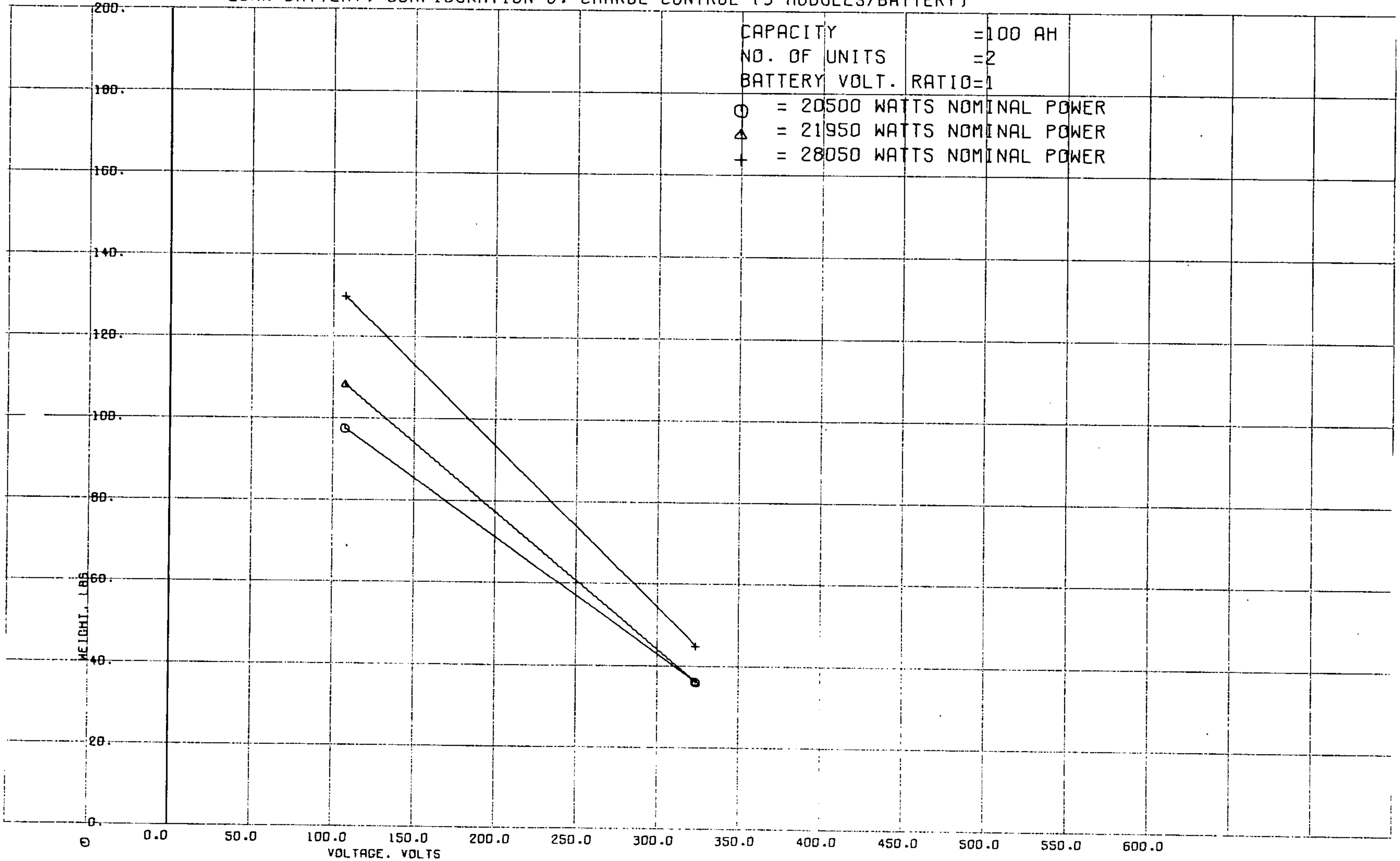


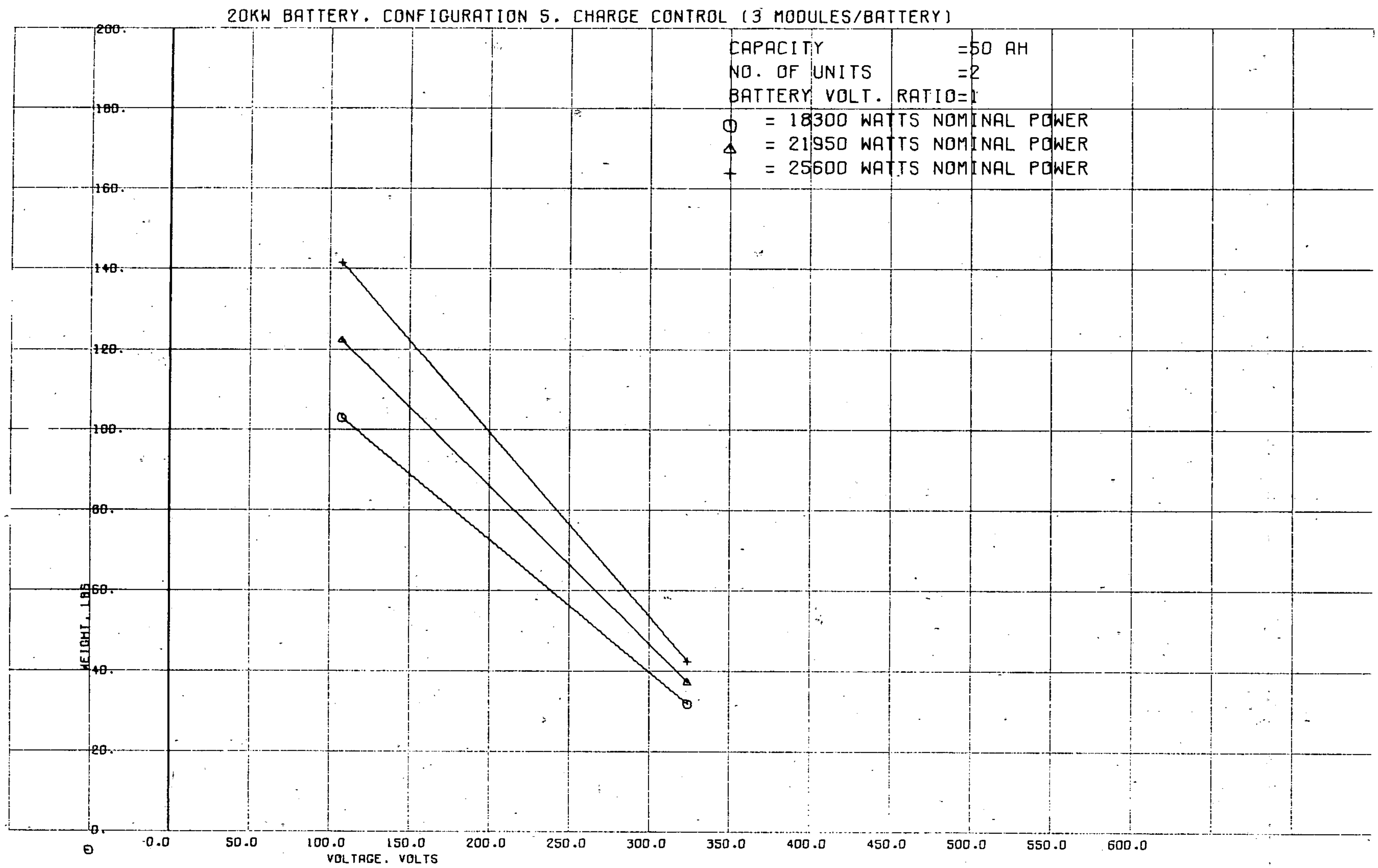

20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (2 MODULES/BATTERY)
CAPACITY =100 HA
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20500 WATTS NOMINAL POWER
= 21950 WATTS NOMINAL POWER
= 28050 WATTS NOMINAL POWER
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
HEAT LOSS, WATTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (2 MODULES/BATTERY)

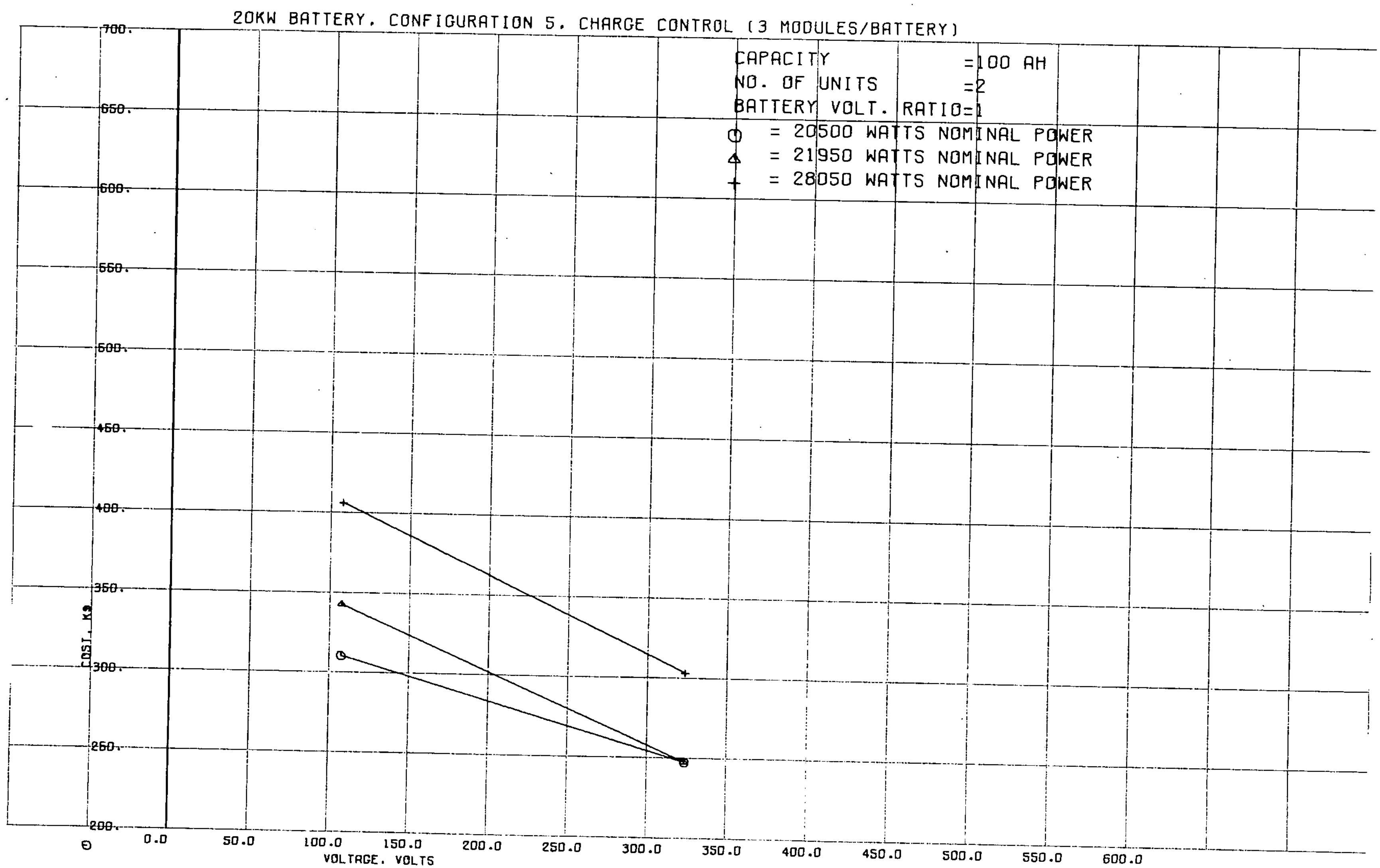


20KW BATTERY. CONFIGURATION 5. CHARGE CONTROL (3 MODULES/BATTERY)

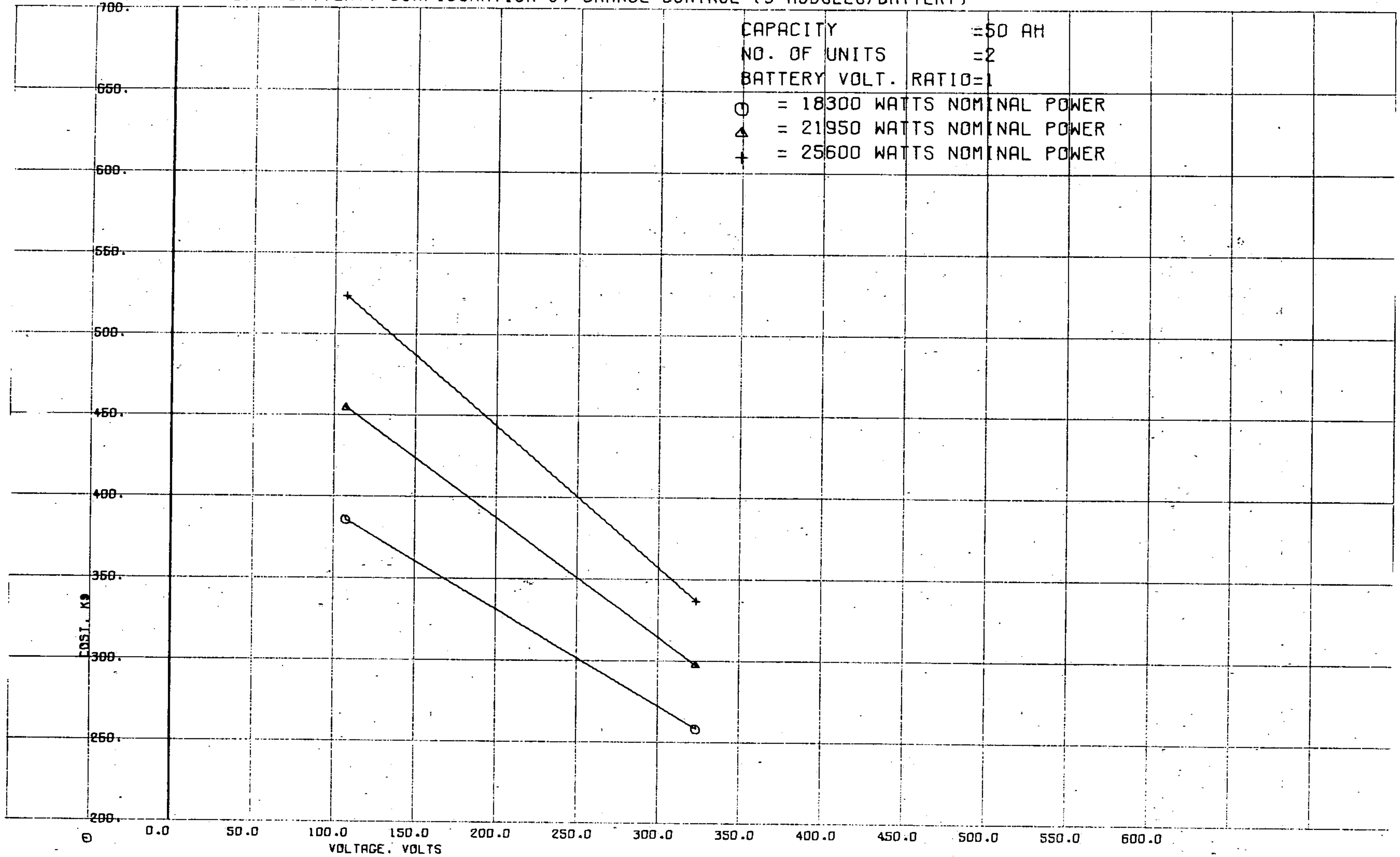




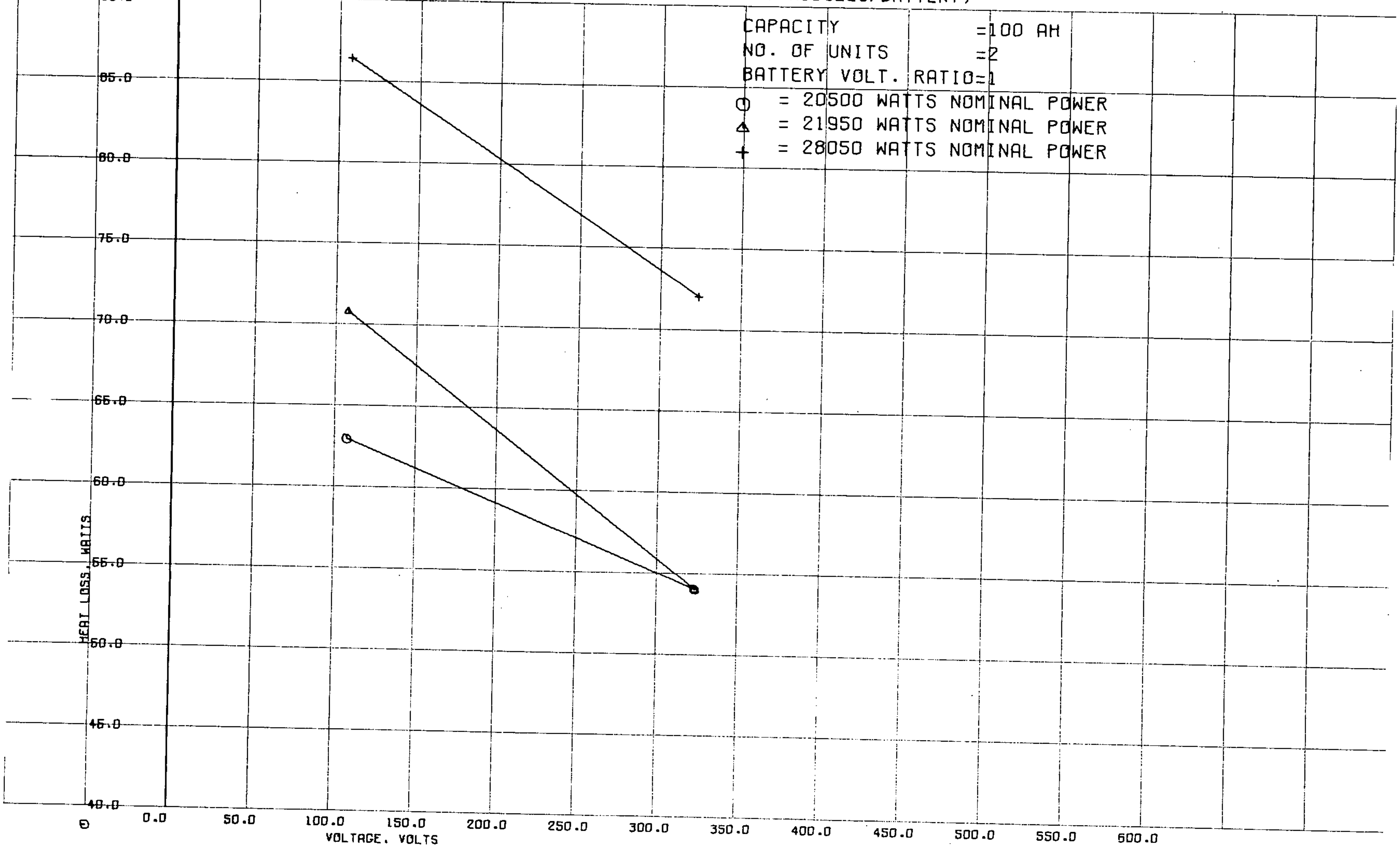
20KW BATTERY. CONFIGURATION 5. CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18300 WATTS NOMINAL POWER
= 21950 WATTS NOMINAL POWER
= 25600 WATTS NOMINAL POWER
WEIGHT, LBS
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
-0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

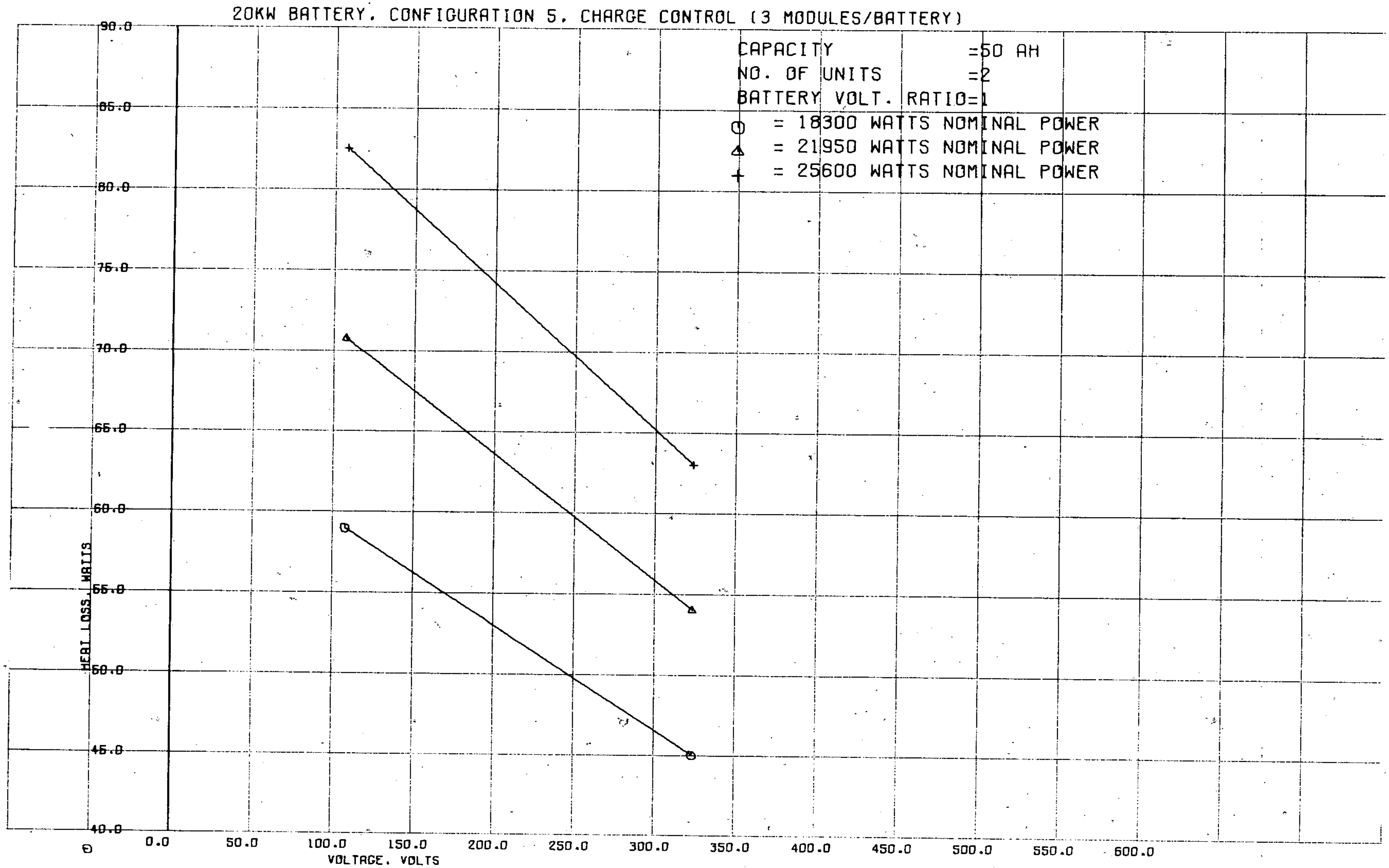

20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20500 WATTS NOMINAL POWER
= 21950 WATTS NOMINAL POWER
= 28050 WATTS NOMINAL POWER
COST, K$
VOLTAGE, VOLTS

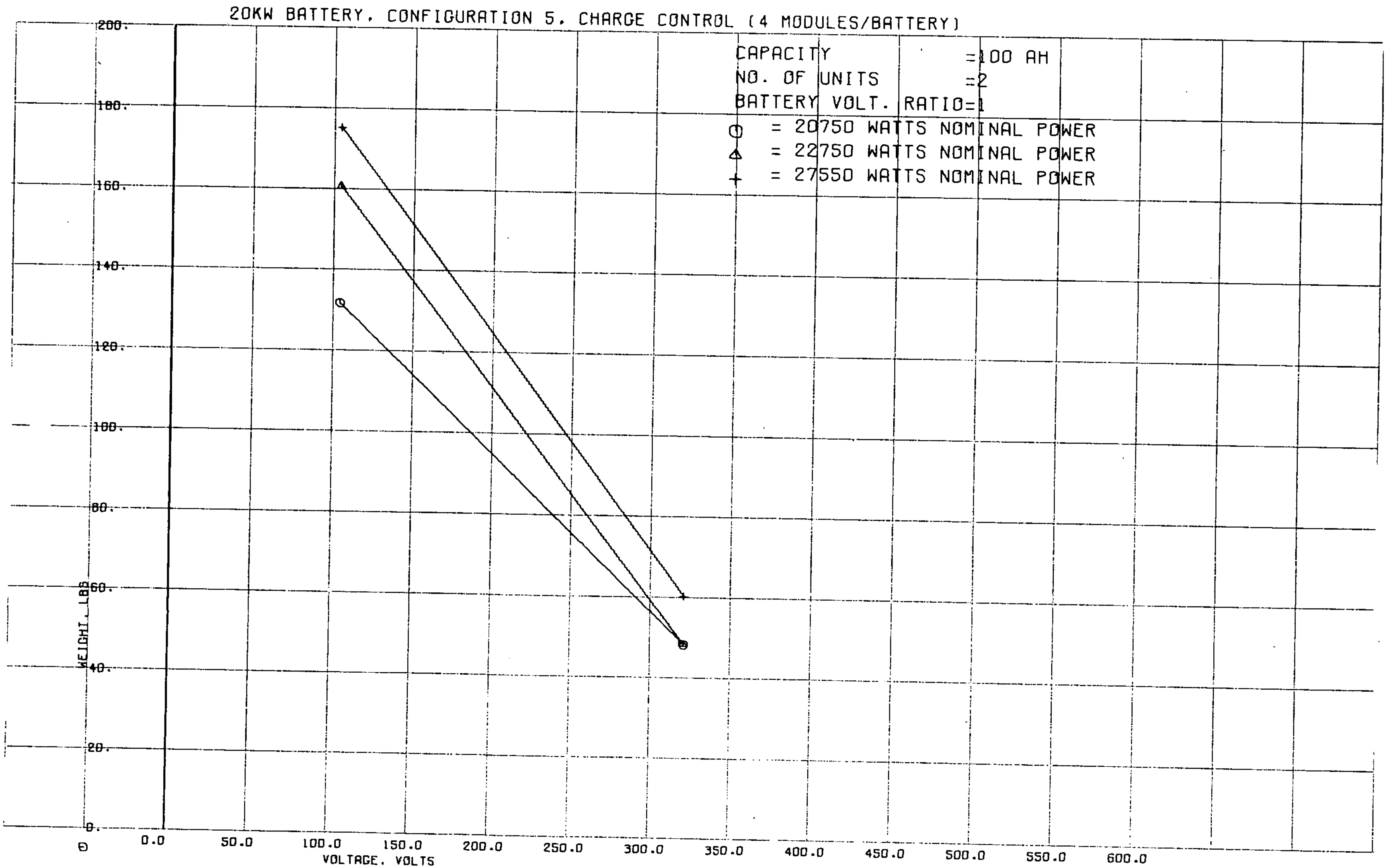
20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (3 MODULES/BATTERY)



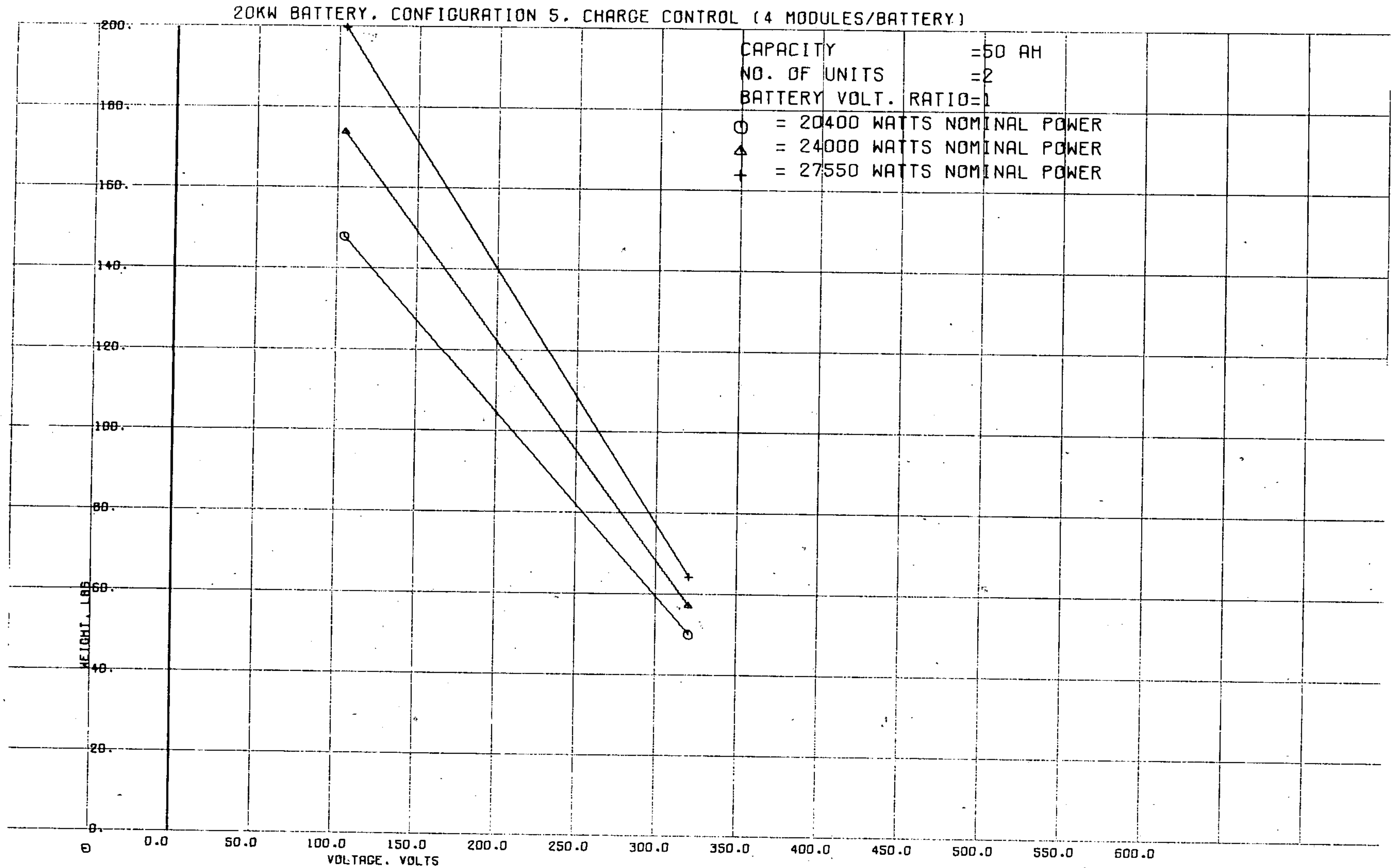
20KW BATTERY. CONFIGURATION 5. CHARGE CONTROL (3 MODULES/BATTERY)

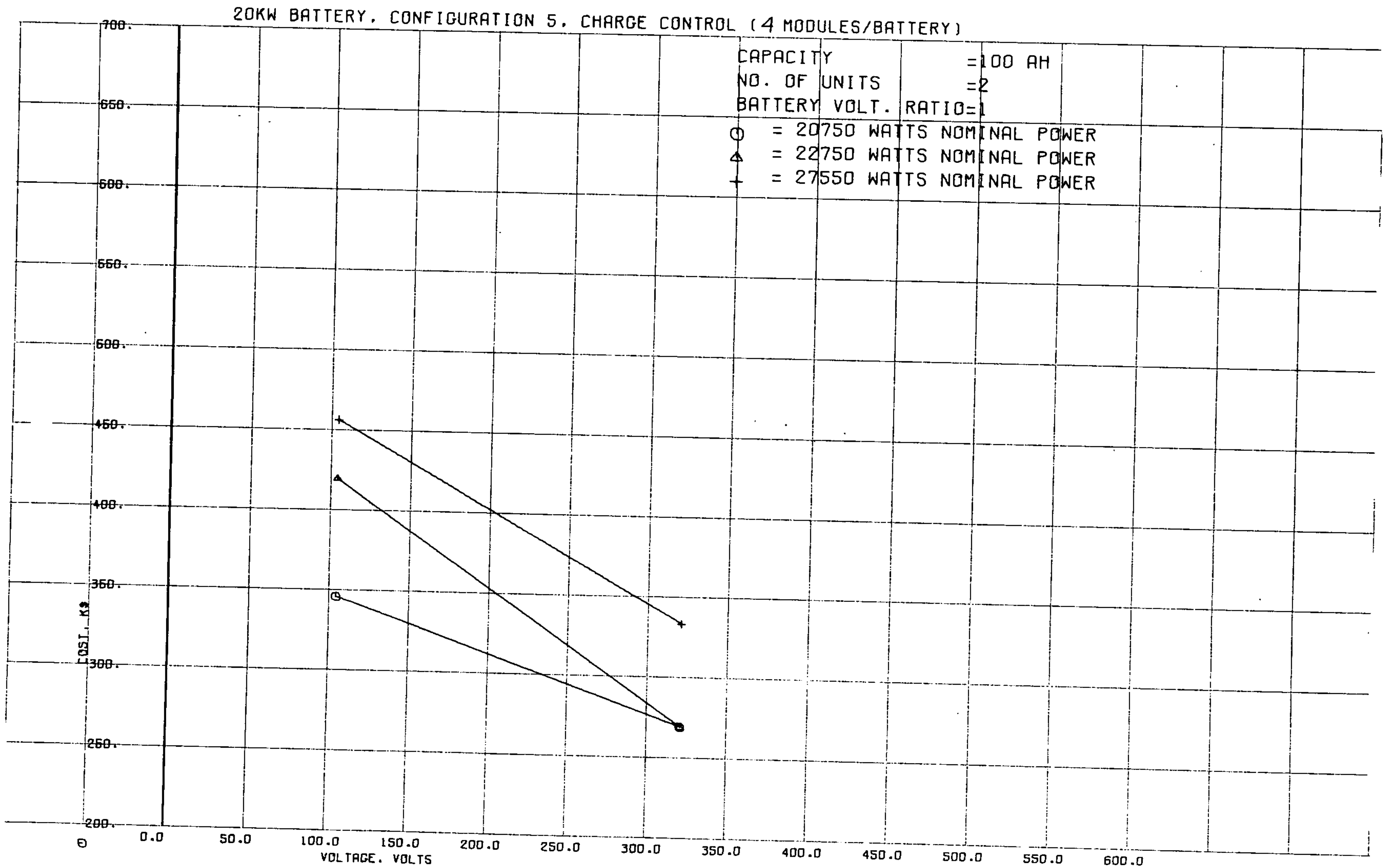


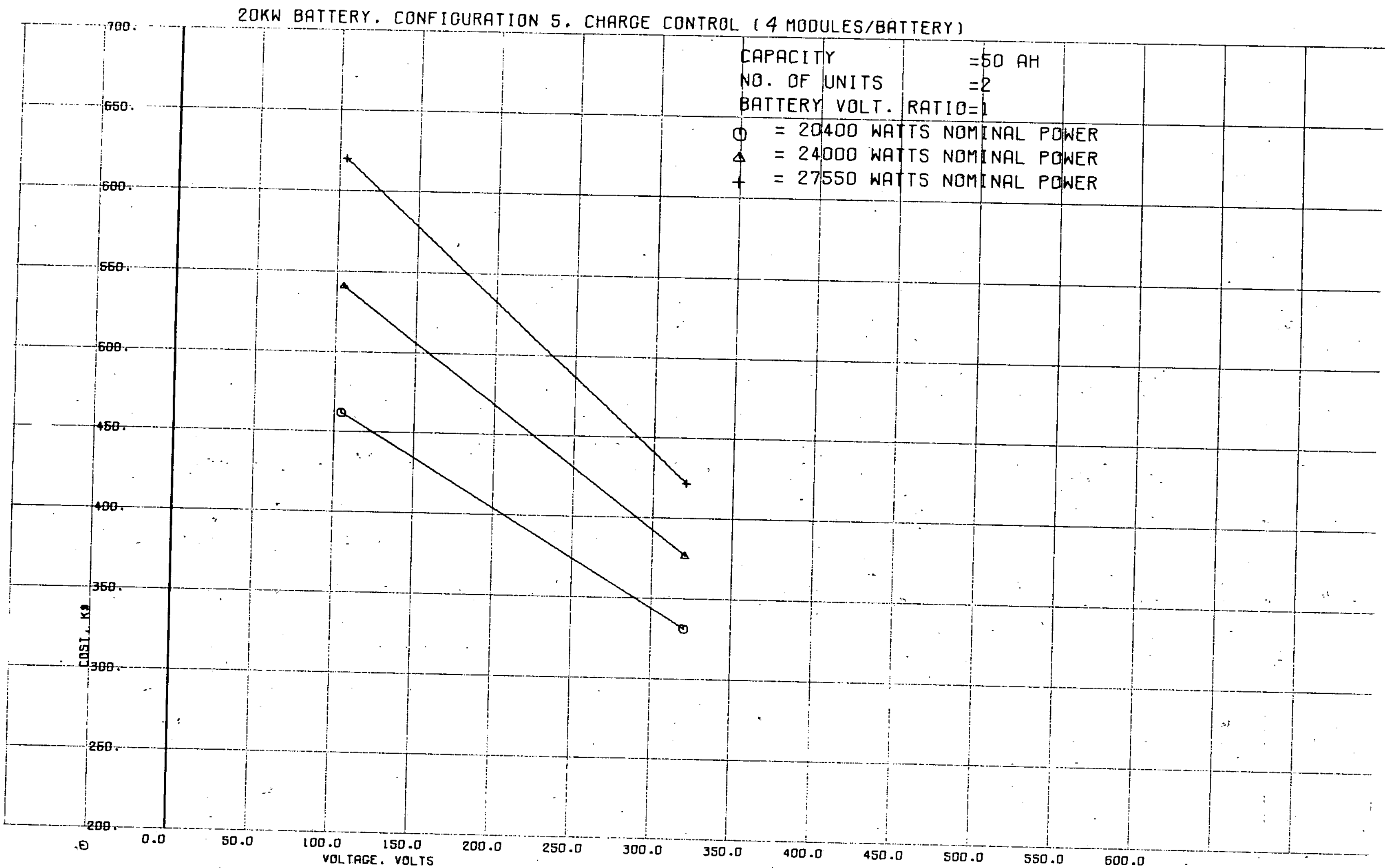

20KW BATTERY. CONFIGURATION 5. CHARGE CONTROL (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18300 WATTS NOMINAL POWER
= 21950 WATTS NOMINAL POWER
= 25600 WATTS NOMINAL POWER
HEAT LOSS, WATTS
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



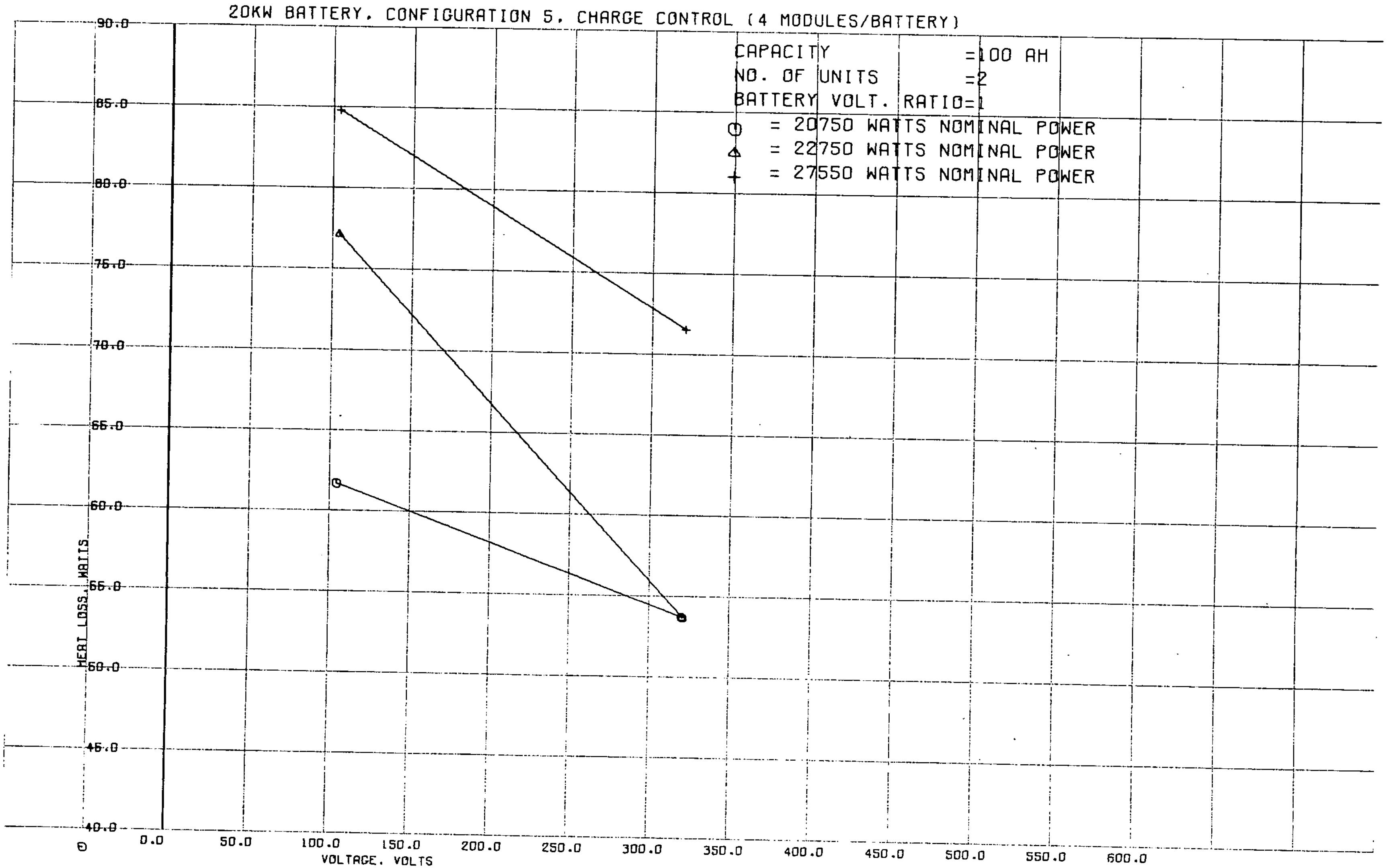
20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20750 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 27550 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 5. CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20400 WATTS NOMINAL POWER
= 24000 WATTS NOMINAL POWER
= 27550 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS

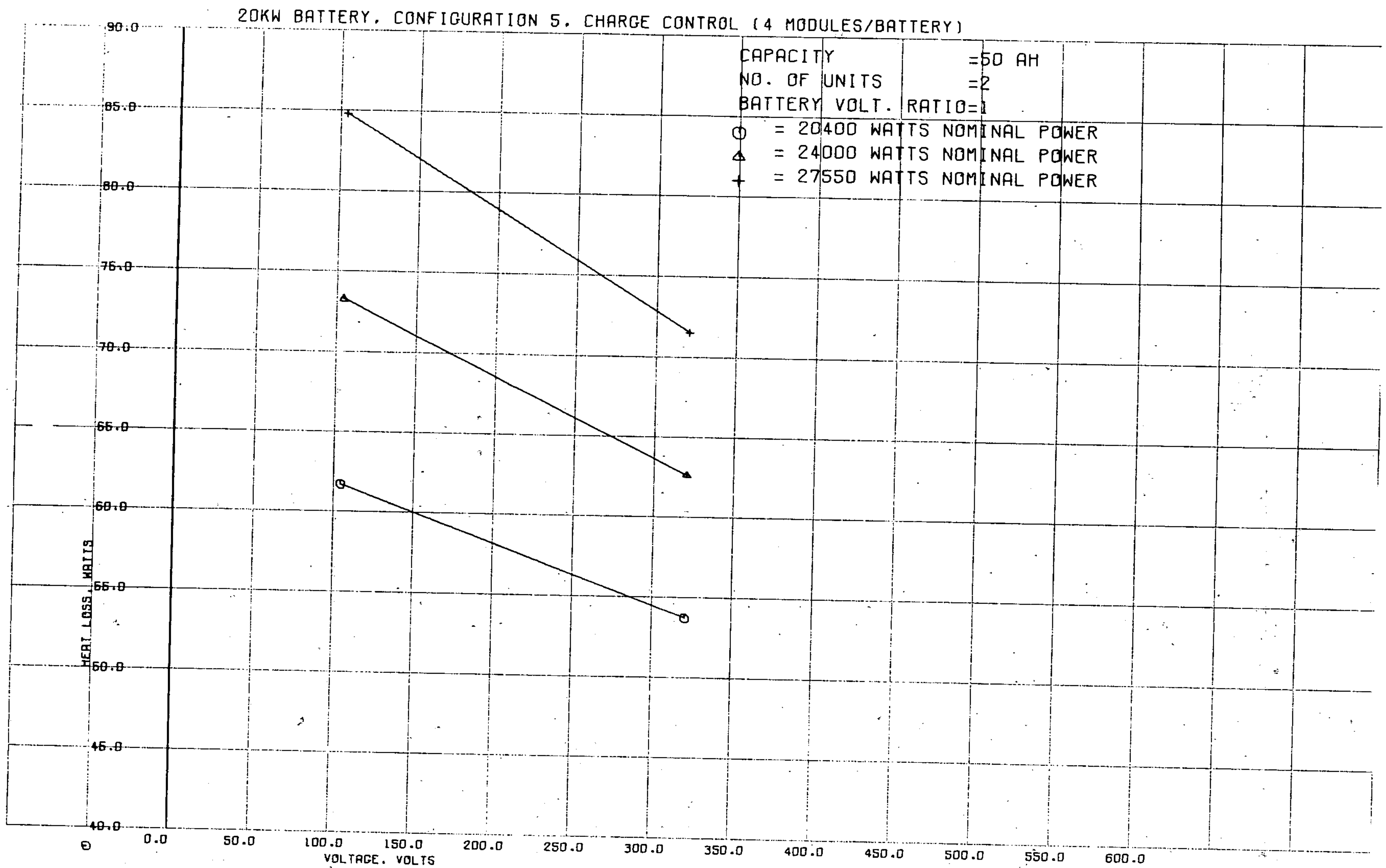

20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20750 WATTS NOMINAL POWER
△ = 22750 WATTS NOMINAL POWER
+ = 27550 WATTS NOMINAL POWER
COST, K$
700.
650.
600.
550.
500.
450.
400.
350.
300.
250.
200.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 5. CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20400 WATTS NOMINAL POWER
= 24000 WATTS NOMINAL POWER
= 27550 WATTS NOMINAL POWER
COST, K$
700.
650.
600.
550.
500.
450.
400.
350.
300.
250.
200.
0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

A-130



20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20750 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 27550 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0


20KW BATTERY, CONFIGURATION 5, CHARGE CONTROL (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20400 WATTS NOMINAL POWER
= 24000 WATTS NOMINAL POWER
= 27550 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
90.0
85.0
80.0
75.0
70.0
65.0
60.0
55.0
50.0
45.0
40.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

SEE CONFIGURATION 1

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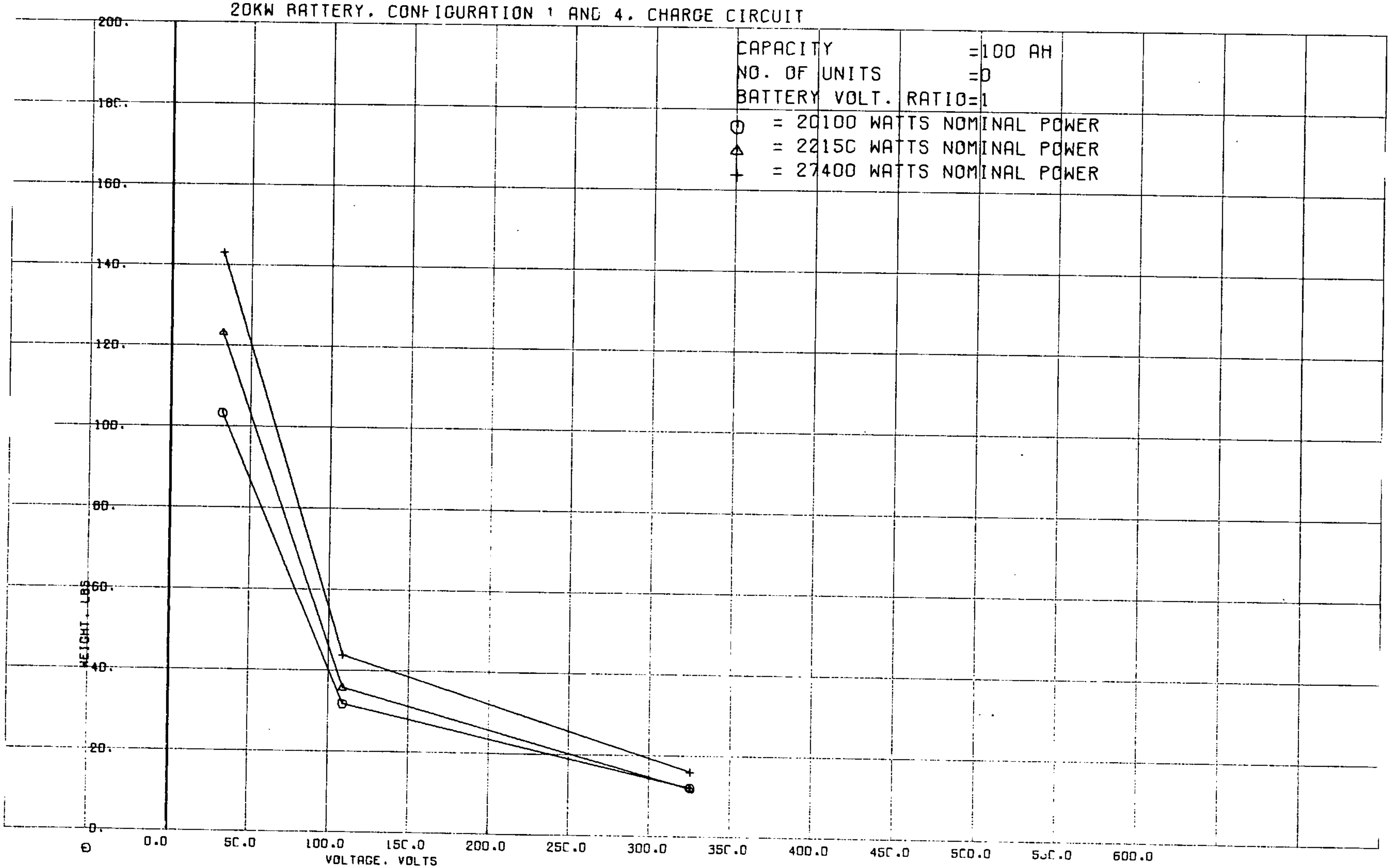

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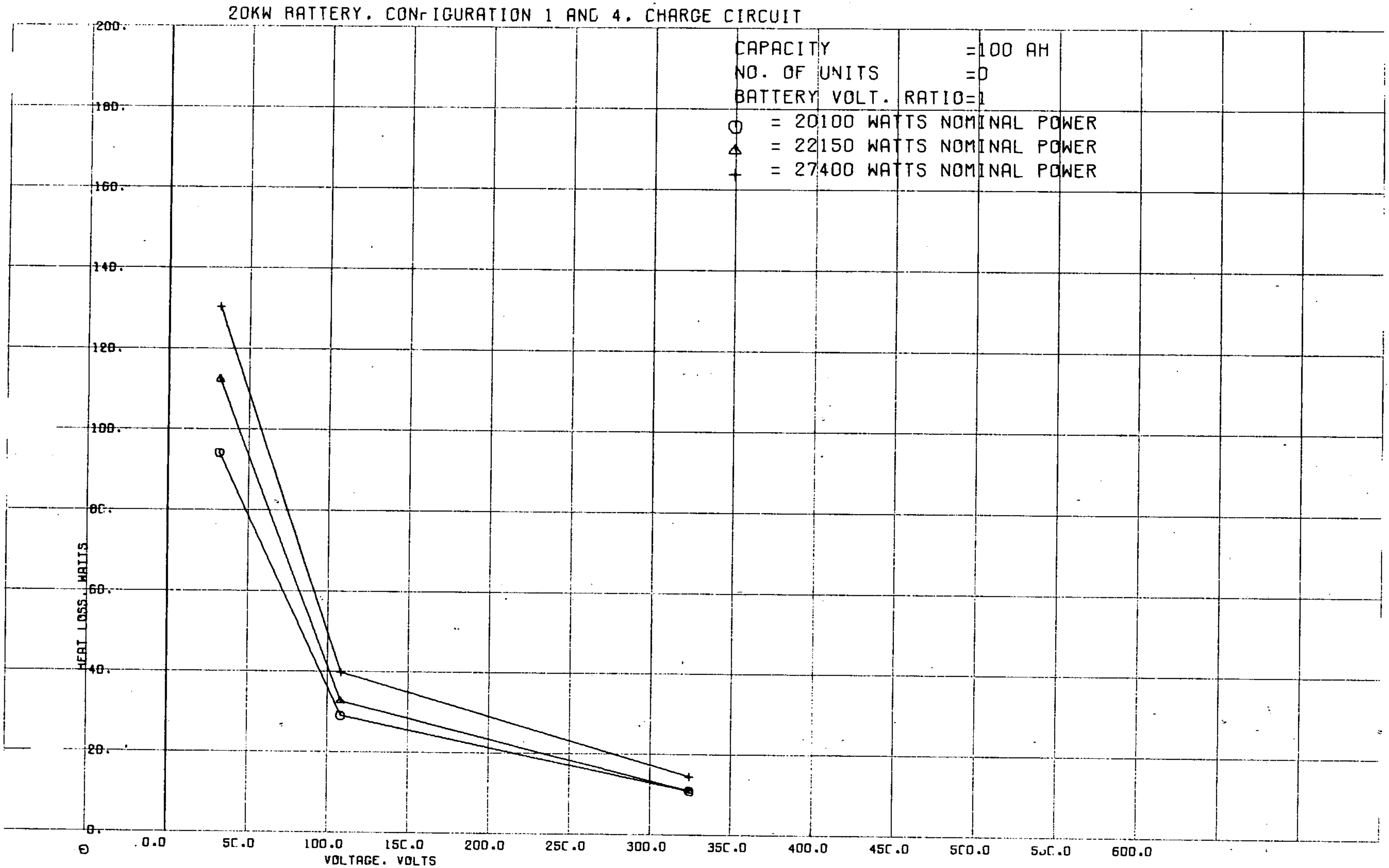
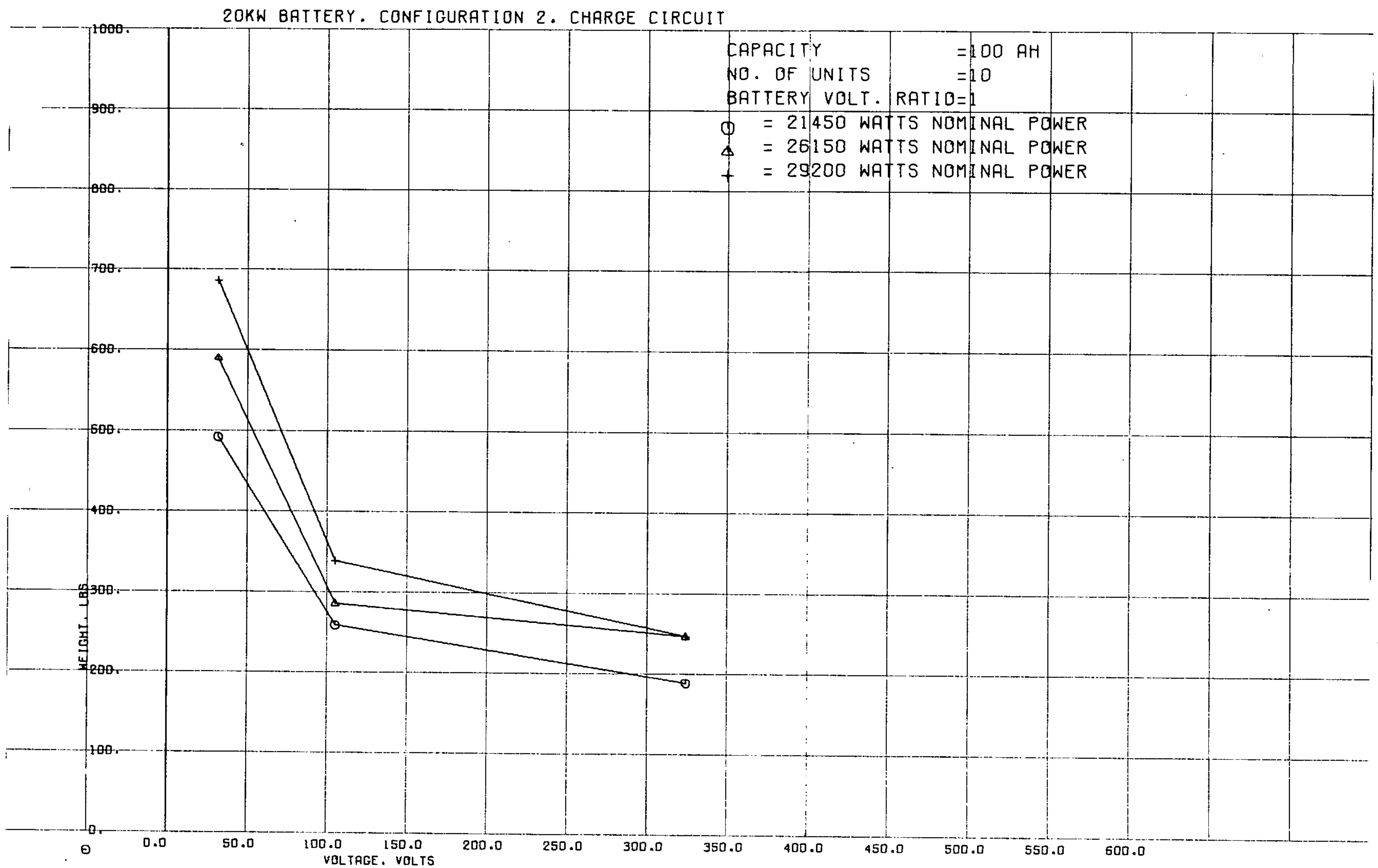
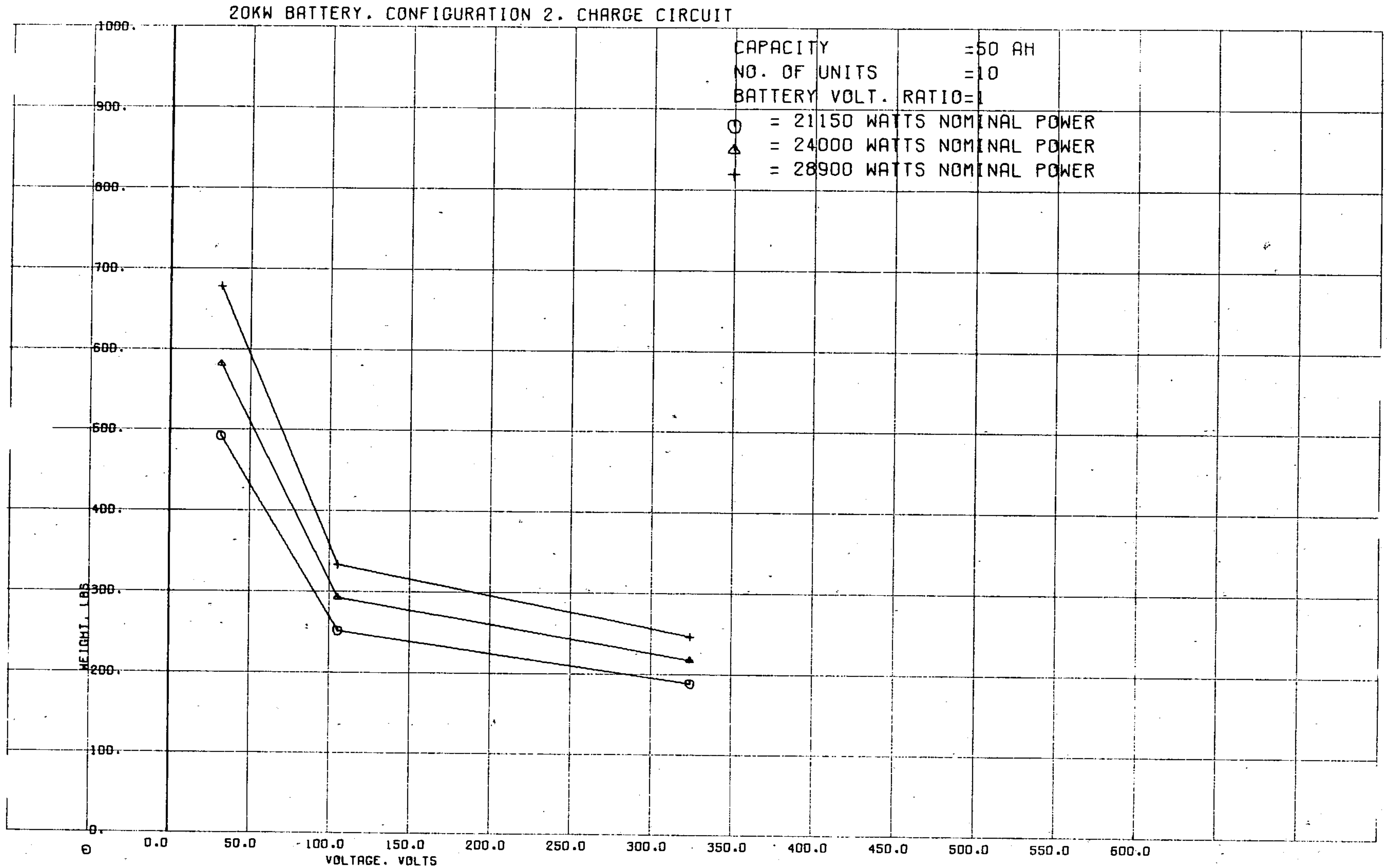
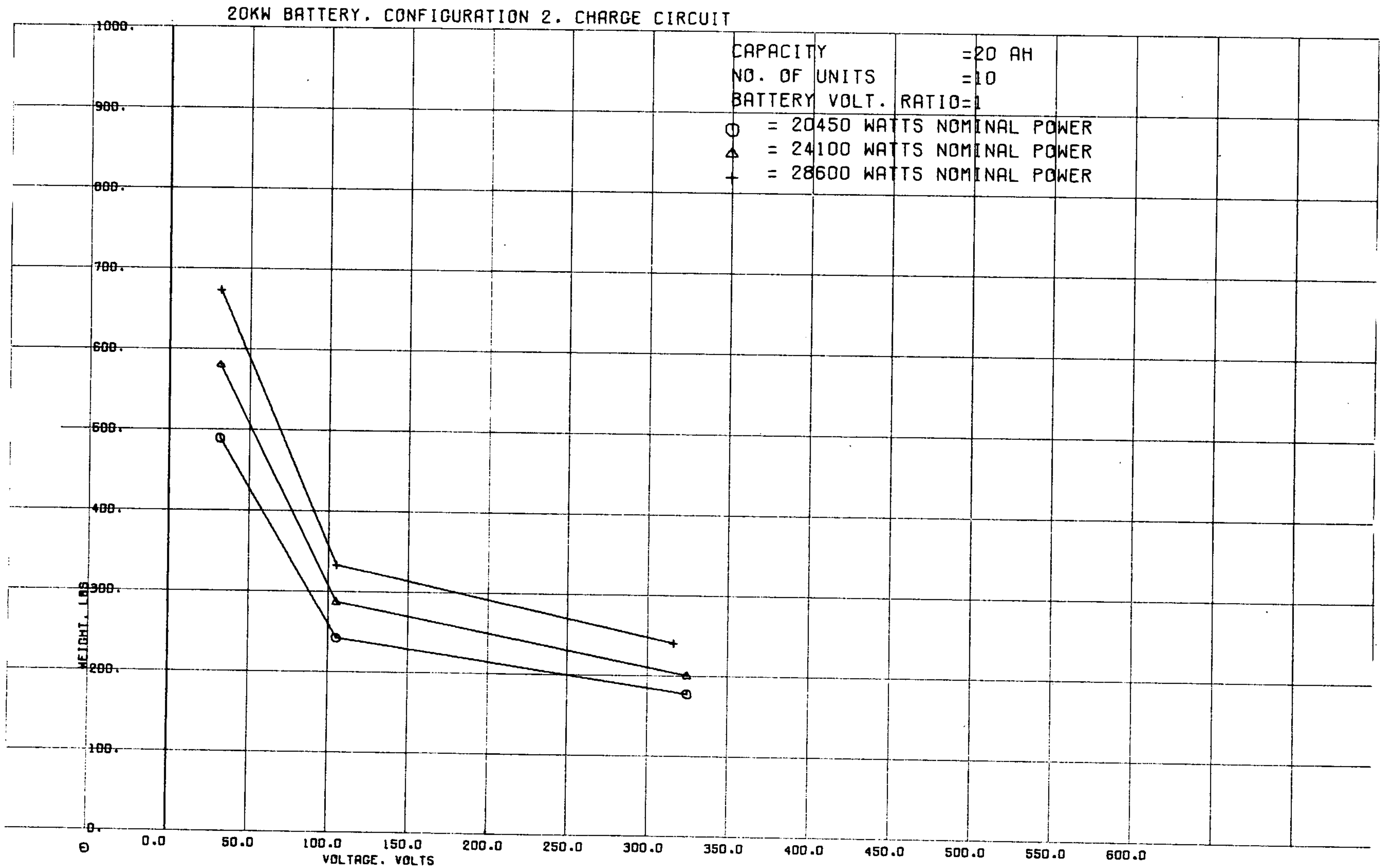


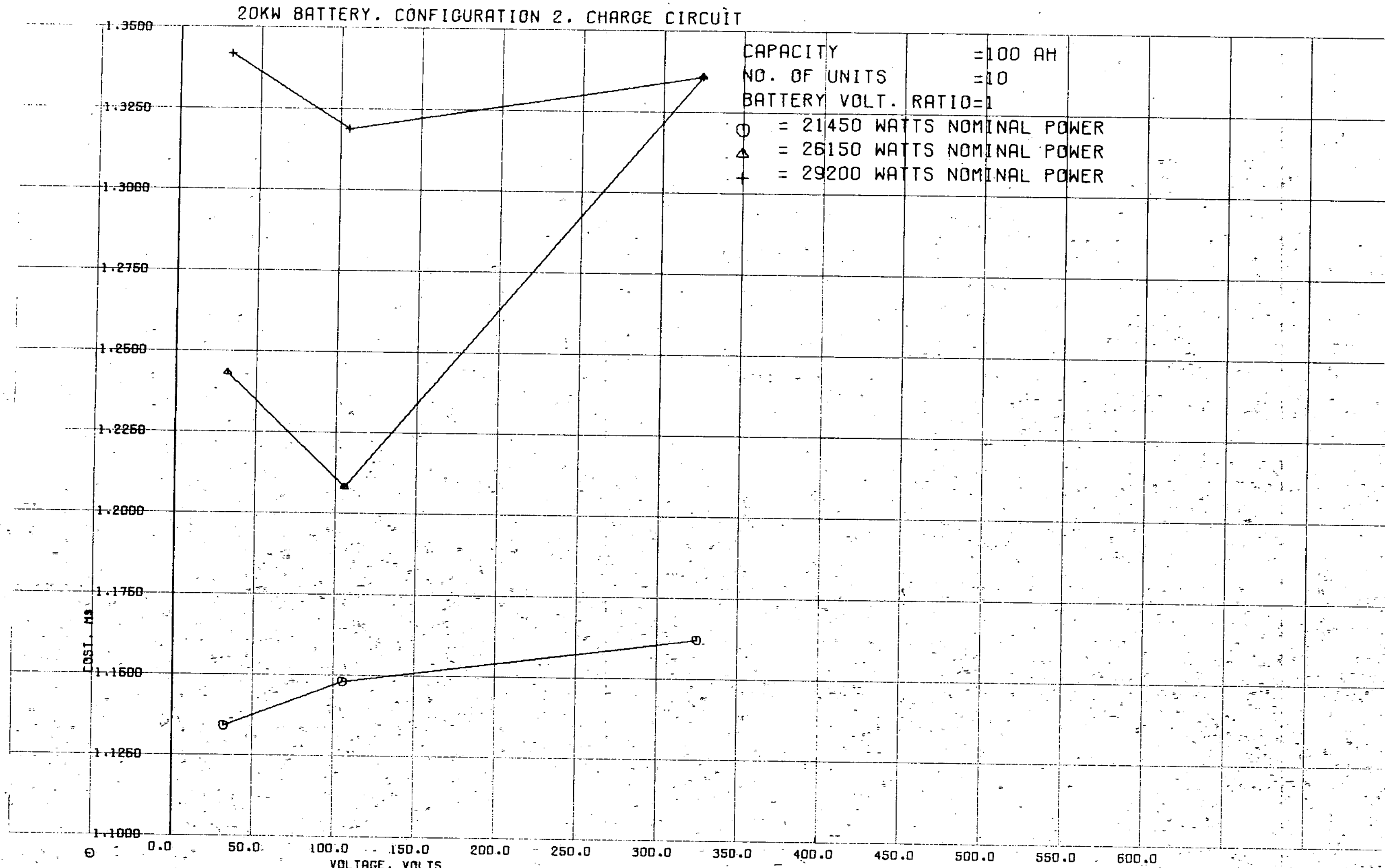
20KW BATTERY. CONFIGURATION 1 AND 4. CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 20100 WATTS NOMINAL POWER
= 22150 WATTS NOMINAL POWER
= 27400 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21450 WATTS NOMINAL POWER
= 26150 WATTS NOMINAL POWER
= 29200 WATTS NOMINAL POWER
WEIGHT. LBS
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

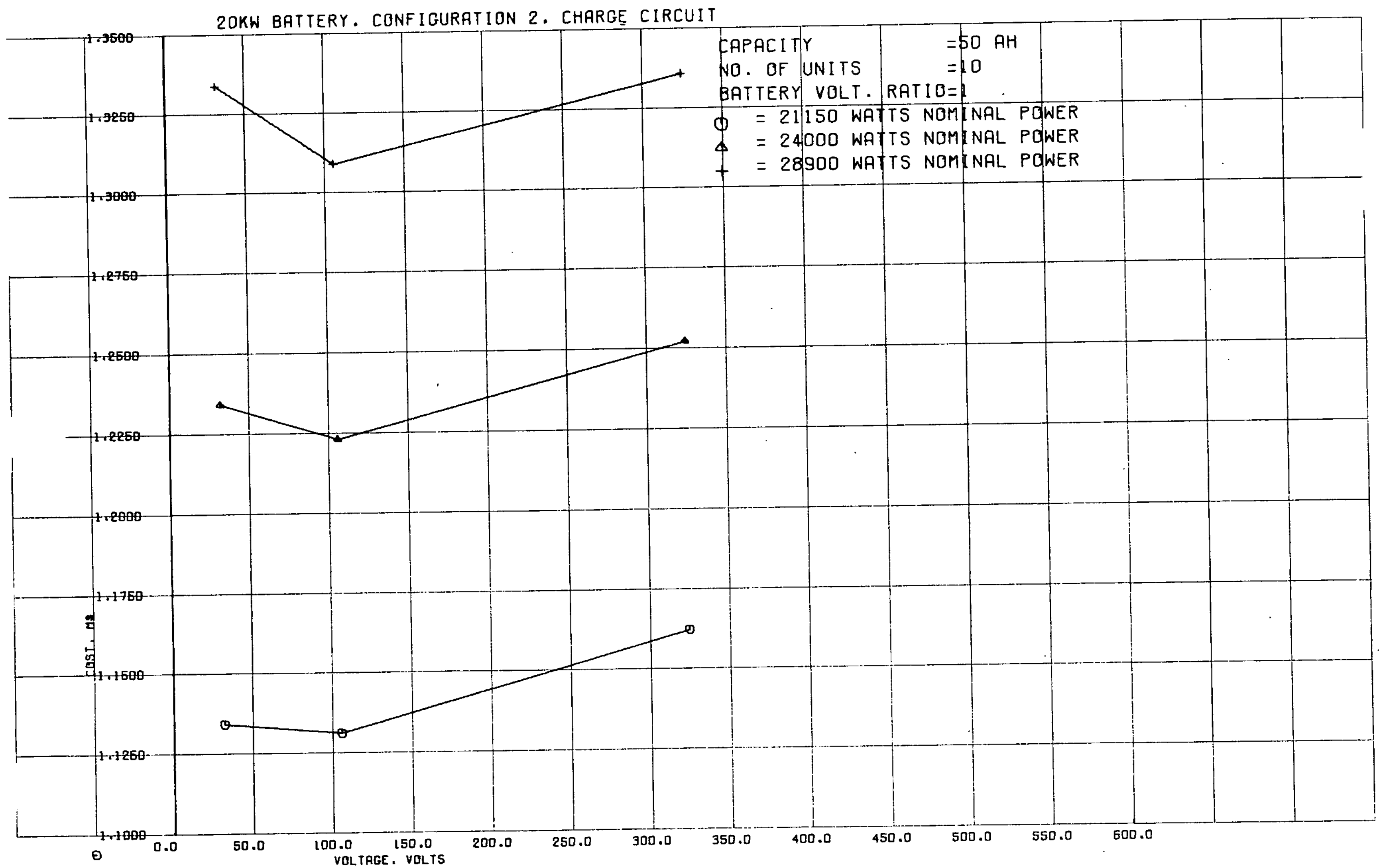

20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21150 WATTS NOMINAL POWER
= 24000 WATTS NOMINAL POWER
= 28900 WATTS NOMINAL POWER
WEIGHT, LBS
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

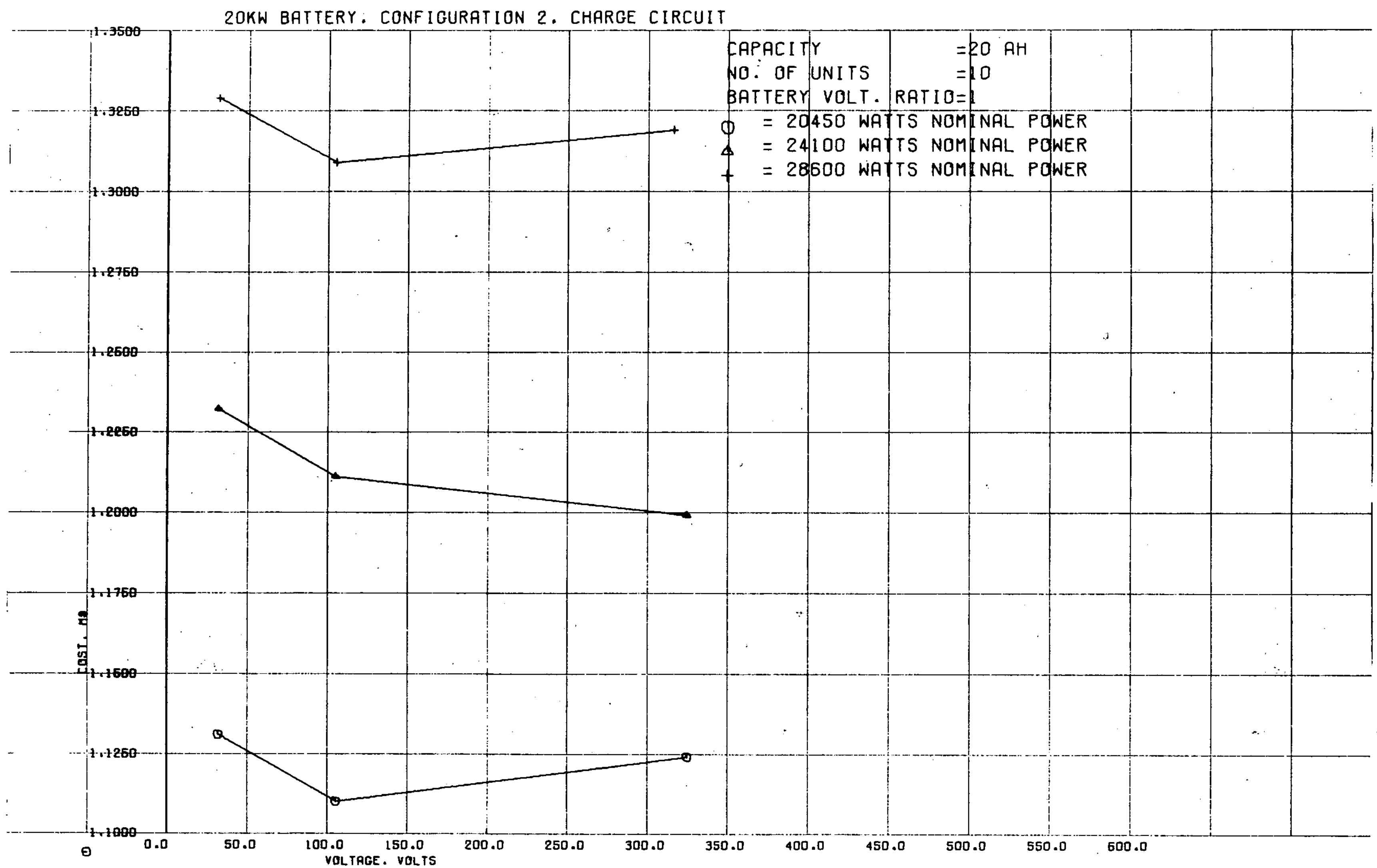


20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 20450 WATTS NOMINAL POWER
= 24100 WATTS NOMINAL POWER
= 28600 WATTS NOMINAL POWER
WEIGHT, LBS
1000.
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

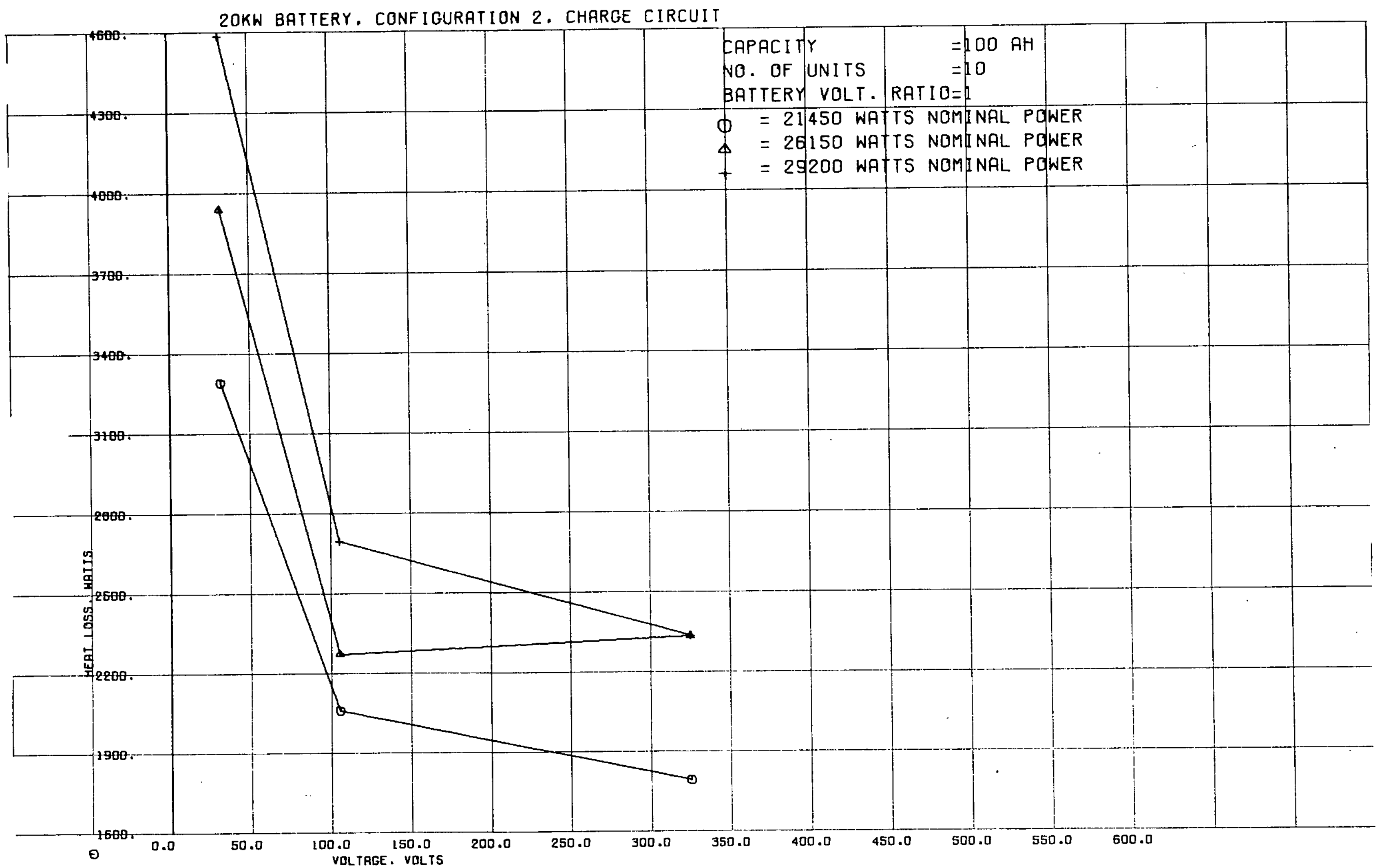


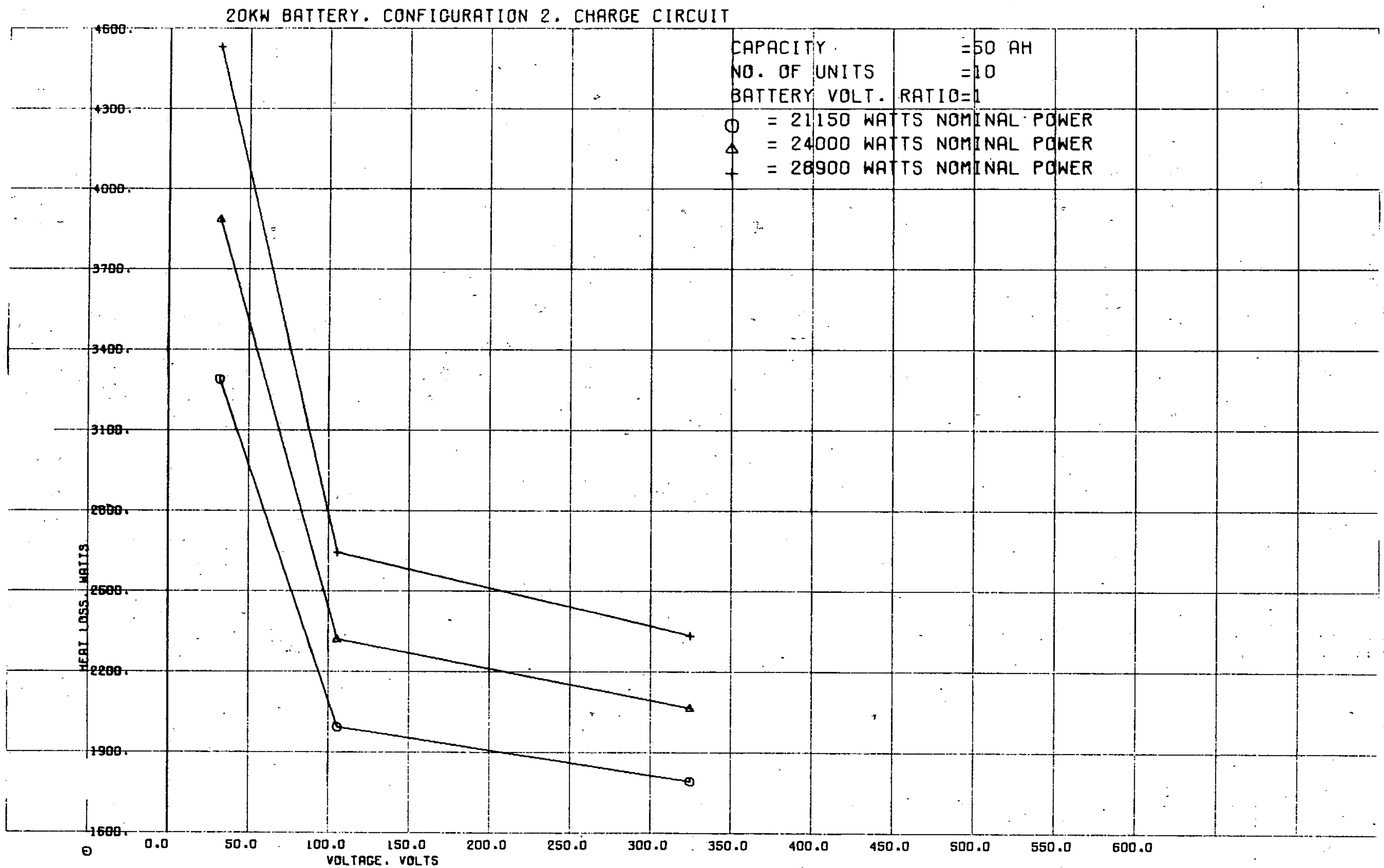
20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21450 WATTS NOMINAL POWER
= 26150 WATTS NOMINAL POWER
= 29200 WATTS NOMINAL POWER
COST. M$
1.3500
1.3250
1.3000
1.2750
1.2500
1.2250
1.2000
1.1750
1.1500
1.1250
1.1000
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

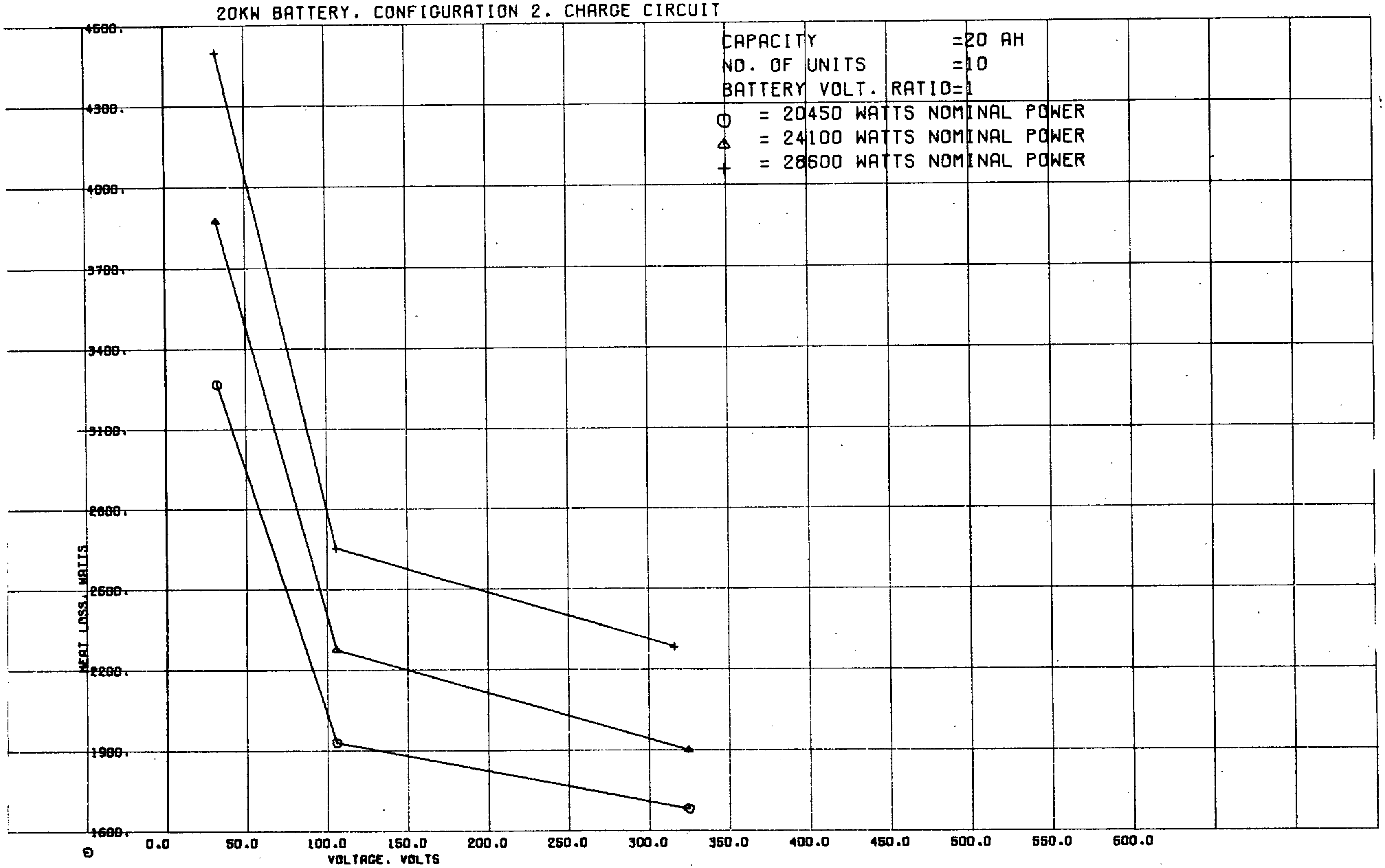

20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21150 WATTS NOMINAL POWER
= 24000 WATTS NOMINAL POWER
= 28900 WATTS NOMINAL POWER
1.3500
1.3250
1.3000
1.2750
1.2500
1.2250
1.2000
1.1750
1.1500
1.1250
1.1000
COST, M$
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS



20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
O = 20450 WATTS NOMINAL POWER
△ = 24100 WATTS NOMINAL POWER
+ = 28600 WATTS NOMINAL POWER
COST. M$
1.3500
1.3250
1.3000
1.2750
1.2500
1.2250
1.2000
1.1750
1.1500
1.1250
1.1000
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY, CONFIGURATION 2, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21450 WATTS NOMINAL POWER
= 26150 WATTS NOMINAL POWER
= 29200 WATTS NOMINAL POWER
HEAT LOSS, WATTS
4600.
4300.
4000.
3700.
3400.
3100.
2800.
2500.
2200.
1900.
1600.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21150 WATTS NOMINAL POWER
= 24000 WATTS NOMINAL POWER
= 28900 WATTS NOMINAL POWER
HEAT LOSS, WATTS
4600.
4300.
4000.
3700.
3400.
3100.
2800.
2500.
2200.
1900.
1600.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 2. CHARGE CIRCUIT
CAPACITY =20 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 20450 WATTS NOMINAL POWER
= 24100 WATTS NOMINAL POWER
= 28600 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
4600.
4300.
4000.
3700.
3400.
3100.
2800.
2500.
2200.
1900.
1600.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

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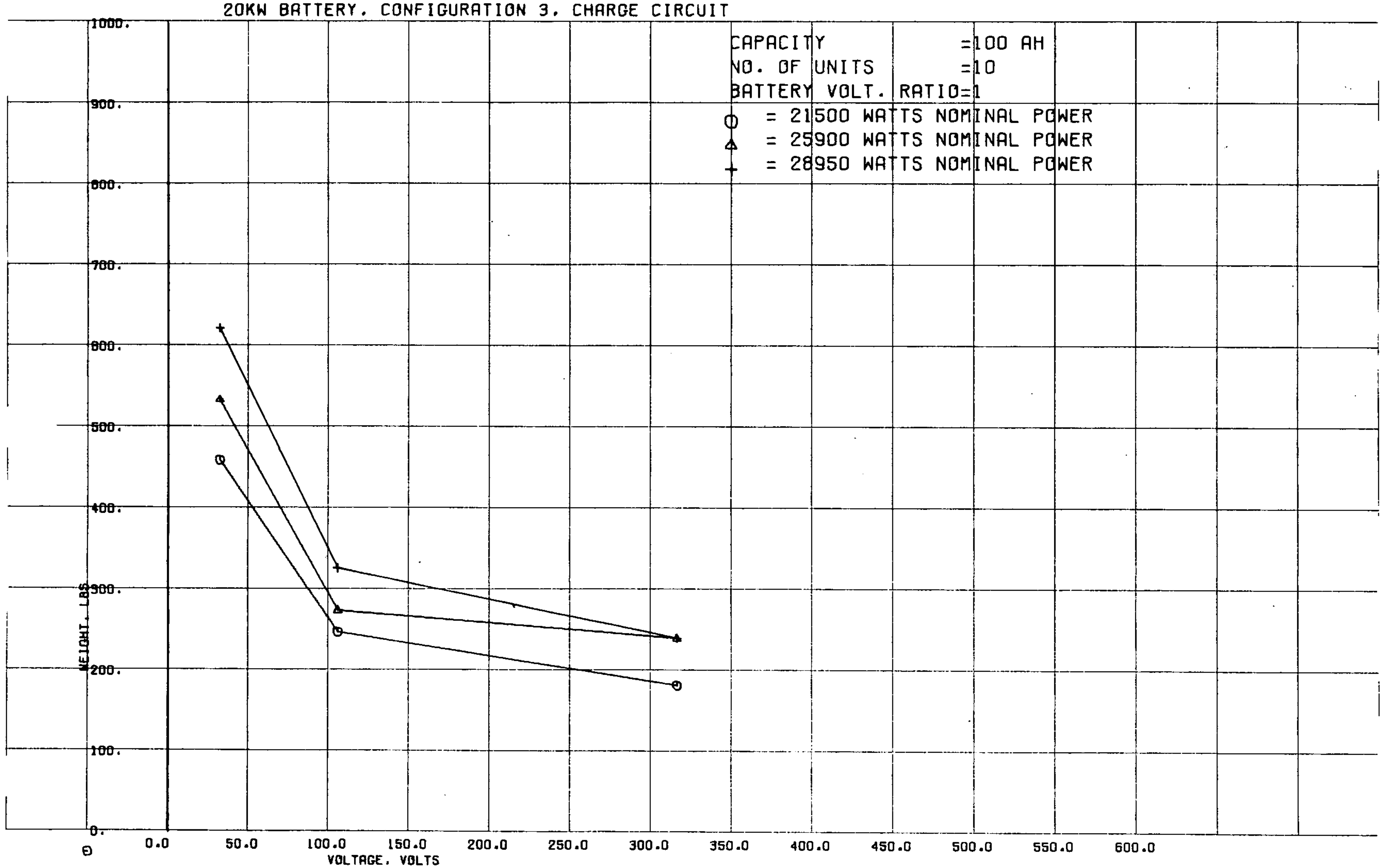
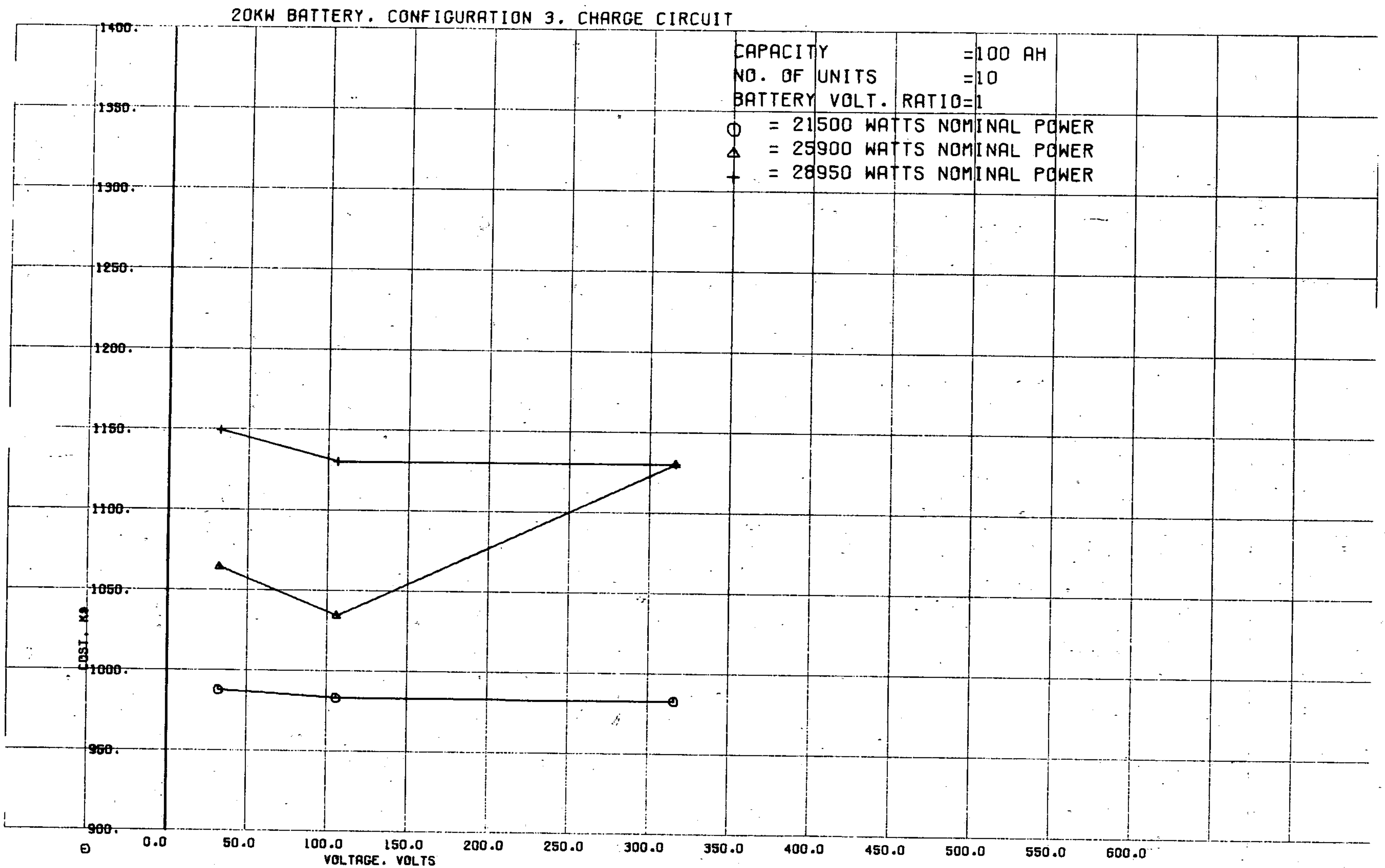
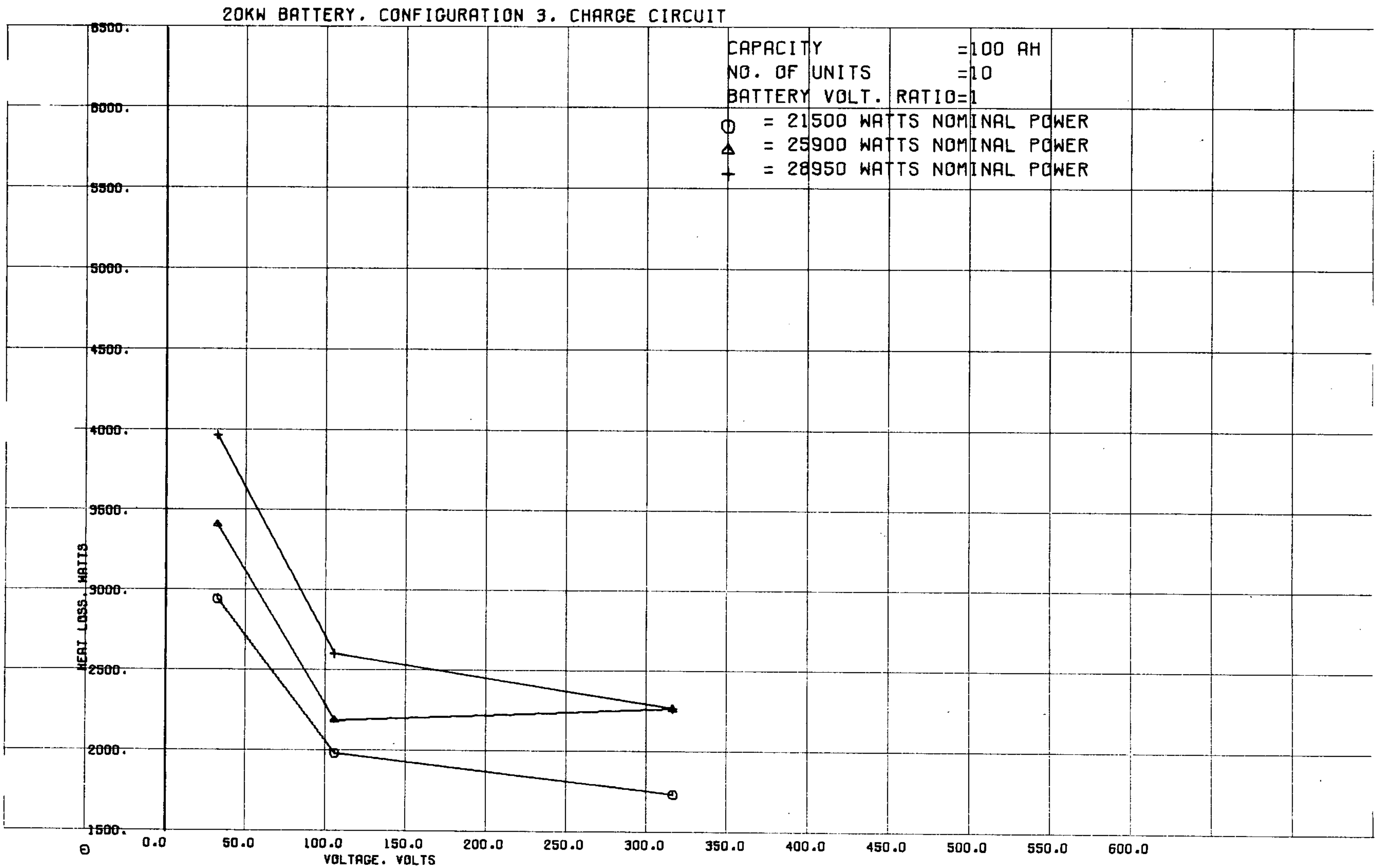
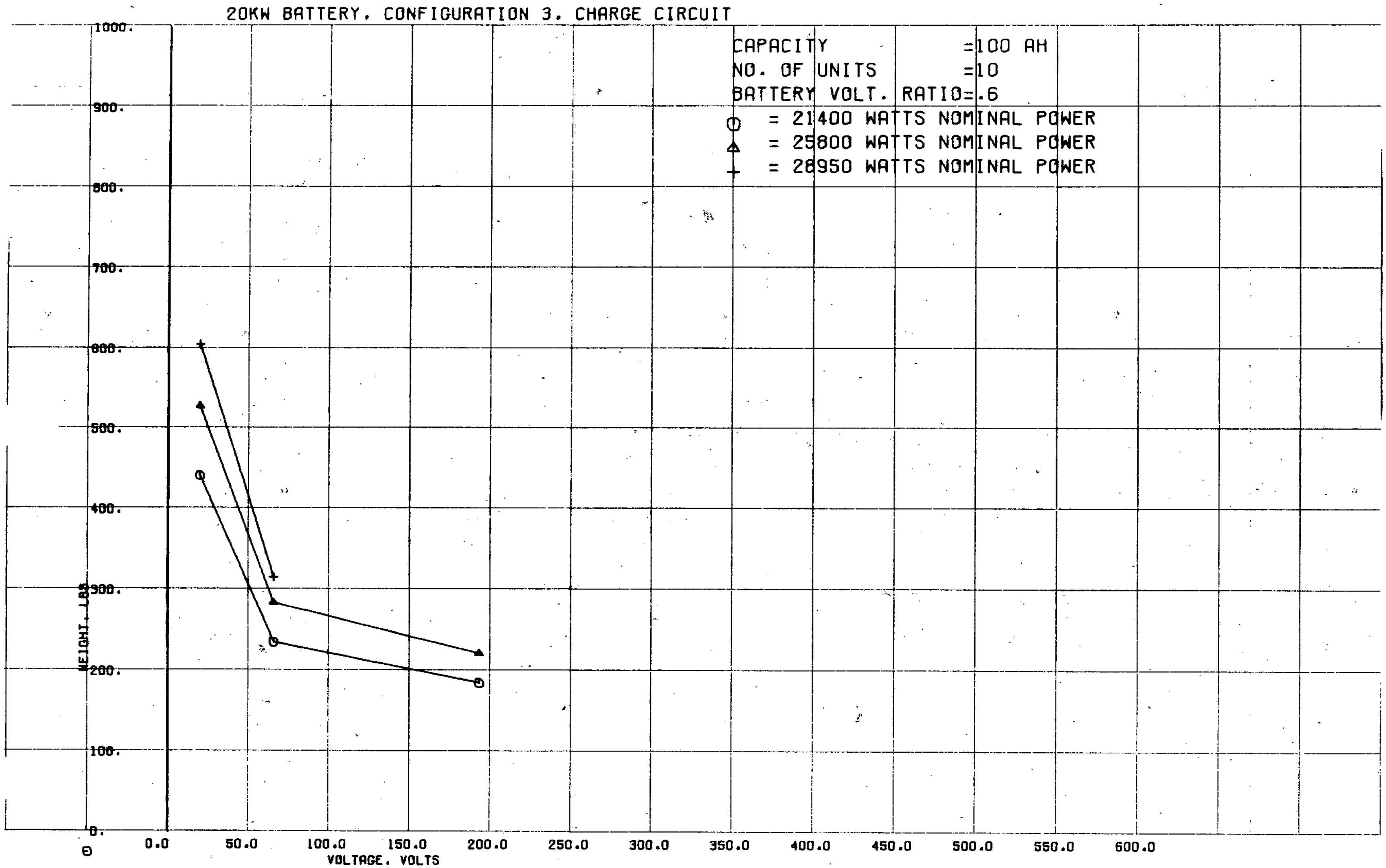
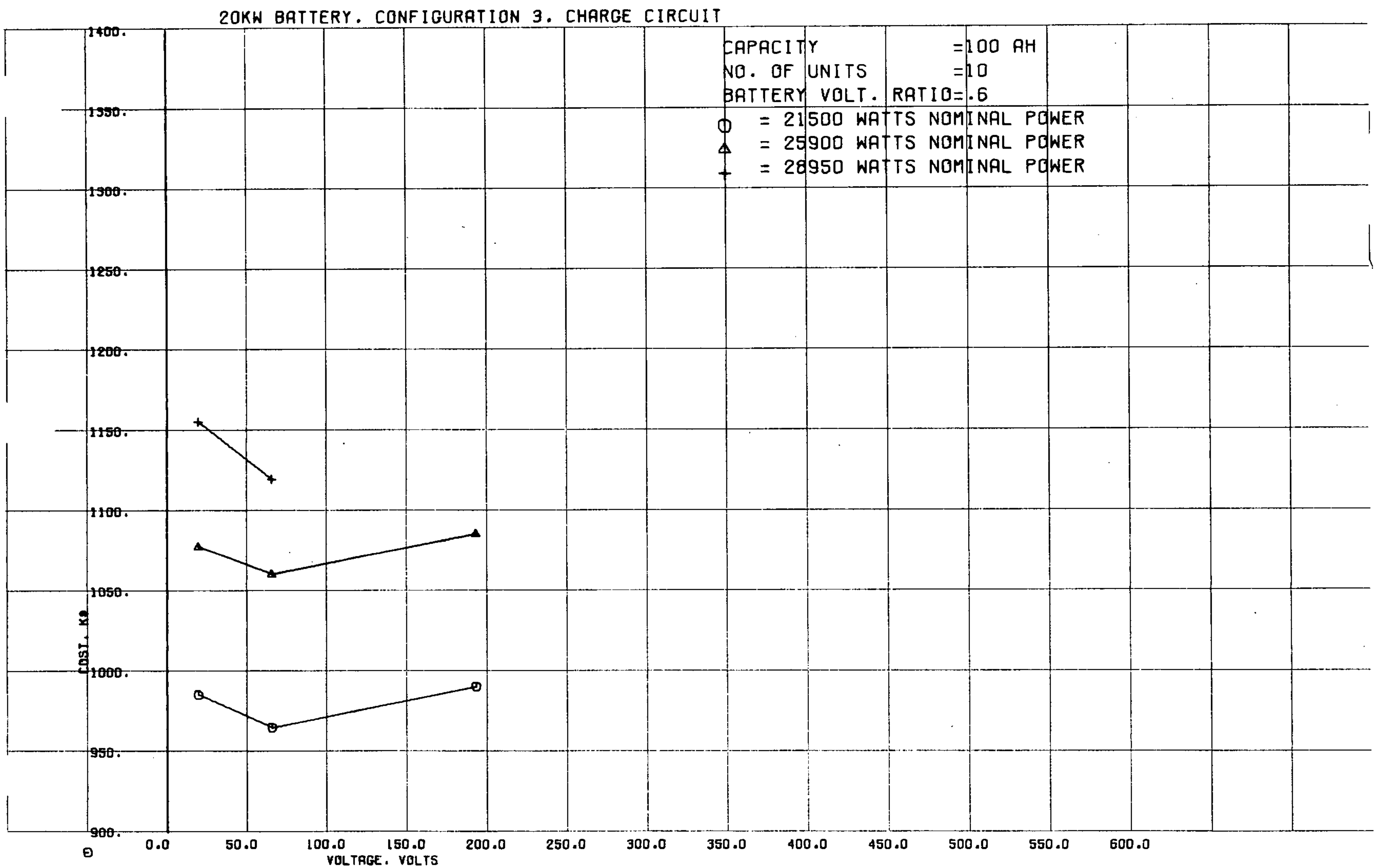
20KW BATTERY, CONFIGURATION 3, CHARGE CIRCUIT




20KW BATTERY, CONFIGURATION 3, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
○ = 21500 WATTS NOMINAL POWER
△ = 25900 WATTS NOMINAL POWER
+ = 28950 WATTS NOMINAL POWER
COST, K$
1400.
1350.
1300.
1250.
1200.
1150.
1100.
1050.
1000.
950.
900.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

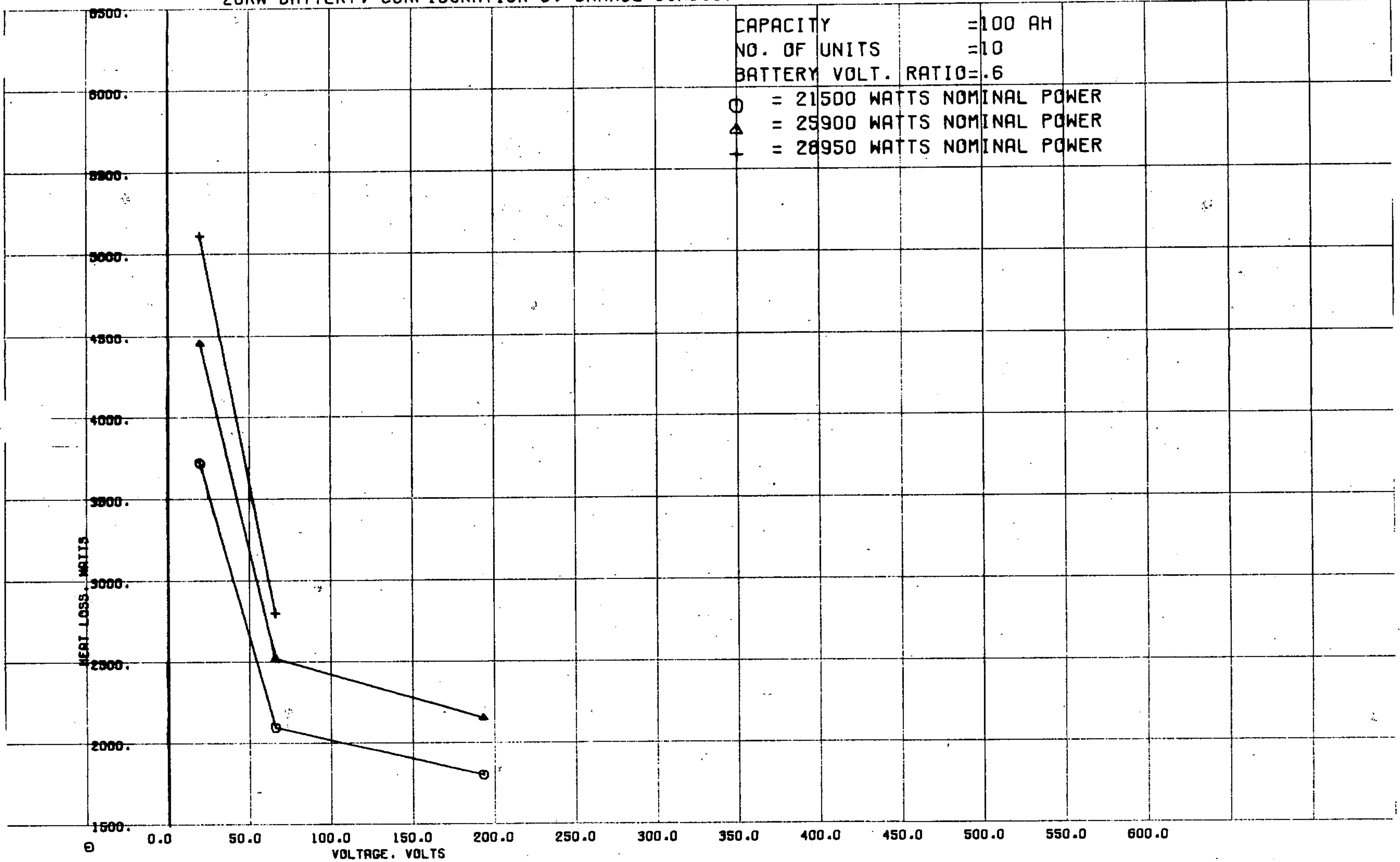

20KW BATTERY. CONFIGURATION 3. CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21500 WATTS NOMINAL POWER
= 25900 WATTS NOMINAL POWER
= 28950 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
6500.
6000.
5500.
5000.
4500.
4000.
3500.
3000.
2500.
2000.
1500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0


20KW BATTERY, CONFIGURATION 3, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 21400 WATTS NOMINAL POWER
= 25800 WATTS NOMINAL POWER
= 28950 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
0. 100. 200. 300. 400. 500. 600. 700. 800. 900. 1000.
0.0 50.0 100.0 150.0 200.0 250.0 300.0 350.0 400.0 450.0 500.0 550.0 600.0



20KW BATTERY. CONFIGURATION 3. CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 21500 WATTS NOMINAL POWER
= 25900 WATTS NOMINAL POWER
= 28950 WATTS NOMINAL POWER
COST. K$
1400.
1350.
1300.
1250.
1200.
1150.
1100.
1050.
1000.
950.
900.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

20KW BATTERY. CONFIGURATION 3. CHARGE CIRCUIT



SEE CONFIGURATION 1

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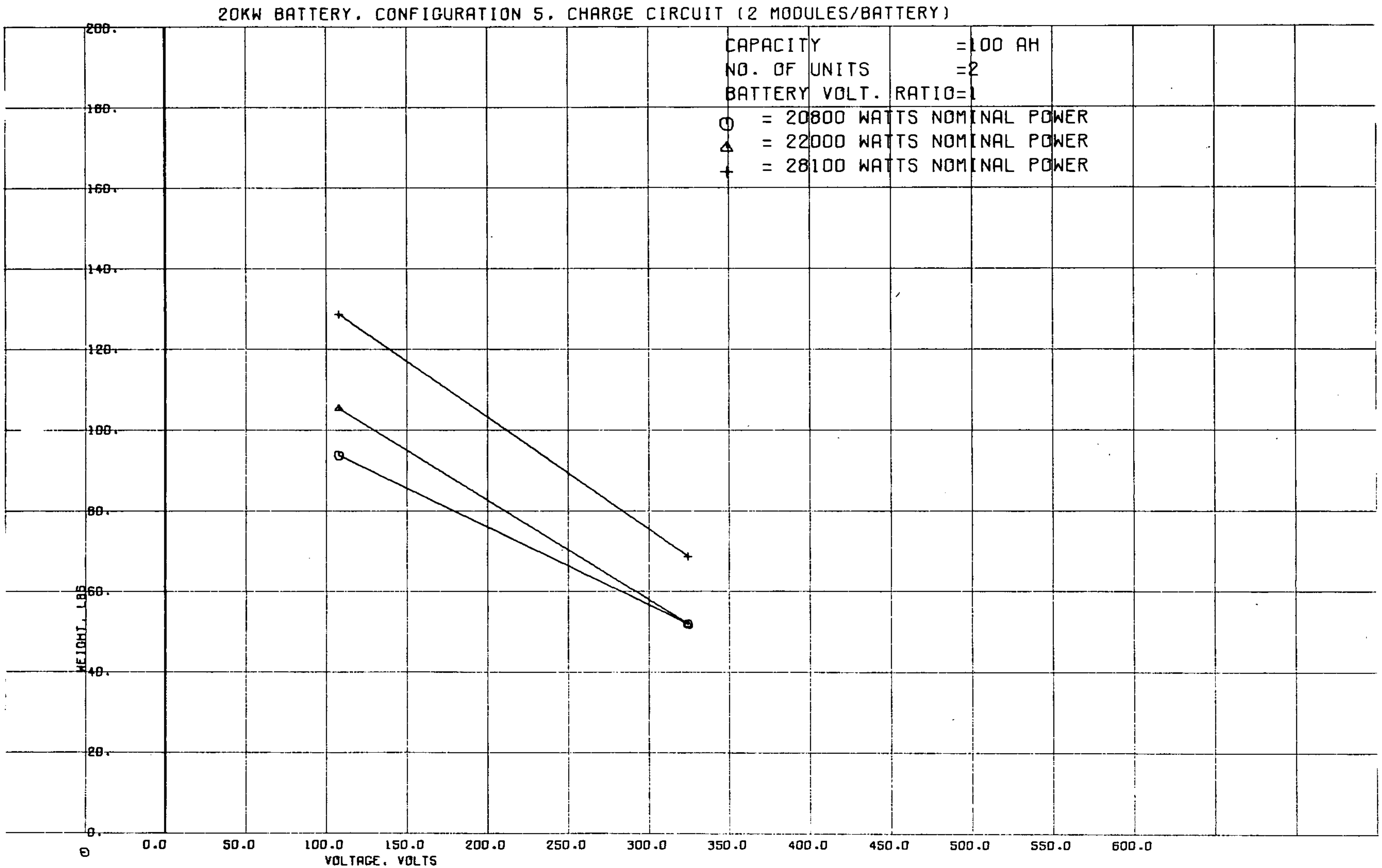

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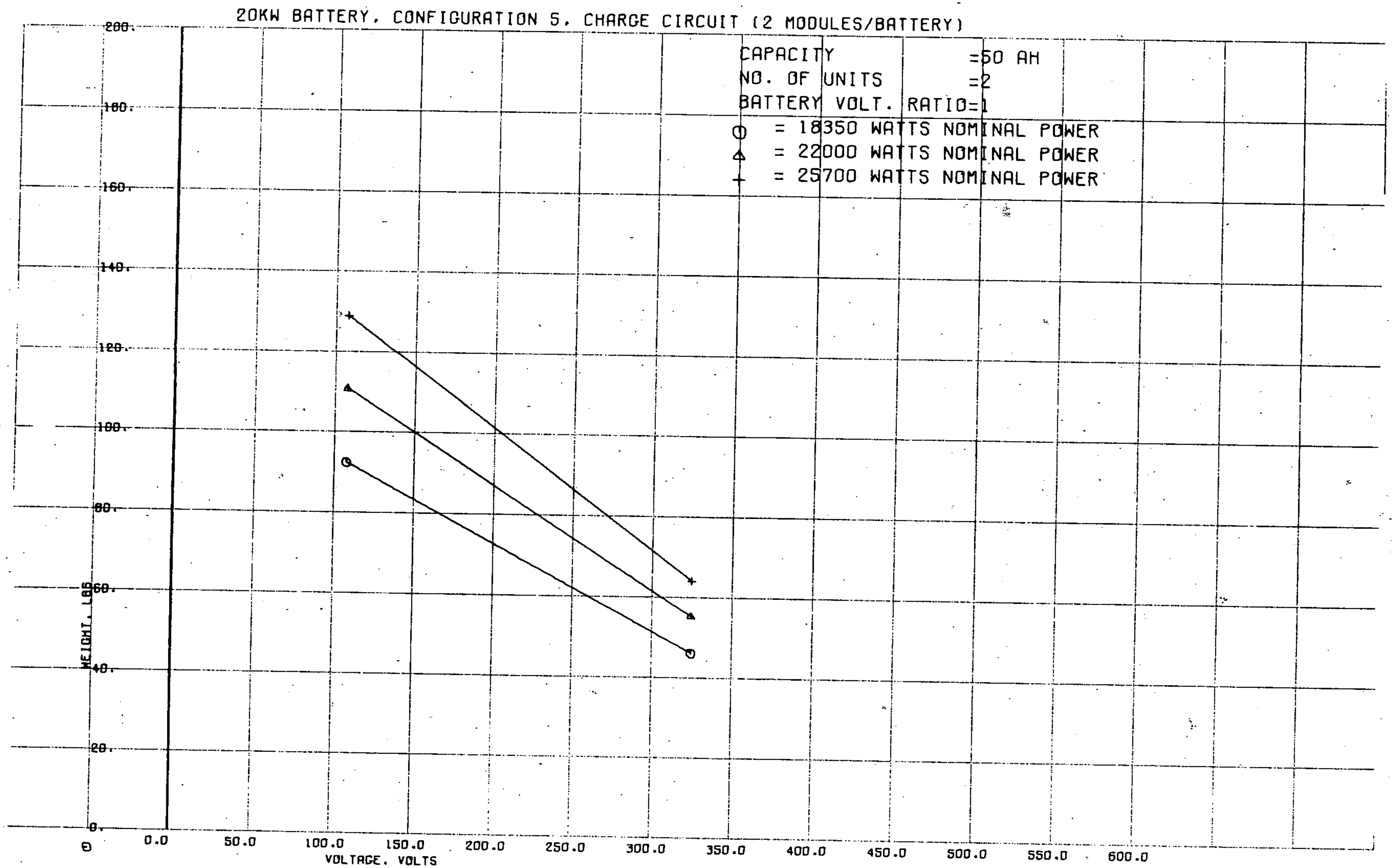
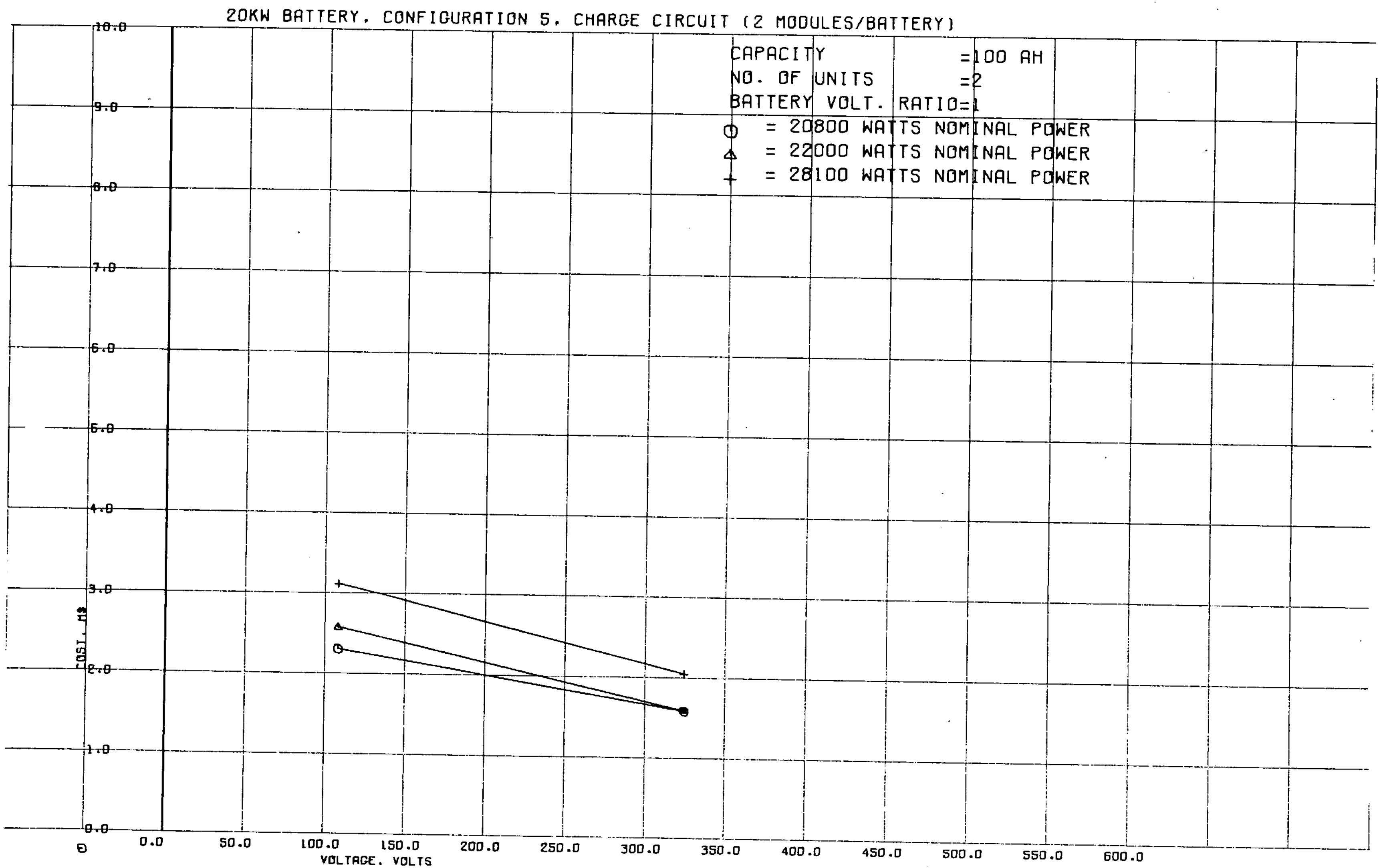
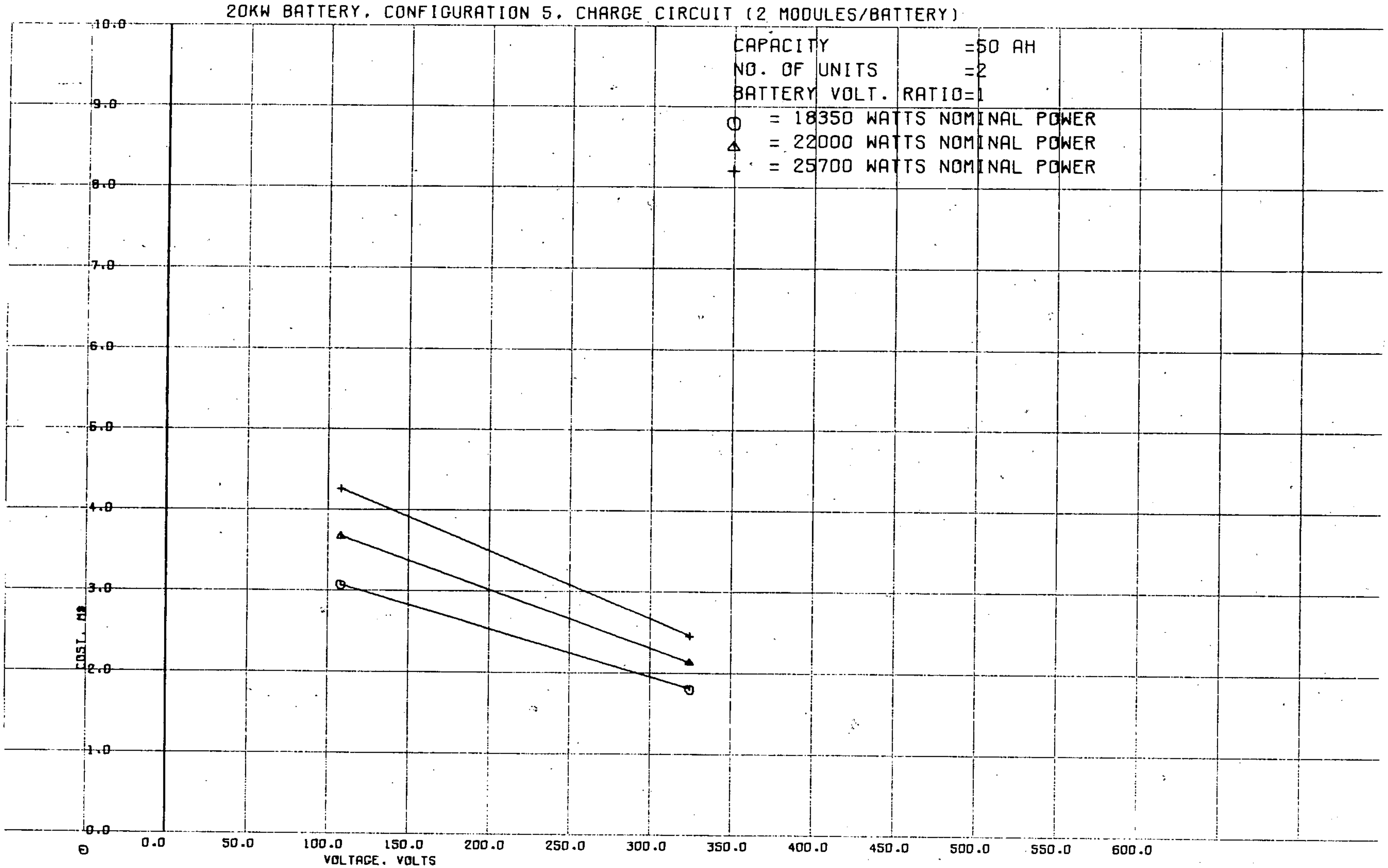
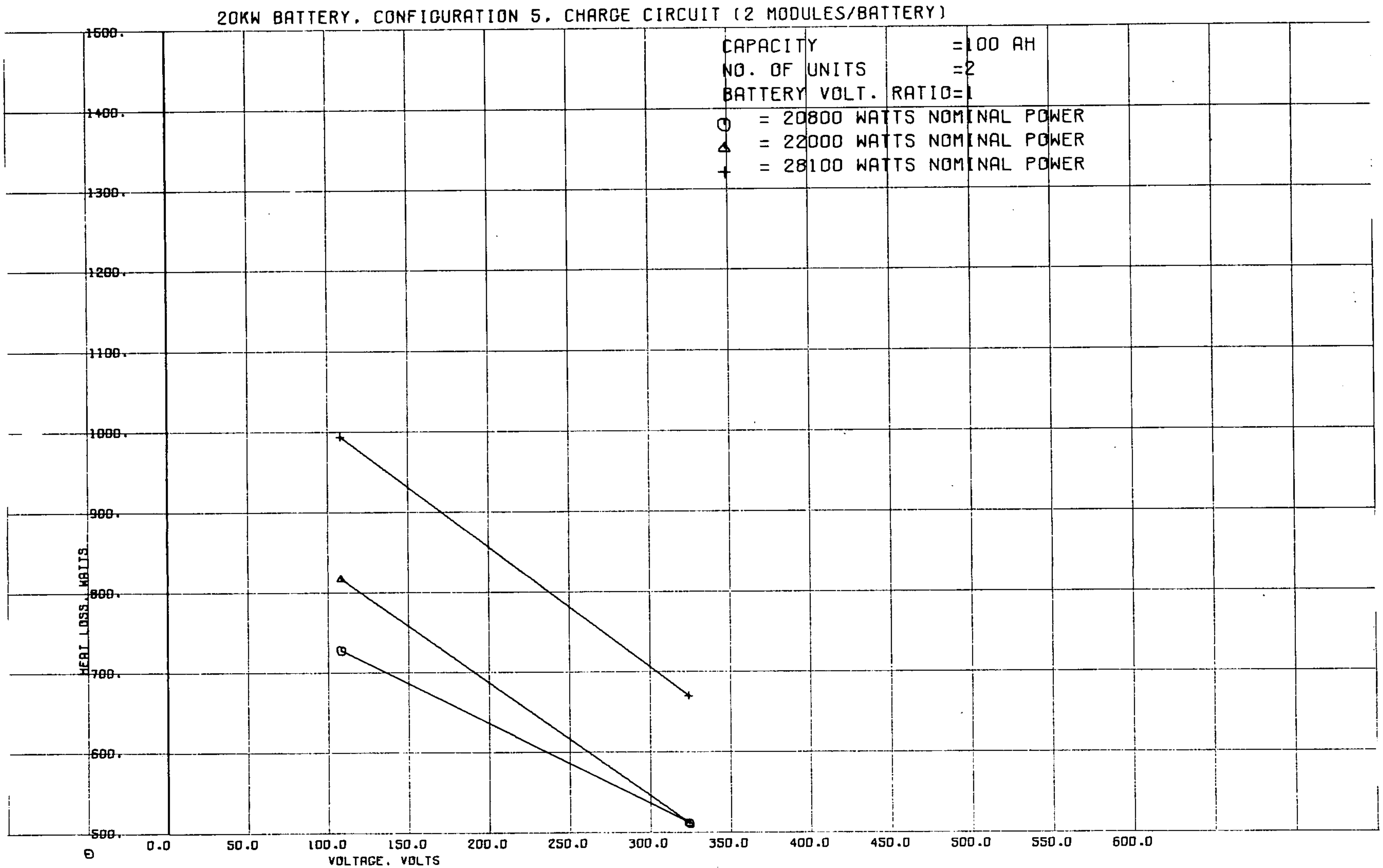
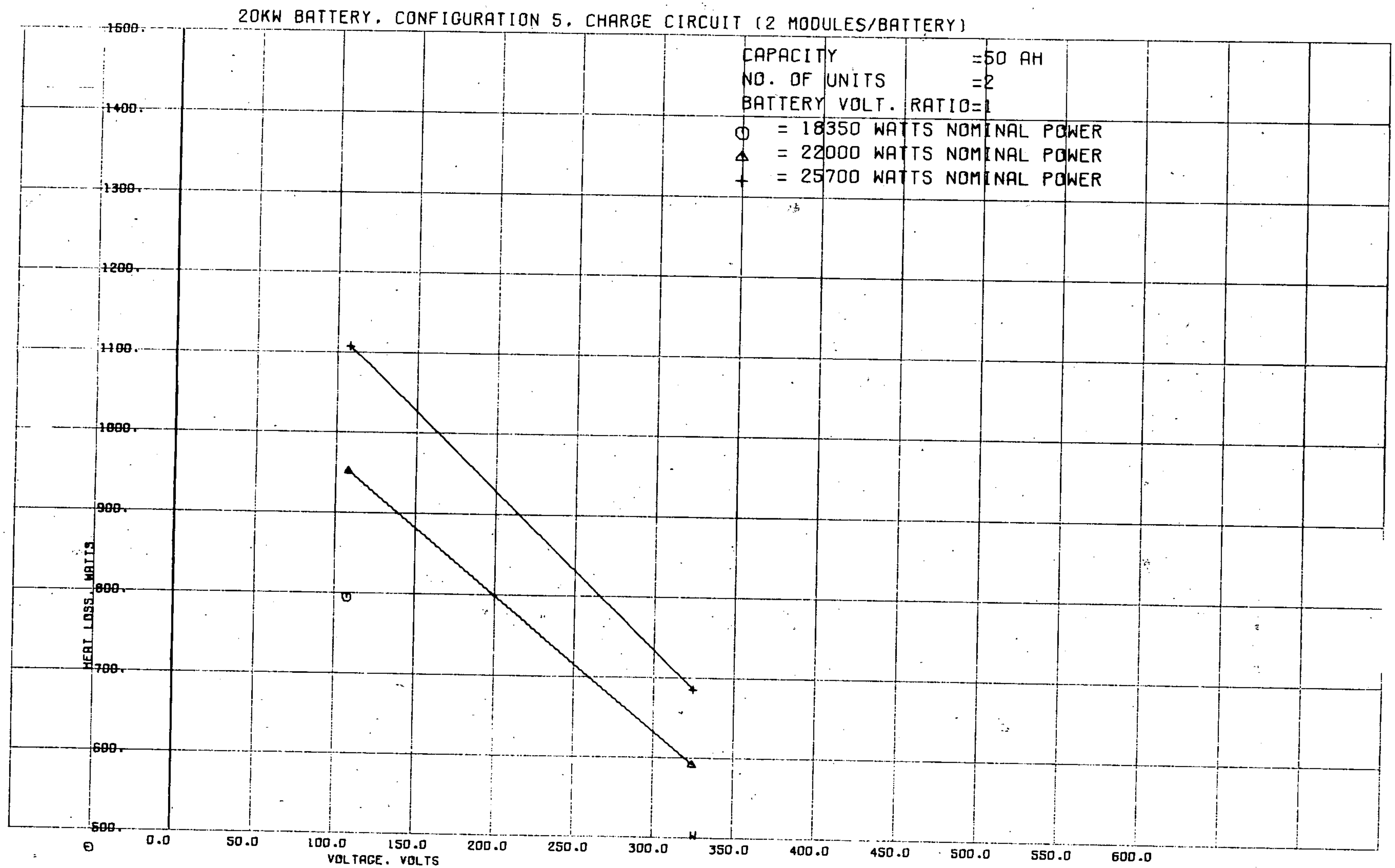

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18350 WATTS NOMINAL POWER
△ = 22000 WATTS NOMINAL POWER
+ = 25700 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
0.
20.
40.
60.
80.
100.
120.
140.
160.
180.
200.

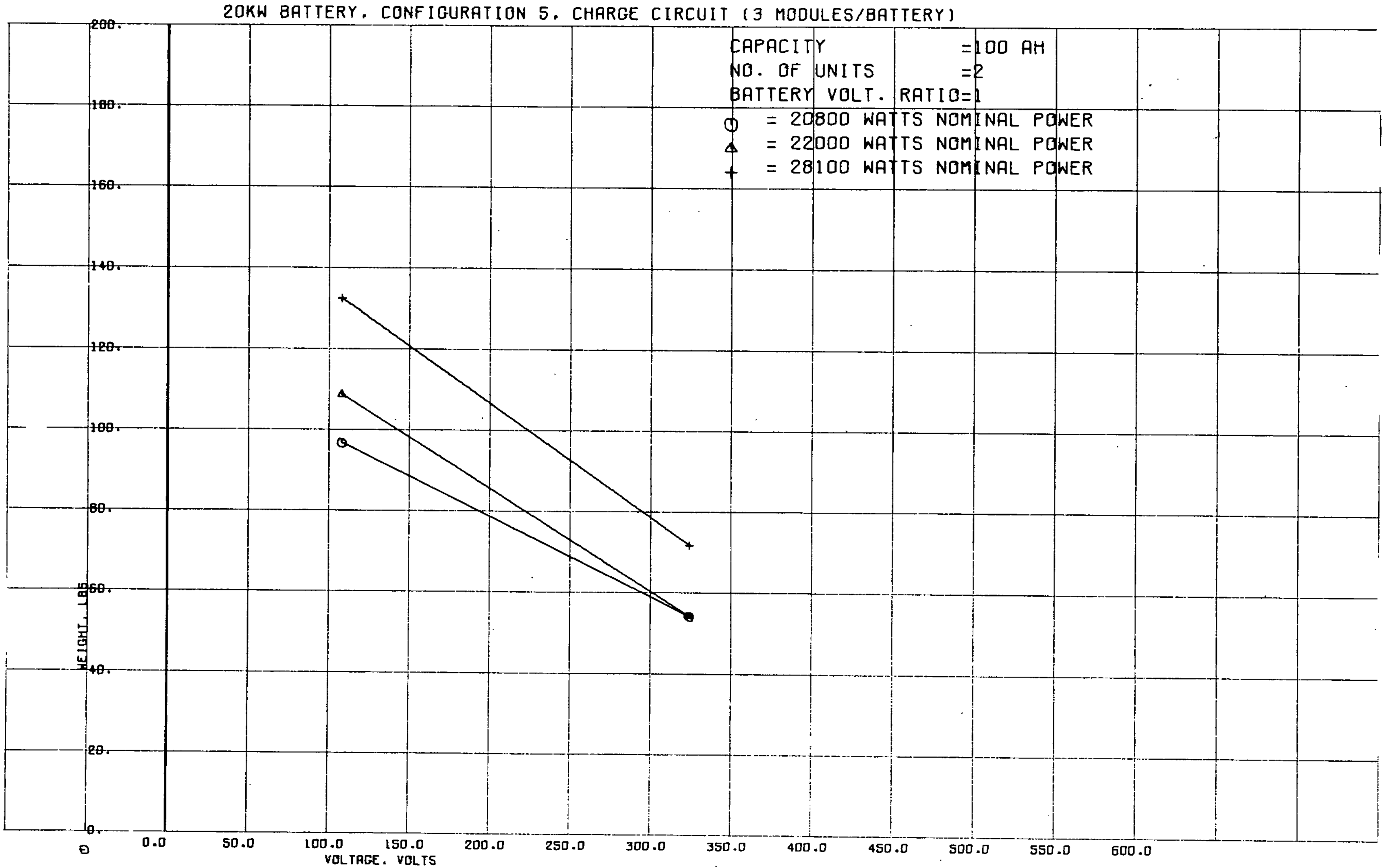

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (2 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20800 WATTS NOMINAL POWER
= 22000 WATTS NOMINAL POWER
= 28100 WATTS NOMINAL POWER
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
COST, M$
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

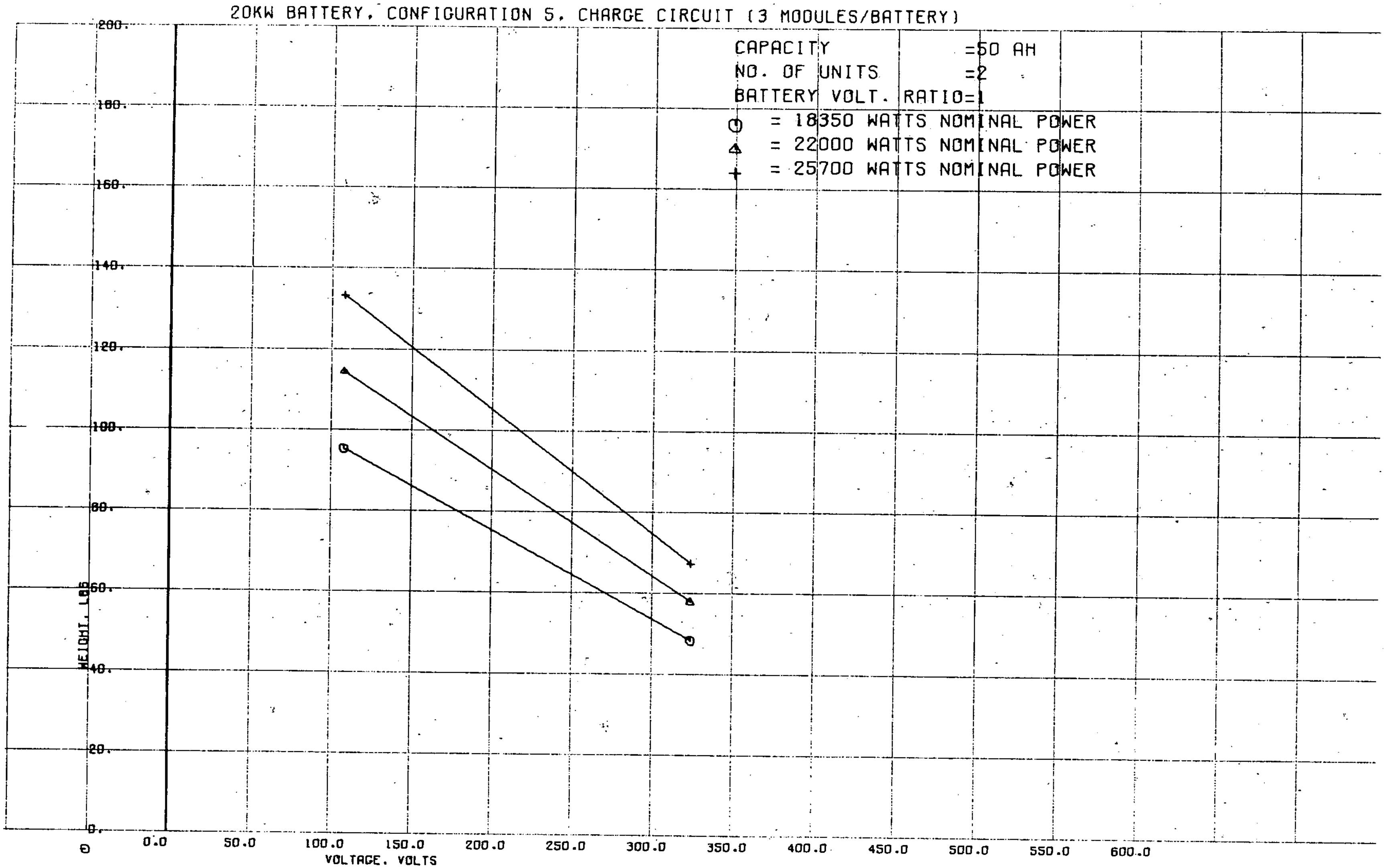

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 18350 WATTS NOMINAL POWER
△ = 22000 WATTS NOMINAL POWER
+ = 25700 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

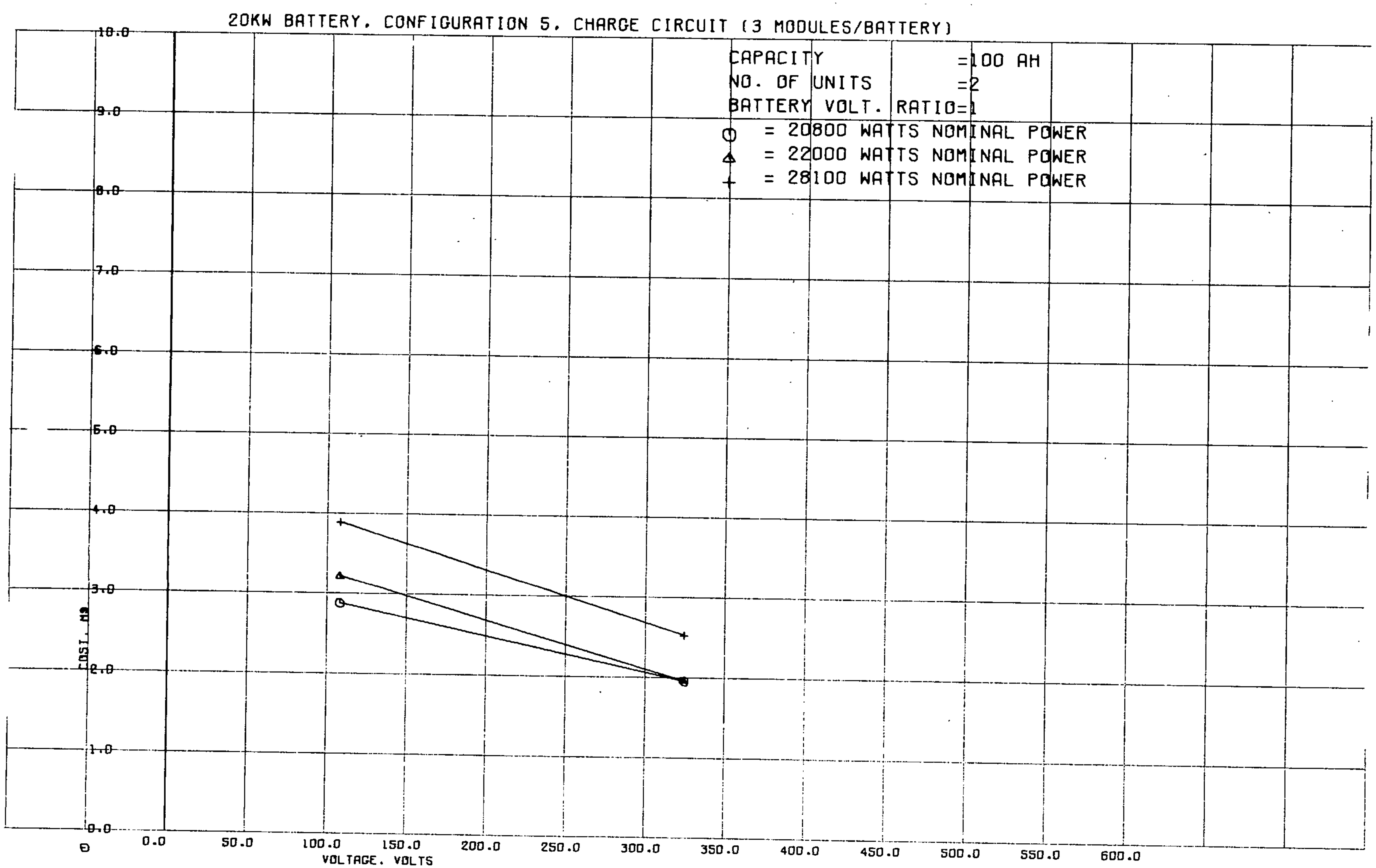


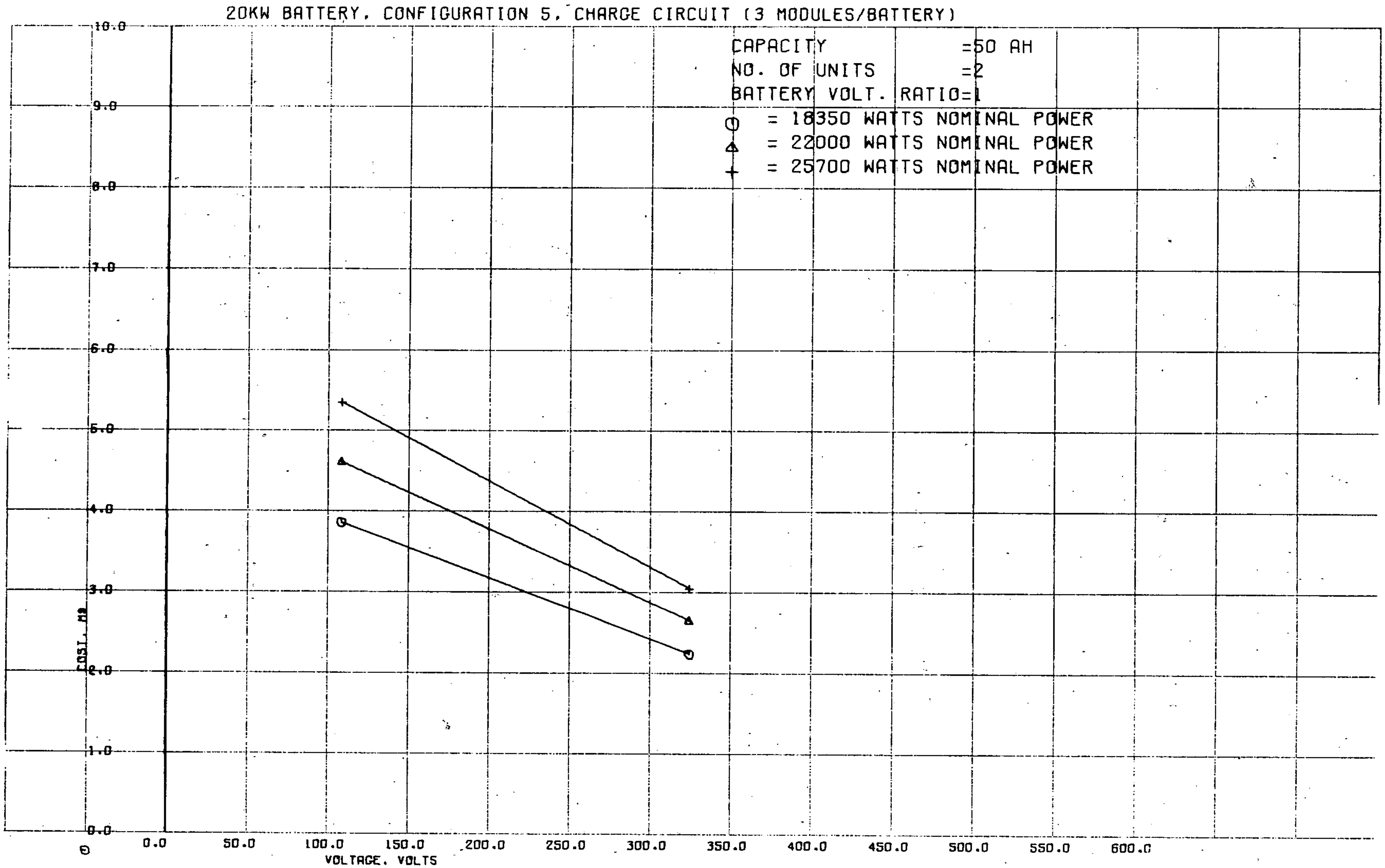
20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (2 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20800 WATTS NOMINAL POWER
= 22000 WATTS NOMINAL POWER
= 28100 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18350 WATTS NOMINAL POWER
= 22000 WATTS NOMINAL POWER
= 25700 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20800 WATTS NOMINAL POWER
= 22000 WATTS NOMINAL POWER
= 28100 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0


20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 18350 WATTS NOMINAL POWER
Δ = 22000 WATTS NOMINAL POWER
+ = 25700 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.


20KW BATTERY. CONFIGURATION 5. CHARGE CIRCUIT (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20800 WATTS NOMINAL POWER
= 22000 WATTS NOMINAL POWER
= 28100 WATTS NOMINAL POWER
COST. M$
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS


20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 18350 WATTS NOMINAL POWER
= 22000 WATTS NOMINAL POWER
= 25700 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
50.0
100.0
150.0
200.0
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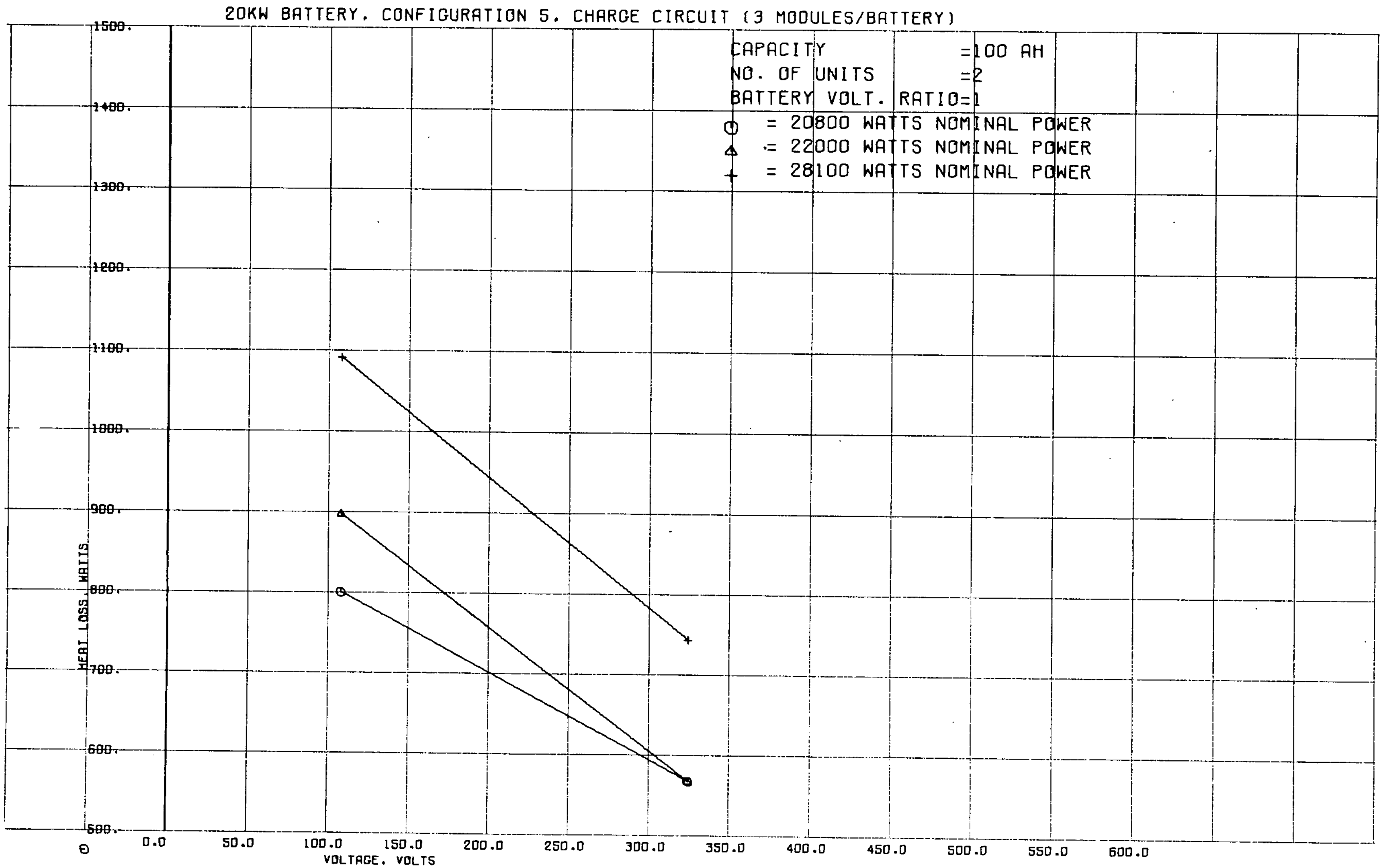
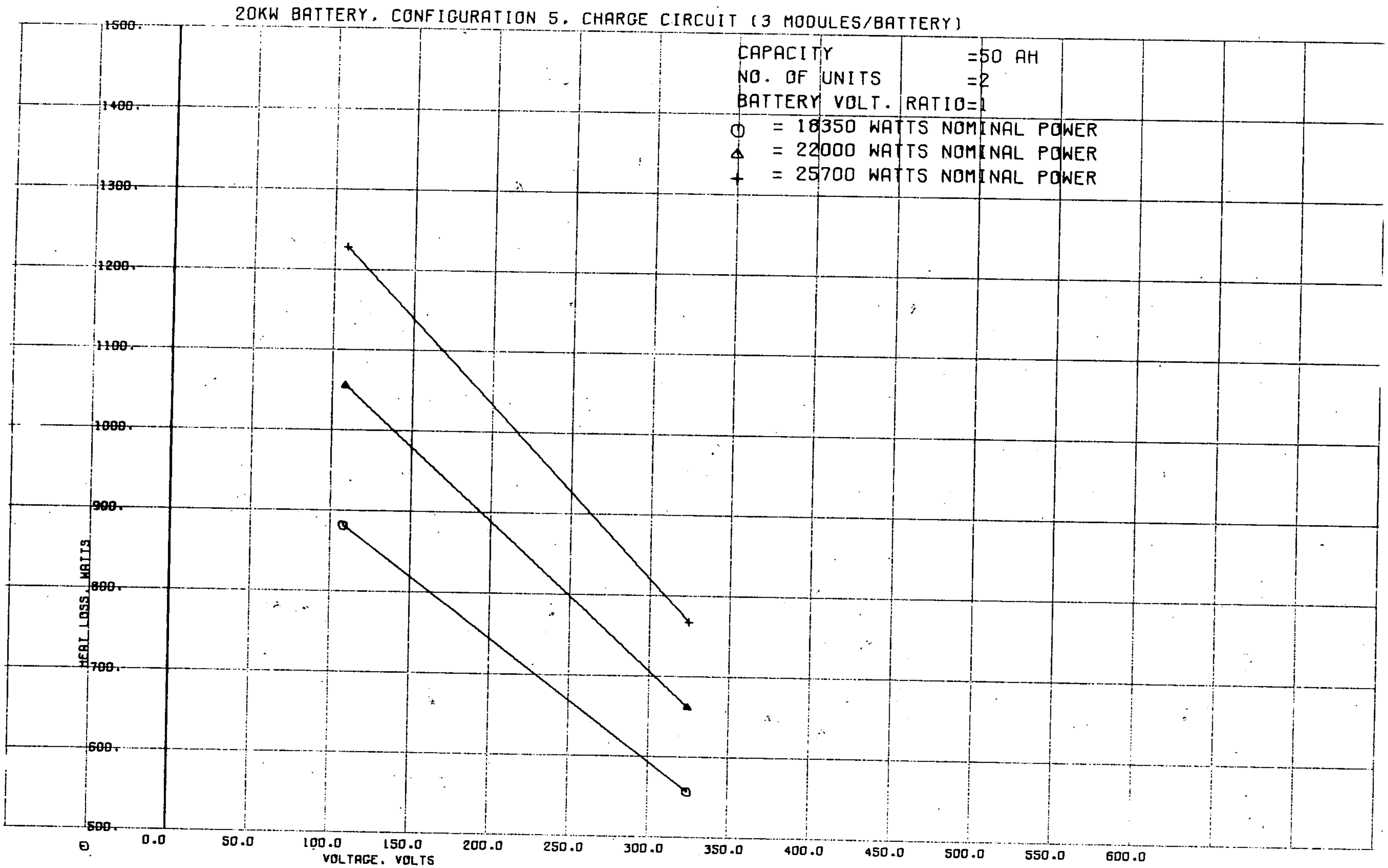
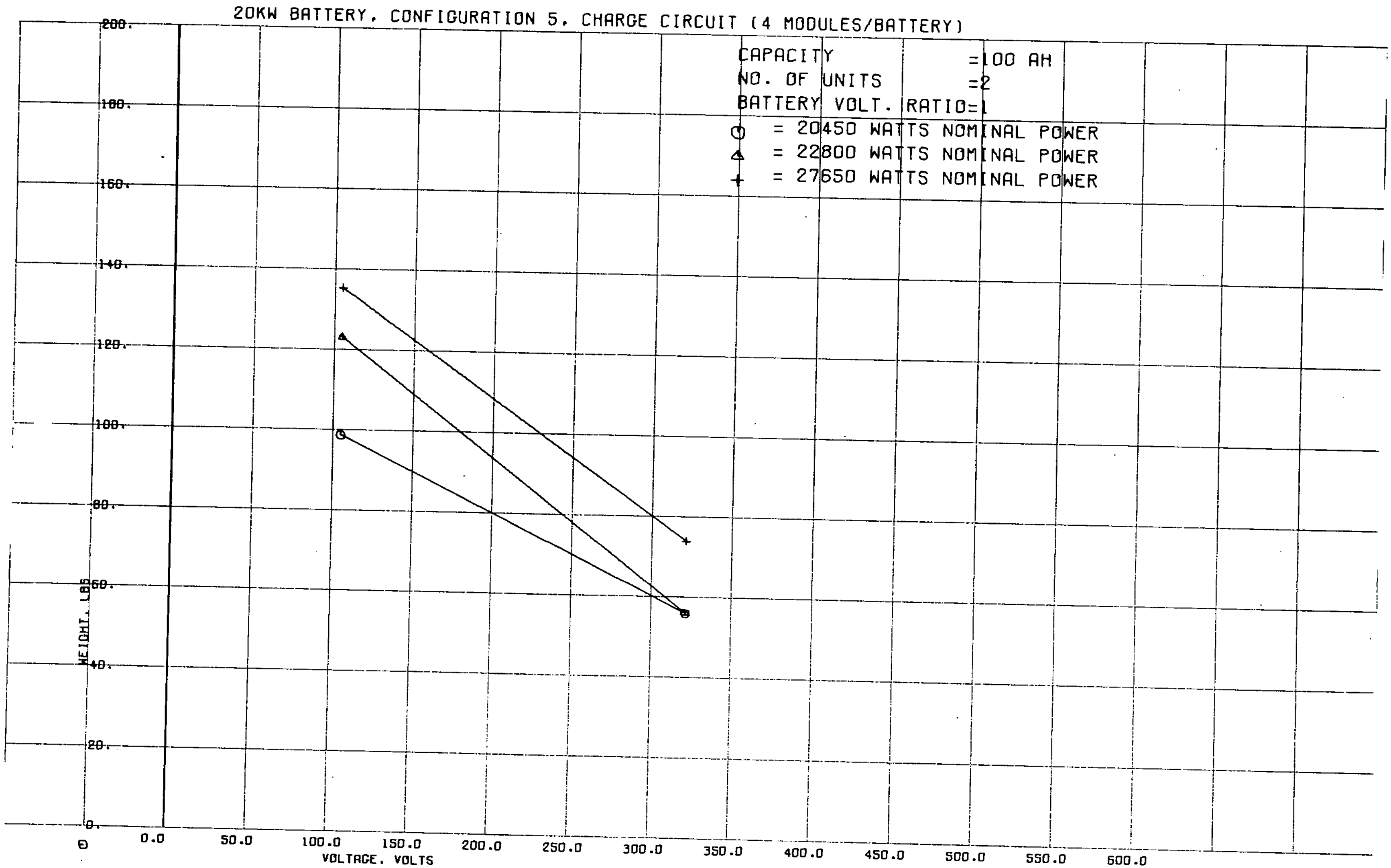
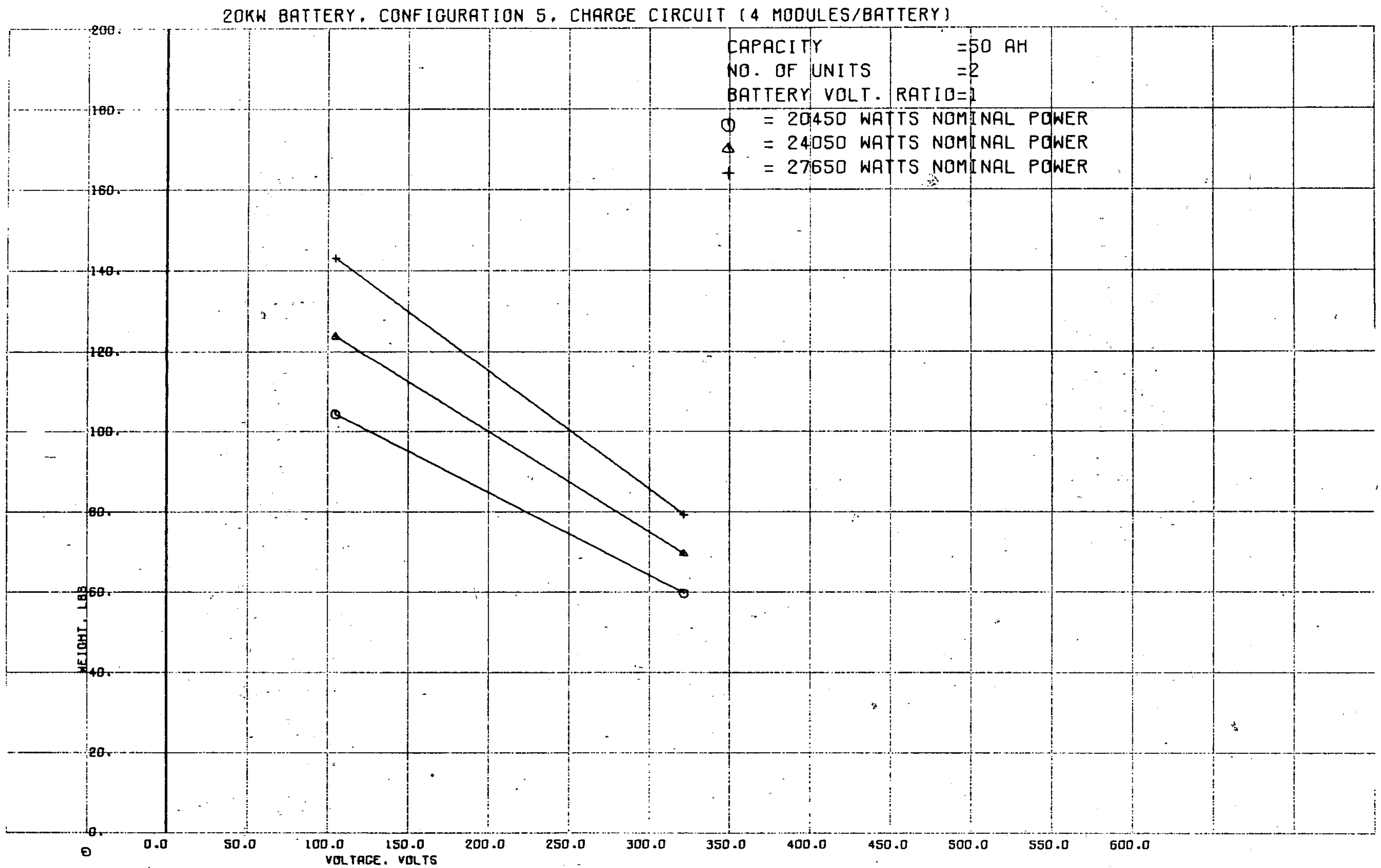
500.0
550.0
600.0

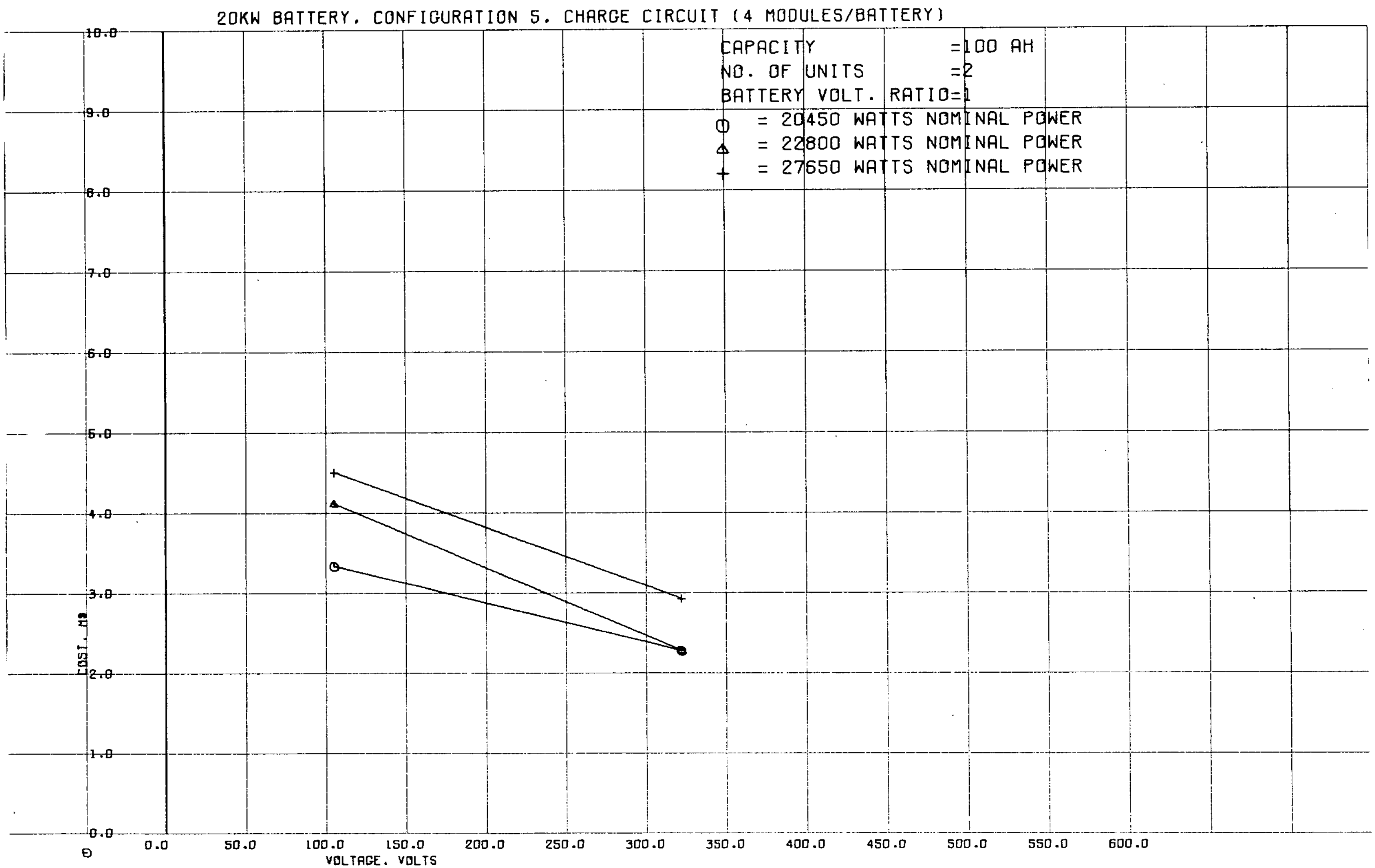

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 20800 WATTS NOMINAL POWER
Δ = 22000 WATTS NOMINAL POWER
+ = 28100 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

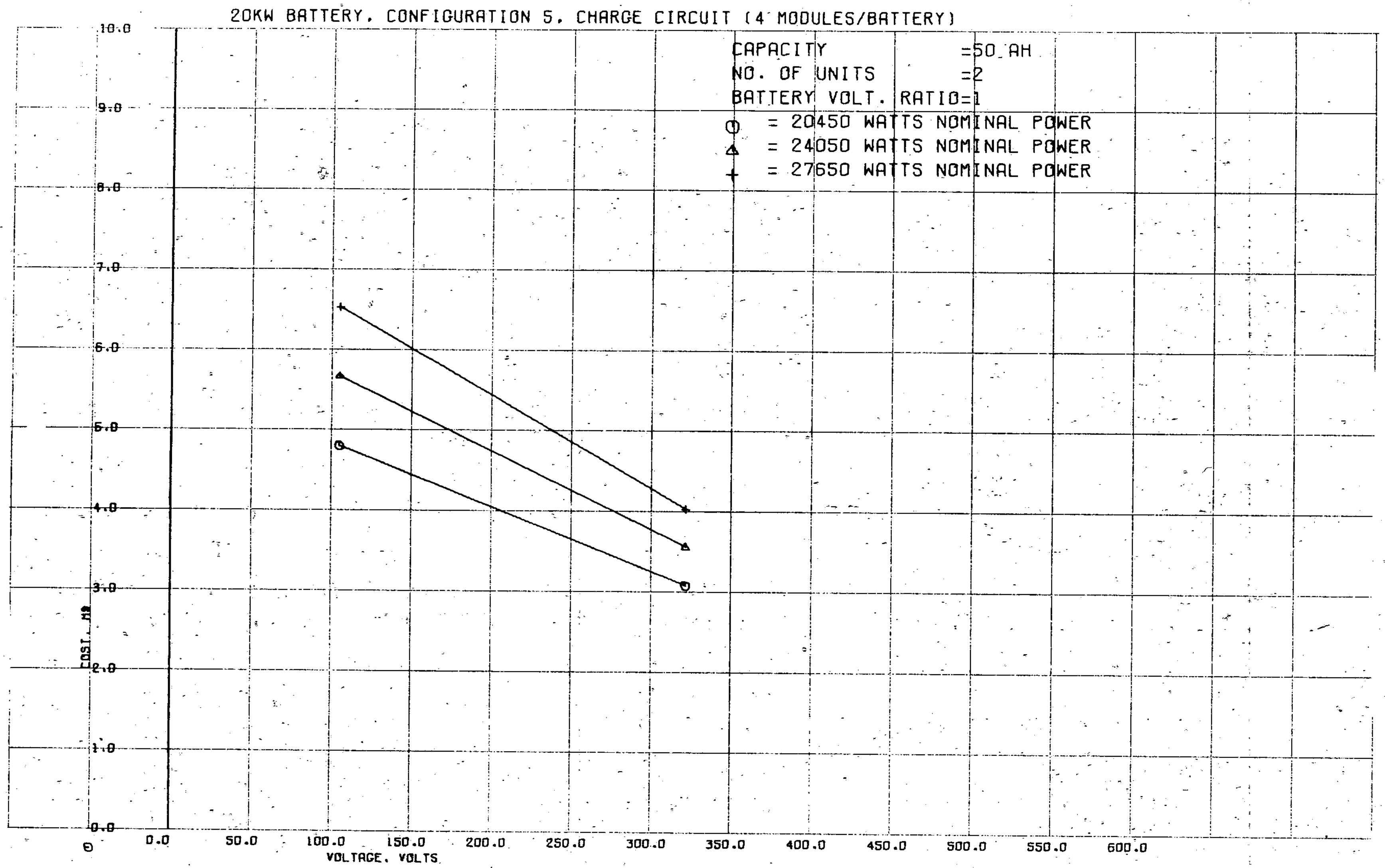

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
O = 18350 WATTS NOMINAL POWER
△ = 22000 WATTS NOMINAL POWER
+ = 25700 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



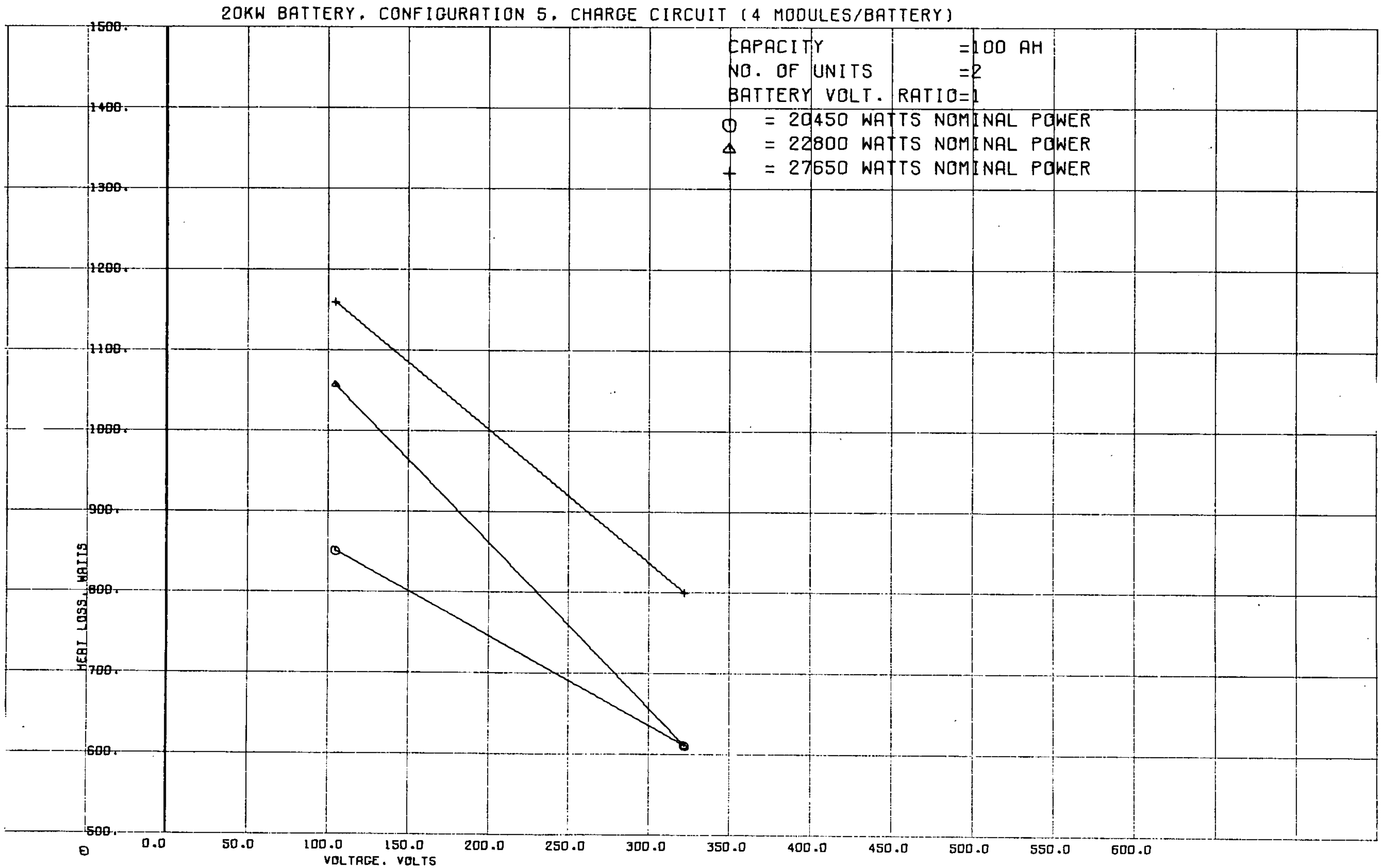
20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20450 WATTS NOMINAL POWER
= 22800 WATTS NOMINAL POWER
= 27650 WATTS NOMINAL POWER
WEIGHT, LBS
200.
180.
160.
140.
120.
100.
80.
60.
40.
20.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

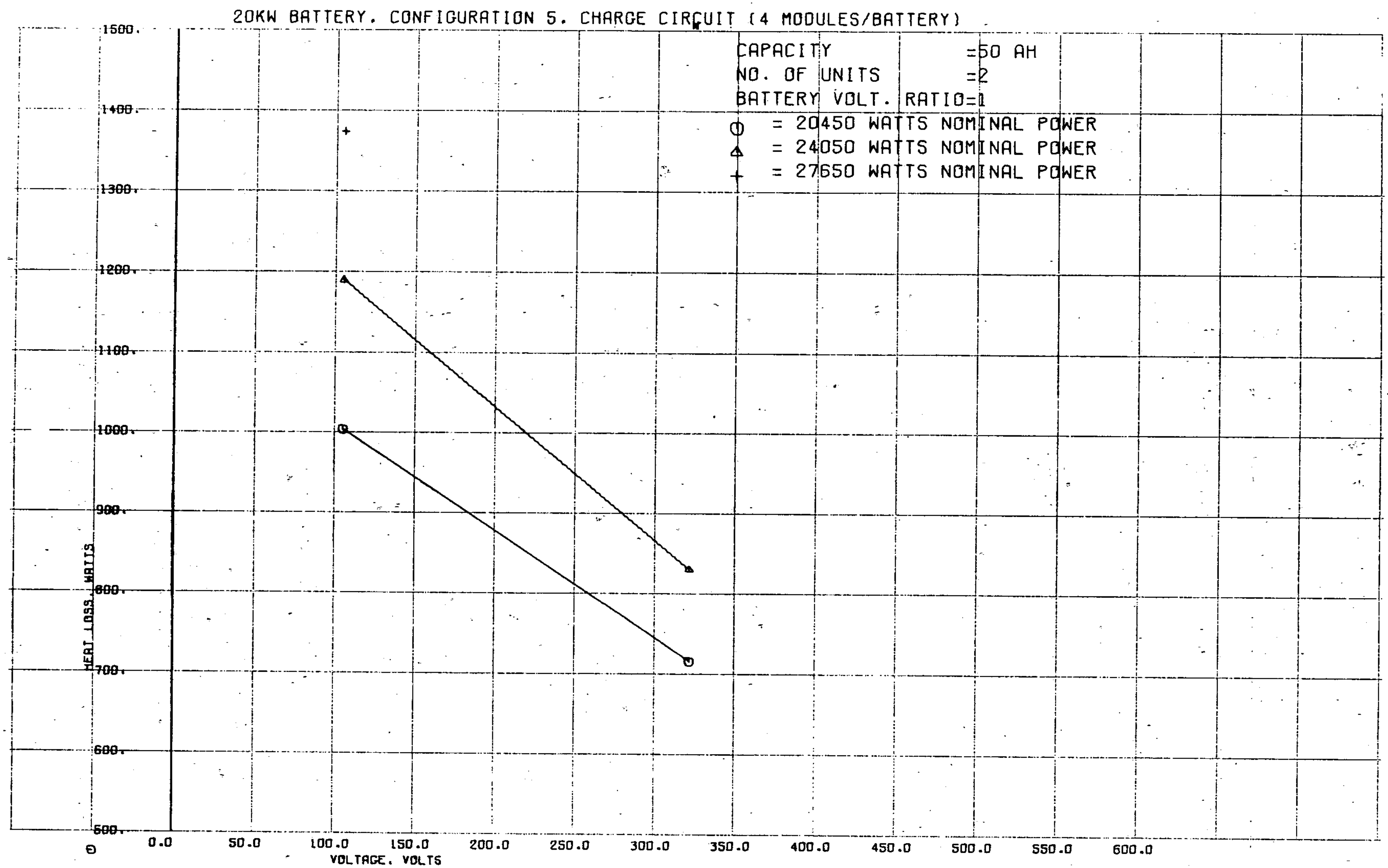

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20450 WATTS NOMINAL POWER
△ = 24050 WATTS NOMINAL POWER
+ = 27650 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 5. CHARGE CIRCUIT (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20450 WATTS NOMINAL POWER
= 22800 WATTS NOMINAL POWER
= 27650 WATTS NOMINAL POWER
COST, M$
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

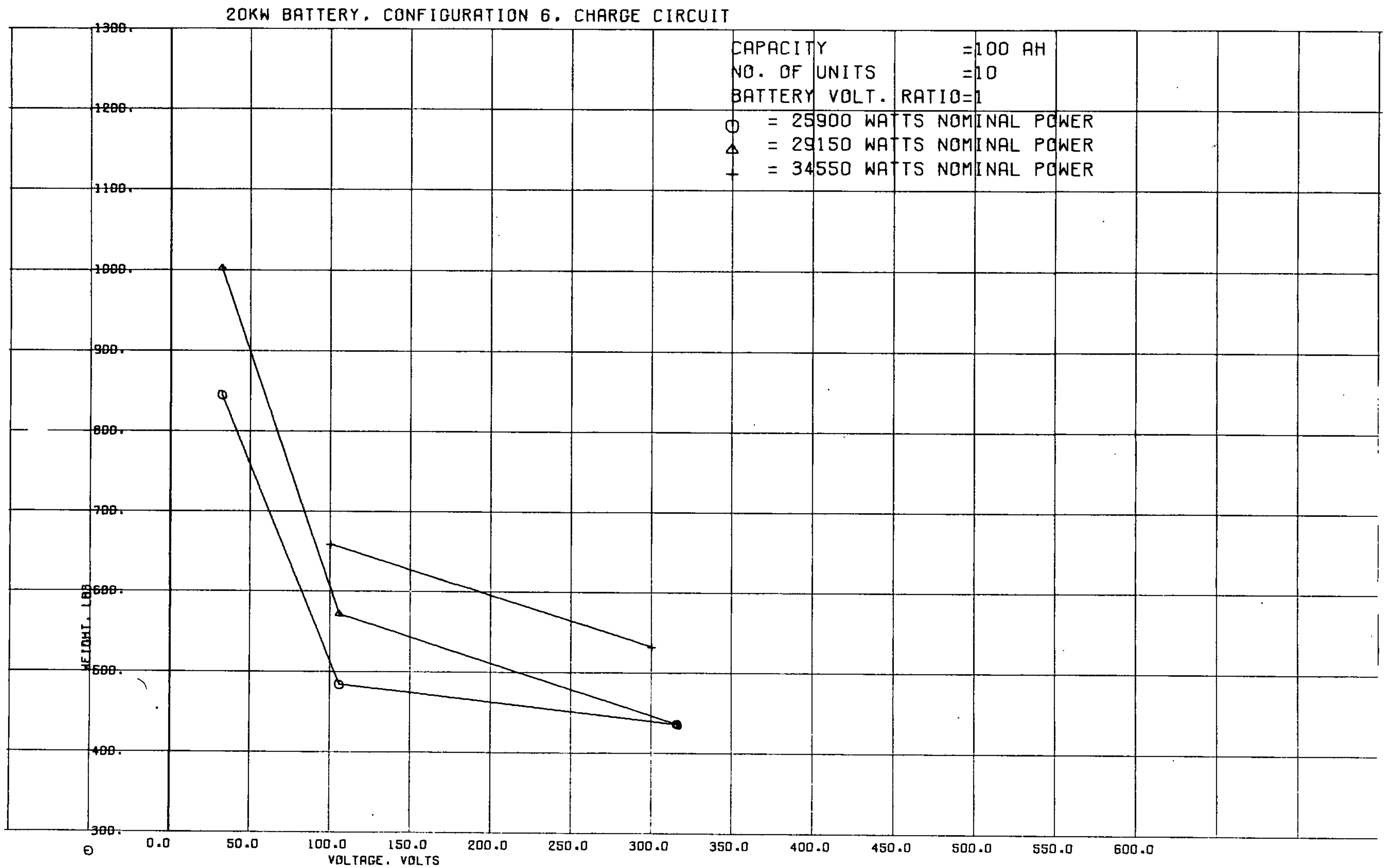


20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
○ = 20450 WATTS NOMINAL POWER
△ = 24050 WATTS NOMINAL POWER
+ = 27650 WATTS NOMINAL POWER
COST, M$
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

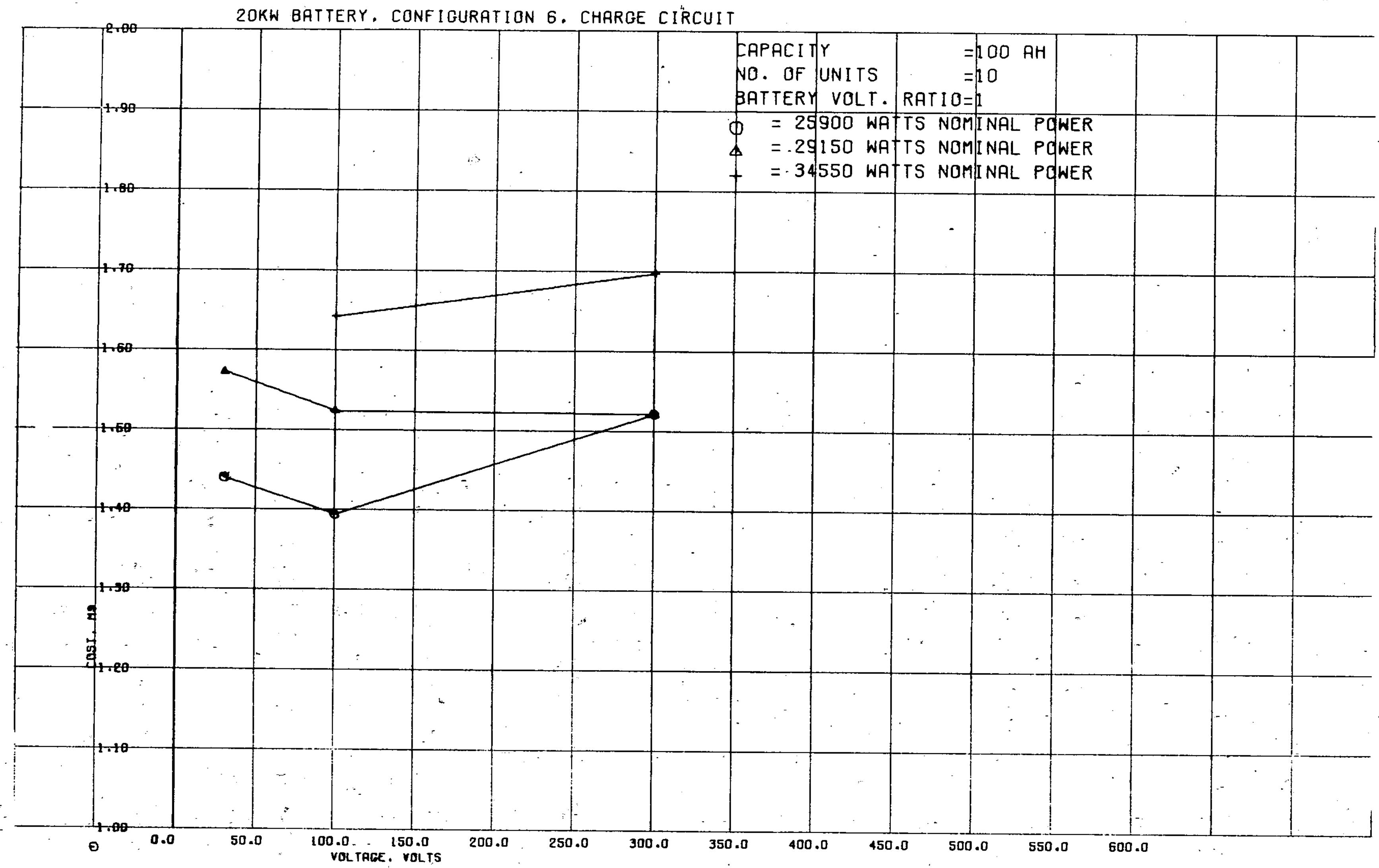

20KW BATTERY, CONFIGURATION 5, CHARGE CIRCUIT (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20450 WATTS NOMINAL POWER
= 22800 WATTS NOMINAL POWER
= 27650 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

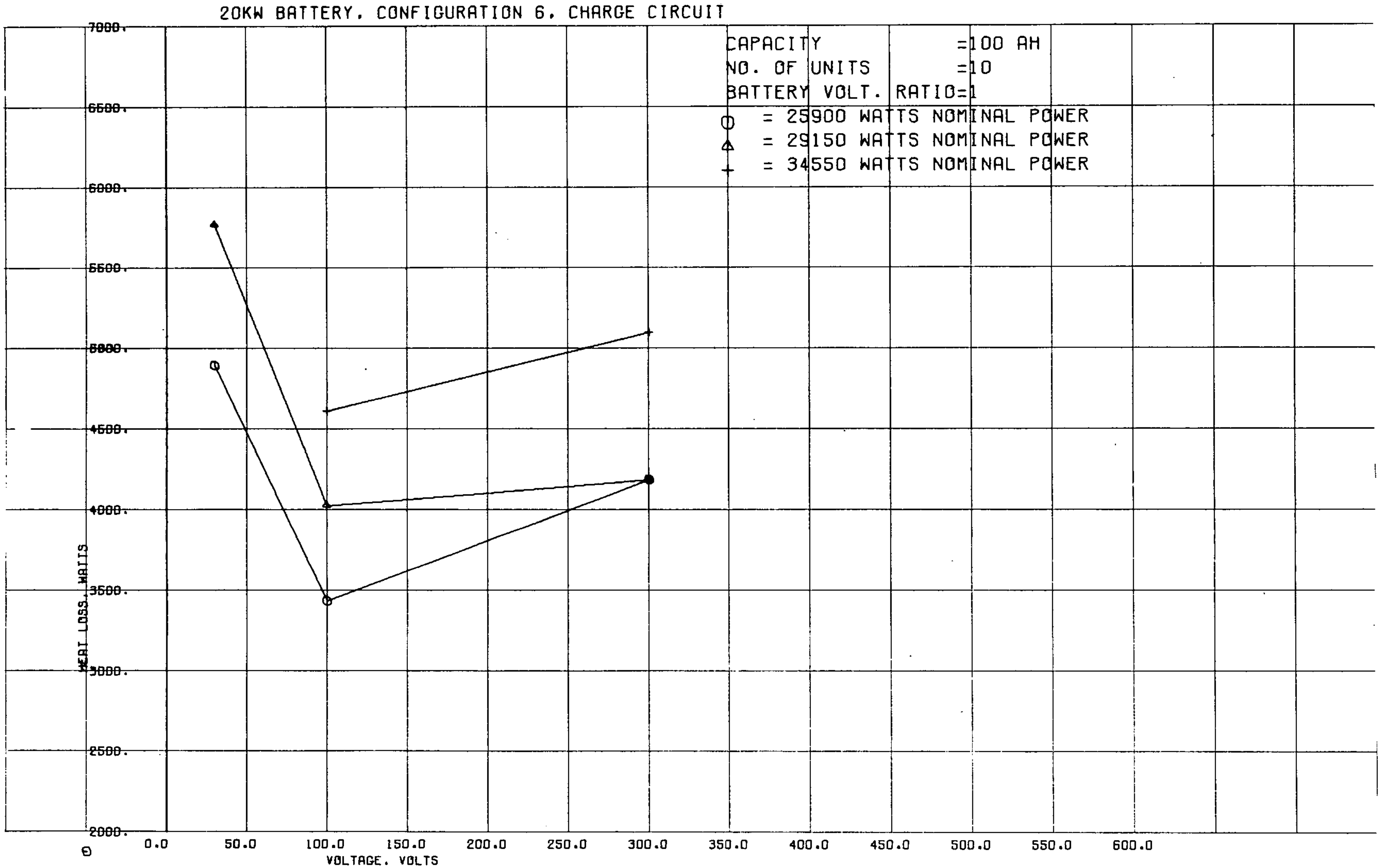


20KW BATTERY. CONFIGURATION 5. CHARGE CIRCUIT (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =2
BATTERY VOLT. RATIO=1
= 20450 WATTS NOMINAL POWER
= 24050 WATTS NOMINAL POWER
= 27650 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

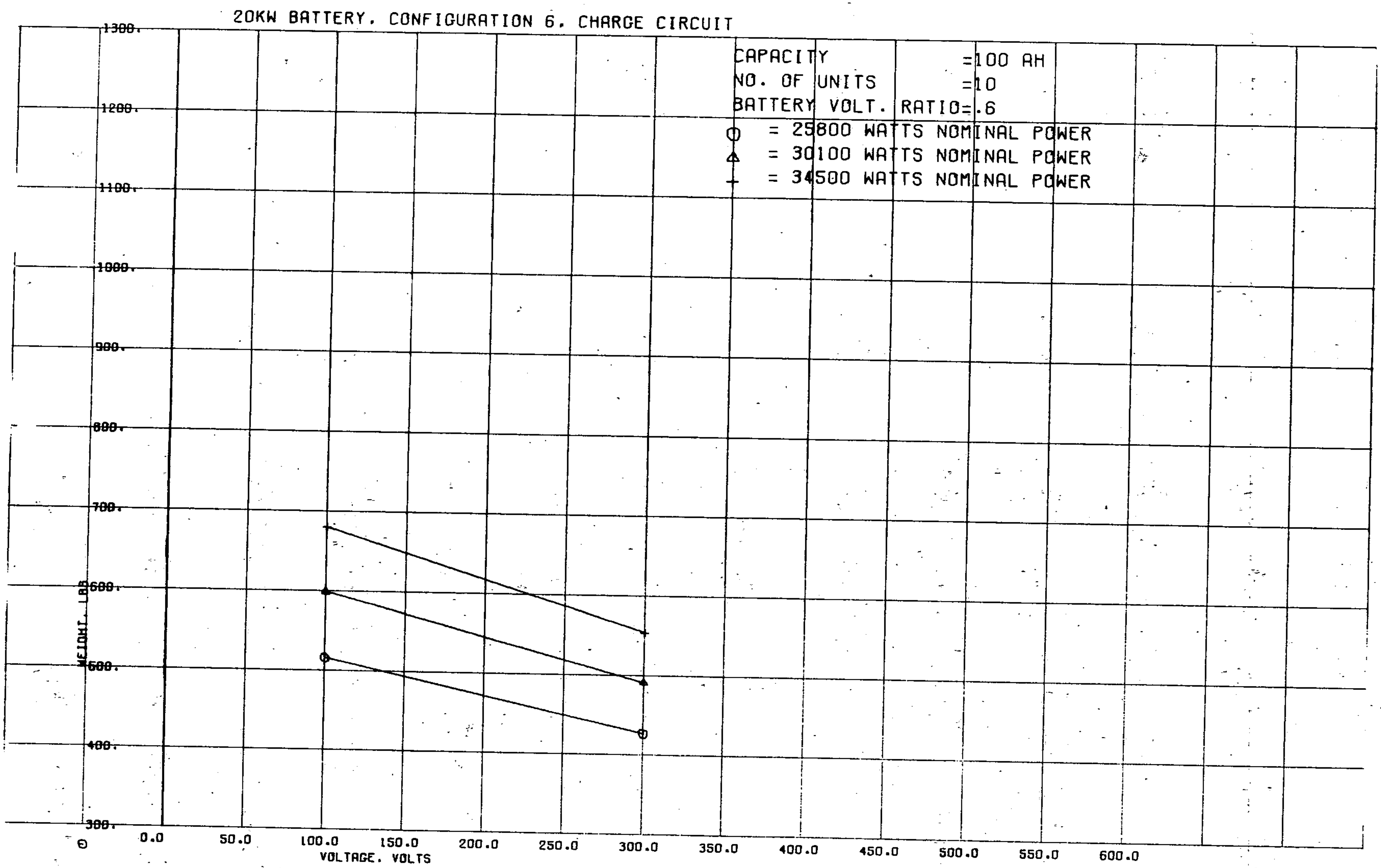


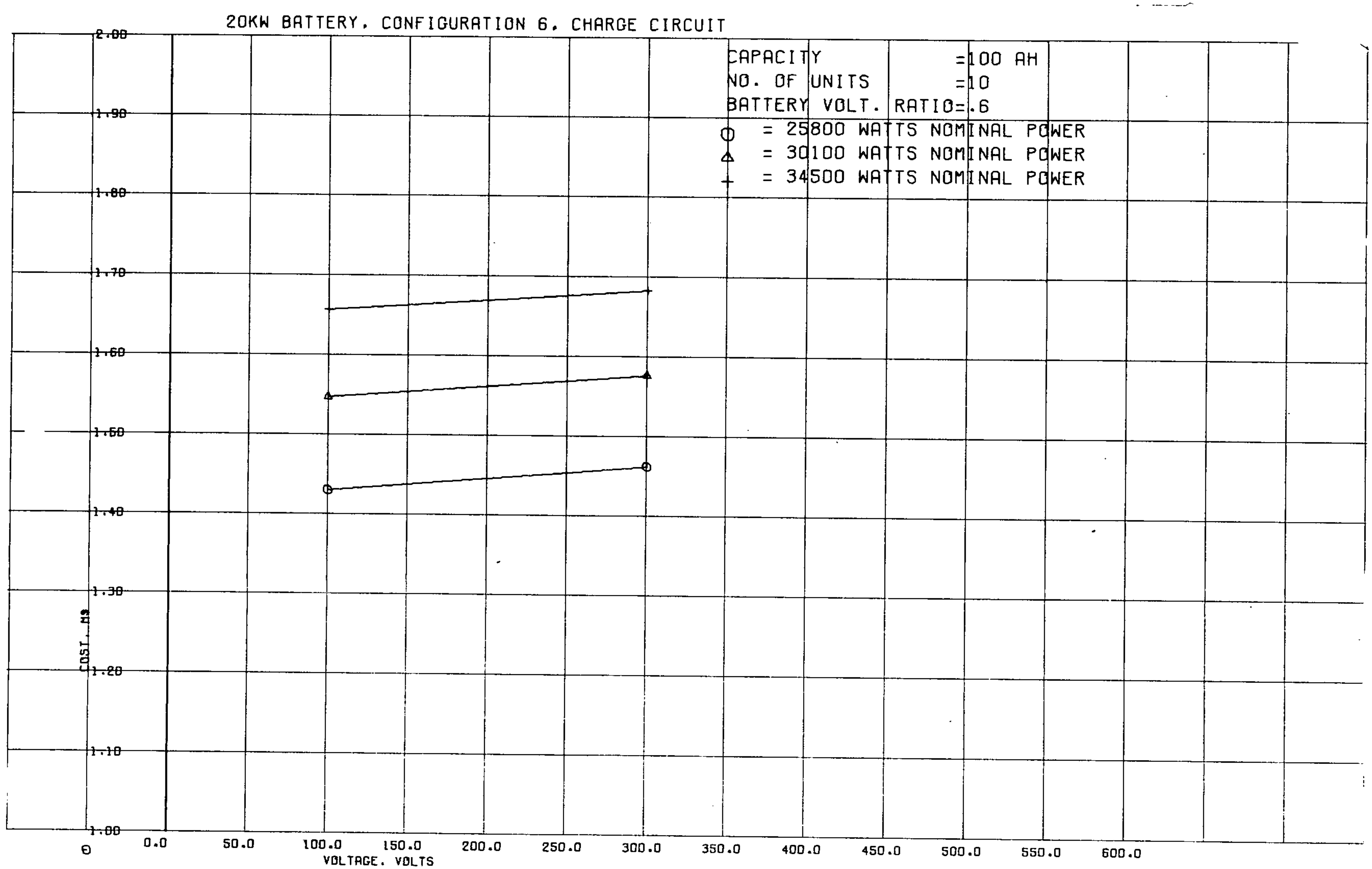
20KW BATTERY, CONFIGURATION 6, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 25900 WATTS NOMINAL POWER
= 29150 WATTS NOMINAL POWER
= 34550 WATTS NOMINAL POWER
WEIGHT, LBS
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
400.
300.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

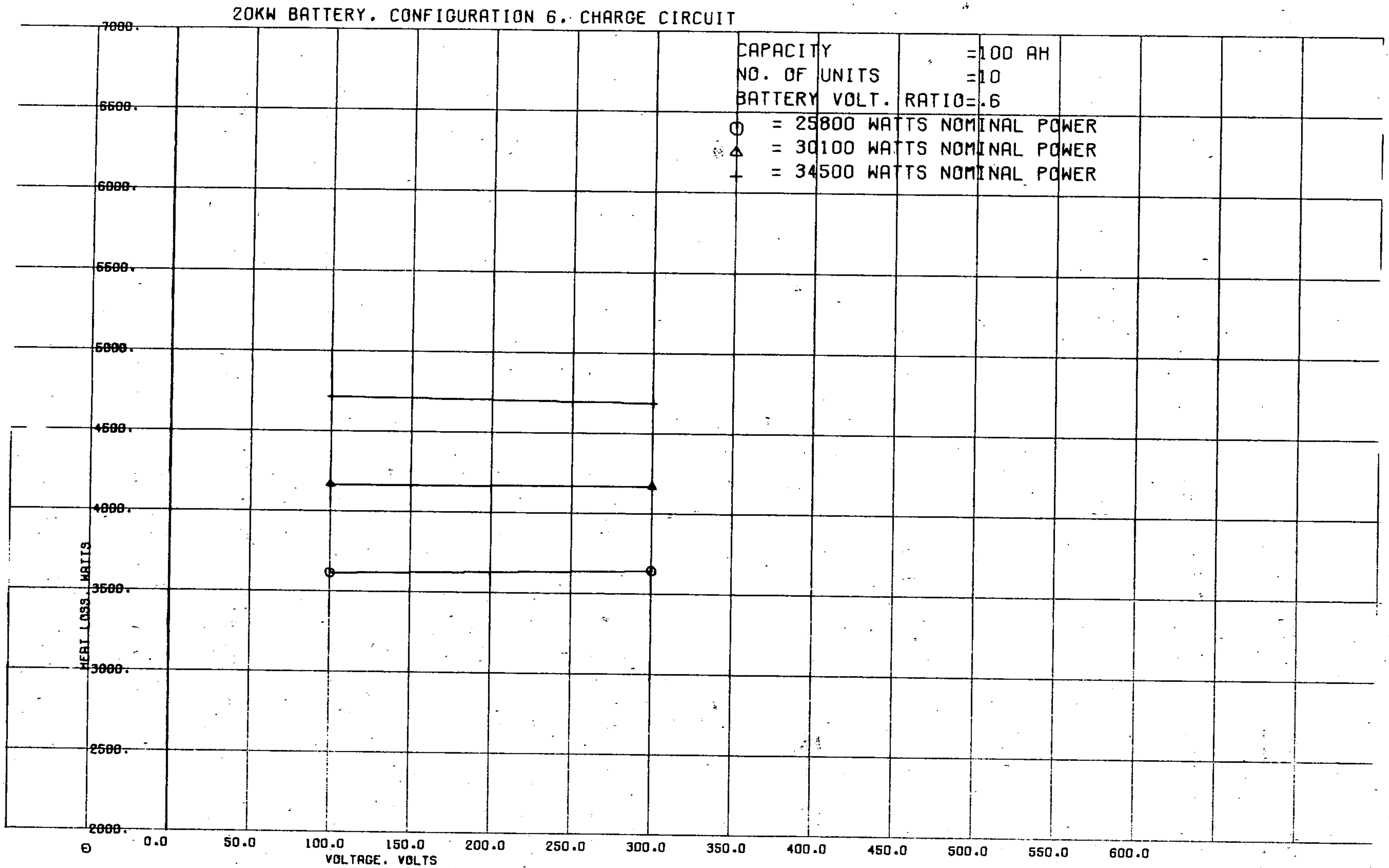

20KW BATTERY, CONFIGURATION 6, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
O = 25900 WATTS NOMINAL POWER
△ = 29150 WATTS NOMINAL POWER
+ = 34550 WATTS NOMINAL POWER
COST, M$
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY, CONFIGURATION 6, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
○ = 25900 WATTS NOMINAL POWER
△ = 29150 WATTS NOMINAL POWER
+ = 34550 WATTS NOMINAL POWER
HEAT LOSS, WATTS
7000.
6500.
6000.
5500.
5000.
4500.
4000.
3500.
3000.
2500.
2000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
O = 25800 WATTS NOMINAL POWER
Δ = 30100 WATTS NOMINAL POWER
+ = 34500 WATTS NOMINAL POWER
WEIGHT, LBS
1300.
1200.
1100.
1000.
900.
800.
700.
600.
500.
400.
300.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25800 WATTS NOMINAL POWER
= 30100 WATTS NOMINAL POWER
= 34500 WATTS NOMINAL POWER
COST, M$
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY. CONFIGURATION 6. CHARGE CIRCUIT
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 25800 WATTS NOMINAL POWER
= 30100 WATTS NOMINAL POWER
= 34500 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
7000.
6500.
6000.
5500.
5000.
4500.
4000.
3500.
3000.
2500.
2000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

NO POWER PROCESSOR

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NO POWER PROCESSOR

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NO POWER PROCESSOR

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NO POWER PROCESSOR

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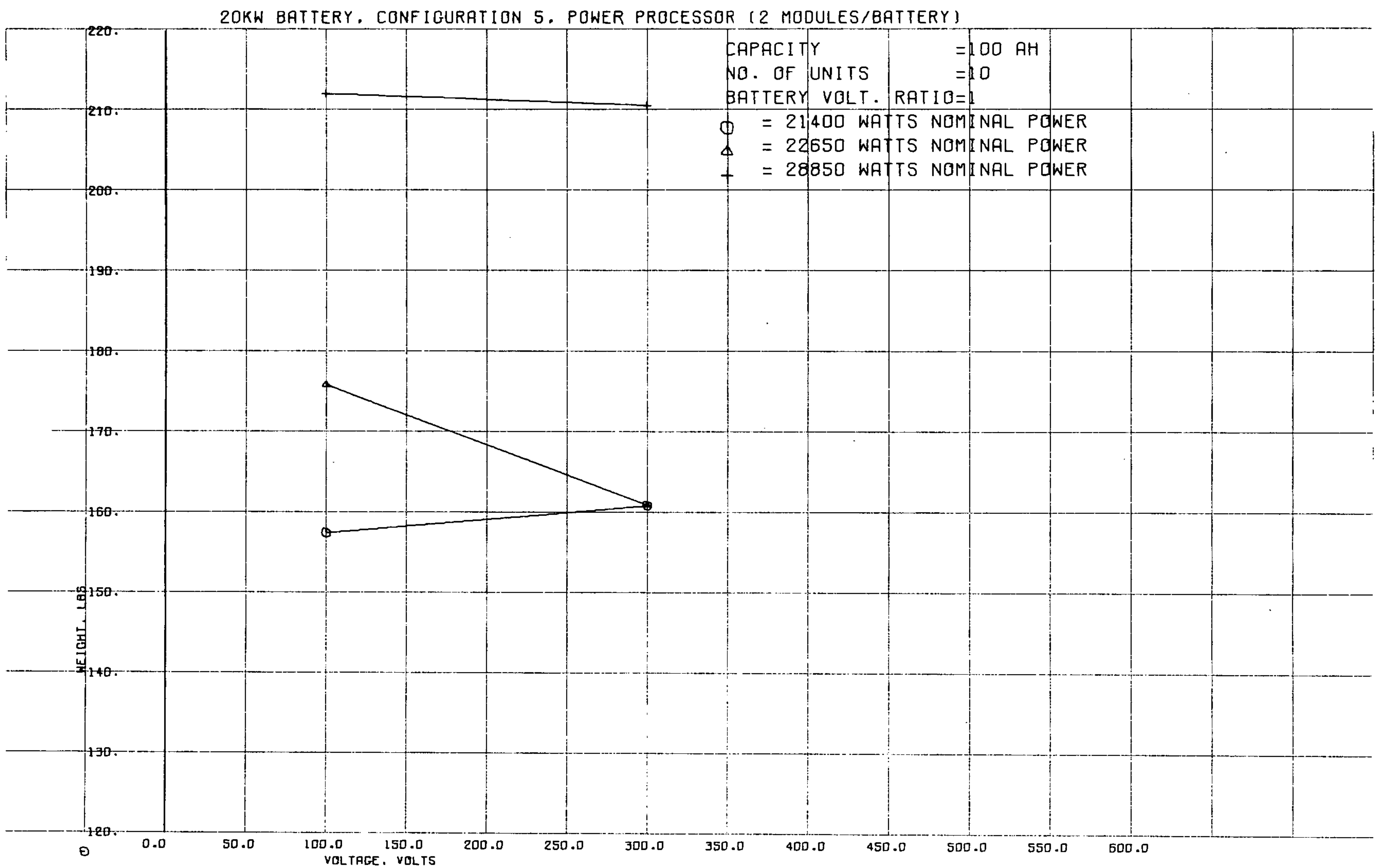

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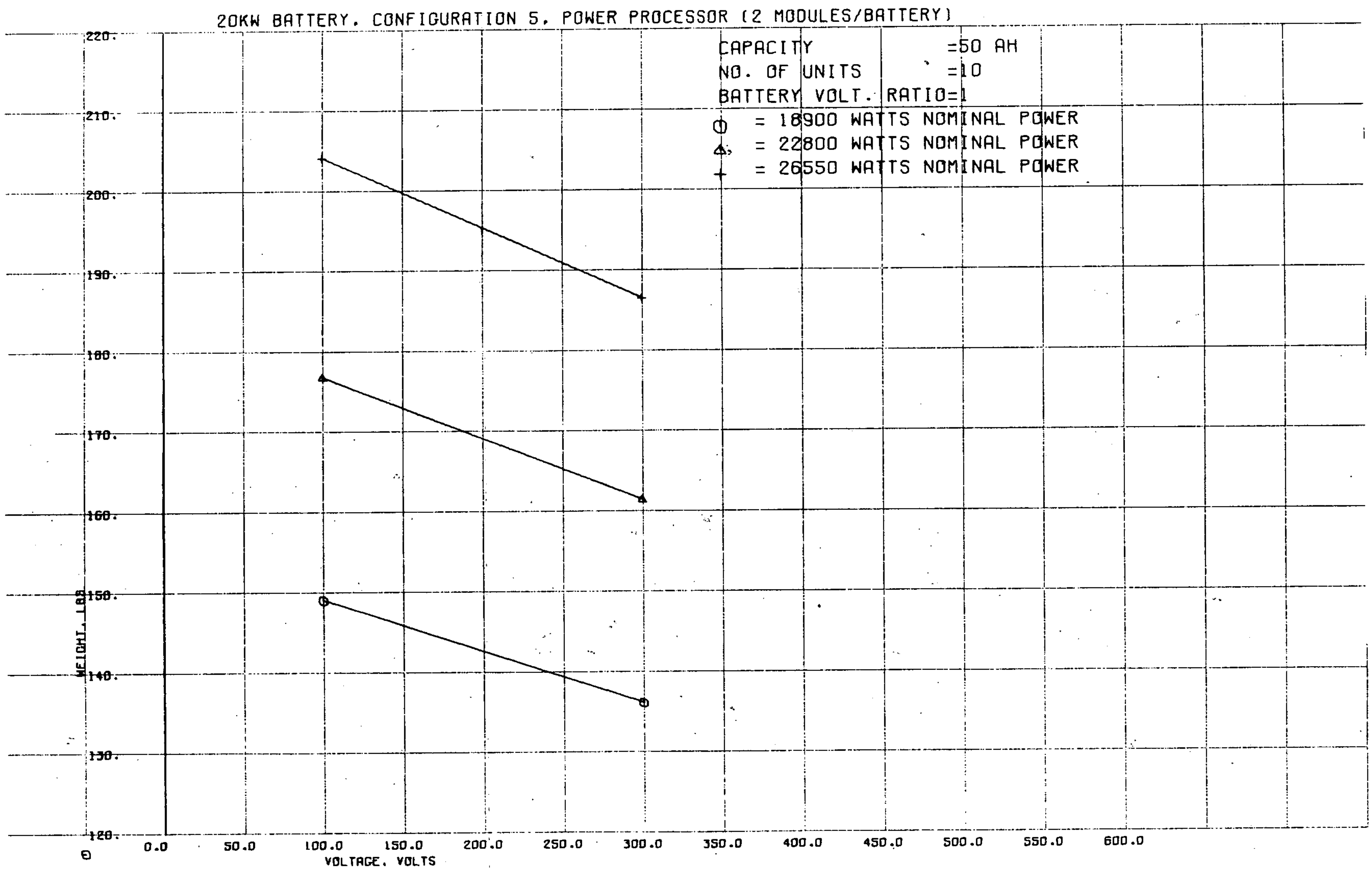
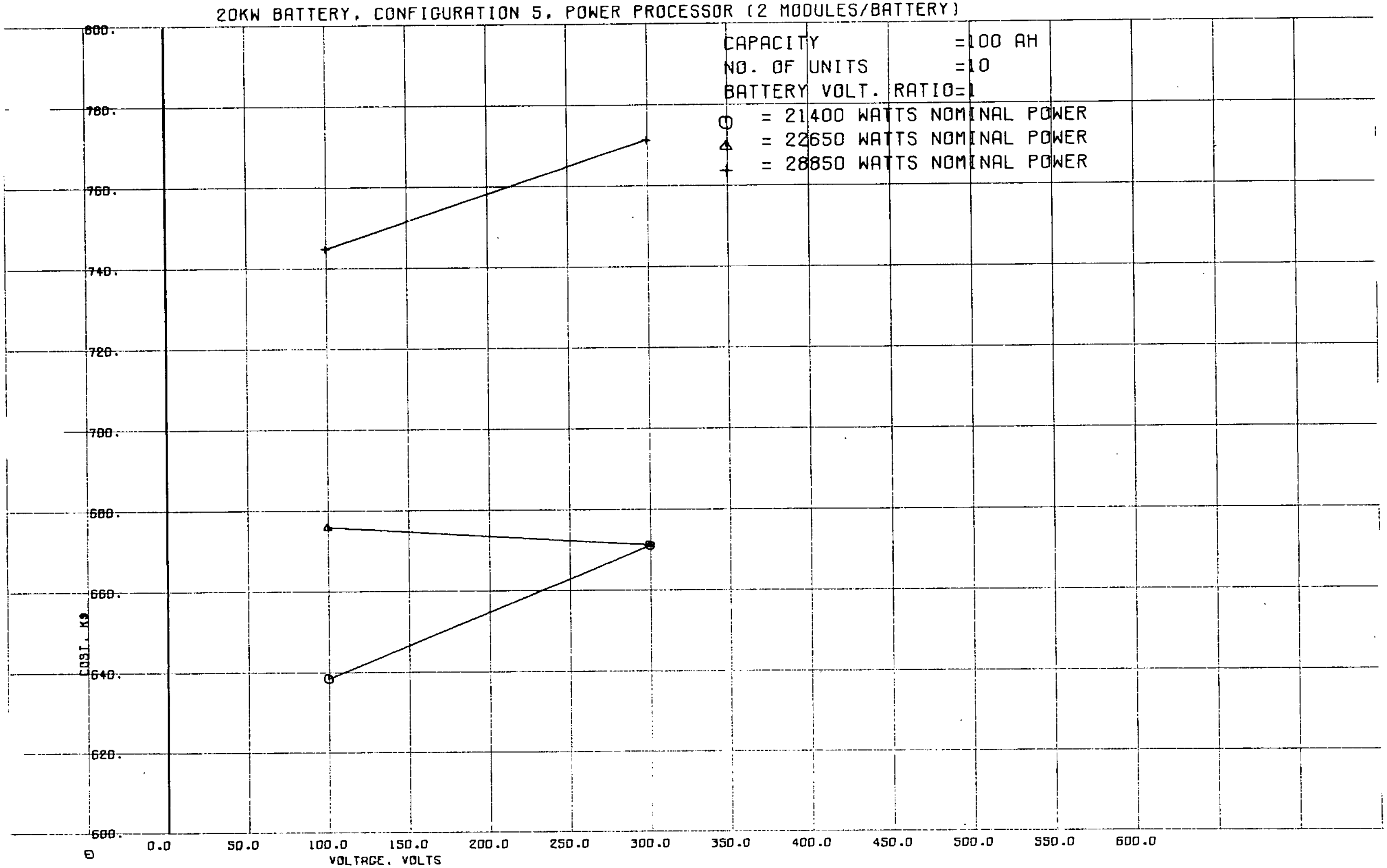
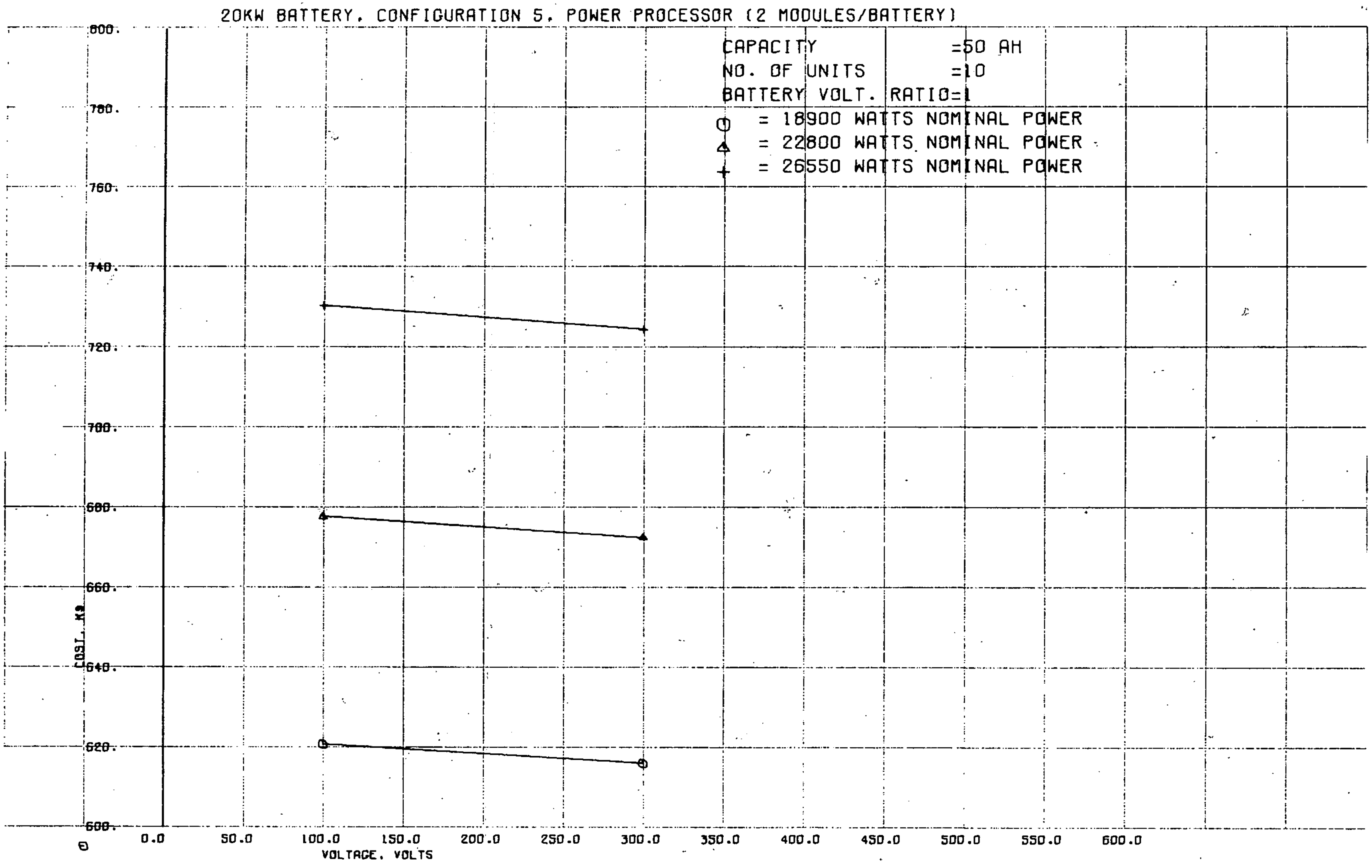

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 18900 WATTS NOMINAL POWER
= 22800 WATTS NOMINAL POWER
= 26550 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
220.
210.
200.
190.
180.
170.
160.
150.
140.
130.
120.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

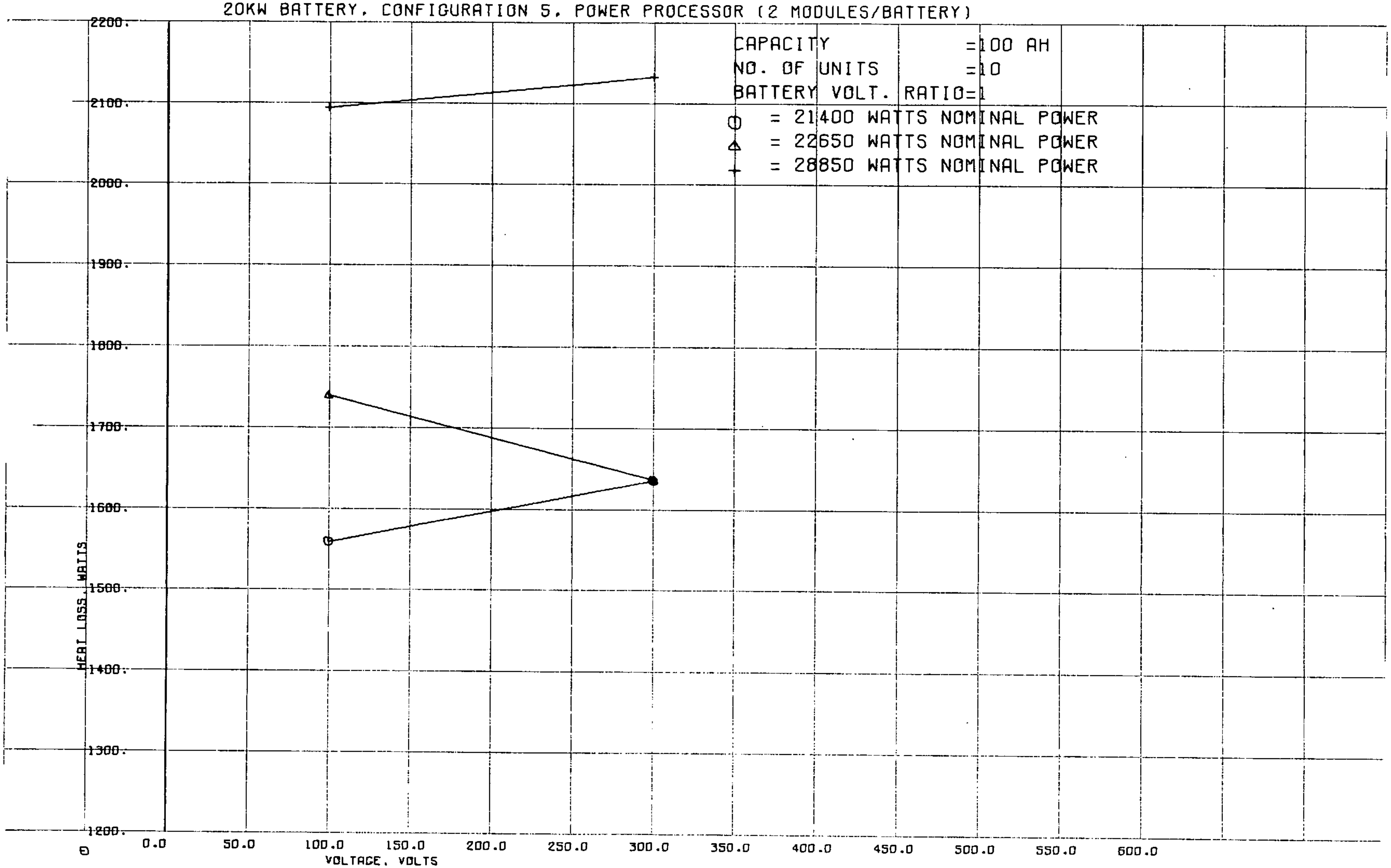
20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (2 MODULES/BATTERY)

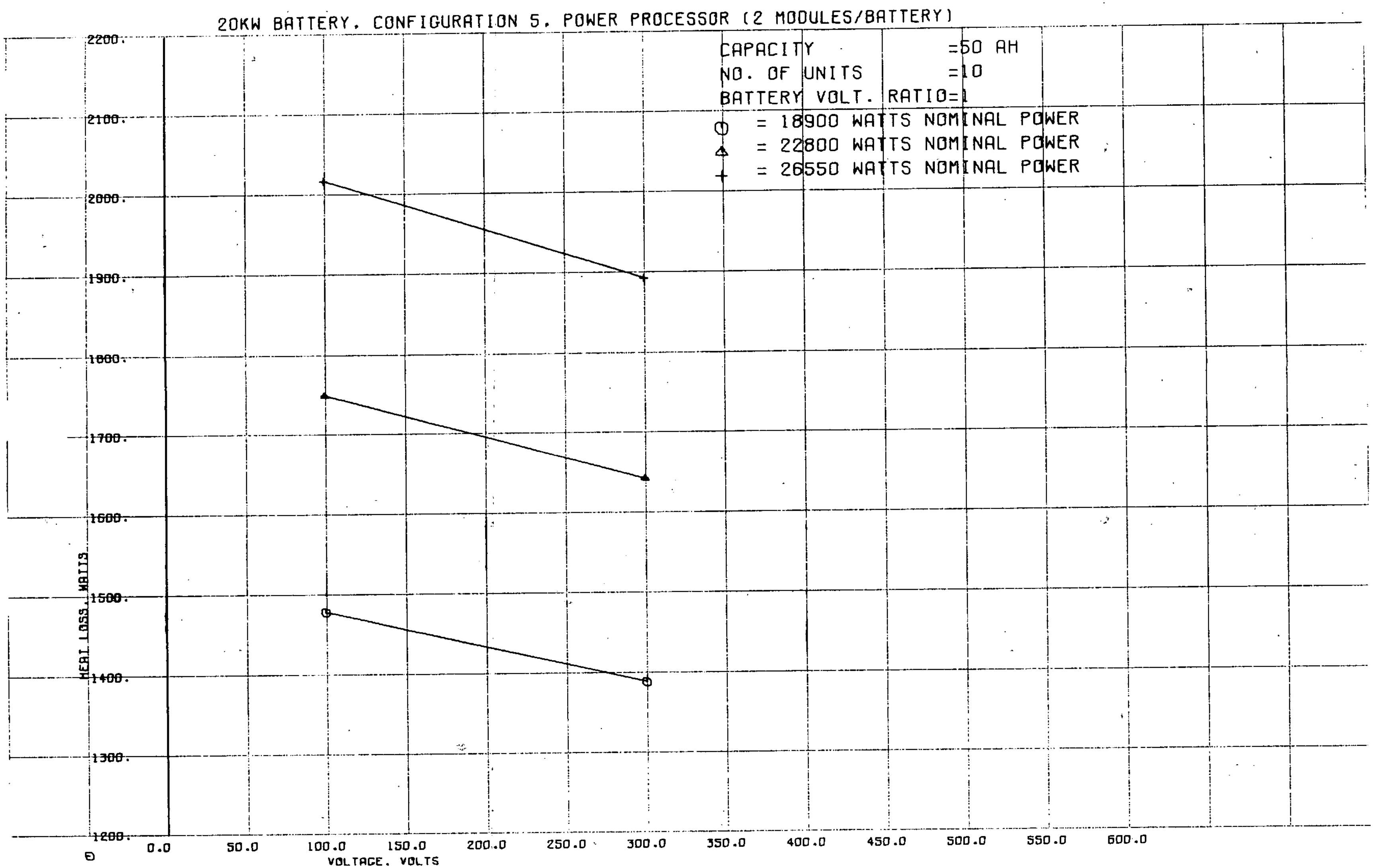


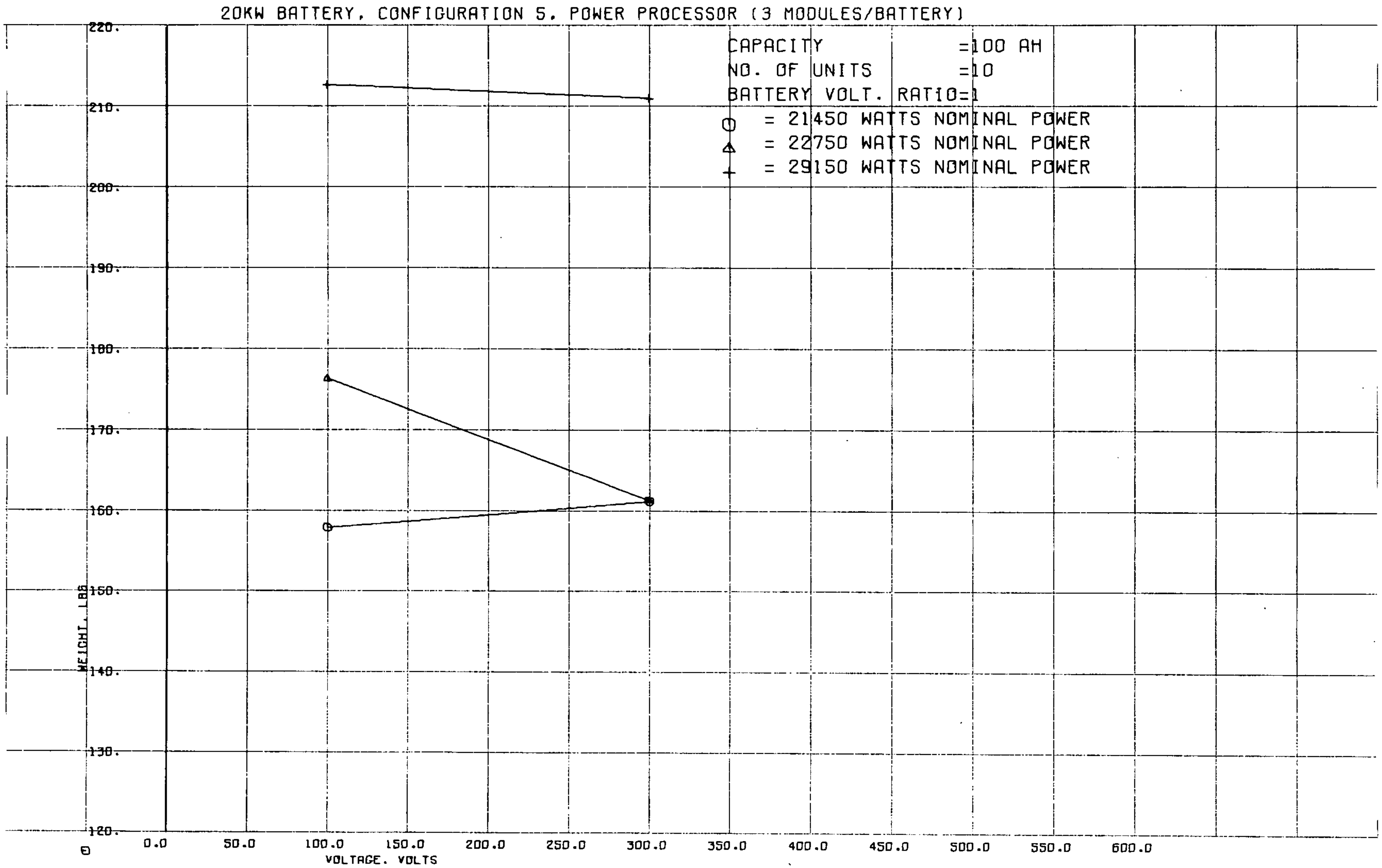


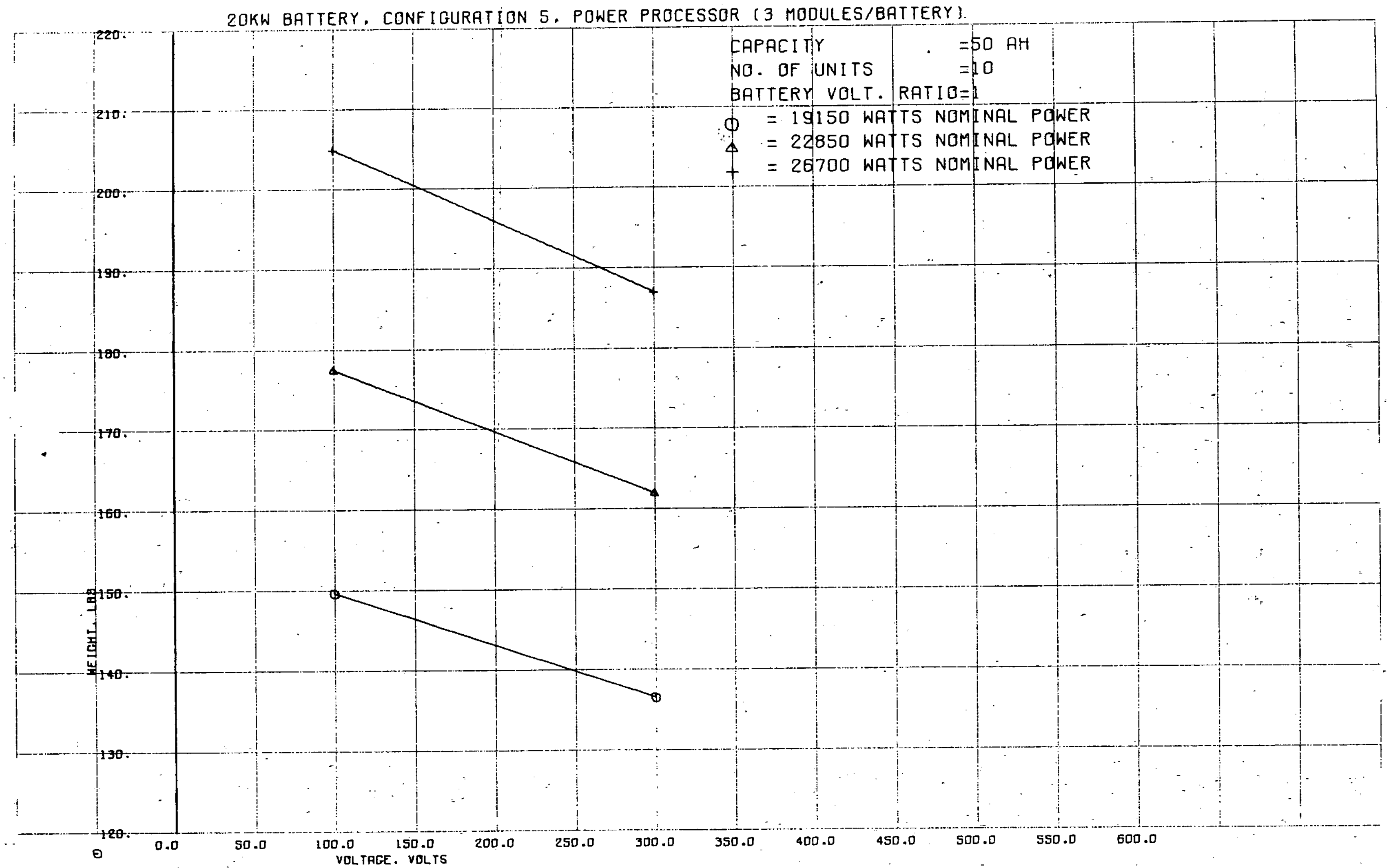
20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 18900 WATTS NOMINAL POWER
= 22800 WATTS NOMINAL POWER
= 26550 WATTS NOMINAL POWER
COST, K$
800.
780.
760.
740.
720.
700.
680.
660.
640.
620.
600.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (2 MODULES/BATTERY)

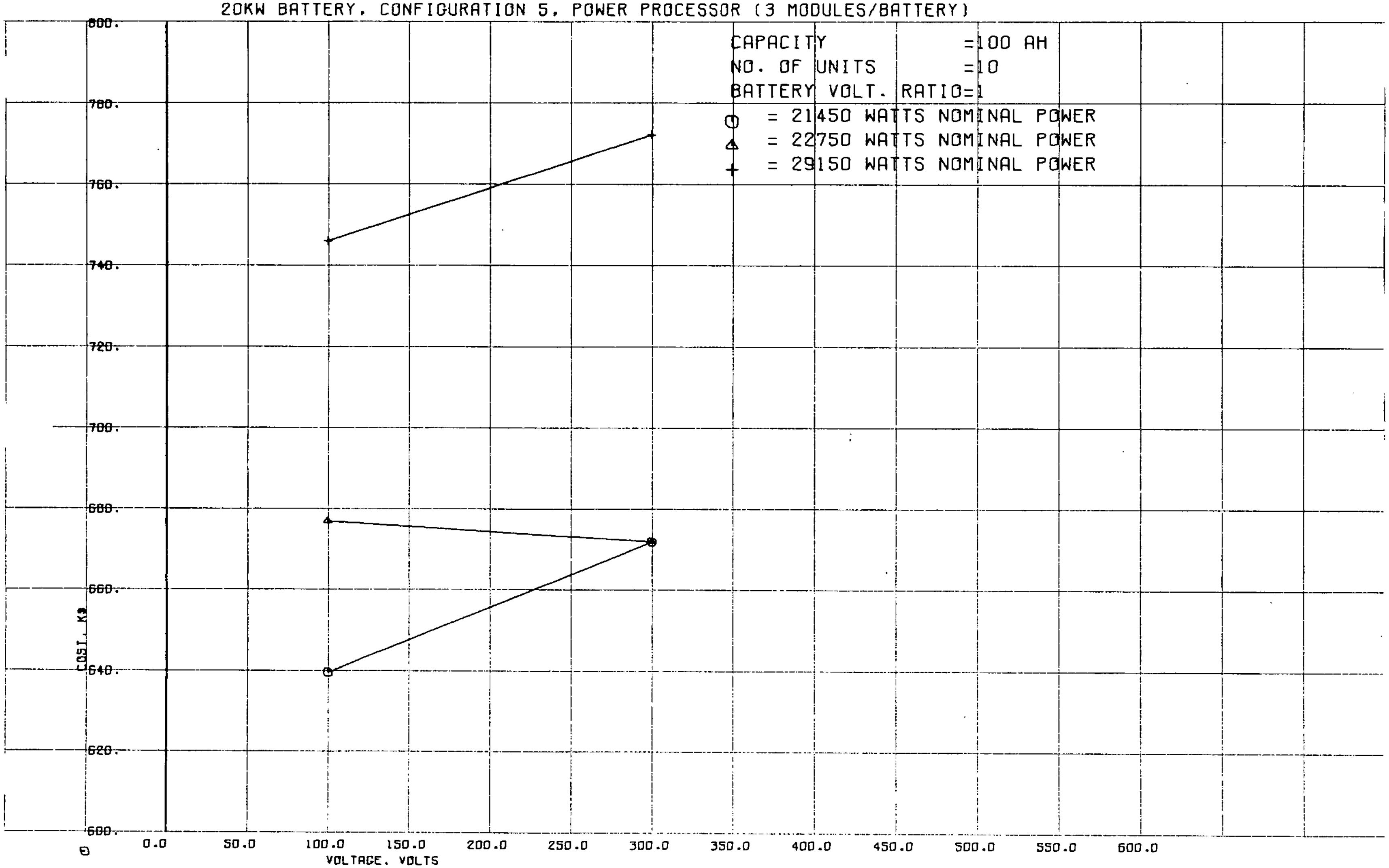


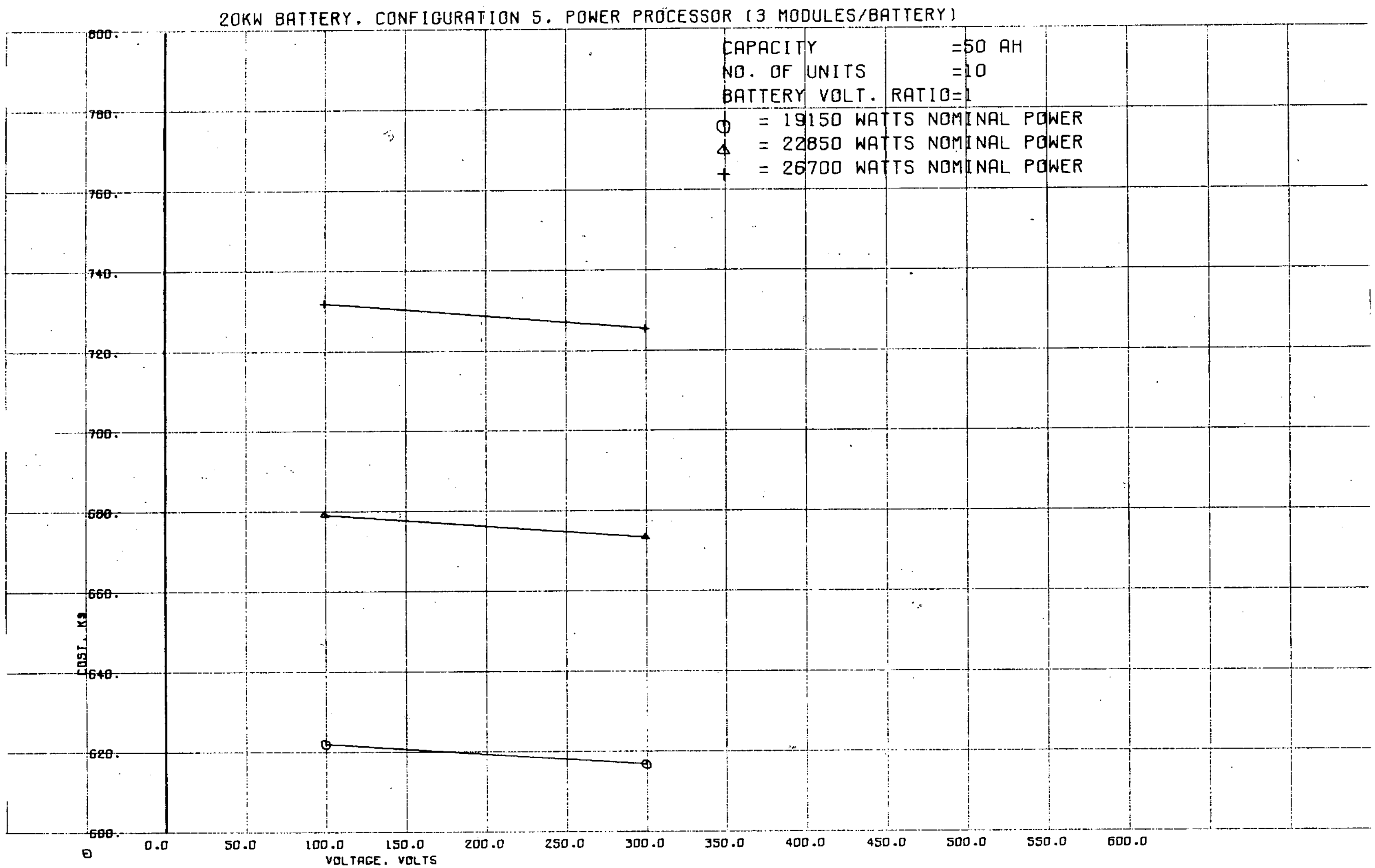

20KW BATTERY. CONFIGURATION 5. POWER PROCESSOR (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
○ = 18900 WATTS NOMINAL POWER
△ = 22800 WATTS NOMINAL POWER
+ = 26550 WATTS NOMINAL POWER
HEAT LOSS, WATTS
2200.
2100.
2000.
1900.
1800.
1700.
1600.
1500.
1400.
1300.
1200.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21450 WATTS NOMINAL POWER
= 22750 WATTS NOMINAL POWER
= 29150 WATTS NOMINAL POWER
WEIGHT, LBS
220.
210.
200.
190.
180.
170.
160.
150.
140.
130.
120.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

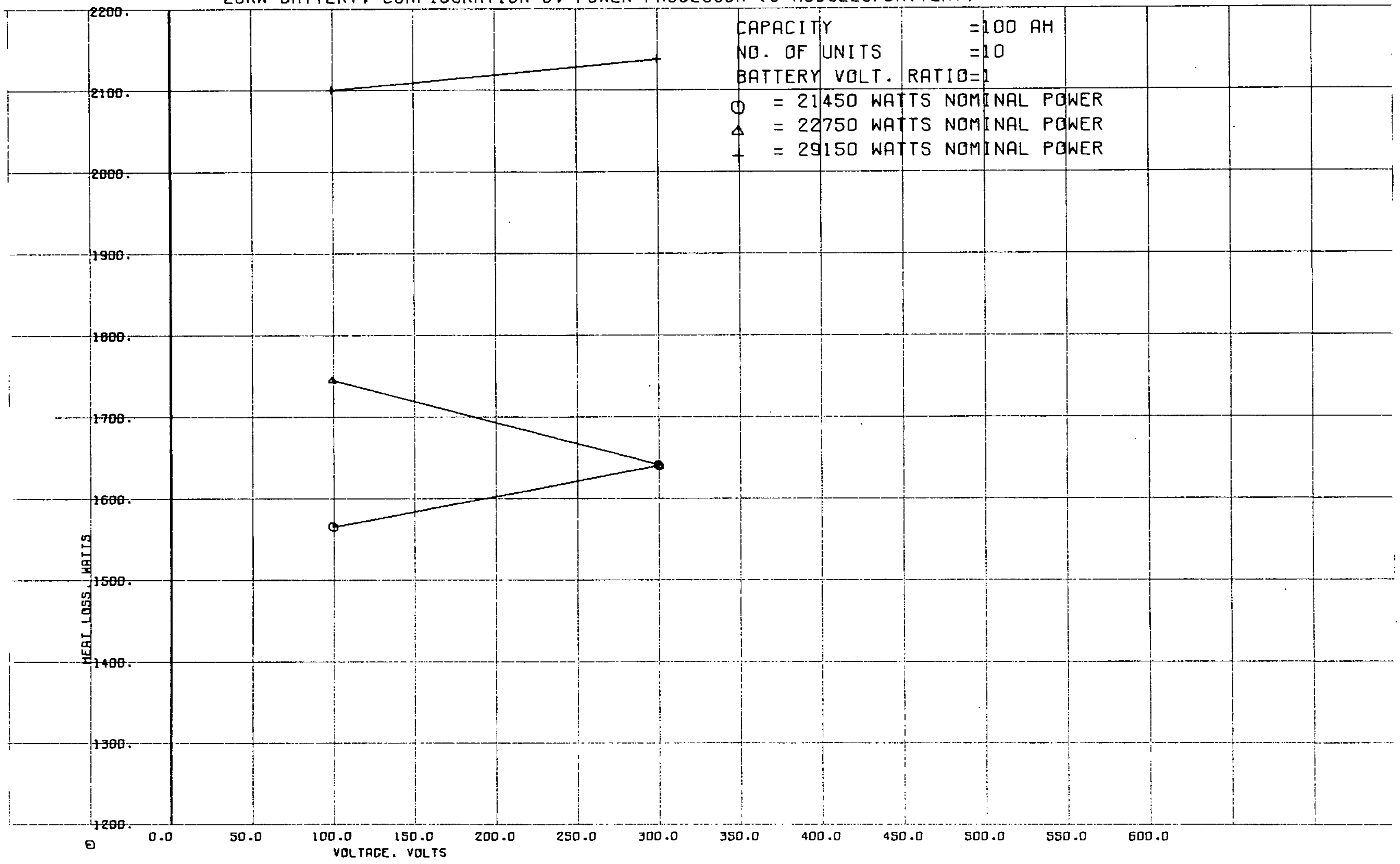

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
O = 19150 WATTS NOMINAL POWER
Δ = 22850 WATTS NOMINAL POWER
+ = 26700 WATTS NOMINAL POWER
WEIGHT, LBS
220.
210.
200.
190.
180.
170.
160.
150.
140.
130.
120.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

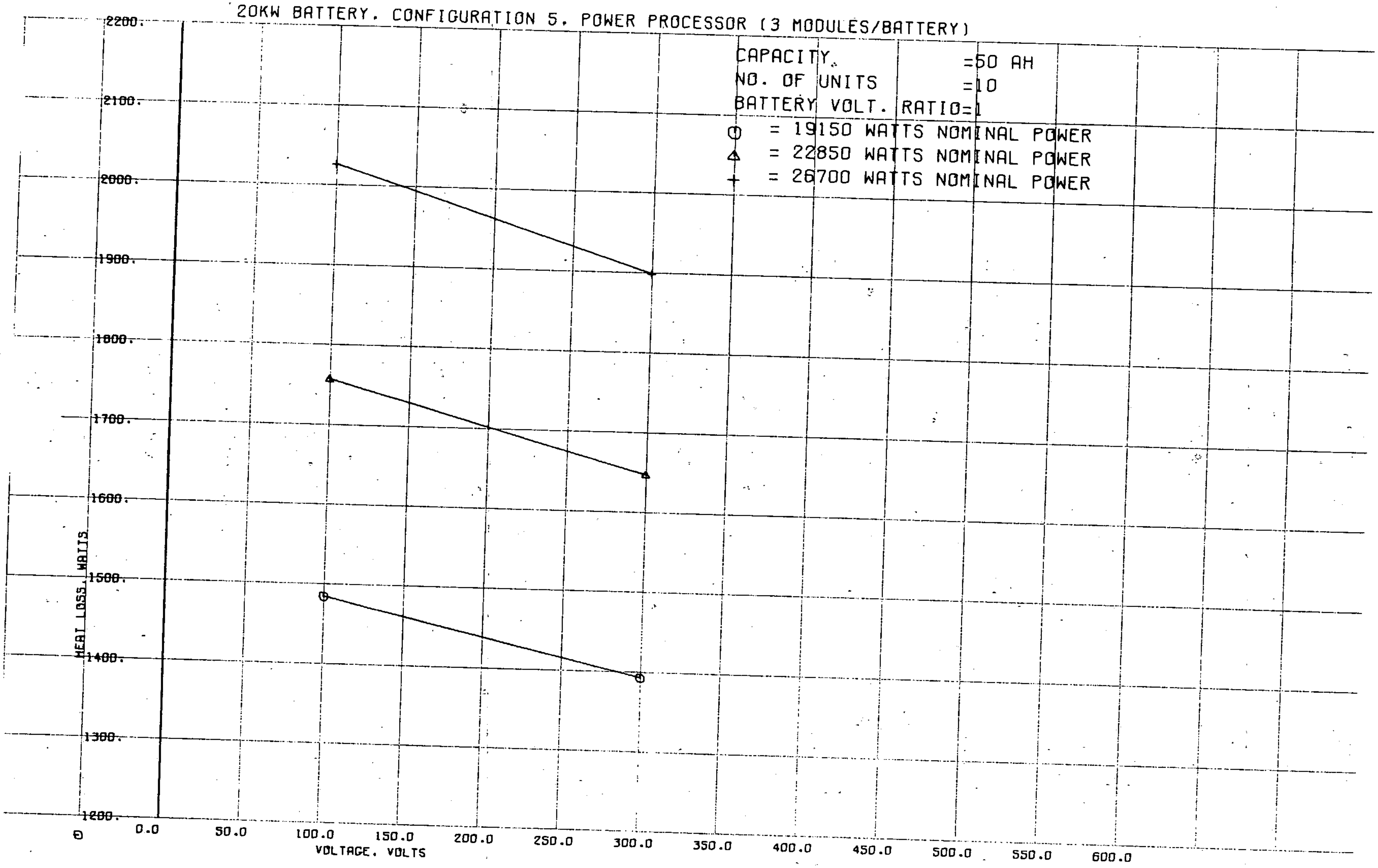
20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (3 MODULES/BATTERY)



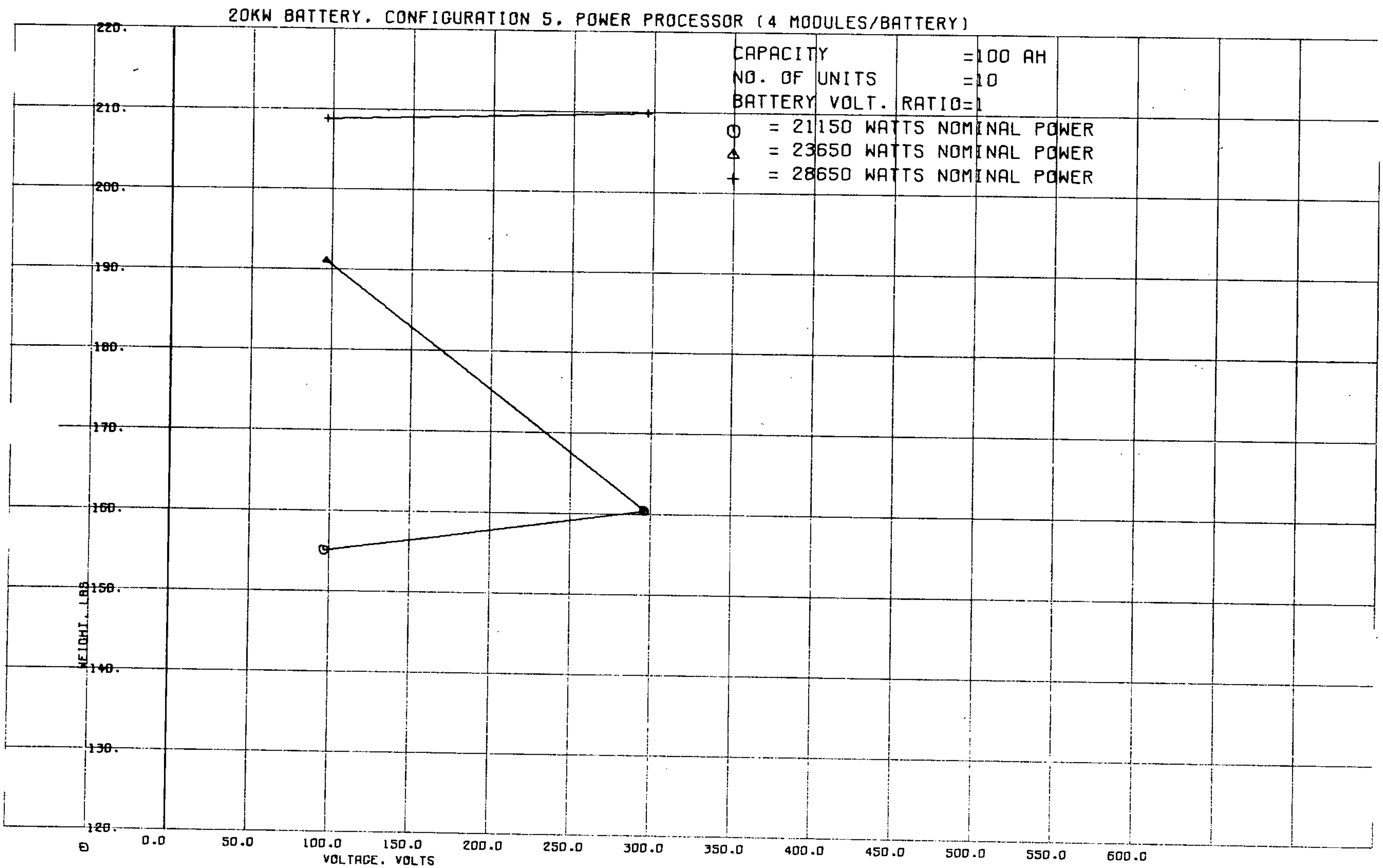

20KW BATTERY. CONFIGURATION 5. POWER PROCESSOR (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
○ = 19150 WATTS NOMINAL POWER
△ = 22850 WATTS NOMINAL POWER
+ = 26700 WATTS NOMINAL POWER
COST, K$
VOLTAGE, VOLTS

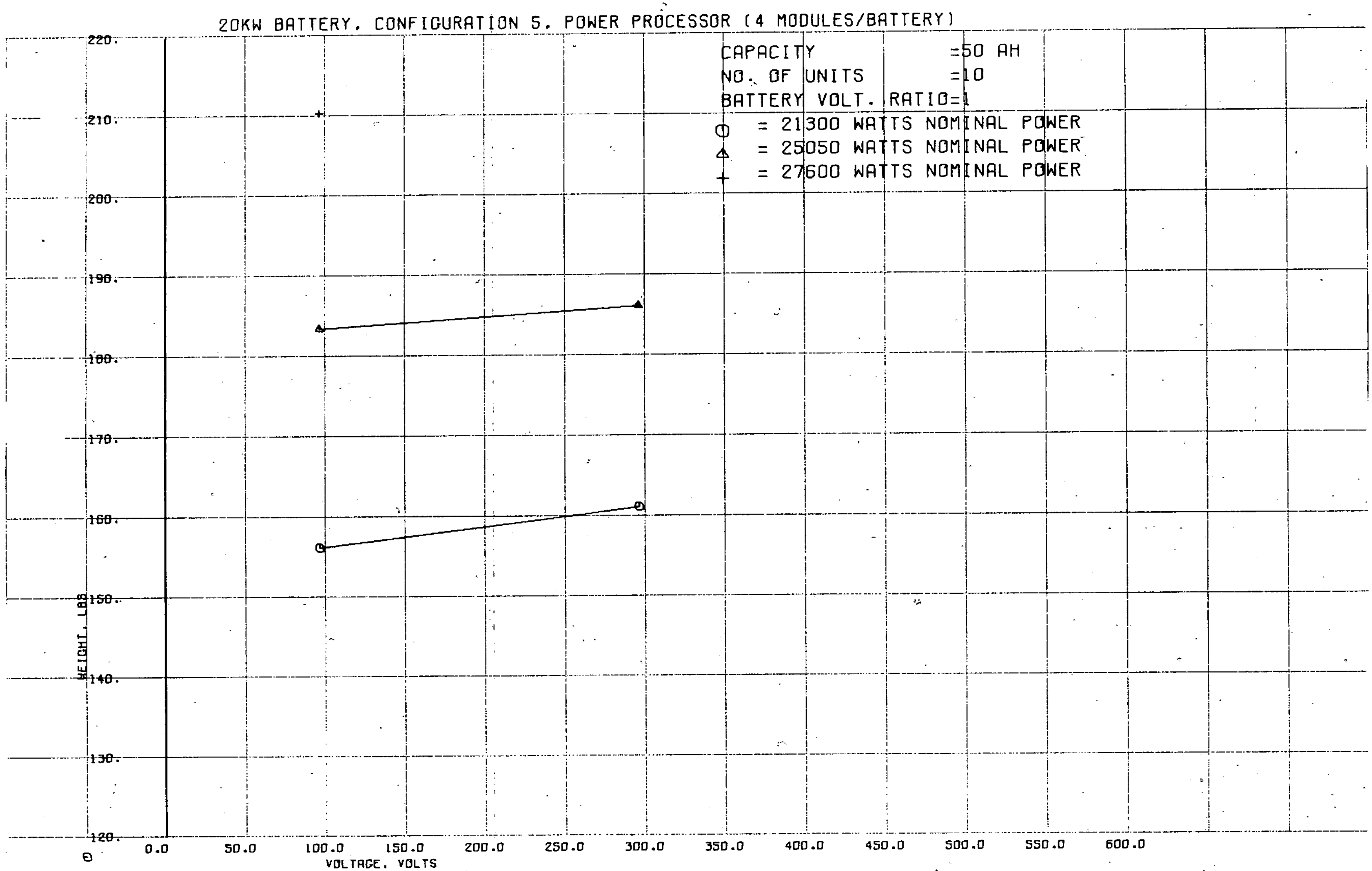
20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (3 MODULES/BATTERY)

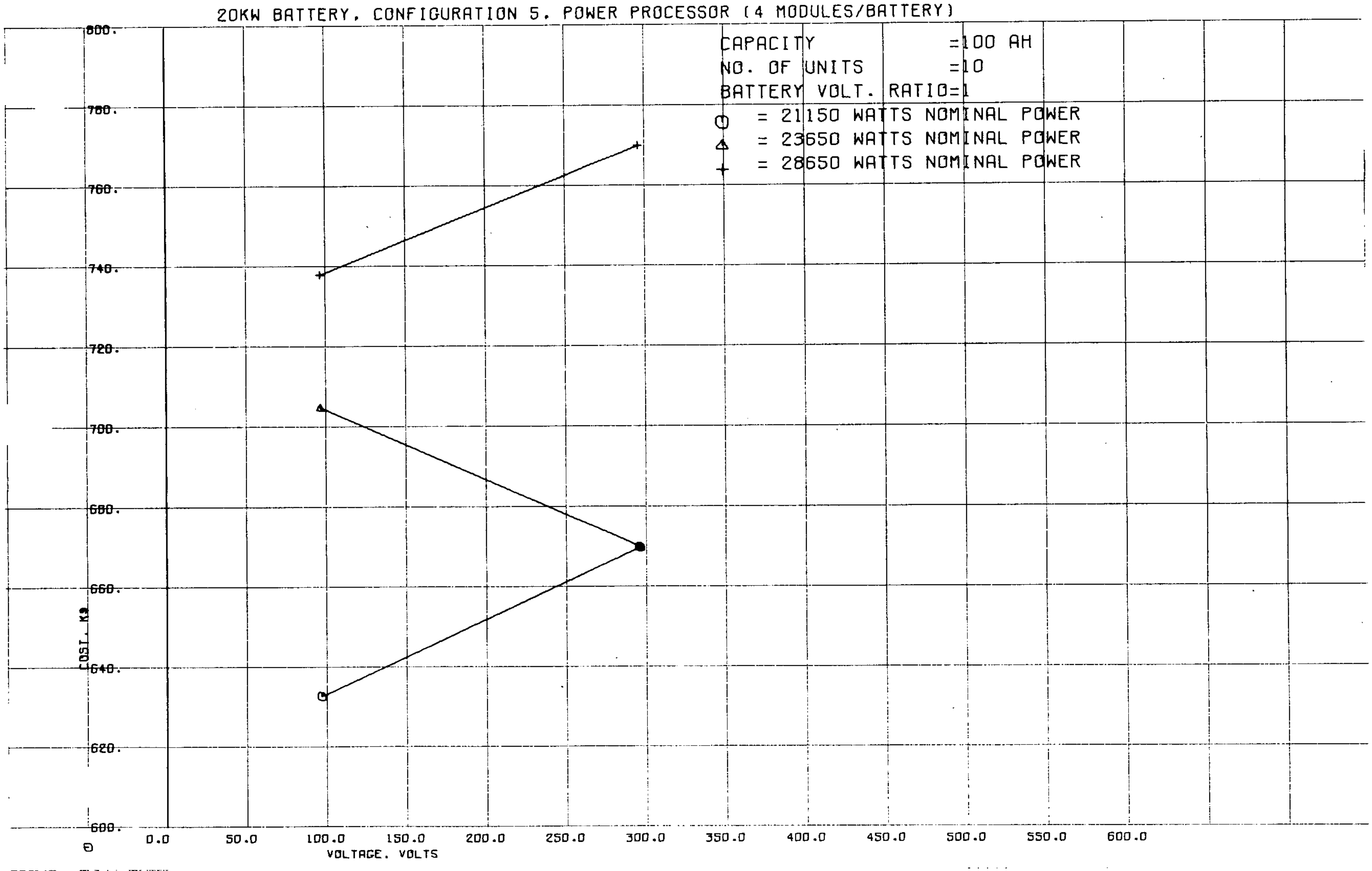




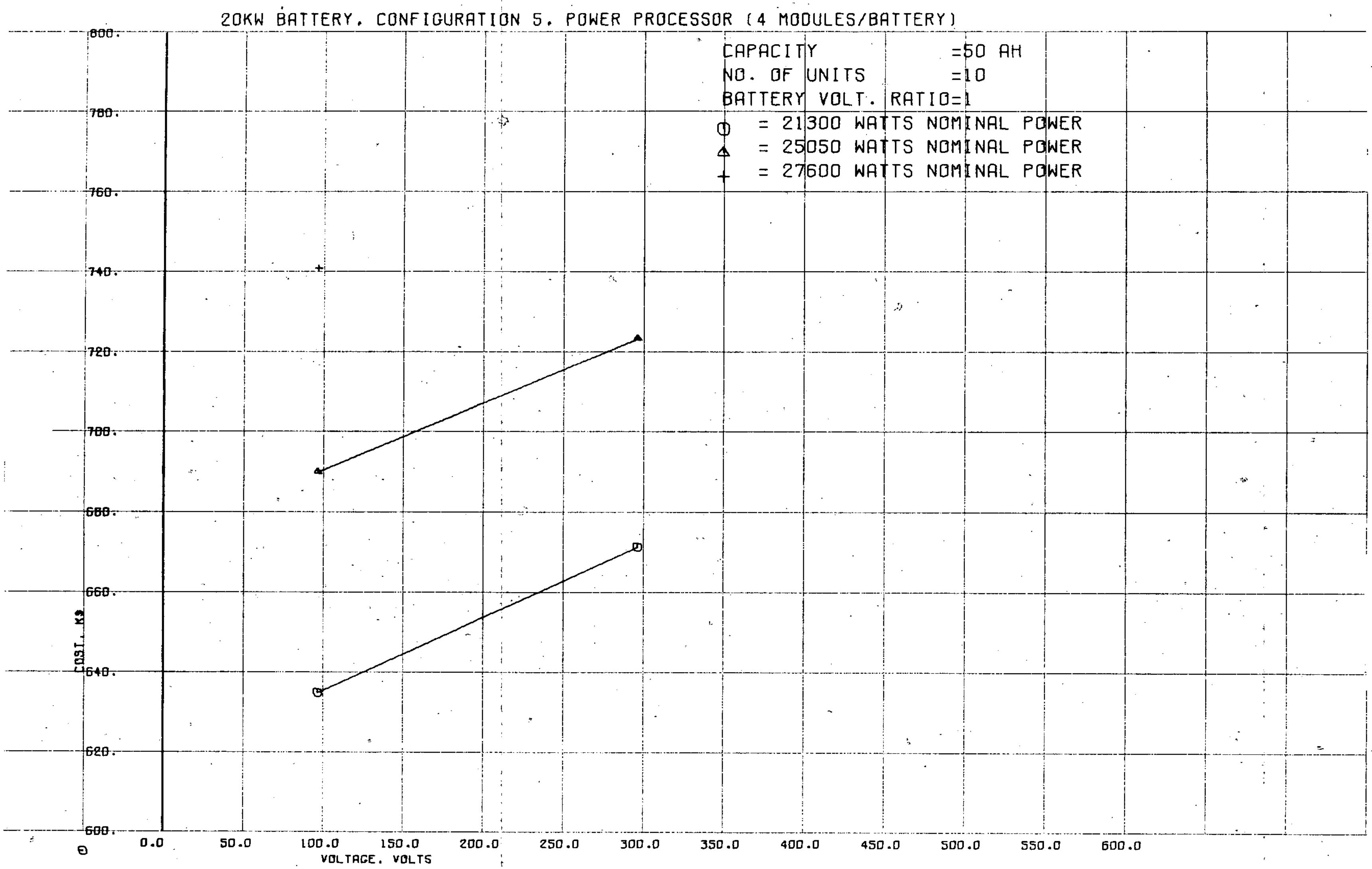
20KW BATTERY. CONFIGURATION 5. POWER PROCESSOR (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 19150 WATTS NOMINAL POWER
= 22850 WATTS NOMINAL POWER
= 26700 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS

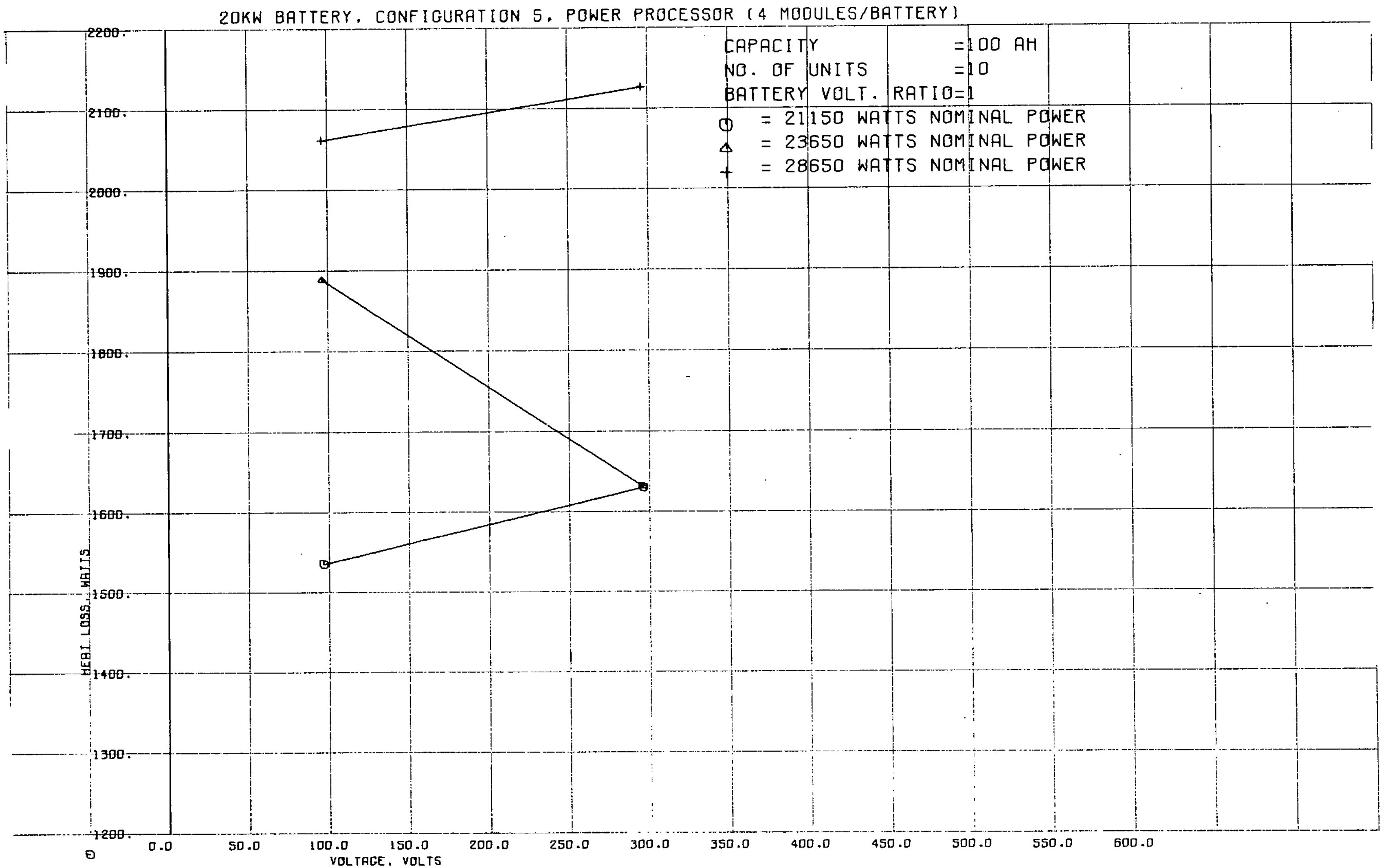

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21150 WATTS NOMINAL POWER
= 23650 WATTS NOMINAL POWER
= 28650 WATTS NOMINAL POWER
WEIGHT, LBS
220.
210.
200.
190.
180.
170.
160.
150.
140.
130.
120.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

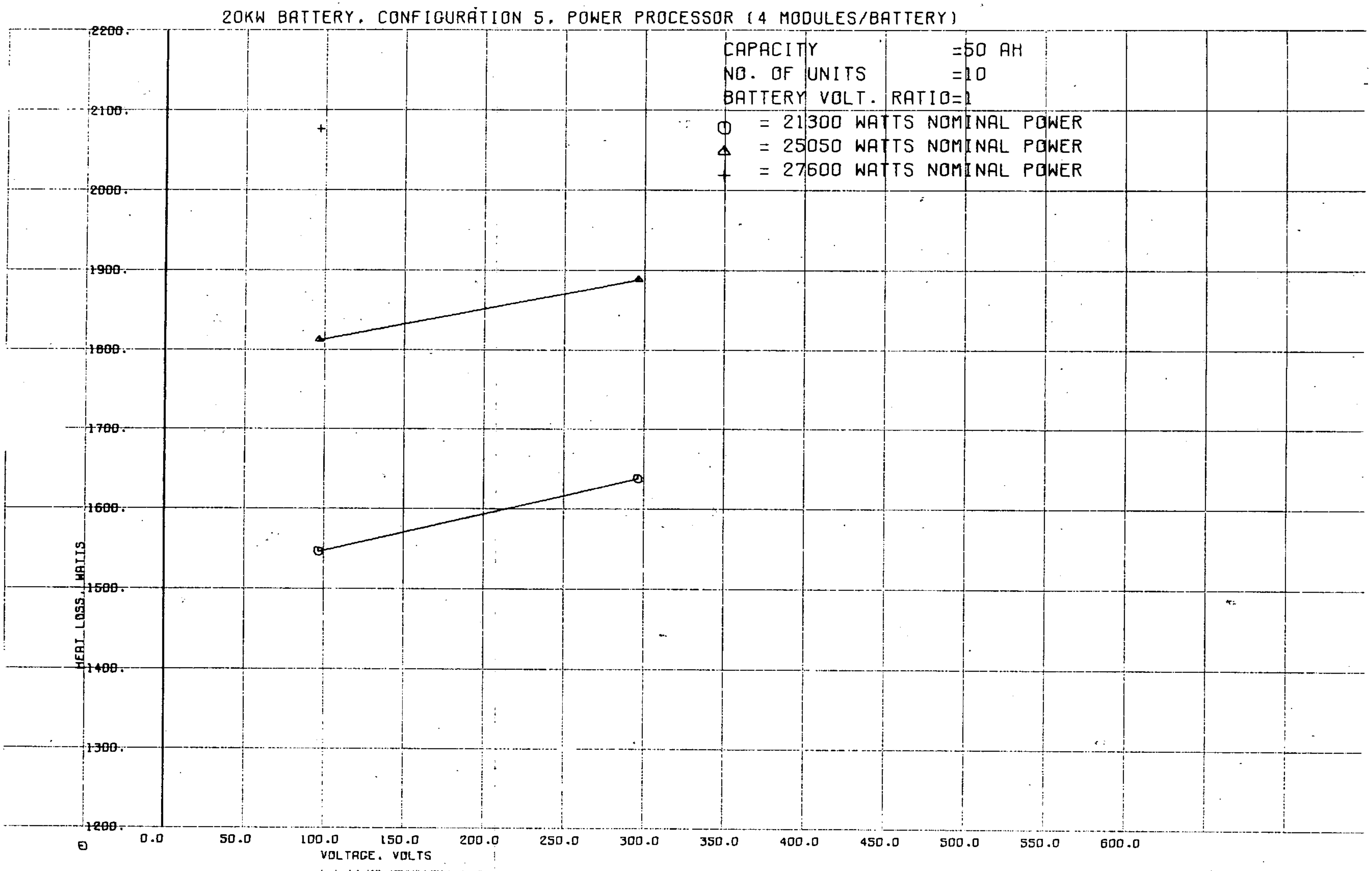

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21300 WATTS NOMINAL POWER
= 25050 WATTS NOMINAL POWER
= 27600 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
220.
210.
200.
190.
180.
170.
160.
150.
140.
130.
120.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0



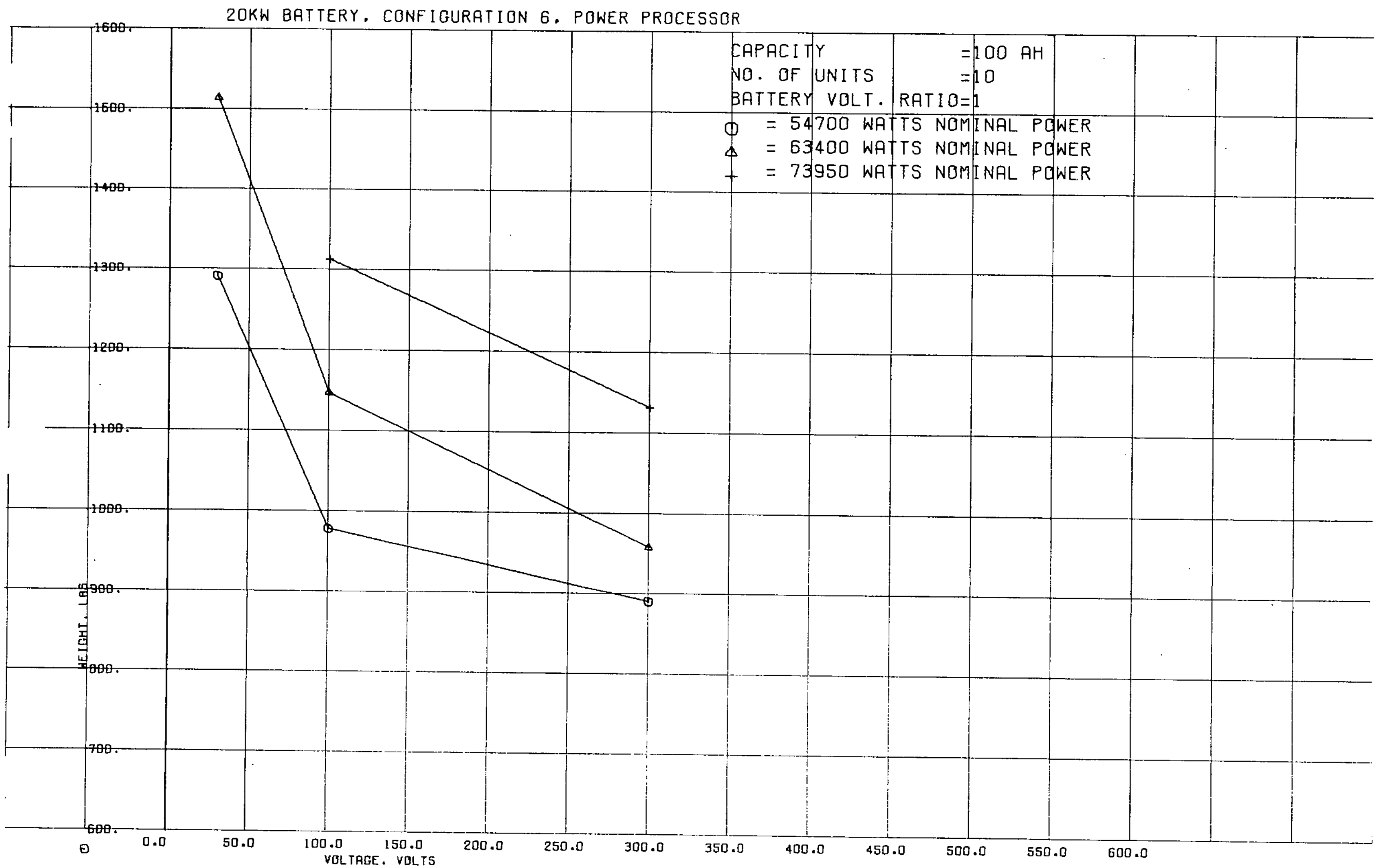
20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
○ = 21150 WATTS NOMINAL POWER
△ = 23650 WATTS NOMINAL POWER
+ = 28650 WATTS NOMINAL POWER
COST, K$
800.
780.
760.
740.
720.
700.
680.
660.
640.
620.
600.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

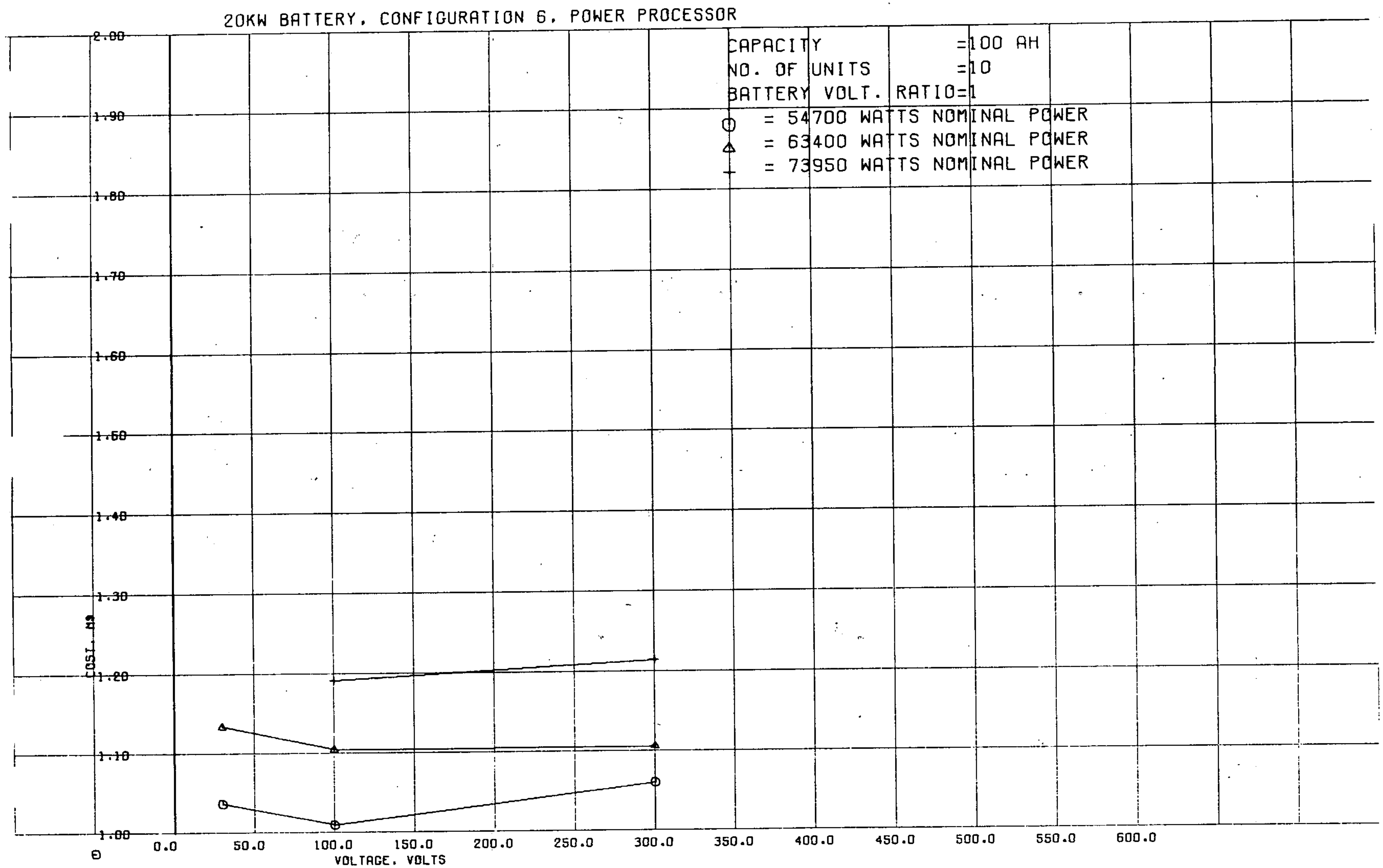

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21300 WATTS NOMINAL POWER
= 25050 WATTS NOMINAL POWER
= 27600 WATTS NOMINAL POWER
800.
780.
760.
740.
720.
700.
680.
660.
640.
620.
600.
COST, K$
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

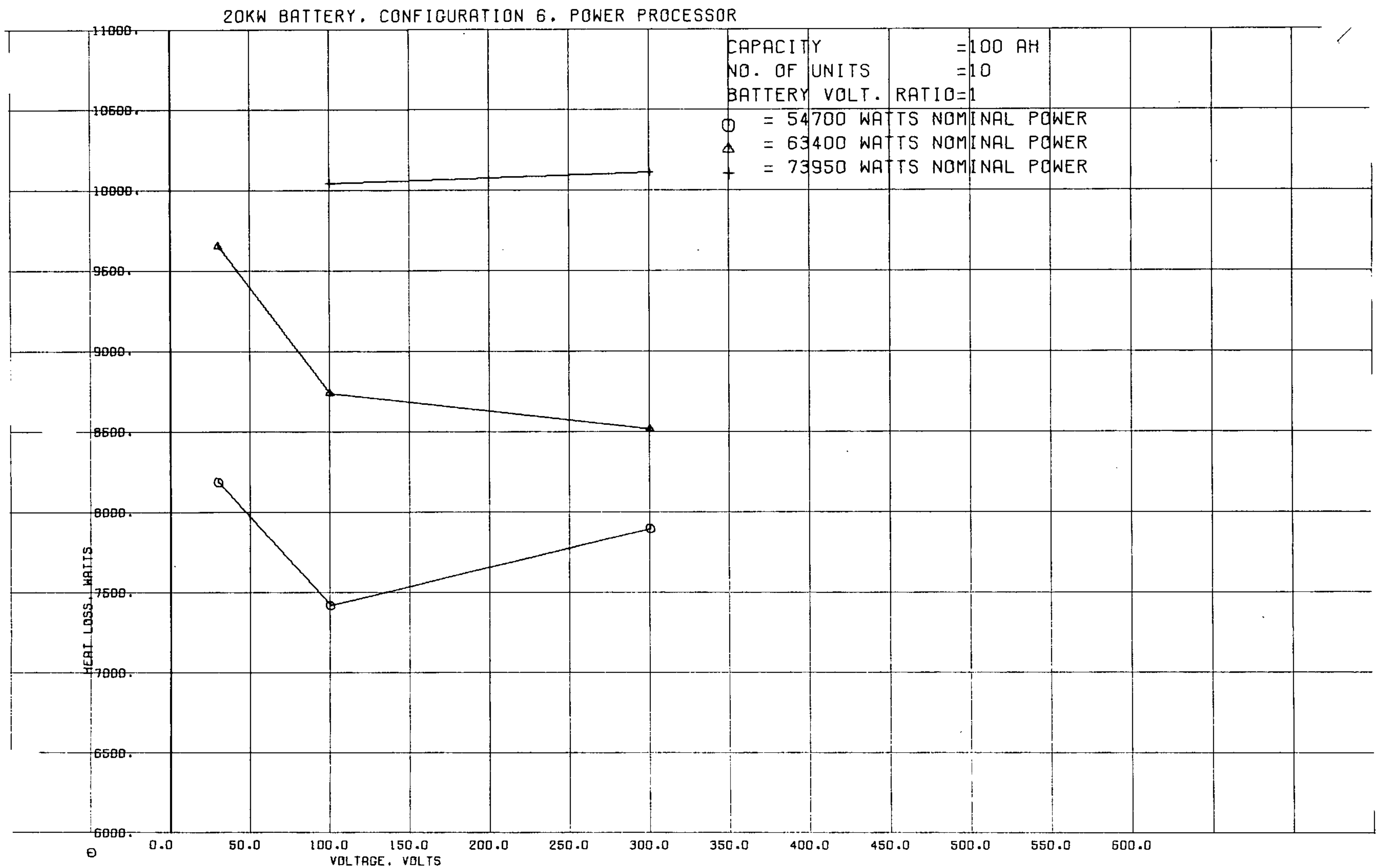

20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21150 WATTS NOMINAL POWER
= 23650 WATTS NOMINAL POWER
= 28650 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
2200.
2100.
2000.
1900.
1800.
1700.
1600.
1500.
1400.
1300.
1200.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

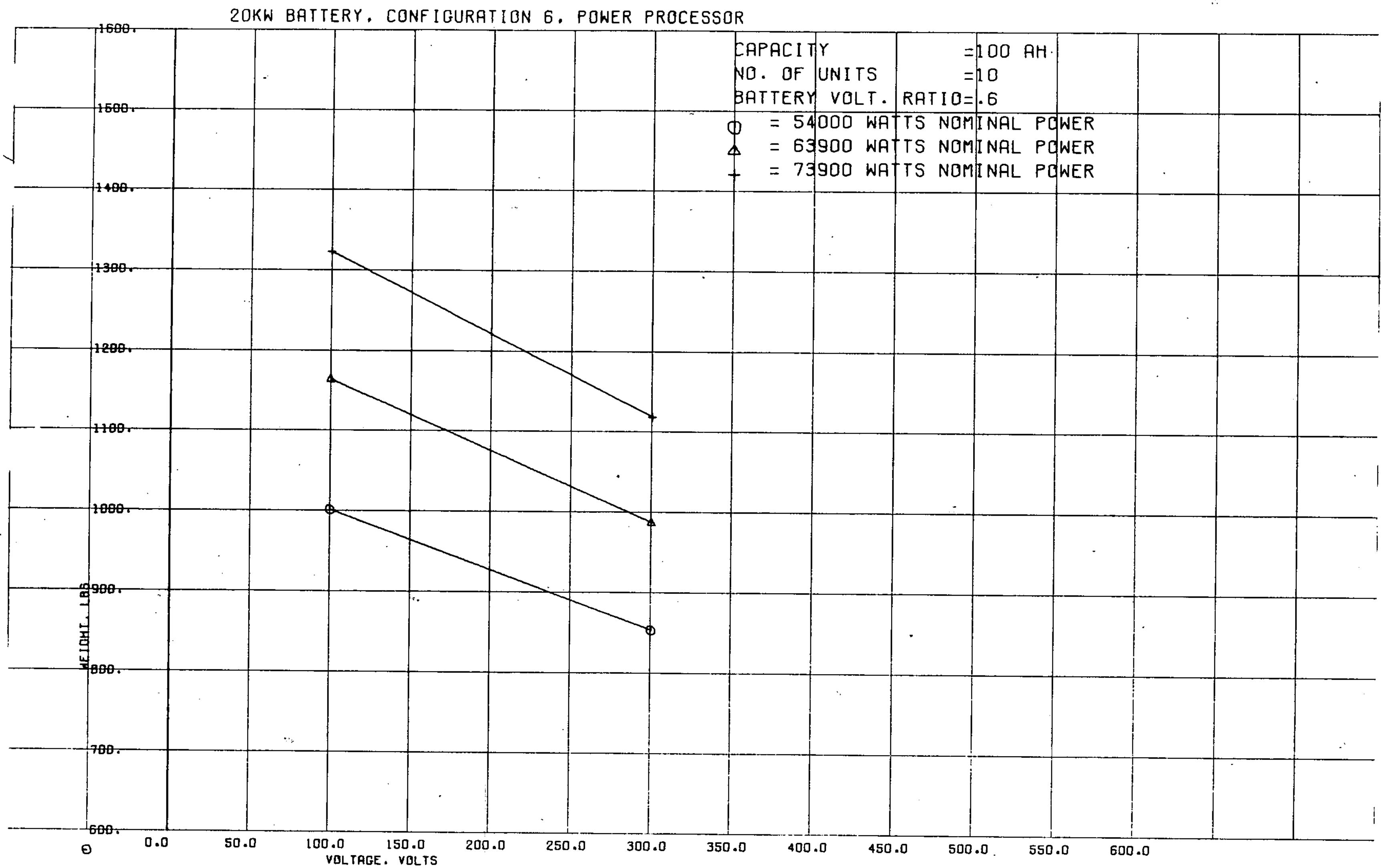


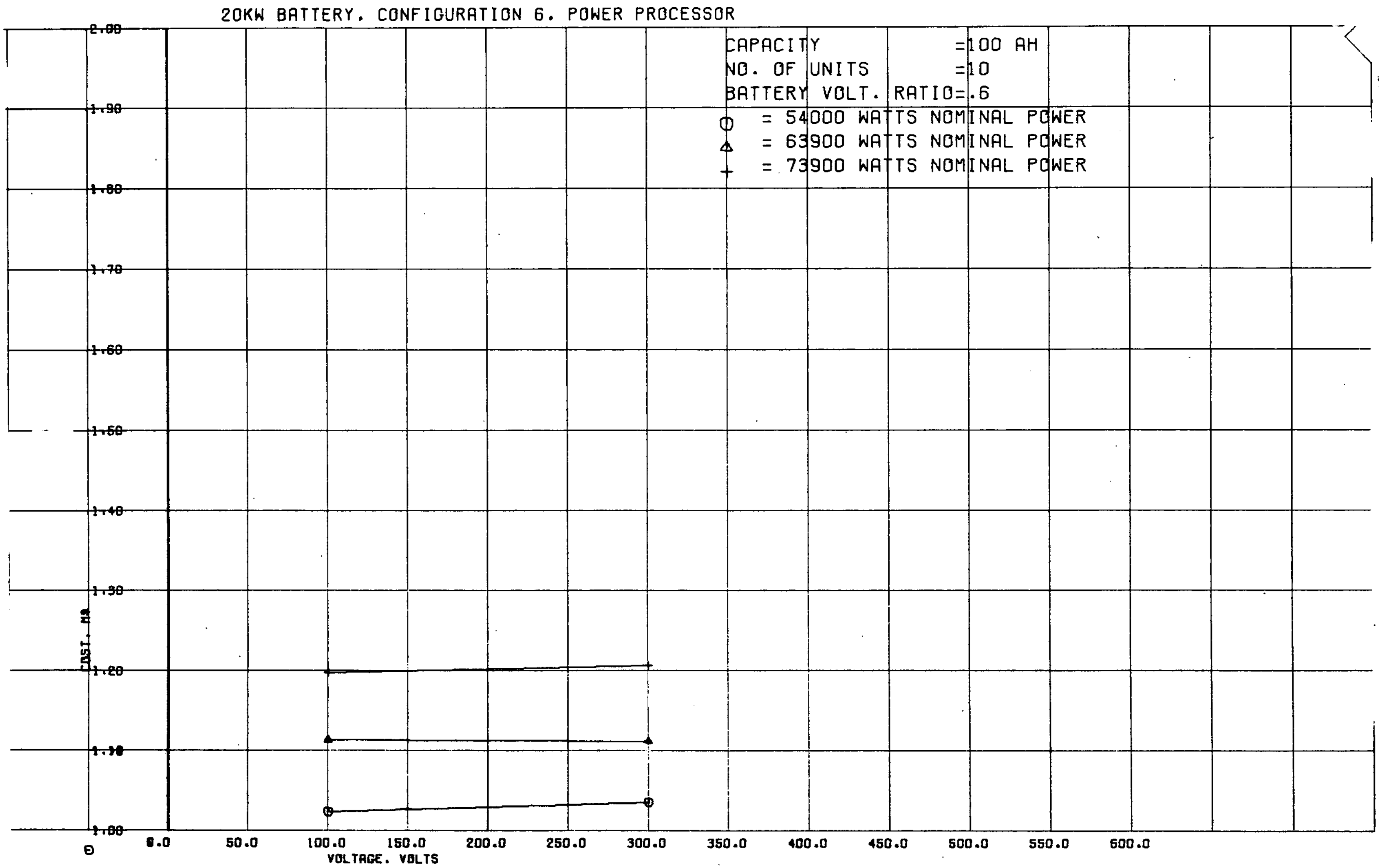
20KW BATTERY, CONFIGURATION 5, POWER PROCESSOR (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 21300 WATTS NOMINAL POWER
= 25050 WATTS NOMINAL POWER
= 27600 WATTS NOMINAL POWER
HEAT LOSS, WATTS
2200.
2100.
2000.
1900.
1800.
1700.
1600.
1500.
1400.
1300.
1200.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, POWER PROCESSOR
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
○ = 54700 WATTS NOMINAL POWER
△ = 63400 WATTS NOMINAL POWER
+ = 73950 WATTS NOMINAL POWER
1600.
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, POWER PROCESSOR
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 54700 WATTS NOMINAL POWER
= 63400 WATTS NOMINAL POWER
= 73950 WATTS NOMINAL POWER
COST, M$
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, POWER PROCESSOR
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=1
= 54700 WATTS NOMINAL POWER
= 63400 WATTS NOMINAL POWER
= 73950 WATTS NOMINAL POWER
HEAT LOSS, WATTS
11000.
10500.
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS


20KW BATTERY, CONFIGURATION 6, POWER PROCESSOR
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
○ = 54000 WATTS NOMINAL POWER
△ = 63900 WATTS NOMINAL POWER
+ = 73900 WATTS NOMINAL POWER
WEIGHT, LBS
1600.
1500.
1400.
1300.
1200.
1100.
1000.
900.
800.
700.
600.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 6. POWER PROCESSOR
CAPACITY =100 AH
NO. OF UNITS =10
BATTERY VOLT. RATIO=.6
= 54000 WATTS NOMINAL POWER
= 63900 WATTS NOMINAL POWER
= 73900 WATTS NOMINAL POWER
COST, M$
VOLTAGE, VOLTS

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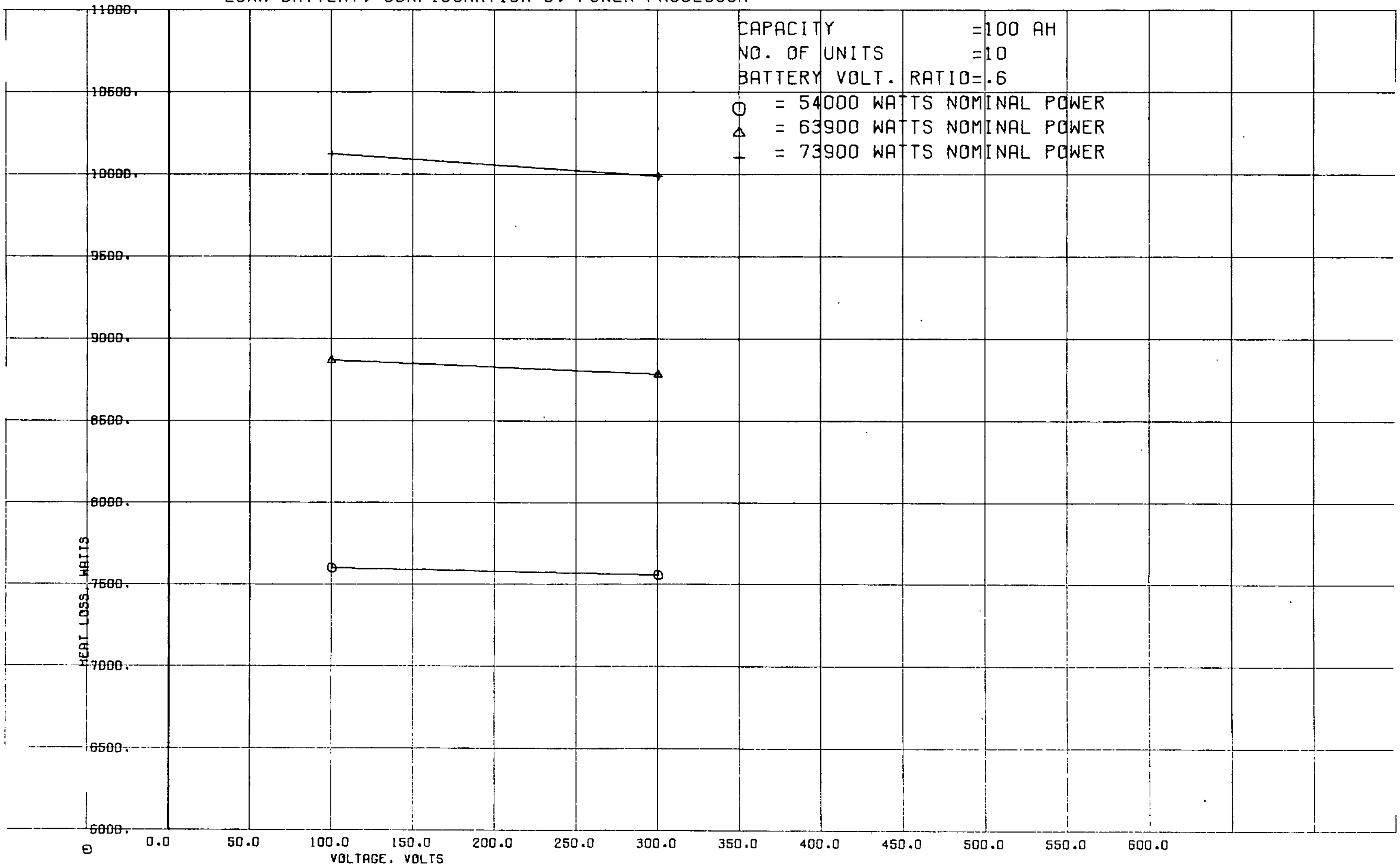
20KW BATTERY, CONFIGURATION 6, POWER PROCESSOR



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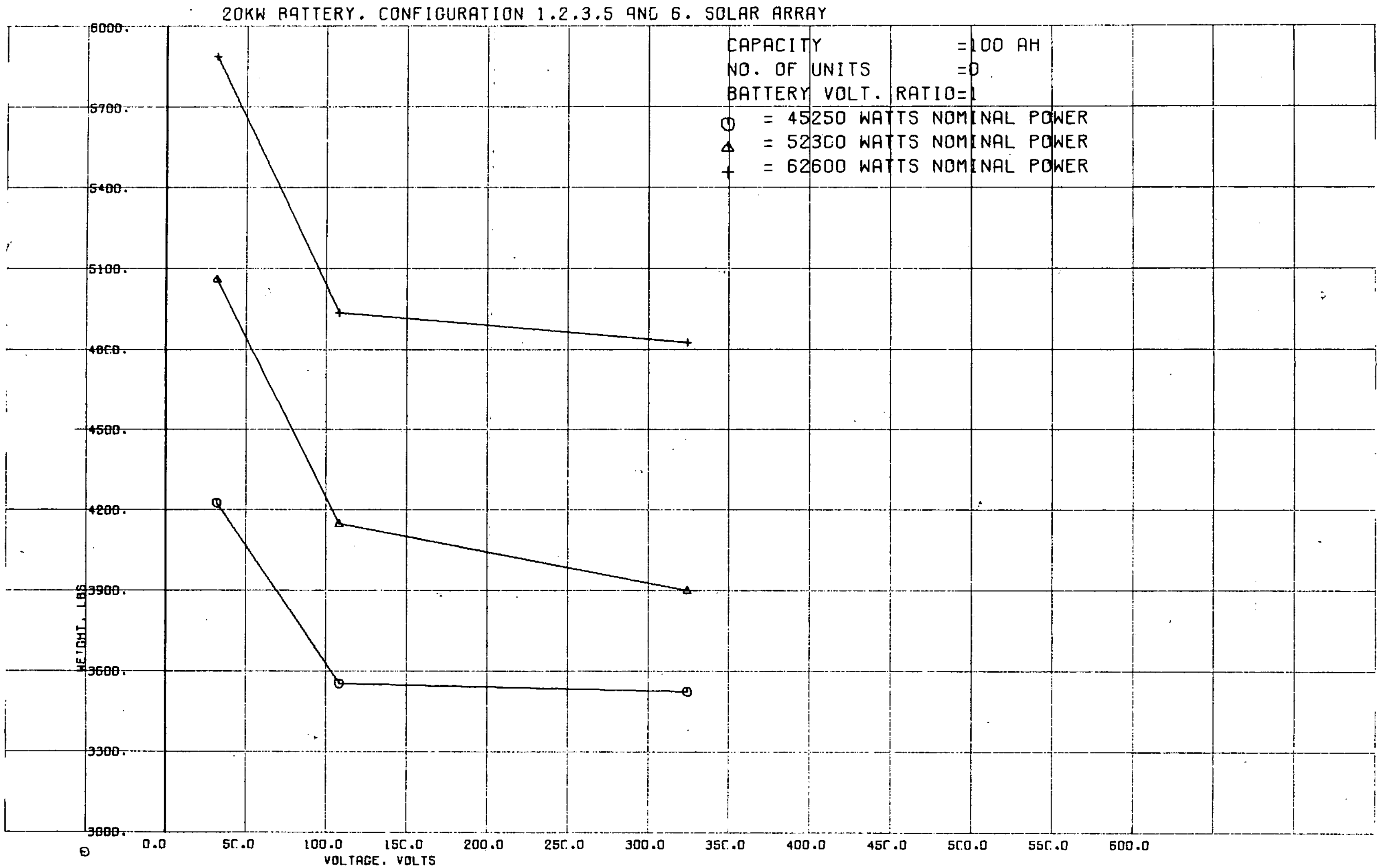
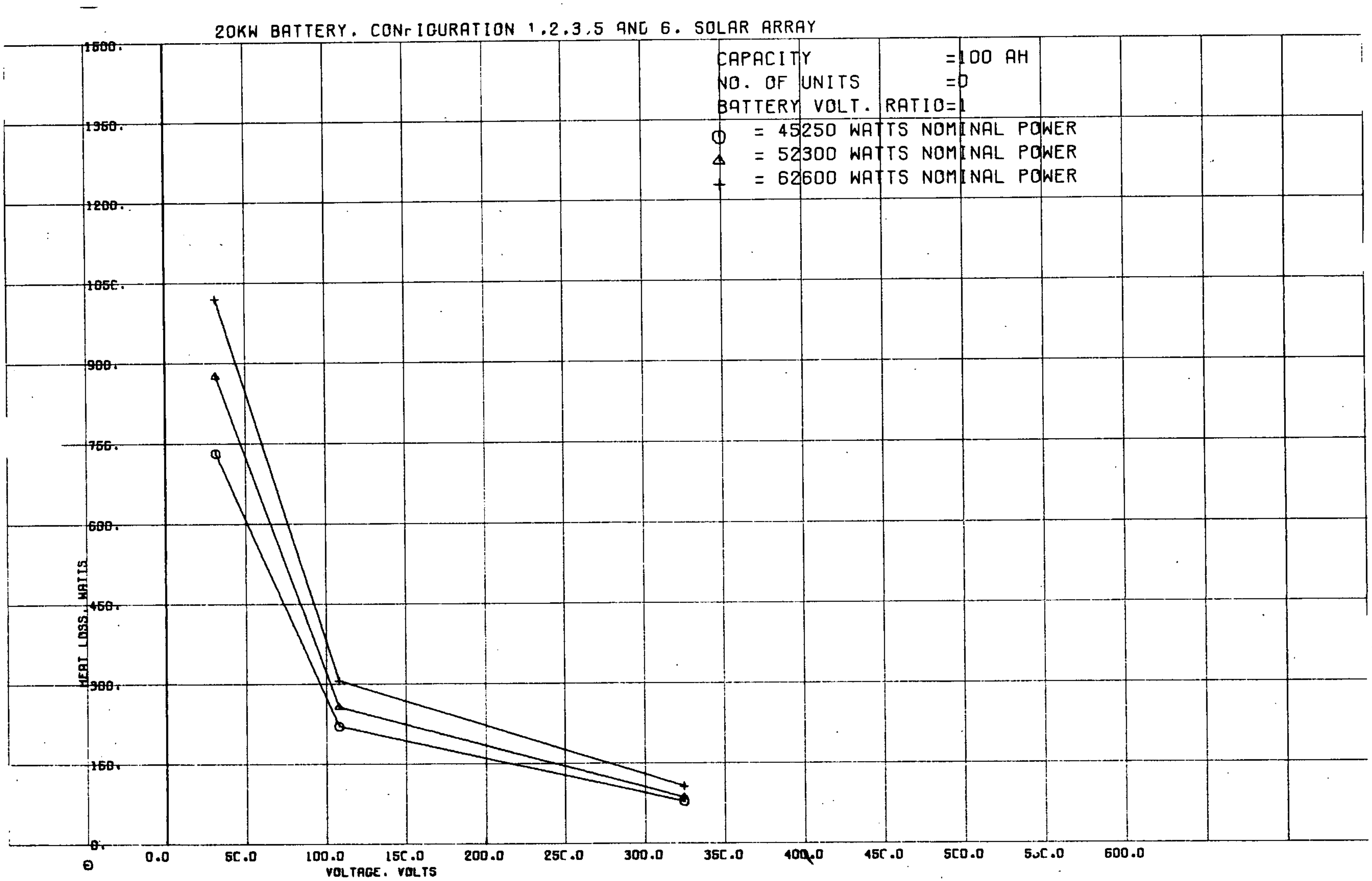

20KW BATTERY. CONFIGURATION 1.2.3.5 AND 6. SOLAR ARRAY
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 45250 WATTS NOMINAL POWER
= 52300 WATTS NOMINAL POWER
= 62600 WATTS NOMINAL POWER
6000.
5700.
5400.
5100.
4800.
4500.
4200.
3900.
3600.
3300.
3000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 1,2,3,5 AND 6. SOLAR ARRAY
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
O = 45250 WATTS NOMINAL POWER
Δ = 52300 WATTS NOMINAL POWER
+ = 62600 WATTS NOMINAL POWER
HEAT LOSS, WATTS
1500.
1350.
1200.
1050.
900.
750.
600.
450.
300.
150.
0.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

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SEE CONFIGURATION 1

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SEE CONFIGURATION 1

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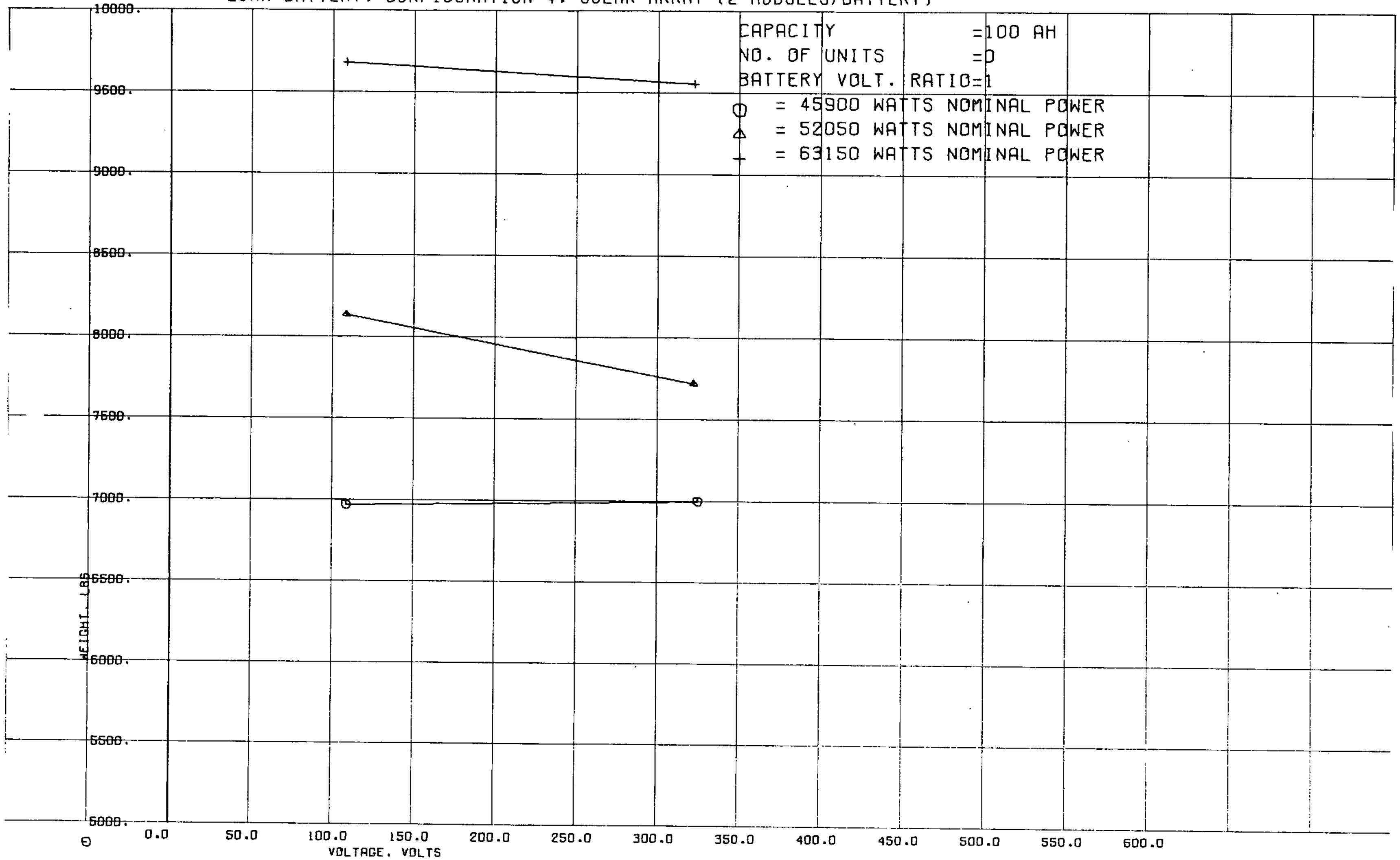
20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (2 MODULES/BATTERY)



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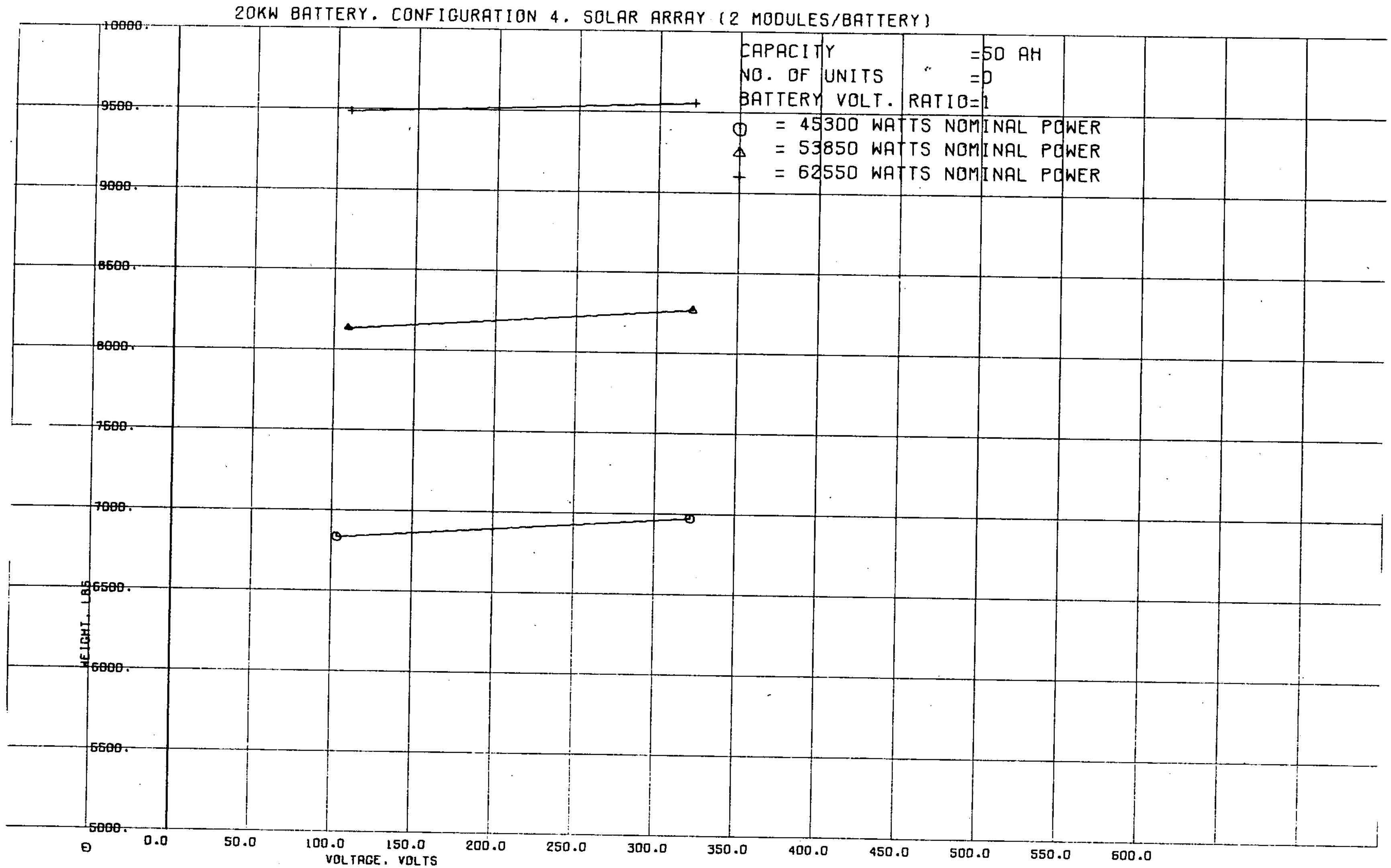
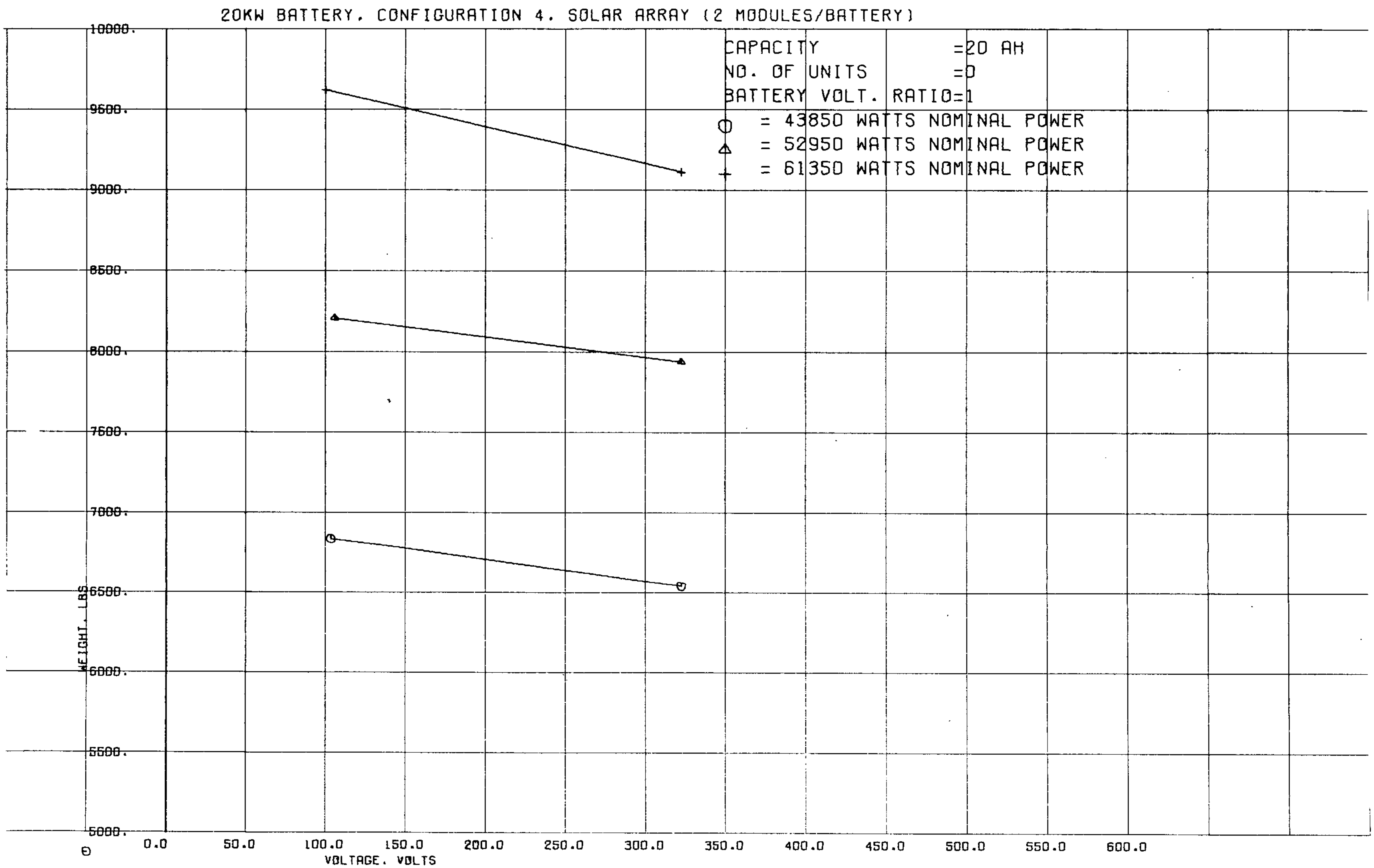
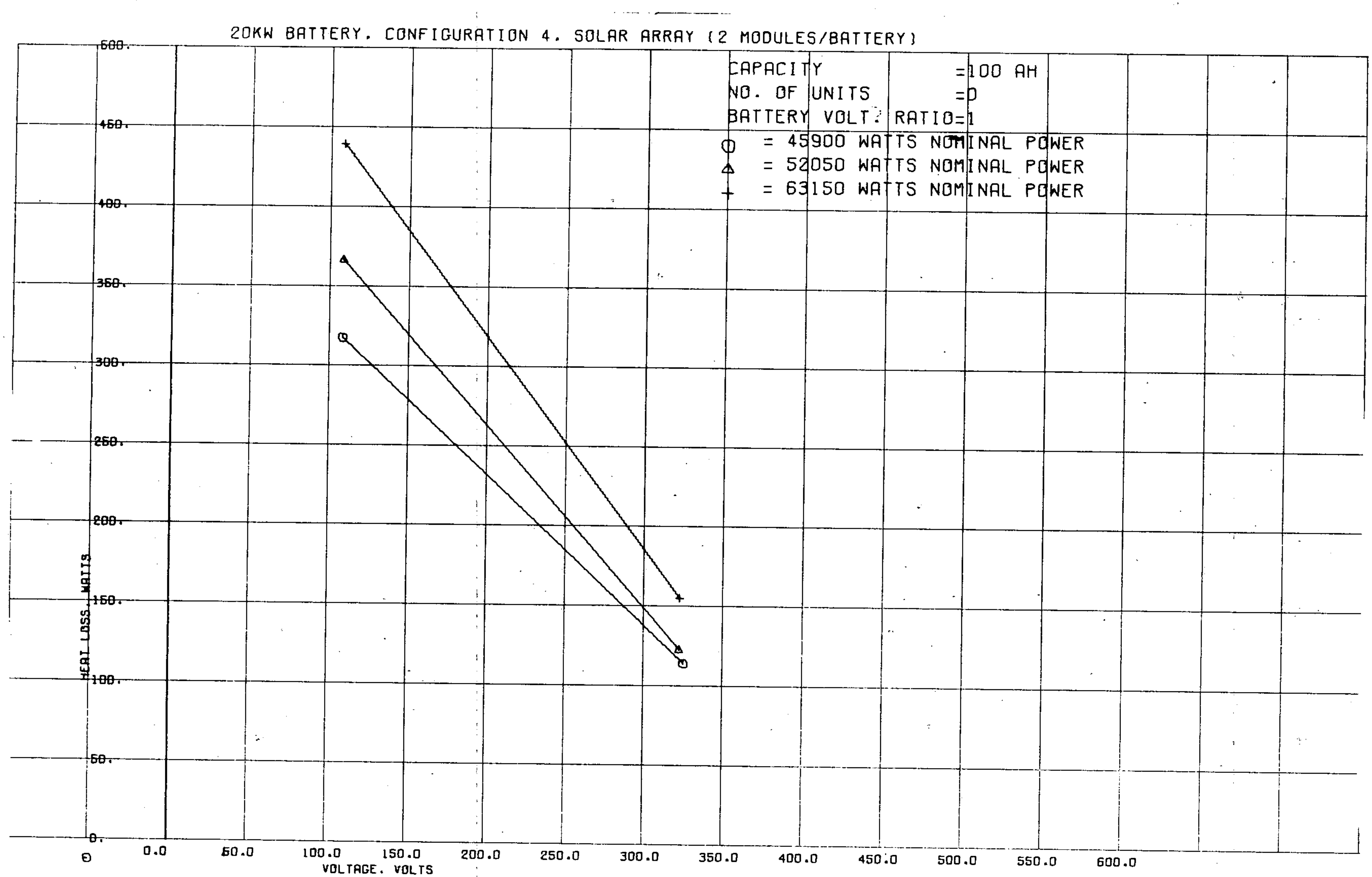
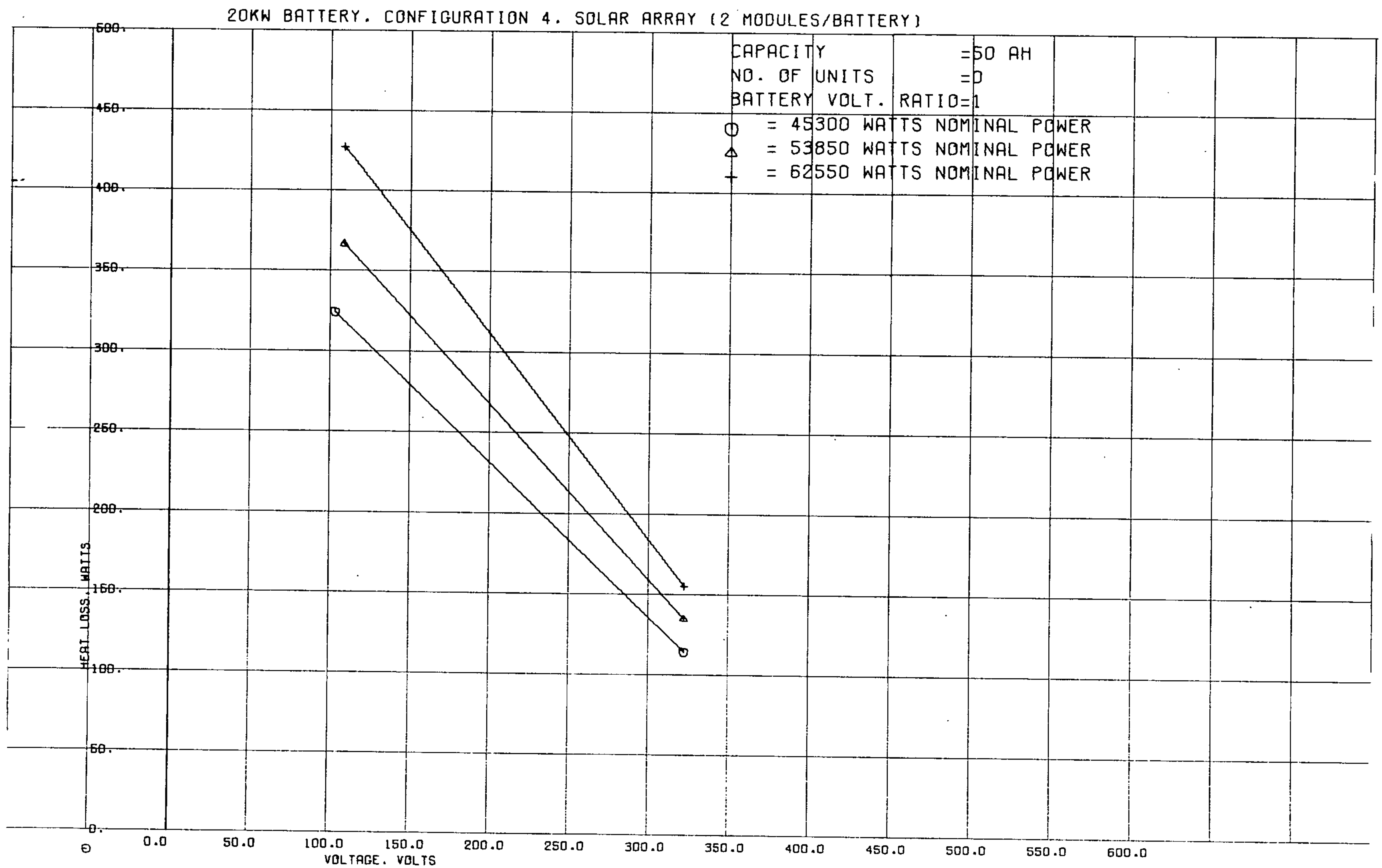

20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 45300 WATTS NOMINAL POWER
= 53850 WATTS NOMINAL POWER
= 62550 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
5500.
5000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0


20KW BATTERY, CONFIGURATION 4. SOLAR ARRAY (2 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 43850 WATTS NOMINAL POWER
= 52950 WATTS NOMINAL POWER
= 61350 WATTS NOMINAL POWER
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
5500.
5000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

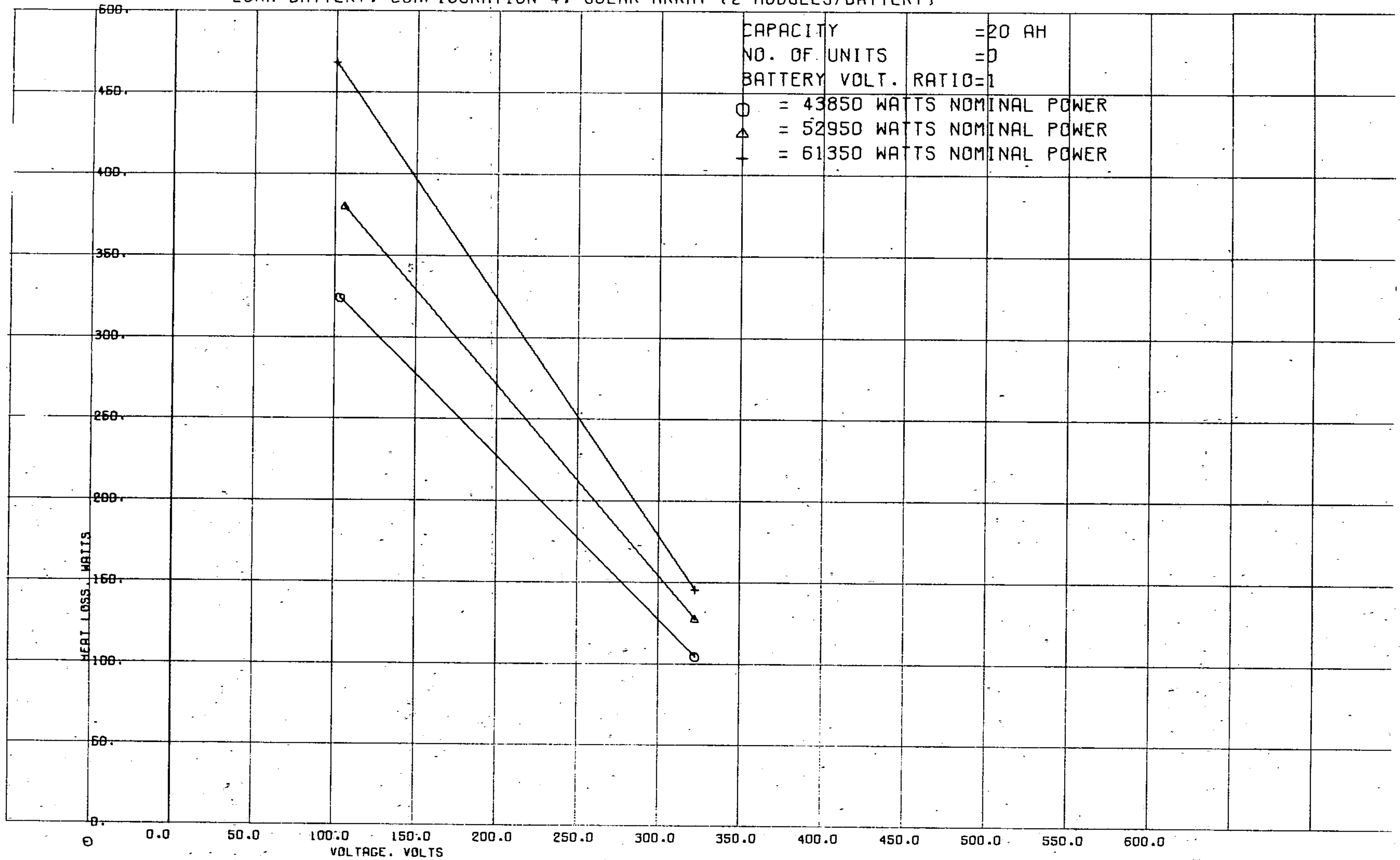


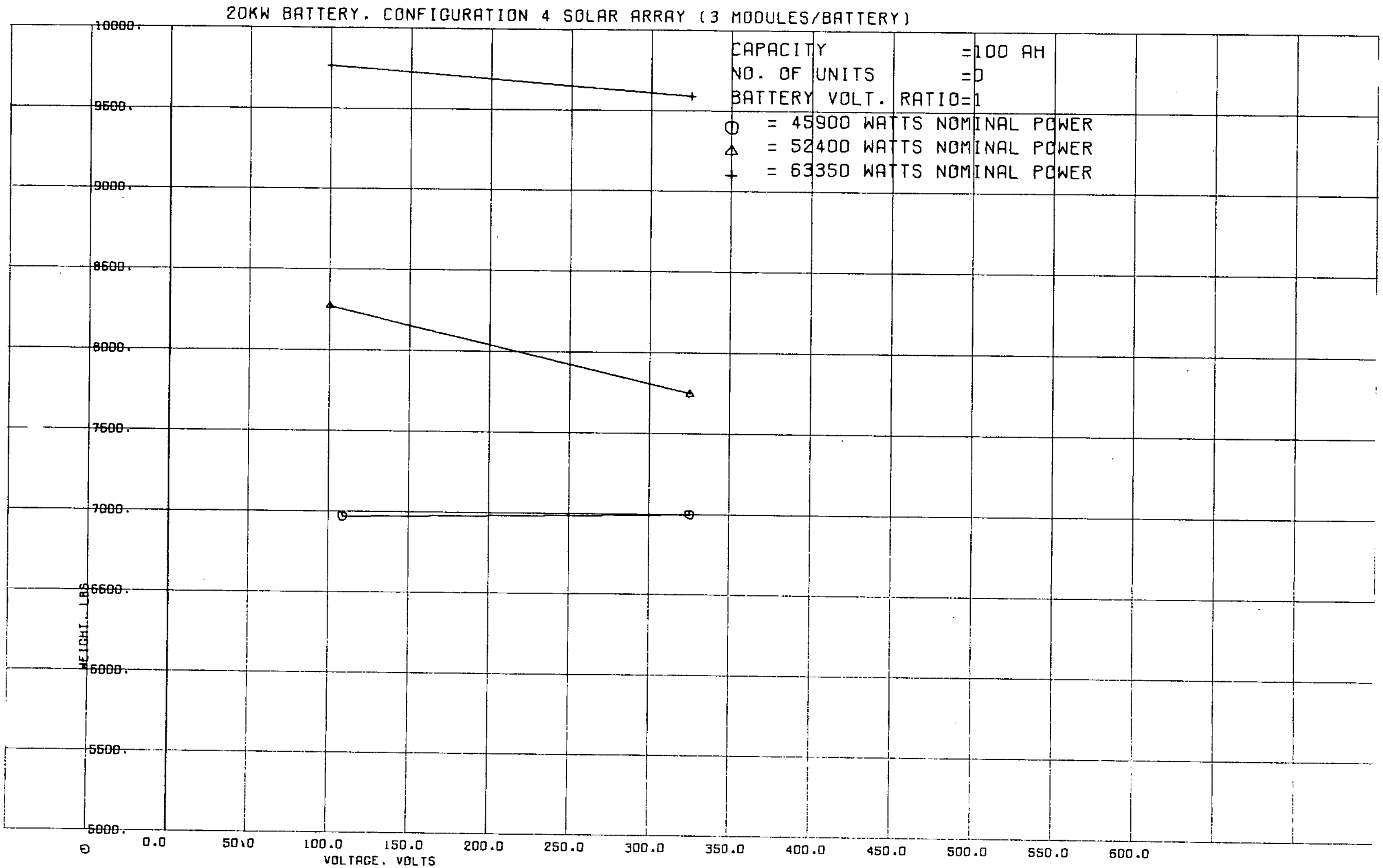
20KW BATTERY, CONFIGURATION 4, SOLAR ARRAY (2 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
○ = 45900 WATTS NOMINAL POWER
△ = 52050 WATTS NOMINAL POWER
+ = 63150 WATTS NOMINAL POWER
HEAT LOSS, WATTS
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

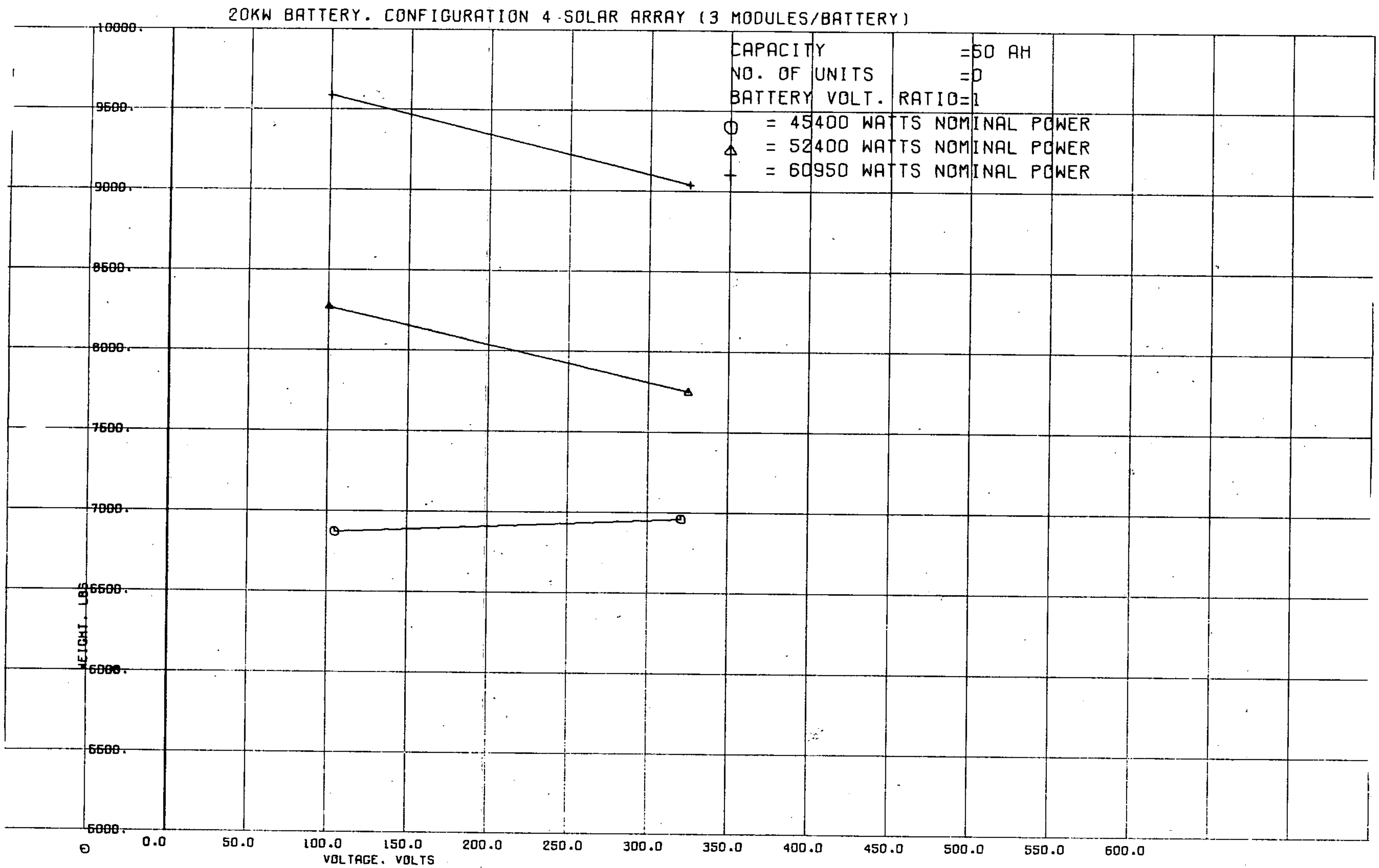


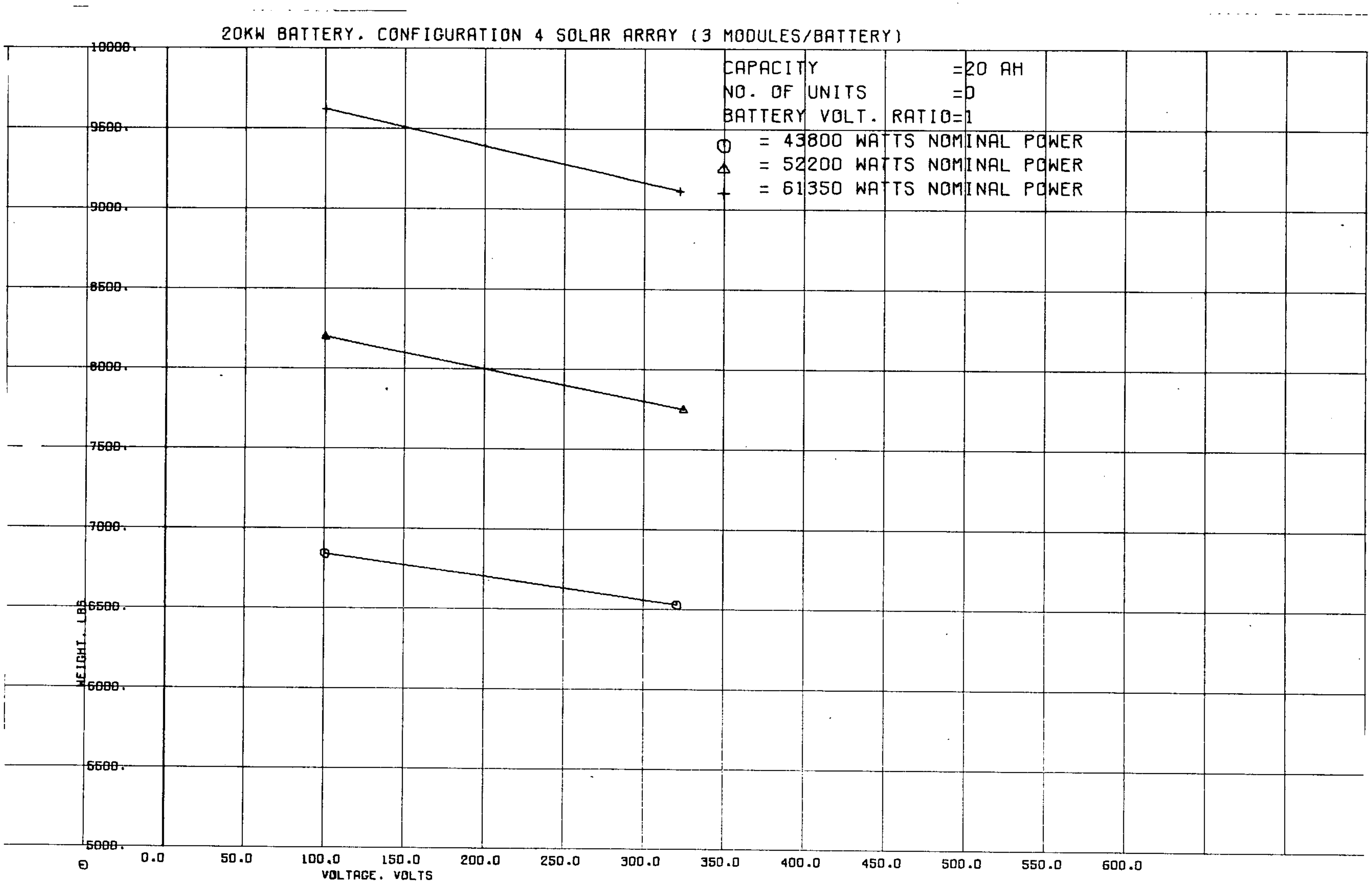
20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (2 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 45300 WATTS NOMINAL POWER
= 53850 WATTS NOMINAL POWER
= 62550 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
500.

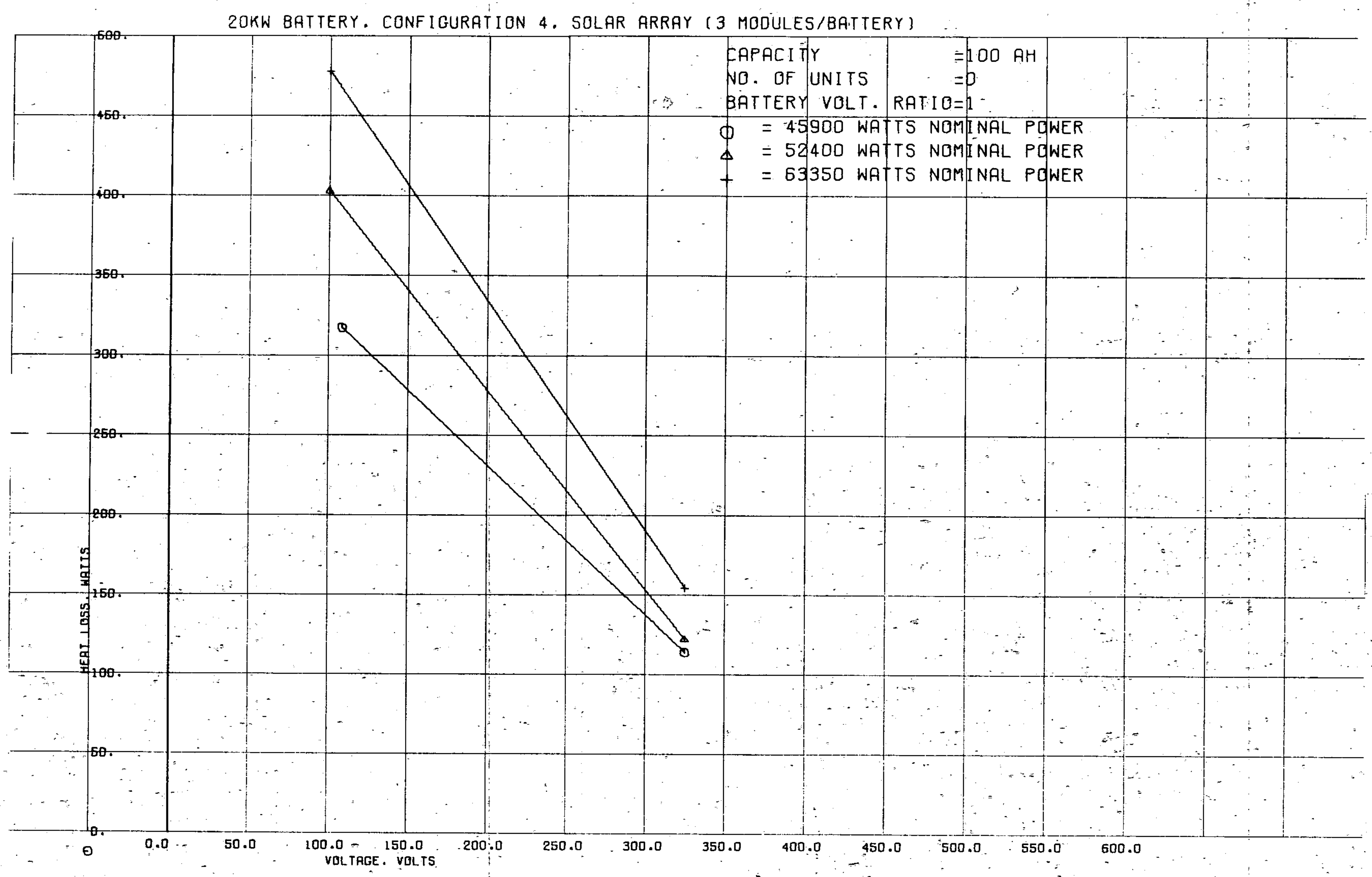
20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (2 MODULES/BATTERY)

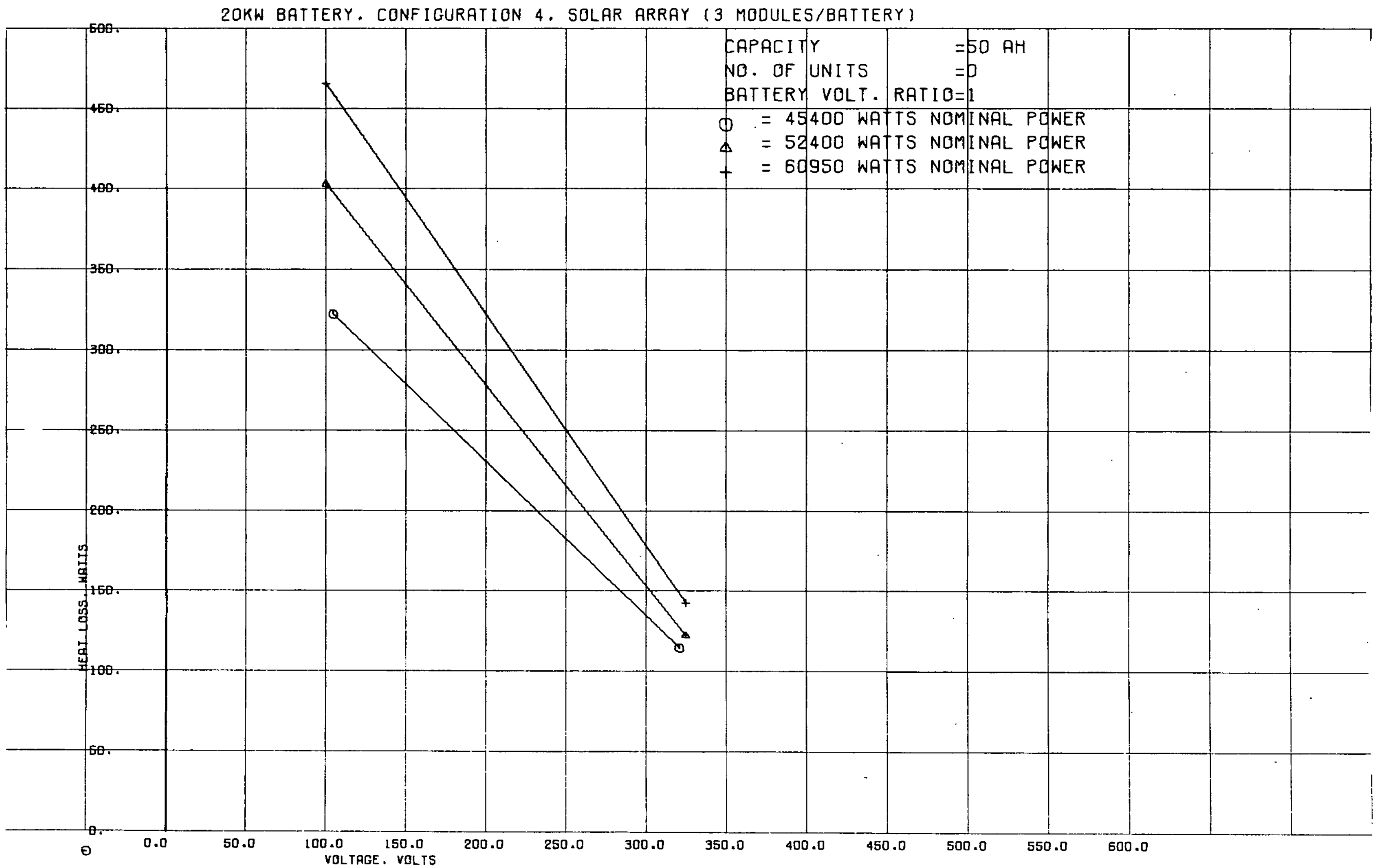



20KW BATTERY. CONFIGURATION 4 SOLAR ARRAY (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 45900 WATTS NOMINAL POWER
= 52400 WATTS NOMINAL POWER
= 63350 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS

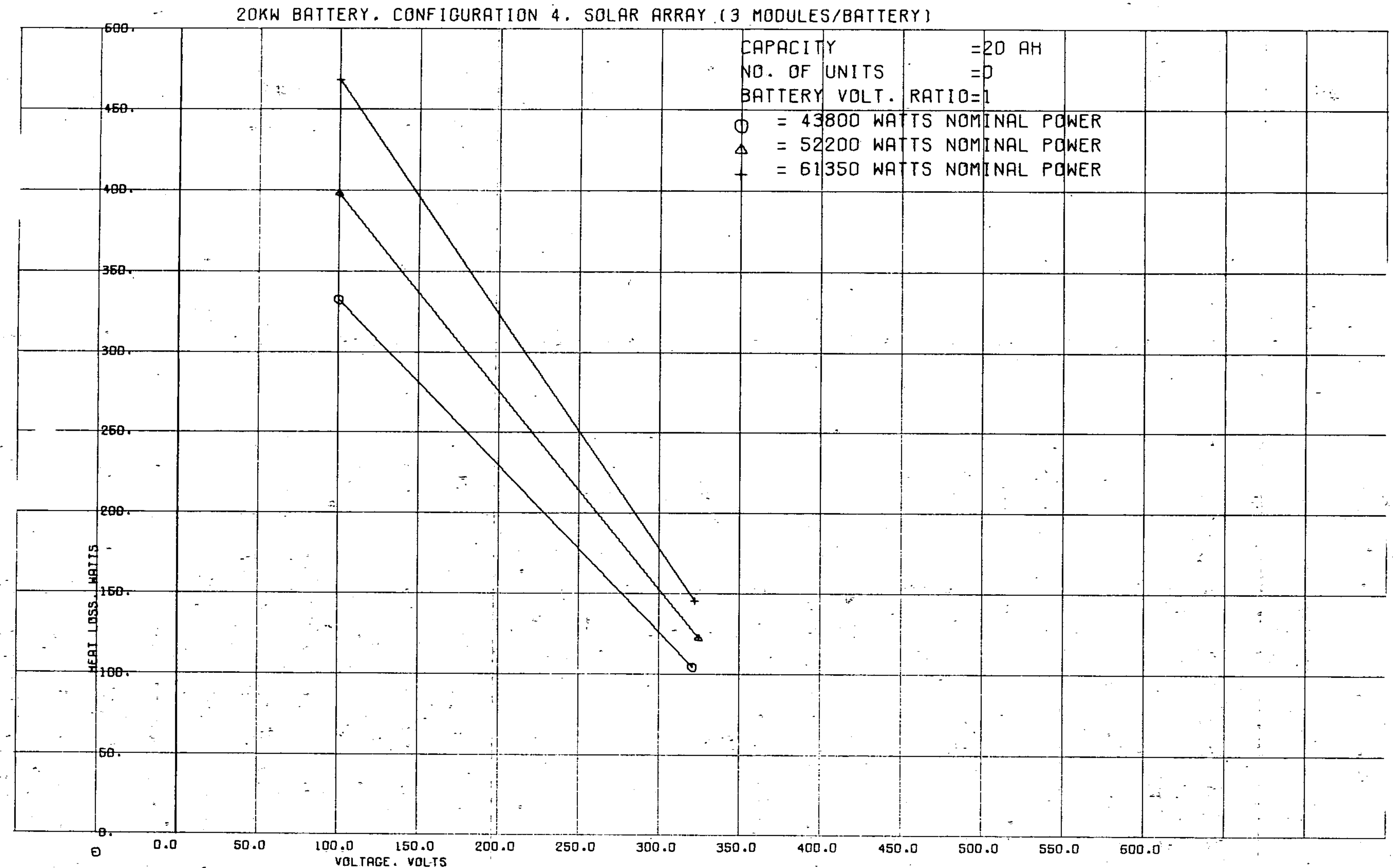

20KW BATTERY. CONFIGURATION 4 SOLAR ARRAY (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 45400 WATTS NOMINAL POWER
= 52400 WATTS NOMINAL POWER
= 60950 WATTS NOMINAL POWER
WEIGHT, LBS
VOLTAGE, VOLTS
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
5500.
5000.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

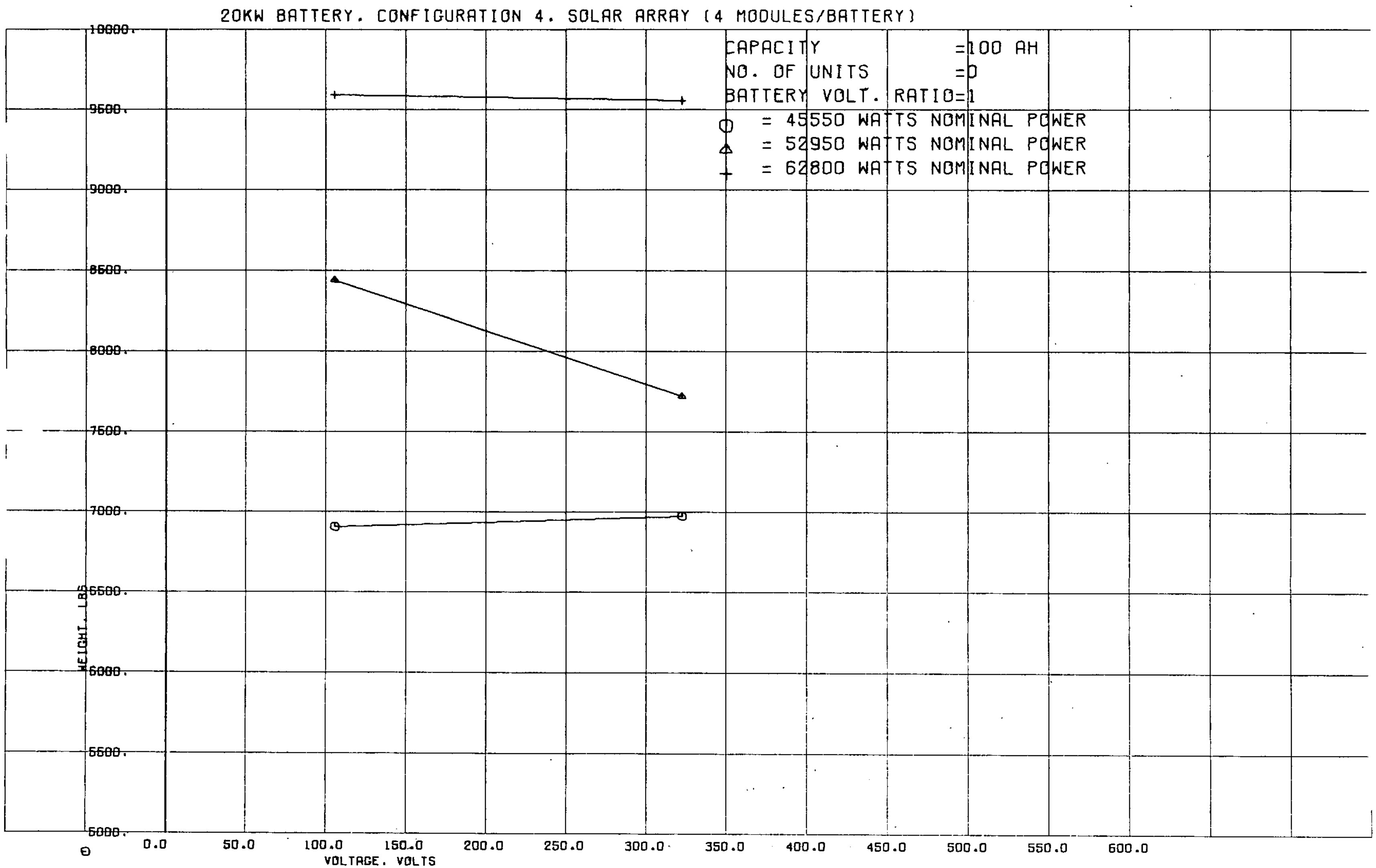

20KW BATTERY. CONFIGURATION 4 SOLAR ARRAY (3 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 43800 WATTS NOMINAL POWER
= 52200 WATTS NOMINAL POWER
= 61350 WATTS NOMINAL POWER
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
5500.
5000.
WEIGHT. LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

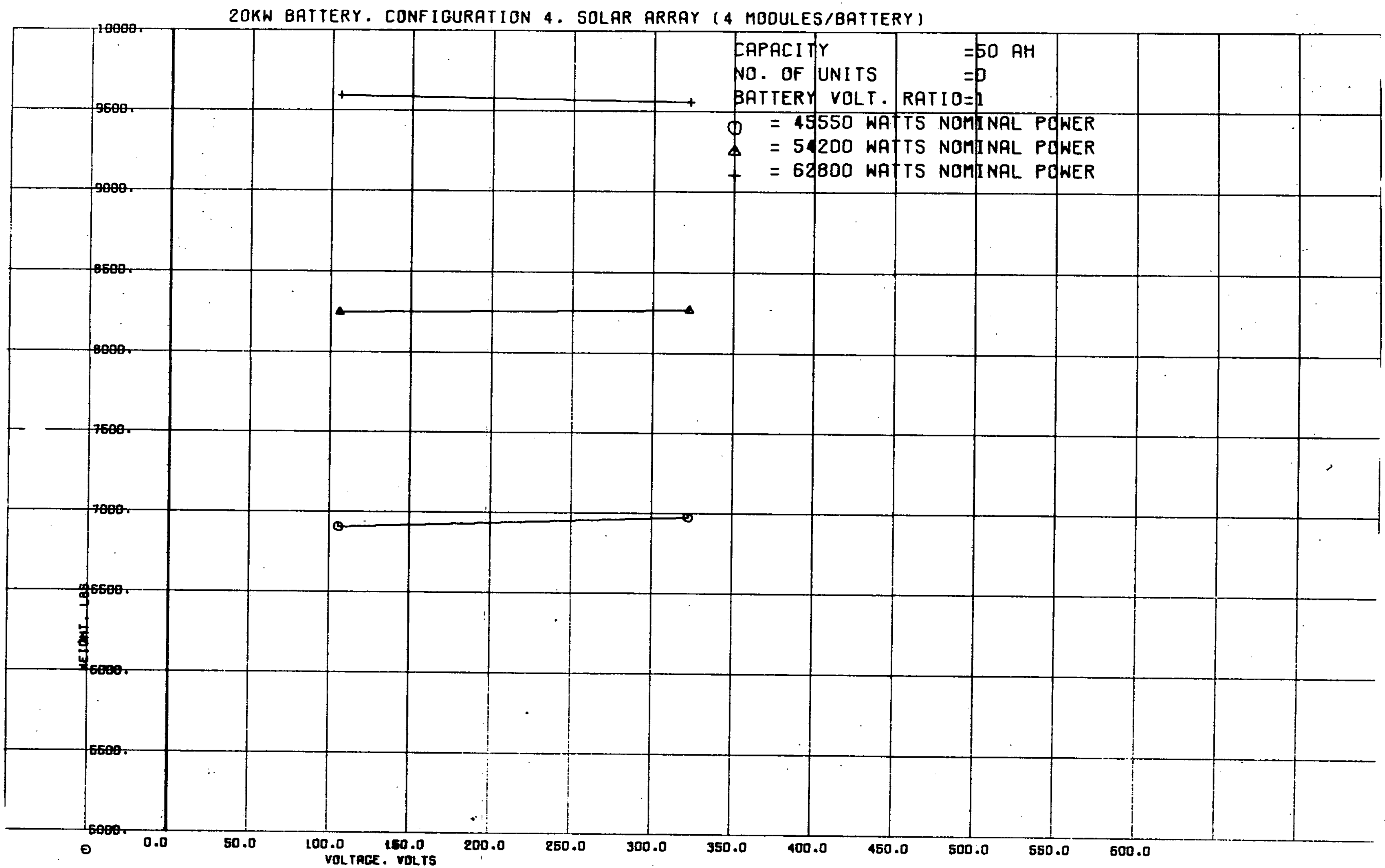

20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (3 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
○ = 45900 WATTS NOMINAL POWER
△ = 52400 WATTS NOMINAL POWER
+ = 63350 WATTS NOMINAL POWER
HEAT LOSS, WATTS
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS



20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (3 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
O = 45400 WATTS NOMINAL POWER
Δ = 52400 WATTS NOMINAL POWER
+ = 60950 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
0. 50. 100. 150. 200. 250. 300. 350. 400. 450. 500.
0.0 50.0 100.0 150.0 200.0 250.0 300.0 350.0 400.0 450.0 500.0 550.0 600.0

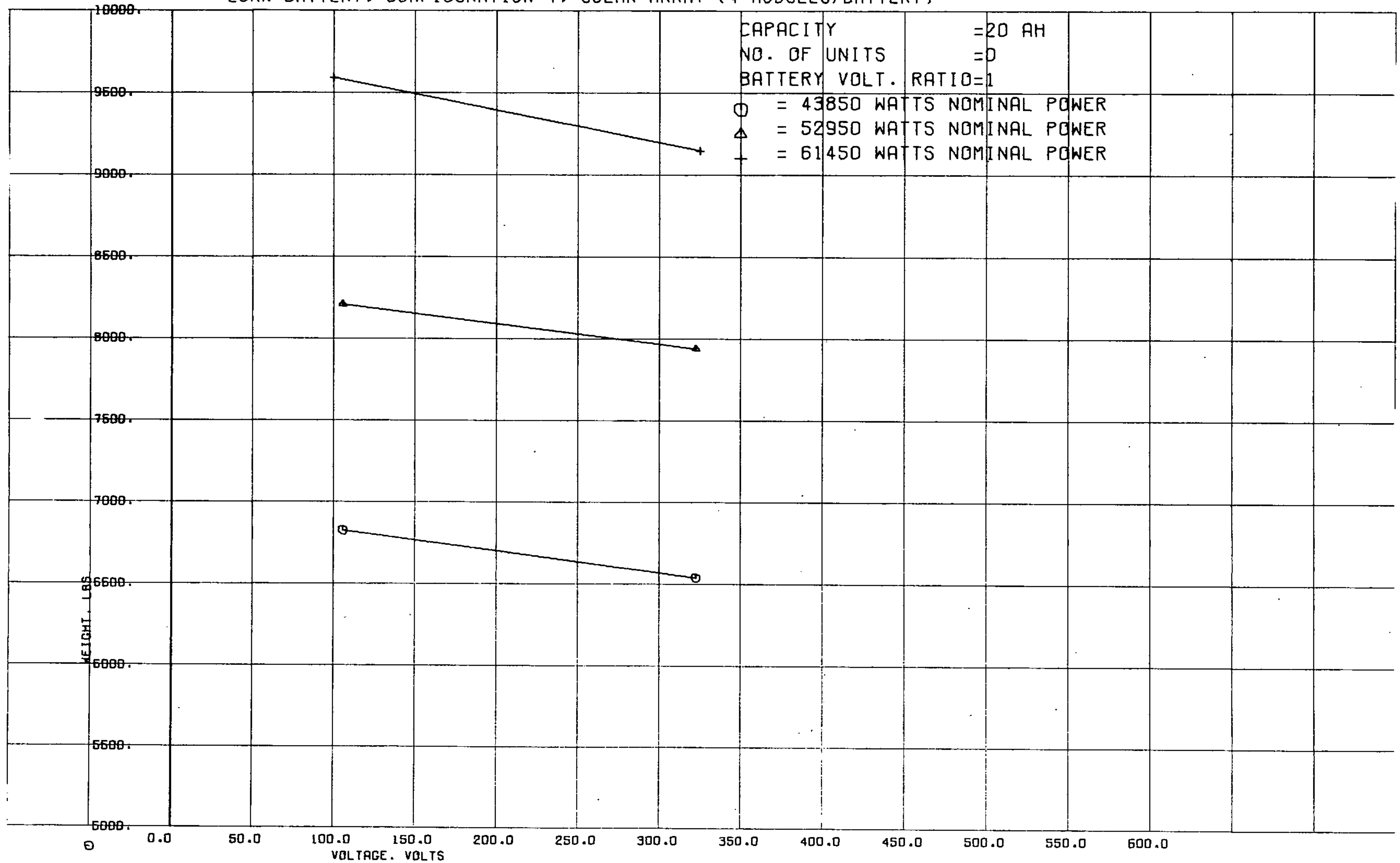

20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (3 MODULES/BATTERY)
CAPACITY =20 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
○ = 43800 WATTS NOMINAL POWER
△ = 52200 WATTS NOMINAL POWER
+ = 61350 WATTS NOMINAL POWER
HEAT LOSS, WATTS
VOLTAGE, VOLTS
0.
50.
100.
150.
200.
250.
300.
350.
400.
450.
500.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0


20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (4 MODULES/BATTERY)
CAPACITY =100 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
○ = 45550 WATTS NOMINAL POWER
△ = 52950 WATTS NOMINAL POWER
+ = 62800 WATTS NOMINAL POWER
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
5500.
5000.
WEIGHT, LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE, VOLTS

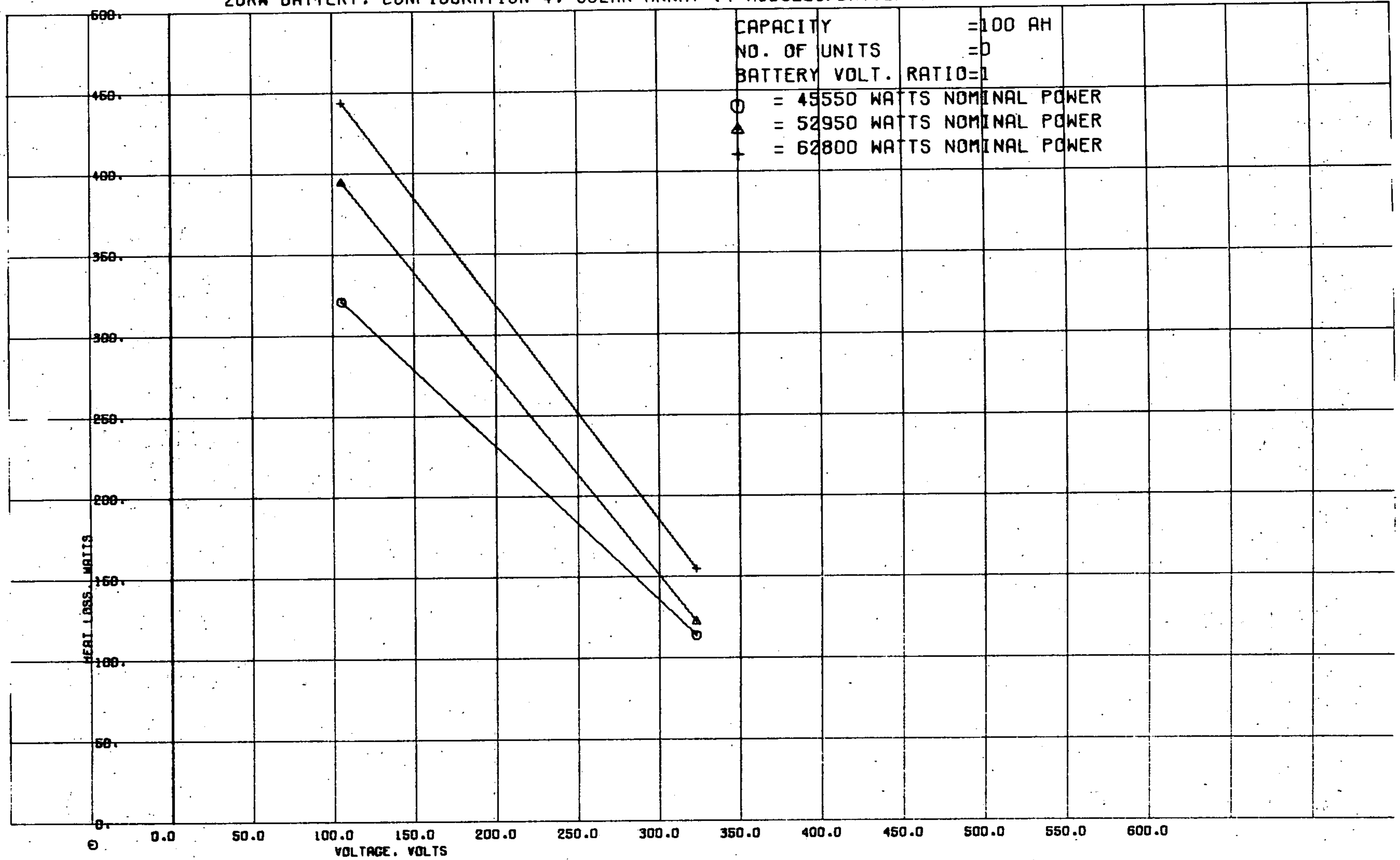


20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (4 MODULES/BATTERY)
CAPACITY =50 AH
NO. OF UNITS =0
BATTERY VOLT. RATIO=1
= 45550 WATTS NOMINAL POWER
= 54200 WATTS NOMINAL POWER
= 62800 WATTS NOMINAL POWER
10000.
9500.
9000.
8500.
8000.
7500.
7000.
6500.
6000.
5500.
5000.
WEIGHT. LBS
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0
VOLTAGE. VOLTS

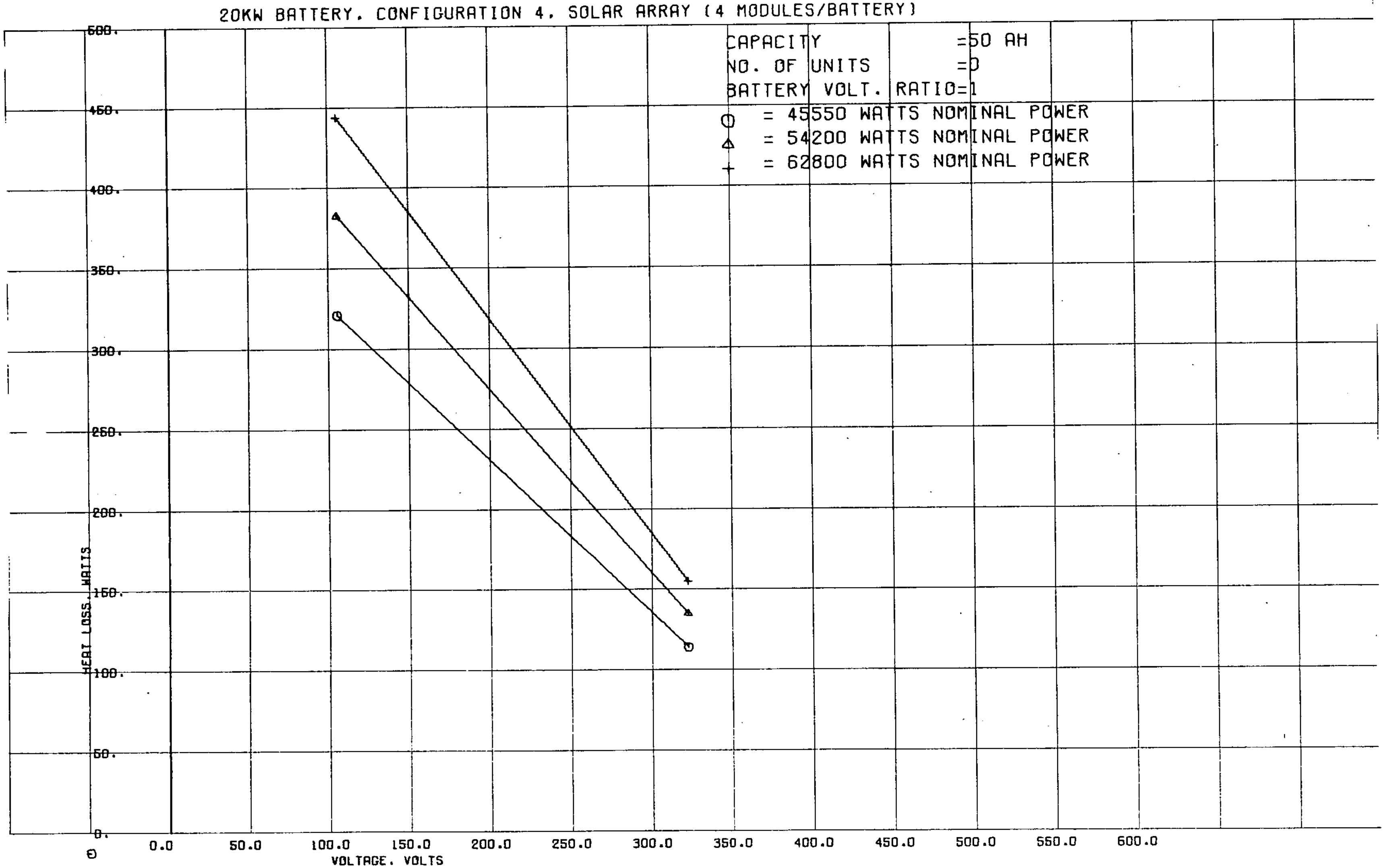
20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (4 MODULES/BATTERY)



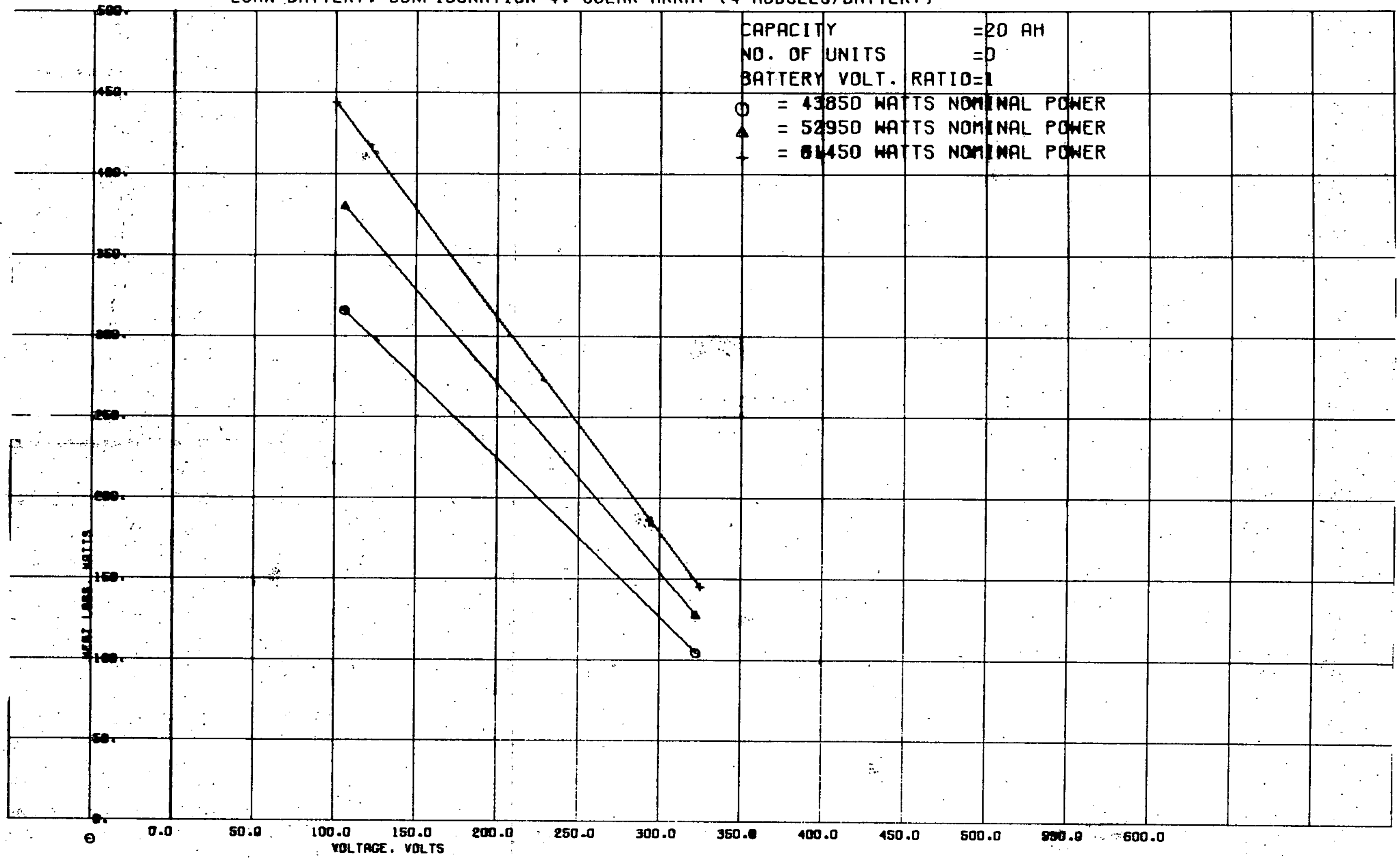
20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (4 MODULES/BATTERY)



20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (4 MODULES/BATTERY)



20KW BATTERY. CONFIGURATION 4. SOLAR ARRAY (4 MODULES/BATTERY)



SEE CONFIGURATION 1

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SEE CONFIGURATION 1

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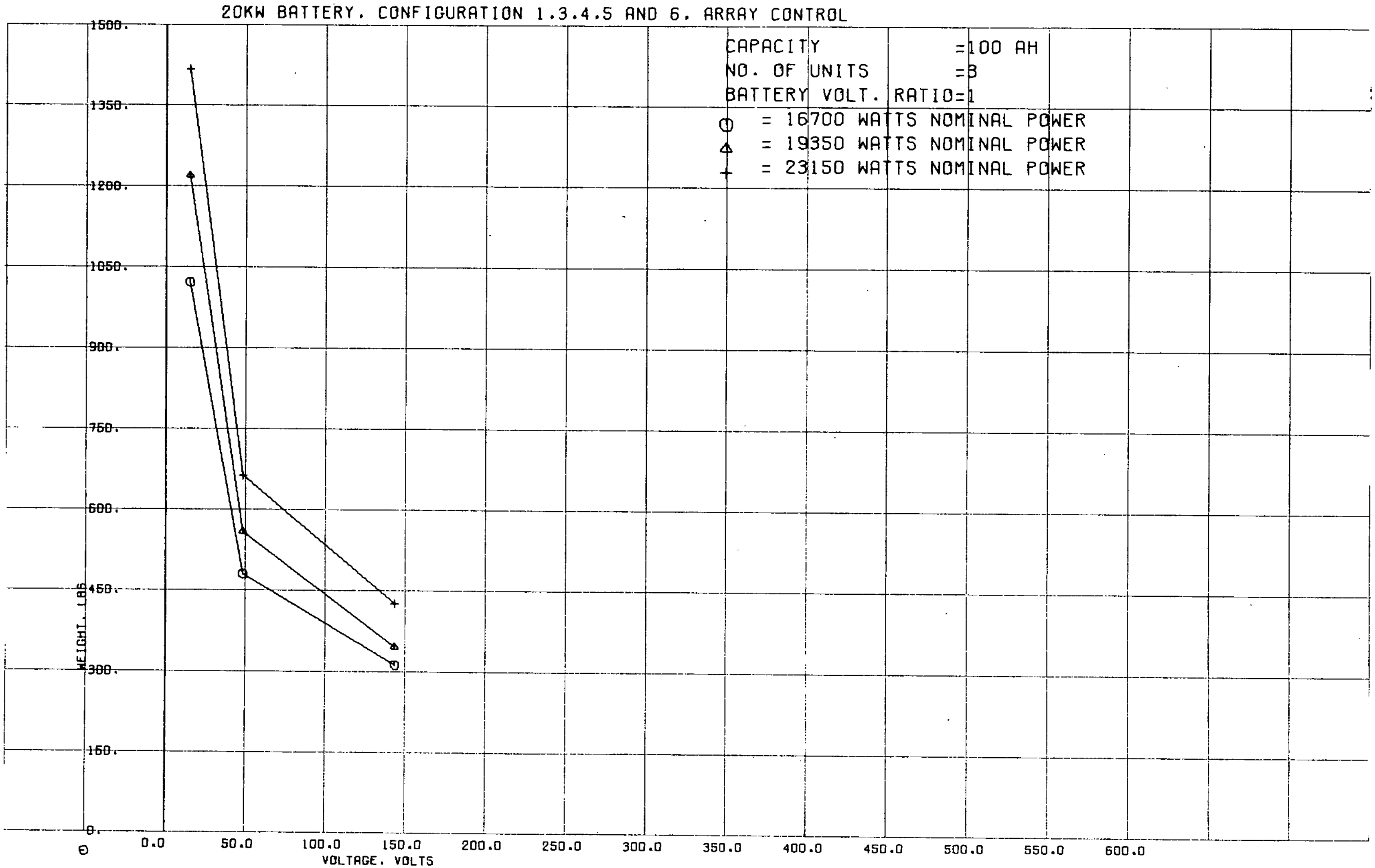

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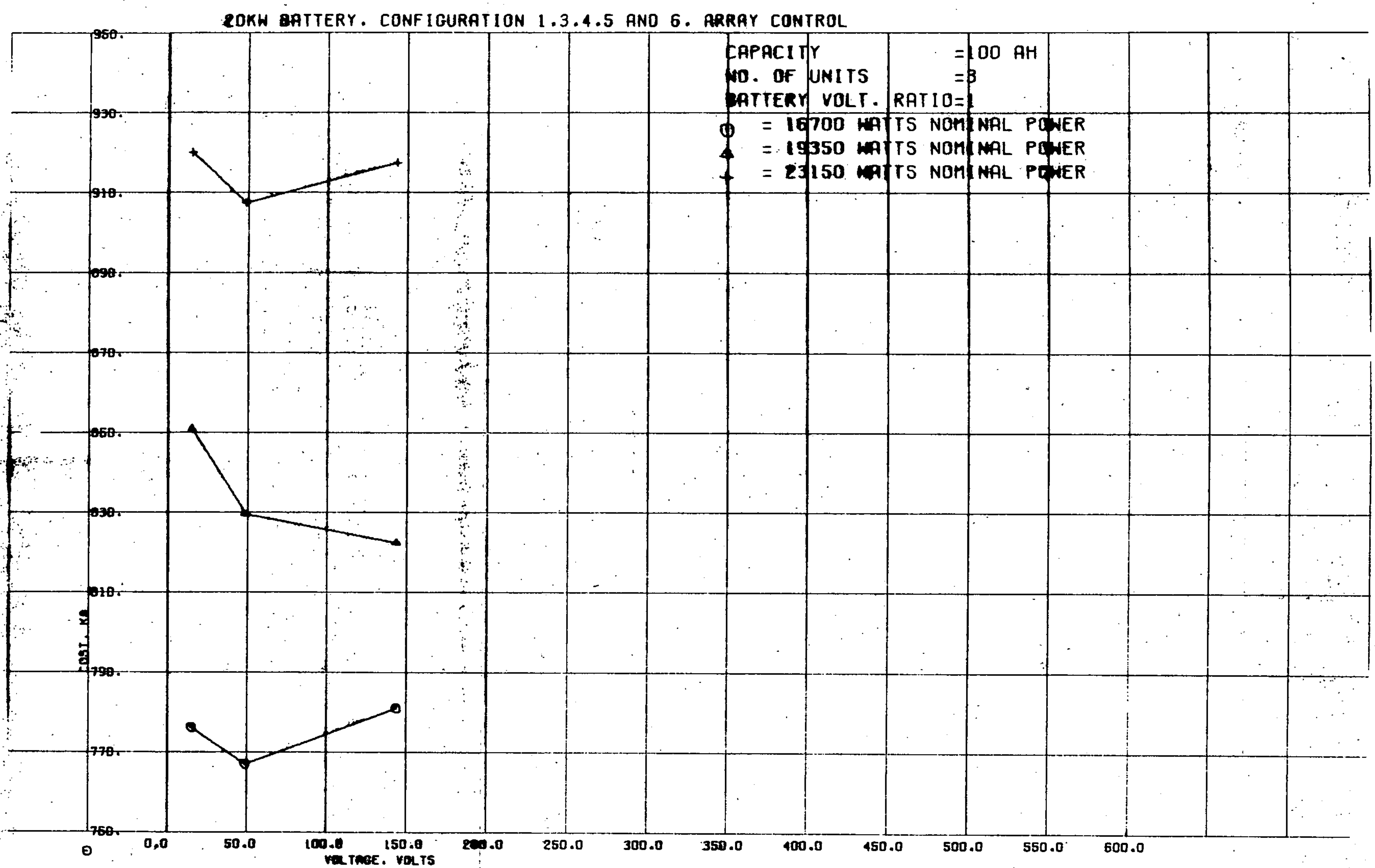
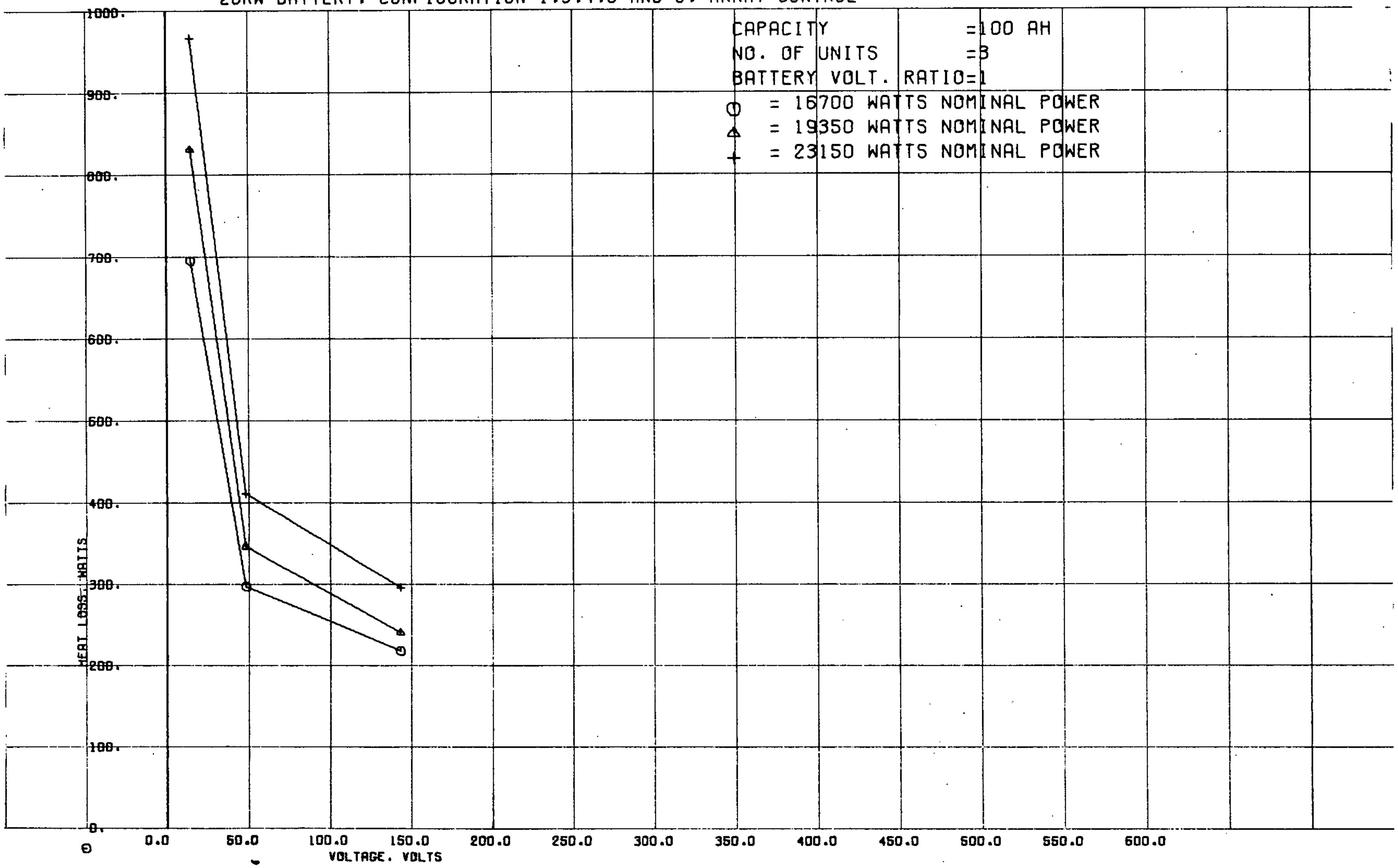

20KW BATTERY. CONFIGURATION 1.3.4.5 AND 6. ARRAY CONTROL
CAPACITY =100 AH
NO. OF UNITS =8
BATTERY VOLT. RATIO=1
= 16700 WATTS NOMINAL POWER
= 19350 WATTS NOMINAL POWER
= 23150 WATTS NOMINAL POWER
COST, K$
VOLTAGE, VOLTS
950.
930.
910.
890.
870.
850.
830.
810.
790.
770.
750.
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
550.0
600.0

20KW BATTERY, CONFIGURATION 1,3,4,5 AND 6, ARRAY CONTROL



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NO ARRAY CONTROL

PRECEDING PAGE BLANK NOT FILMED

SEE CONFIGURATION 1

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SEE CONFIGURATION 1

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SEE CONFIGURATION 1

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SEE CONFIGURATION 1

78

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CORRECTION FACTOR CHARTS

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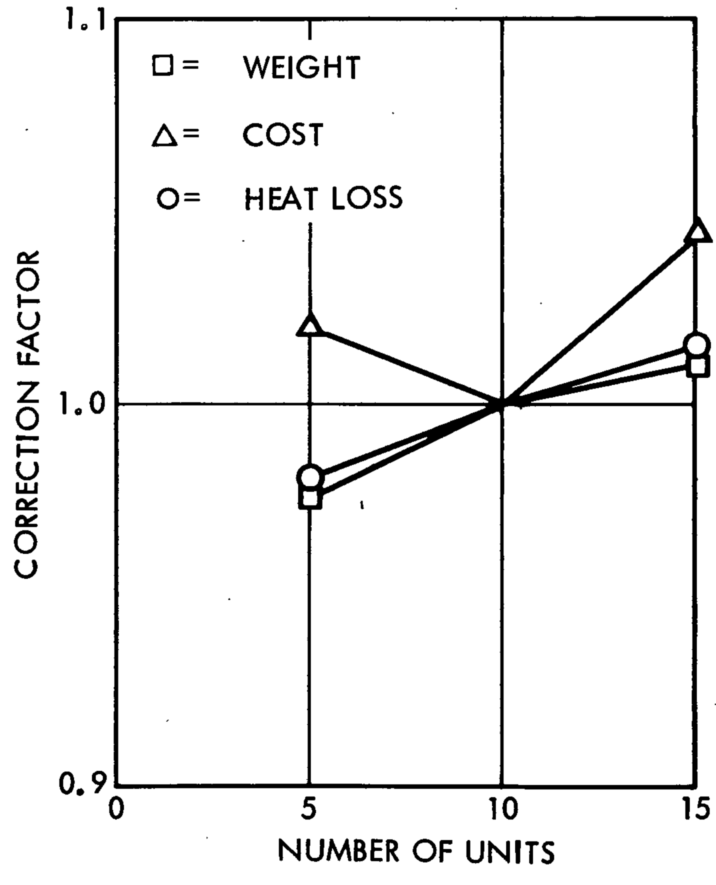
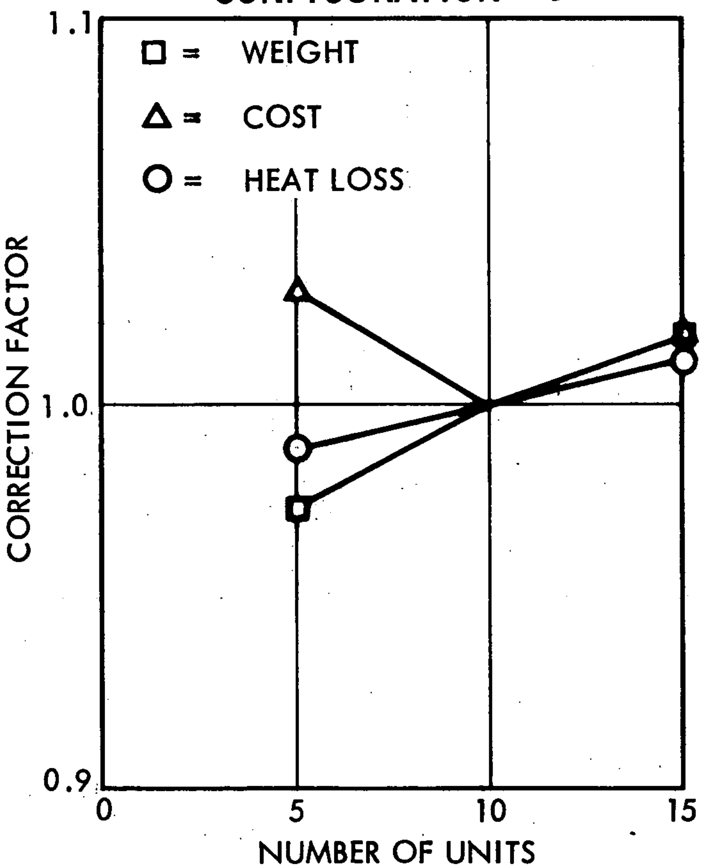
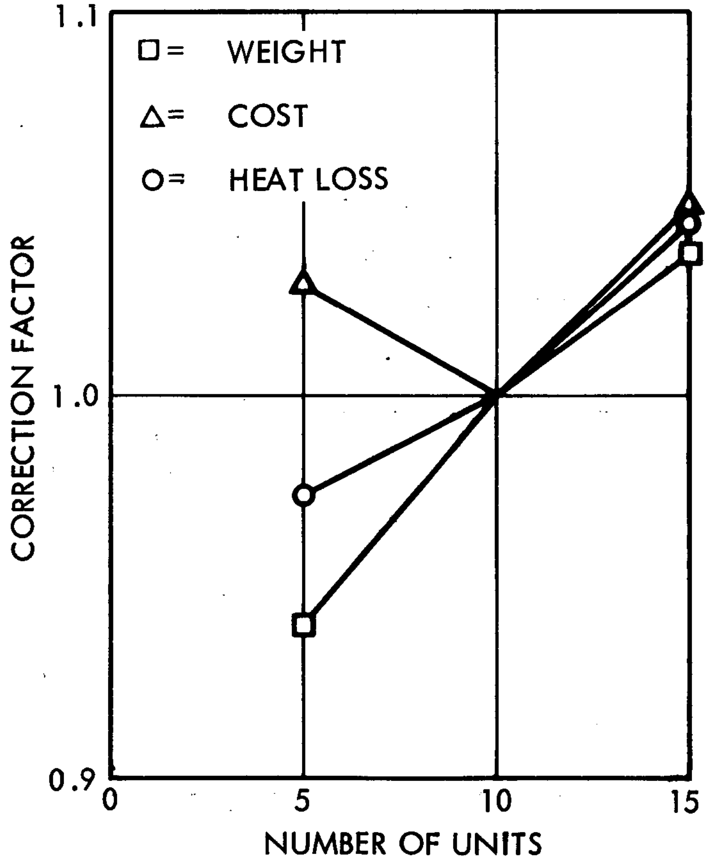
DISCHARGE CIRCUIT
CORRECTION FACTOR
CONFIGURATION 2

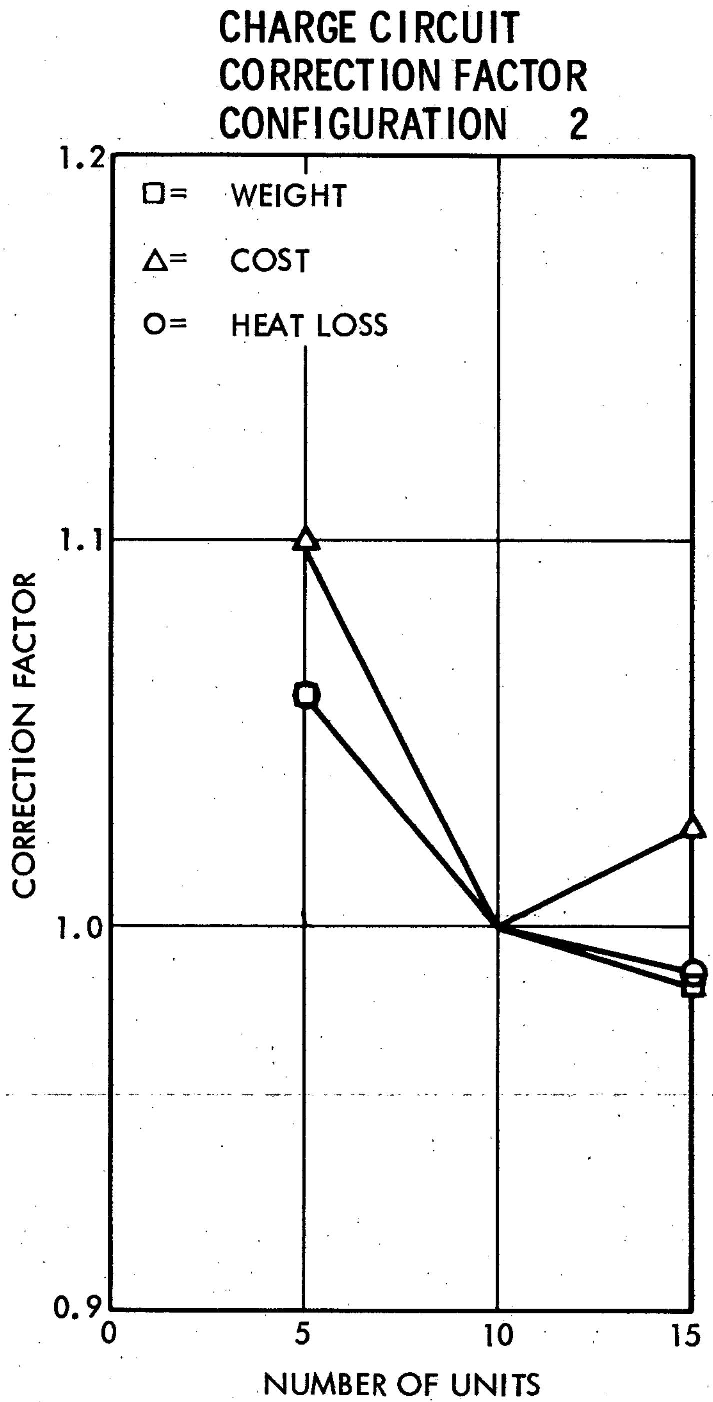


DISCHARGE CIRCUIT
CORRECTION FACTOR
CONFIGURATION 3



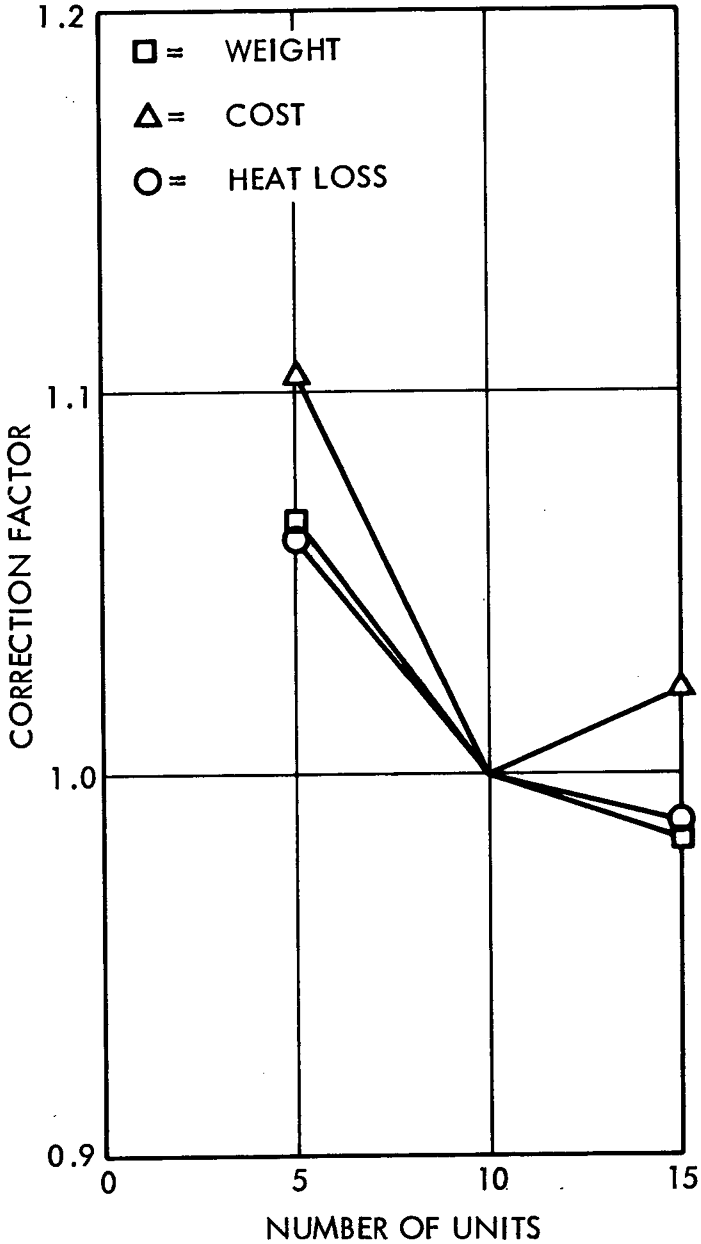
DISCHARGE CIRCUIT CORRECTION FACTOR CONFIGURATION 6

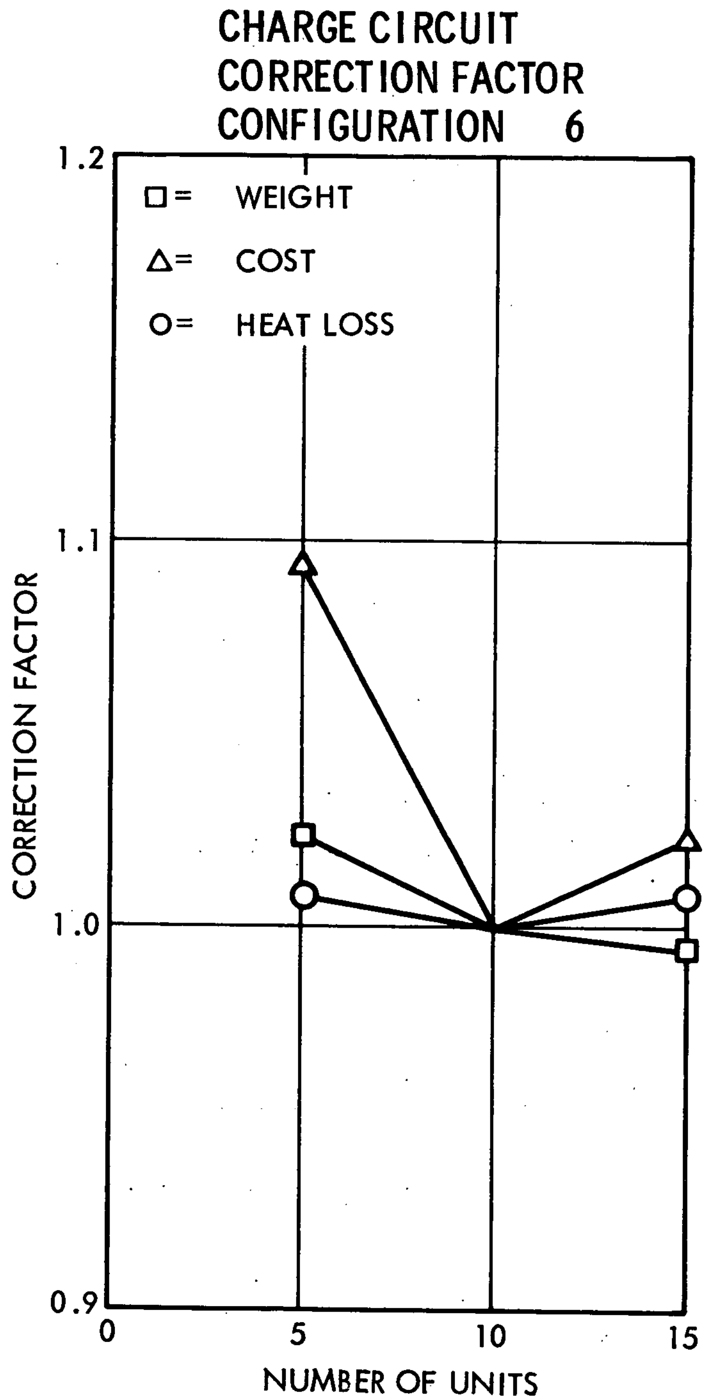


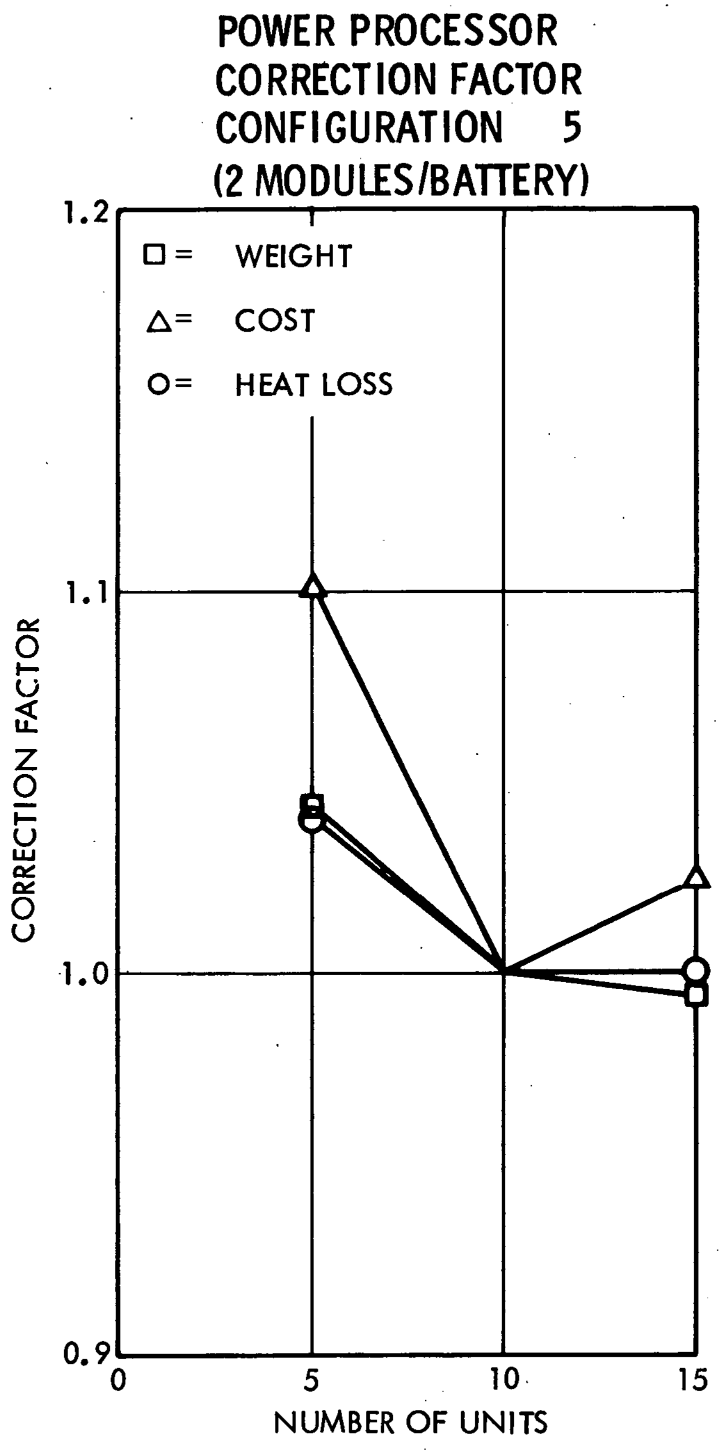


CHARGE CIRCUIT
CORRECTION FACTOR
CONFIGURATION 2
□= WEIGHT
△= COST
O= HEAT LOSS
1.2
1.1
1.0
0.9
CORRECTION FACTOR
0
5
10
15
NUMBER OF UNITS

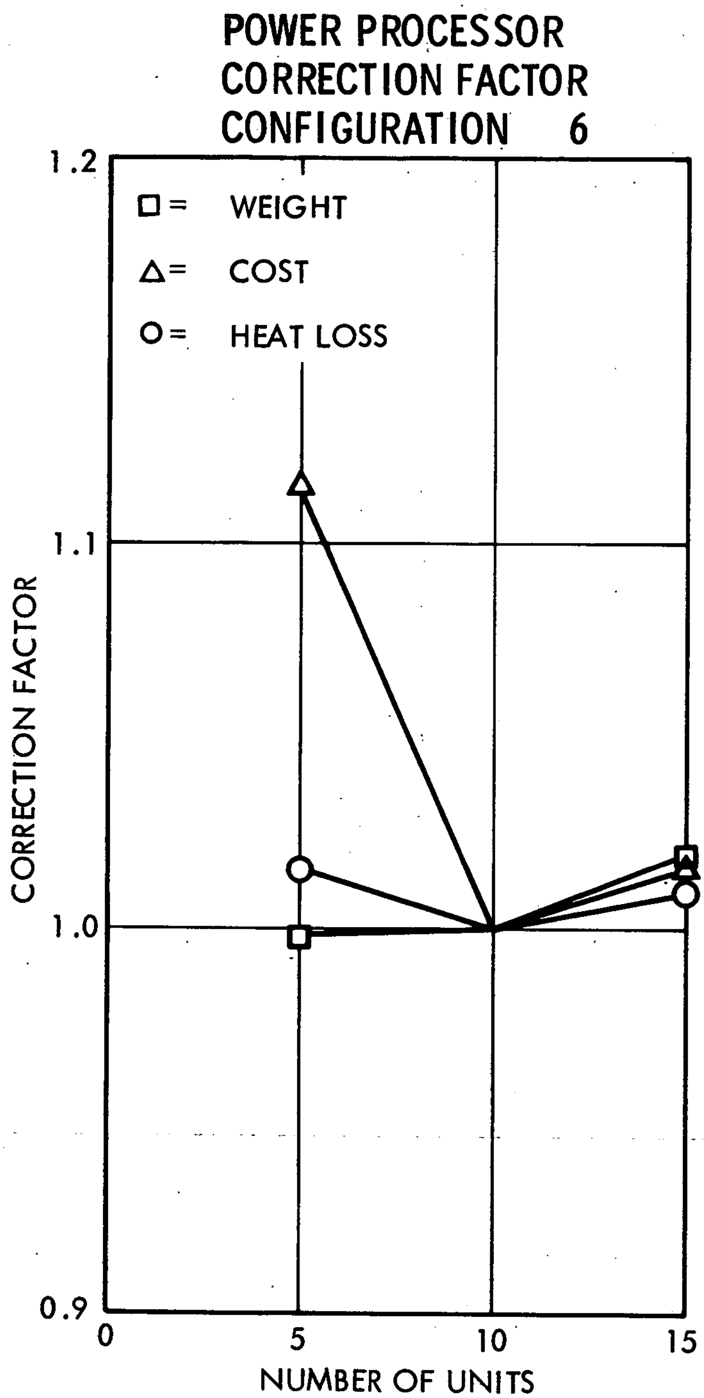
CHARGE CIRCUIT CORRECTION FACTOR CONFIGURATION 3



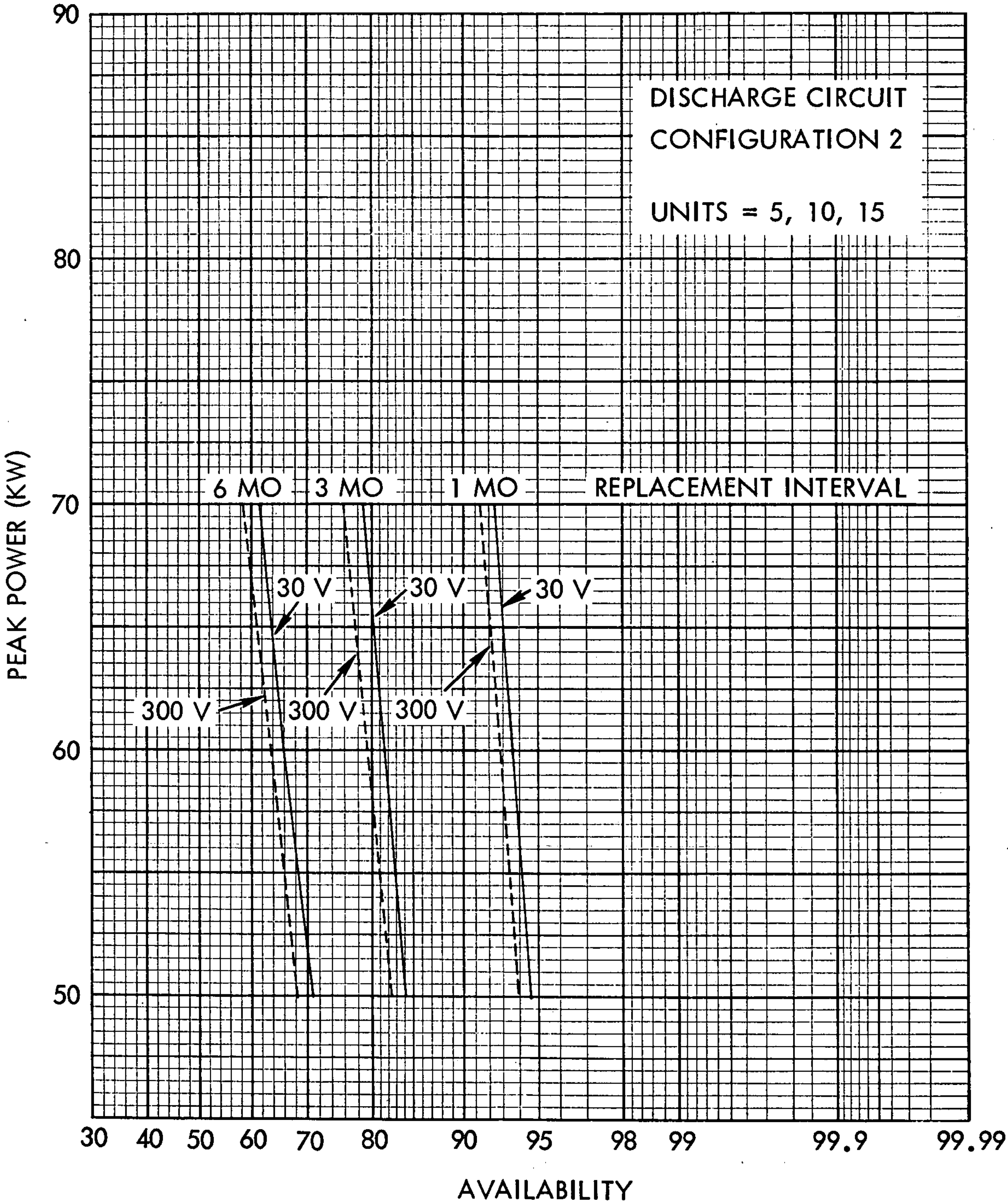

CHARGE CIRCUIT
CORRECTION FACTOR
CONFIGURATION 6
□= WEIGHT
△= COST
○= HEAT LOSS
1.2
1.1
1.0
0.9
CORRECTION FACTOR
0
5
10
15
NUMBER OF UNITS

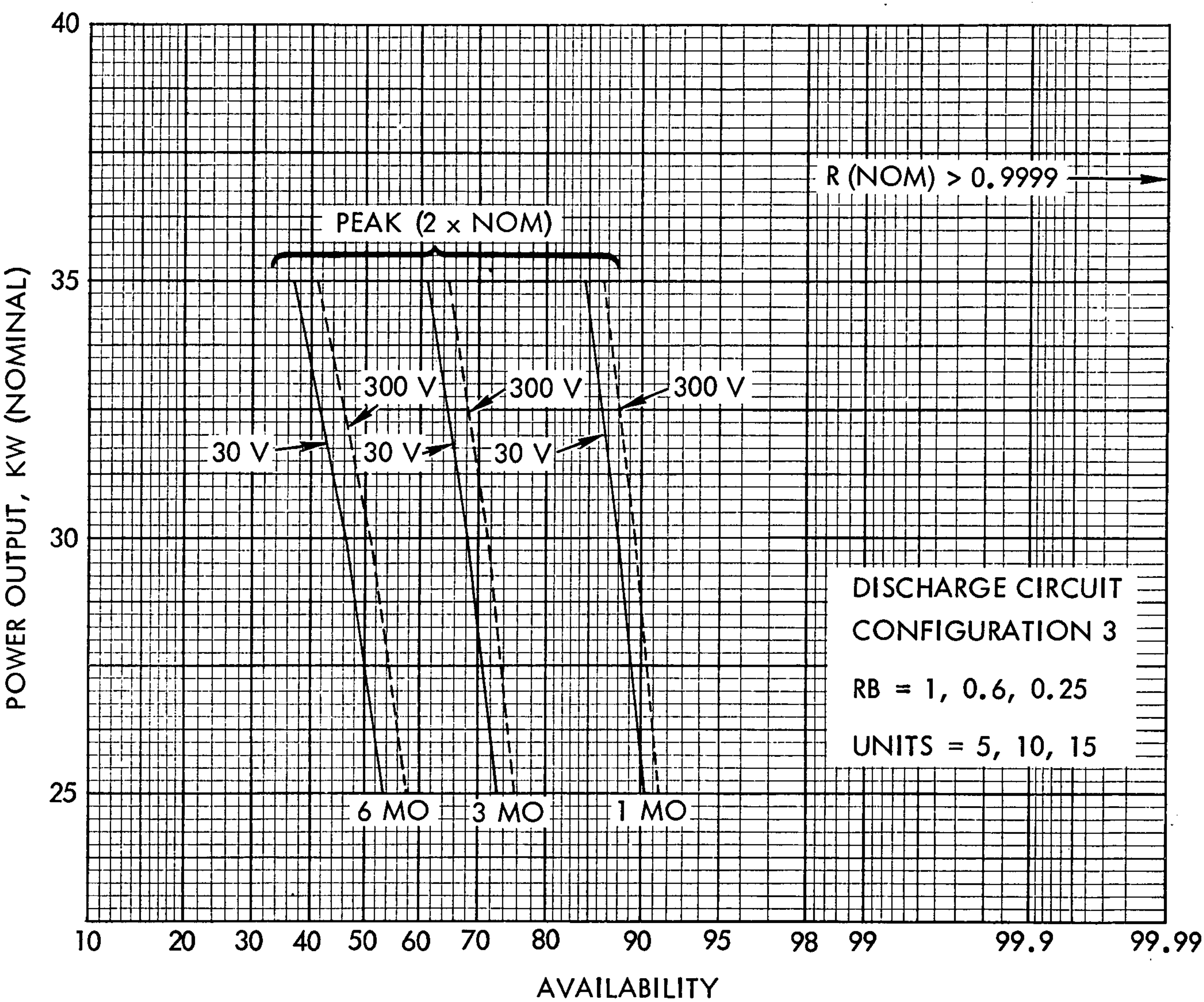


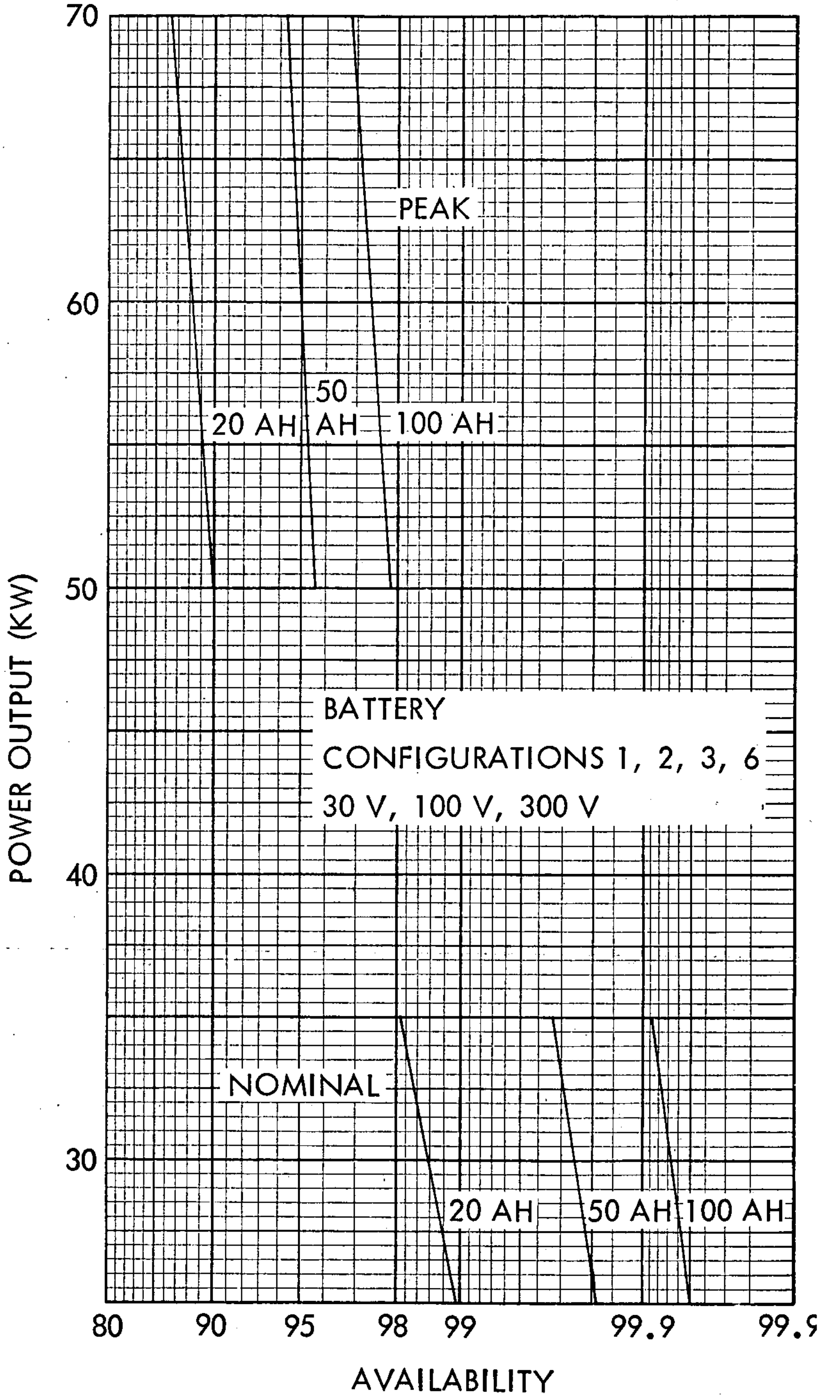
POWER PROCESSOR
CORRECTION FACTOR
CONFIGURATION 5
(2 MODULES/BATTERY)
□ = WEIGHT
△ = COST
○ = HEAT LOSS
CORRECTION FACTOR
1.2
1.1
1.0
0.9
0
5
10
15
NUMBER OF UNITS


POWER PROCESSOR
CORRECTION FACTOR
CONFIGURATION 6
□ = WEIGHT
△ = COST
○ = HEAT LOSS
CORRECTION FACTOR
1.2
1.1
1.0
0.9
0
5
10
15
NUMBER OF UNITS

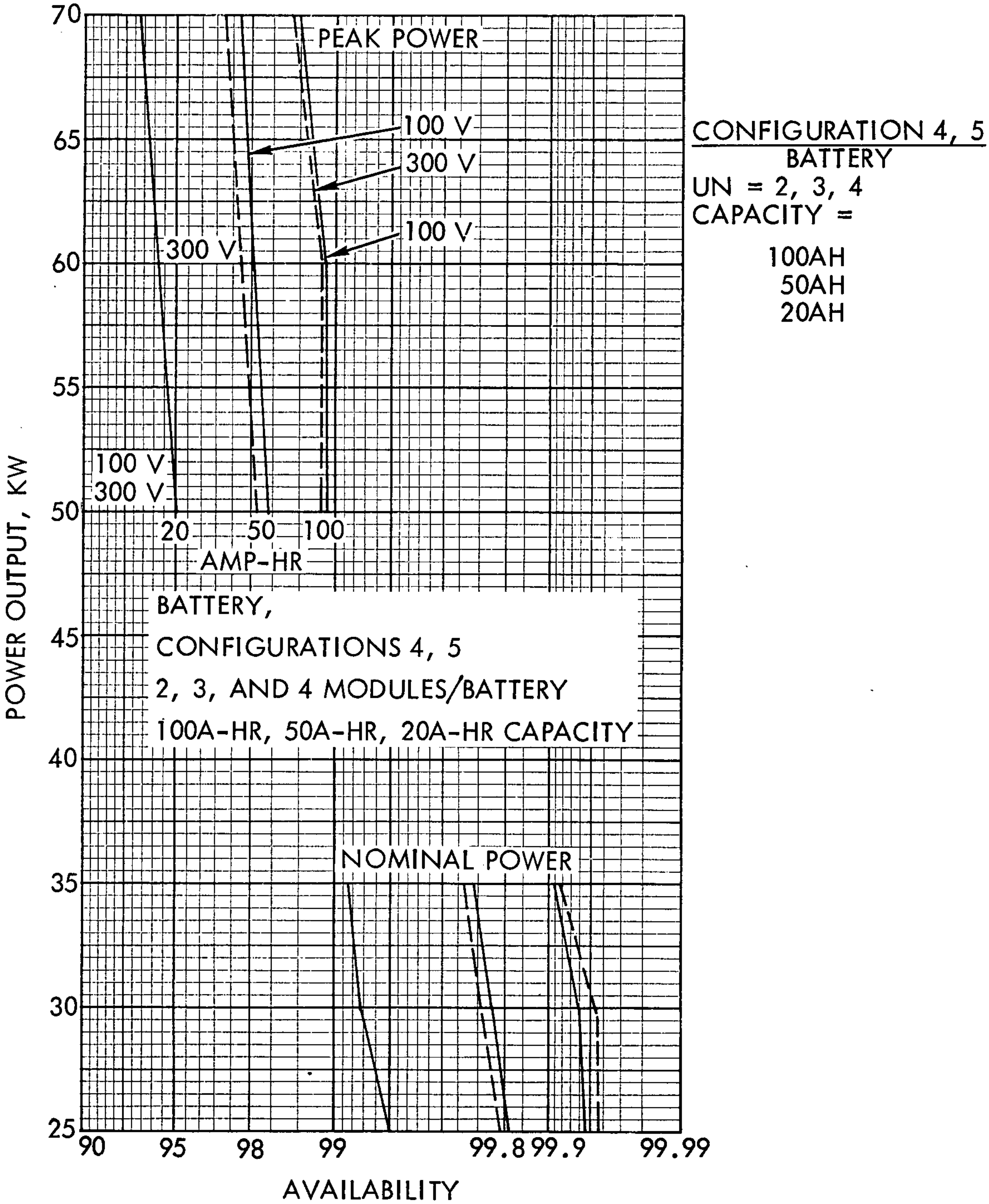
AVAILABILITY CHARTS

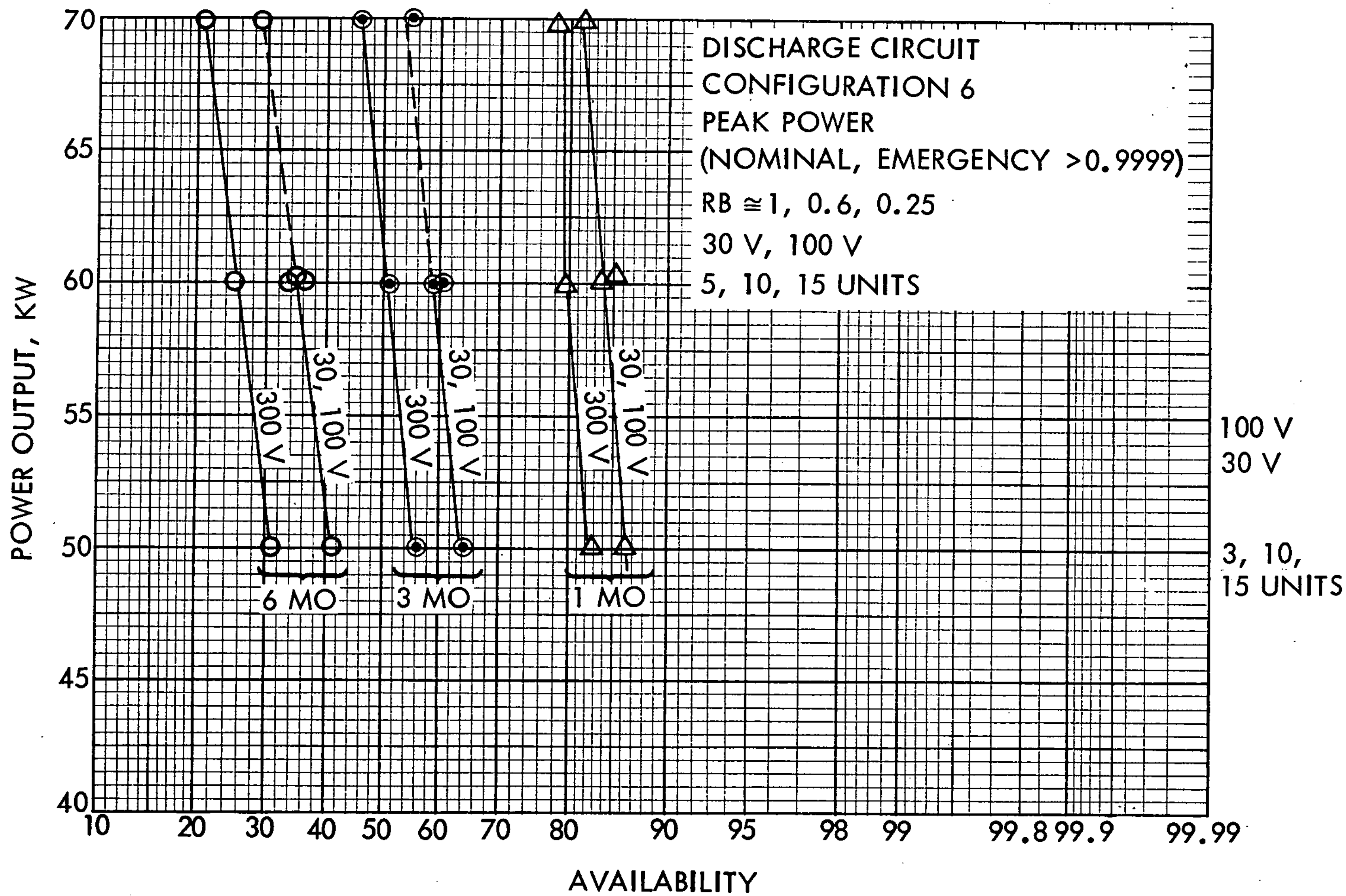

DISCHARGE CIRCUIT
CONFIGURATION 2
UNITS = 5, 10, 15
6 MO
3 MO
1 MO
REPLACEMENT INTERVAL
30 V
30 V
30 V
300 V
300 V
300 V
PEAK POWER (KW)
90
80
70
60
50
30
40
50
60
70
80
90
95
98
99
99.9
99.99
AVAILABILITY

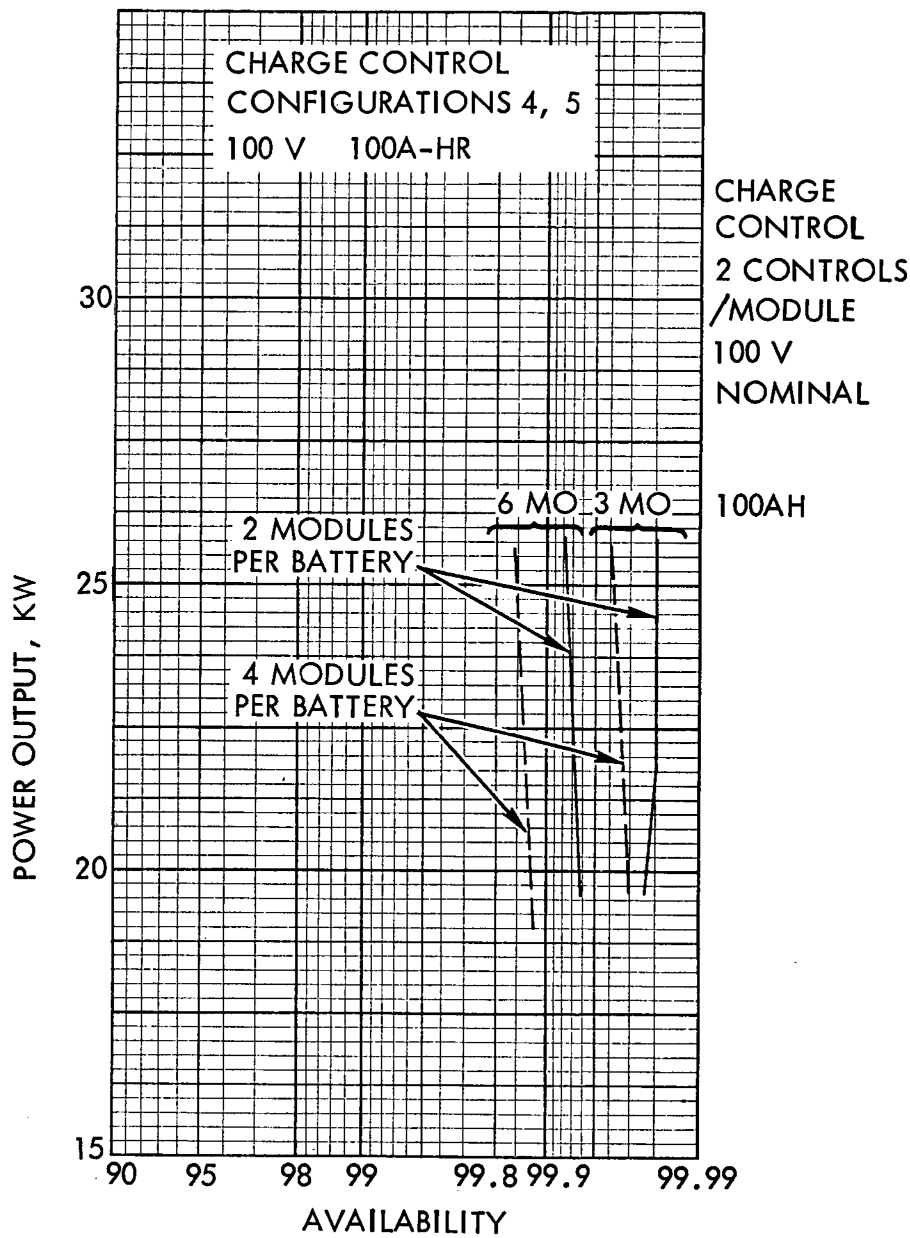

40
35
30
25
POWER OUTPUT, KW (NOMINAL)
R (NOM) > 0.9999
PEAK (2 x NOM)
300 V
300 V
300 V
30 V
30 V
30 V
6 MO
3 MO
1 MO
DISCHARGE CIRCUIT
CONFIGURATION 3
RB = 1, 0.6, 0.25
UNITS = 5, 10, 15
10 20 30 40 50 60 70 80 90 95 98 99 99.9 99.99
AVAILABILITY

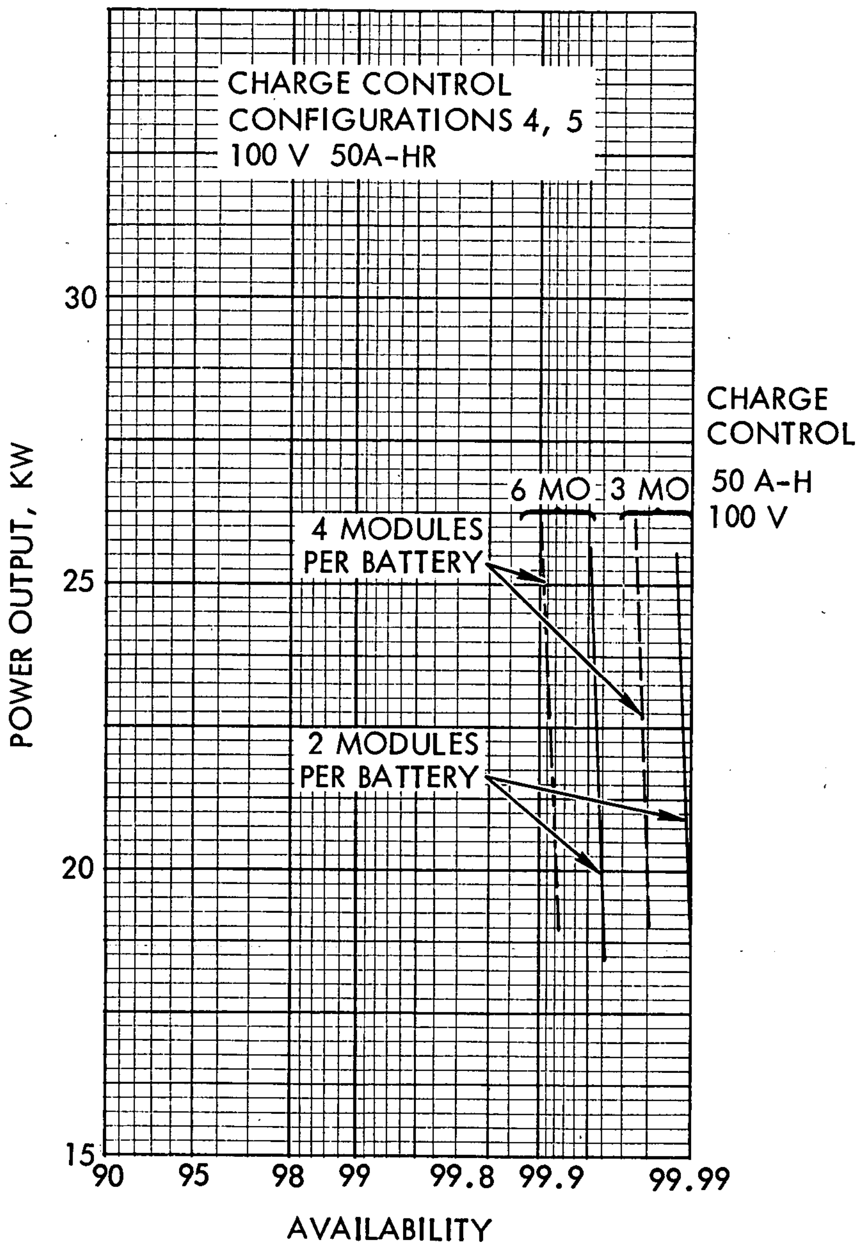


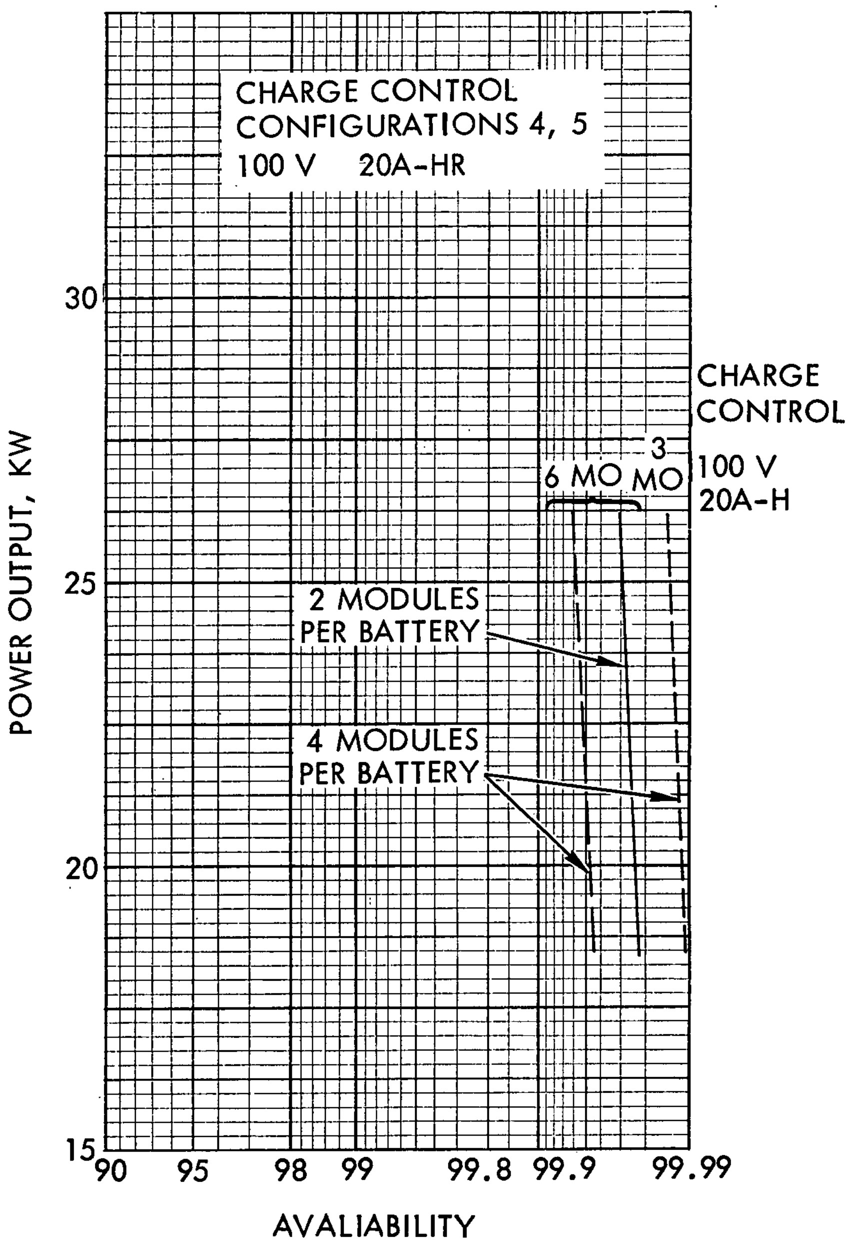
PEAK
20 AH
50
AH
100 AH
BATTERY
CONFIGURATIONS 1, 2, 3, 6
30 V, 100 V, 300 V
NOMINAL
20 AH
50 AH
100 AH
POWER OUTPUT (KW)
70
60
50
40
30
80
90
95
98
99
99.9
AVAILABILITY

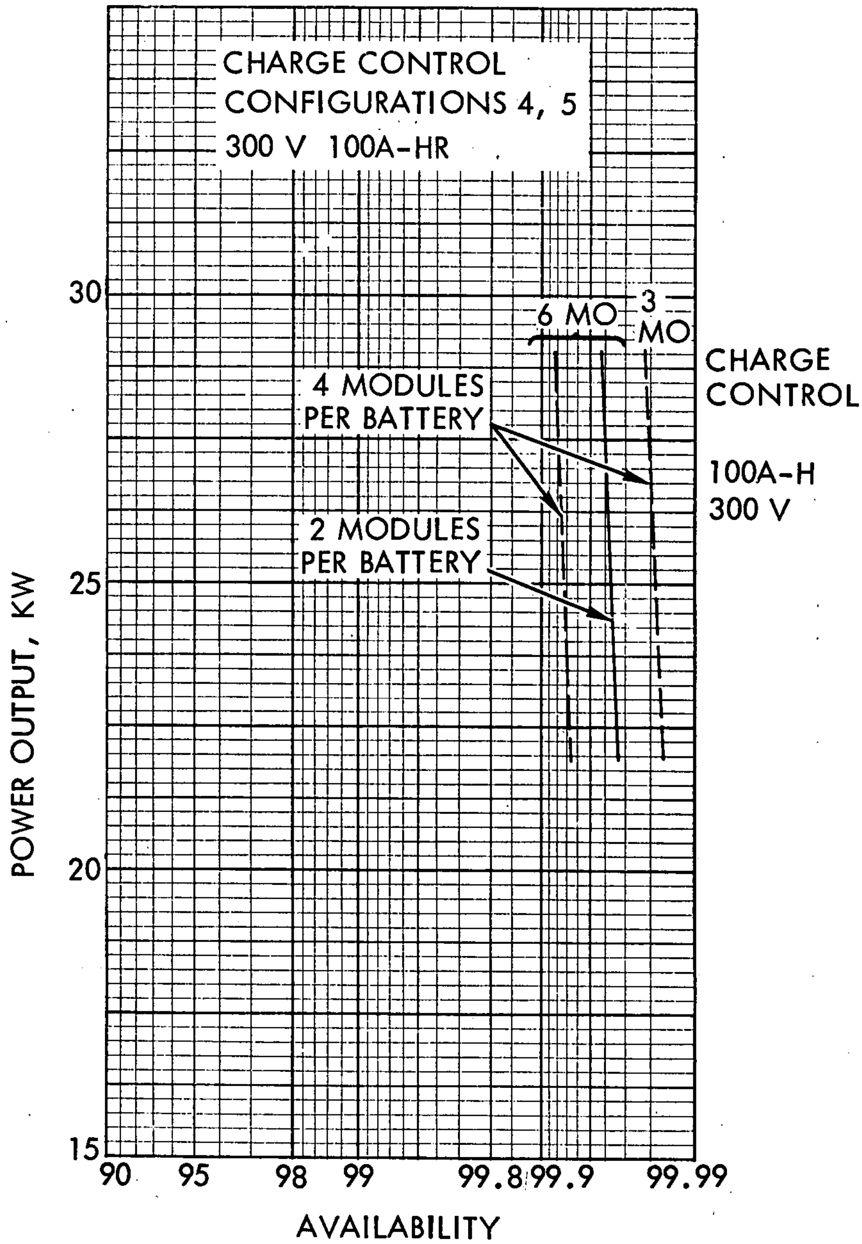

PEAK POWER
100 V
300 V
100 V
300 V
100 V
300 V
20
50
100
AMP-HR
BATTERY,
CONFIGURATIONS 4, 5
2, 3, AND 4 MODULES/BATTERY
100A-HR, 50A-HR, 20A-HR CAPACITY
NOMINAL POWER
POWER OUTPUT, KW
70
65
60
55
50
45
40
35
30
25
90
95
98
99
99.8
99.9
99.99
AVAILABILITY
CONFIGURATION 4, 5
BATTERY
UN = 2, 3, 4
CAPACITY =
100AH
50AH
20AH

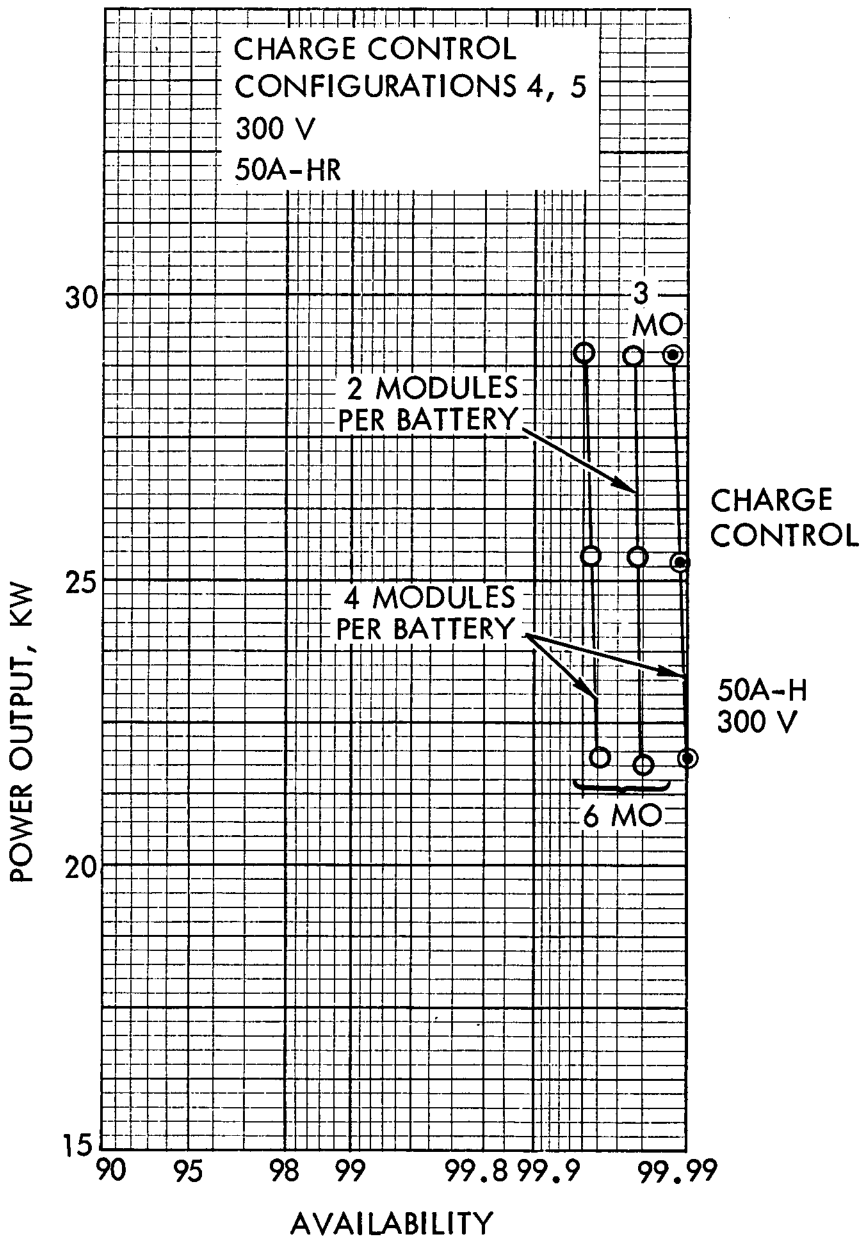

DISCHARGE CIRCUIT
CONFIGURATION 6
PEAK POWER
(NOMINAL, EMERGENCY >0.9999)
RB ≅ 1, 0.6, 0.25
30 V, 100 V
5, 10, 15 UNITS
300 V
30, 100 V
6 MO
3 MO
1 MO
100 V
30 V
3, 10,
15 UNITS
POWER OUTPUT, KW
70
65
60
55
50
45
40
AVAILABILITY
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
99.99

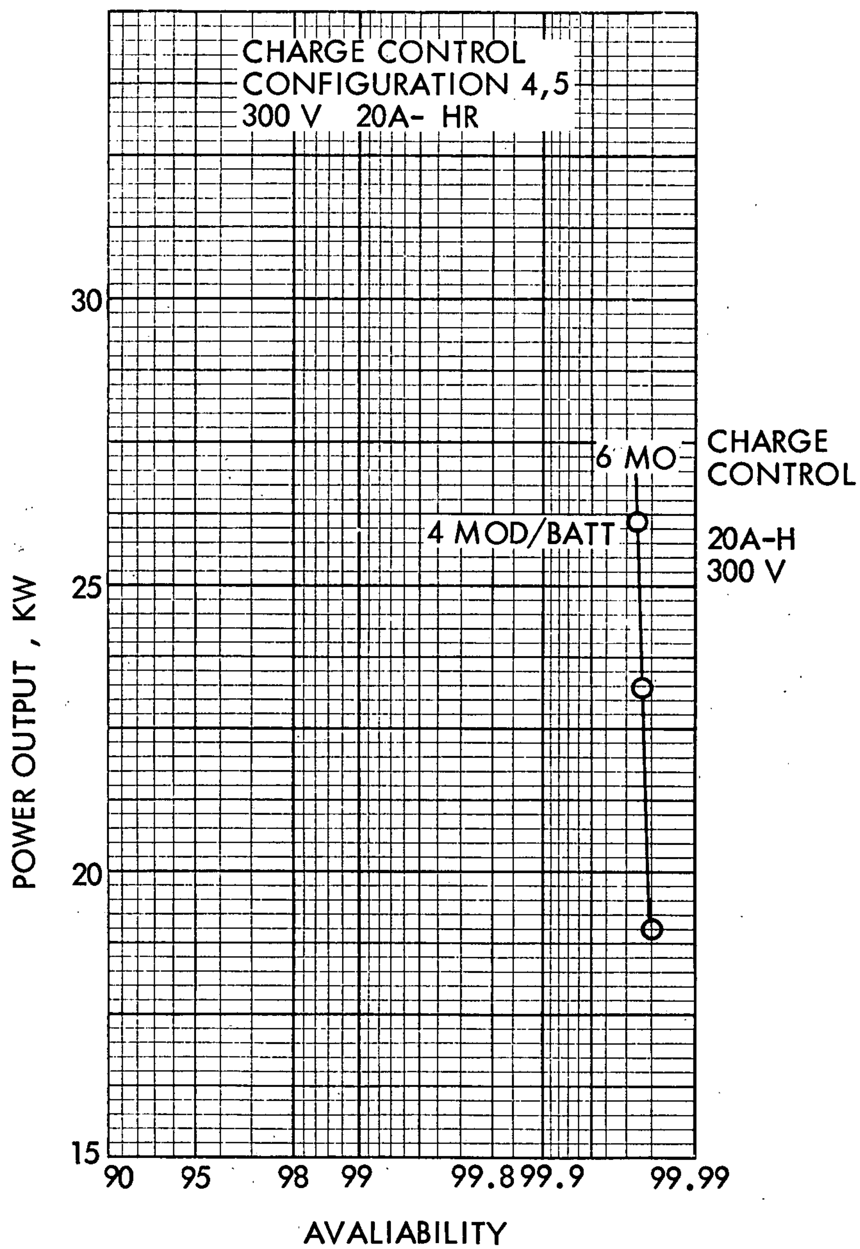

CHARGE CONTROL
CONFIGURATIONS 4, 5
100 V 100A-HR
CHARGE
CONTROL
2 CONTROLS
/MODULE
100 V
NOMINAL
100AH
6 MO
3 MO
2 MODULES
PER BATTERY
4 MODULES
PER BATTERY
POWER OUTPUT, KW
15
20
25
30
90
95
98
99
99.8
99.9
99.99
AVAILABILITY

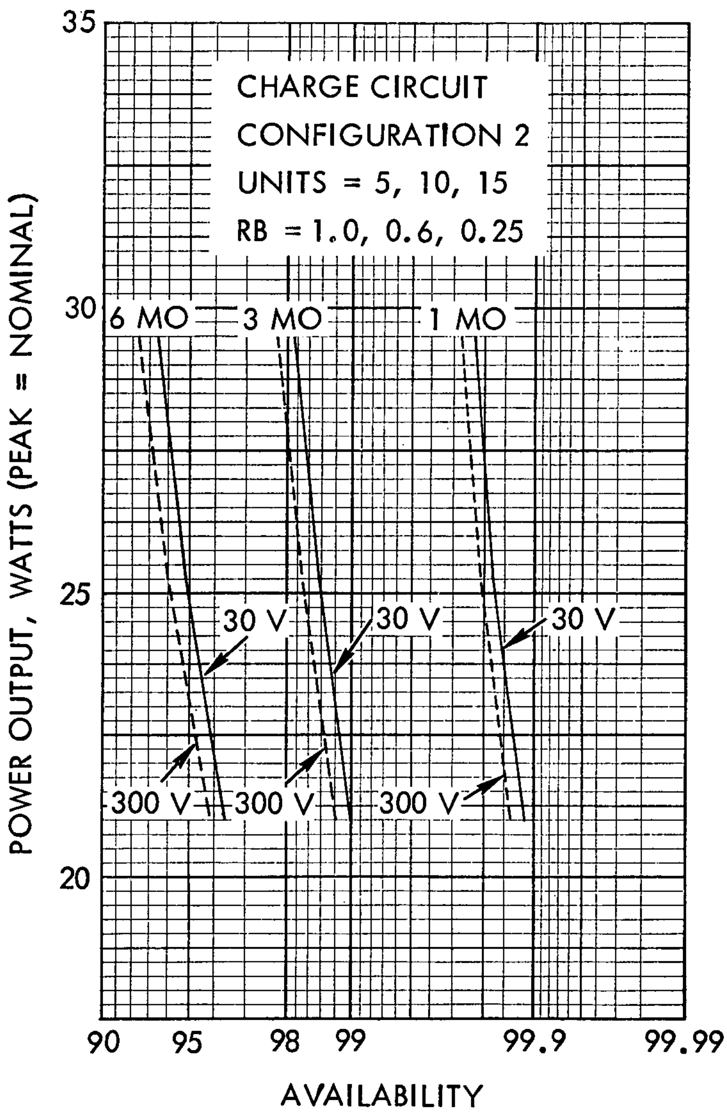

CHARGE CONTROL
CONFIGURATIONS 4, 5
100 V 50A-HR
POWER OUTPUT, KW
30
25
20
15
CHARGE
CONTROL
50 A-H
100 V
6 MO
3 MO
4 MODULES
PER BATTERY
2 MODULES
PER BATTERY
90
95
98
99
99.8
99.9
99.99
AVAILABILITY

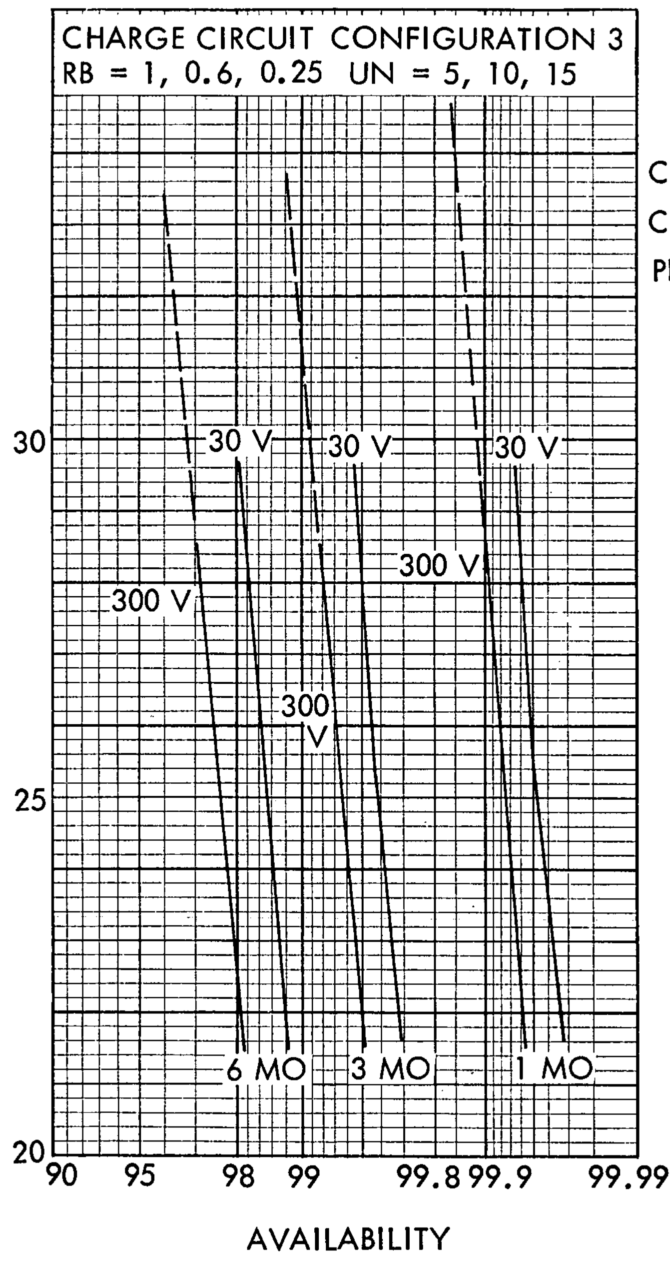

CHARGE CONTROL
CONFIGURATIONS 4, 5
100 V 20A-HR
CHARGE
CONTROL
100 V
20A-H
6 MO
3 MO
2 MODULES
PER BATTERY
4 MODULES
PER BATTERY
POWER OUTPUT, KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVALIABILITY


CHARGE CONTROL
CONFIGURATIONS 4, 5
300 V 100A-HR
6 MO
3
MO
CHARGE
CONTROL
100A-H
300 V
4 MODULES
PER BATTERY
2 MODULES
PER BATTERY
POWER OUTPUT, KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVAILABILITY

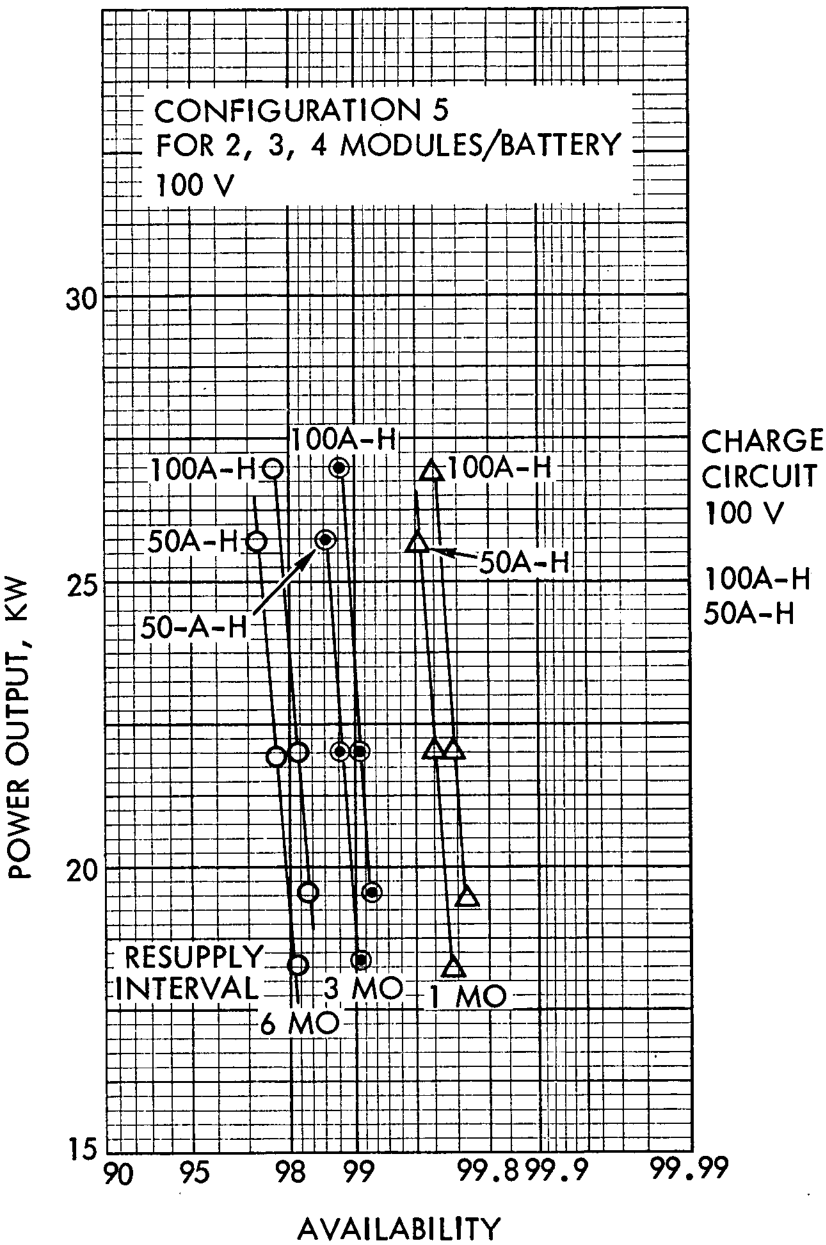

CHARGE CONTROL
CONFIGURATIONS 4, 5
300 V
50A-HR
3
MO
2 MODULES
PER BATTERY
CHARGE
CONTROL
4 MODULES
PER BATTERY
50A-H
300 V
6 MO
30
25
20
15
POWER OUTPUT, KW
90
95
98
99
99.8
99.9
99.99
AVAILABILITY

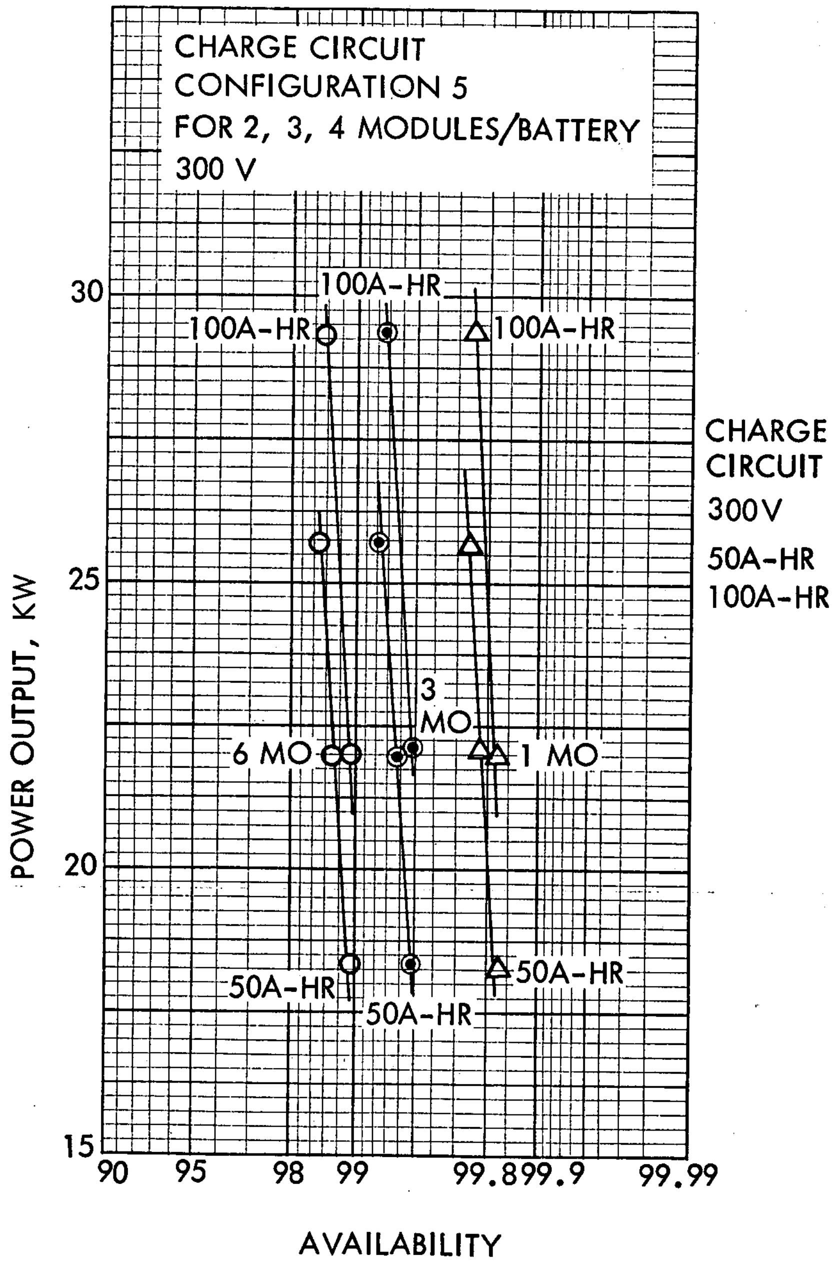

CHARGE CONTROL
CONFIGURATION 4,5
300 V 20A- HR
6 MO
4 MOD/BATT
CHARGE
CONTROL
20A-H
300 V
POWER OUTPUT , KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVALIABILITY

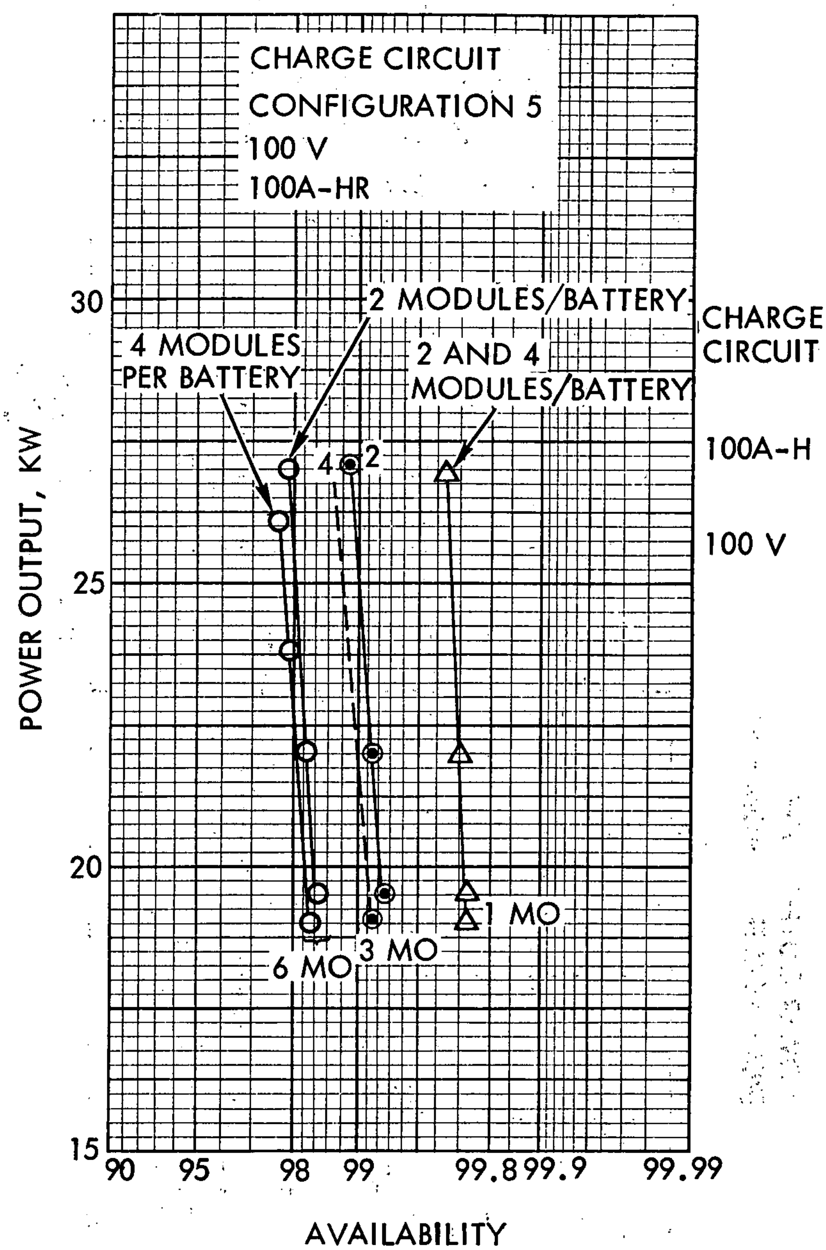

CHARGE CIRCUIT
CONFIGURATION 2
UNITS = 5, 10, 15
RB = 1.0, 0.6, 0.25
6 MO
3 MO
1 MO
30 V
30 V
30 V
300 V
300 V
300 V
35
30
25
20
90
95
98
99
99.9
99.99
AVAILABILITY
POWER OUTPUT, WATTS (PEAK = NOMINAL)



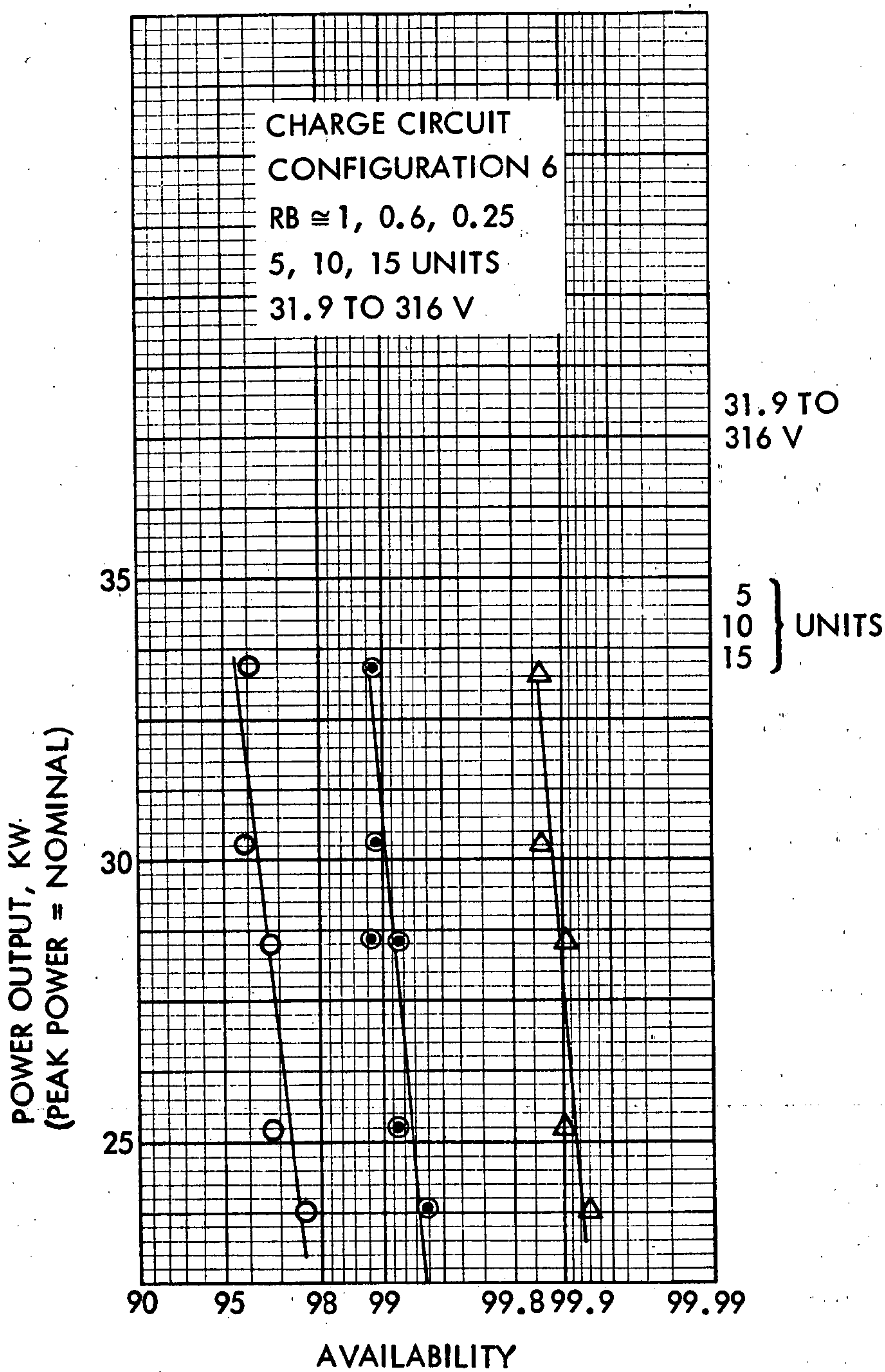
CONFIGURATION 3
CHARGE CIRCUIT
PEAK, NOMINAL


CONFIGURATION 5
FOR 2, 3, 4 MODULES/BATTERY
100 V
POWER OUTPUT, KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVAILABILITY
100A-H
100A-H
100A-H
50A-H
50-A-H
50A-H
CHARGE
CIRCUIT
100 V
100A-H
50A-H
RESUPPLY
INTERVAL
6 MO
3 MO
1 MO

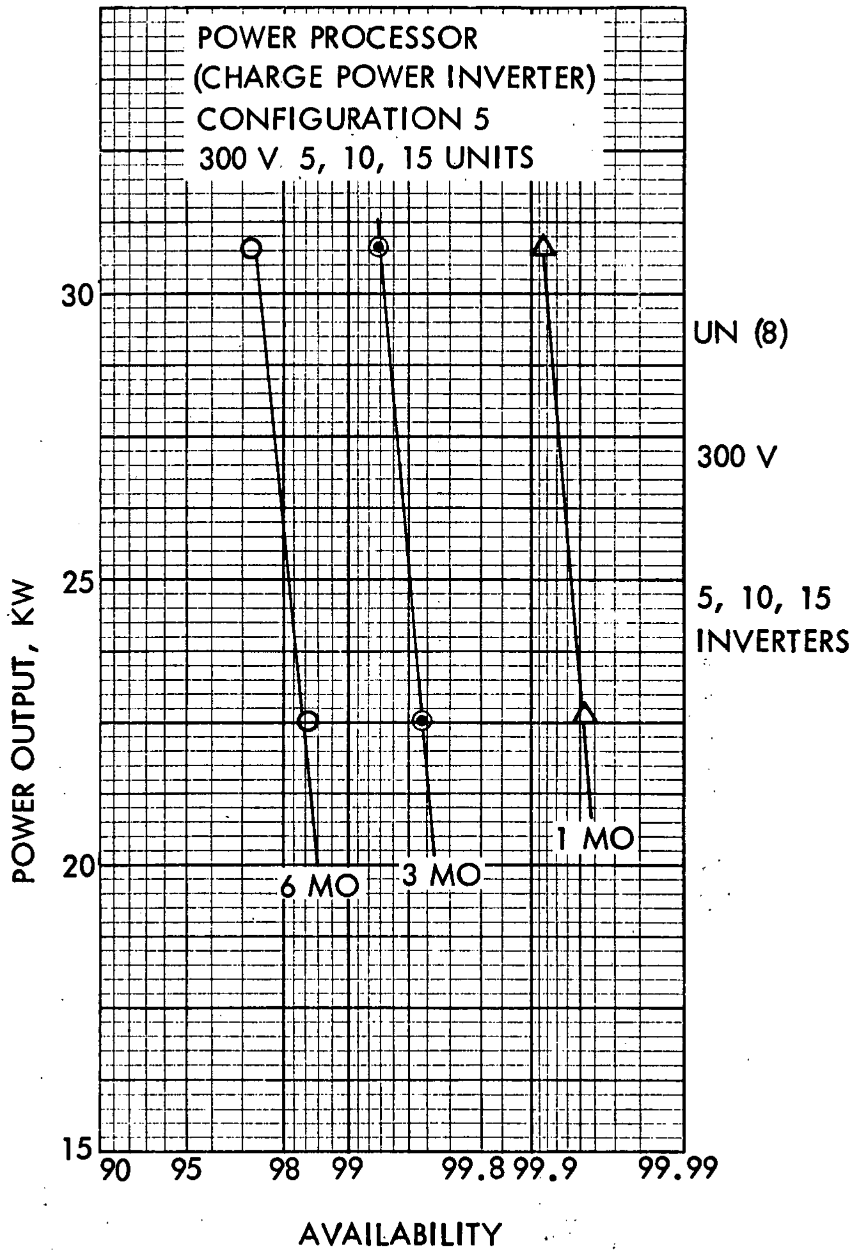

CHARGE CIRCUIT
CONFIGURATION 5
FOR 2, 3, 4 MODULES/BATTERY
300 V
100A-HR
100A-HR
100A-HR
CHARGE
CIRCUIT
300V
50A-HR
100A-HR
3
MO
6 MO
1 MO
50A-HR
50A-HR
50A-HR
POWER OUTPUT, KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVAILABILITY



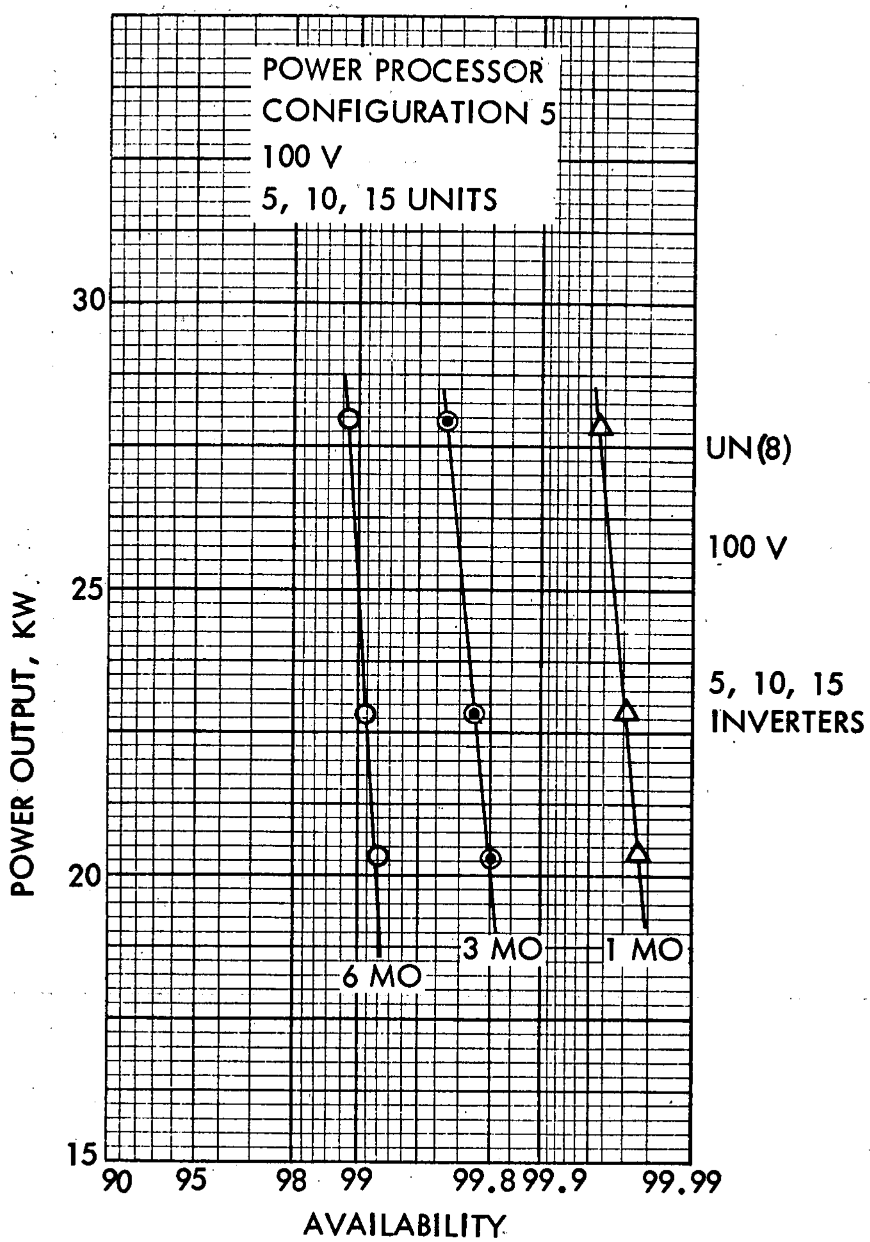
CHARGE CIRCUIT
CONFIGURATION 5
100 V
100A-HR
2 MODULES/BATTERY
4 MODULES
PER BATTERY
2 AND 4
MODULES/BATTERY
CHARGE
CIRCUIT
100A-H
100 V
4
2
1 MO
3 MO
6 MO
POWER OUTPUT, KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVAILABILITY

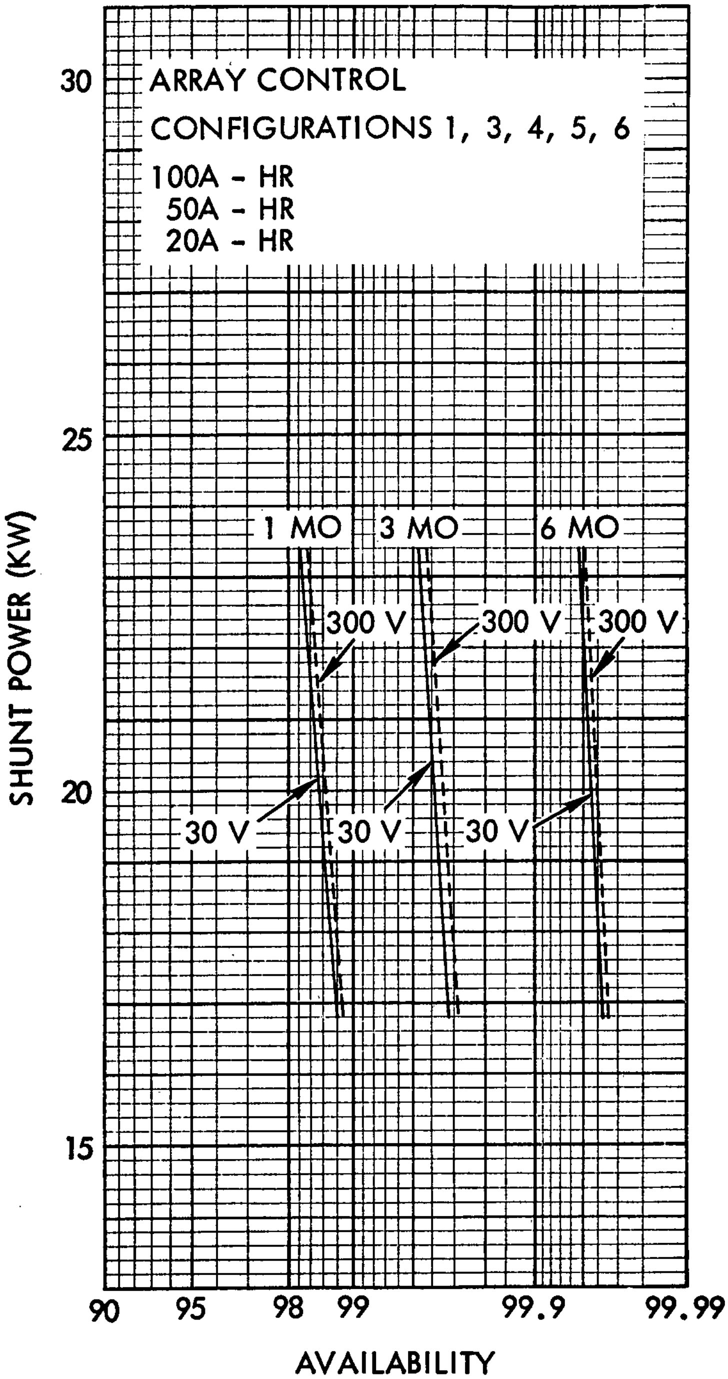


CHARGE CIRCUIT
CONFIGURATION 6
RB ≅ 1, 0.6, 0.25
5, 10, 15 UNITS
31.9 TO 316 V
31.9 TO
316 V
5
10
15
UNITS
35
30
25
POWER OUTPUT, KW.
(PEAK POWER = NOMINAL)
90
95
98
99
99.8
99.9
99.99
AVAILABILITY



POWER PROCESSOR
(CHARGE POWER INVERTER)
CONFIGURATION 5
300 V 5, 10, 15 UNITS
UN (8)
300 V
5, 10, 15
INVERTERS
6 MO
3 MO
1 MO
POWER OUTPUT, KW
30
25
20
15
90
95
98
99
99.8
99.9
99.99
AVAILABILITY


POWER PROCESSOR
CONFIGURATION 5
100 V
5, 10, 15 UNITS
30
25
20
15
POWER OUTPUT, KW
UN(8)
100 V
5, 10, 15
INVERTERS
6 MO
3 MO
1 MO
90
95
98
99
99.8
99.9
99.99
AVAILABILITY


ARRAY CONTROL
CONFIGURATIONS 1, 3, 4, 5, 6
100A - HR
50A - HR
20A - HR
1 MO
3 MO
6 MO
300 V
300 V
300 V
30 V
30 V
30 V
SHUNT POWER (KW)
30
25
20
15
90
95
98
99
99.9
99.99
AVAILABILITY