UNIVERSITY OF MINNESOTA

ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 280

PERFORMANCE TESTS OF HYDROELECTRIC GENERATING UNITS AT THE SAULT STE. MARIE POWER STATION

by

Judson Woods

Richard L. Voigt, Jr.

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Prepared for:

Edison Sault Electric Company
Sault Ste. Marie, Michigan

November 1988

Minneapolis, Minnesota

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I. INTRODUCTION

Edison Sault Electric Company's (ESELCO) hydroelectric plant in Sault Ste. Marie, Michigan, was originally constructed at the turn of the century to house 78 horizontal, tandem–mounted, camelback turbines of various manufacture. The original distribution of turbines consisted of:

41 – Webster, Camp & Lane units (Nos. 2 thru 42);
22 – S. Morgan Smith units (Nos. 44 thru 65);
15 – Wellman, Seaver & Morgan Company units (Nos. 66 thru 80)

Subsequent to original construction, turbine/generator unit Nos. 2 thru 4 were taken out of commission in order to use the space for a fishery. Unit Nos. 41, 42, 44 and 45 are devoted to providing power to four (2) DC generators for exciting the remaining 71 AC generators. At present the total generation capacity at the ESELCO plant consists of 71 operating turbine/generator units of approximately 500 kW capacity each.

Commensurate with a program to upgrade and automate the hydro plant, ESELCO contracted with the St. Anthony Falls Hydraulic Laboratory to conduct performance tests of the plant's turbine/generator units. The automation scheme calls for the optimum utilization of the available water resource based on head water level and/or time–of–day, an effort requiring current, in–place performance diagrams for each turbine/generator unit. This information, derived from the performance tests discussed in this report, will be incorporated into an automatic generation control system designed to manage the assignment of each unit's production, which is additionally subject to 1) the maintenance of the most effective allowable head, 2) the assigned discharge or flow regimen, framed in the context of the plant's monthly flow allocation, and 3) the "time–of–day" demand requirements. The underlying premise of the control system is the maximization of overall plant efficiency.

The performance tests were commenced on July 18, 1988, and completed September 8, 1988.

II. SITE CHARACTERISTICS AND PLANT OPERATION

The ESELCO hydro plant is billed as the longest horizontal shaft hydropower plant in the world, extending almost a quarter–mile in length across its forebay. Water is drawn from the St. Mary's River through a two–mile long power canal whose inlet is located within site of Ashmun Bay at the east end of Lake Superior. The first mile of canal is primarily of rectangular shape with the remaining length up to the forebay entrance being trapezoidal. The canal lining consists primarily of indigenous rock and timber, and though canal dimensions vary somewhat, the width is generally around 200 feet and depth around 20 feet. Headgates near the intake of the power canal may be used as required by plant operations to determine the flow of water and/or headwater level in the powerhouse forebay, in addition to providing a means to isolate and drain the power canal.

Head on the order of 18 feet is created by the difference between Lake Superior's elevation and the level of the river below the site of the St. Mary's rapids, a drop which is regulated by the presence of the Soo and Canadian Locks, a spillway, and two additional power plants operated on the river.

Each turbine/generator unit actually consists of four water wheels—two pairs of tandem–mounted Francis runners—turning a single shaft. The center–line of this runner and shaft arrangement is set at an elevation of 589.5 msl, or roughly ten feet below the average headwater level in the forebay. Thrust collars and bearings support the horizontal shaft, and the units are mounted in series on the floor of U–shaped "wheel pits," also referred to as "open penstocks." The wheel pits are 15 feet wide at the entrance, 17 feet deep, and about 37 feet from the entrance to the back of the pit. The pit walls are constructed of reinforced concrete and steel plate, with the turbine/generator shaft extending through the back of the pit to the generator. Each pair of runners discharges through a vertical draft tube into the unit's tailpit below the floor of the wheel pit, where it flows immediately back into the St. Mary's River, about a mile downstream from the Soo Locks.

Plant operations are generally determined by the establishment of peak production hours and off–peak hours, which can vary from month to month. At the commencement of the testing program and on through the month of August, peak hours were from 10 AM to 5 PM, Monday through Friday, the rest of the time being off–peak. In September, peak hours were shifted to the hours between 5 PM and 9 PM, Monday through Friday. Peak hours are determined through consideration of loading patterns and constraints placed on water usage. The monthly discharge of water from Lake Superior to the St. Mary's River is controlled in accordance with water resource management policies established by the governments of the United States and Canada.

The canal, forebay, and plant designs are far from ideal hydraulically. This is dramatically evident in the peak hours of production, when all of the turbine/generator units are on–line. At this time, velocities in the power canal may be higher than seven or eight feet per second, creating substantial head loss in the canal. Within less than 500 feet in front of the powerhouse, the canal widens rapidly into the forebay which must span the quarter–mile width of the powerhouse. In order to achieve a uniform distribution of flow to the 75 wheel pits that comprise this width, strong currents of flow are drawn from the center region of the forebay in front of the powerhouse to the west and east sides. The result is a strong cross–flow component of flow across the front of the open penstocks, only four to five feet in front of the foremost runner. Each unit must draw water from this rushing flow. In the open penstock itself there can be a great deal of circulation and turbulence, with surface flows rushing along one side of the pit around the U–shaped steel plate to the other side. The east side units of the powerhouse exhibit the greatest degree of turbulence. Even with only a few of these units on–line, a large circulation of flow is evident in the forebay. The far west side units (Nos. 71 to 80) also draw water across the front of the powerhouse on that side, though the turbulence exhibited in the wheel pits is not quite so dramatic.

There are no trash racks at this site. Consequently, "wheel–cleaning" comprises a significant portion of the plant's maintenance budget. The east side of the powerhouse tends to get most of the debris that floats down the power canal, occasionally including such objects as trash bags, traffic barrels, logs, large branches and other items requiring immediate removal before the affected unit may continue operation. The east–side units are especially vulnerable to the inflow of trash during the downsurge of water created when those units are first brought on–line, such as at the onset of peak production. Three gate–hoists are equipped to travel the length of the plant along rails and lower penstock gates across the front of any wheel pits that need to be isolated and dewatered for reasons of maintenance, etc. Each penstock gate, of which there are four available, is designed to slide down vertical "channels" fastened to the front of the pit walls and seal off water to the unit.

The swift current in the power canal, the lack of walls or devices to "straighten the flow" from the forebay to the turbine/generator units (indeed, without the pit walls they would virtually be **in** the forebay), and the open nature of the "penstocks" contribute to a significant drop in the head available to generate power during the plant's peak operating hours. The water level in the forebay drops rapidly and markedly—on the order of three to four feet—in the plant's transition to peak production from off–peak production. Part of the difference is transitory due to surging in the power canal by running units up and bringing them on line, but the forebay level in peak hours will generally remain at least two feet lower than its level in off–peak hours.

There are times during peak hours when the demand may be low, and plant output may be reduced. Water level in the forebay will rise in accordance with this reduction. Units are run–up and brought on–line as needed in a priority from the west to the east side of the powerhouse (unit numbering is from No. 5 on the far east side to No. 80 on the far west). Consequently, some west–side units are always on line meeting the plant's minimal baseload requirements. This priority is currently established in recognition not only of the slightly larger capacity of the turbine/generator units on the west side, but also of the more favorable flow conditions (and by implication, more efficient operation) to the west–side units.

Changes or fluctuations of head may be fairly significant over short periods of time as a result not only of operation changes initiated at the plant (including headgate settings), but also of lake tiding, storm and wind effects (wind set–up, for example), and even shipping on the river behind the plant, which can have a noticeable transient effect on the tailwater level.

The existing seventy–one turbines are presently controlled by a like number of Lombard hydraulic governors. Each governor must be manually controlled (like the plant, as a whole) in order to effect a stable change in wicket gate position. Before bringing a generator on–line, the wicket gate position is set and locked to correspond to the generator's synchronous speed and brought on line to the turbine's nominal peak efficiency, a point that is presently determined from generic performance diagrams. These performance diagrams were derived at the turn of the century from tests on similar turbines at the Holyoke Turbine Testing Facility in Massachusetts. They lack the accuracy required for proper turbine operation. The construction of each turbine unit and the flow conditions entering that unit will be unique, requiring an individual performance test. It is the purpose of the testing program discussed in this report to derive current, in–place performance diagrams for each turbine/generator unit.

III. PERFORMANCE TESTING EQUIPMENT AND PROCEDURES

Since the ultimate result of the performance testing program is the derivation of efficiency curves for each generating unit, simultaneous measurements of discharge, head, and power must be carried out. In order to adequately define an efficiency curve, the measurements were performed at a series of wicket gate openings as determined by indicator scales on the hydraulic governors. These scales were calibrated from 0 (closed) to 1.0 (full open), with the peak efficiency for the units expected to fall somewhere between 0.6 and 0.9. It was decided to perform measurements at the maximum gate openings allowed by the governors (which were usually between 0.9 and 1.0), another gate opening midway between the maximum gate opening and 0.8, and then the gate openings corresponding to 0.8, 0.7, 0.6, and 0.5. There were a few units for which measurements between maximum gate and 0.8, or measurements at 0.5, were foregone, but there are generally six gate openings at which measurements were performed. Seventy of the seventy–one AC generating units were tested, unit No. 70 being the exception because it was never operable during the testing program.

The performance tests were commenced on July 18, 1988 and completed September 8, 1988. Often one of the difficulties of field testing programs is the lack of control one may exercise over conditions necessary to yield data with the degree of accuracy and/or uniformity possible in the Laboratory. It was not possible to tailor plant operations for the duration of the testing program (and certainly not possible to control those factors dependent on weather, etc.) to the extent that "uniform" conditions of measurement were possible. The testing program was consequently carried out within the context of the normal, and sometimes unpredictable operations and conditions at the plant.

A. DISCHARGE

As is usually the case, discharge is the most tedious of the parameters to measure, and the one that presents the greatest potential for measurement errors. The large angle of flow into the units rules out the use of conventional current meters. The axial component of flow alone is desired (i.e., the component of the velocity vector parallel to the turbine/generator shaft and perpendicular to the wheel pit entrance), but since cross–flow and even back–flow can be significant, it was necessary to use a current meter capable of resolving the velocity vector into its axial– and cross–flow components while yielding the direction (in or out, right or left) of each. For this purpose, a Marsh–McBirney Model 511 Electromagnetic Water Current Meter was chosen.

The Model 511 flow meter consists of (1) a transducer probe with cable and (2) a signal processor housed in a portable case. The instrument senses water flow in a plane normal to the longitudinal axis of the electromagnetic sensor. Analog panel meters indicate the water velocity components in feet per second along the X and Y axes of the electromagnetic sensor to an accuracy of plus or minus 2%. A time constant may be selected to determine the response time of the meter to changes in water velocity. It was used in this application to "dampen" the meter fluctuations due to turbulence, in order to more accurately determine the mean axial-flow component of the velocity.

The open penstock entrance was the only possible location to measure the generating unit's discharge. The vertical plane of measurement could not be set back much from the entrance due to the presence of the foremost thrust collar and runner near the front of the pit. The vertical plane of measurement was resolved into a series of grid points at which the flow meter would measure the component of velocity perpendicular to the plane (flow parallel to the plane could also be measured). The grid consisted of five horizontal rows and six vertical columns, yielding 30 points of measurement (see Example IV-1). Discharge was found by determining the mean velocity component perpendicular to the entrance cross-section and multiplying by the area of the cross-section.

A constant spacing of 30" between rows from the bottom row up was chosen to ensure that the top row of measurements would be below the lowest expected forebay water level for a given series of measurements. Though the top row of measurements might at times be more than two feet beneath the water surface, the water surface might easily and unpredictably drop to a level only slightly above the meter sensor. At times when "high" forebay levels were known to be relatively stable, such as in off-peak hours, the row spacing was set to 33" with the effect that the top row was a foot closer to the water surface than it would have been otherwise.

The electromagnetic water current meter was mounted on an aluminum carriage designed to roll back and forth on a horizontal rack constructed primarily of 2" steel tubing and aluminum rails. The ends of the rack were fitted with frames on which casters were mounted and positioned to roll up and down the vertical channels at the entrance of the open penstocks. A gate hoist was equipped to raise and lower the rack while keeping it level across the width of the pit, and the movable carriage mount for the meter was controlled by a length-adjustable 3/4" steel rod designed to pivot about the carriage. The rails along which the carriage could roll were "notched" at regular intervals to allow for stable placement of the carriage and meter at points on the grid where measurements could be taken. Once the rack was lowered into the vertical channels of the pit, the rod could quickly move the meter carriage to the notched column location where measurements were desired. Then the gate hoist lowered the rack and carriage into the water for the measurement(s) called for in that vertical column. In the presence of strong cross-flows or surges the steel rod was an aid to holding the carriage in place. (Occasionally, the carriage threatened to roll out of position despite the notches in which it sat, but the rod prevented it from moving.) It also had two other important functions: 1) it provided the only connection from the operator above on the gate hoist to the carriage and meter, important for its retrieval (and salvation, in light of the strong pull of the current and the rotating machinery in the pit) in the event that the carriage should somehow come off the rack; and 2) the cable from the sensing probe to the meter panel was tied to the rod, necessary as well to keep the cable from being pulled by the current and, worse yet, pulled into rotating machinery at deeper levels. Fortunately neither of these scenarios ever developed.

Time would not permit a full grid (30 points) of water velocity measurements to be performed for all six (occasionally five) gate openings of all 70 units. It was therefore decided to "measure full grids" for maximum and 0.7 **or** 0.6 gate openings only, for all but five units. Full grid measurements were performed at all gate openings in unit Nos. 20, 34, 51, 64 and 79, which are fairly evenly distributed along the width of the powerhouse. For each full grid of measurements, an average velocity is computed through the average cross–sectional area encompassing the grid (data analysis is discussed further in the next section). In addition, the average velocity may be computed for any row of measurements in the grid. A ratio of the average velocity for the row to the velocity of the cross–section may then be determined and used to estimate the average cross–sectional velocity at gate openings where **only an individual row of measurements** is taken. Thus, for all gate openings of units for which full grid measurements were not performed, a **single row** of velocity measurements was performed (in row 2 for unit Nos. 5 thru 67 and 76, row 3 for the rest) and the average ratio of row average to cross–sectional average velocities determined from maximum and 0.7 gate openings was used to compute an initial estimate of cross–sectional average velocity at the other gate openings where only the row average had been determined. With a value of the average velocity for the cross–section thus derived, the discharge may then be estimated as the product of that value and average cross–sectional area.

Barring unforeseen difficulties, a full grid of measurements generally took about 35 to 45 minutes to perform, and a single horizontal row of six measurements took about 10 to 15 minutes. With the exception of those five units where full grid measurements were carried out at all gate openings, a unit could be tested in less than three hours. The aforementioned five units took up to five hours to complete, not including occasional interruptions in the work. The water wheels of each unit were checked and cleaned shortly before the unit was tested.

Readings in row 1 and row 2 of the grid were relatively stable, and it is primarily row 2 measurements from which average cross–sectional velocities are computed in the data analysis. (The horizontal row measurements were performed in row 3 in the initial days of the testing program, but were abandoned in favor of row 2 measurements because of the increased accuracy and ease with which the latter could be read.)

B. HEAD

The headwater, or the level of water in the forebay, was considered for these tests to be the level read from a float gage in a stilling well which accessed the water level in the wheel pit of unit No. 45. A similar gage arrangement was used to measure tailwater, which was the level of water as accessed in the tail pit of unit No. 44. Unit Nos. 44 and 45 are both DC "exciter" generators located at the center of the plant, and the headwater and tailwater levels observed there were felt to be as standard and representative a measure as any that could easily be recorded at a powerhouse whose intake and outlet is essentially a quarter–mile long.

Headwater and tailwater values were read at the plant gallery by the operators on duty. These readings were requested via a two–way radio and recorded by the individual taking velocity measurements on the forebay side of the plant. Even in the fairly short span of time required to complete the velocity measurements at one gate opening, the head, and the headwater level in particular, could change discernibly and quickly, and it was especially important to record these when changes took place. For the three to five hour period of time it takes to complete measurements in one unit, the head can easily exhibit variations of more than a half–foot, and often exceed one foot.

Weather and tiding, too, can dramatically effect the level of the headwater, as was demonstrated in one particularly bad day of stormy weather on the upper peninsula. A rare tornado touchdown in Marquette, Michigan, and winds of up to 70 mph on the Straits of Mackinac were manifestations of weather that was reported to contribute to tiding of up to six feet in Lake Superior on August 16. Apparently, tiding can result in up to three foot fluctuations of the lake level within an hour. The result of the stormy weather was an ever–fluctuating headwater which, in the space of one and a half hours, reached a low level of 595.6 msl and then a high level of 600.6 msl — a change of five feet. Data taken during this period were discarded.

Along with headwater and tailwater, measurements of depth of water at the entrance of the wheel pit itself are necessary. Discharge is determined as the product of the average areal velocity over the cross section and the area of the cross section, but since the "penstock" has an open surface, the cross–sectional area varies with depth of water at the entrance of the wheel pit where the velocity measurement plane is located. The depth of water was consequently measured and recorded as often as changing conditions required it. Using a vertical rod marked every six inches, distance was measured between a reference point on the gate hoist, of known elevation, and the water surface. The water depth was thus ascertained as the difference between this distance and the known distance between the reference point and the pit floor.

C. POWER

Power was measured using a Dranetz Series 808 Power/Demand Analyzer. With the analyzer configured in a two–wattmeter mode, power was measured at the front control panel (the generator terminals) by way of plugs which accessed existing current transformers and potential transformers. Current was measured using the Dranetz current probe, Model TR2012A, and the voltage was measured directly by the analyzer. With this configuration, the Dranetz was programmed and the proper CT and PT ratios were entered. For the duration of a test, the analyzer would print out the power, power factor, and time of measurement every minute.

D. TEMPERATURE

Power production depends not only on discharge, head, and the efficiency of the generating equipment, but also on the specific weight of the fluid driving the turbines. The specific weight of fresh water may be determined from tables as a function of water temperature, and this temperature was measured and recorded daily during the testing program. Water temperatures between July 18 and September 8 varied between 62°F and 72°F, corresponding to specific weights of 62.356 pcf and 62.293 pcf, respectively.

IV. DATA ANALYSIS AND RESULTS

At each gate opening, a series of velocity measurements were recorded, either a full grid (30 points) of measurements or a horizontal row (six points) of measurements. Headwater and tailwater levels, the depth of water at the wheel pit entrance, and the time of measurement were also recorded. The power output was simultaneously printed out every minute at the control panel.

It was not practical to measure the headwater, tailwater, or depth of water **each time** the velocity at a grid point was measured. Consequently, there were "gaps" in the recorded data that were filled in by interpolation between measured values with respect to time. In the spreadsheet program used to process the data, there was therefore listed for each measurement of velocity a value of headwater level, tailwater level (head is computed as the difference of the two), depth of water at the wheel pit entrance, power, and power factor. Water temperature is recorded as well.

It is necessary to adjust the actual, recorded values of all parameters to their values at a single, reference head and depth. Discharge and power are related to head (for small head variations) as

$$Q \sim H^{1/2} \tag{1}$$

$$P \sim H^{3/2} \tag{2}$$

where Q is discharge; P is power; and H is head. Since

$$A_{cs} = d \times w \tag{3}$$

where A_{cs} is the cross-sectional area of the measurement plane; d is the depth of water in this plane; and w is width, which is constant; then

$$V = \frac{Q}{A_{cs}} \sim \frac{H^{1/2}}{d} \tag{4}$$

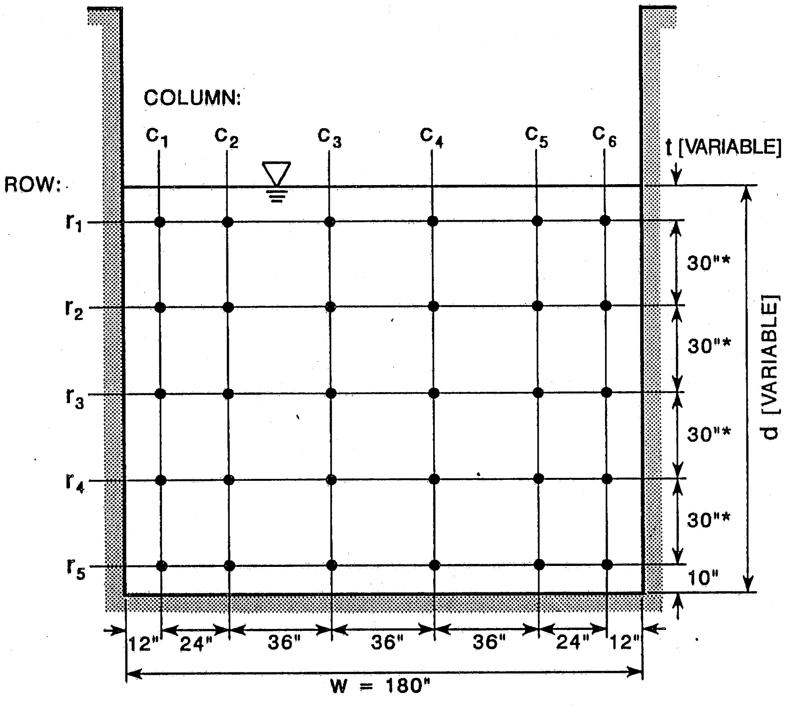
where V denotes velocity. The following relations are then derived:

$$V_r = V_a \left[\frac{d_a}{d_r}\right] \left[\frac{H_r}{H_a}\right]^{1/2} \tag{5}$$

$$P_r = P_a \left[\frac{H_r}{H_a}\right]^{3/2} \tag{6}$$

The reference head, H_r, for each series of measurements (all the measurements at one gate opening) was computed to be the average head recorded during that series. Likewise, the reference water depth at the wheel pit entrance, d_r, was computed to be the average value recorded for the series. Then, the velocities and power values at each grid point were adjusted to reference values, V_r and P_r, using Eqs. 5 and 6. The reference values were then used to compute the discharge, head, and power which were in turn used to compute unit efficiency for that gate opening.

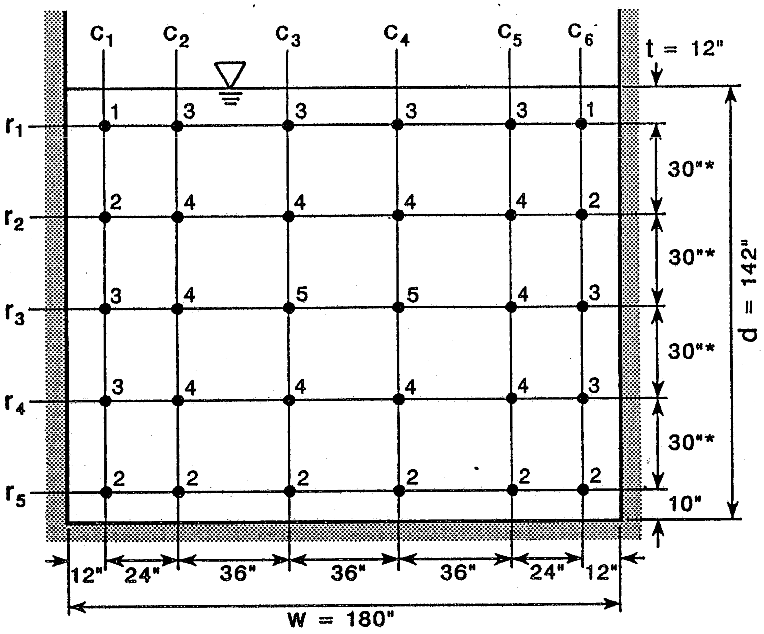
For full grid measurements, subsequent to the value adjustments just described, an average velocity through the cross–sectional area was computed, integrating the axial component of velocities over the area first in the vertical columns, then integrating these average vertical column velocities in the horizontal direction. A 1/7 power law for velocity profile was used between the bottom row of measurements and the floor of the wheel pit. The side column measurements were assumed to be valid at the wall since no boundary layer would be present there at the entrance. The same assumption was applied to the top row of measurements, since no boundary existed because of the open surface. A linear interpolation was used between grid points. A sample computation is provided in Example IV–1.



* SET TO 33" AT STABLE "HIGH" DEPTHS.

Example IV–1. The flow, Q, to an open penstock is computed using a grid of velocity measurements consisting of six points across and 5 points down.

The methodology used to compute Q is exhibited in the following example:



Subscripts denote row and column respectively. Assume the measured velocities are the numbers next to each measdurement point. Therefore,

$\nu_{C_1,r_1} = 1$ fps
$\nu_{C_2,r_1} = 3$ fps
$\nu_{C_2,r_2} = 4$ fps...etc.

At the floor, the seventh root law shall be used as follows:

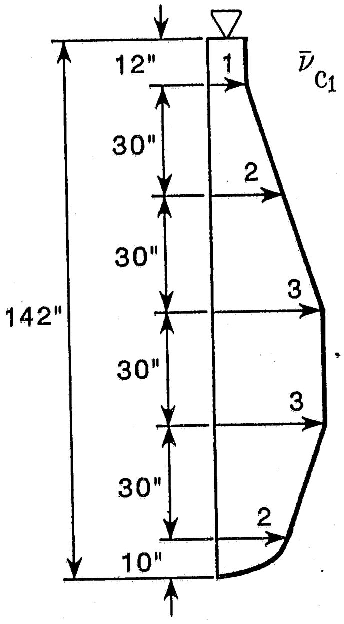
$$\nu_X = VX^{1/7} \tag{7}$$

where

X = fractional distance from the floor to any point between the floor and row 5, (X = 1 at row 5)
V = velocity measured at the row 5 metering point
ν_X = velocity at any point X.

Note: The average velocity between row 5 and the floor is mathematically determined under the seventh root law to be 7/8 of the velocity at the row 5 metering point.

Then, for each vertical column of measurements, the average velocity for that column shall be determined as follows:



$$
\begin{aligned}
\bar{\nu}_{c_1} = \Big\{ & 10'' \cdot \frac{7}{8} \cdot \nu_{c_1,r_5} + 30'' \cdot \left[\frac{\nu_{c_1,r_5} + \nu_{c_1,r_4}}{2}\right] \\
& + 30'' \cdot \left[\frac{\nu_{c_1,r_4} + \nu_{c_1,r_3}}{2}\right] \\
& + 30'' \cdot \left[\frac{\nu_{c_1,r_3} + \nu_{c_1,r_2}}{2}\right] \\
& + 30'' \cdot \left[\frac{\nu_{c_1,r_2} + \nu_{c_1,r_1}}{2}\right] \\
& + 12'' \cdot \nu_{c_1,r_1} \Big\} / 142'' \text{ [depth]} \qquad (8) \\
= \; & 2.21 \text{ fps}
\end{aligned}
$$

Similarly,

$$\bar{\nu}_{c_2} = 3.44 \text{ fps}$$
$$\bar{\nu}_{c_3} = 3.65 \text{ fps}$$
$$\bar{\nu}_{c_4} = 3.65 \text{ fps}$$
$$\bar{\nu}_{c_5} = 3.44 \text{ fps}$$
$$\bar{\nu}_{c_6} = 2.21 \text{ fps}$$

Then, these vertically–averaged velocities are themselves averaged horizontally, to get the areally–averaged velocity for the cross–section:

$$
\begin{aligned}
\nu_{av} = \Big\{ & 12'' \cdot \bar{\nu}_{c_1} + 24'' \cdot \left[\frac{\bar{\nu}_{c_1} + \bar{\nu}_{c_2}}{2}\right] + 36'' \cdot \left[\frac{\bar{\nu}_{c_2} + \bar{\nu}_{c_3}}{2}\right] \\
& + 36'' \cdot \left[\frac{\bar{\nu}_{c_3} + \bar{\nu}_{c_4}}{2}\right] + 36'' \cdot \left[\frac{\bar{\nu}_{c_4} + \bar{\nu}_{c_5}}{2}\right] \\
& + 24'' \cdot \left[\frac{\bar{\nu}_{c_5} + \bar{\nu}_{c_6}}{2}\right] + 12'' \cdot \bar{\nu}_{c_6} \Big\} / 180'' \text{ [width]} \qquad (9) \\
= \; & 3.20 \text{ fps}
\end{aligned}
$$

Finally,

$$Q = \nu_{av} \cdot A_{cs} = 3.20 \cdot \frac{(142)(180)}{144} = 568 \text{ cfs} \tag{10}$$

Now, we could compute the average velocity in row 2 as

$$\begin{aligned}\nu_2 &= \left\{12'' \cdot 2 \text{ fps} + 24'' \cdot \left[\frac{2+4}{2}\right] \text{fps}\right. \\ &\quad \left. + 36'' \cdot \left[\frac{4+4}{2}\right] \text{fps} + \ldots\right\} / 180'' \\ &= 3.47 \text{ fps}\end{aligned}$$

Then, we would find for this unit that

$$\frac{\nu_2}{\nu_{av}} \approx \frac{3.47}{3.20} = 1.08$$

If, at another gate opening, measurements were recorded only in row 2, and ν_2 was computed, for example, to be

$$\nu_2 = 3.13 \text{ fps},$$

then we could, using the assumption stated in Section III–A, estimate the discharge to be

$$Q \approx \frac{\nu_2}{\left[\frac{\nu_2}{\nu_{av}}\right]} \cdot A_{cs} = \frac{3.13}{1.08} \cdot (177.5) = 514 \text{ cfs}; \tag{11}$$

(assuming, that d = 142").

The cross–sectional area was simply taken to be the product of width (a constant 15 feet) and the average (reference) depth for the series of measurements. This was multiplied by the average cross–sectional velocity, computed above, to yield the discharge.

The unit efficiency for the gate opening was then computed as

$$e = 737.3 \left[\frac{\bar{P}_r}{Q_r H_r \gamma}\right] \tag{12}$$

where $\bar{P}_r$ is the average value of the adjusted (referenced) power measurements; and γ is the specific weight of water. In this equation, power is expressed in kW; discharge as cfs; head as ft; and γ as lbs/ft^3.

At gate settings where velocity measurements were taken only in row 2, the ratio of the mean velocity computed in row 2 to the cross–sectional mean velocity, from the full grid measurements at 0.7, and full open gate settings was used to estimate the cross–sectional mean velocity and discharge. For example, if this ratio, V_2/V_{av}, is found to equal 1.31 for maximum gate opening and 1.29 at 0.7, then the average of these two (1.30) would be used at the other gate openings. The average row velocity would be divided by this ratio to get the estimated mean cross–sectional velocity for that gate opening.

For the sake of consistency and appropriate comparisons from one gate opening to the next or one unit to the next, it becomes necessary to determine the values of discharge, power output, and efficiency at various gate openings **with reference to a given, overall reference head.** The old performance diagrams, to be superseded by the results of this testing program, were drawn with reference to a head of 18 feet. The reference head **for the performance diagrams presented in this report** is thus denoted as

$$H_{18} = 18 \text{ feet},$$

and the values of Q_r and P_r computed for each gate opening of each turbine/generating unit are adjusted accordingly:

$$Q_{18} = Q_r \left[\frac{H_{18}}{H_r}\right]^{1/2} \qquad (13)$$

$$P_{18} = \bar{P}_r \left[\frac{H_{18}}{H_r}\right]^{3/2} \qquad (14)$$

The efficiency at H_r is assumed to be no different than that at H_{18}. Although this assumption is not strictly correct, it is valid within the accuracy of the efficiency measurements.

Performance diagrams were constructed by plotting discharge (in cfs), power (in kilowatts), and efficiency (percent) all as functions of gate opening, with all parameters referenced to 18 feet head.

Having plotted the points derived in the analysis, it becomes necessary to acknowledge the degree of uncertainty with which discharge was estimated, being based most often on a single row of six velocity measurements and a ratio V_2/V_{av} which is normally accurate to plus or minus 5 percent. In extreme cases, such as those described below, the uncertainty in discharge could be plus or minus 15 percent. Based on this uncertainty and the knowledge that the true discharge is fairly linear with gate opening, a curve of such nature was drawn through the plotted points of discharge on the new diagrams. The discharge values **defined by this curve** were then used to **recompute** the efficiencies at the gate openings where discharge had previously been estimated:

$$e^* = 737.3 \left[\frac{P_{18}}{Q^*_{18} H_{18} \gamma} \right] \tag{15}$$

where the **asterisk**, *, is a reference to the fact that the discharge used in the equation is that derived from the fitted curve.

Finally, a best–fit curve is drawn through the recomputed efficiency points, e*, and from this curve, peak efficiencies, maximum output efficiencies, and the corresponding gate openings, are tabulated. These are listed in Table 1. The individually measured performance and the fitted curves for discharge, power, and efficiency are plotted versus gate opening for each unit in the Appendix.

Some Remarks About Specific Plots

Special consideration was given to five of the 74 plots, because they exhibited some unusual anomalies.

<u>Unit No. 10</u>. This plot is probably the most anomalous of the plots. Values of discharge estimated for 0.5, 0.6, 0.8, and 0.9 gate openings (where velocities were only measured in row 2 of the grid) define a curve that is above, yet parallel to, the curve actually drawn. It was decided to draw the discharge curve through the points computed at 0.7 and 0.95 (maximum) gate openings because these values were computed from full grid measurements and are likely to be more accurate. In addition, the corresponding efficiency curve delineates a range of values one would expect to find.

<u>Unit No. 38</u>. This plot is an example of one that reveals significantly lower estimated values of discharge at 0.8 and 0.9 gate openings than are reasonably expected based on the more accurate full grid measurements at 0.7 and 0.99 gates. The curve extends through the points plotted at the latter two gates, and 0.6 besides, to yield a reasonable efficiency curve.

Other examples of this, though not quite as striking, include the plots for unit Nos. 14, 29, 72 and 78.

<u>Unit Nos. 58, 62, and 64</u>. Two plots will be noted for each of these units: 58 and 58*, 62 and 62*, and 64 and 64*. While the measurements at all the gate openings for these units were internally consistent, the initially derived efficiency curves were obviously too high, not only in relation to the other units around them, but also compared against the efficiencies attainable from modern machines in favorable flow conditions.

It was immediately apparent that the values derived for the ratio V_2/V_{av} in these units were significantly higher than those values derived for the surrounding units. The average value of this ratio in unit Nos. 56, 57, 59 and 60 was 1.27, but for unit No. 58 it had been initially derived to be 1.48. For the plot denoted 58*, the discharges were recomputed using the ratio value of 1.27, and the subsequently rederived efficiency curve is in the expected range of values. Likewise, the V_2/V_{av} ratio initially derived for unit Nos. 62 and 64 (equal to 1.58) was much higher than the average ratio value of 1.33 derived for unit Nos. 60, 61, 63, 65 and 66. The discharge curves drawn in the plots denoted 62* and 64* reflect the lower value of 1.33, and again, the rederived efficiency curves are as would be expected

The high V_2/V_{av} ratios initially computed for 58, 62 and 64 may be the result of local flow blockages at the lower levels of the grid. A blockage of this sort may well result from deposits of debris or sediment on the wheel pit floor in front of the entrance near grid points in rows 4 and 5, and though they would not reduce the **actual** turbine discharge, they could reduce the discharge **measured** on the basis of too–heavily weighted low velocities at the lower levels of the grid. This incorrect, low **measured** discharge then manifests itself in excessively high computed efficiencies. The adjustments reflected in 58*, 62* and 64* are readily justified on the premise that similar, adjacent units should be fairly consistent in terms of the v_2/v_{avg} ratios by which their discharges are derived.

V. RECOMMENDED PLANT OPERATION FOR MAXIMUM PERFORMANCE

The purpose of these performance tests was to determine an operating procedure that would maximize the power output attained at a given flow. This may be done with the results of Table 1. One must consider the normal uncertainty of ± 5% in efficiency. Therefore, small differences in efficiency will not be considered significant. In general, the S. Morgan Smith units are the most efficient, the Wellman, Seaver, and Morgan units are second, and the Webster, Camp, and Lane units are a poor third.

Let us assume the plant is running at full output. The sequence to **reduce plant output** may be seen from Table 1 to be the following:

1. Throttle Units No. 5 through 40 back to peak efficiency.
2. Shut down Units 5 through 40. If less reduction of discharge is desired, shut down a portion of the units. The order of shut down does not matter because any differences in efficiency are all within ± 5%.
3. Throttle units No. 68, 70 through 75, and 77 through 80 back to peak efficiency.
4. Shut off units No. 68, 70 through 75, and 77 through 80.
5. Throttle units No. 46 through 63 back to peak efficiency.
6. Throttle units No. 64, 65, 66, 67, 69, and 76 back to peak efficiency.
7. Shut off units No. 46, 47, 50, 54, 55, 56, 58, 60, 62, and 63.
8. Shut off the remaining units (48, 49, 51, 52, 53, 57, 59, 61, 64, 65, 66, 67, 69, and 76).

To **start up the plant**, the sequence would be reversed or:

1. Turn on Units No. 48, 49, 51, 52, 53, 57, 59, 61, 64, 65, 66, 67, 69, and 76 and run up to peak efficiency.
2. Turn on Units No. 46, 47, 50, 54, 55, 56, 58, 60, 62, and 63 and run up to peak efficiency.
3. Open Units No. 64, 65, 66, 67, 69, and 76 up to full output.
4. Open units No. 46 through 63 up to full output.

5. Turn on Units No. 68, 70 through 75, and 77 through 80 and run up to peak efficiency.

6. Open units No. 68, 70 through 75, and 77 through 80 up to full output.

7. Turn on Units No. 5 through 40 and run up to peak efficiency.

8. Open units No. 5 through 40 up to full output.

The discharge through each unit may be computed from the discharge given in Table 1, at 18–ft head, and the following equation:

$$Q = Q_{18} \sqrt{\frac{H}{18}} \tag{16}$$

where Q is the actual discharge through the unit, Q_{18} is the discharge taken from Table 1, and H is the net head (headwater – tailwater) in feet.

Table 1. Peak and Maximum Output Efficiencies. Efficiency values are derived from the "best-fit" curves and do not necessarily equal those values derived from the power equation using the corresponding values of power and discharge given in the table. All values correspond to a head of 18 feet.

Unit No.	Peak Efficiency: e_p	Gate Opening @ e_p	Power @ e_p (kw)	Discharge @ e_p (cfs)	Maximum Output Efficiency: e_m	Gate Opening @ e_m	Power @ e_m (kw)	Discharge @ e_m (cfs)
Unit Nos. 5 thru 40 (east side): Webster, Camp & Lane; Rated Power @ 18 ft = 600 kw								
5	61.5%	.83	407	434	59.4%	.95	427	471
6	66.5%	.82	428	421	64.0%	.94	446	453
7	62.0%	.76	398	422	58.6%	.94	434	485
8	65.2%	.80	412	414	61.8%	.98	444	470
9	67.6%	.71	391	381	61.4%	.95	443	471
10	60.5%	.95	437	468	60.5%	.95	437	468
11	62.4%	.73	397	419	59.0%	.96	443	494
12	61.9%	.76	402	427	58.0%	.96	430	487
13	64.8%	.93	428	430	64.8%	.93	428	430
14	64.1%	.74	398	413	62.1%	.95	434	454
15	57.6%	.86	410	468	57.1%	.93	416	479
16	65.0%	.77	417	423	61.4%	.98	460	492
17	66.6%	.73	401	395	63.5%	.94	449	466
18	62.7%	.98	431	451	62.7%	.98	431	451
19	65.9%	.82	416	414	64.5%	.95	424	432
20	57.7%	.84	420	480	56.6%	.97	431	499
21	57.5%	.85	399	456	56.6%	.98	411	477

Table 1. Cont'd

Unit No.	Peak Efficiency: e_p	Gate Opening @ e_p	Power @ e_p (kw)	Discharge @ e_p (cfs)	Maximum Output Efficiency: e_m	Gate Opening @ e_m	Power @ e_m (kw)	Discharge @ e_m (cfs)
Unit Nos. 5 thru 40 (east side): Webster, Camp & Lane; Rated Power @ 18 ft = 600 kw (Cont'd)								
22	63.6%	.75	385	400	57.0%	.98	419	479
23	60.2%	.77	391	427	57.1%	.99	414	476
24	60.0%	.70	364	400	56.5%	.95	394	459
25	60.6%	.81	375	408	57.4%	.98	392	447
26	59.9%	.84	394	430	57.7%	.98	407	464
27	65.2%	.72	362	364	62.0%	.97	386	408
28	61.9%	.75	396	424	56.1%	.96	420	486
29	59.4%	.73	370	411	53.6%	.95	408	503
30	64.3%	.78	403	411	61.9%	.96	417	441
31	62.9%	.78	387	405	61.1%	.94	404	435
32	62.5%	.88	421	443	61.6%	.95	421	450
33	63.1%	.85	431	449	61.3%	.98	435	468
34	65.1%	.73	397	402	60.9%	.98	441	472
35	61.6%	.70	382	404	61.1%	.98	434	466
36	66.4%	.85	446	442	65.5%	.93	451	453
37	62.3%	.74	381	403	59.5%	.98	425	466
38	64.8%	.91	432	440	64.5%	.99	434	444
39	67.5%	.79	421	410	62.6%	.95	448	465
40	64.3%	.72	376	383	60.2%	.99	446	487

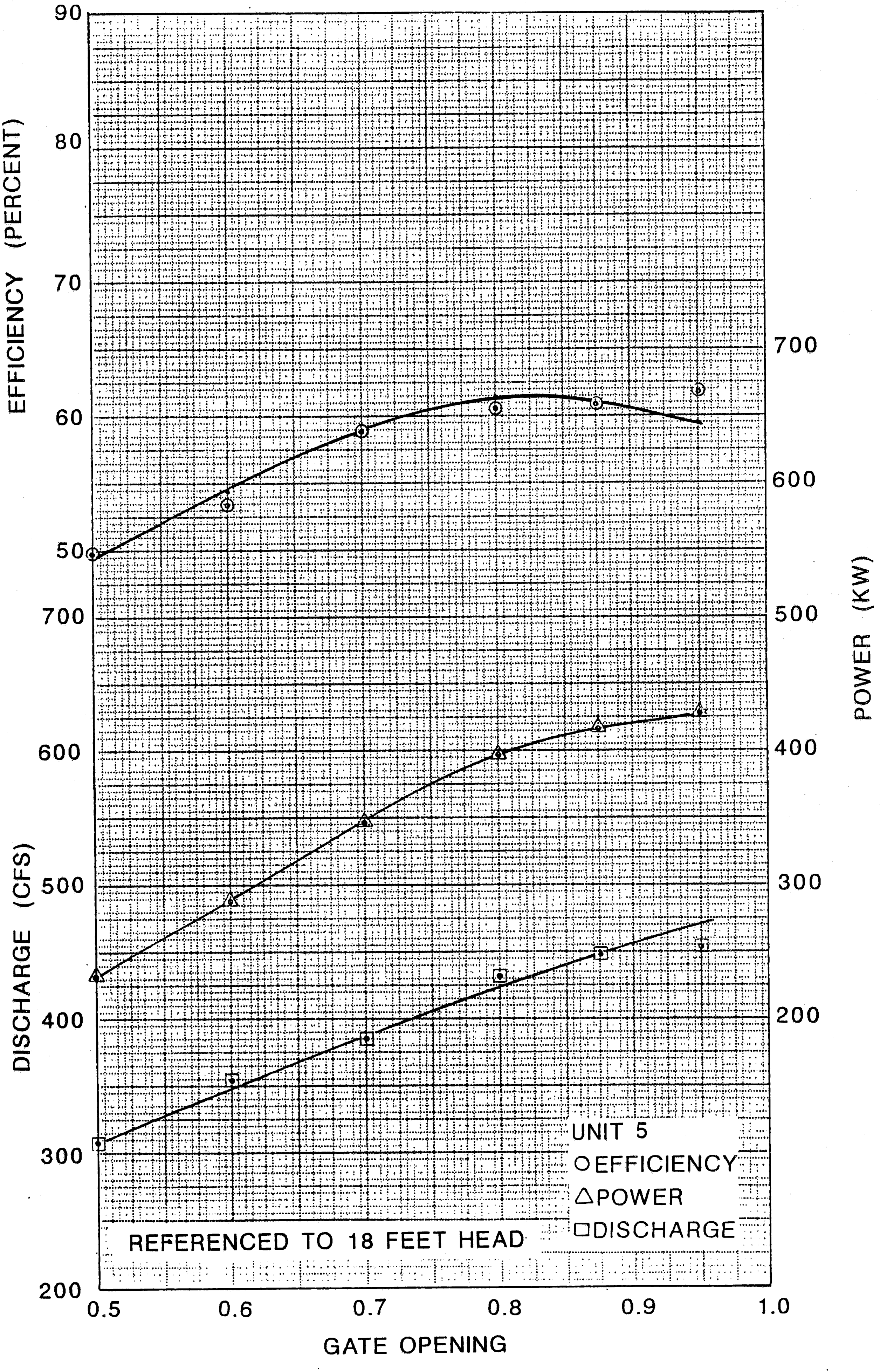
Table 1 (cont'd)

Unit No.	Peak Efficiency: e_p	Gate Opening @ e_p	Power @ e_p (kw)	Discharge @ e_p (cfs)	Maximum Output Efficiency: e_m	Gate Opening @ e_m	Power @ e_m (kw)	Discharge @ e_m (cfs)
Unit Nos. 46 thru 51: S. Morgan Smith Co.; Rated Power @ 18 ft = 675 kw								
46	77.1%	.66	485	413	73.3%	.87	568	508
47	76.7%	.73	540	462	73.5%	.94	592	527
48	79.6%	.69	521	429	71.6%	.92	576	522
49	80.0%	.64	486	400	71.6%	.93	573	523
50	75.2%	.66	513	449	66.5%	.93	573	555
51	79.5%	.63	480	395	69.9%	.92	572	528
Unit Nos. 52 thru 65: S. Morgan Smith Co.; Rated Power @ 18 ft = 725 kw								
52	79.9%	.60	465	380	67.3%	.95	593	580
53	82.0%	.59	456	361	71.1%	.95	600	556
54	73.1%	.86	585	528	72.4%	.93	597	540
55	72.5%	.73	536	486	65.7%	.95	586	581
56	74.7%	.65	468	413	69.9%	.90	561	527
57	78.3%	.67	515	431	64.0%	.94	572	578
58*	73.9%	.61	440	392	67.5%	.90	550	539
59	80.0%	.66	486	398	65.0%	.90	558	556
60	74.6%	.71	513	450	71.6%	.88	538	490
61	81.1%	.64	448	361	71.8%	.85	531	487
62*	74.5%	.63	425	378	66.6%	.90	519	510

Table 1 (cont'd)

Unit No.	Peak Efficiency: e_p	Gate Opening @ e_p	Power @ e_p (kw)	Discharge @ e_p (cfs)	Maximum Output Efficiency: e_m	Gate Opening @ e_m	Power @ e_m (kw)	Discharge @ e_m (cfs)
Unit Nos. 52 thru 65: S. Morgan Smith Co.; Rated Power @ 18 ft = 725 kw (Cont'd)								
63	76.0%	.63	450	383	72.0%	.90	545	498
64*	81.0%	.77	523	423	79.0%	.93	551	456
65	79.2%	.58	419	350	75.3%	.90	539	469
Unit Nos. 66 thru 80: Wellman, Seaver, Morgan Co.; Rated Power @ 18 ft = 750 kw								
66	85.6%	.72	483	370	73.0%	1.00	584	519
67	83.3%	.77	527	414	75.0%	1.00	585	515
68	67.1%	.68	513	500	60.5%	1.00	613	662
69	80.7%	.76	534	434	74.1%	1.00	586	517
70‡	‡Unit No. 70 was out of commission during the time of testing.							
71	65.7%	.83	564	563	63.1%	1.00	610	631
72	61.9%	.74	524	550	57.1%	1.00	610	698
73	64.1%	.74	520	531	59.6%	1.00	614	673
74	68.1%	.77	569	542	59.4%	1.00	605	654
75	72.8%	.70	514	458	63.0%	1.00	629	659
76	80.6%	.77	555	448	73.7%	1.00	607	542
77	72.0%	.62	492	445	60.2%	1.00	594	645
78	64.0%	.73	542	556	57.2%	1.00	622	712
79	67.6%	.70	470	456	56.2%	1.00	586	686
80	70.0%	.70	514	488	60.6%	1.00	626	675

APPENDIX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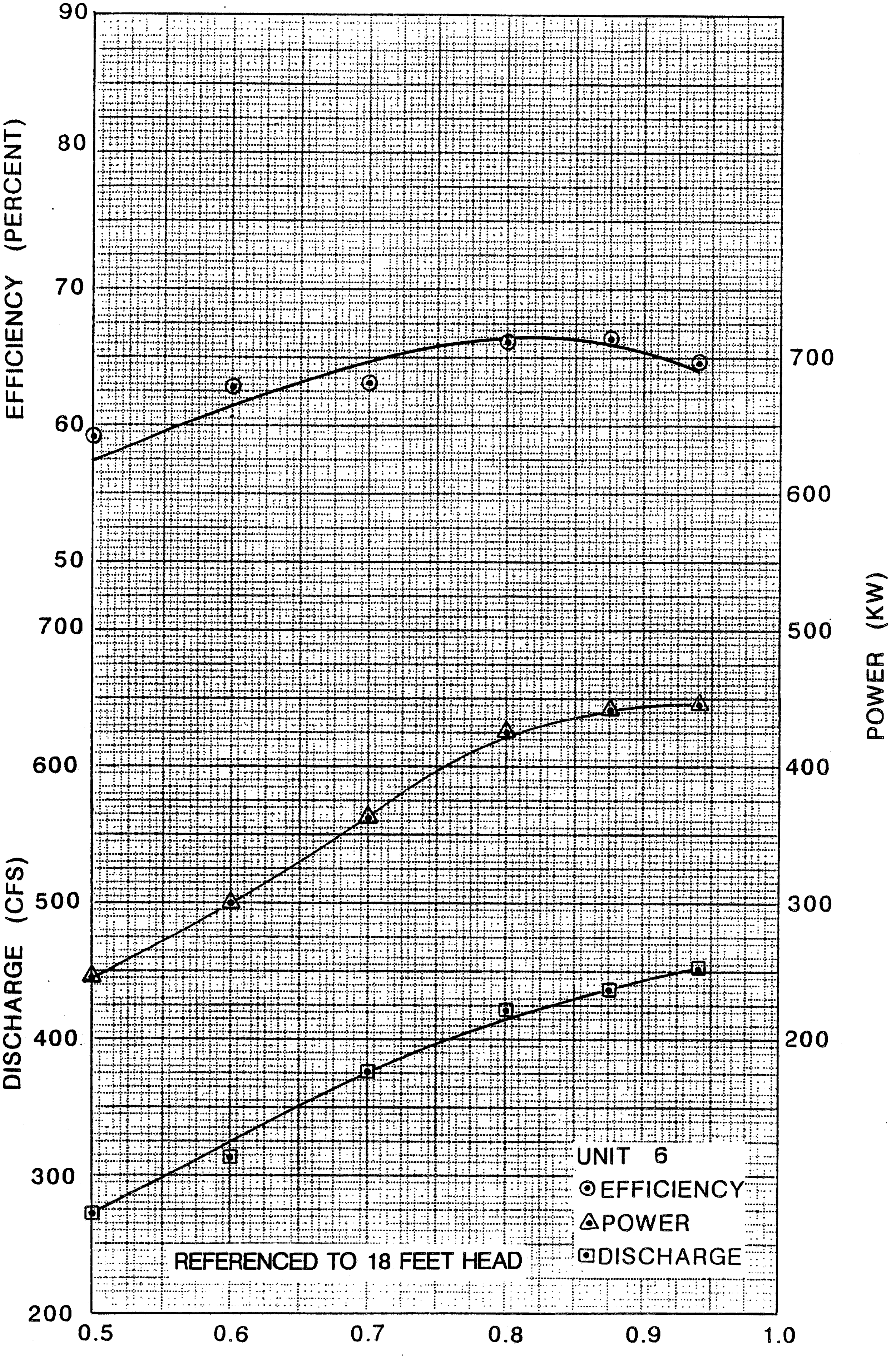
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 5
○ EFFICIENCY
△ POWER
□ DISCHARGE
REFERENCED TO 18 FEET HEAD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80
70
60
50
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500
400
300
200
DISCHARGE (CFS)
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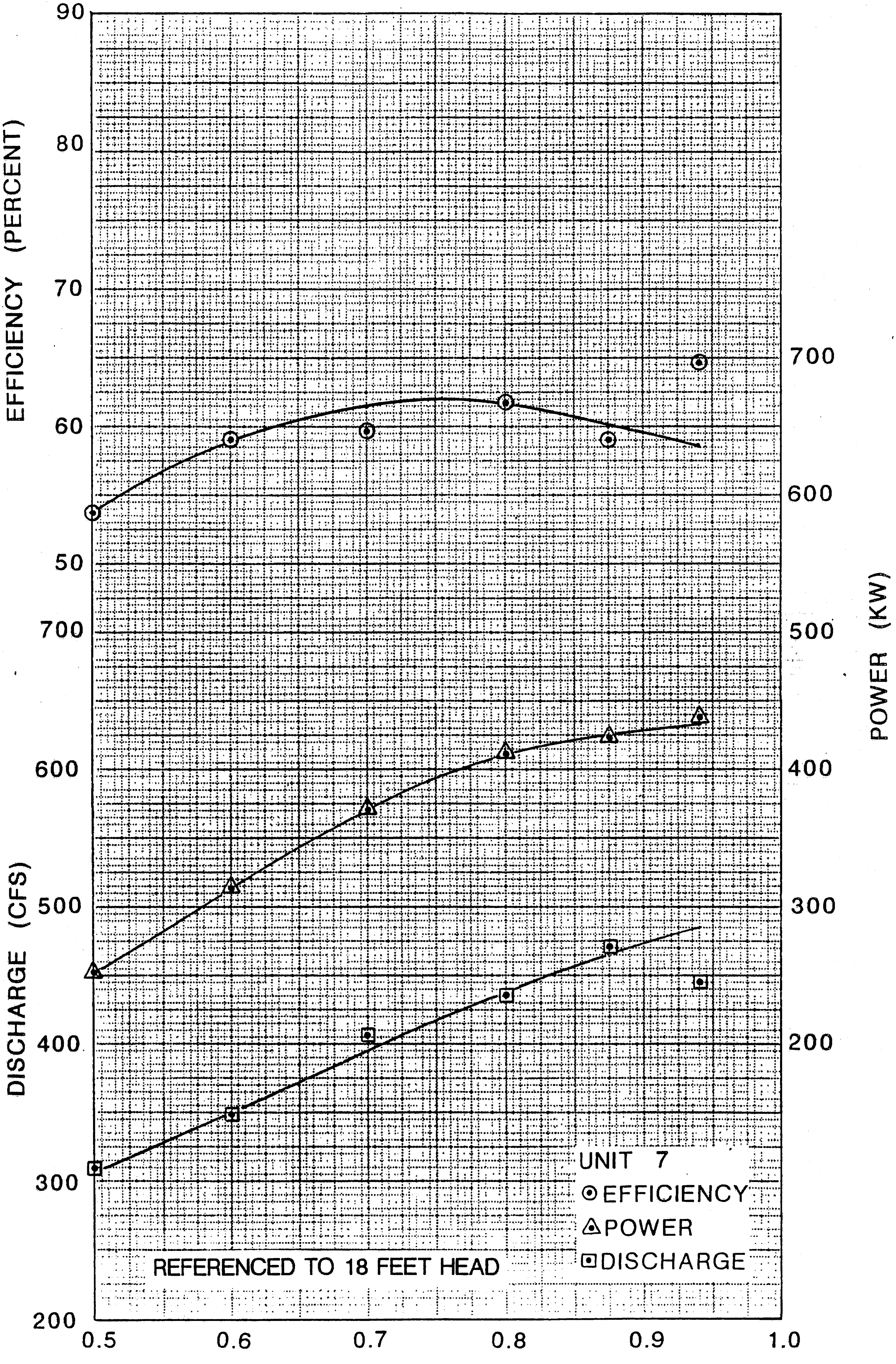
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 6
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD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60
50
DISCHARGE (CFS)
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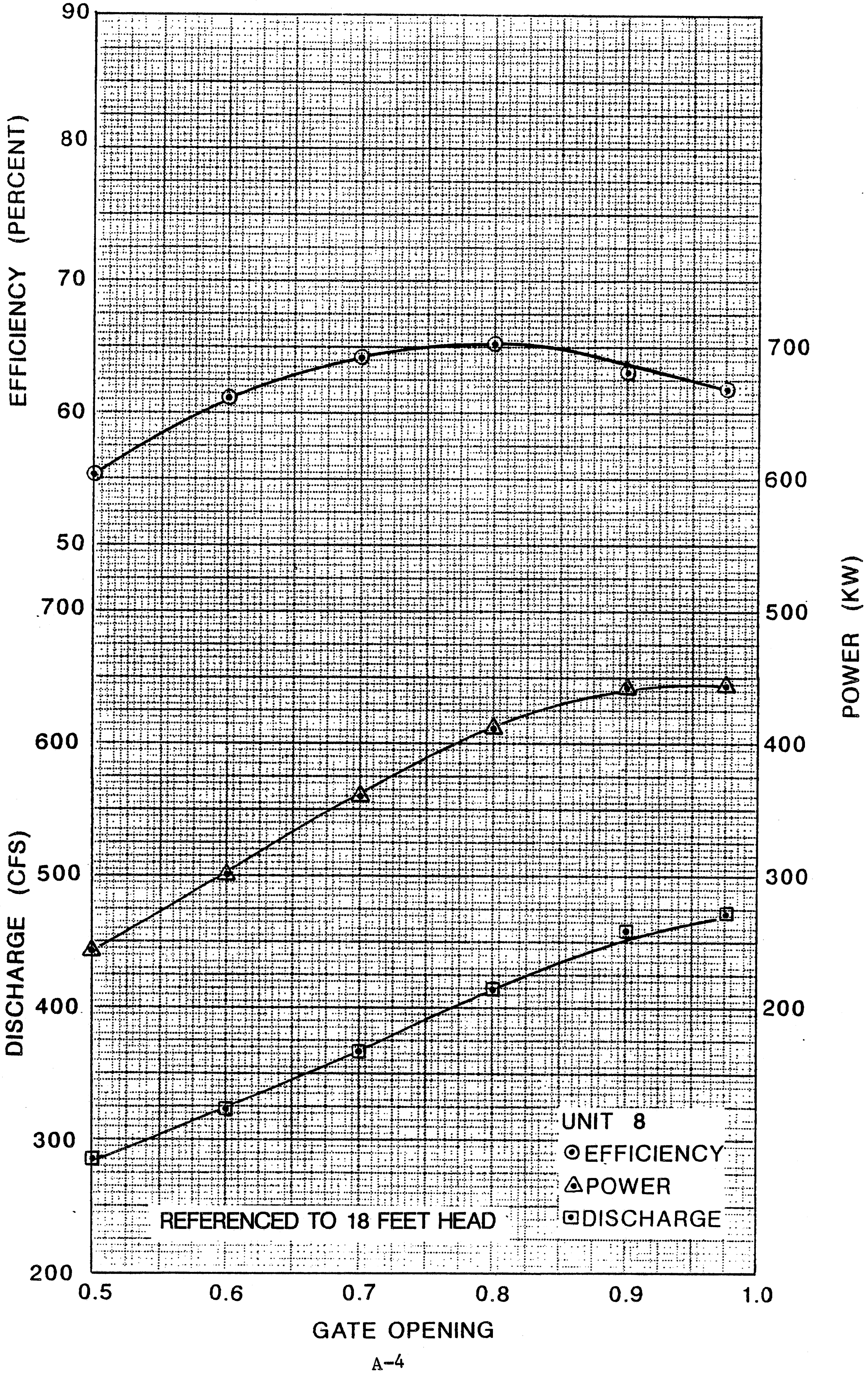
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 7
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD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60
50
700
600
500
400
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200
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DISCHARGE (CFS)
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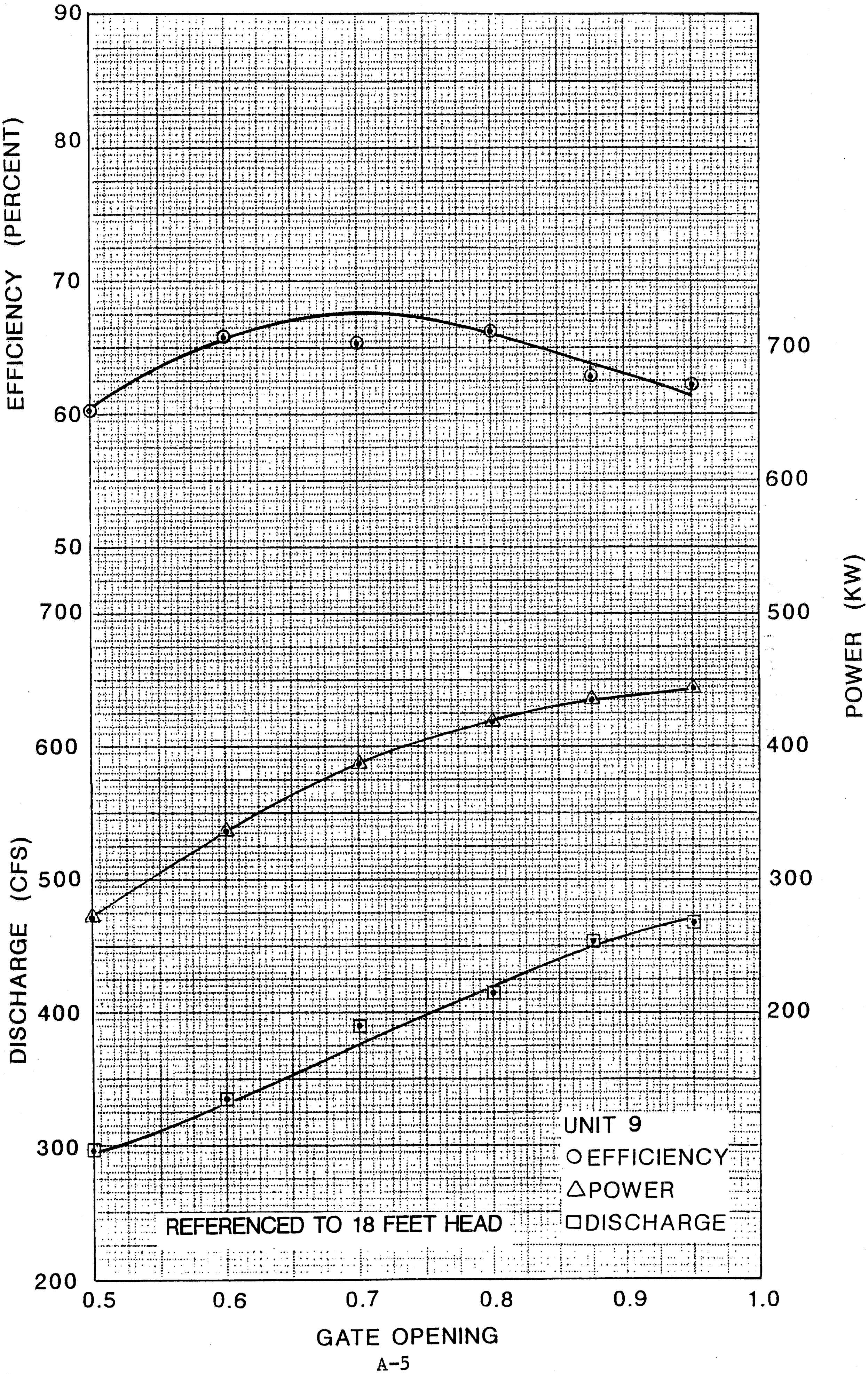
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 8
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD


90
80
70
60
50
700
600
500
400
300
200
EFFICIENCY (PERCENT)
DISCHARGE (CFS)
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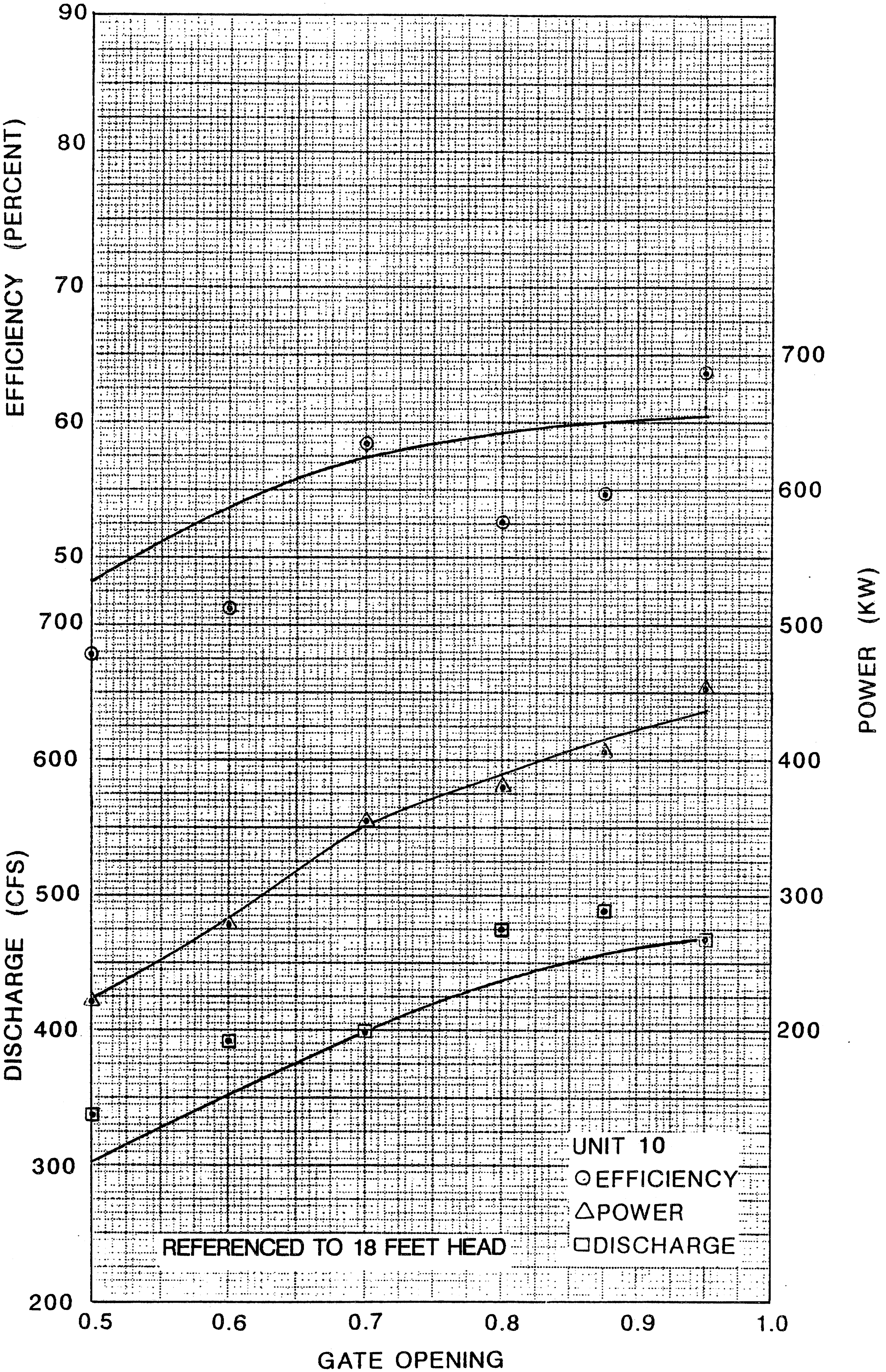
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 9
○EFFICIENCY
△POWER
□DISCHARGE
REFERENCED TO 18 FEET HEAD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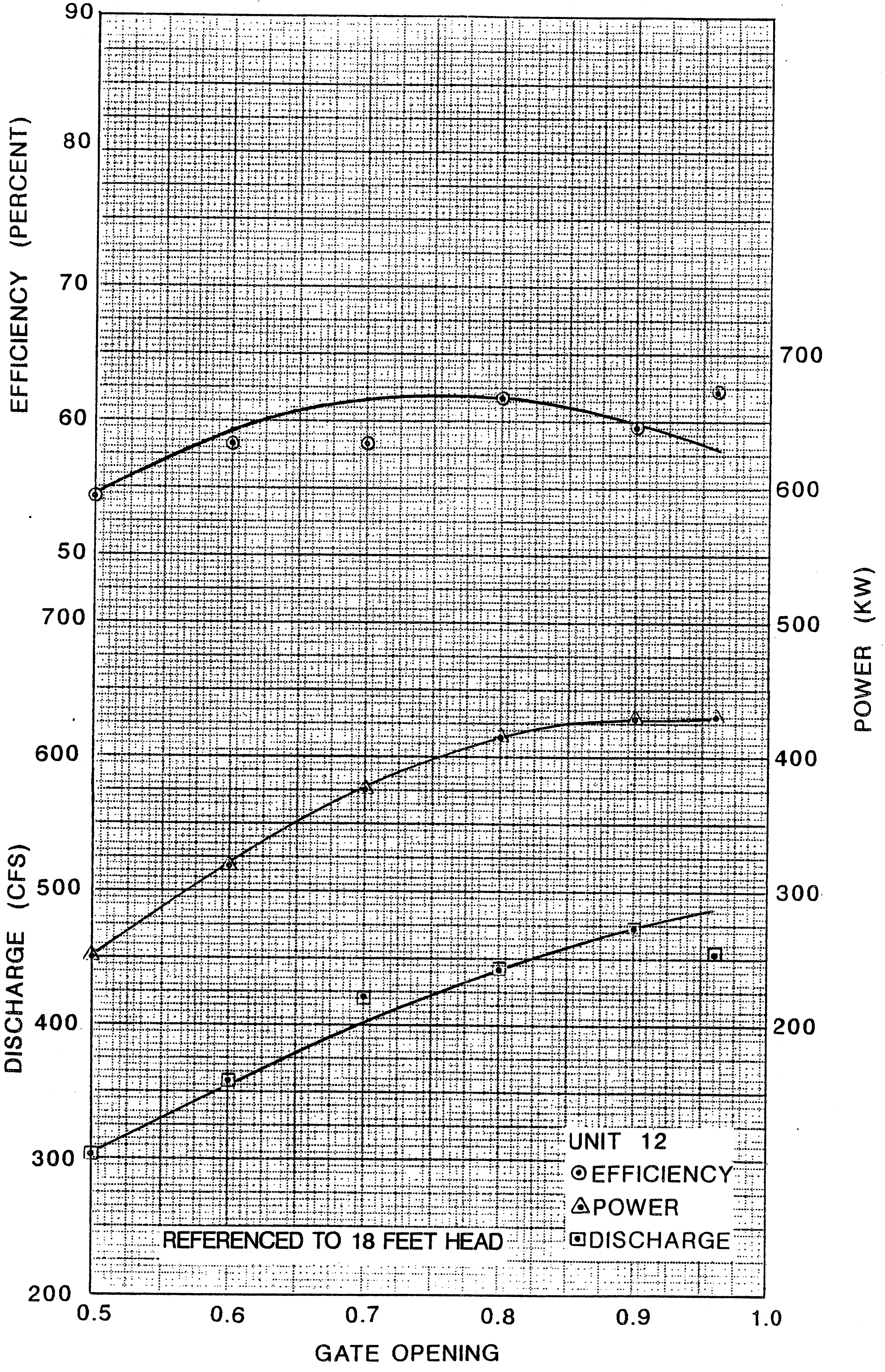
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 10
○EFFICIENCY
△POWER
□DISCHARGE
REFERENCED TO 18 FEET HEAD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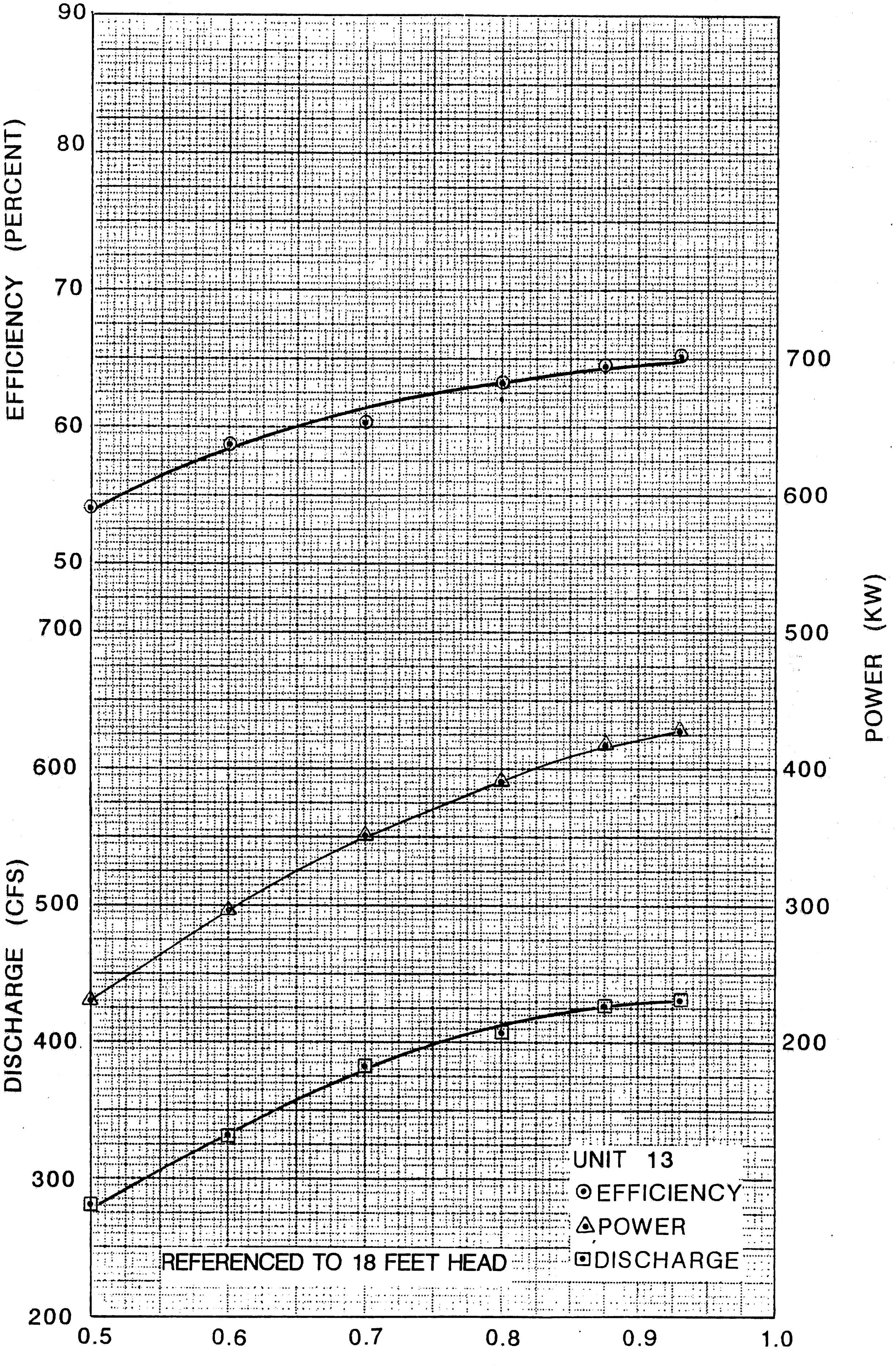
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 12
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD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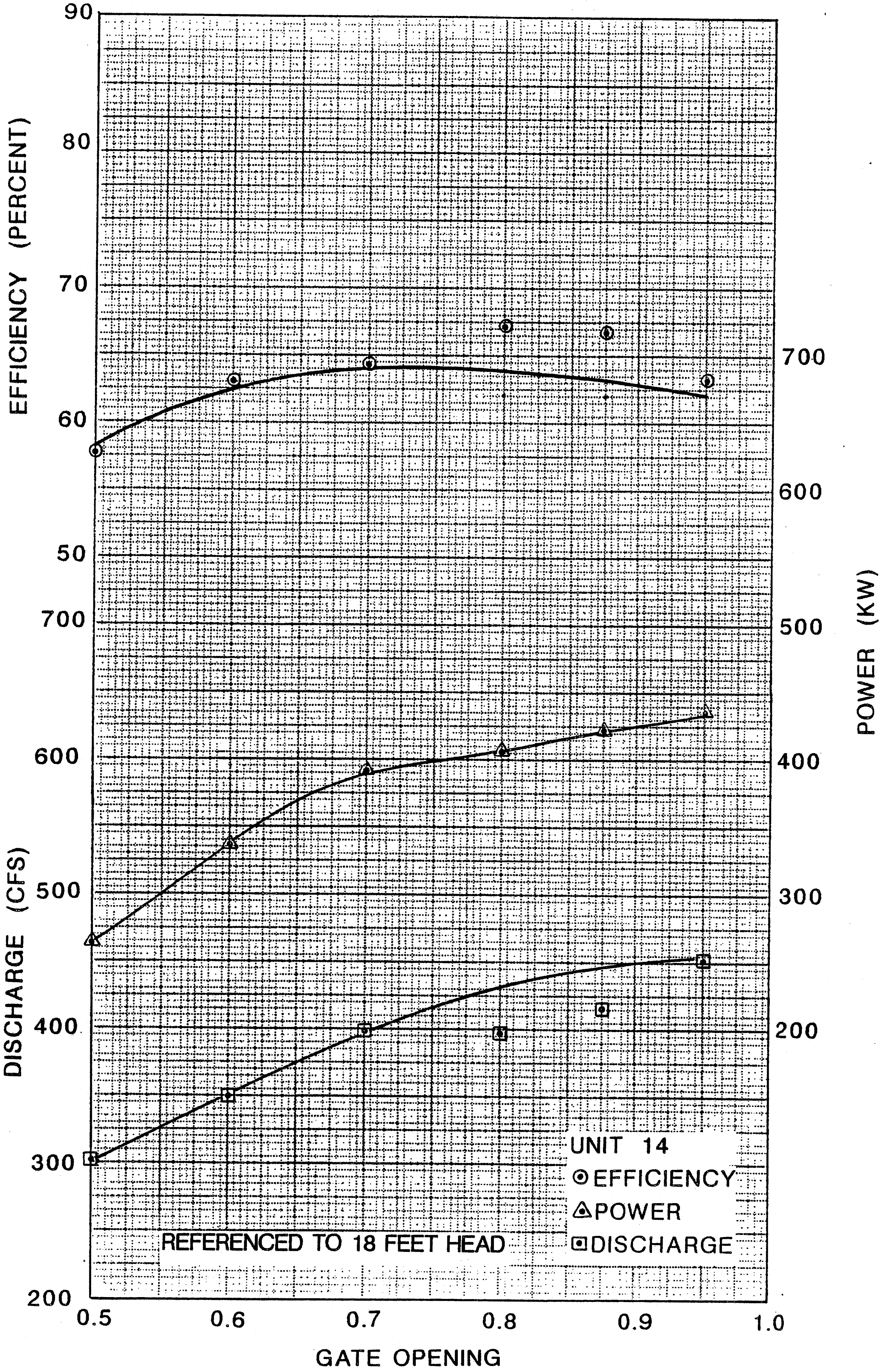
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 13
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
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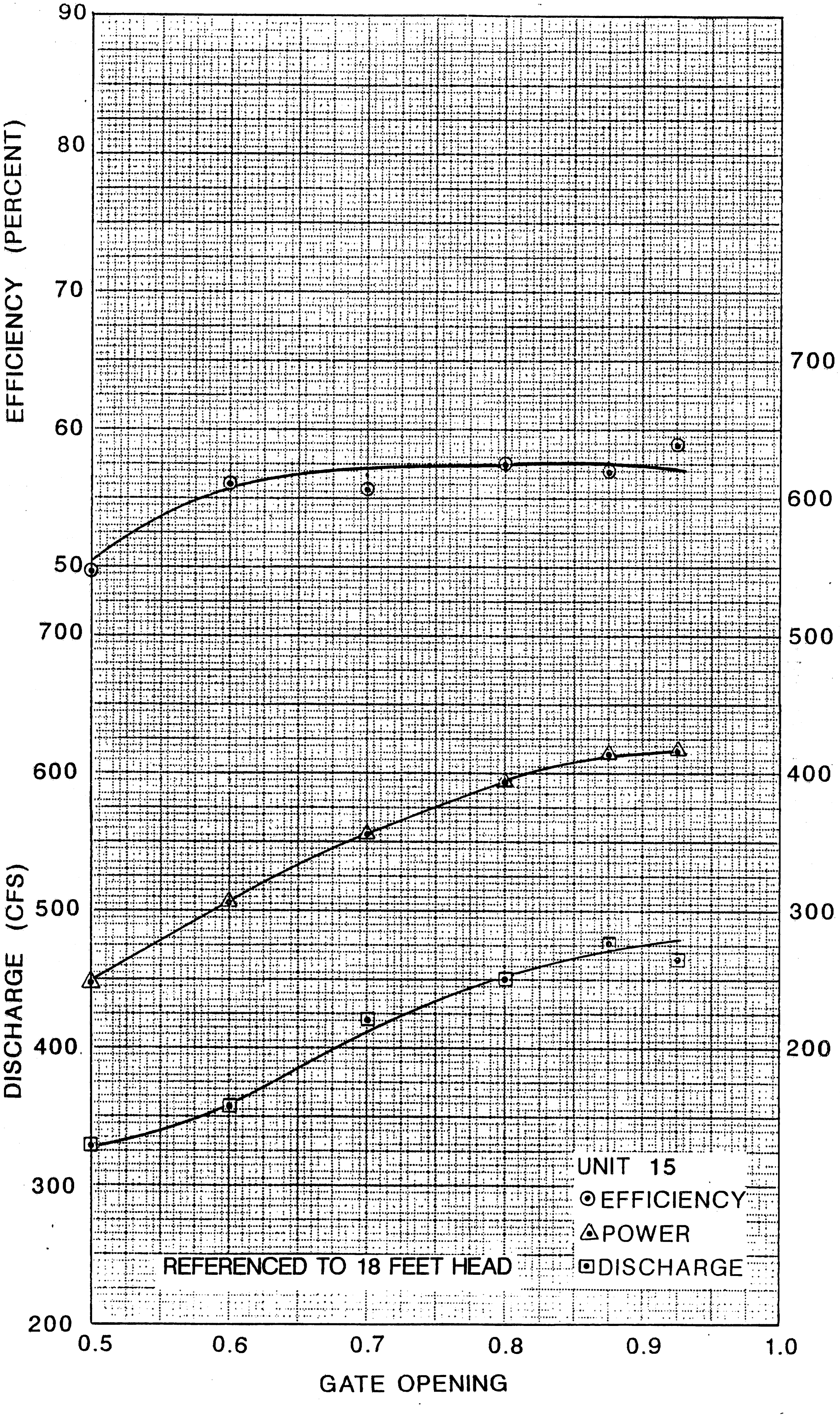
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 14
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD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50
DISCHARGE (CFS)
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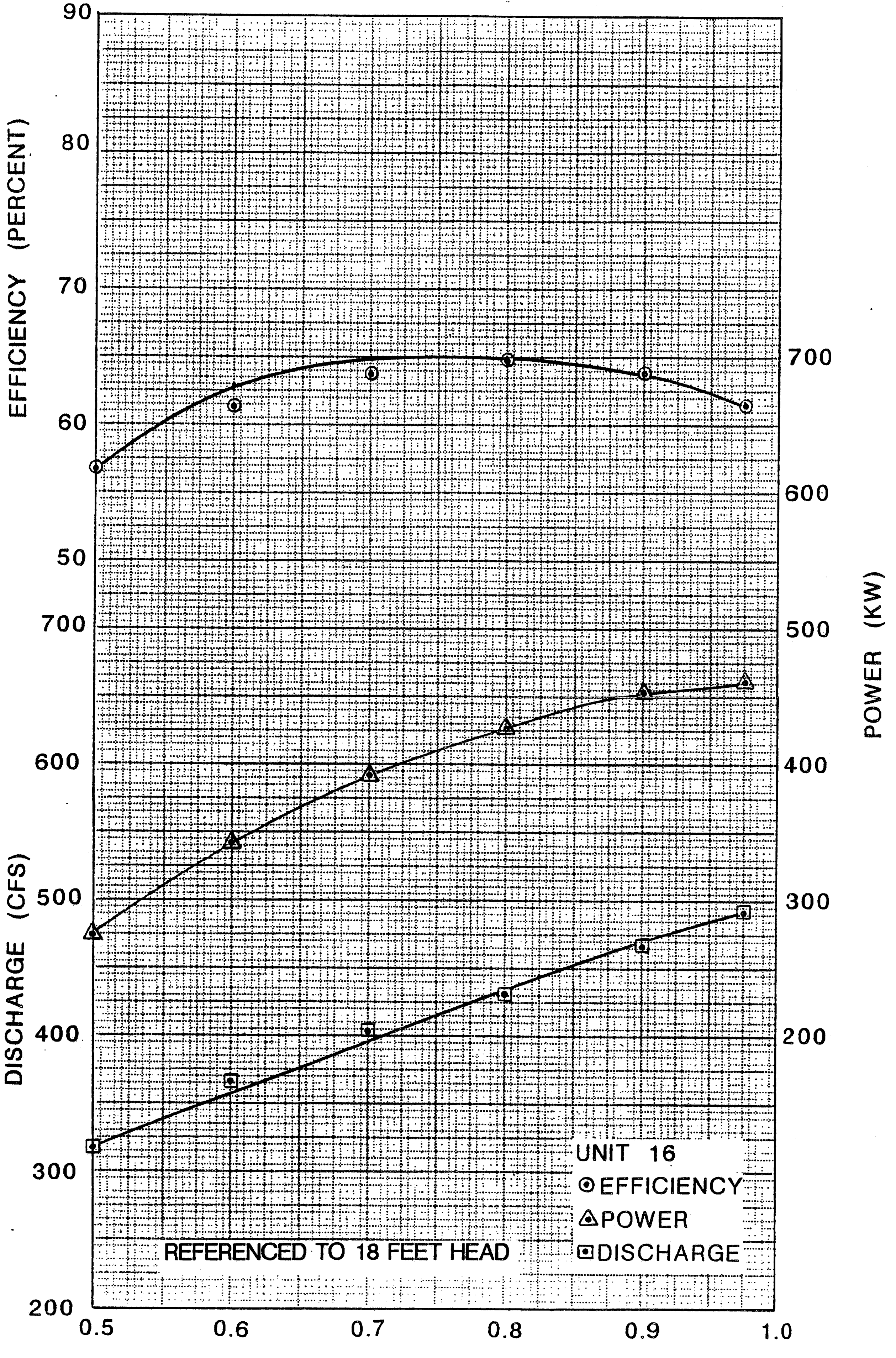
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 15
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD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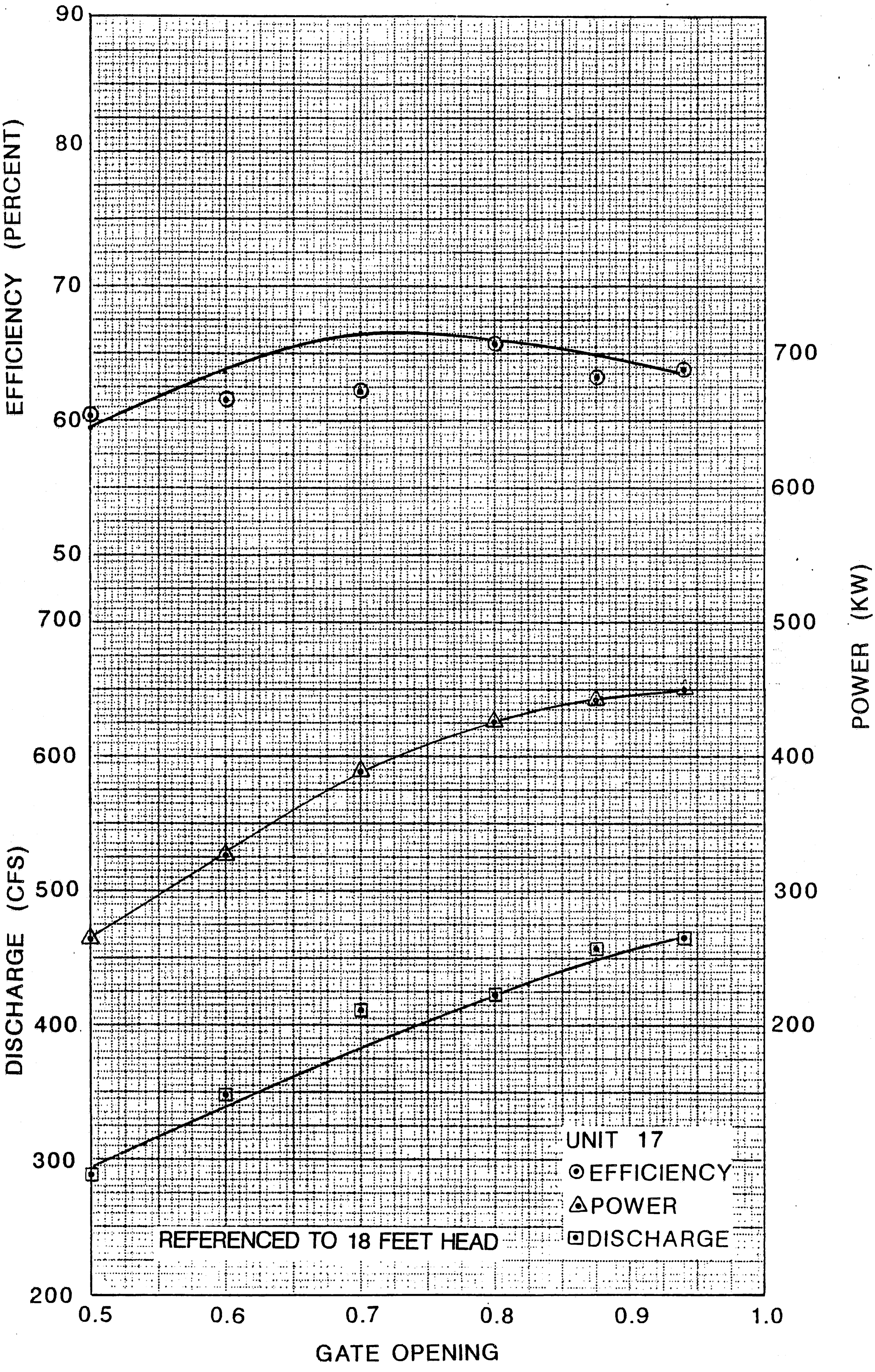
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 16
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
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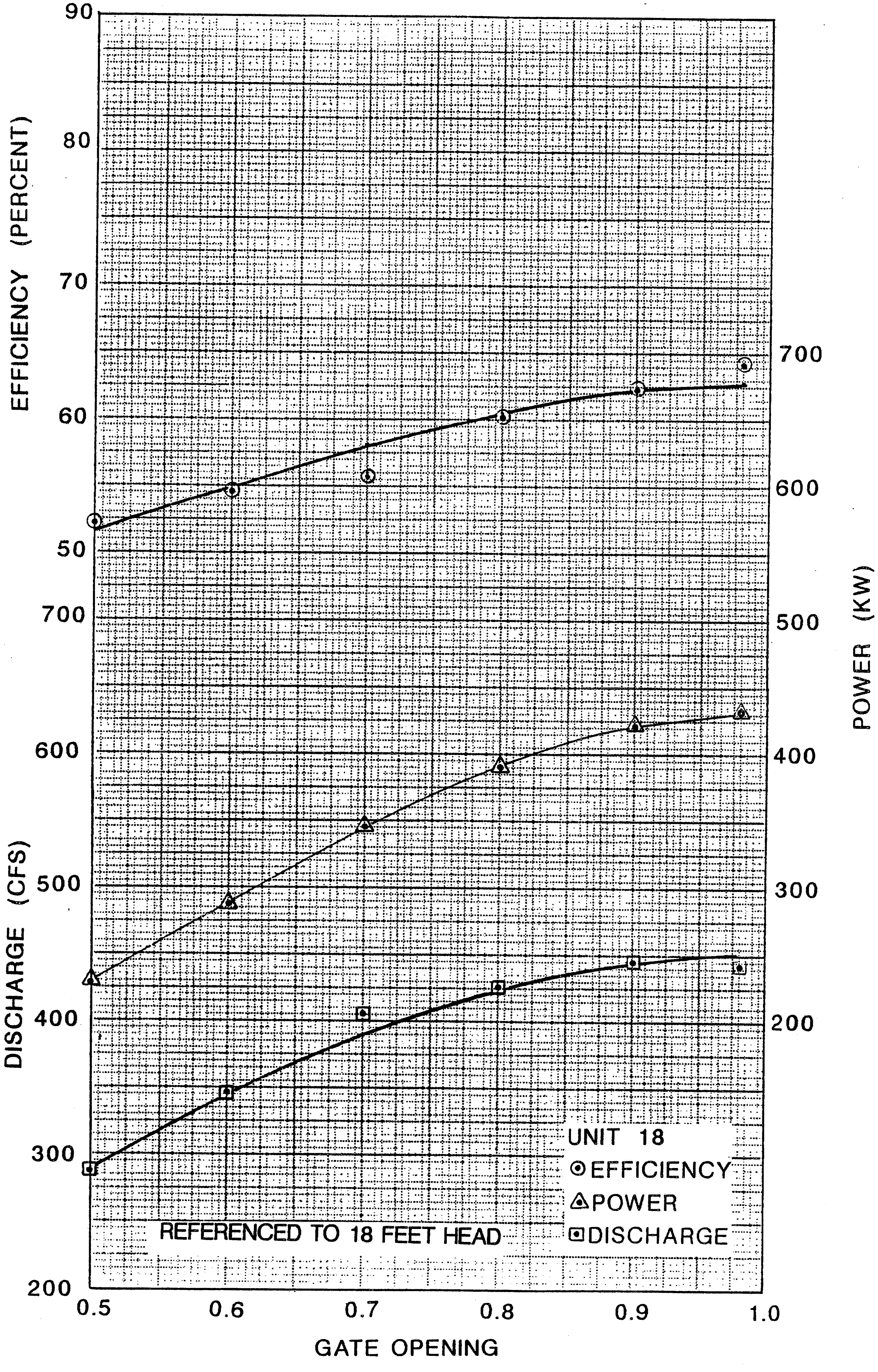
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 17
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD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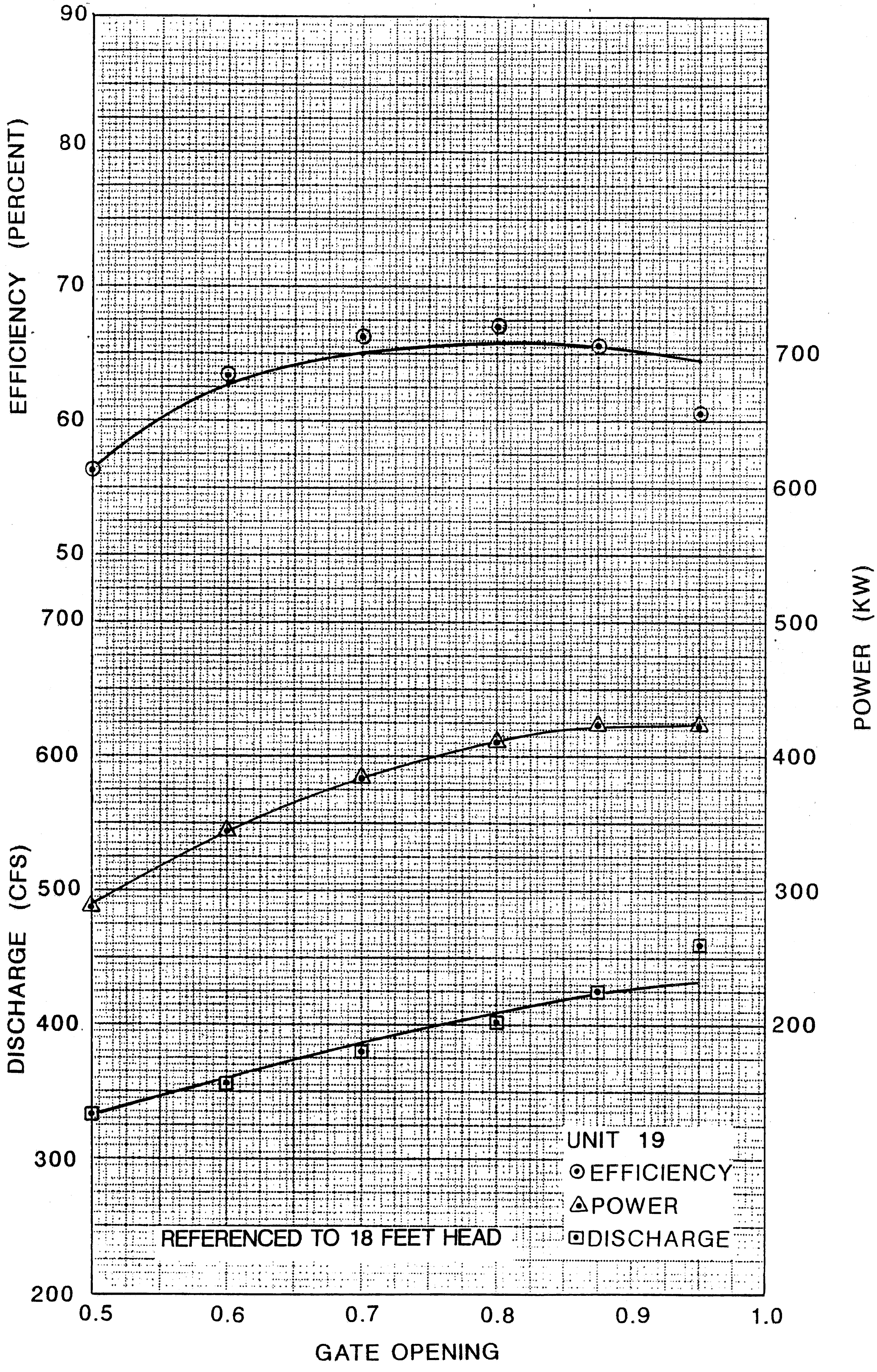
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 18
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
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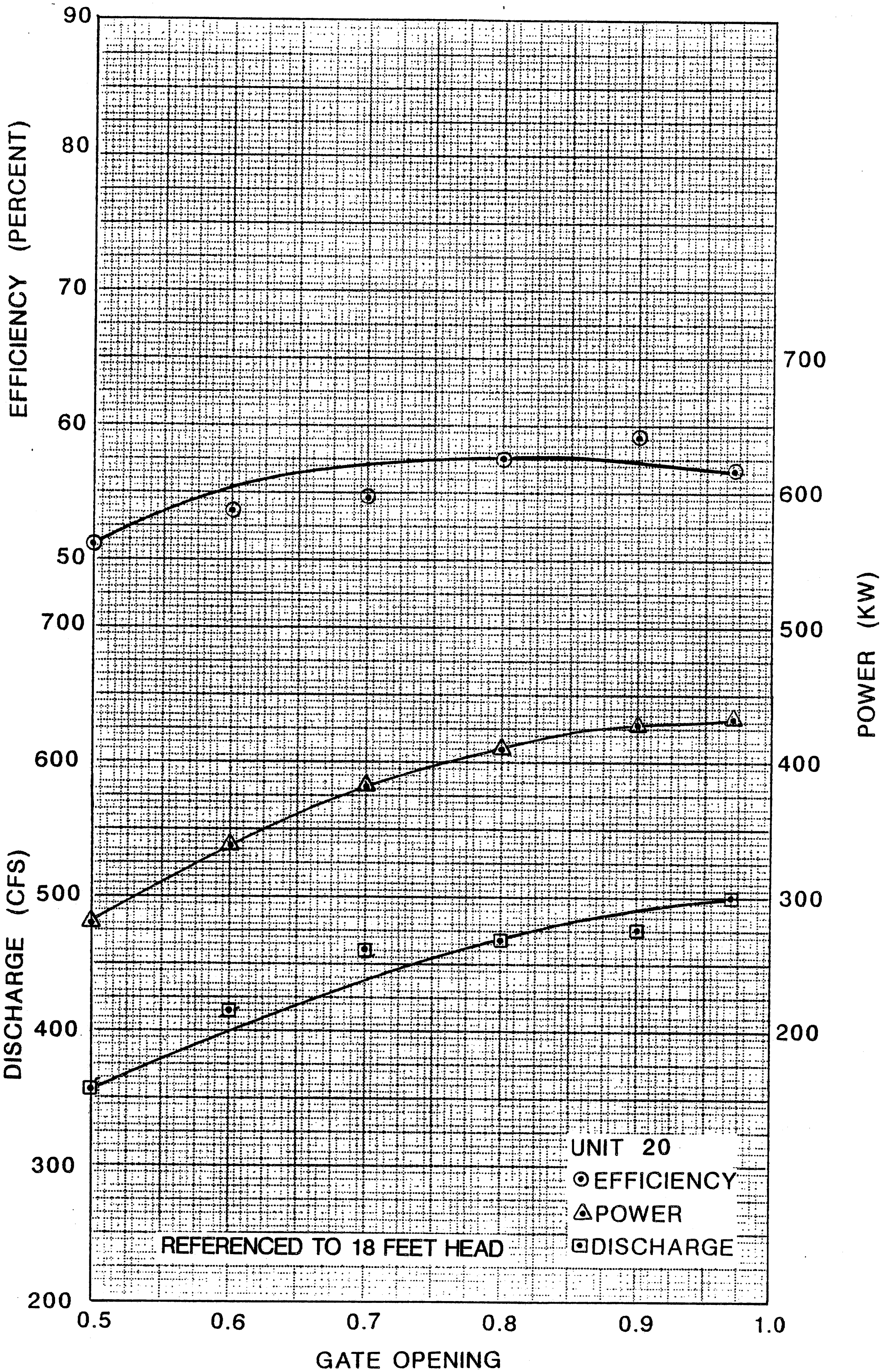
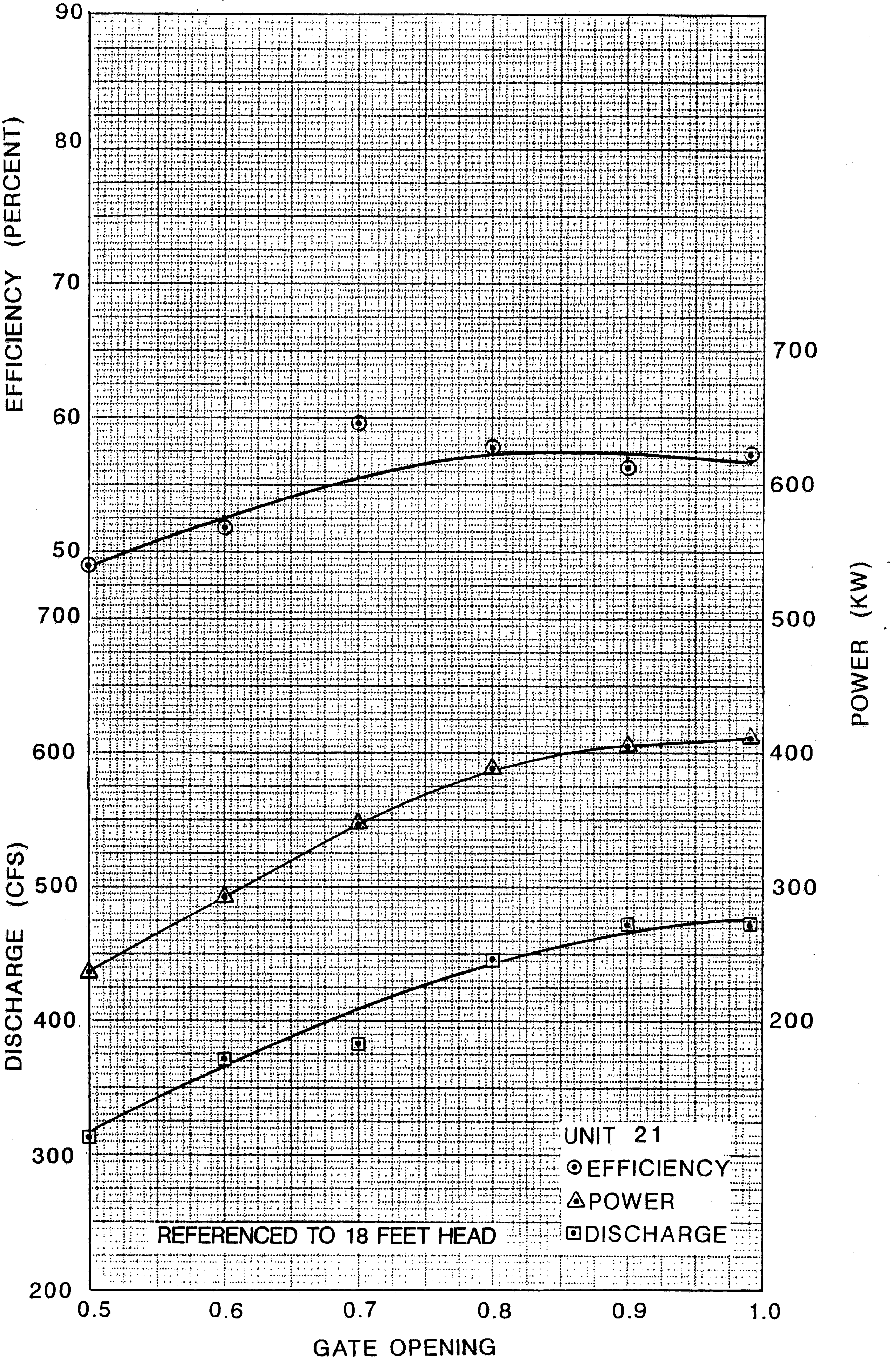
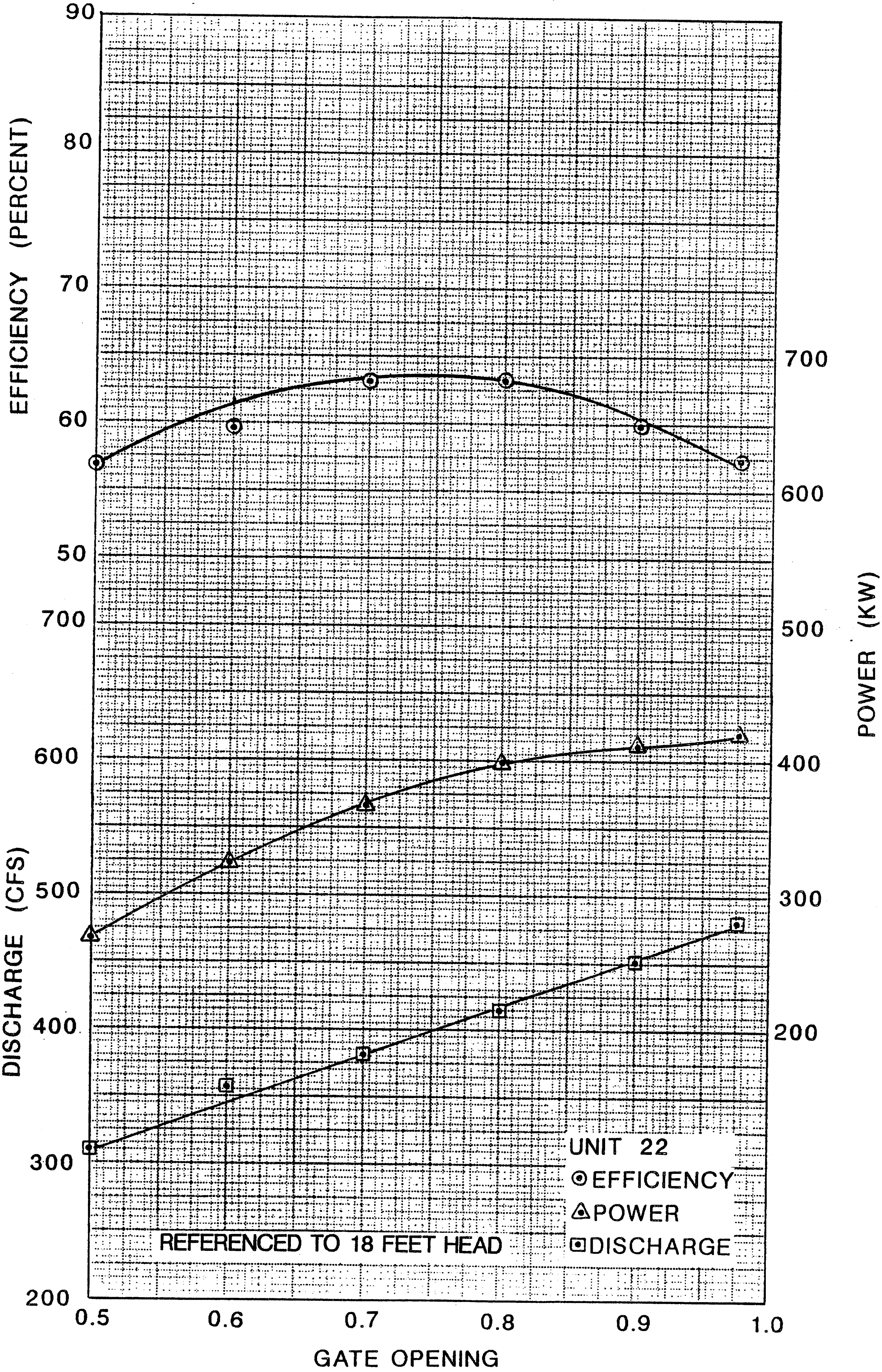
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 19
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

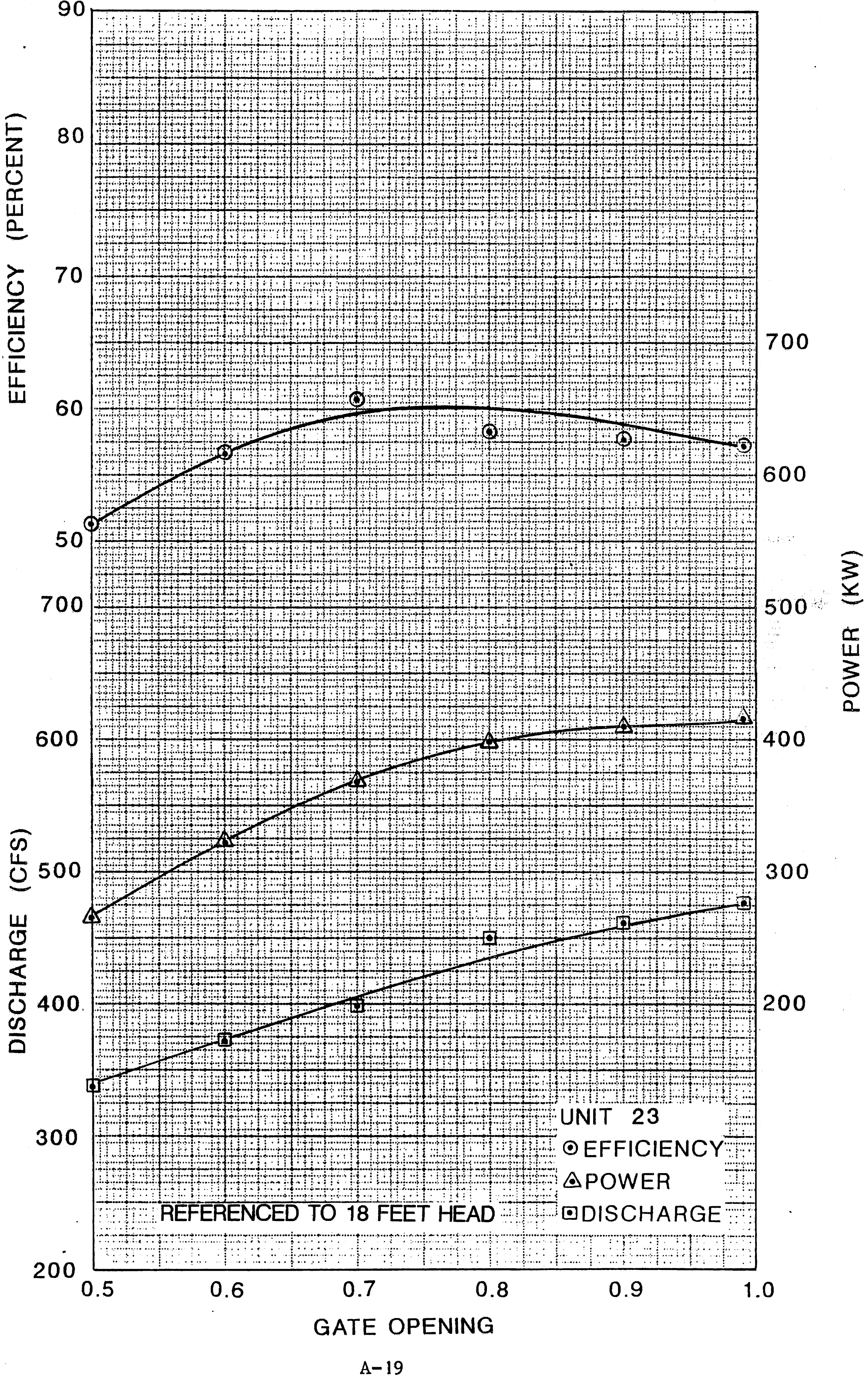

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 20
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

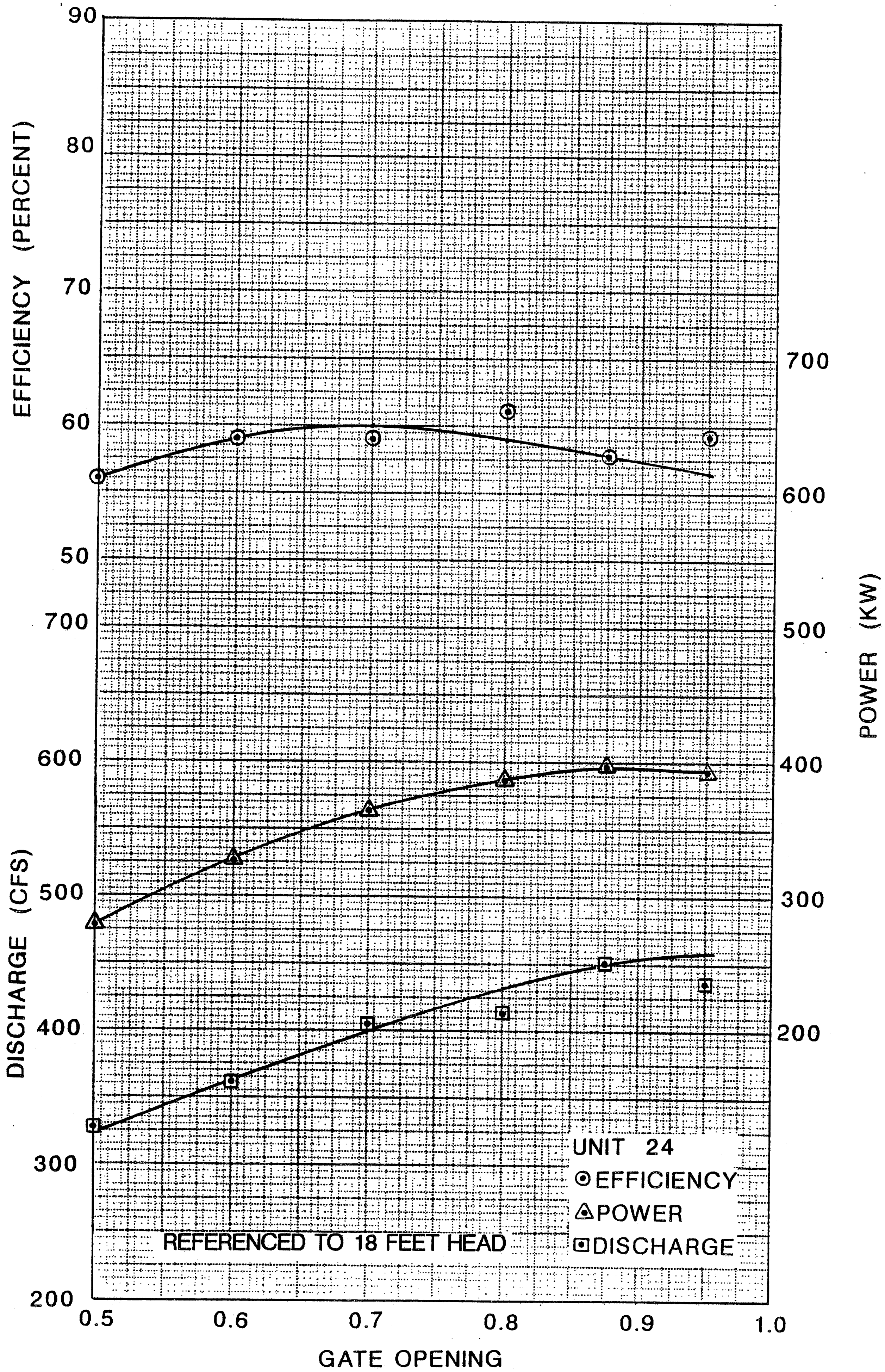


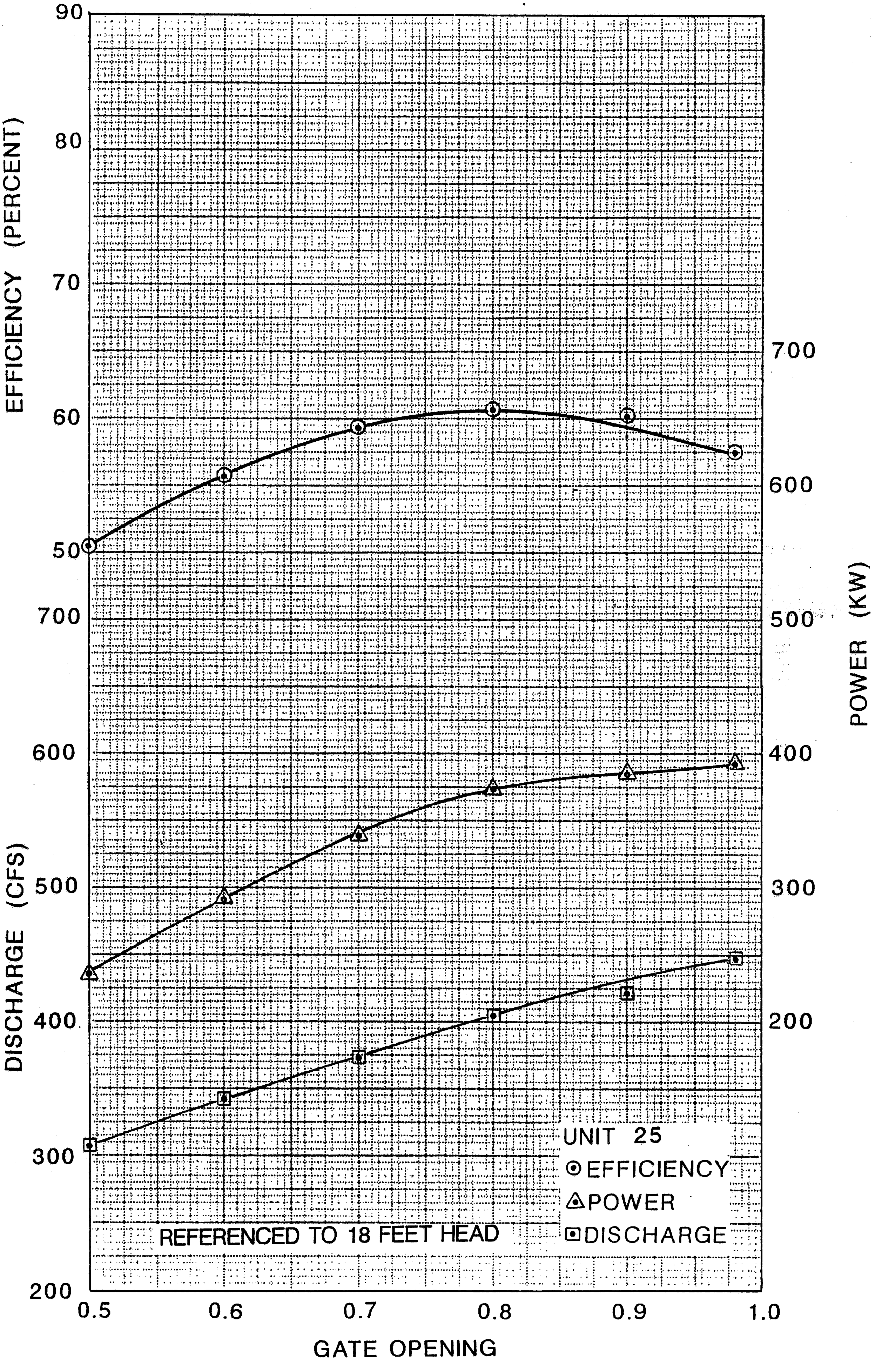
EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 21
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

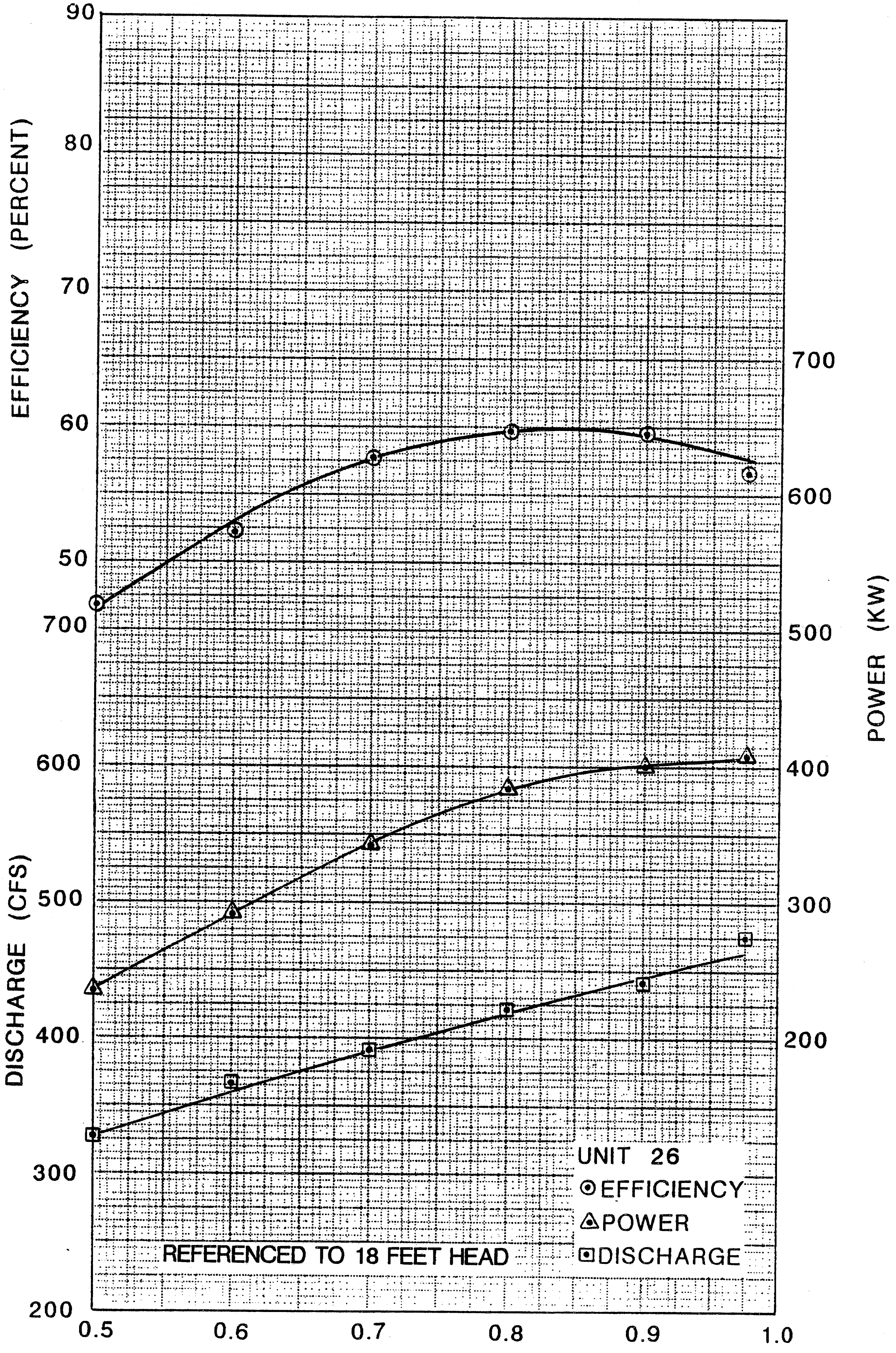


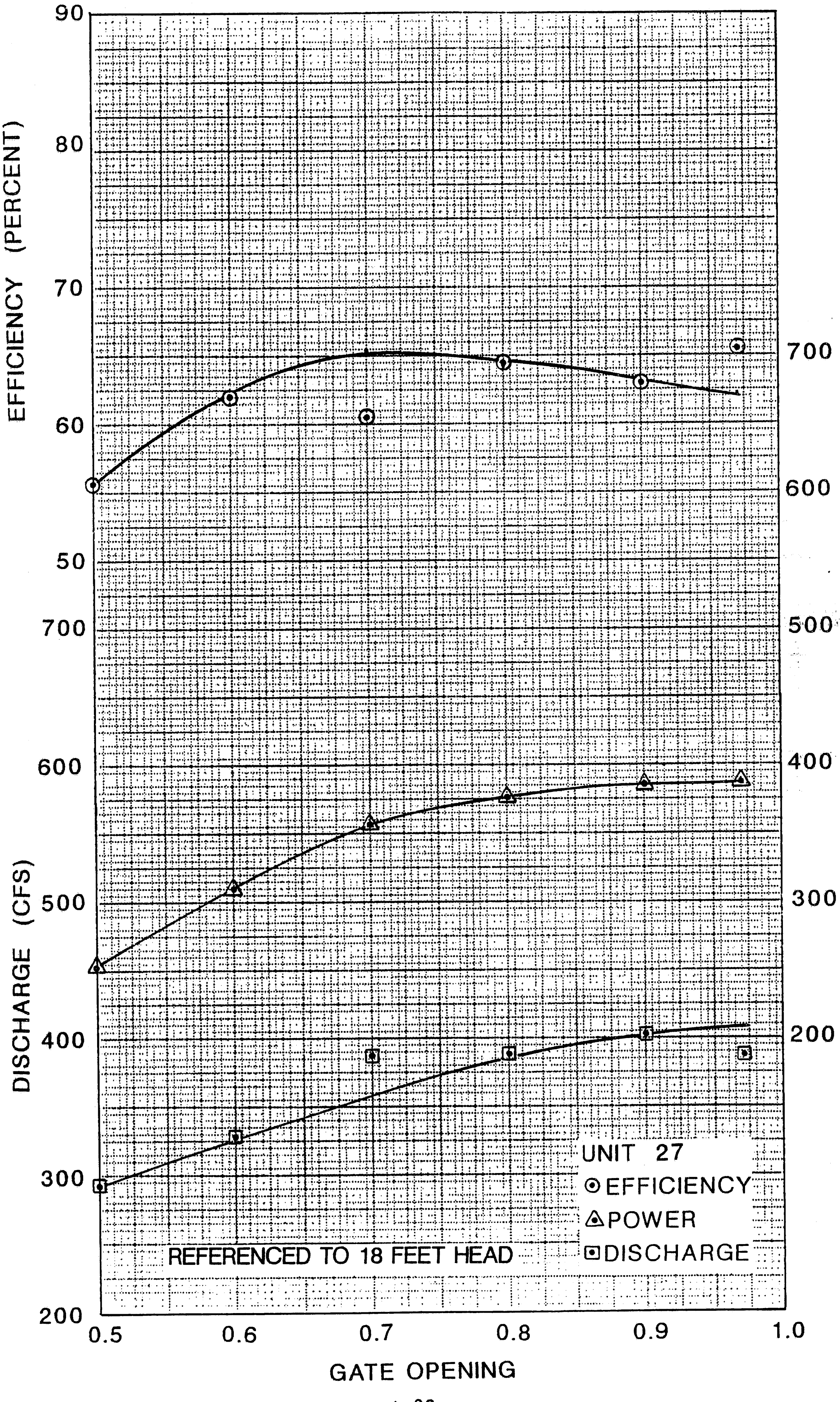
90
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 22
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

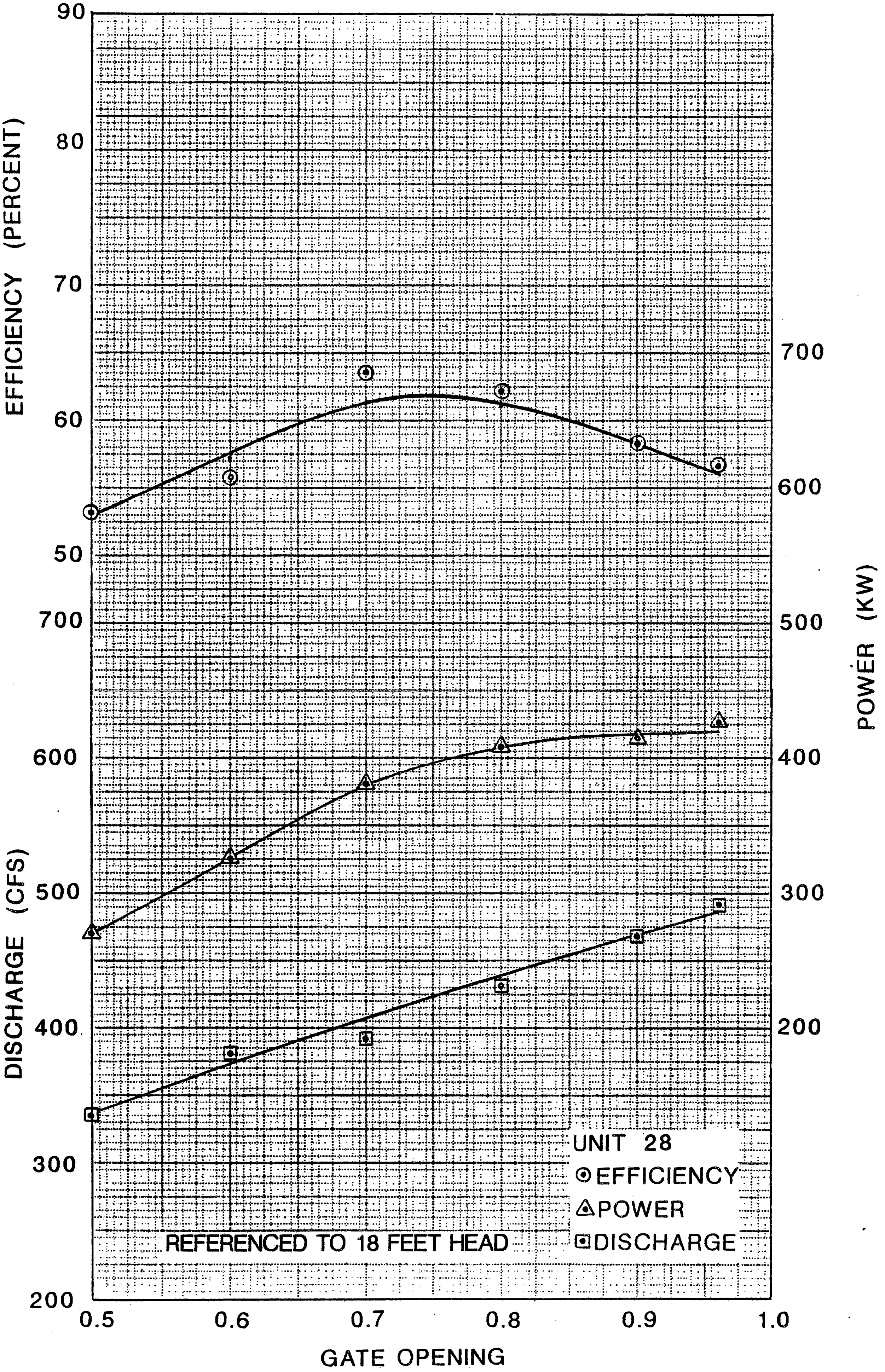
EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
REFERENCED TO 18 FEET HEAD
UNIT 23
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE

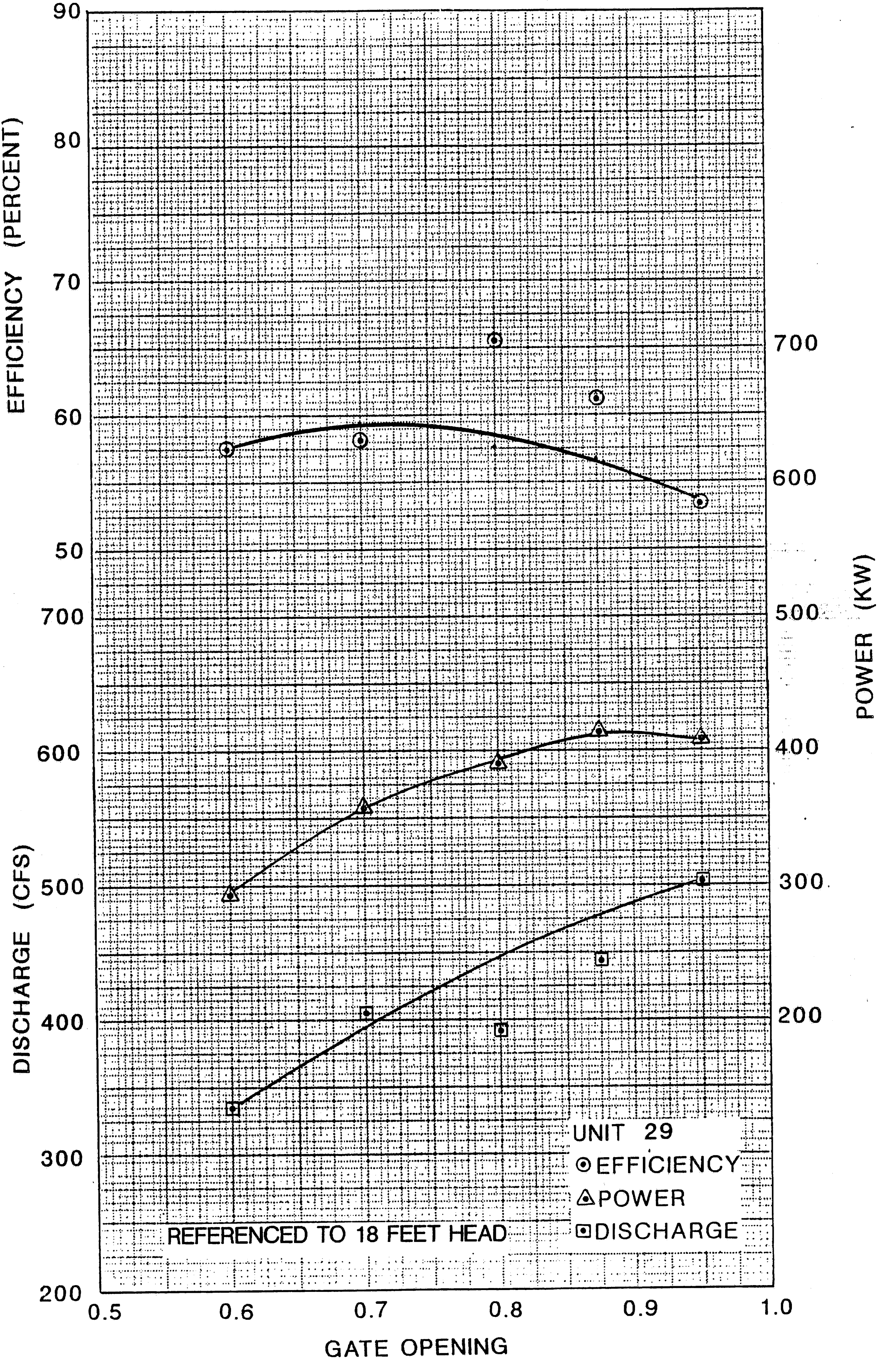

90
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 24
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

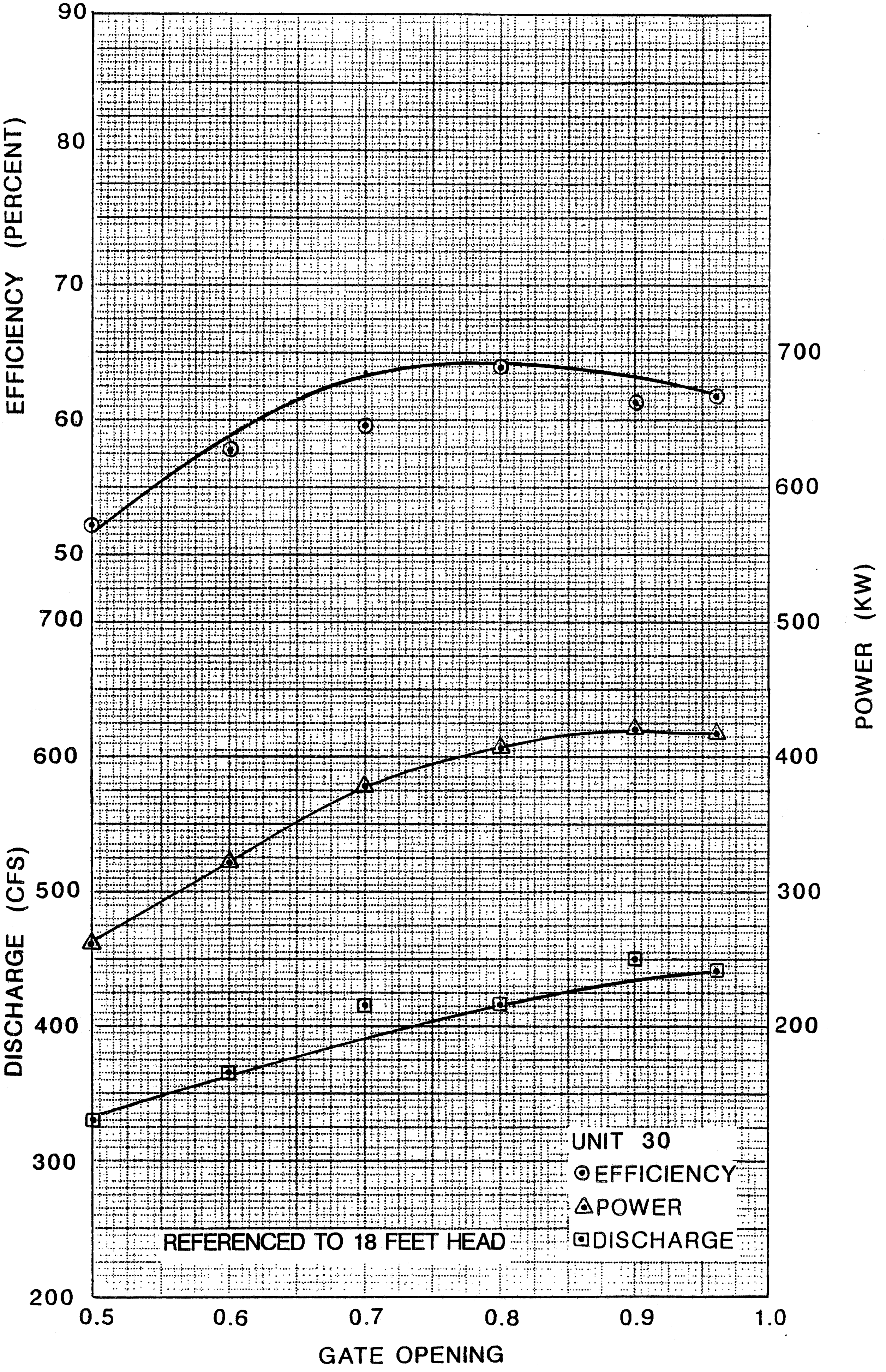

90
80
70
60
50
700
600
500
400
300
200
EFFICIENCY (PERCENT)
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 25
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD

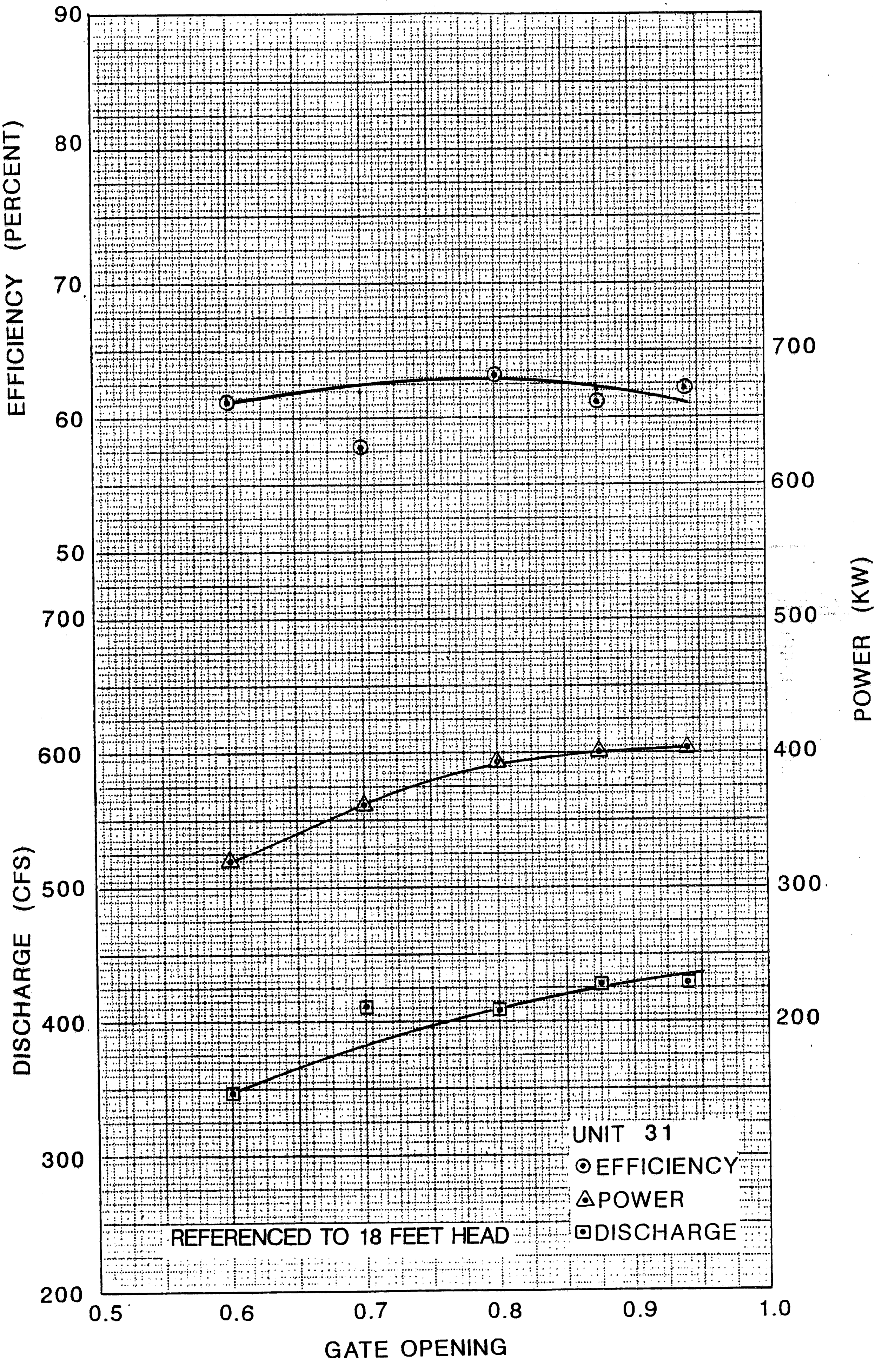

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 26
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD

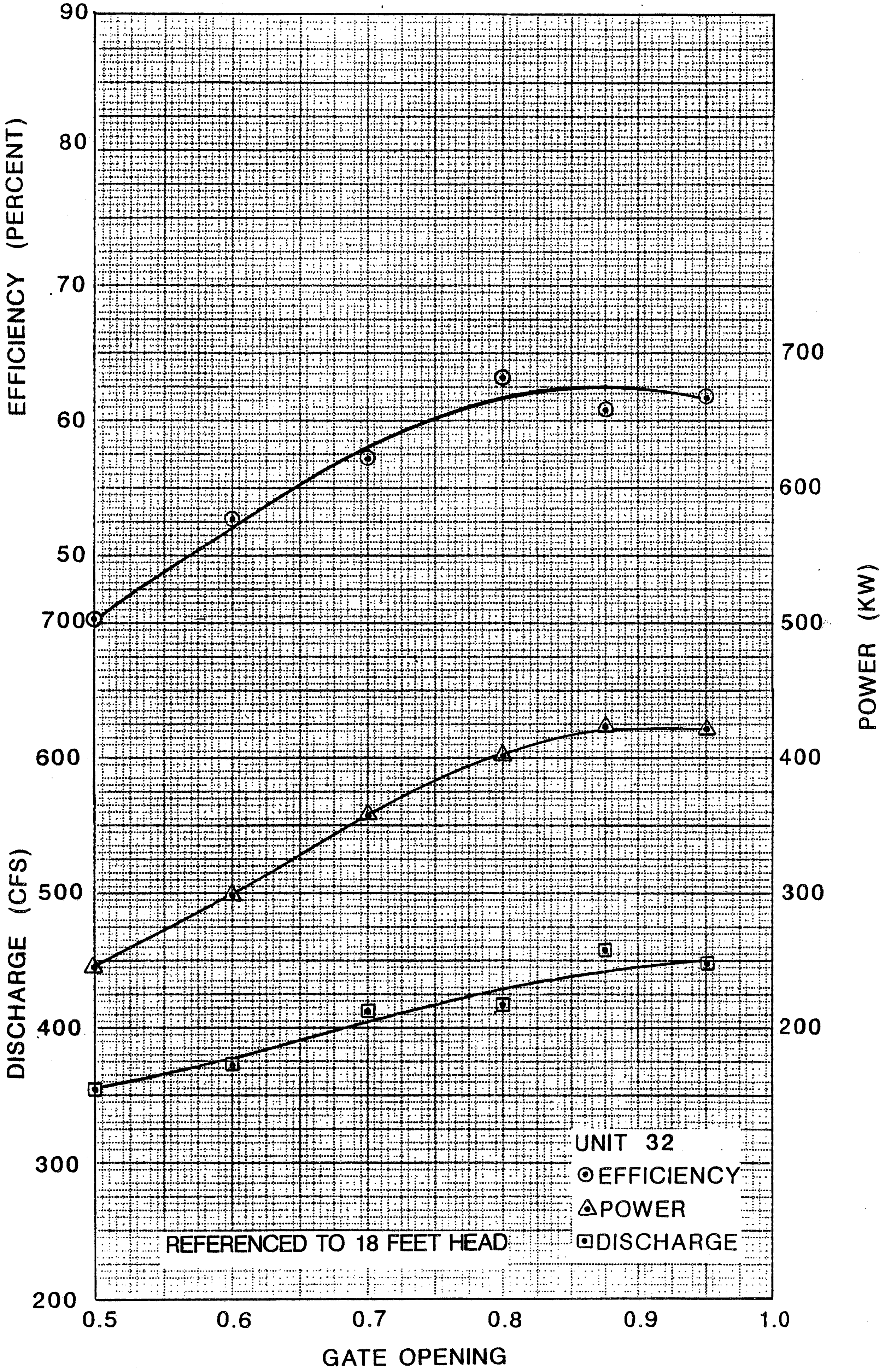

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 27
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

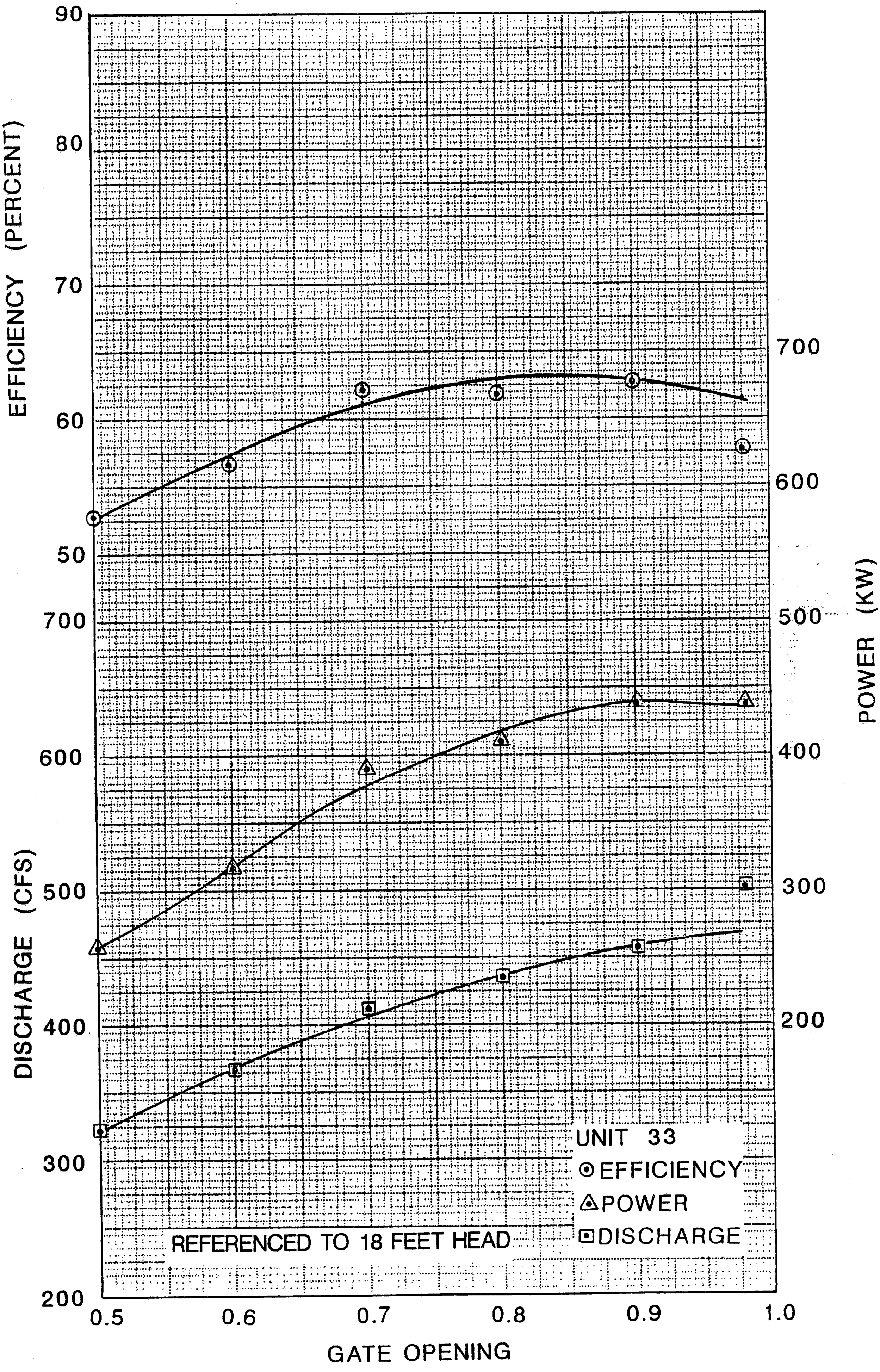

90
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 28
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

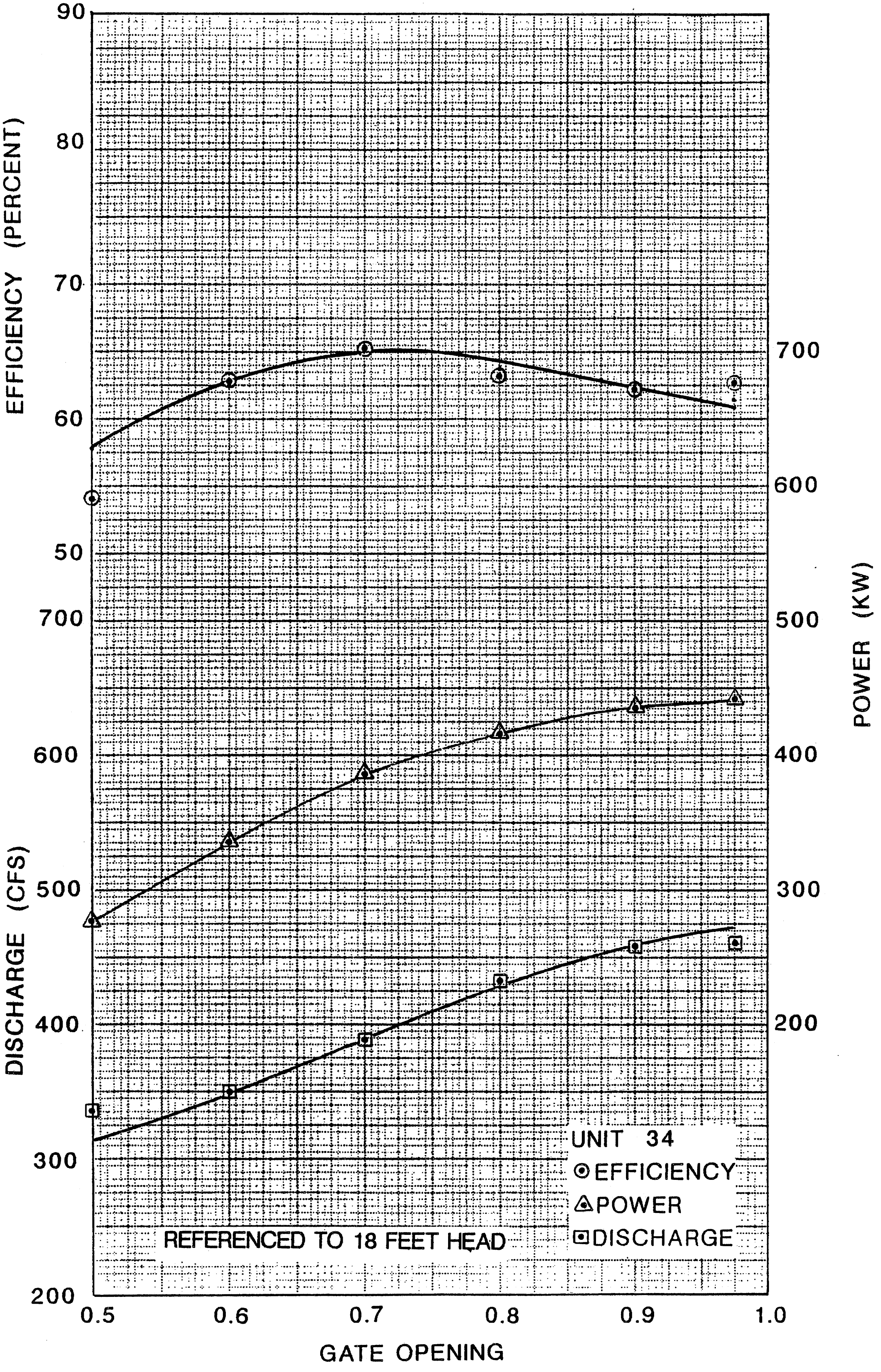

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
REFERENCED TO 18 FEET HEAD
UNIT 29
⊙EFFICIENCY
△POWER
⊡DISCHARGE

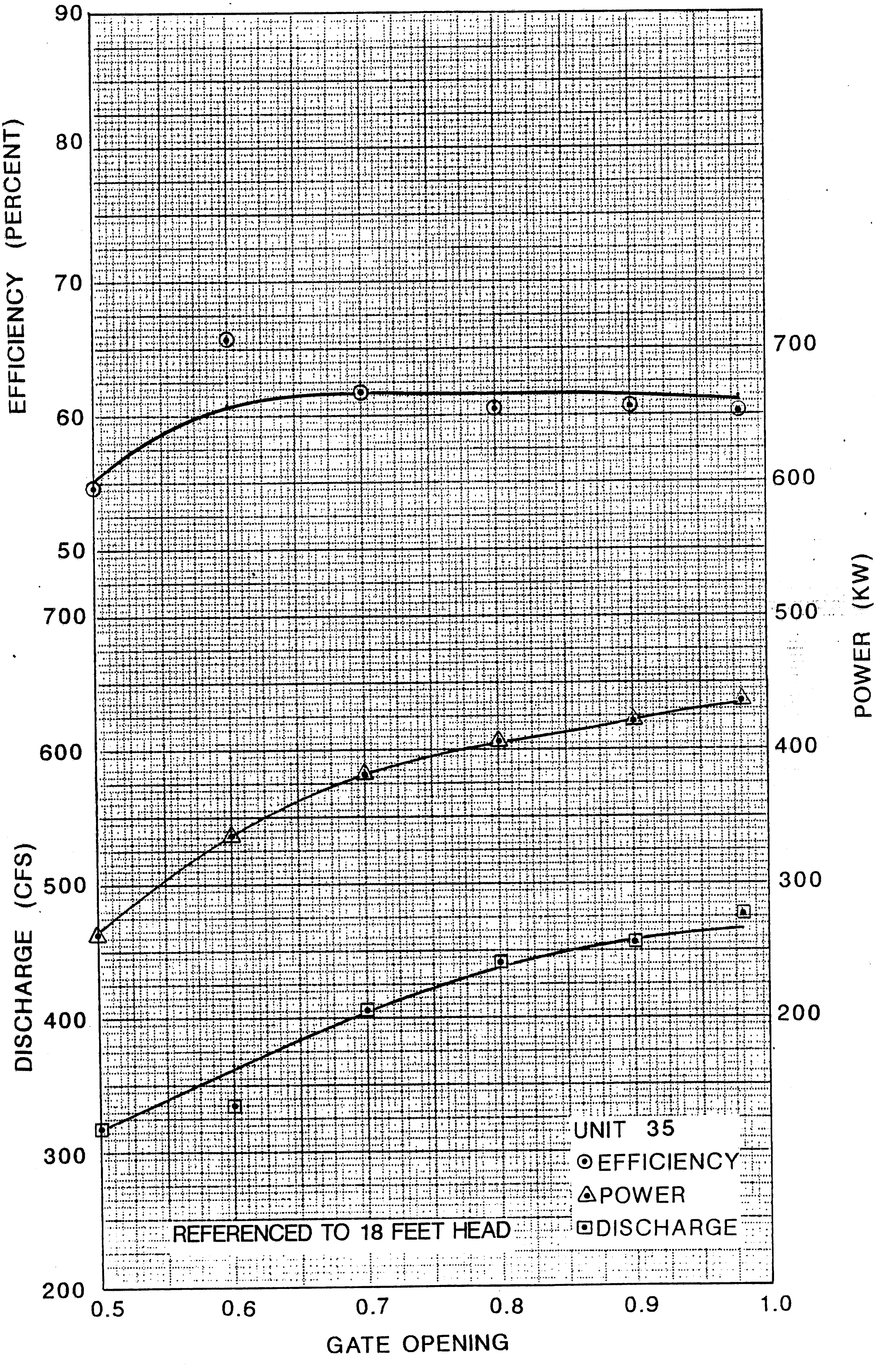

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 30
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

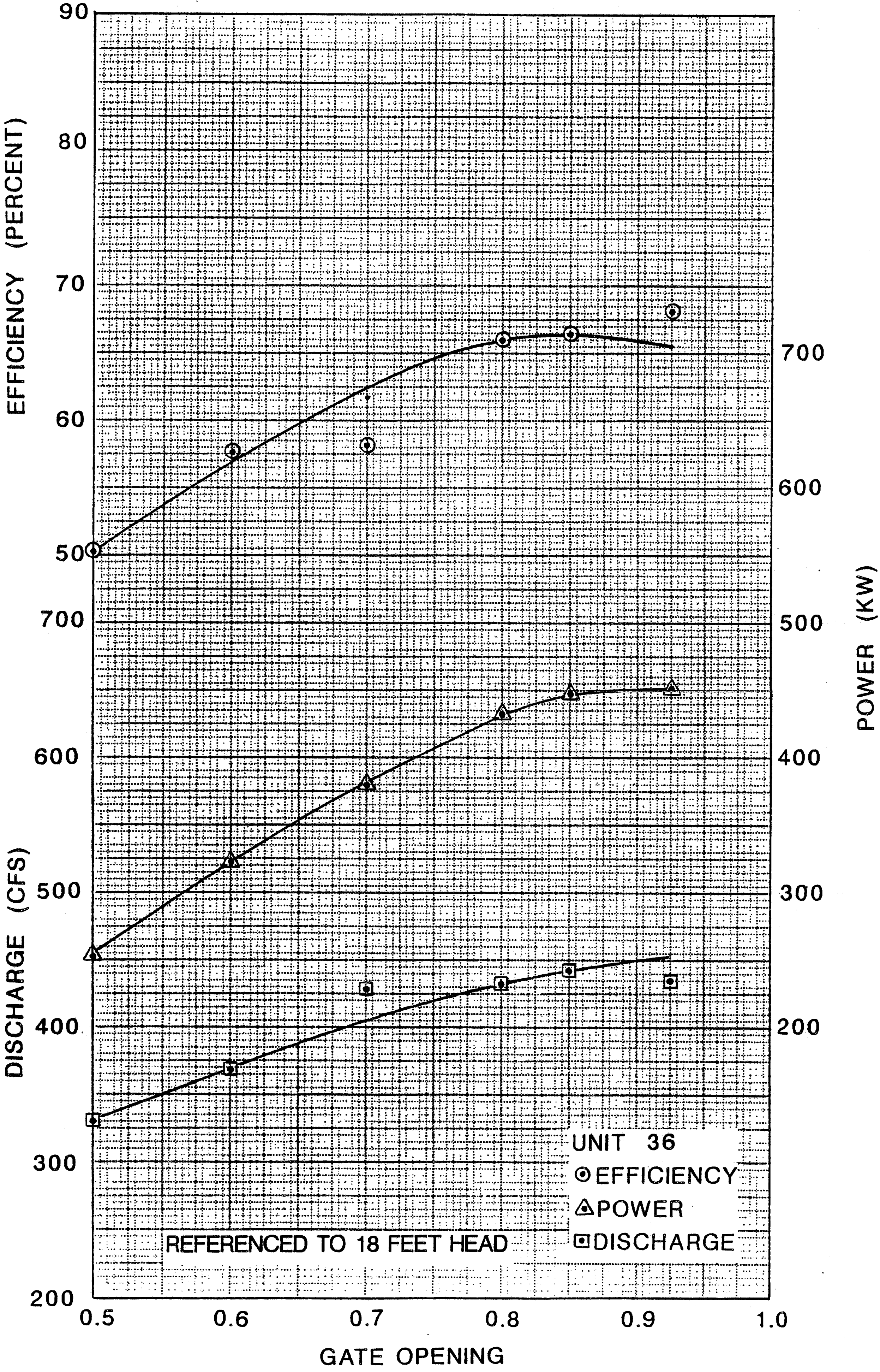

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 31
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

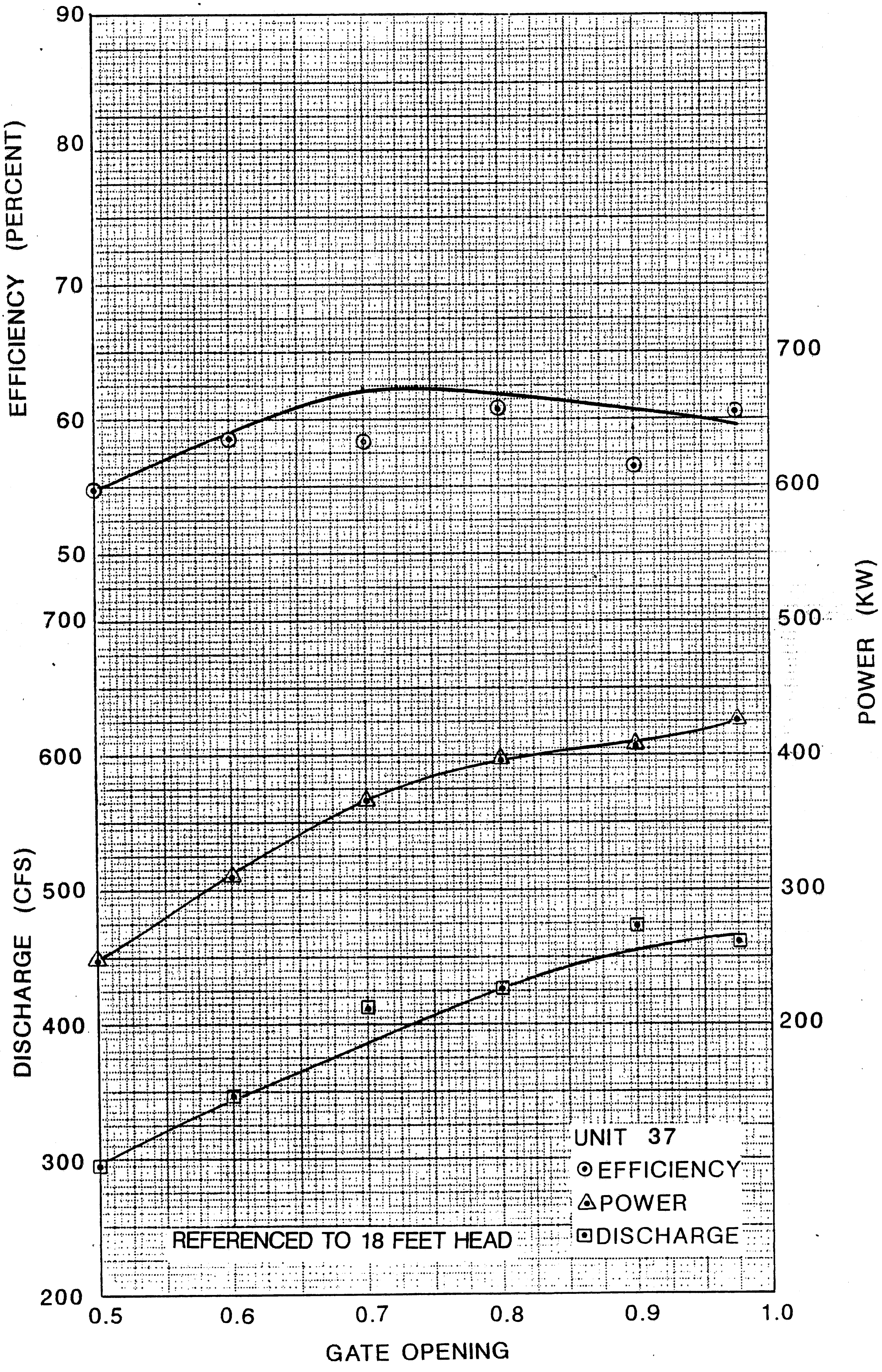

EFFICIENCY (PERCENT)
90
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 32
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

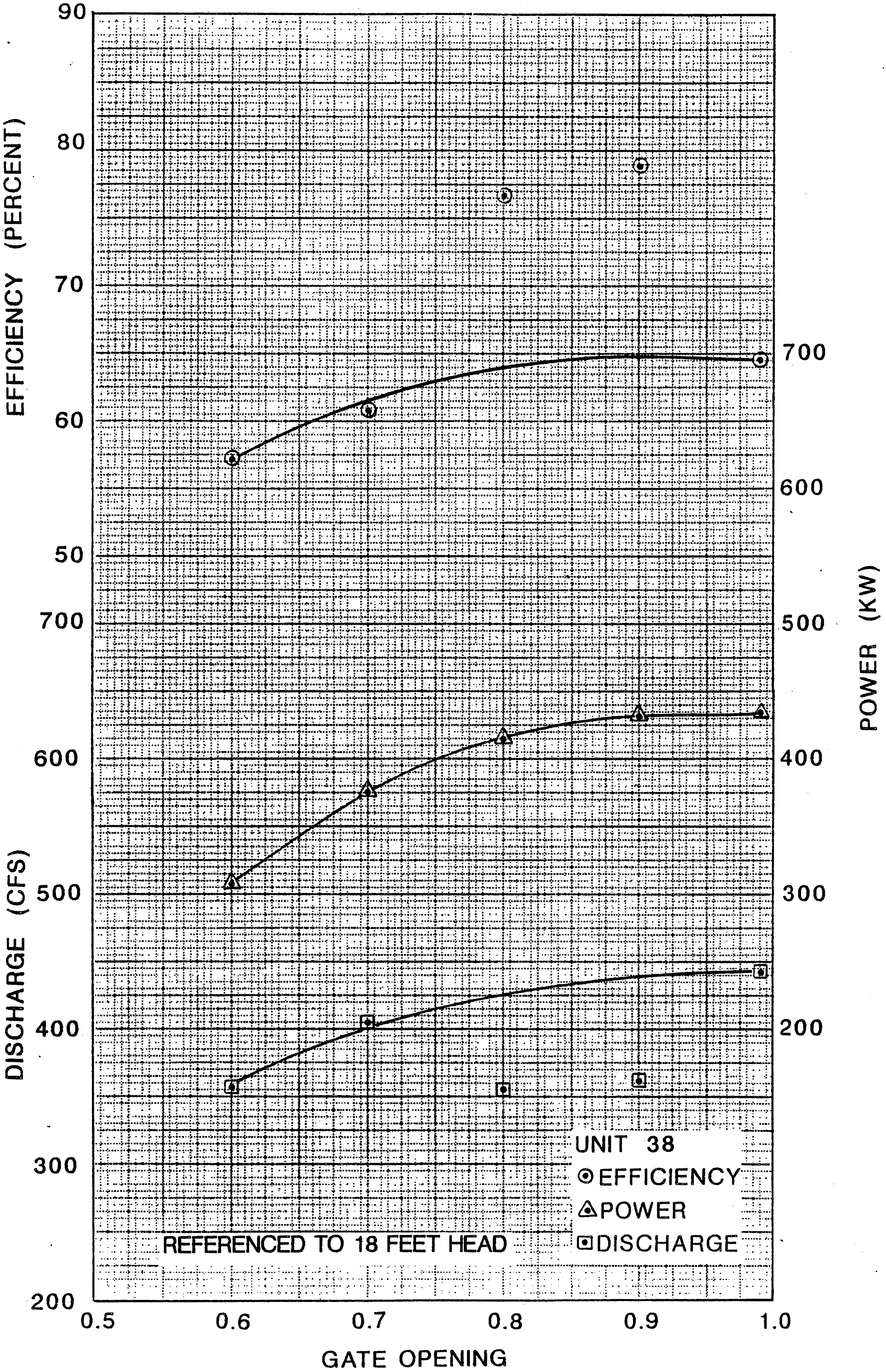

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 33
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

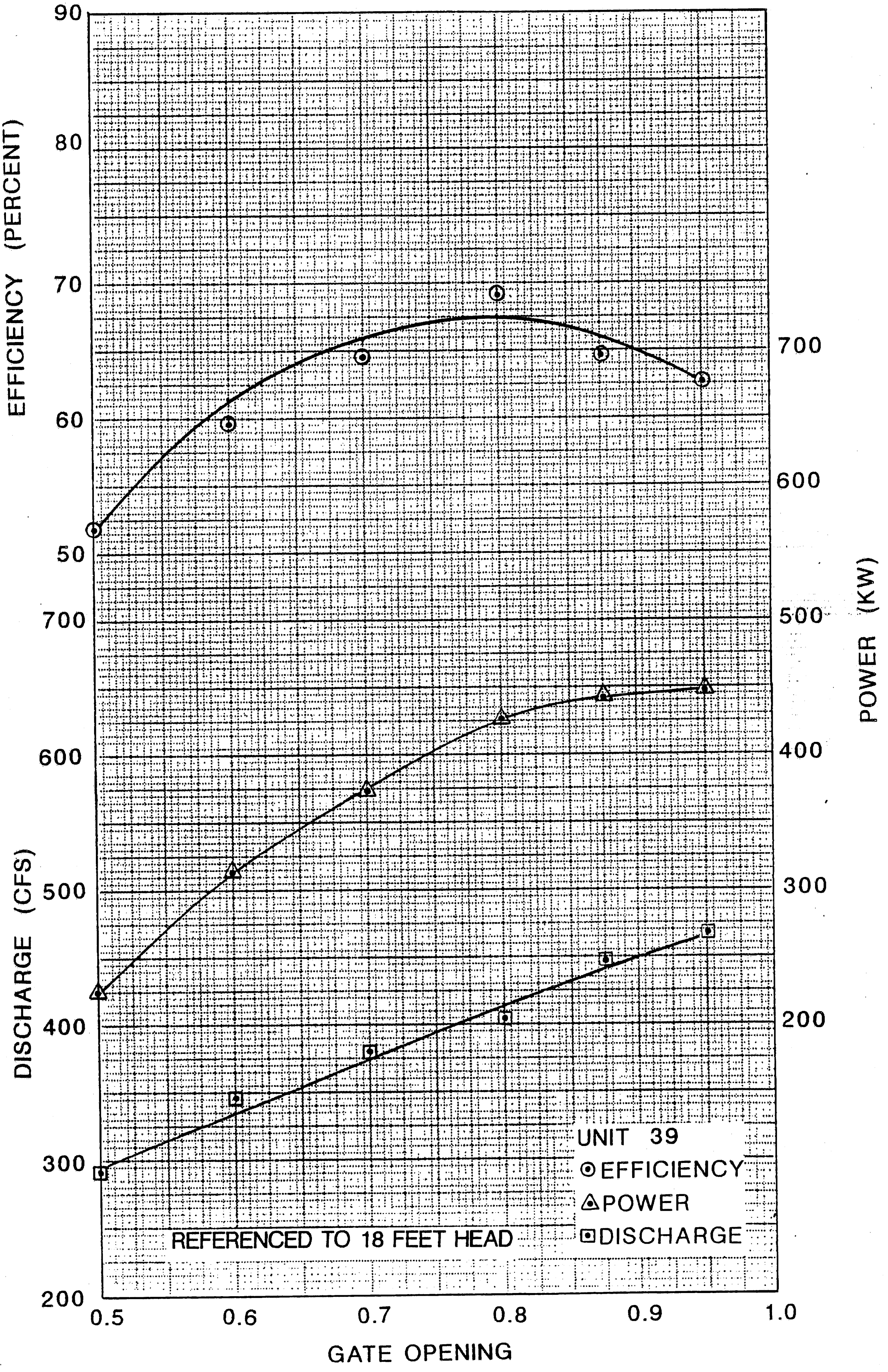

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 34
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

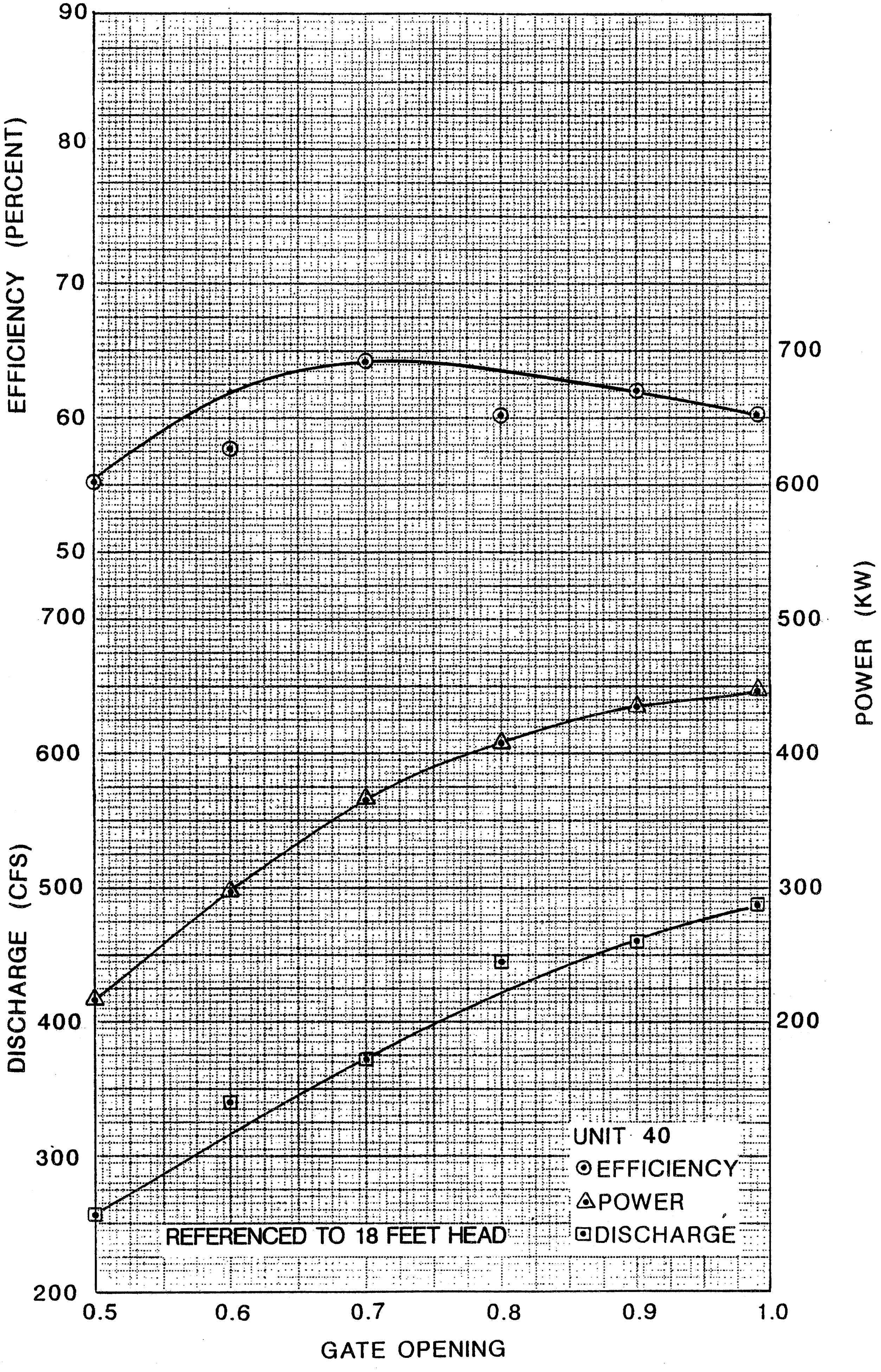

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
UNIT 35
⊙EFFICIENCY
⚠POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING

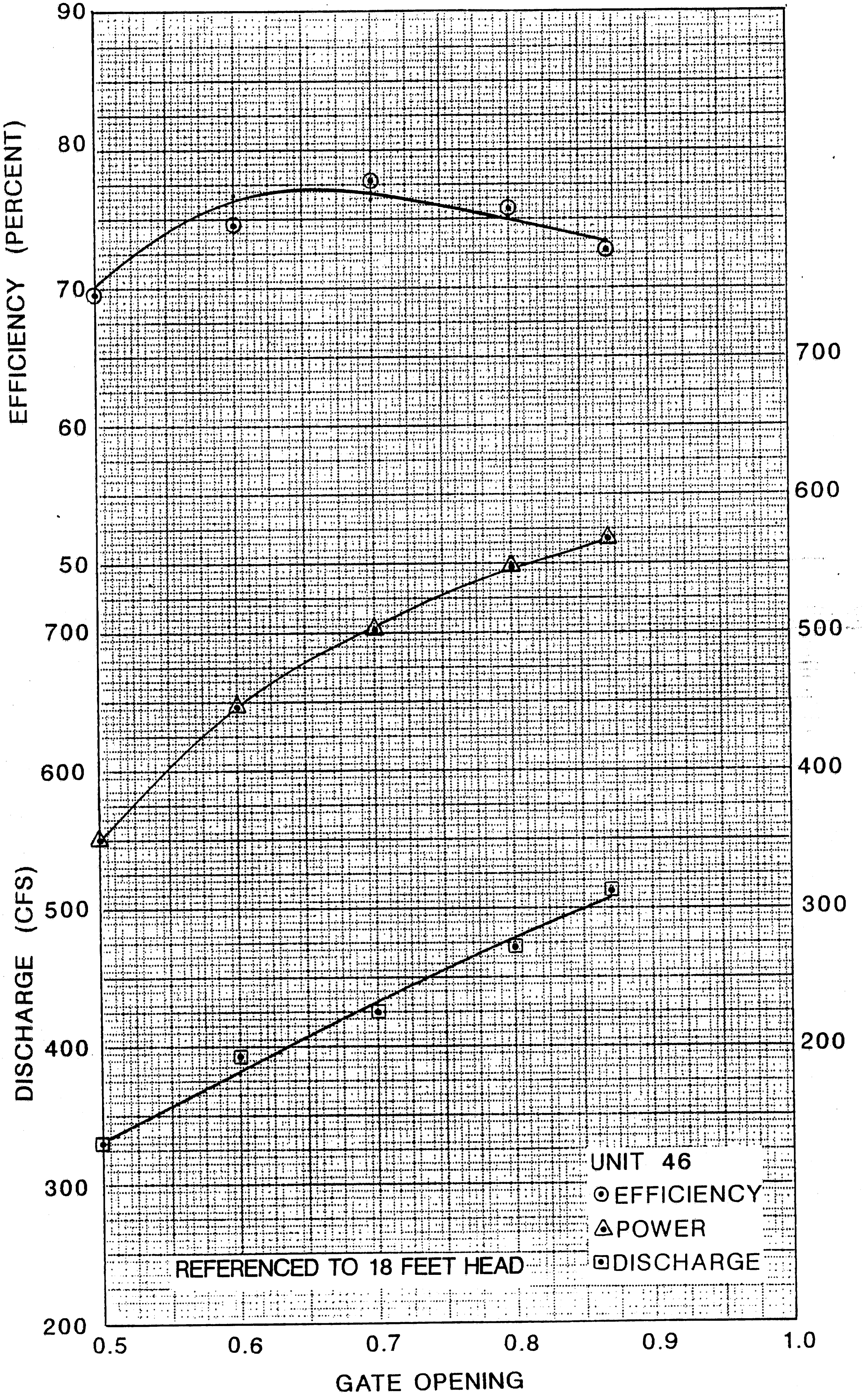

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 36
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

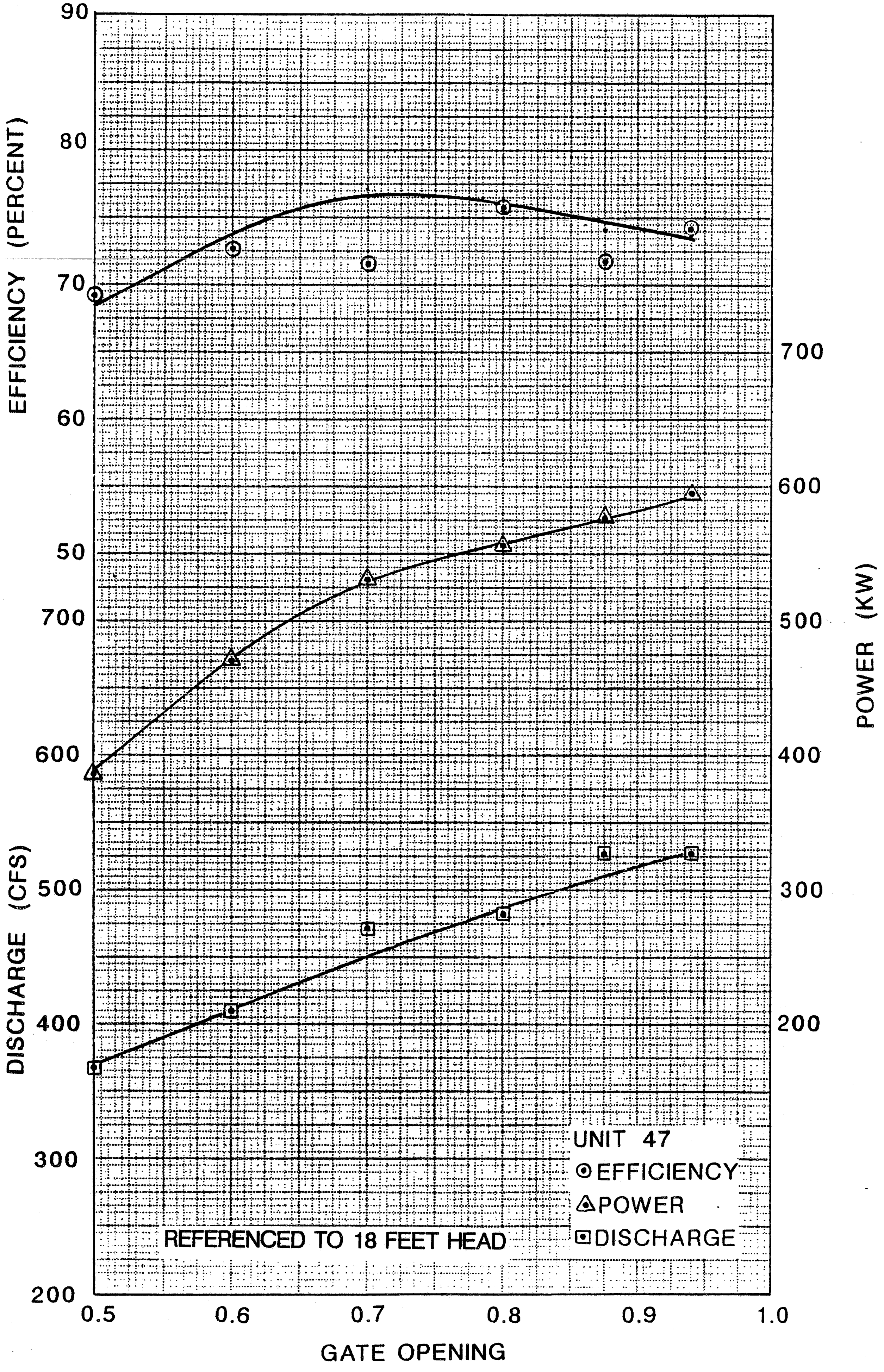

EFFICIENCY (PERCENT)
90
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 37
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

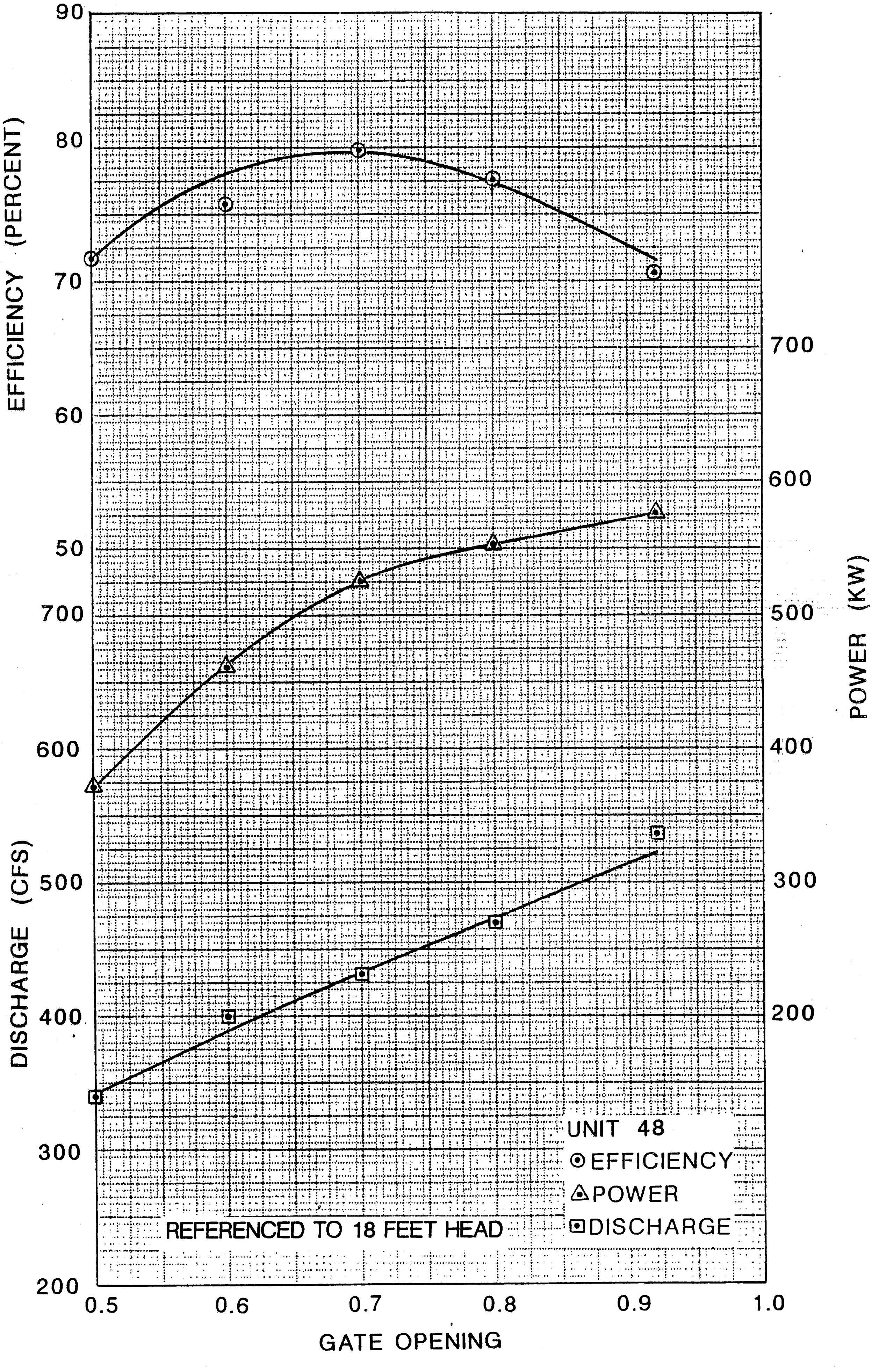

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 38
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

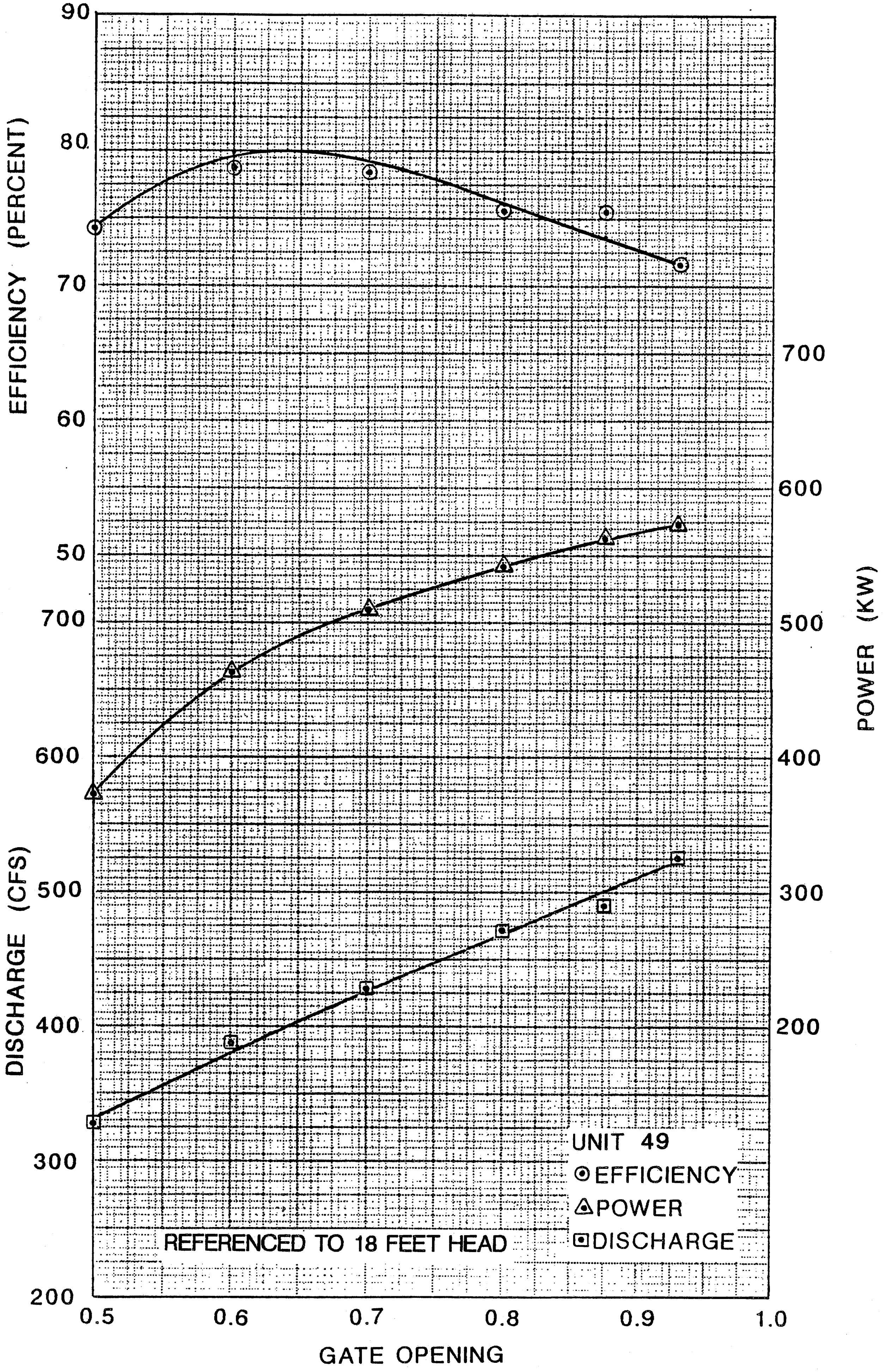

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 39
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

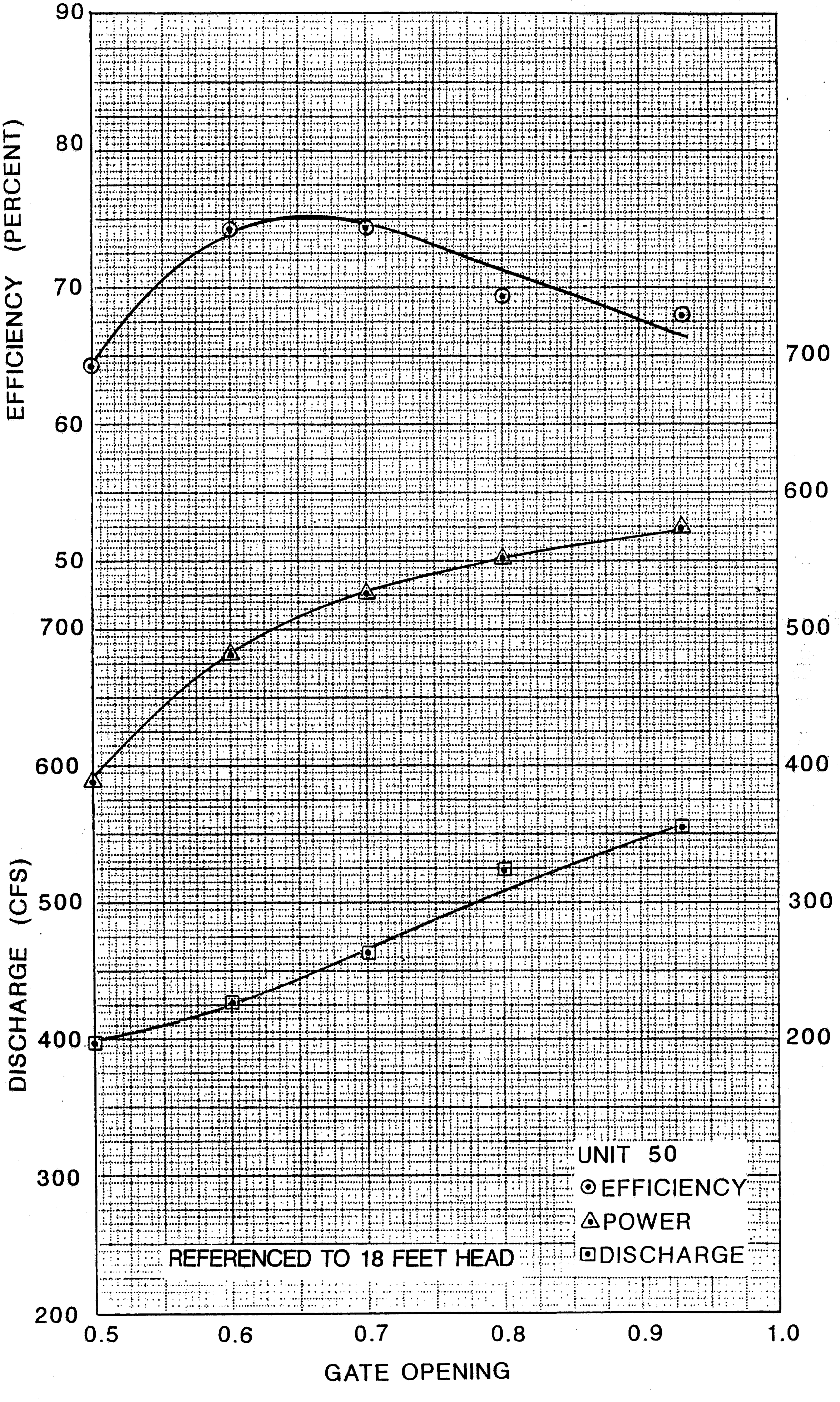

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 40
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

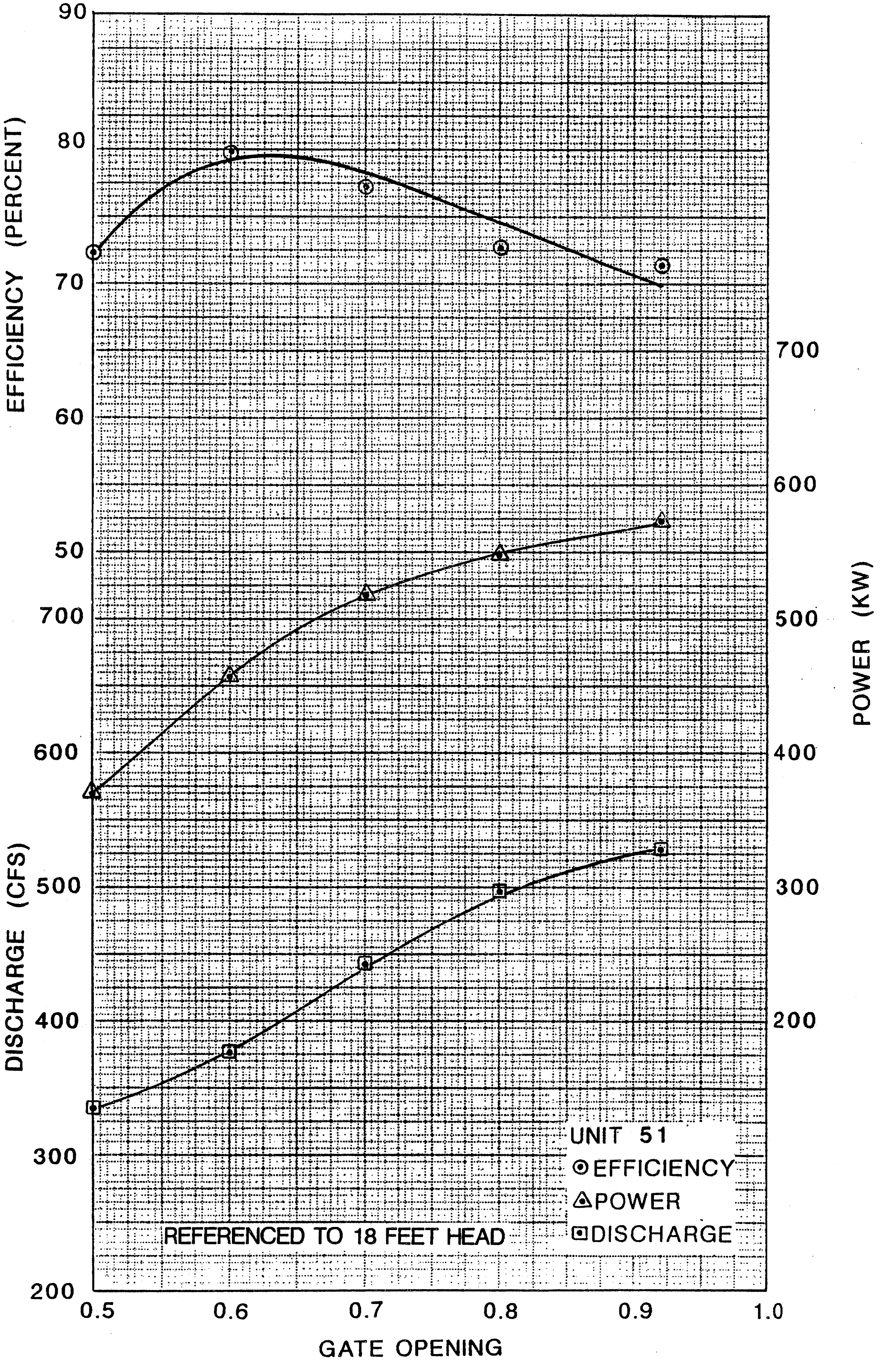

90
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 46
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

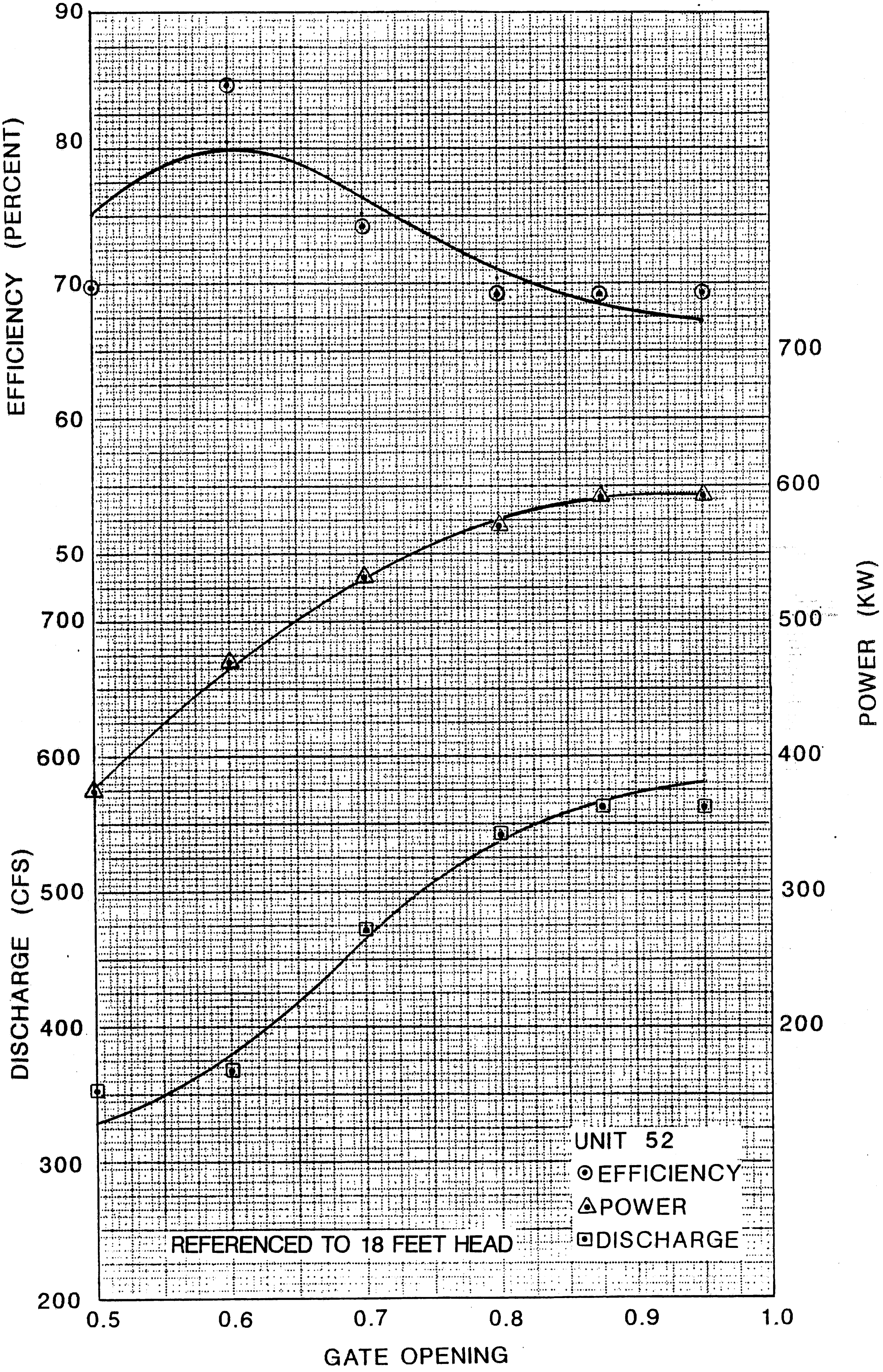

EFFICIENCY (PERCENT)
90
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
POWER (KW)
700
600
500
400
300
200
UNIT 47
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING

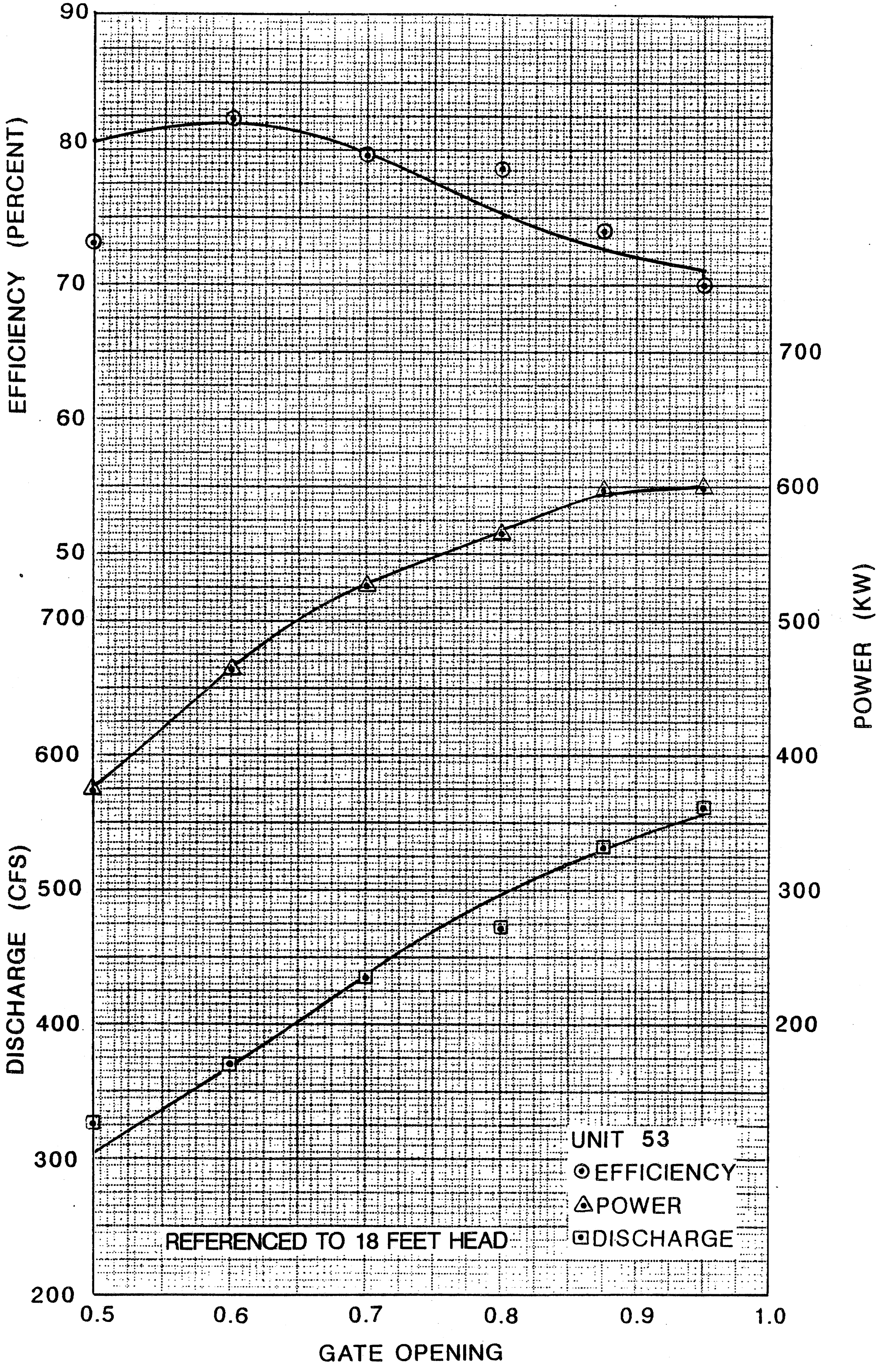

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 48
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

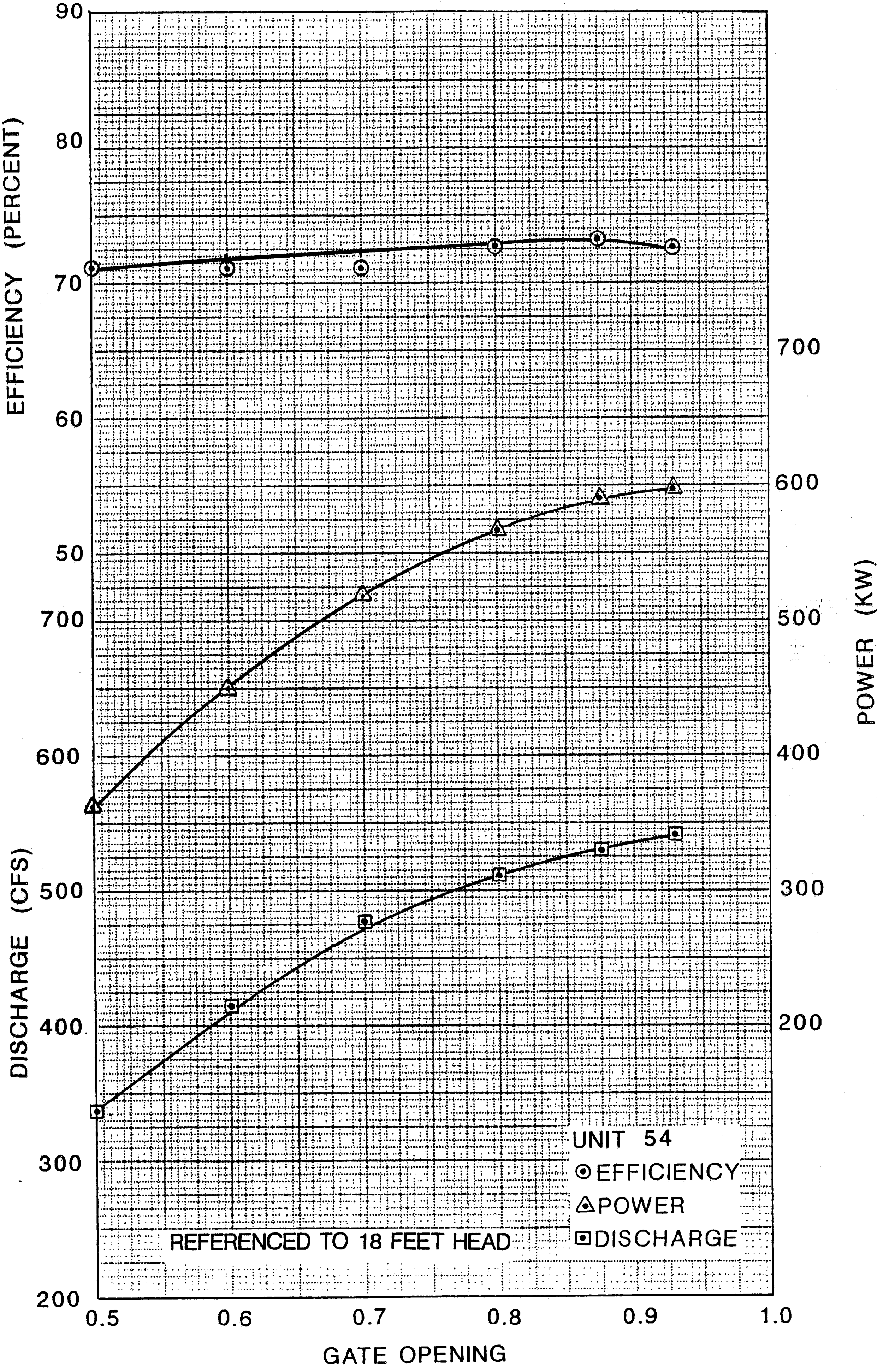

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 49
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

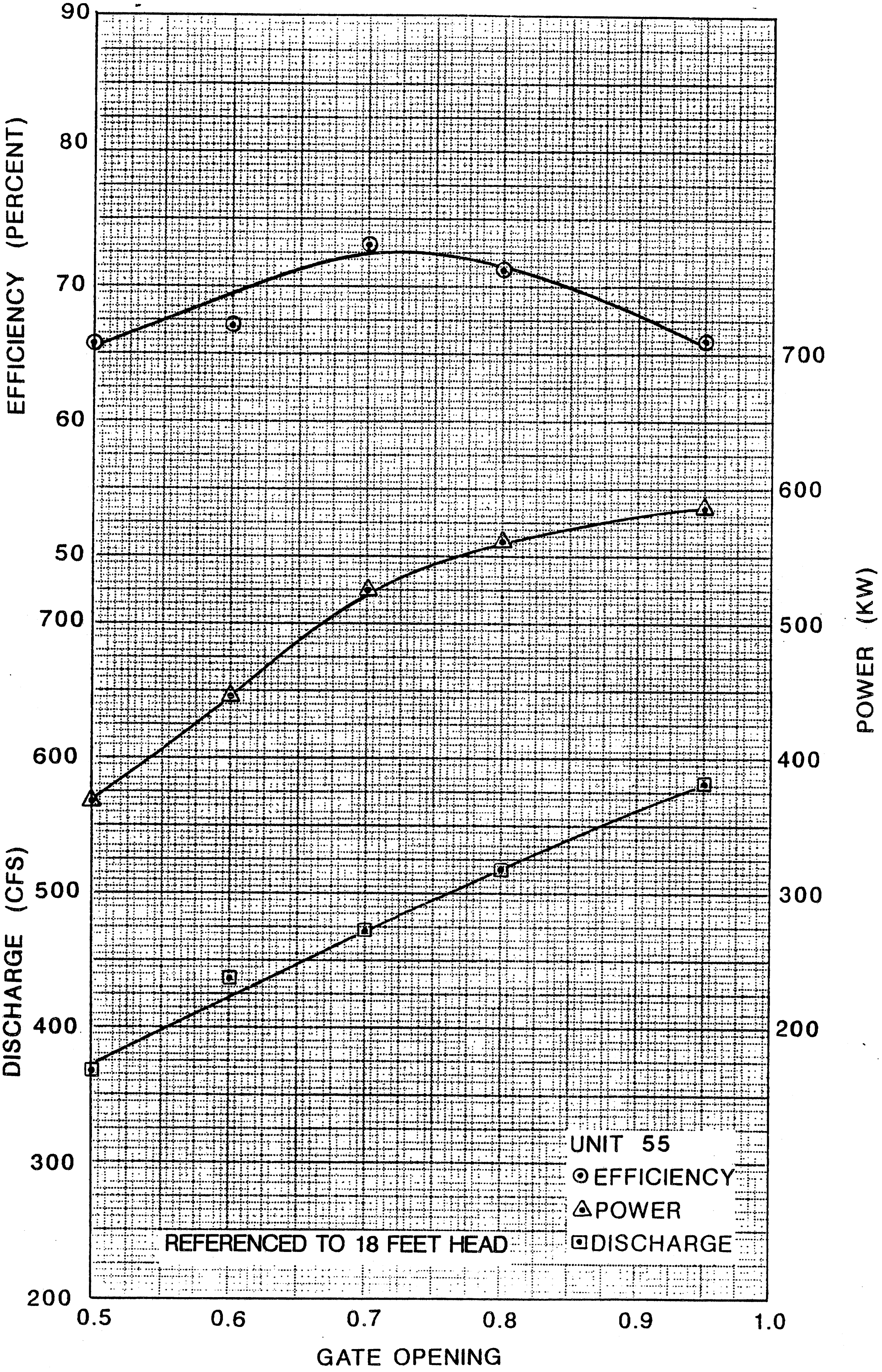

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
UNIT 50
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING


90
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 51
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

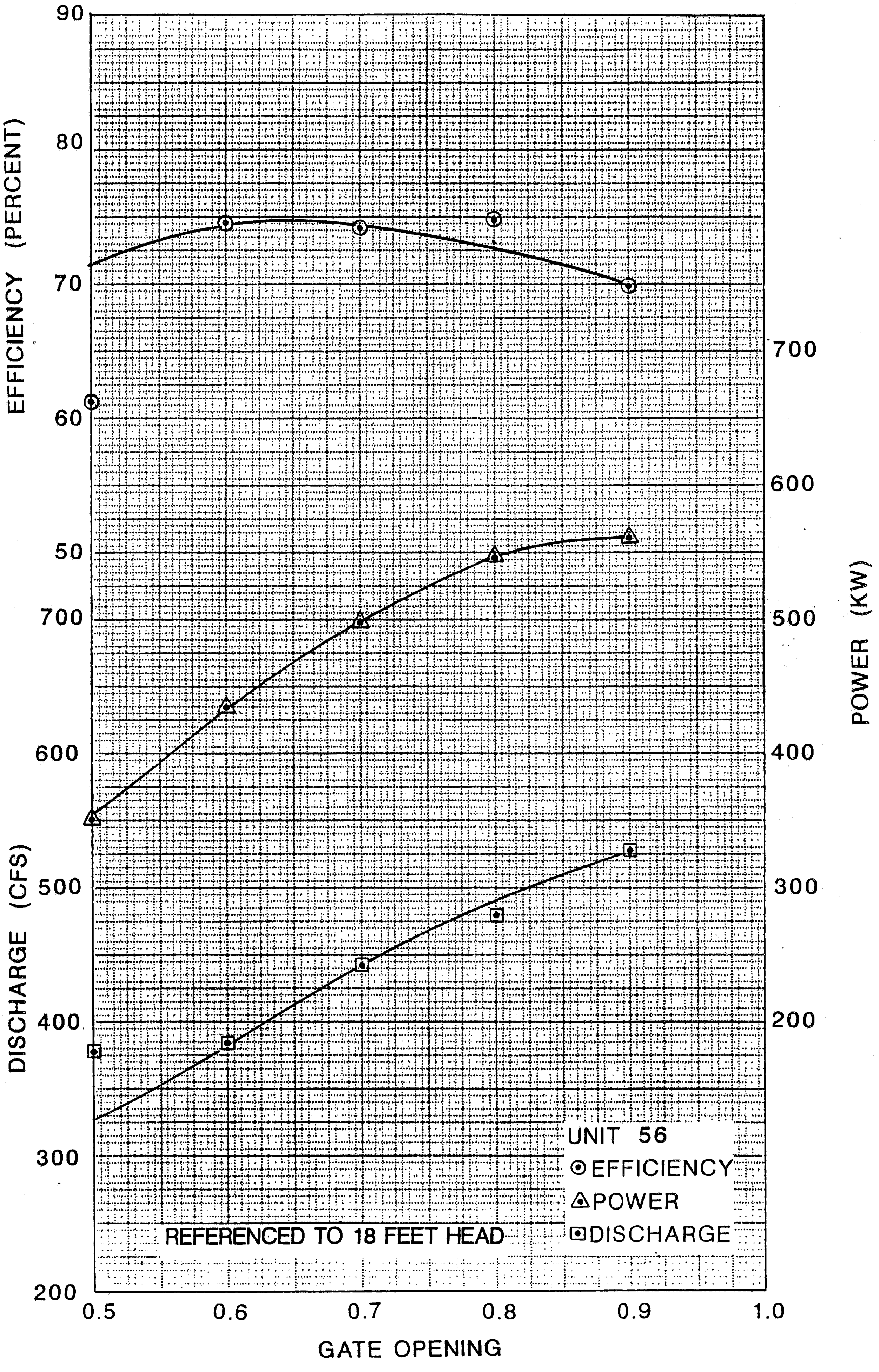

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
REFERENCED TO 18 FEET HEAD
UNIT 52
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE

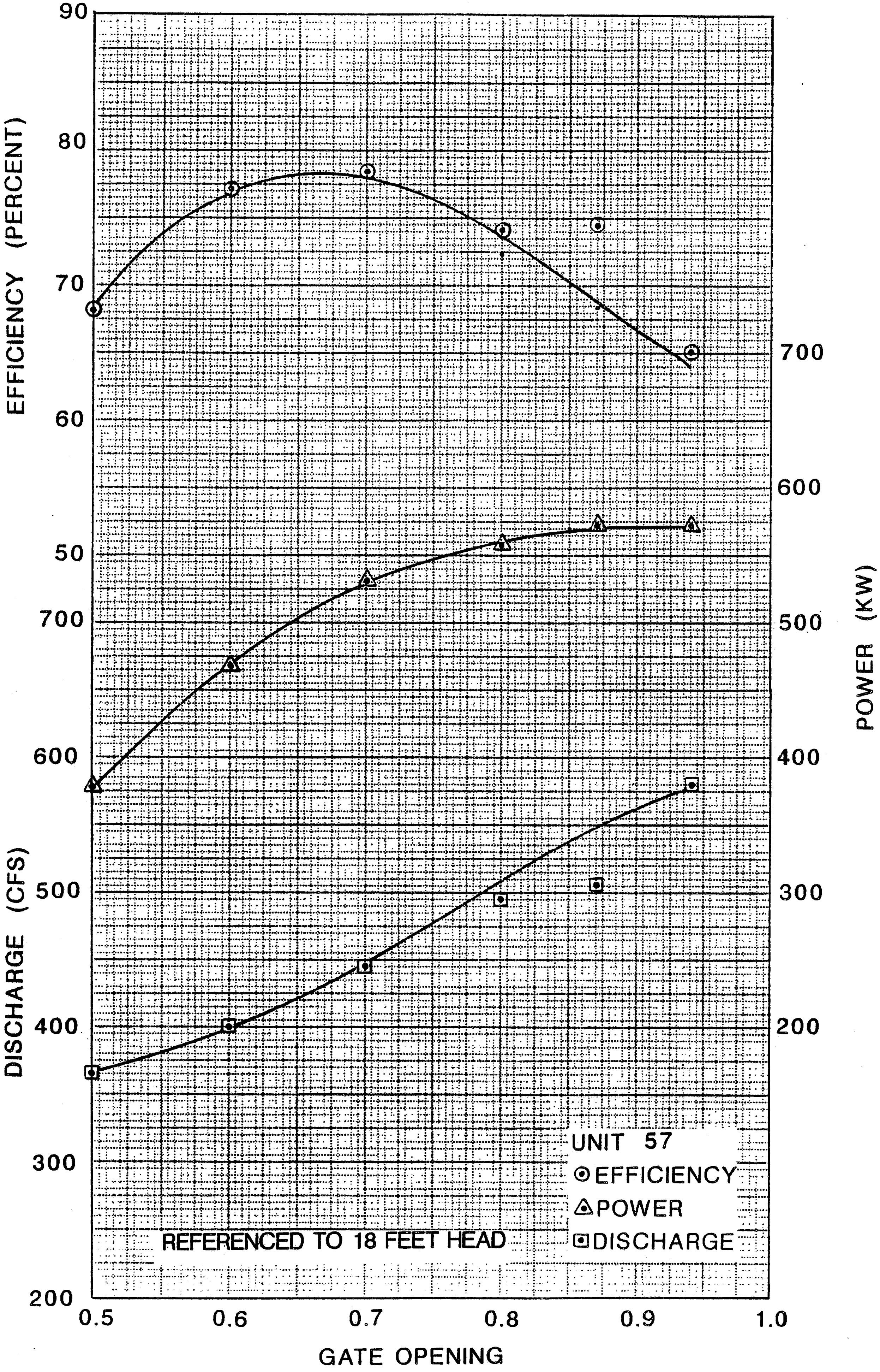

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
GATE OPENING
0.5
0.6
0.7
0.8
0.9
1.0
UNIT 53
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

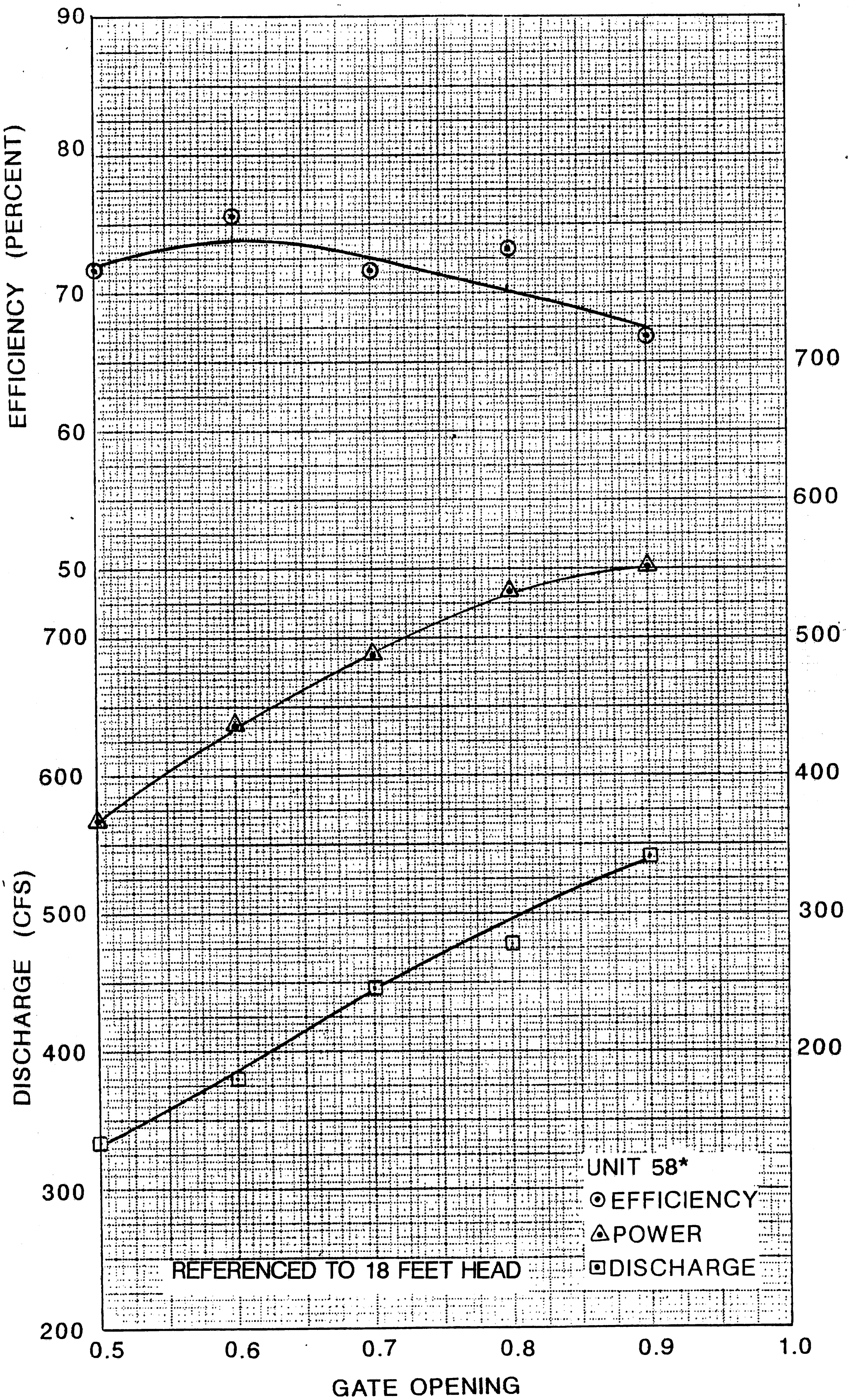

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 54
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

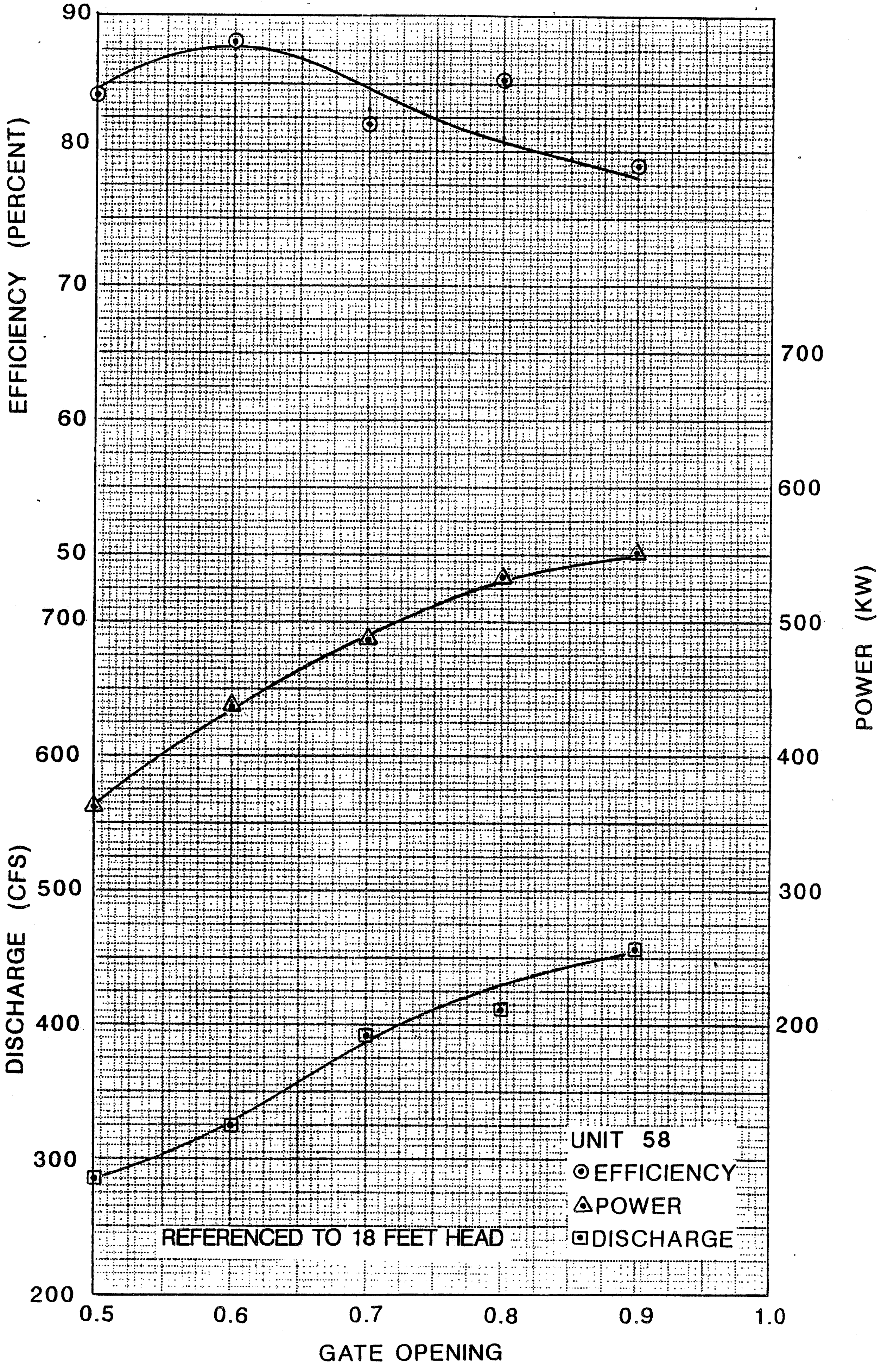


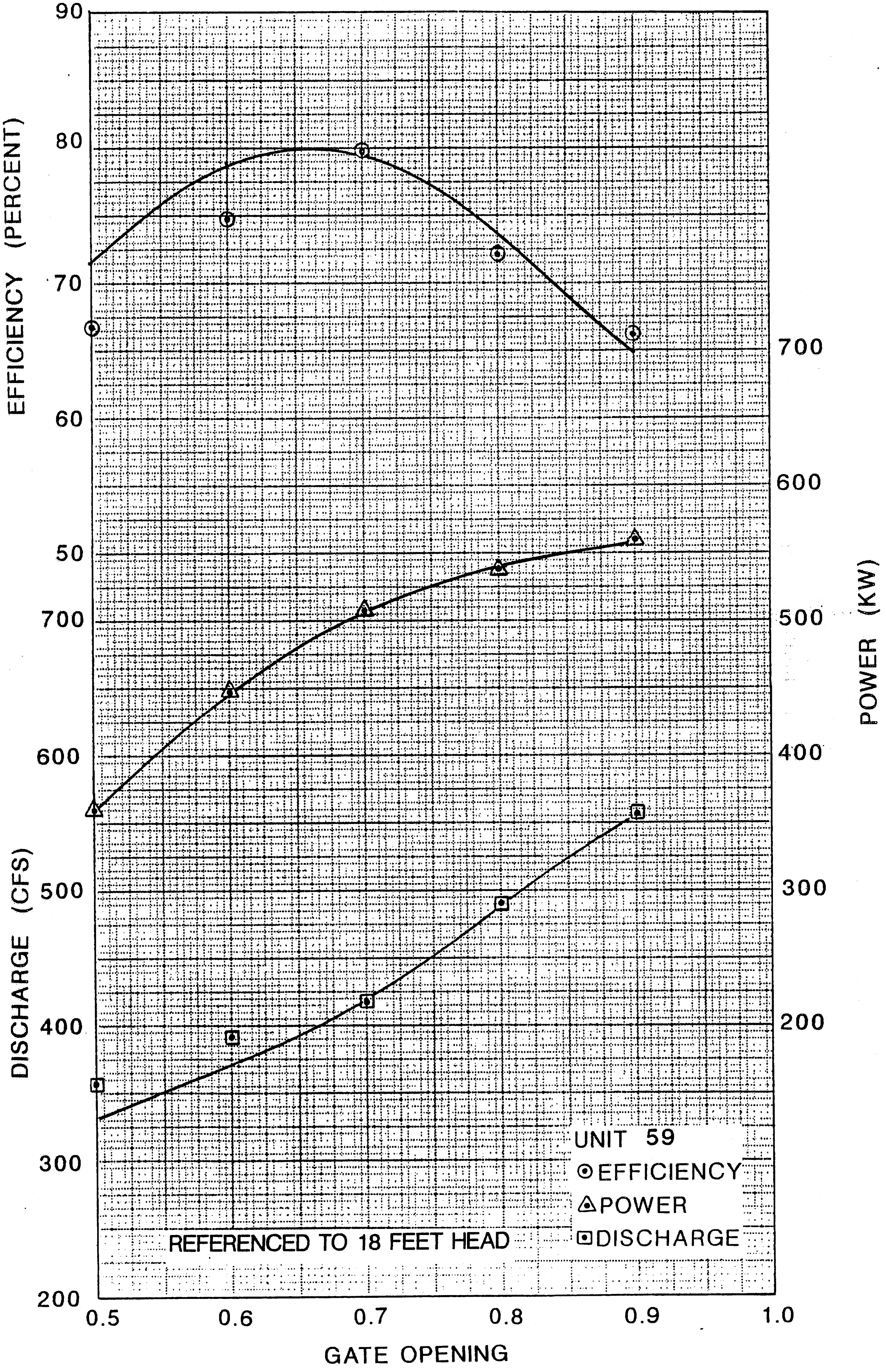
EFFICIENCY (PERCENT)
90
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 55
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

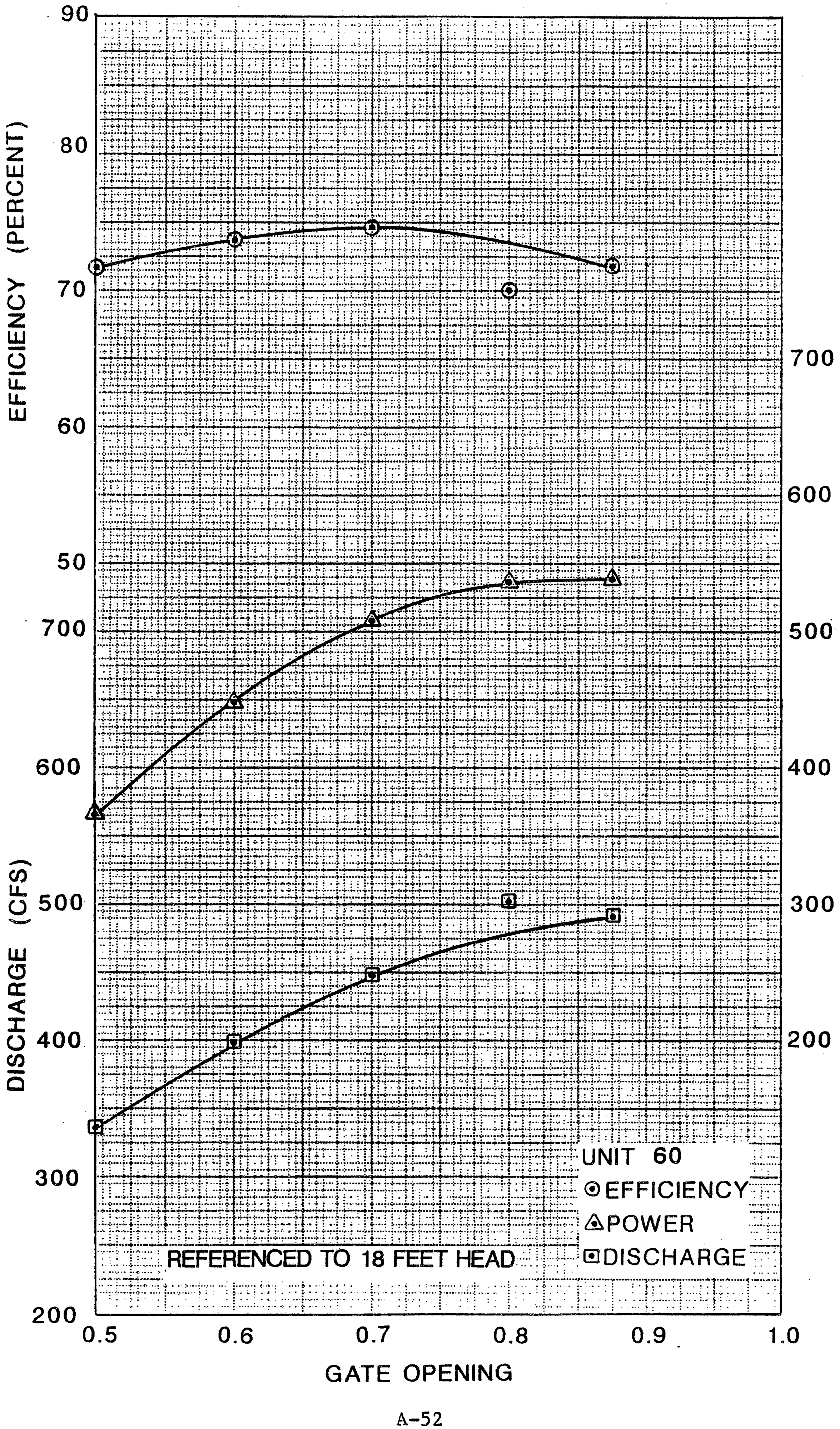

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 56
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD

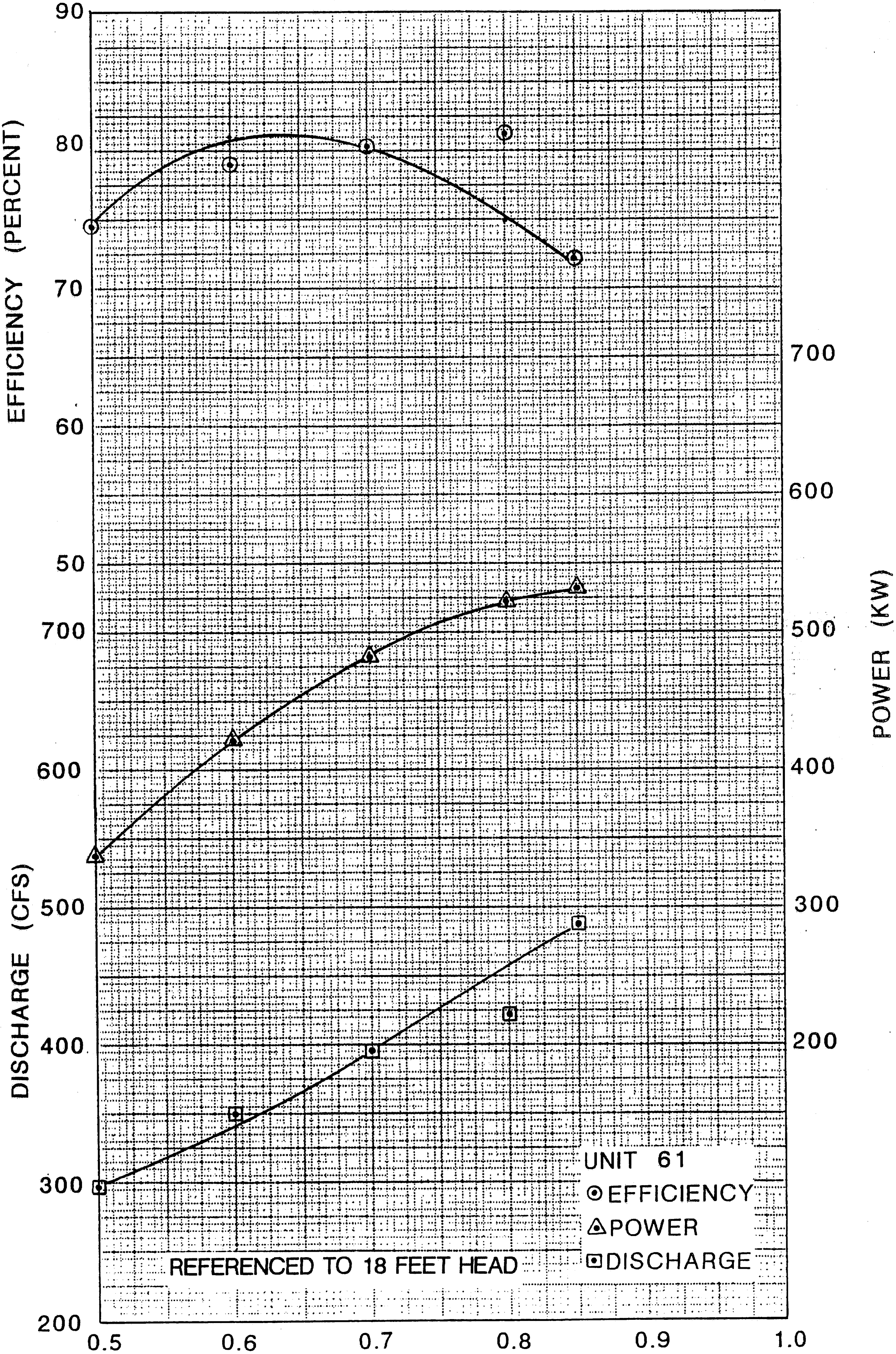
EFFICIENCY (PERCENT)
90
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 57
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 58*
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

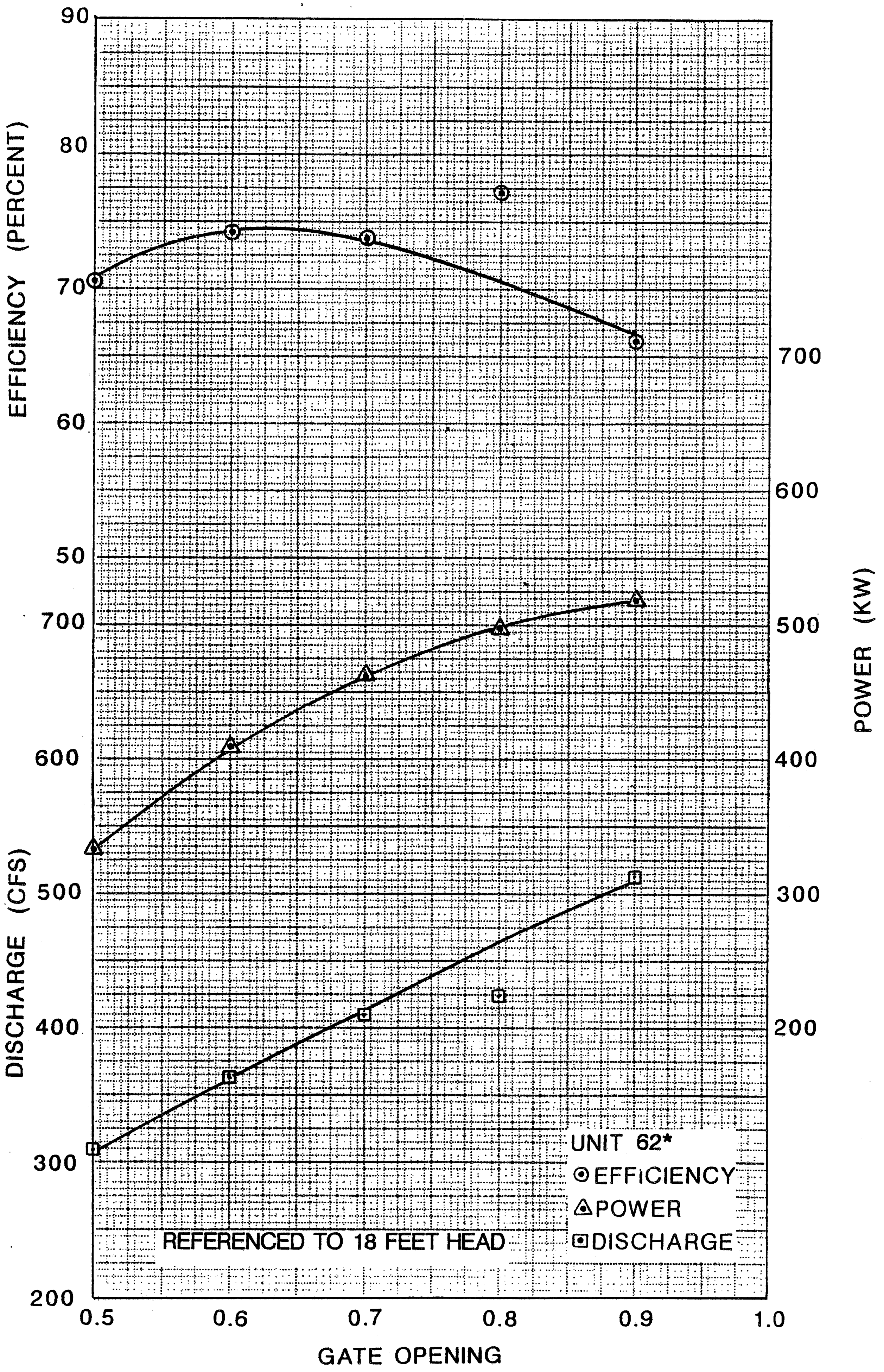

90
80
70
60
50
700
600
500
400
300
200
EFFICIENCY (PERCENT)
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 58
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

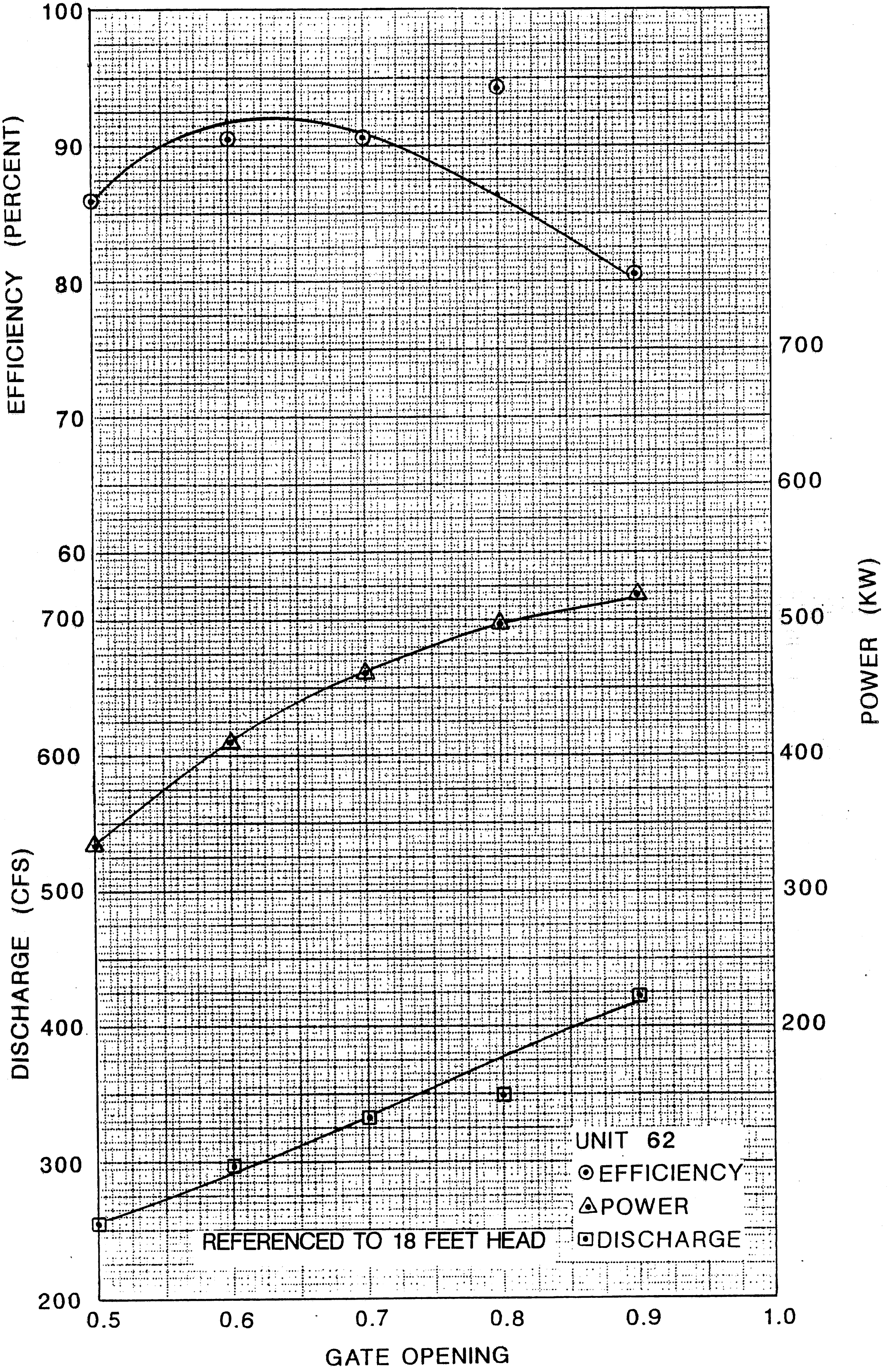

EFFICIENCY (PERCENT)
90
80
70
60
50
700
600
500
400
300
200
DISCHARGE (CFS)
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 59
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

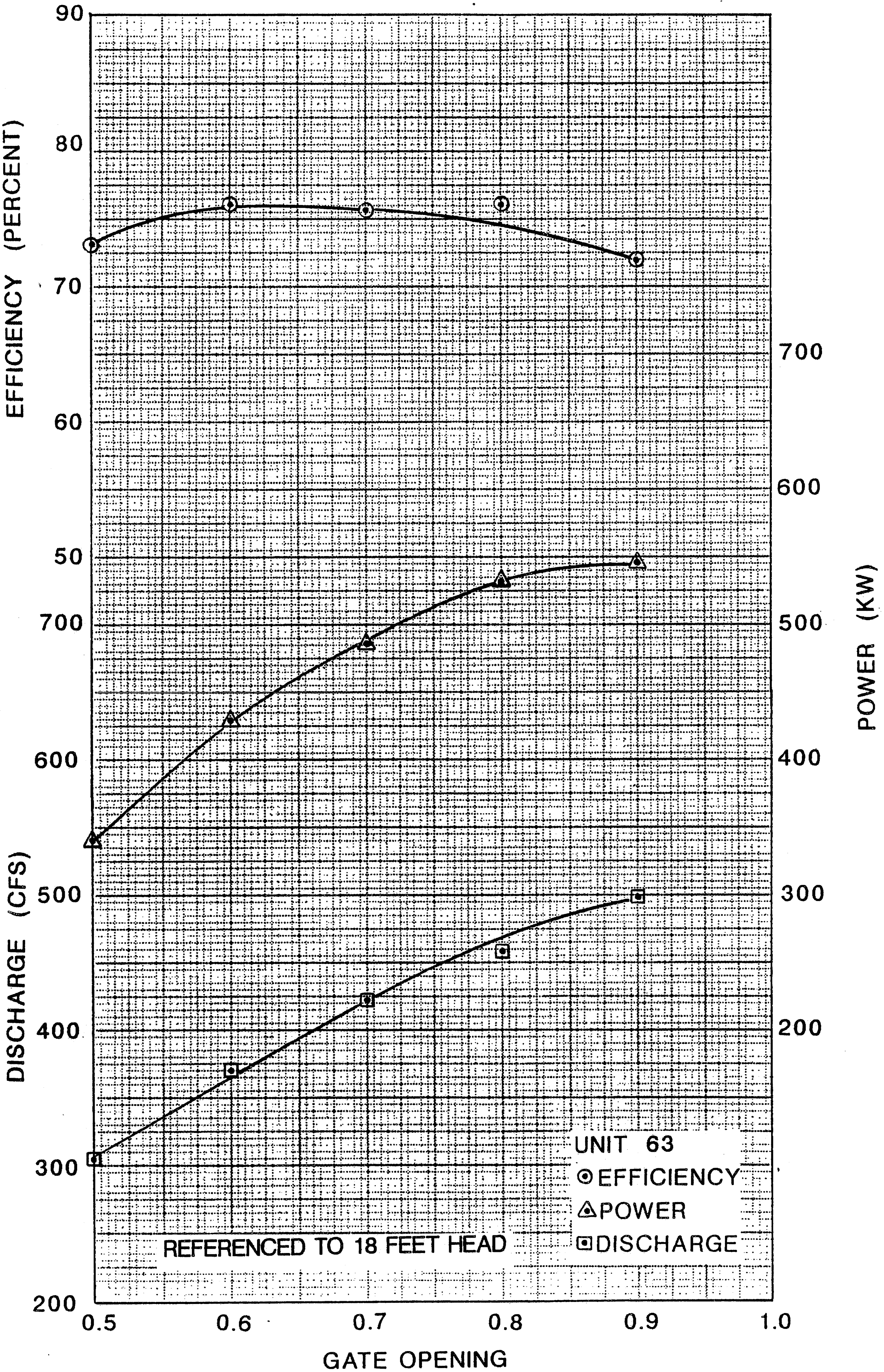

90
80
70
60
50
700
600
500
400
300
200
EFFICIENCY (PERCENT)
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 60
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

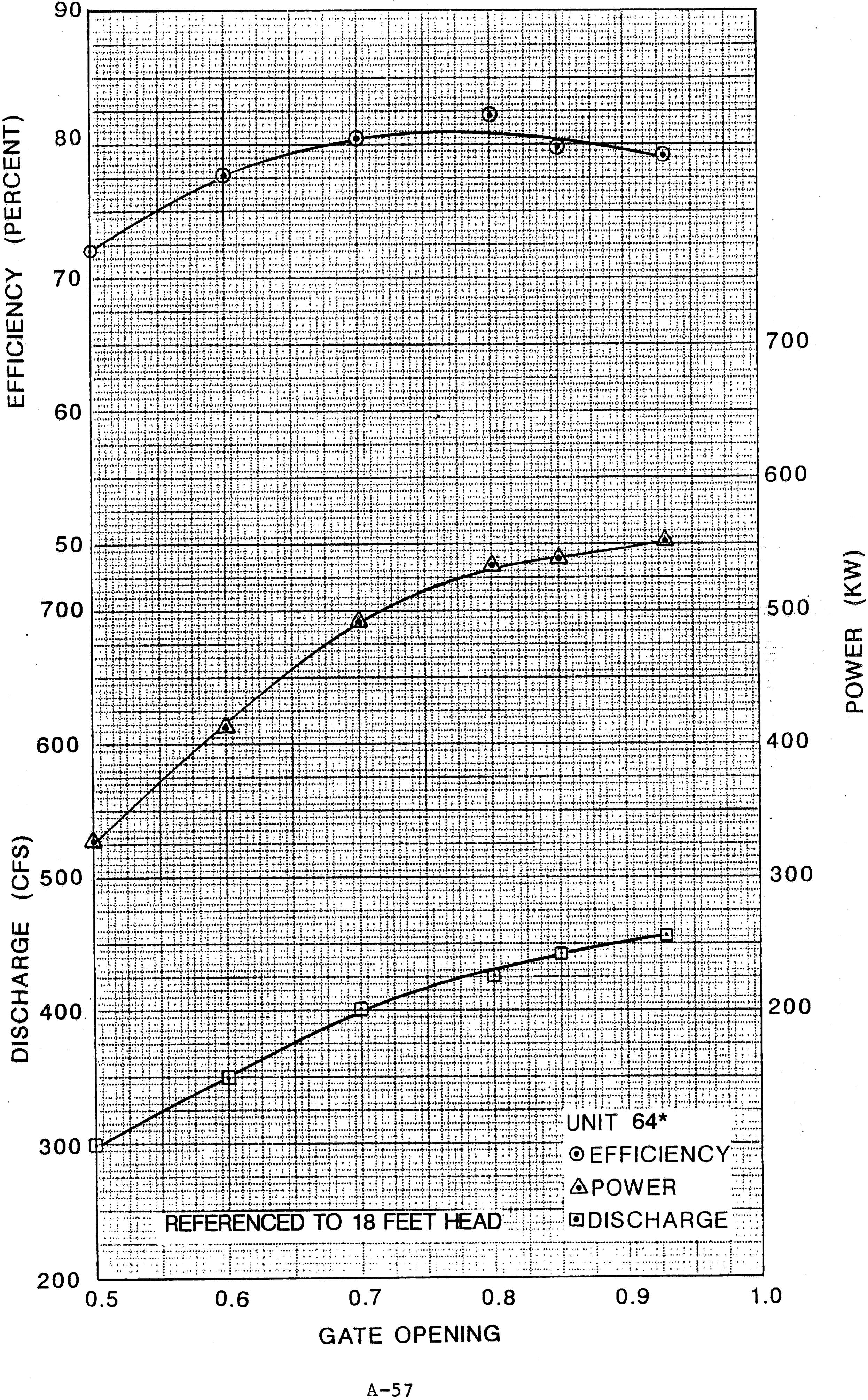


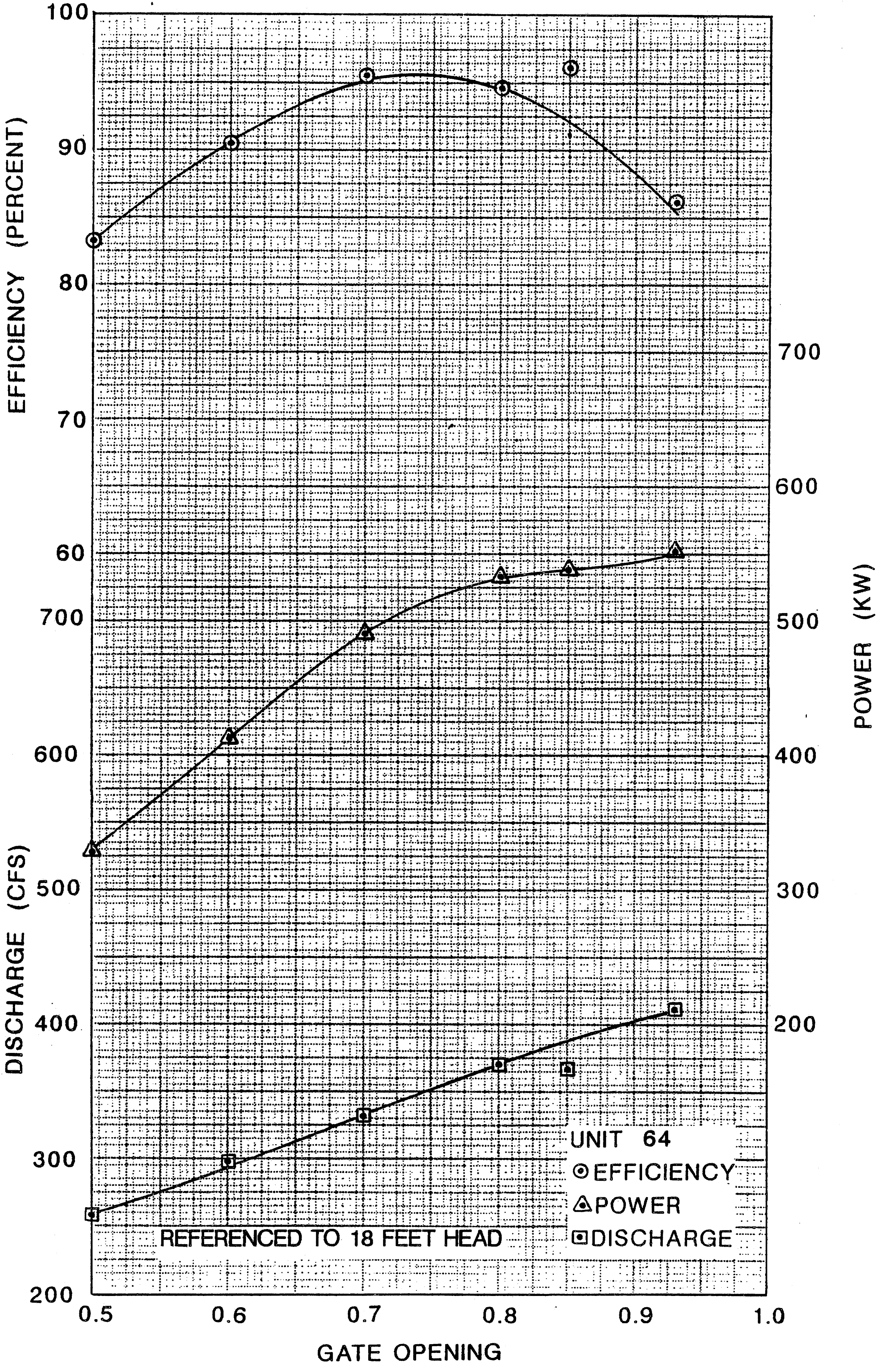
EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 61
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

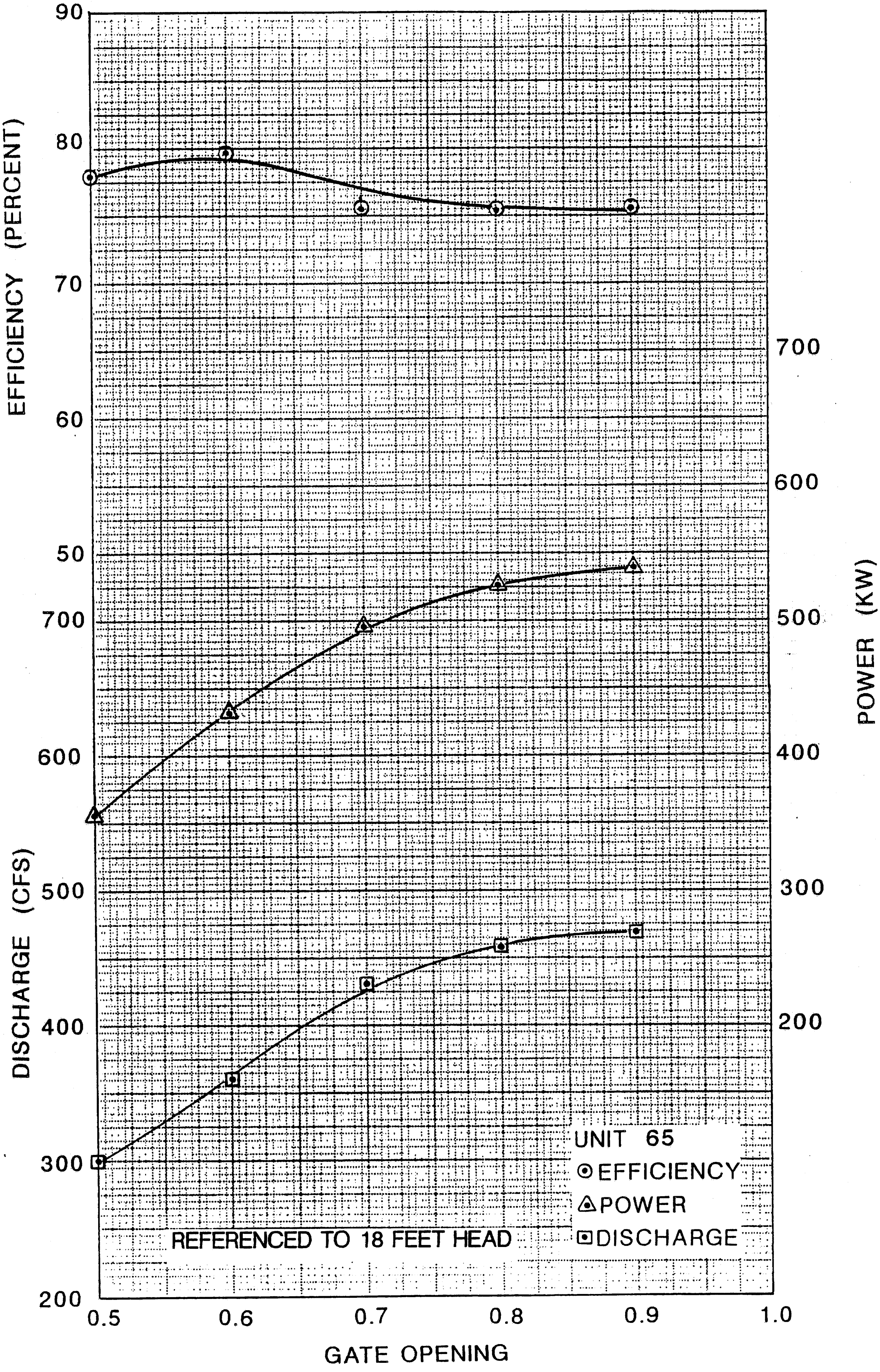

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
GATE OPENING
0.5
0.6
0.7
0.8
0.9
1.0
UNIT 62*
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

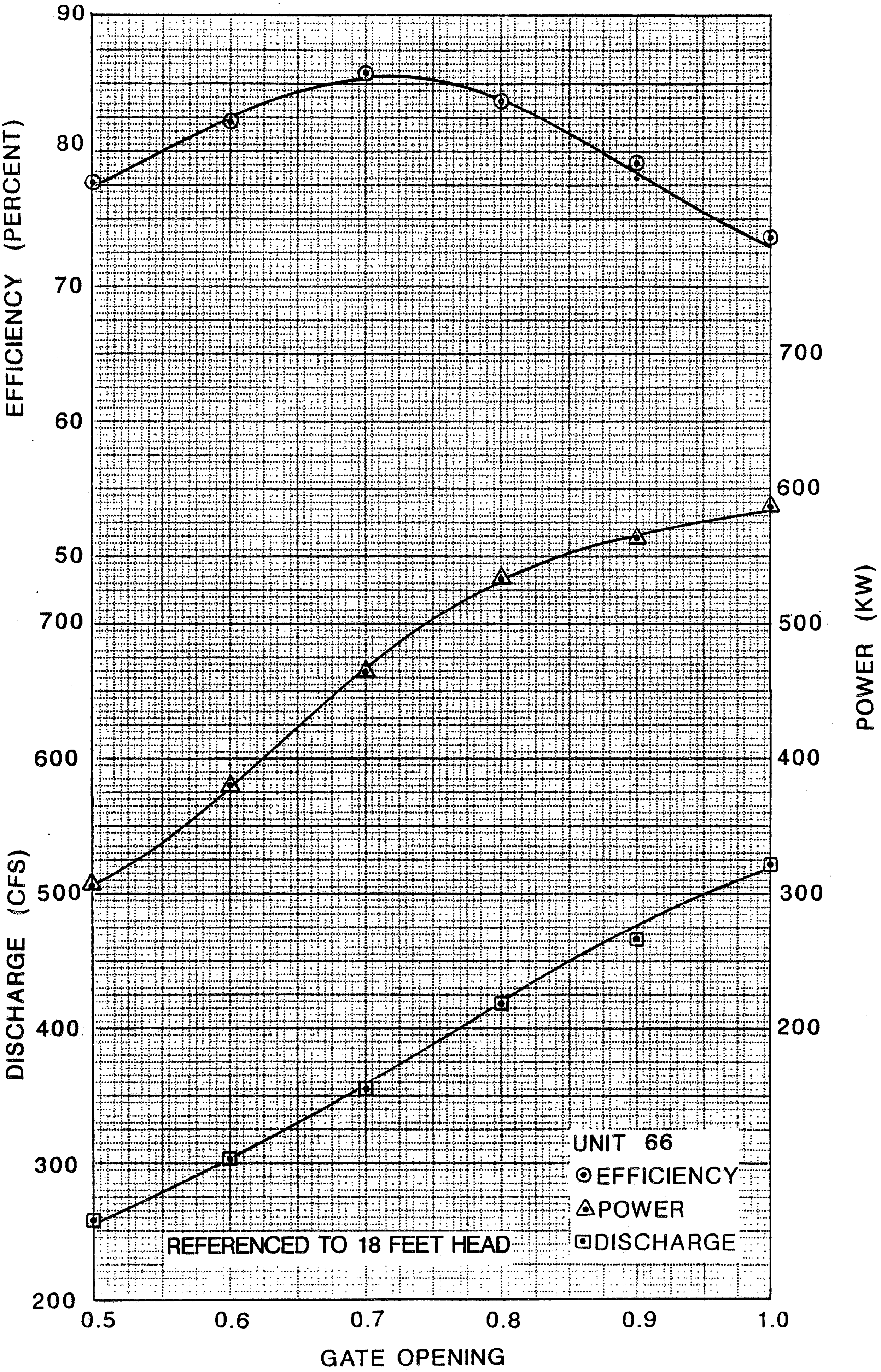

EFFICIENCY (PERCENT)
100
90
80
70
60
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 62
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

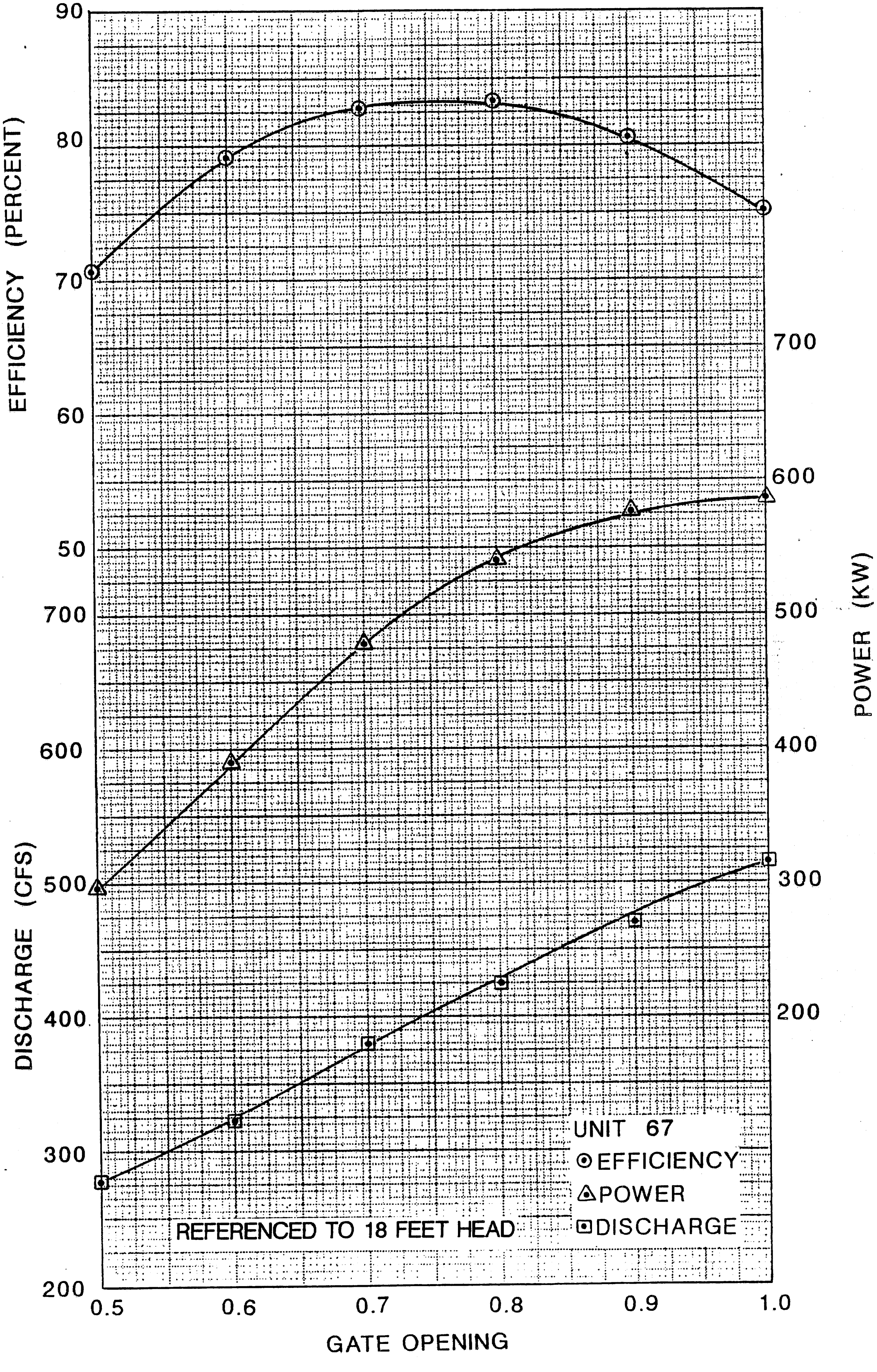

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 63
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

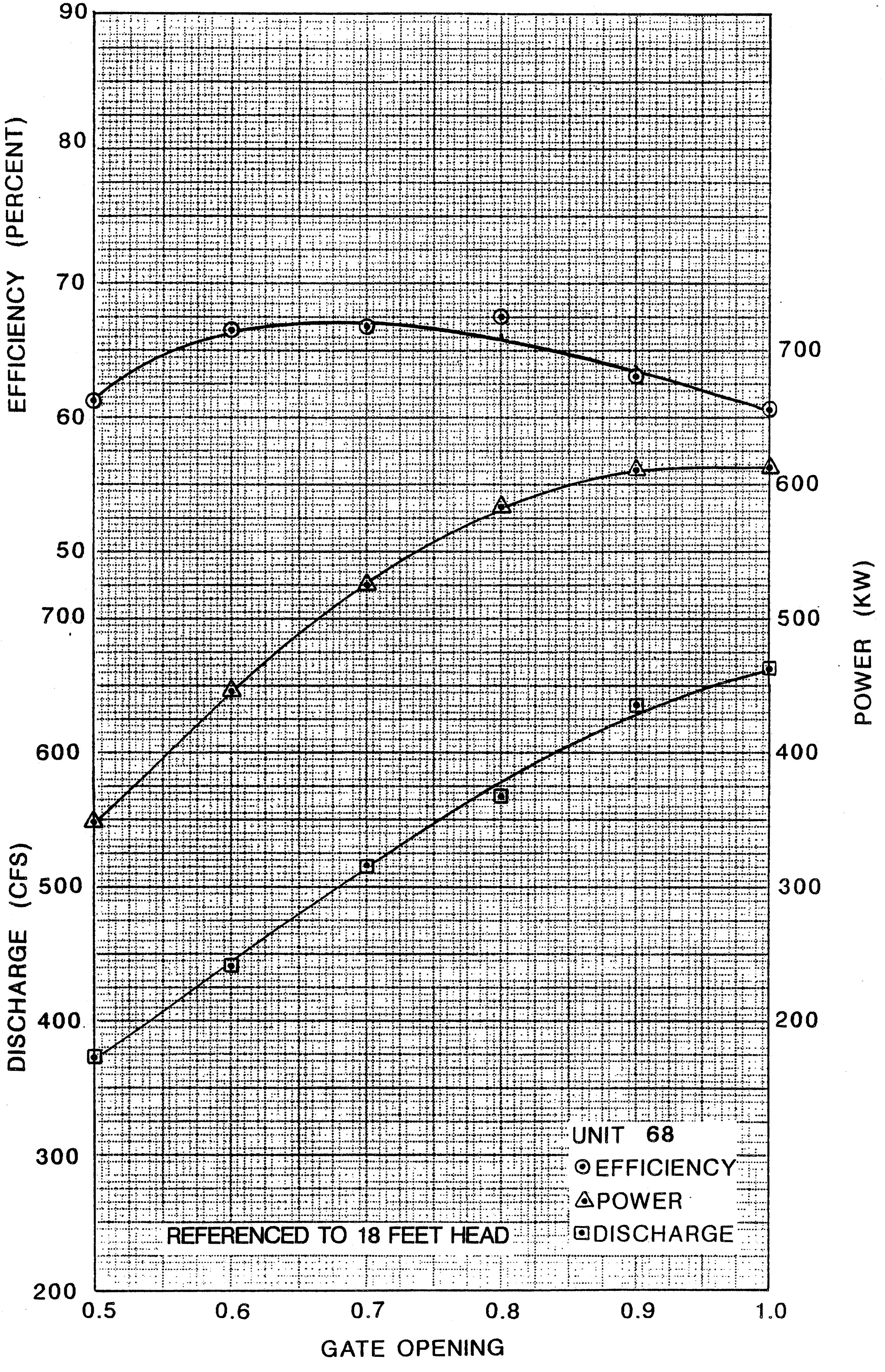

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 64*
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

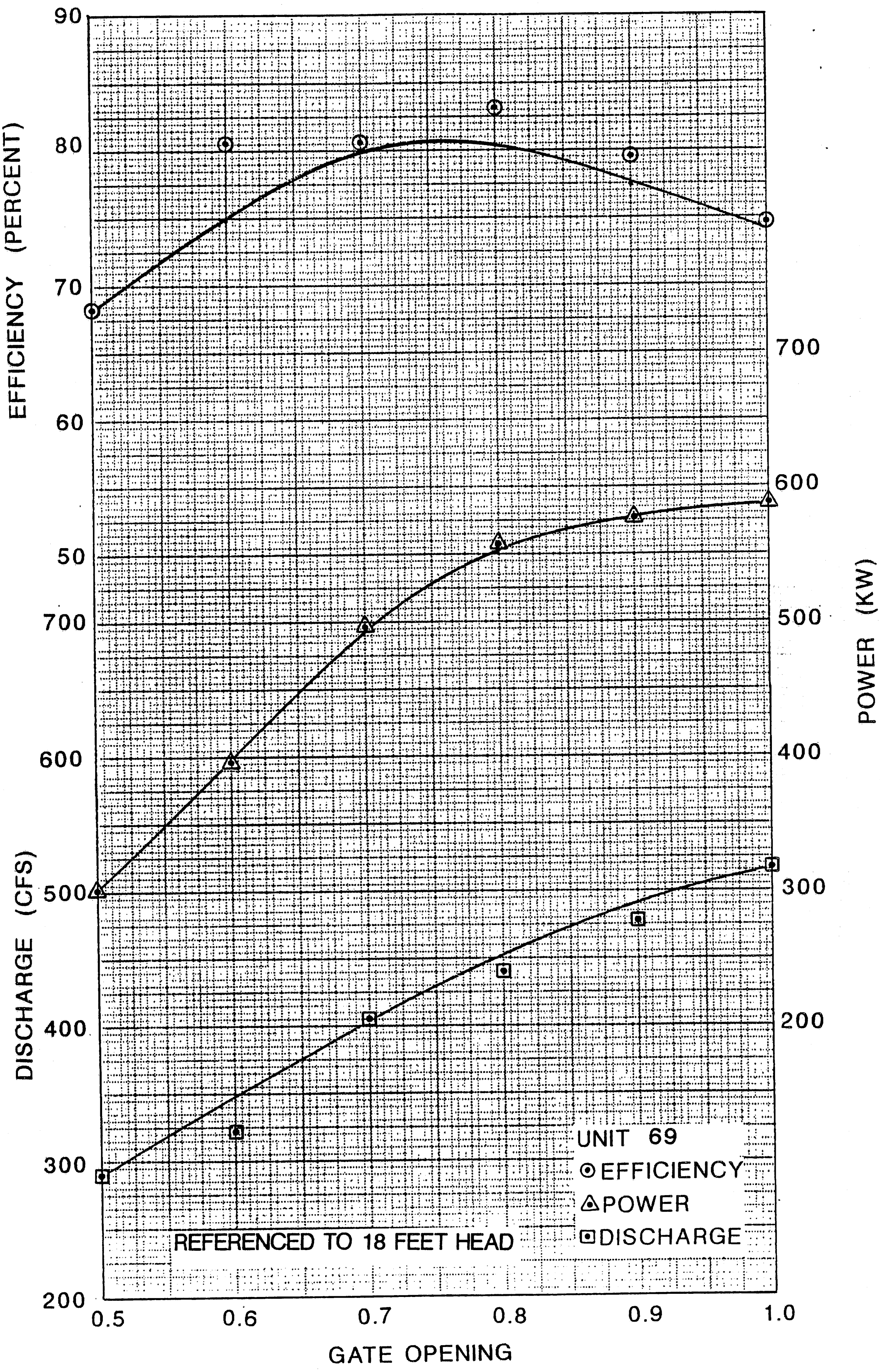

EFFICIENCY (PERCENT)
100
90
80
70
60
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 64
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

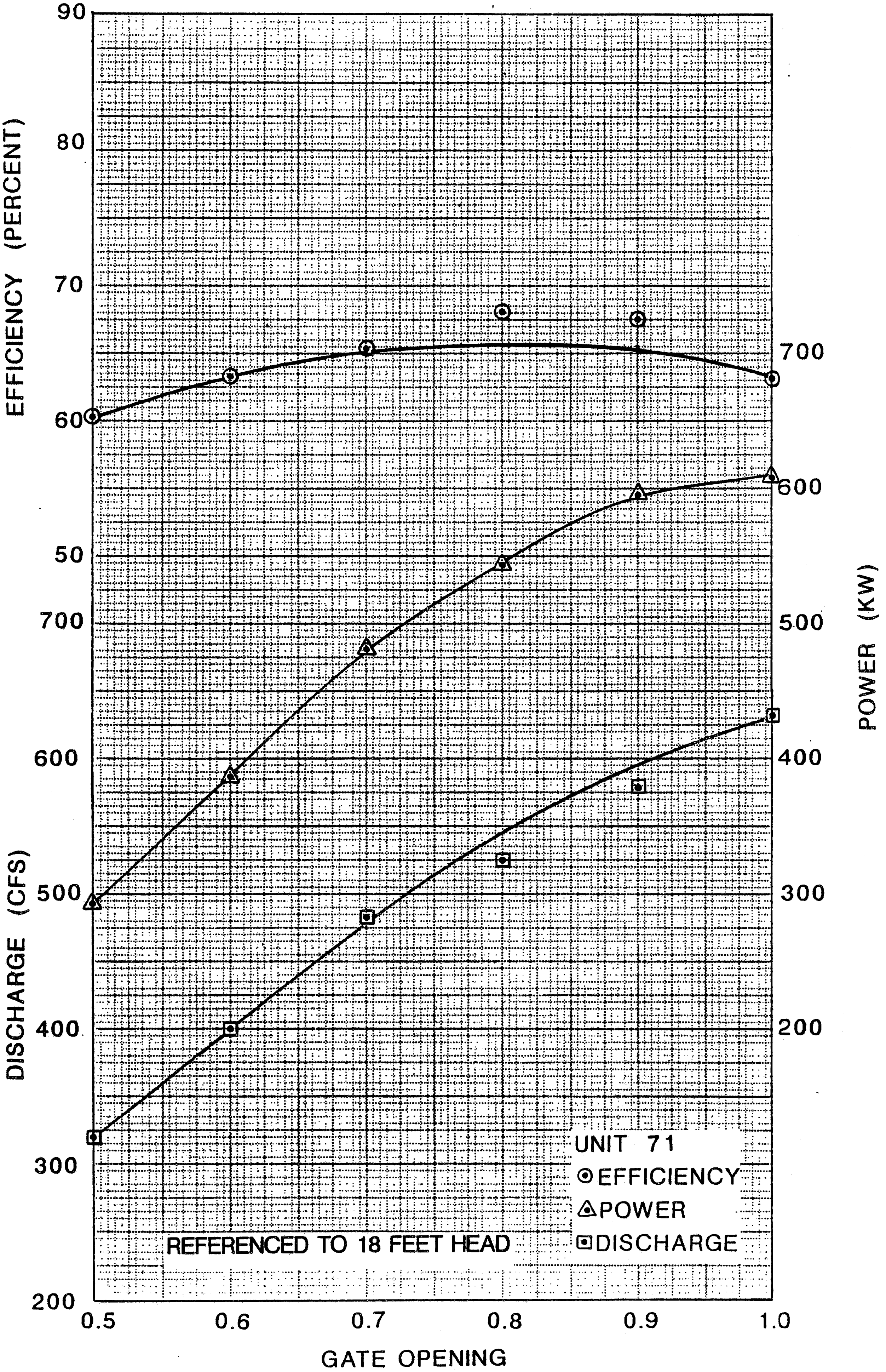

90
80
70
60
50
700
600
500
400
300
200
EFFICIENCY (PERCENT)
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 65
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

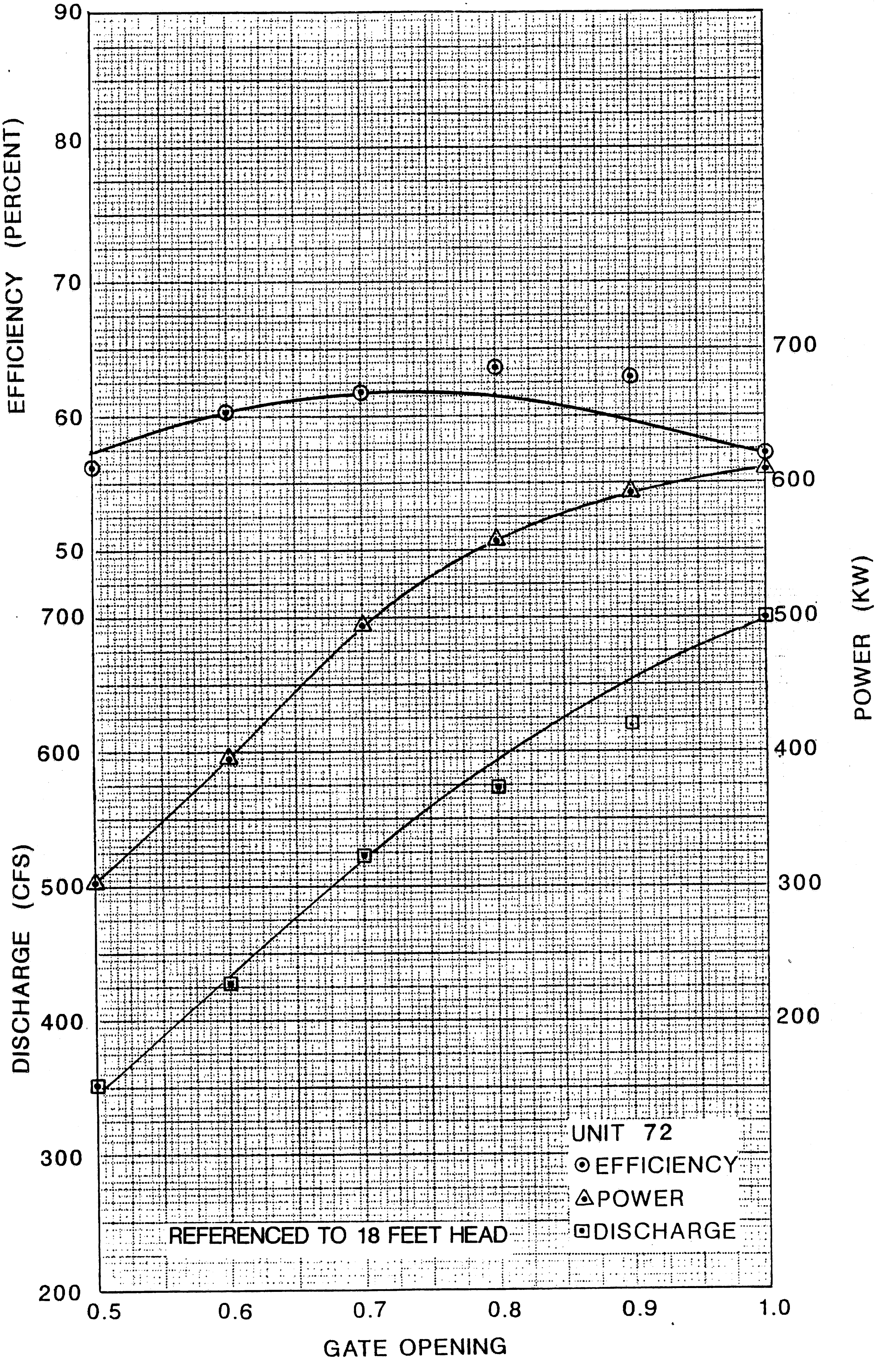

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 66
⊙EFFICIENCY
△POWER
⊡DISCHARGE
REFERENCED TO 18 FEET HEAD

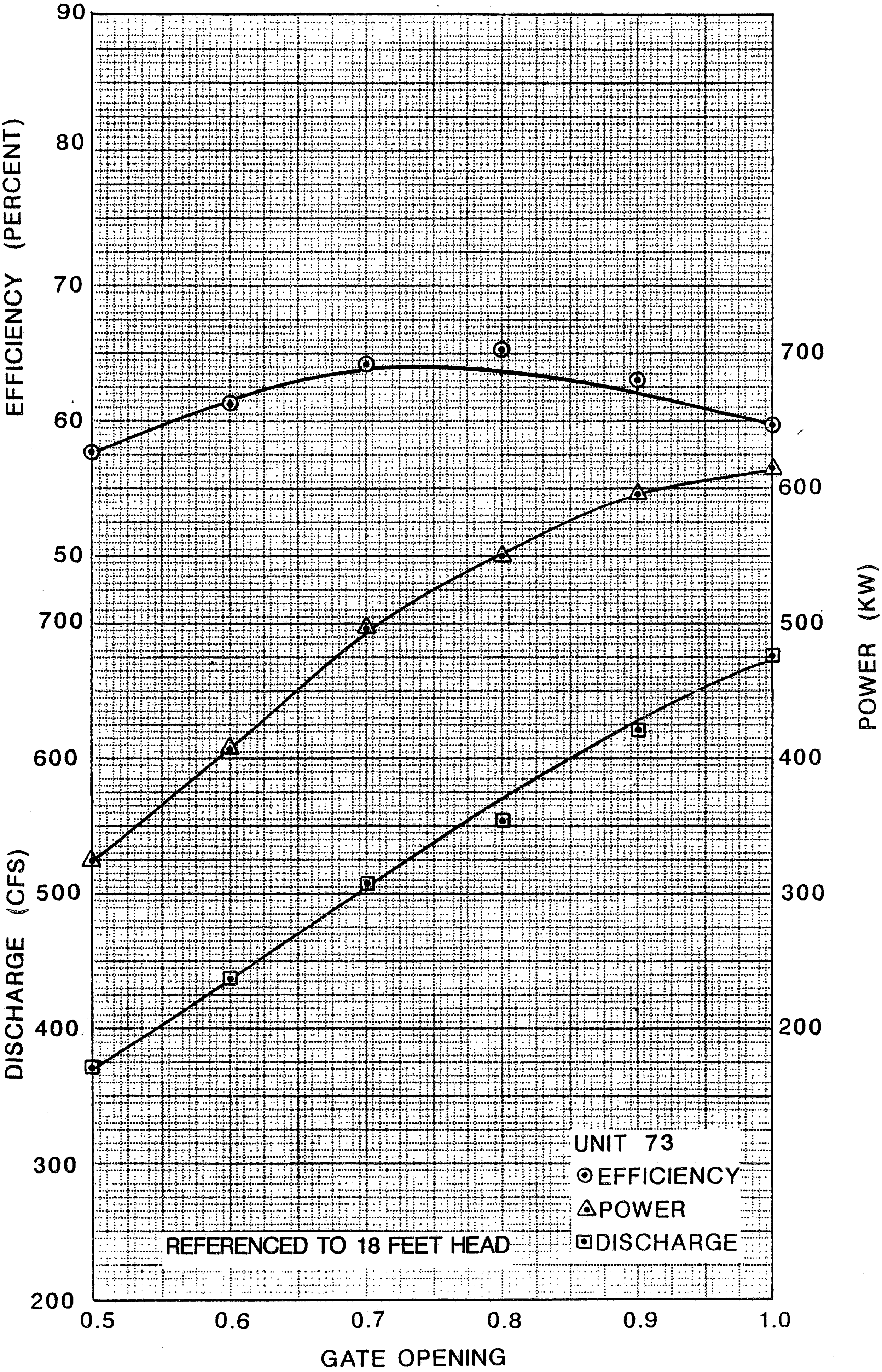

90
80
70
60
50
EFFICIENCY (PERCENT)
700
600
500
400
300
200
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 67
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

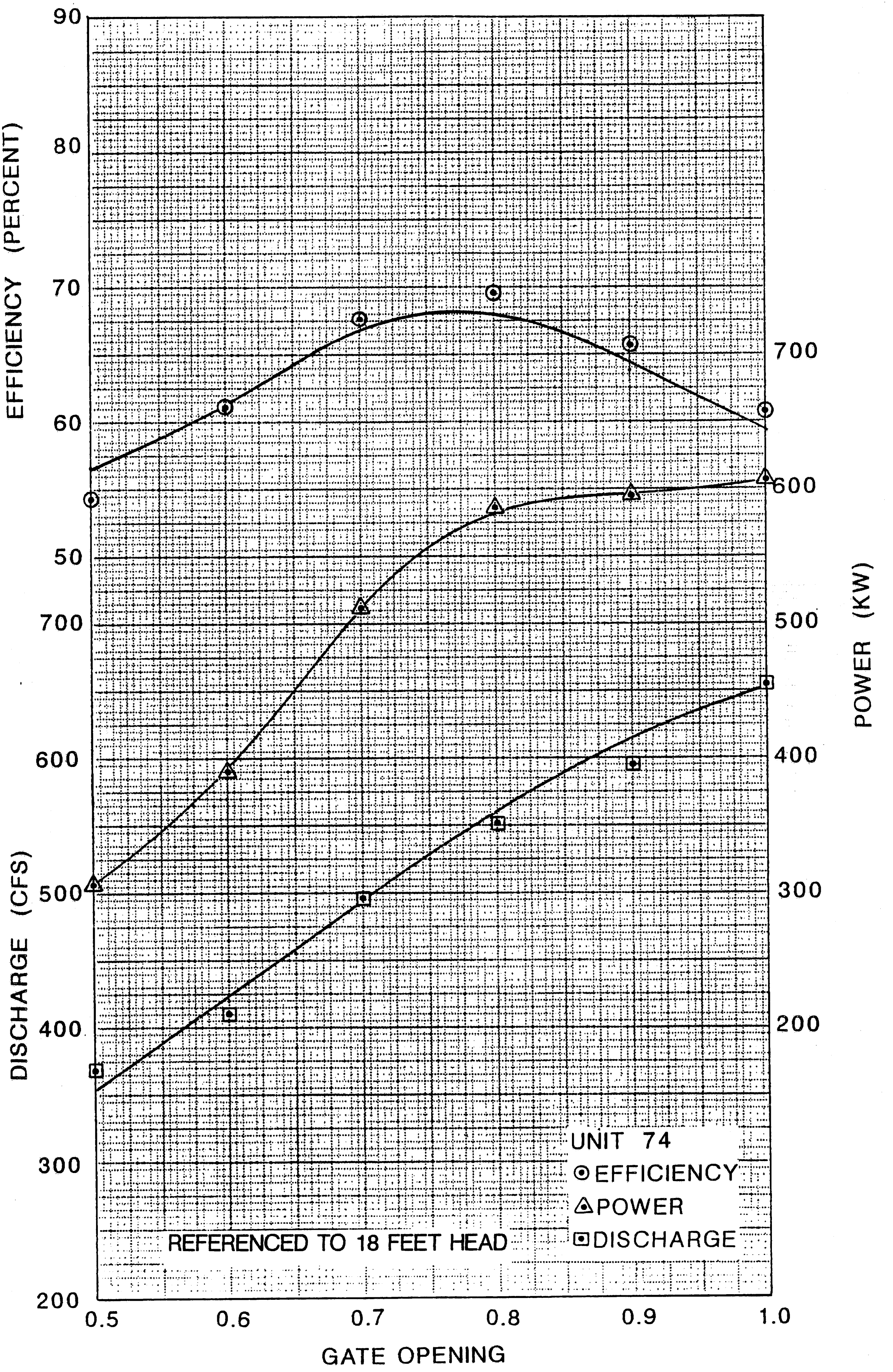

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 68
EFFICIENCY
POWER
DISCHARGE
REFERENCED TO 18 FEET HEAD

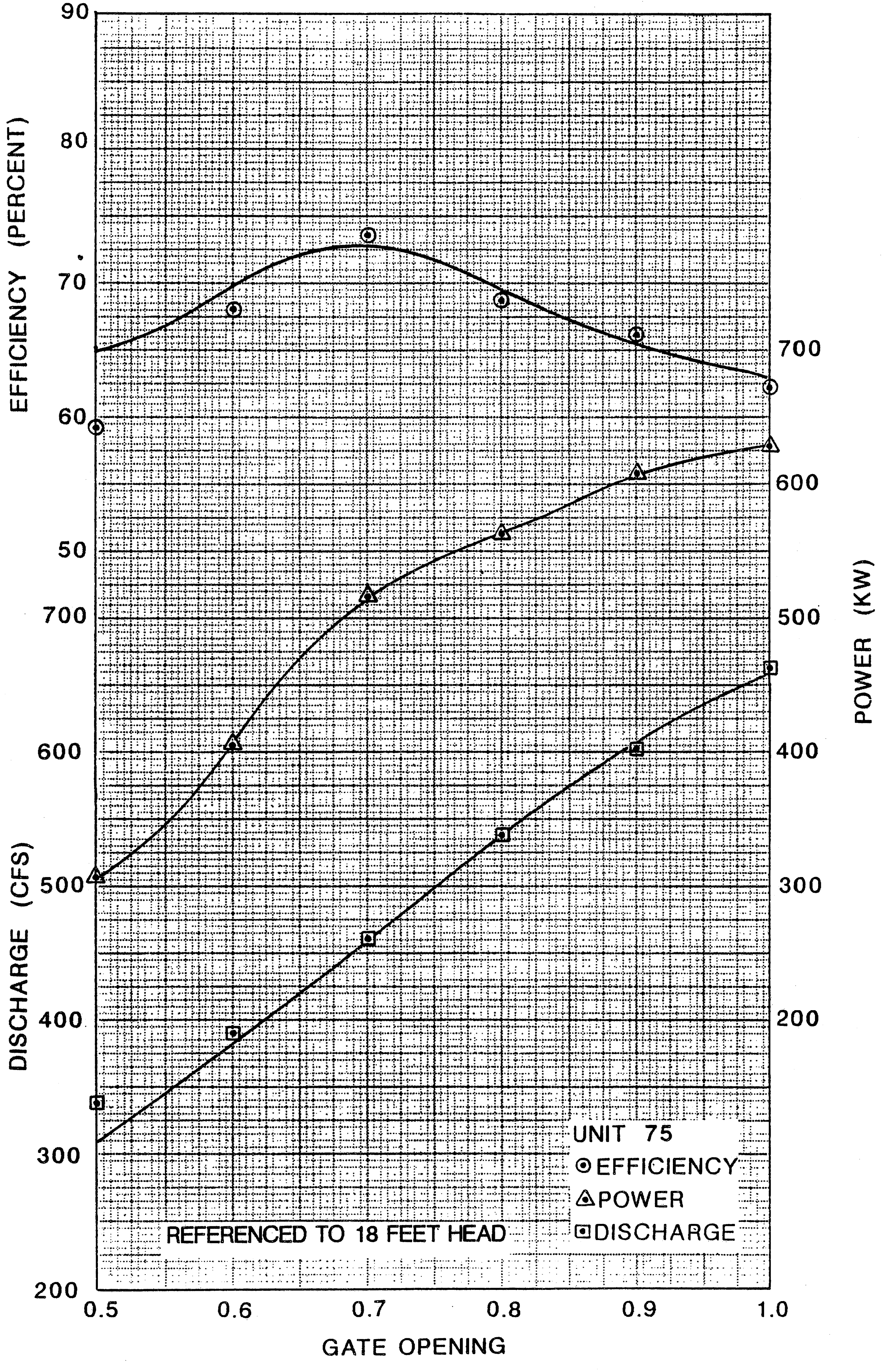

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 69
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

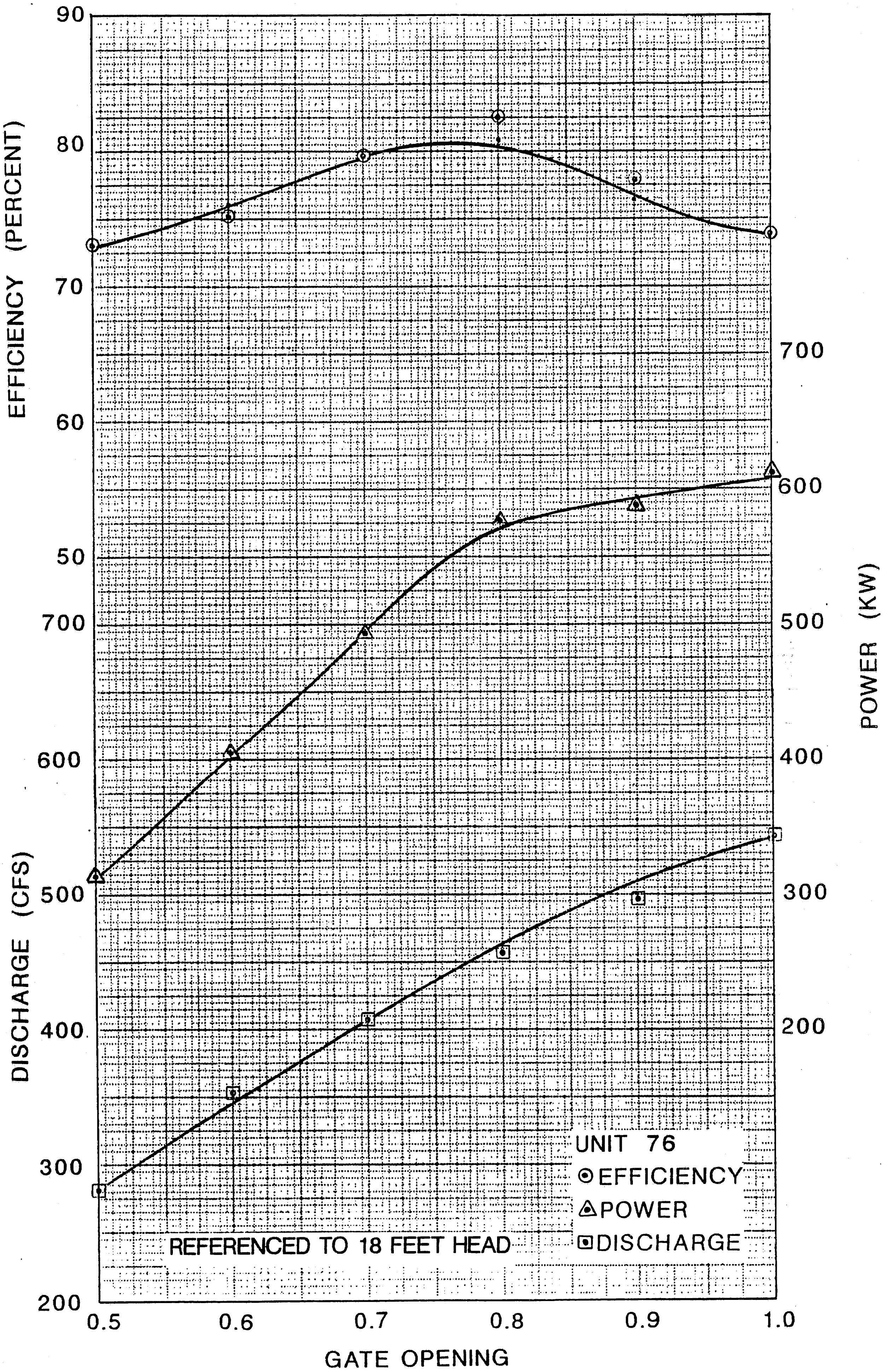

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
REFERENCED TO 18 FEET HEAD
UNIT 71
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE

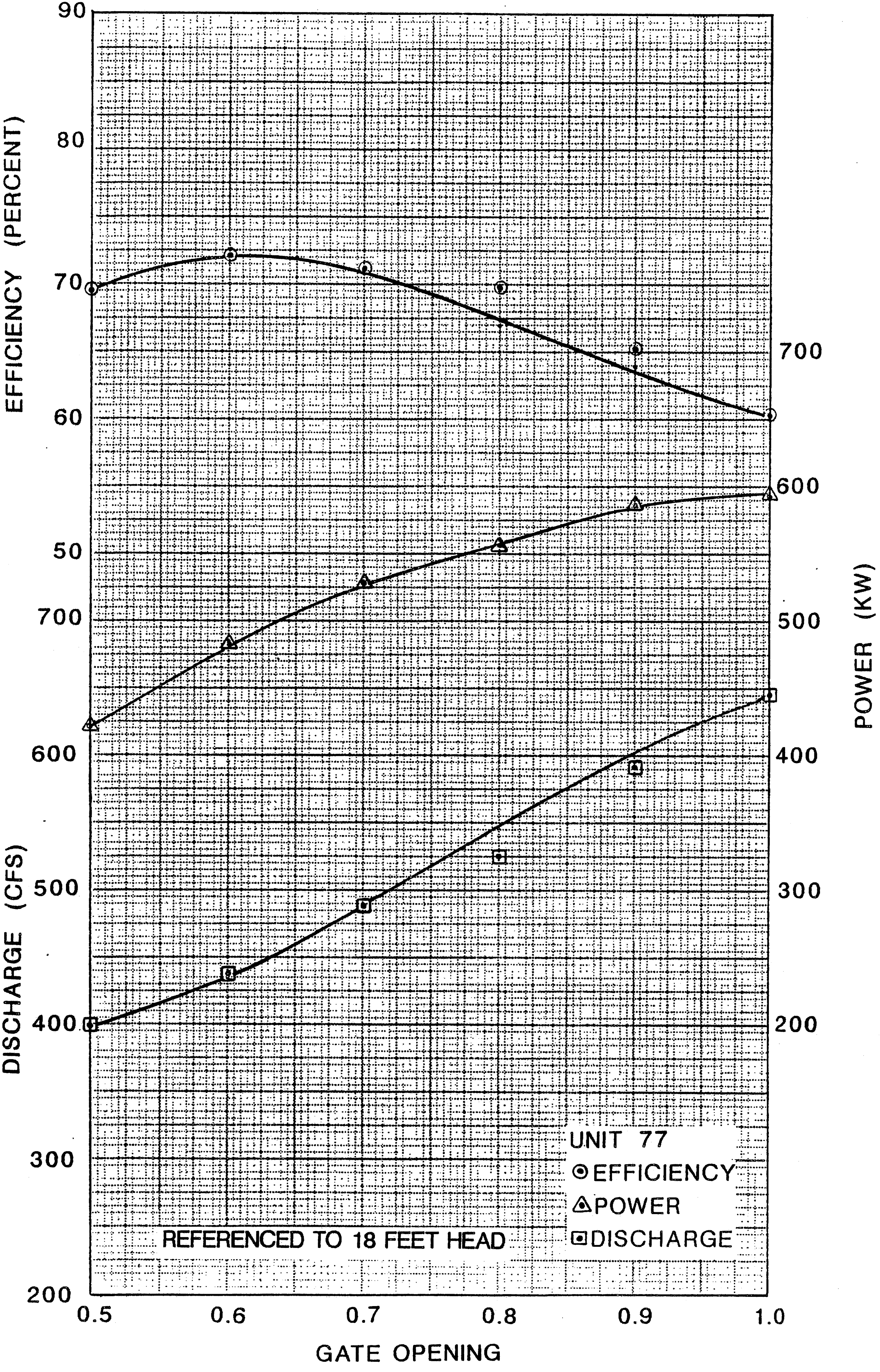

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 72
⊙ EFFICIENCY
△ POWER
▣ DISCHARGE
REFERENCED TO 18 FEET HEAD

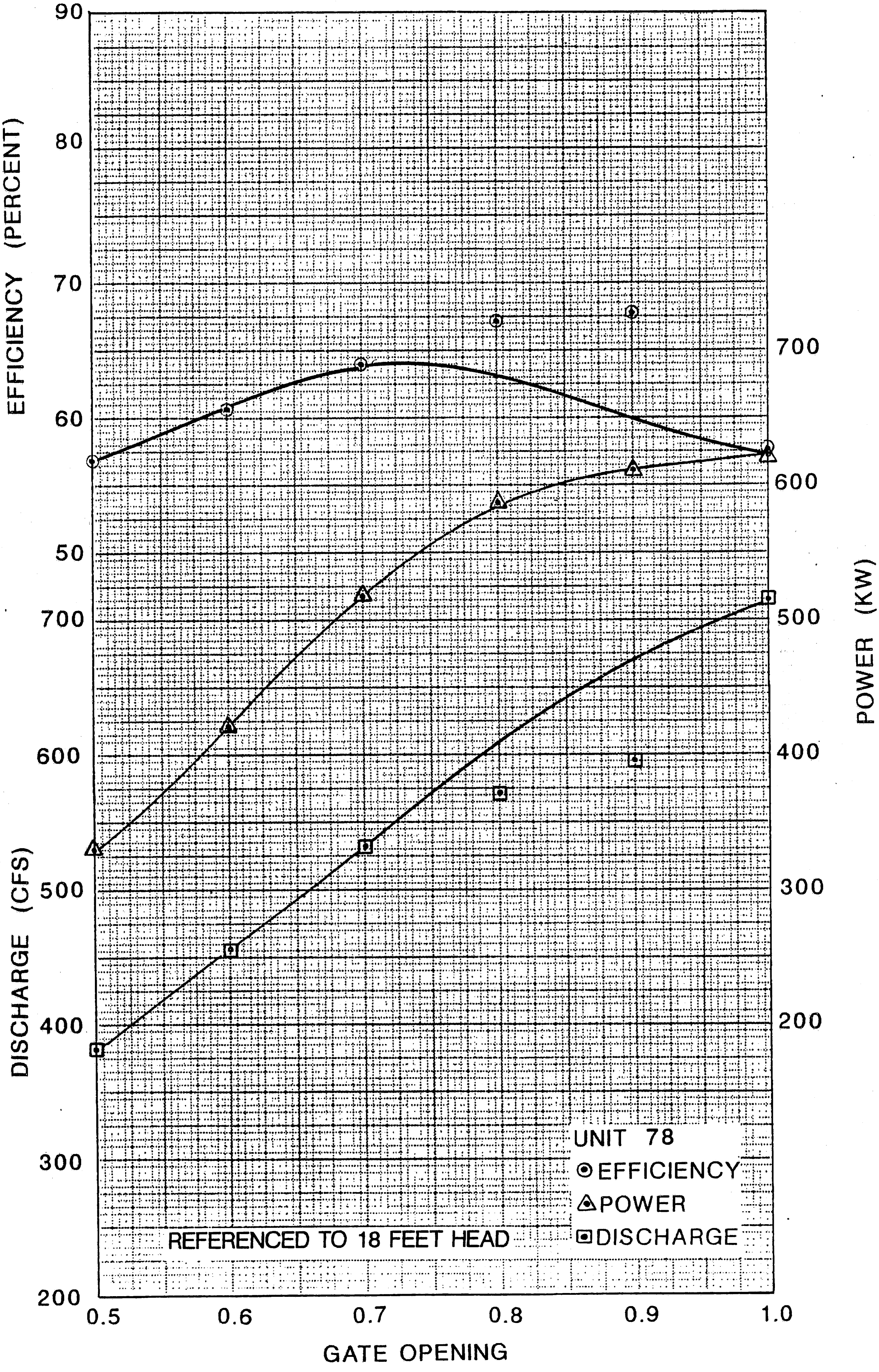

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 73
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 74
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

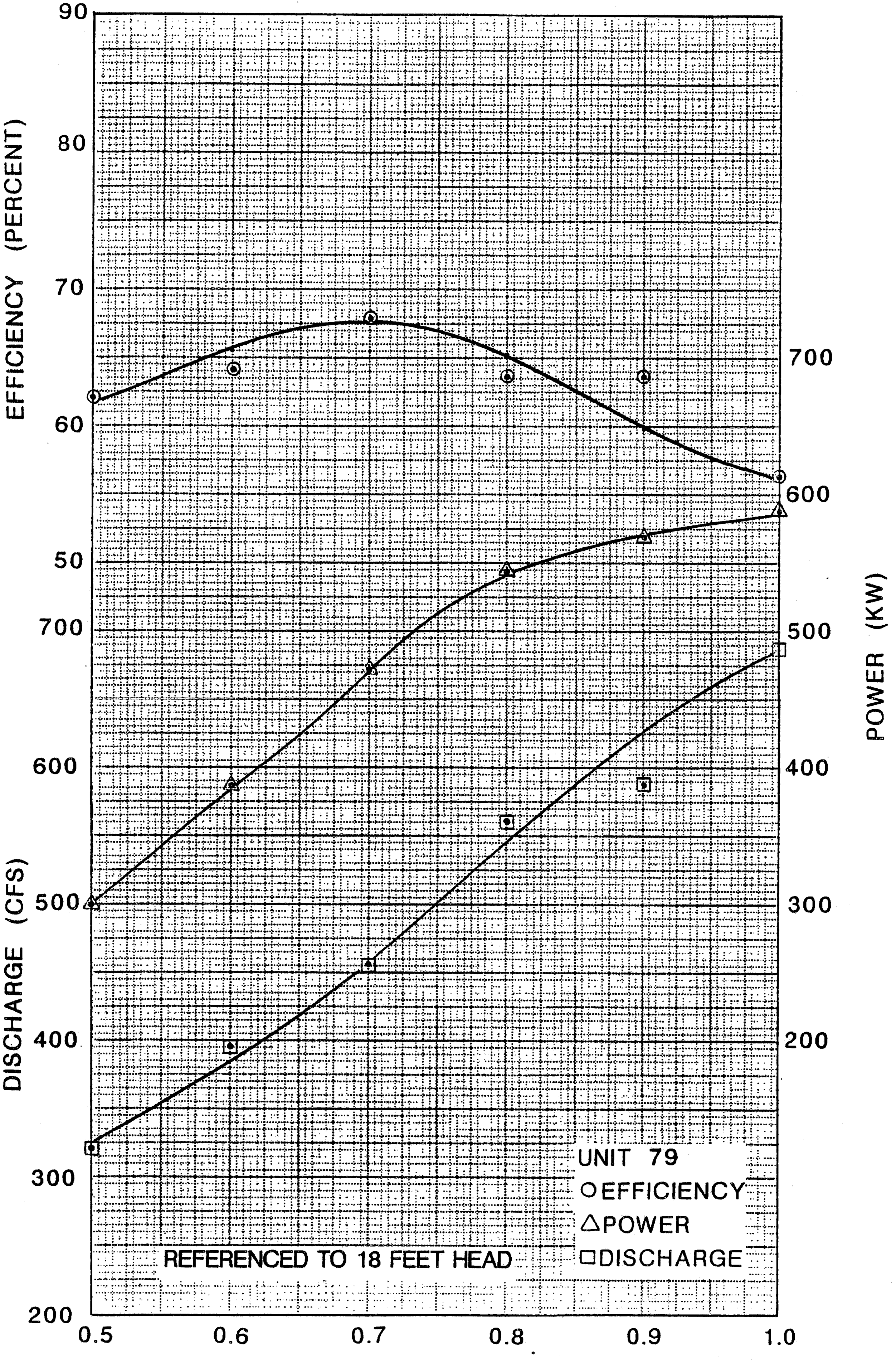

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 75
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD

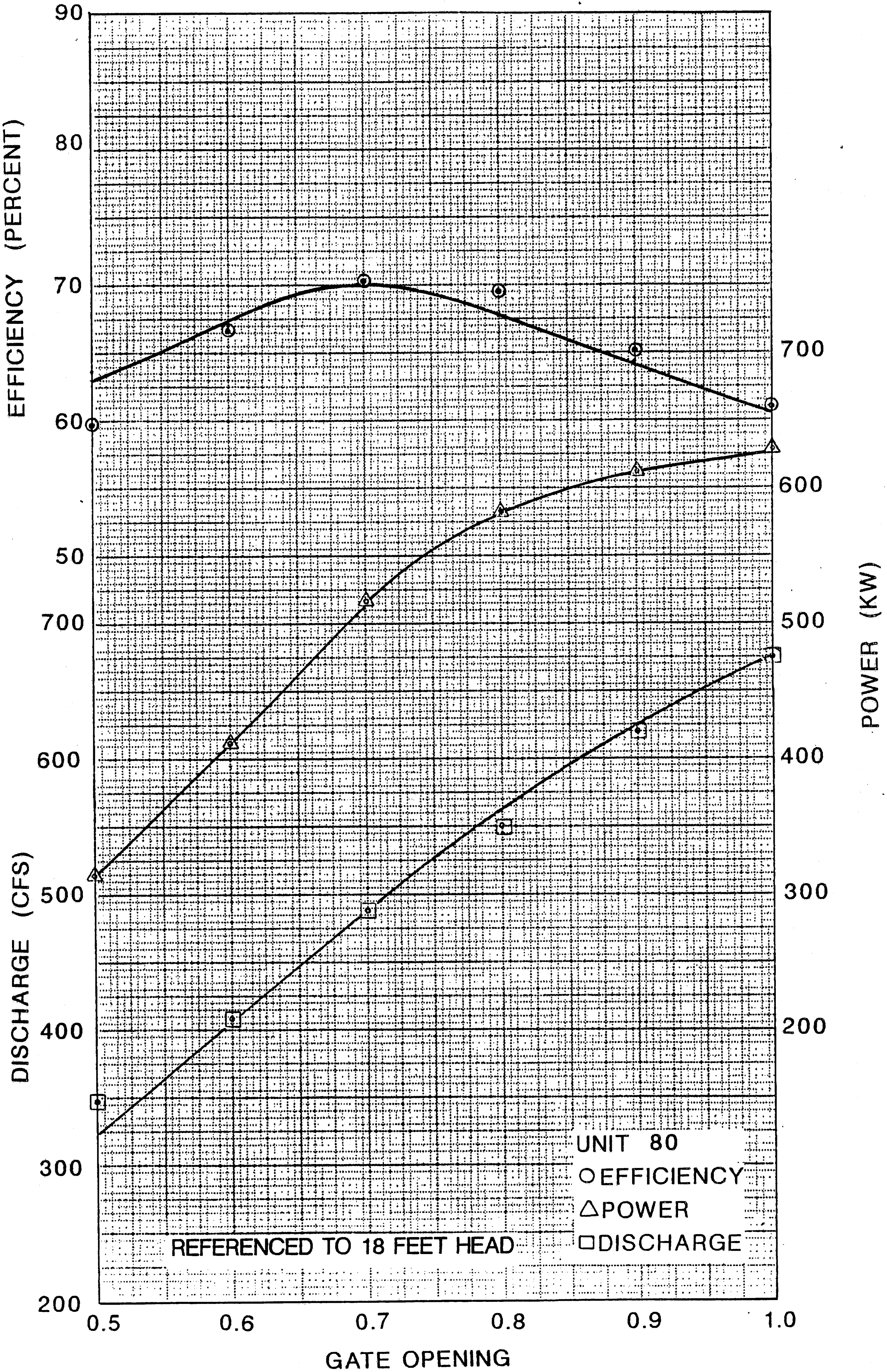

EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 76
⊙ EFFICIENCY
△ POWER
▣ DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 77
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD



EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 78
⊙ EFFICIENCY
△ POWER
⊡ DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 79
○EFFICIENCY
△POWER
□DISCHARGE
REFERENCED TO 18 FEET HEAD


EFFICIENCY (PERCENT)
90
80
70
60
50
DISCHARGE (CFS)
700
600
500
400
300
200
POWER (KW)
700
600
500
400
300
200
0.5
0.6
0.7
0.8
0.9
1.0
GATE OPENING
UNIT 80
○EFFICIENCY
△POWER
□DISCHARGE
REFERENCED TO 18 FEET HEAD