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DEVELOPMENT OF A MERCURY ELECTROMAGNETIC CENTRIFUGAL PUMP FOR THE SNAP-8 REFRACTORY BOILER DEVELOPMENT PROGRAM

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16. Abstract

An electromagnetic pump, in which pressure is developed in mercury because of the interaction of the magnetic field and current which flows as a result of the voltage induced in the mercury contained in the pump duct, was developed for the SNAP-8 refractory boiler test facility. Pump performance results are presented for ten duct configurations and two stator sizes. These test results were used to design and fabricate a pump which met the SNAP-8 criteria of 530 psi developed pressure at 12,500 lb/hr. The pump operated continuously for over 13,000 hours without failure or performance degradation. Included in this report are descriptions of the experimental equipment, measurement techniques, all experimental data, and an analysis of the electrical losses in the pump.

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An electromagnetic pump, in which pressure is developed in mercury due to the interaction of the magnetic field and current which flows as a result of the voltage induced in the mercury contained in the pump duct, was developed by General Electric for the SNAP-8 refractory boiler test facility.

Pump performance results are presented for ten duct configurations and two stator sizes. These test results were used to design and fabricate a pump which met the SNAP-8 criteria of 530 psi developed pressure at 12,500 lb/hr. The pump operated continuously for over 13,000 hours without failure or performance degradation.

Included in this report are descriptions of the experimental equipment, measurement techniques, all experimental data, and an analysis of the electrical losses in the pump.

II. INTRODUCTION

Electromagnetic pumps, due to their inherent reliability, are attractive to pump potentially hazardous fluids or in a system that must be kept hermetically sealed. Experience at General Electric has shown that the alkali metals can be pumped reliably at temperatures as high as 2400°F. Thousands of hours of pump time have been accumulated at General Electric on electromagnetic pumps without a failure.

For this reason a test program was undertaken to develop an electromagnetic pump for mercury, which, unlike the alkali metals, is a non-wetting fluid, for use in a refractory metal boiler test facility as part of NASA contract NAS 3-10610.

Background Information

The early work in electromagnetic pumps is summarized by Trocki,(1) Barnes and Cage.(2) This work was primarily concerned with the pumping of the alkali metals.

The advent of the Systems for Nuclear Auxiliary Power (SNAP) Program revived an interest in the development of an electromagnetic pump for mercury. Some preliminary work and a model (Figure 1) were completed by Collins(3) to develop a high head mercury pump. Rhudy(4) investigated the use of an electromagnetic pump for non-wetting metals and tested several models. These investigators did not develop their investigations enough to be able to design a prototype pump.

The development described herein augments these investigations in the development of a prototype pump.

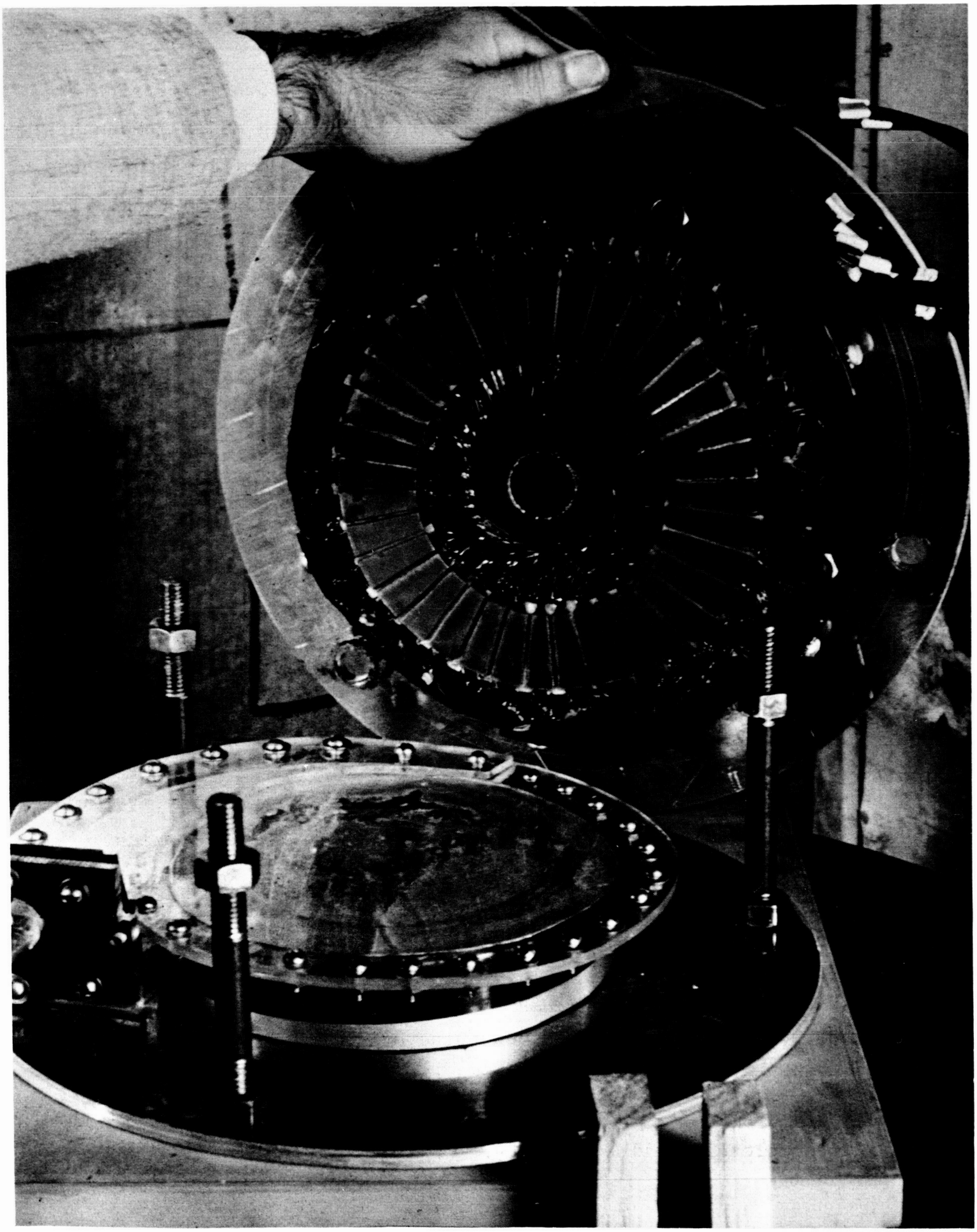

Figure 1. - Test model mercury electromagnetic pump.

III. TEST FACILITY

The mercury electromagnetic pump test facility, shown isometrically and schematically in Figure 2, consists of the following major components: electromagnetic pump stator with duct, throttle valve, orifice and bypass, surge tank, water cooled heat exchanger, EM flowmeter and dump tank. The instrumentation provided were chromel-alumel thermocouples, bourdon pressure gages, voltmeter, ammeter and wattmeter.

Two electromagnetic pump stators were used to develop the mercury pump. The first stator was a General Electric model 5KY416PB-1, three-phase, 60 cycle rated at 460 volts and 222 amperes. The stack accommodated a 6.5-inch-diameter by 12-inch-long duct. The second stator was a General Electric model 5KY416PL-1, three-phase, 60 cycle rated at 550 volts and 270 amperes. This stack accommodated a pump duct 6.5-inch-diameter by 16 inches long.

The throttle valve is a standard "HOKE" 1/2 NPS, Catalog No. 433V8Y, bellows sealed with stellited plug and seat. The orifice diameter of this valve is 5/16 inch diameter. The orifice, by-pass section consists of one of the "HOKE" valves in parallel with an orifice section. The orifice section consists of a .147-inch-diameter bore in a .635-inch-diameter tube. The orifice assembly was calibrated at the Ohio State University hydraulic test facility. The results of this test are shown in Figure 3 which represents a pressure drop of 10 psi at 2260 lb/hr and 300 psi at 12,500 lb/hr. These pressure drops assure the readability of the pressure gages over the anticipated range of test operation.

The surge tank consists of a short section of 2-inch pipe capped at one end and reduced to line pipe size at the other end for connection into the facility. Venting is provided at the top of the surge tank to allow for the removal of entrained gases in the mercury, and to assure that the facility is completely full of mercury.

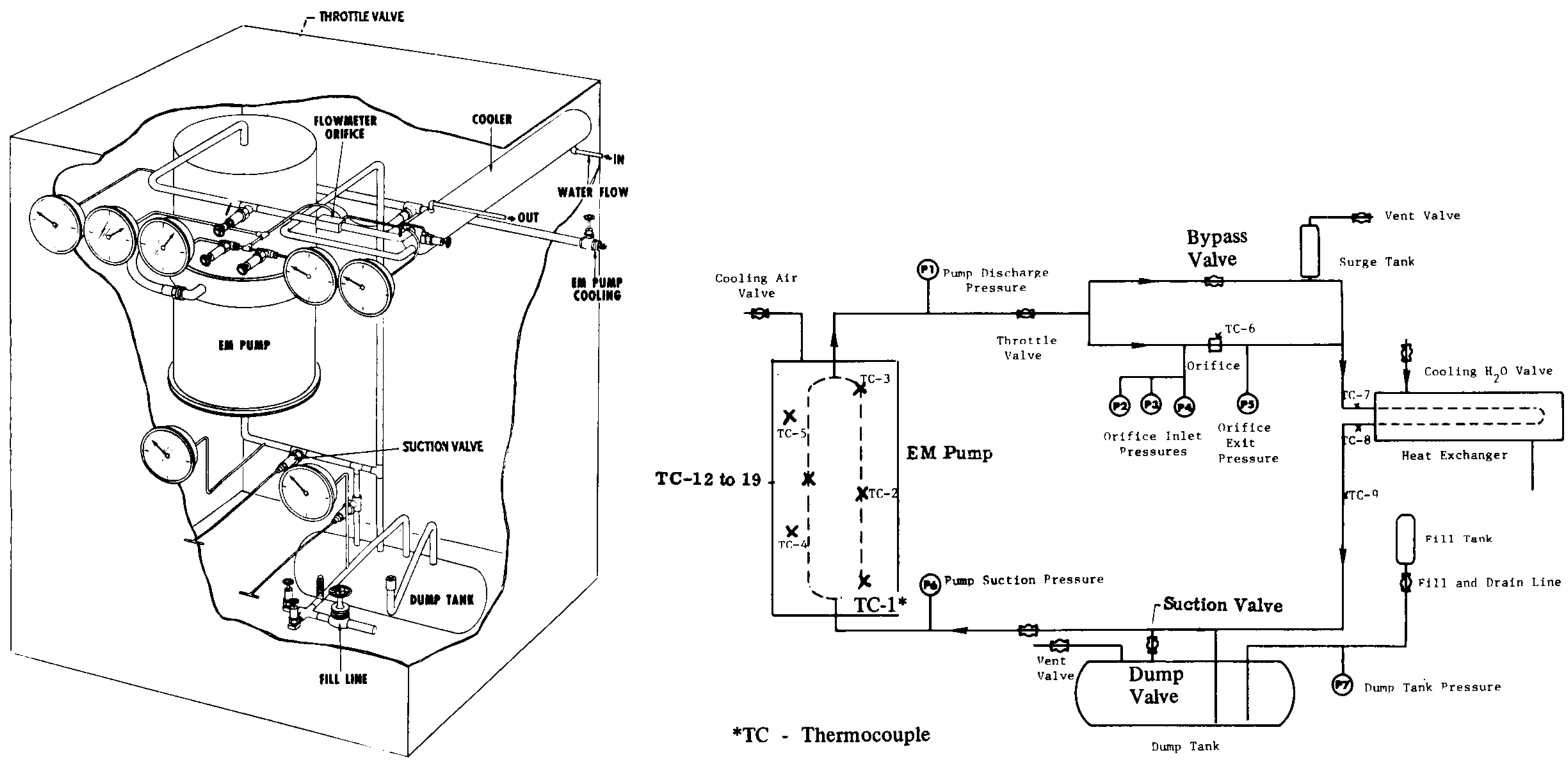

Figure 2. Isometric Drawing and Schematic of Mercury Pump Test Facility.

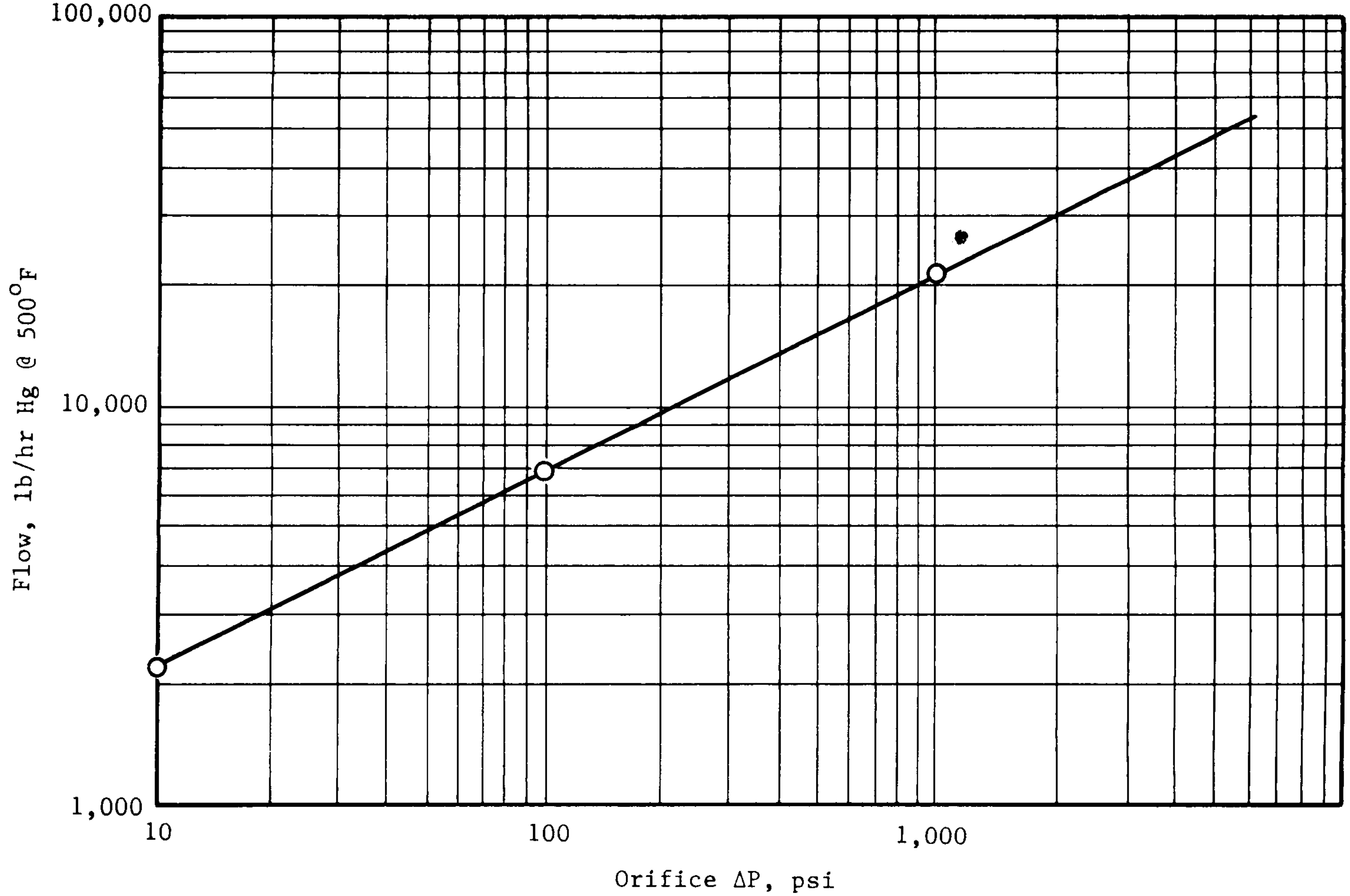

Figure 3. Calibration Curve for Mercury Flowmeter.

The EM flowmeter was installed as a means of detecting the conditions at which mercury wetted the stainless steel piping. However, initial testing showed the flowmeter did not provide sufficient output signal and throughout the test program gave no indication of wetting.

The dump tank is fabricated from a section of 8-inch Schedule 40 pipe with end caps, fill, vent and drain lines attached.

The material of construction of all components was Type 316 stainless steel which were acid cleaned prior to installation. All welds were inspected radiographically and the entire facility subjected to helium mass spectrometer testing prior to operation.

The thermocouple locations are tabulated in Table I and their respective locations shown on the schematic (Figure 2). The thermocouples are chromel-alumel with the bare wire tack welded to the pipe to form the junction. Temperatures were read on a calibrated 48 point Leeds and Northrup temperature indicator.

The pressure gages are tabulated in Table II and are also located on the schematic. The gages are Ashcroft Duragages with Type 316 stainless steel bourdon tubes which were cleaned with alcohol to remove residual oil used during manufacture.

The power instrumentation, shown schematically in Figure 4, is comprised of the following:

1. General Electric P3 ammeter, 5 amps full scale, accuracy 0.2% of full scale.
2. General Electric P3 voltmeter, 600 volts full scale, accuracy 0.2% of full scale.
3. Scientific Columbus 3-phase wattmeter and transducer, Model No. 32K605010, accuracy 0.2% full scale.
4. Three Weston current transformers, Model No. 327, 25 VA, Freq. 25-500, 2500 volts.

TABLE I

THERMOCOUPLE LIST

TC No.	Location
1	Pump duct temperature - inlet
2	Pump duct temperature - middle
3	Pump duct temperature - discharge
4	Stator winding temperature
5	Stator winding temperature
6	Orifice temperature
7	Hx inlet temperature - hg
8	Hx exit temperature - hg
9	EM flowmeter pipe temperature
10	Flowmeter signal
11	Enclosure ambient temperature
12	Pump duct temperature - inlet
13	Pump duct temperature - middle
14	Pump duct temperature - exit
15	Pump duct temperature - one half the distance between TC-14 and TC-16 on the domed cap
16	Pump duct temperature - exit pipe
17	Pump duct temperature - 180^{o} T-14
18	Pump duct temperature - one stator slot to the left of T-14
19	Pump duct temperature - one stator slot to the right of T-14

Note:
1. Thermocouples 1, 2, 3 were all installed in line on duct along one axial stator slot.
2. Thermocouples 12, 13, 14, 15, 16, 17 were all installed in line on duct along one axial stator slot.

TABLE II

PRESSURE GAGE LIST

P_1	Pump discharge pressure - 0-600 psi + 5 lb subdivisions
P_2	Orifice inlet pressure - 0-600 psi, 5 lb subdivisions
P_3	Orifice inlet pressure - 0-300 psi, 5 lb subdivision
P_4	Orifice inlet pressure - 0-160 psig, 2 lb subdivision
P_5	Orifice discharge pressure - 0-30 psig, 1/2 lb subdivision
P_6	Pump suction pressure - 0-60 psig, 1 lb subdivision
P_7	Dump tank pressure, 30-in. vacuum to 60 psig, 1 in. and 1 lb subdivisions

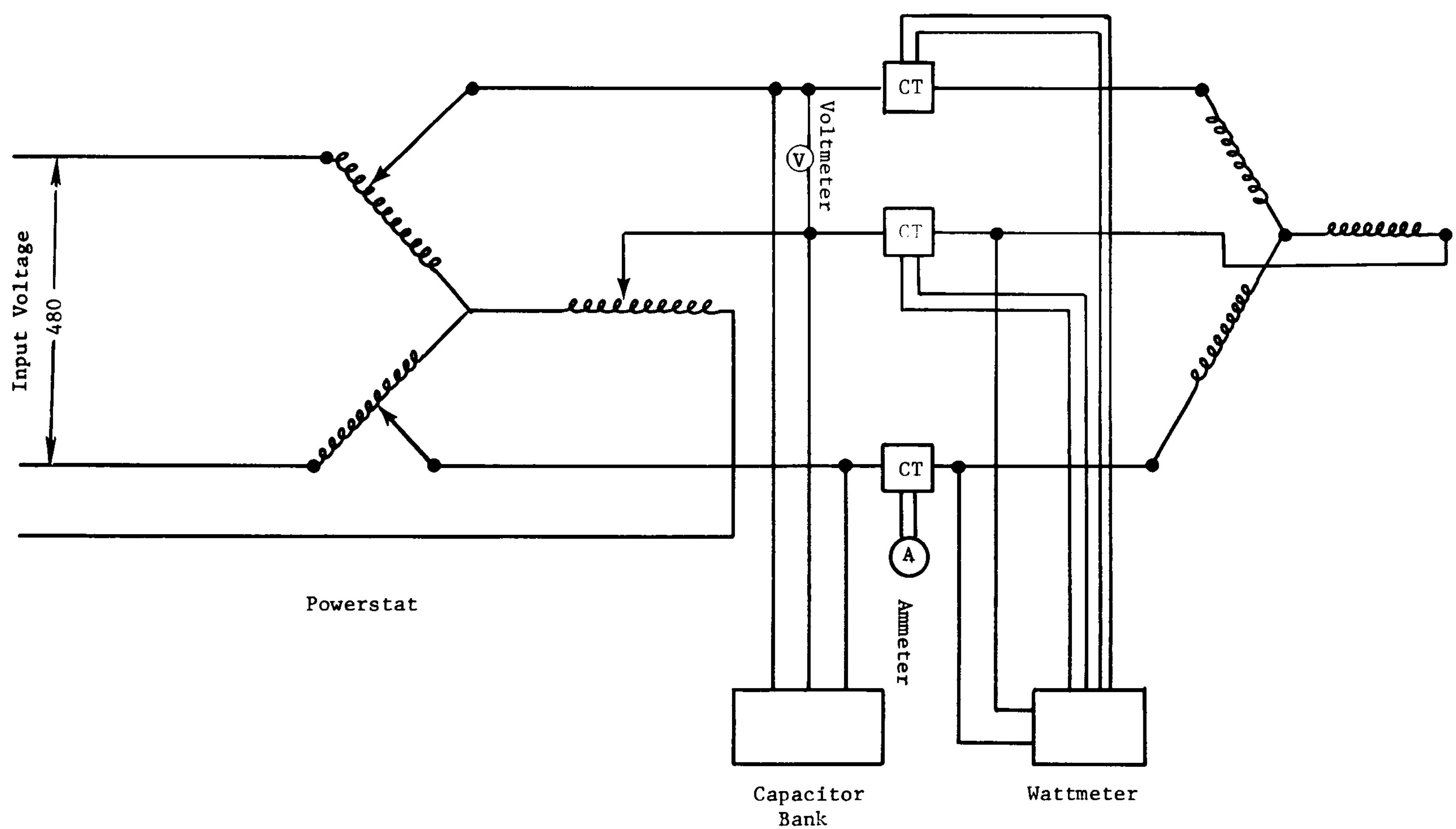

Figure 4. Power Schematic Mercury Electromagnetic Pump.

IV. PUMP TEST PROGRAM

GENERAL OPERATING PROCEDURE

Prior to the testing of a particular pump duct configuration, each pump duct was radiographically inspected to assure weld integrity and each installation was helium mass spectrometer tested to assure maximum weld and component quality. In addition, all components were cleaned to remove residual oils that might have accumulated during manufacture.

At the completion of each mass spectrometer test the loop instrumentation, EM pump stator cooling air and heat exchanger water were activated. The loop, if evacuated, was filled; if not, was evacuated to approximately 10 microns. At all times a liquid nitrogen cold trap was in the line between the facility and the pumps to prevent oil from diffusing into the facility.

The dump tank pressure was then increased with the equalizer valve closed until pressure gage P-5 showed a pressure of 5 to 15 psig. At this time the mercury EM pump power was activated and set a low power to circulate the mercury at a low flow rate to remove entrained argon at the surge tank.

Performance of any particular pump duct configuration was obtained by setting pump power at several power levels. At each power level data was taken with flow through the orifice and the bypass line, flow through the orifice only, and shutoff. At shutoff only the pump power and pressures were read to keep the duct temperature rise to a minimum.

The above operation was deviated from when, at high pressure drops across the throttle valve and bypass valve, chatter occurred. At this time the valves were throttled until chatter ceased.

PUMP DUCT CONFIGURATIONS

The original pump duct configuration, shown in Figure 5, is a two-stage duct. The outside of the duct consists of a section of 6 inch

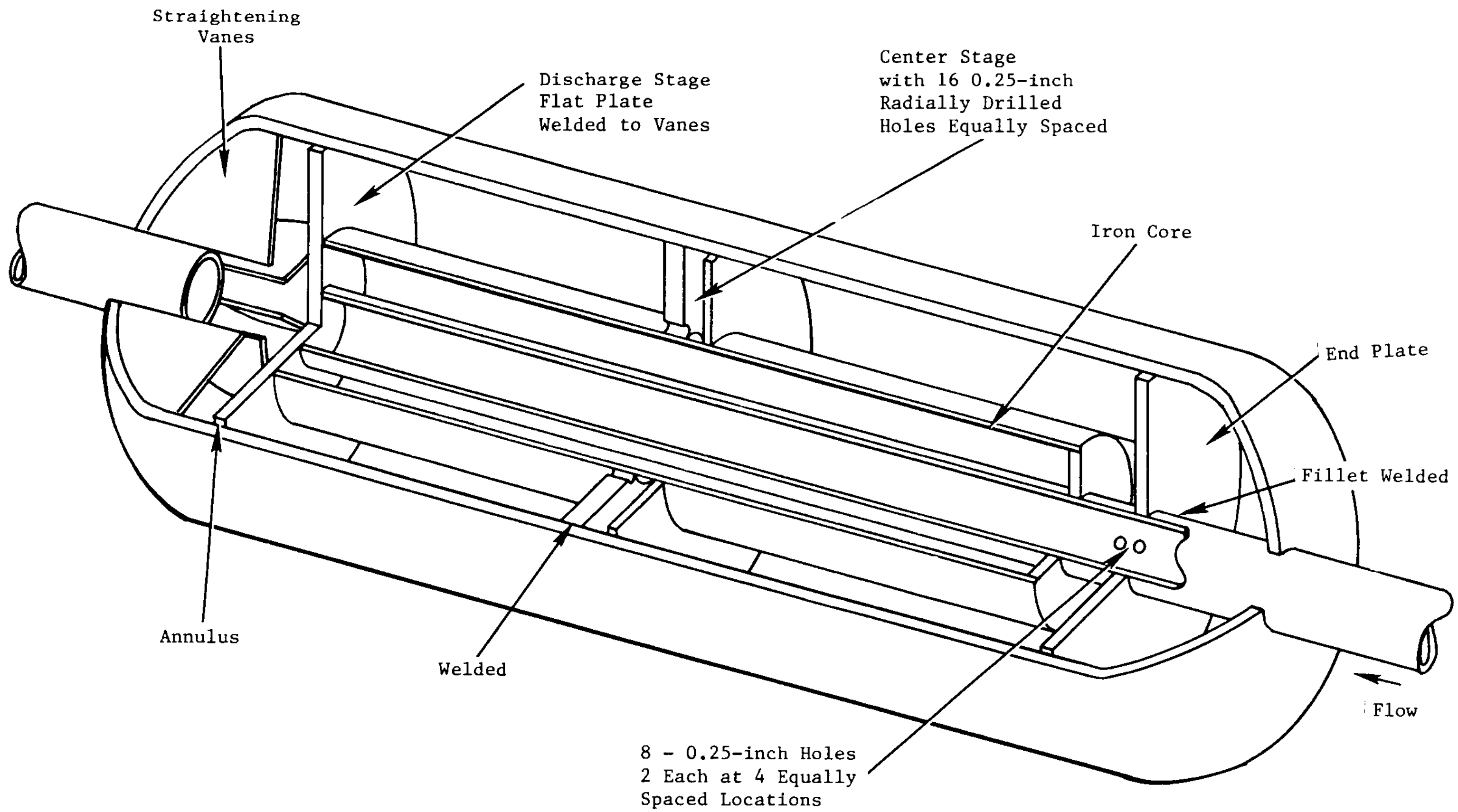

Figure 5. Original Pump Duct Design.

Schedule 40 pipe with 6-inch caps and 3/4-inch pipe attached at each end. The OD of the assembly is machined to fit the 6.5-inch-diameter of the stack in the stator. The internals of the duct, from suction, to discharge, are:

1. A plate welded to the 3/4-inch suction pipe inside the 6-inch cap. The purpose of this plate is to act as an end ring.
2. An iron core inside a stainless steel container. The iron core provides a flux path and improves the power factor.
3. The center stage plate provides a means for directing the mercury flow from the high pressure,high velocity region at the outer periphery of the 6-inch duct to the low pressure, low velocity region of the core of the duct. The plate consists of 1/4-inch holes drilled radially into the edge of the plate to provide a path for the mercury. The discharge of this pump consists of a flat plate with 6 axial vanes welded at 60° intervals to the discharge cap.

The developed pressure versus flow for this pump configuration is shown in Figure 6. The performance of this duct is obviously erratic and an inspection of the raw data in the appendix shows two possible reasons:

1. The pump suction pressure (P6) appears to go negative regardless of loop pressure. This could indicate pump cavitation.
2. The pump duct discharge temperature (TC No. 3) shows an unexpectedly high temperature. An examination of the duct drawing indicates that gas may be trapped in the discharge end of the duct.

Since the shutoff pressure of the pump (200 psi at maximum volts) was much less than the desired 530 psi at 12,500 lb/hr mercury flow, it was decided to proceed to the next duct configuration. The facility would be modified to alleviate the problems detected.

MODIFICATION NO. 1

The pump duct was modified by installing axial baffles as shown in Figure 7. The purpose of the axial baffles was to minimize any internal fluid circulation due to secondary field effects.

Venting was also provided in the discharge cap to eliminate possible gas entrapment.

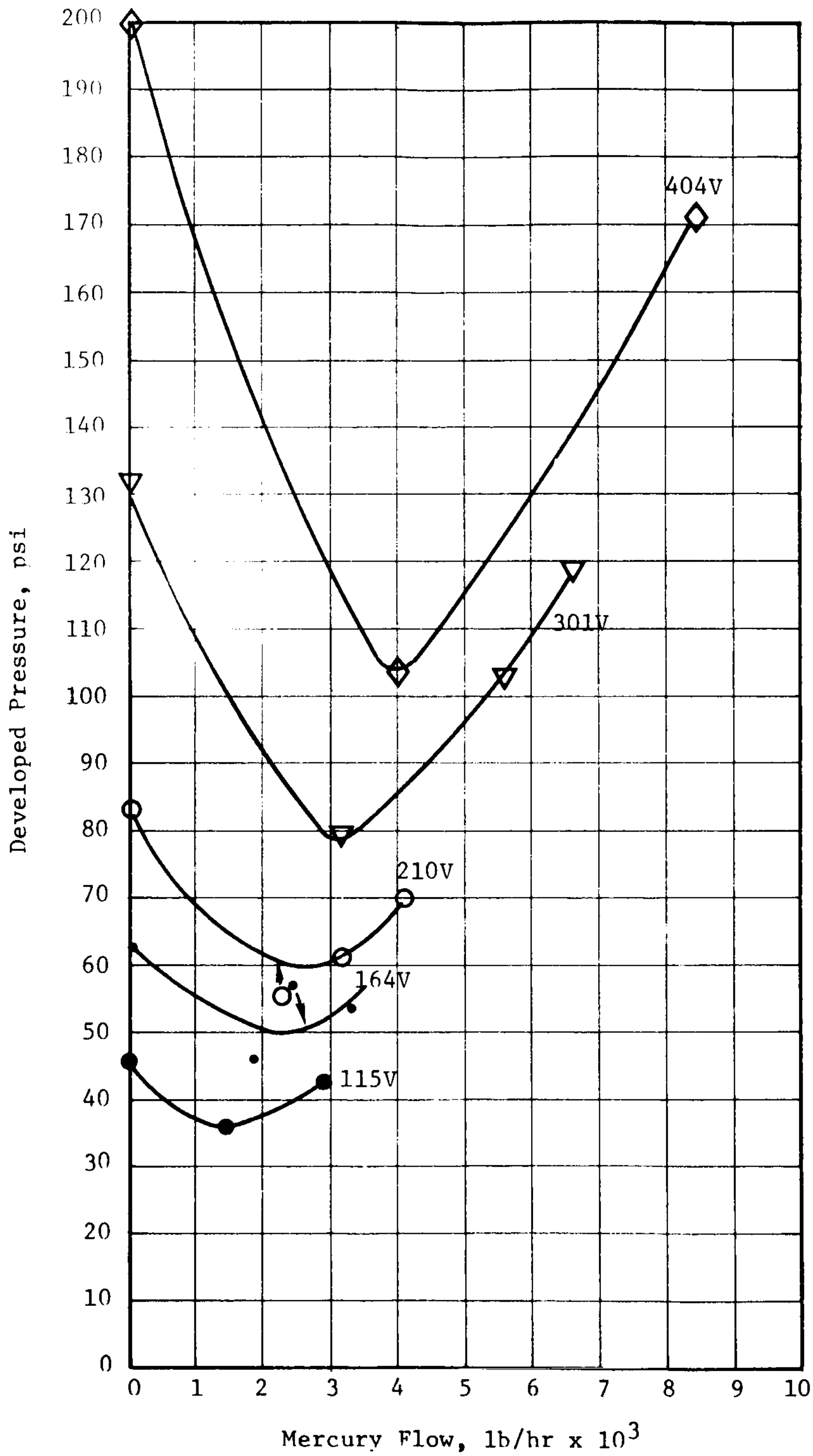

Figure 6 SNAP-8 Centrifugal EM Pump - Original Design - Developed Pressure Versus Flow at Several Voltages.

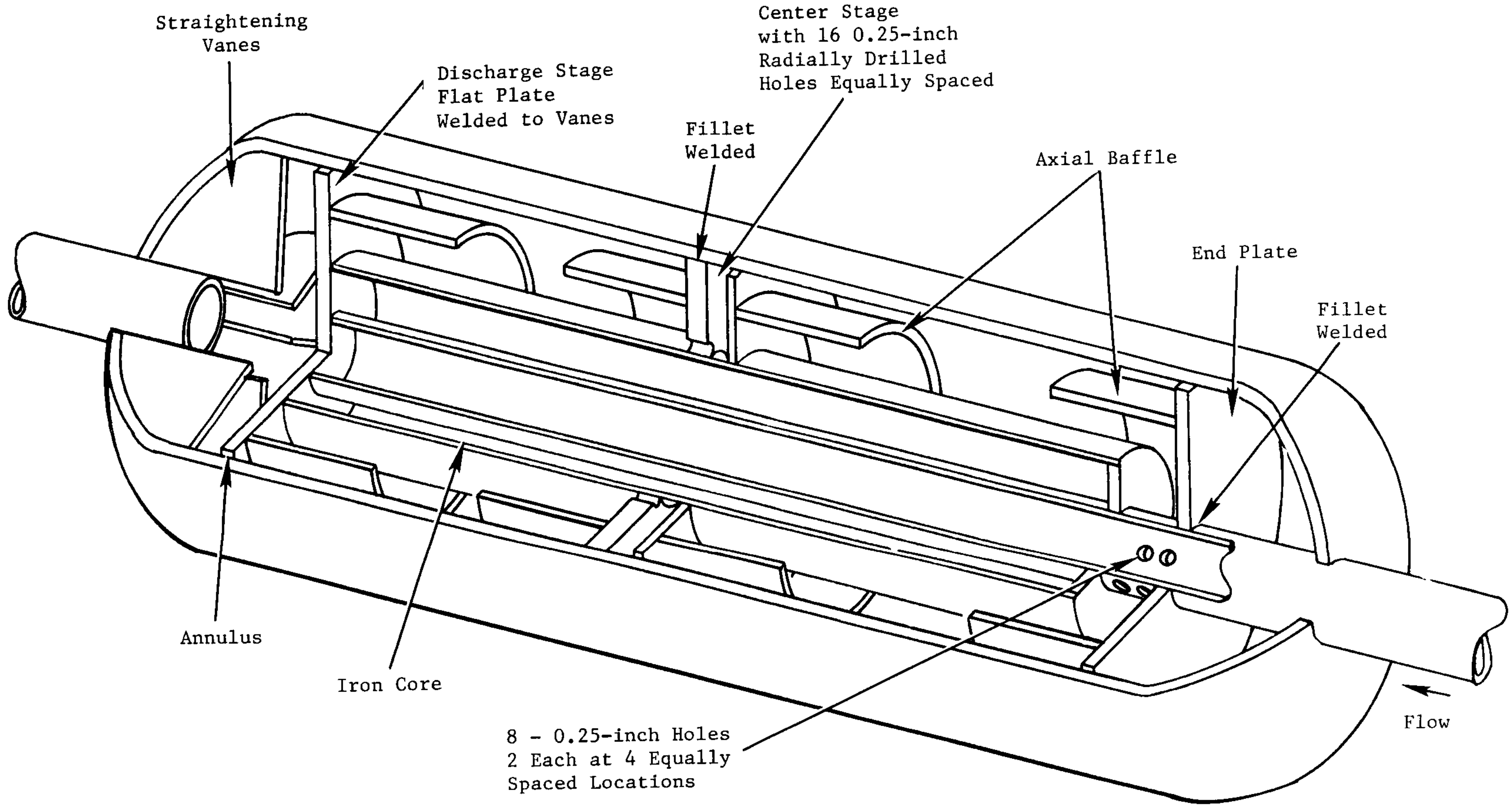

Figure 7. Pump Duct Modification No. 1.

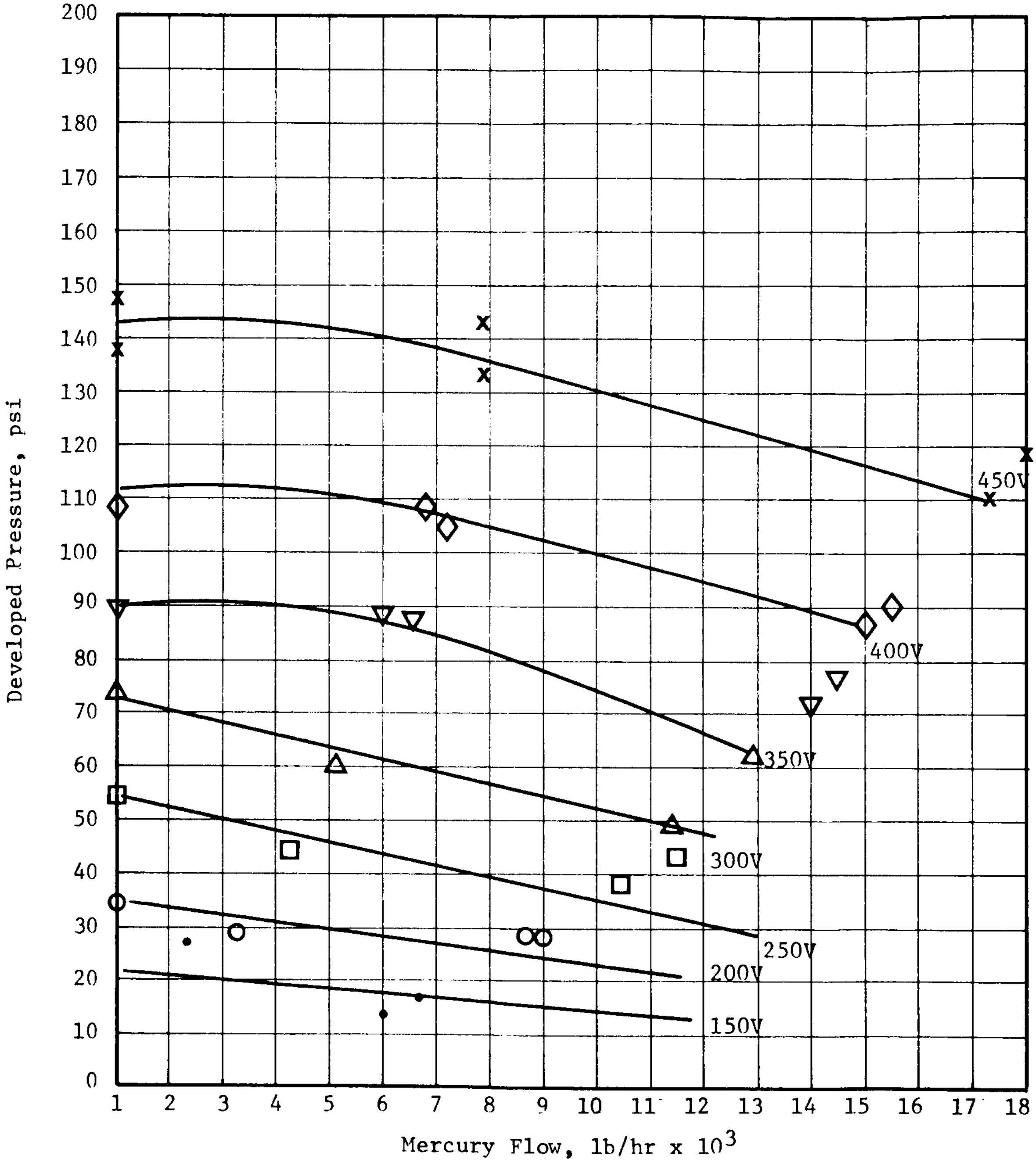

Figure 8. SNAP-8 Centrifugal EM Pump - Modification #1 - Developed Pressure Versus Flow at Several Voltages.

Concurrently, the facility was modified by removing the pump suction valve, installing a bypass valve around the orifice and the surge tank.

The developed pressure versus flow for this duct is shown in Figure 8. The conclusion is that axial baffles are detrimental to the pump's performance. However, an inspection of the raw data in the appendix shows that the pump duct axial temperature profile is much improved and that the negative suction pressure problem has been solved.

PUMP DUCT MODIFICATION NO. 2

For this test the duct was modified by removing the axial baffles, iron core and center stage from the pump duct as shown in Figure 9. The pump is now single stage with the flat plate and axial vanes located in the discharge cap.

The developed pressure versus flow for this duct at different voltages is shown in Figure 10. Compared to the previous duct performances this duct is a much better performer. It has been postulated that the addition of wetted surface in the pump increases the frictional pressure losses, thus off-setting any possible electrical gains due to the addition of the iron and the minimizing of secondary flows. In addition, the holes in the suction end of the pump internal to the duct as well as the holes in the center stage of the original configuration created significant hydraulic losses. Unfortunately, time did not permit the hydraulic testing of the duct to determine hydraulic losses.

PUMP DUCT MODIFICATION NO. 3

Pump duct modification No. 3 consisted of installing the iron core without the center stage in the pump duct. A spider consisting of 3-1/2-inch-diameter rods was attached at the suction end of the iron core for centering purposes and the end plate was welded to the 6-inch suction cap to promote duct drainability. This configuration is shown in Figure 11.

The performance results for this configuration are shown in Figure 12. However, the welding of the end plate and the spider installation might account for the poor performance.

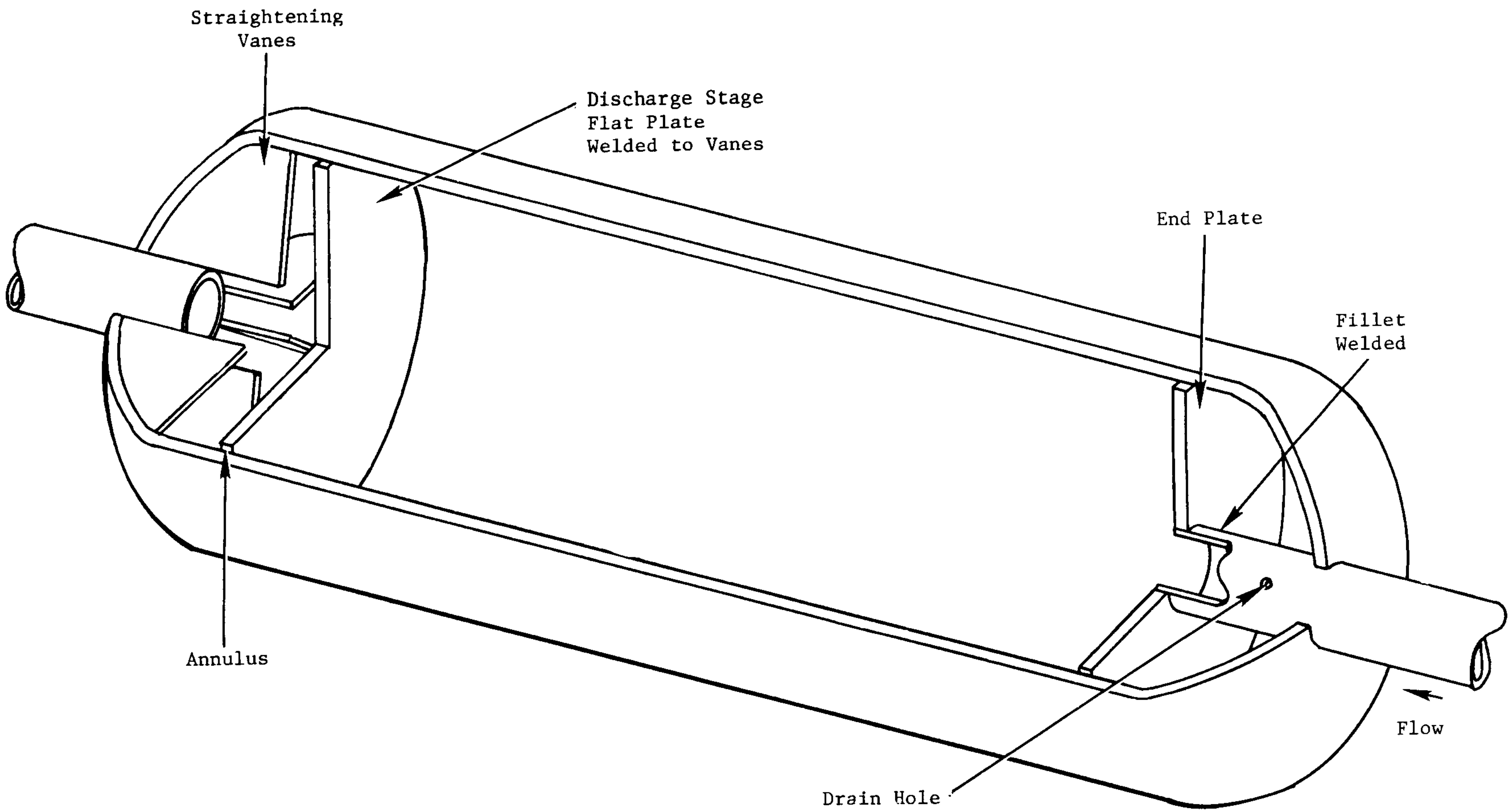

Figure 9. Pump Duct Modification No. 2.

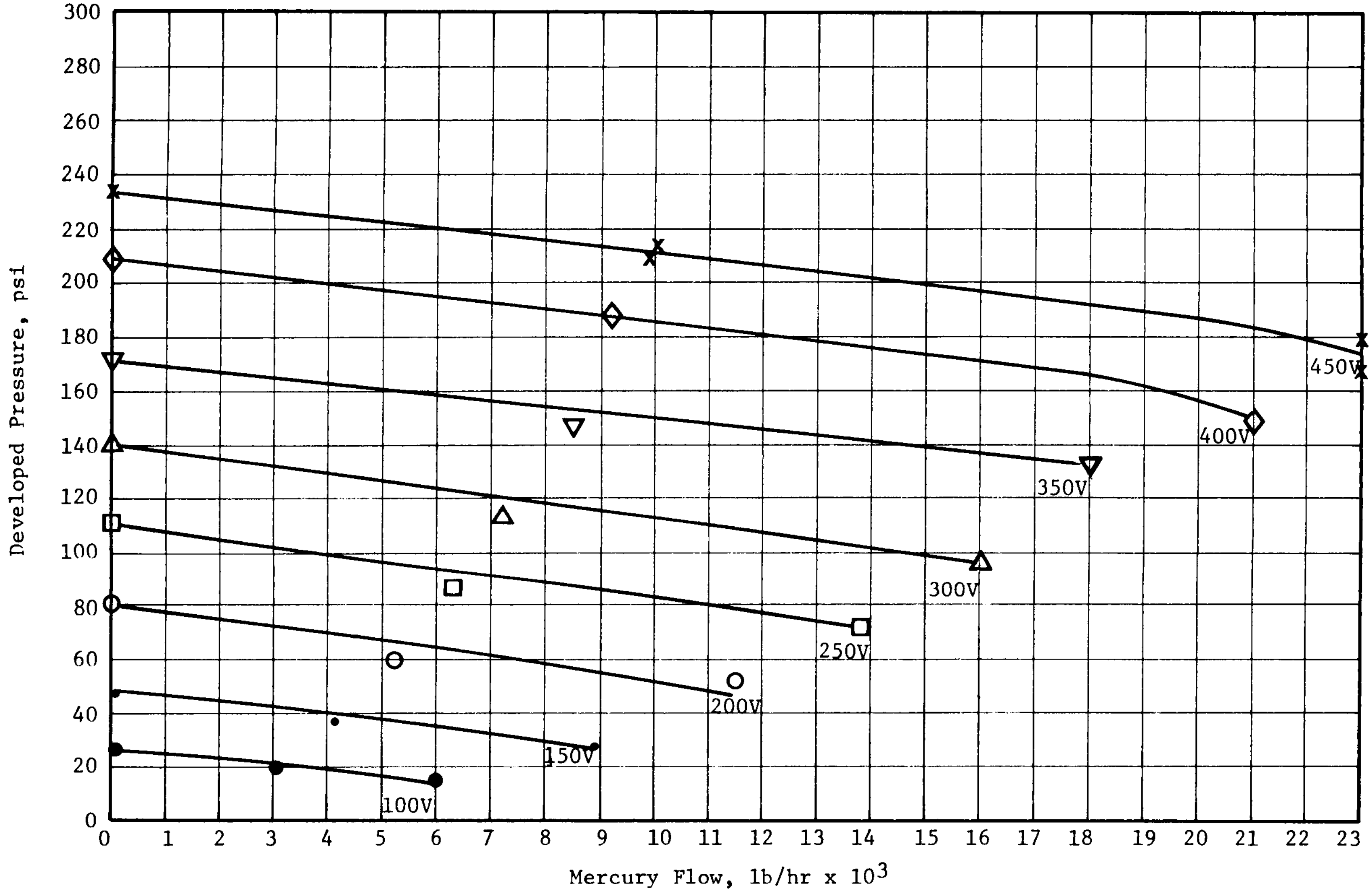

Figure 10. SNAP-8 Centrifugal EM Pump - Modification #2 - Developed Pressure Versus Flow at Several Voltages.

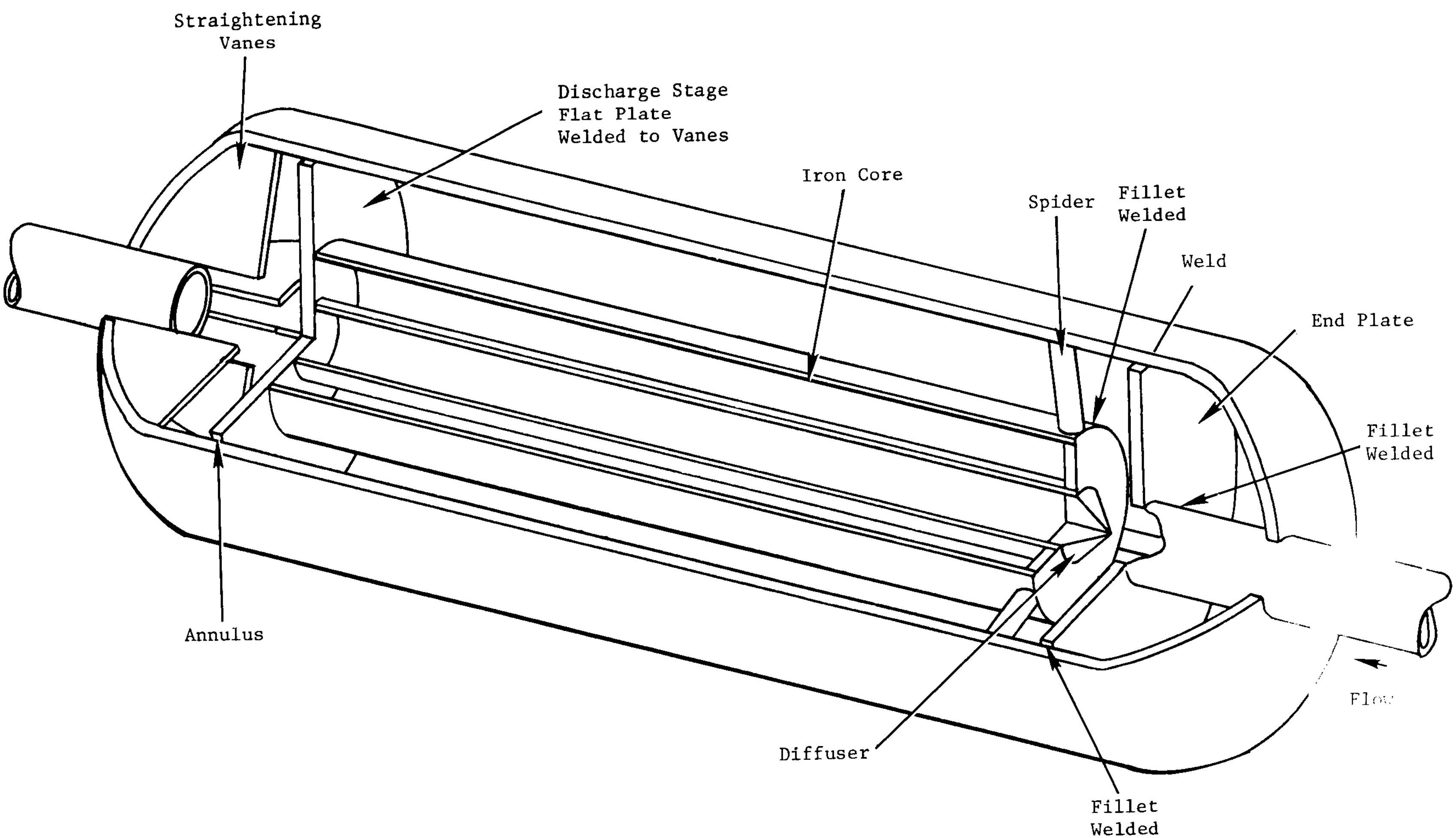

Figure 11. Pump Duct Modification No. 3.

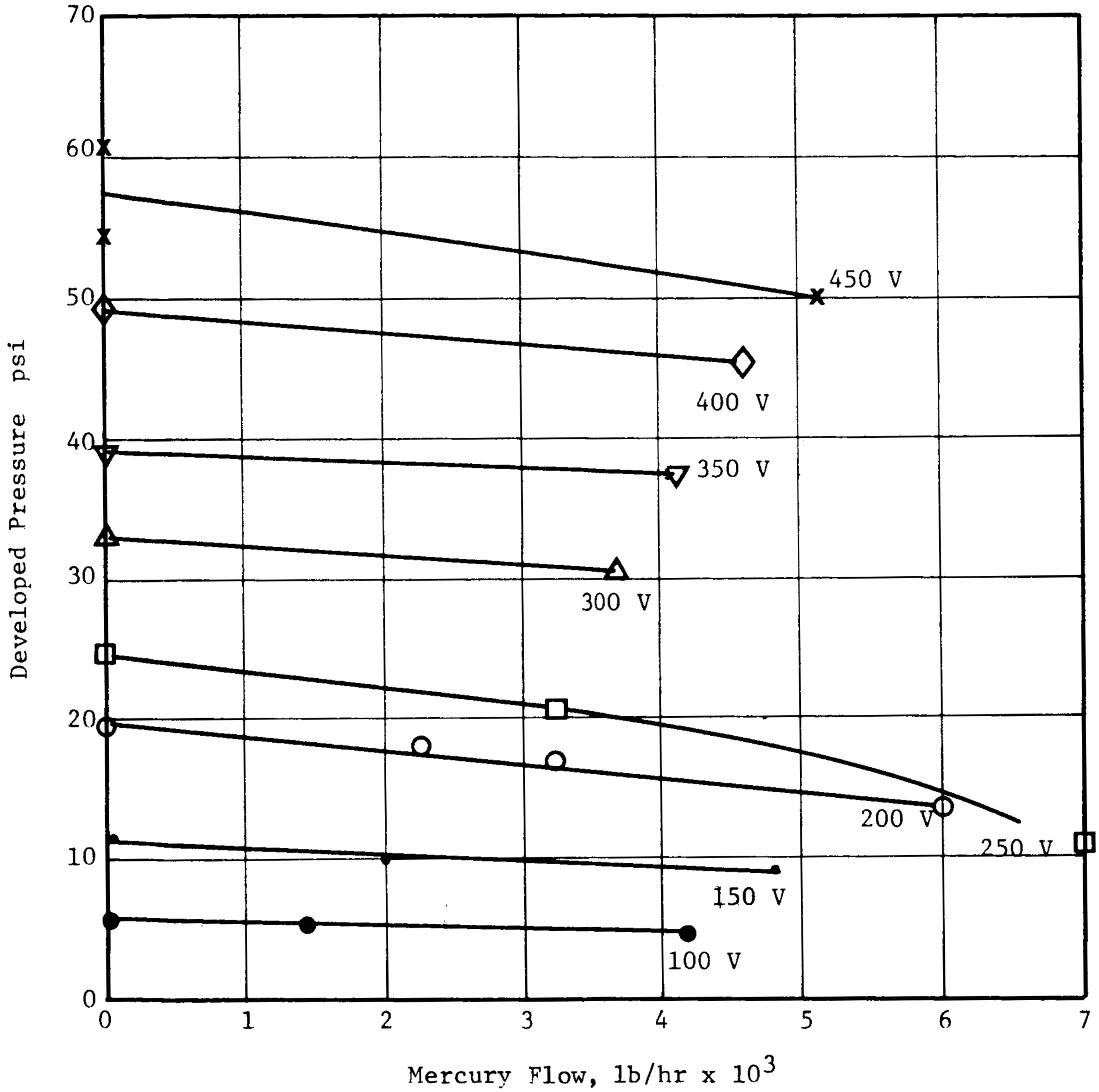

Figure 12. SNAP-8 Centrifugal EM Pump - Modification #3 - Developed Pressure Versus Flow at Several Voltages.

PUMP DUCT MODIFICATION NO. 3A

For this test the spider was removed and a new end plate installed and not welded to the end cap as shown in Figure 13. The results are shown in Figure 14 which indicate that the removal of the spider and the unwelding of the end plate greatly improved performance. However, when compared to modification No. 2 (Figure 10), it is postulated that the additional wetted surface within the pump duct offsets any electrical improvement made by the addition of the iron core. This is probably true only if the pumped fluid is non-wetting.

PUMP DUCT MODIFICATION NO. 4

Pump duct modification No. 4 consisted of installing two diffuser stages (Figure 15) into the 6-inch pipe. The diffusers were made from sections of 3-inch OD x 0.065-inch wall tubing 120° of arc, 1/4-inch wide. The gap at the periphery is 1/4 inch and the diameter of the orifice at the center is 1-1/2 inch.

The performance results for this configuration are shown in Figure 16. The poor results are probably due to the fact that the discharge impeller could not be welded against the vanes in the discharge cap, and the center orifice was too large. For this configuration, the three-phase connections were changed to reverse the electrical rotation of the field. It is interesting to note that the pump is insensitive to phase rotation.

PUMP DUCT MODIFICATION NO. 5

In pump duct modification No. 5 (Figure 17), the discharge impeller plate was replaced by the flat plate and the center stage orifice reduced from 1.5 inch to 1 inch diameter. The suction end plate was not welded to the suction end cap.

The performance data for this duct is shown in Figure 18. These data indicate the best performance yet but not near the necessary 530 psi at 12,500 lb/hr mercury flow.

PUMP DUCT MODIFICATION NO. 6

Pump duct No. 6 (Figure 19) is exactly the same as No. 5 with the exception of the elimination of the suction end plate to make the pump completely drainable.

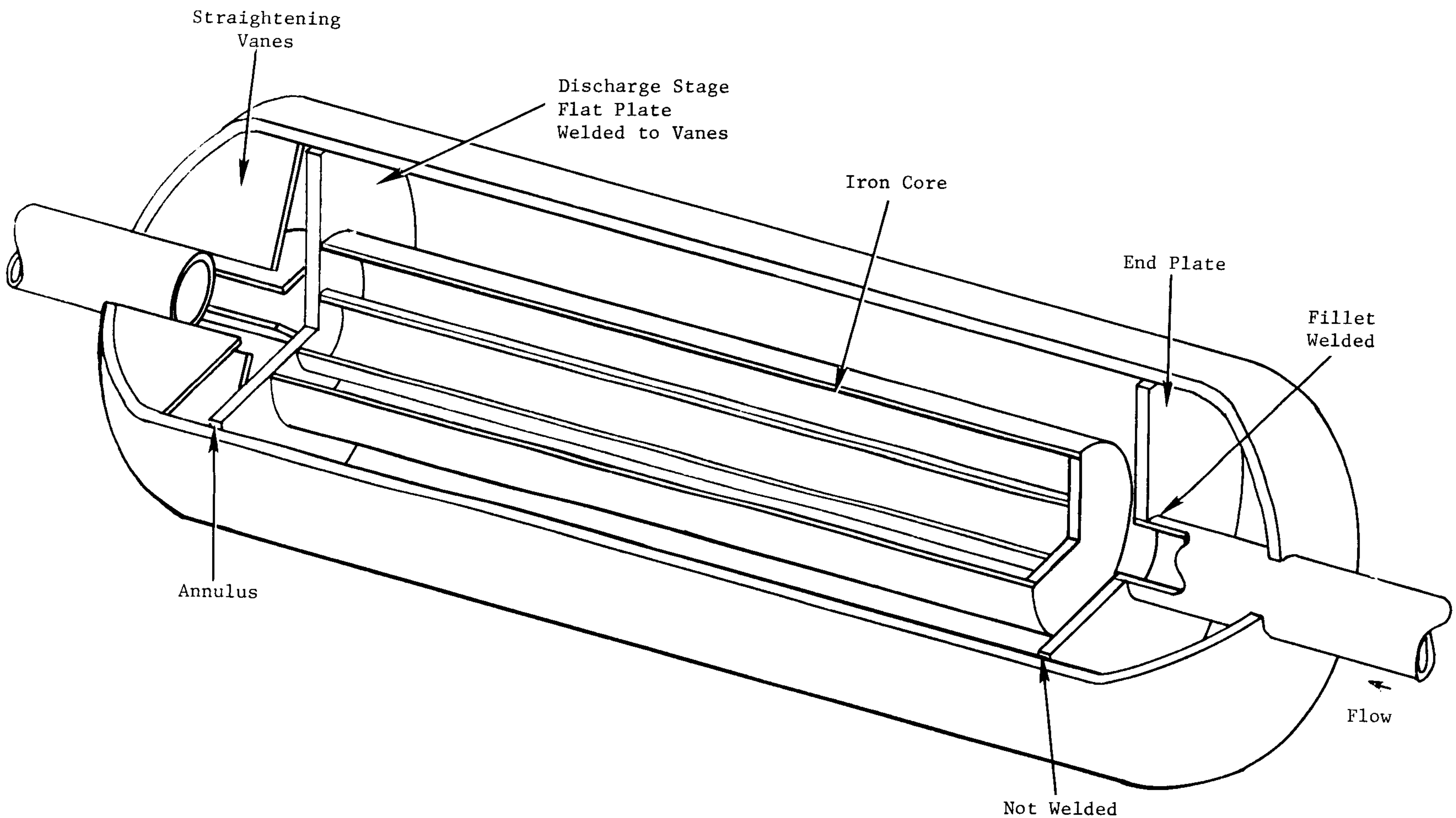

Figure 13. Pump Duct Modification No. 3A.

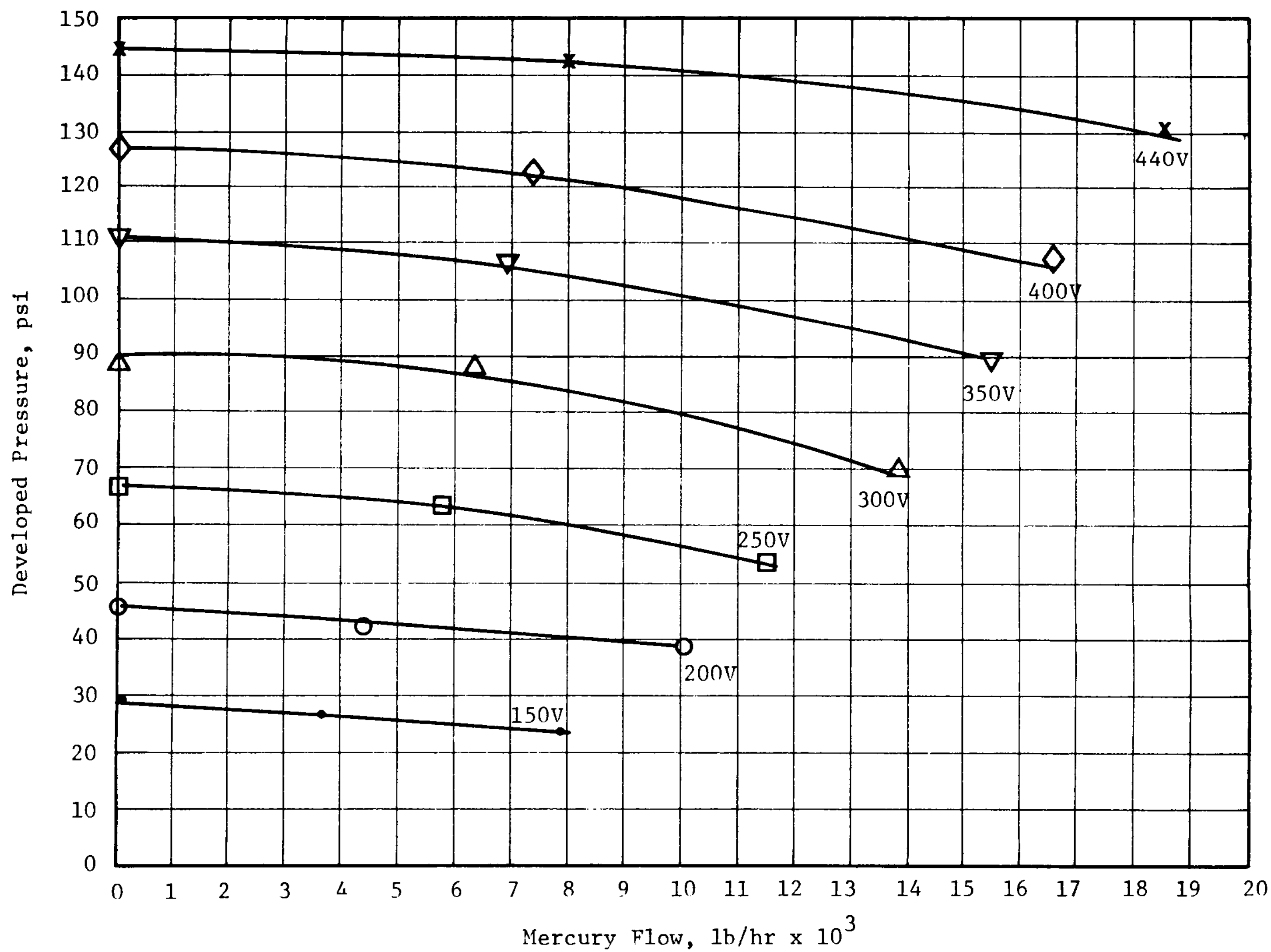

Figure 14. SNAP-8 Centrifugal EM Pump - Modification #3A - Developed Pressure Versus Flow at Several Voltages.

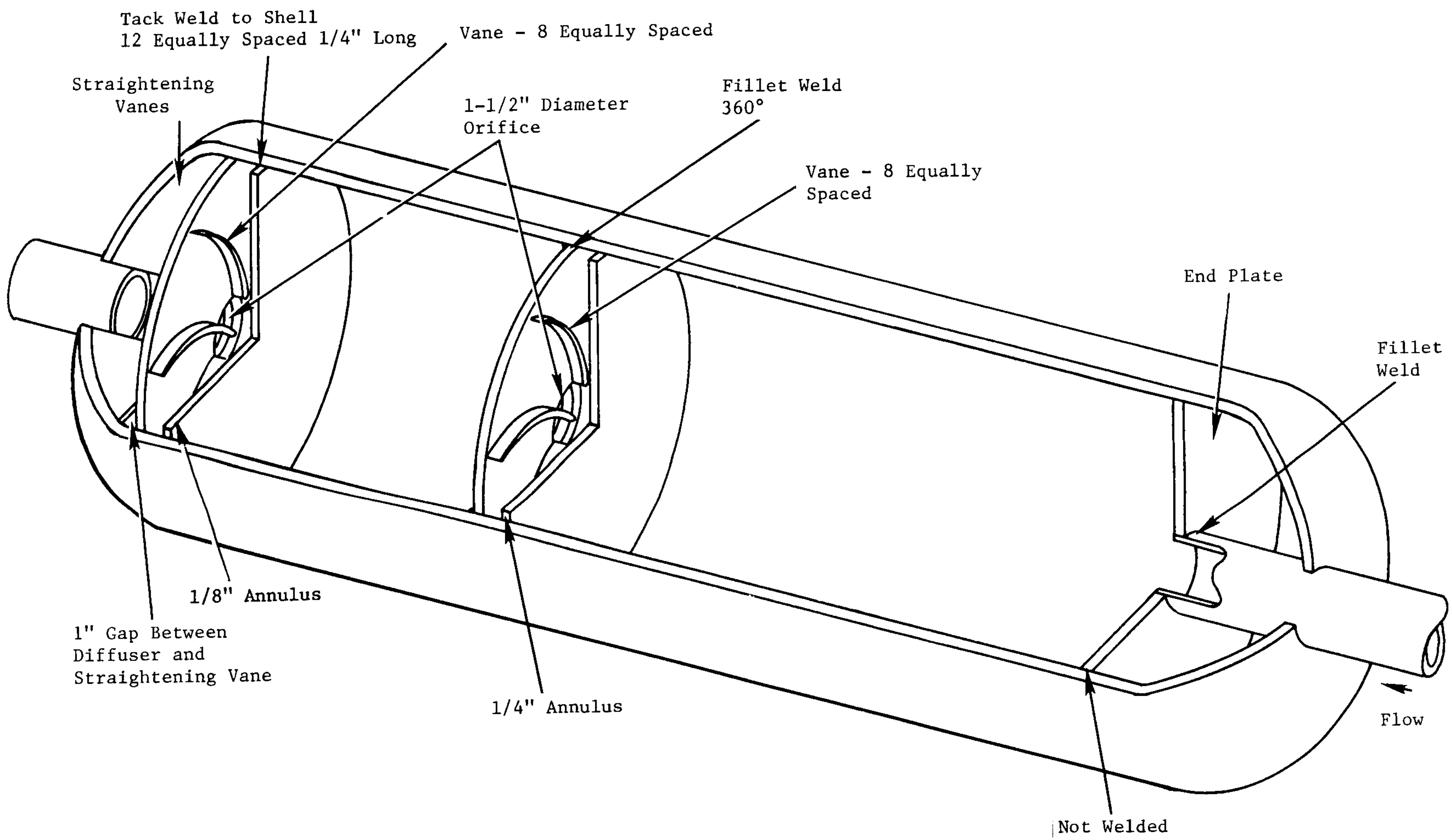

Figure 15. Modification No. 4.

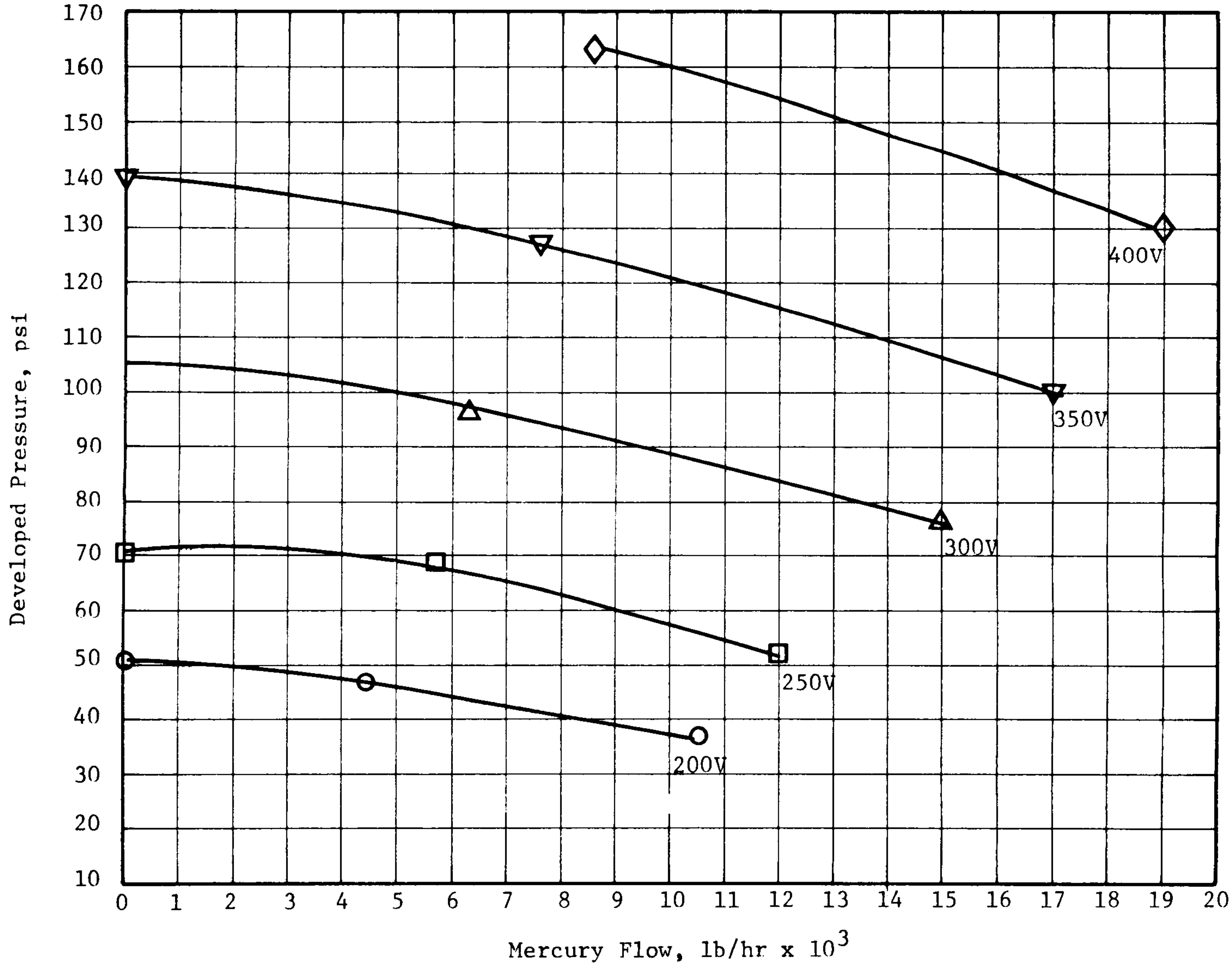

Figure 16. SNAP-8 Centrifugal EM Pump - Modification #4 - Developed Pressure Versus Flow at Several Voltages.

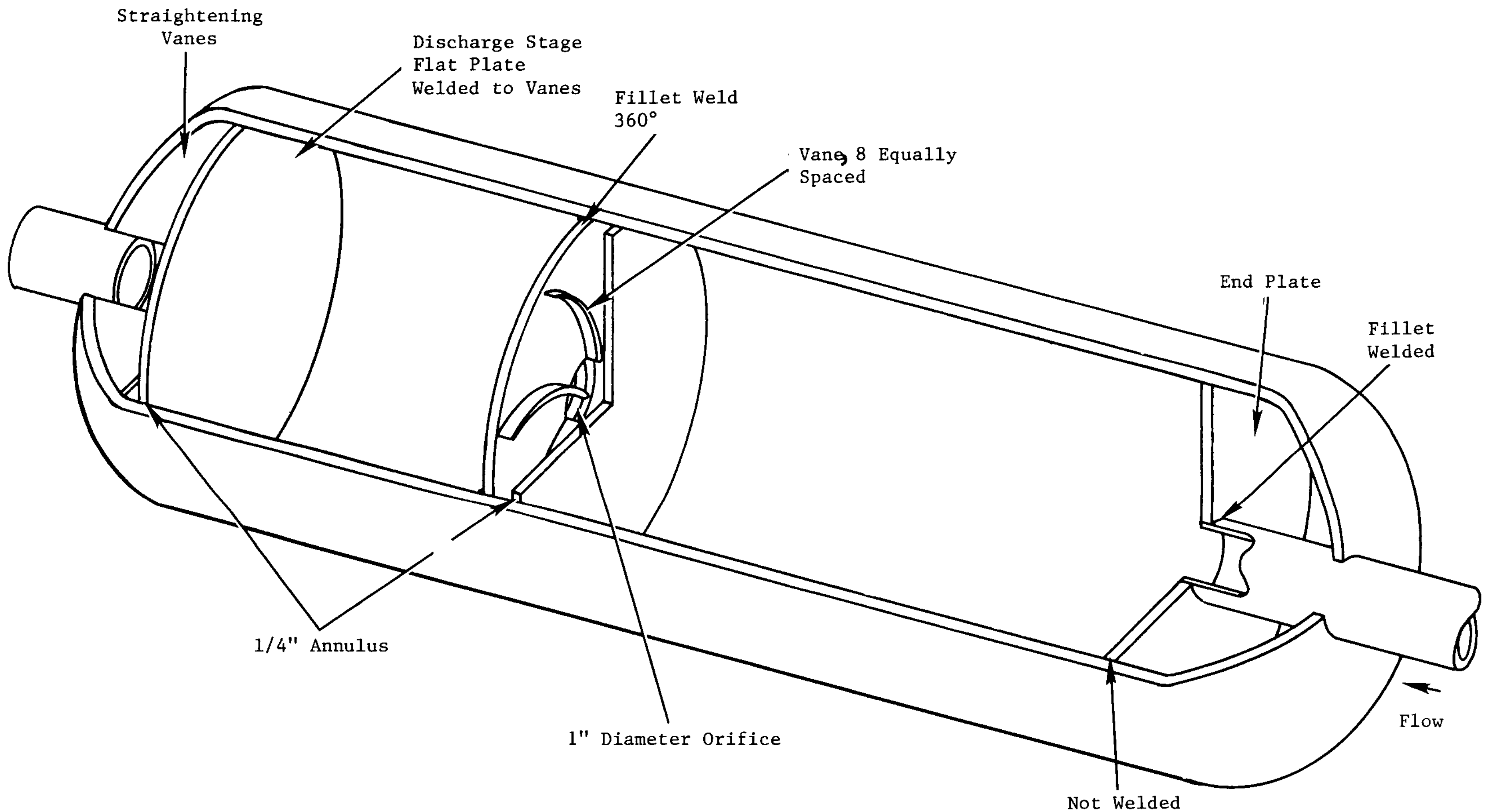

Figure 17. Pump Duct Modification No. 5.

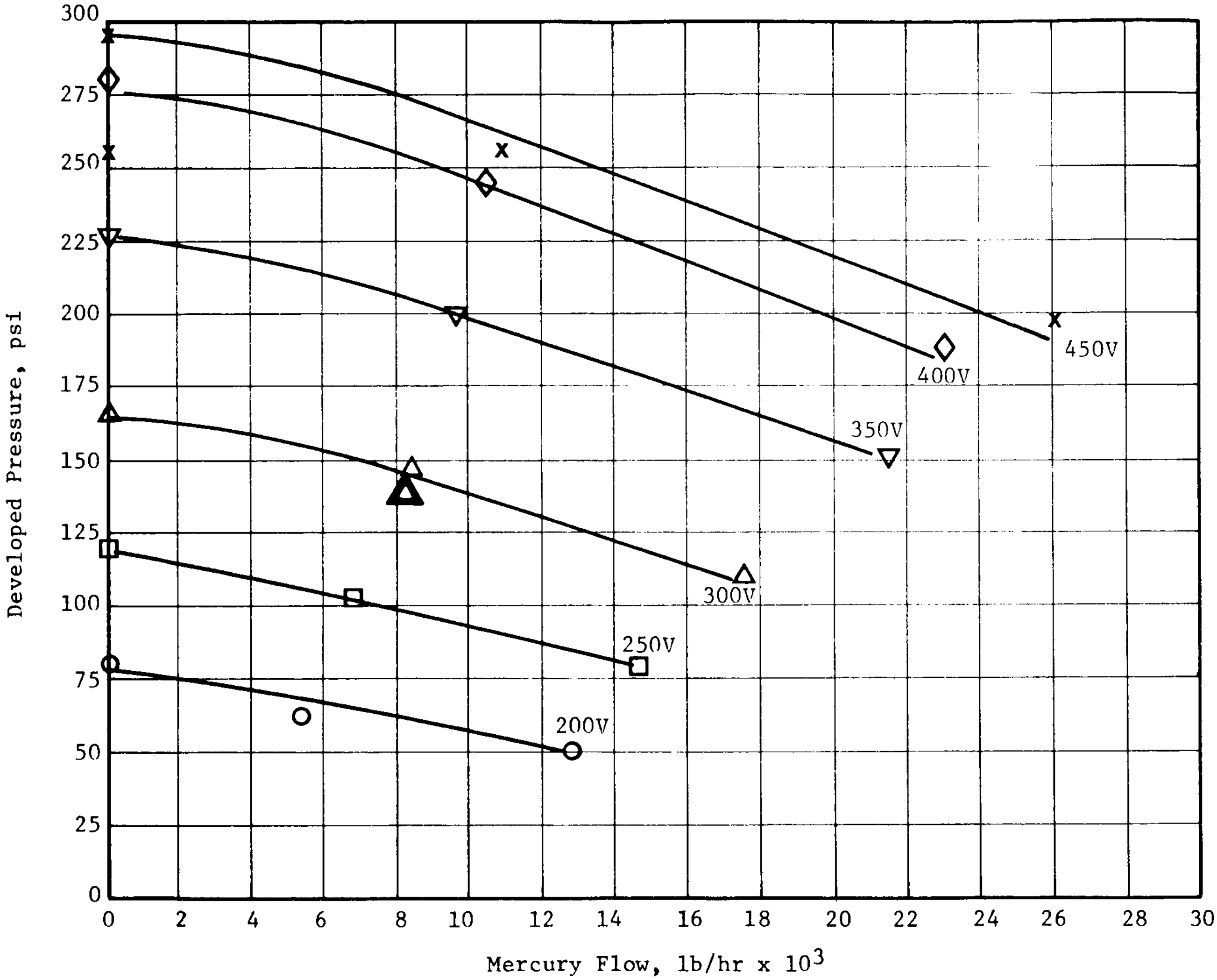

Figure 18. SNAP-8 Centrifugal EM Pump - Modification #5 - Developed Pressure Versus Flow at Several Voltages.

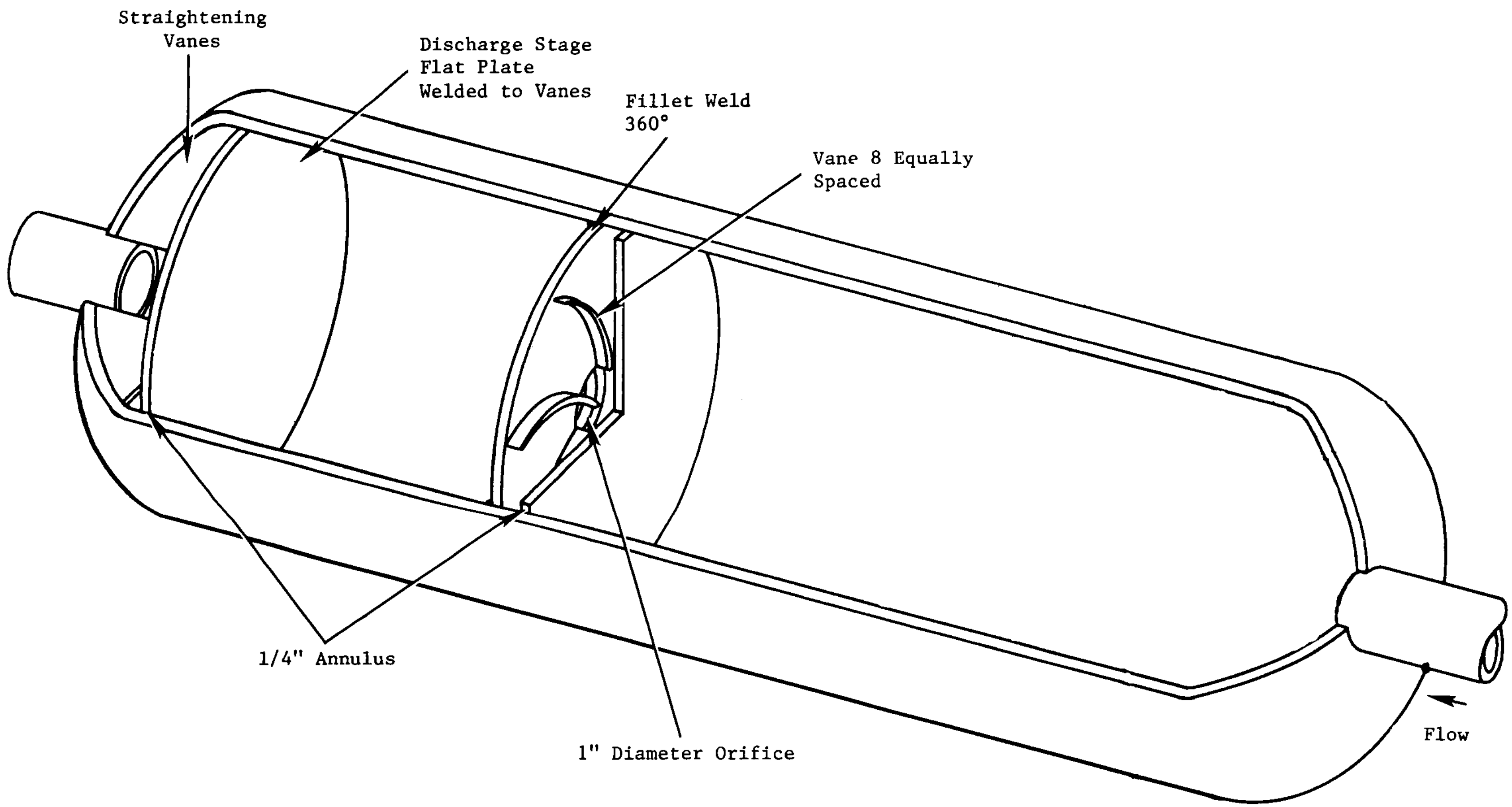

Figure 19. Pump Duct Modification No.6

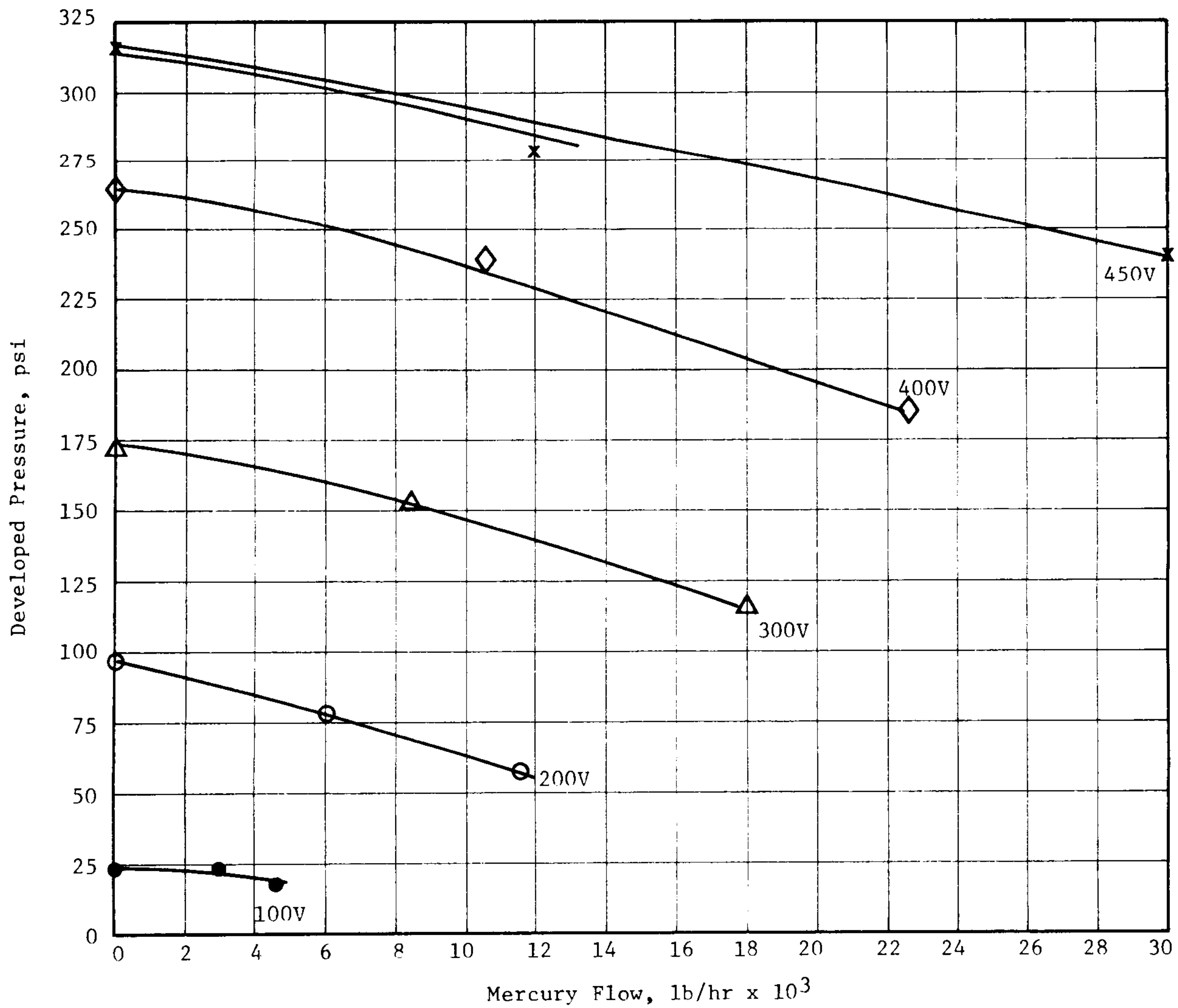

Figure 20. SNAP-8 Centrifugal EM Pump - Modification #6 - Developed Pressure Versus Flow at Several Voltages.

A comparison of the performance curve (Figure 20) with that of No. 5 (Figure 18) indicate no loss of performance without the end plate.

PUMP DUCT MODIFICATION NO. 7

At this stage in testing, the decision was made to test a three-stage duct with a large stator. The stator utilized is one scheduled for installation in the Boiler Development Test Facility and is described as follows:

Model No. 5KY416PL1 No. 8332944 Three phase, sixty cycle

The pump is rated at 160 gpm of NaK at 1400°F, 70 psi at 430 volts and 270 amperes. Power factor is 0.18. Along with the stator the power supply and capacitor banks were utilized to supply adequate power over the full range of interest.

The pump duct configuration is shown in Figure 21 and consists of two impeller type stages as used in modifications No. 5 and 6 and a flat plate welded to the straightening vanes in the discharge cap. The developed head versus flow curve is shown in Figure 22. The results from testing this configuration prove that a 500 psi mercury pump is feasible. However, the second stage of the test duct was deformed during testing.

The second set of data on this curve is to show the effect of the shift of the pump duct within the magnetic field. The duct was shifted 7/8 inch in the axial direction. The results were inconclusive.

PUMP DUCT MODIFICATION NO. 8

Pump duct modification No. 8, shown in Figure 23, is a three-stage pump similar to modification No. 7. The vanes were thickened to prevent deformation and the orifice diameter was changed from 1 inch to 3/4 inch diameter. The performance curve shown in Figure 24, shows an increase in performance when compared to pump modification No. 7.

PUMP MODIFICATION NO. 9

Pump modification No. 9 is similar to No. 7 except that the vanes are thickened and is similar to pump No. 8 except that the orifice diameter was increased to 1 inch diameter. This configuration is shown in figure 25. A comparison of performance curves for modifications 8 and 9 suggests a somewhat poorer performance for pump duct No. 9.

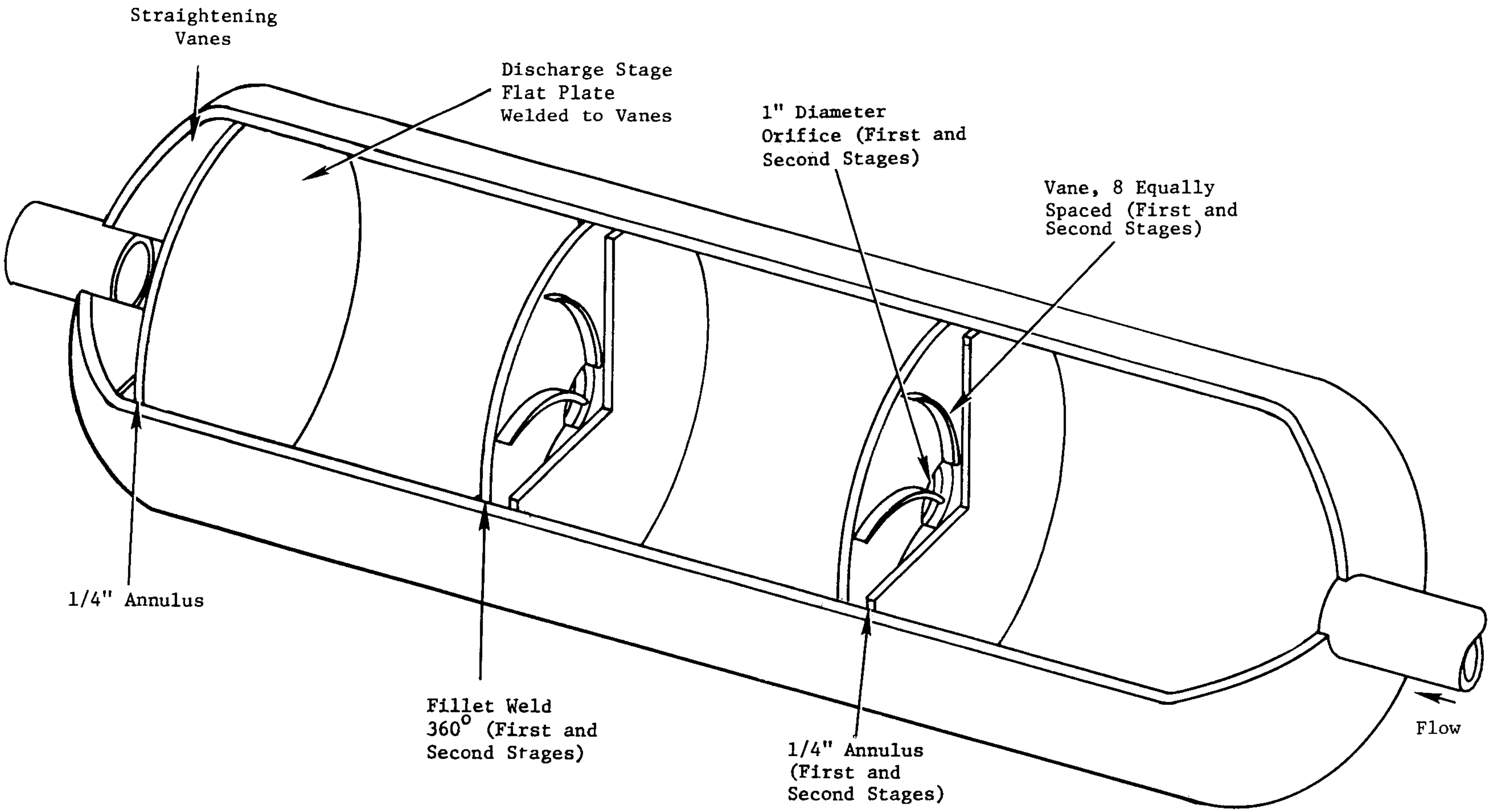

Figure 21. Pump Duct Modification No. 7.

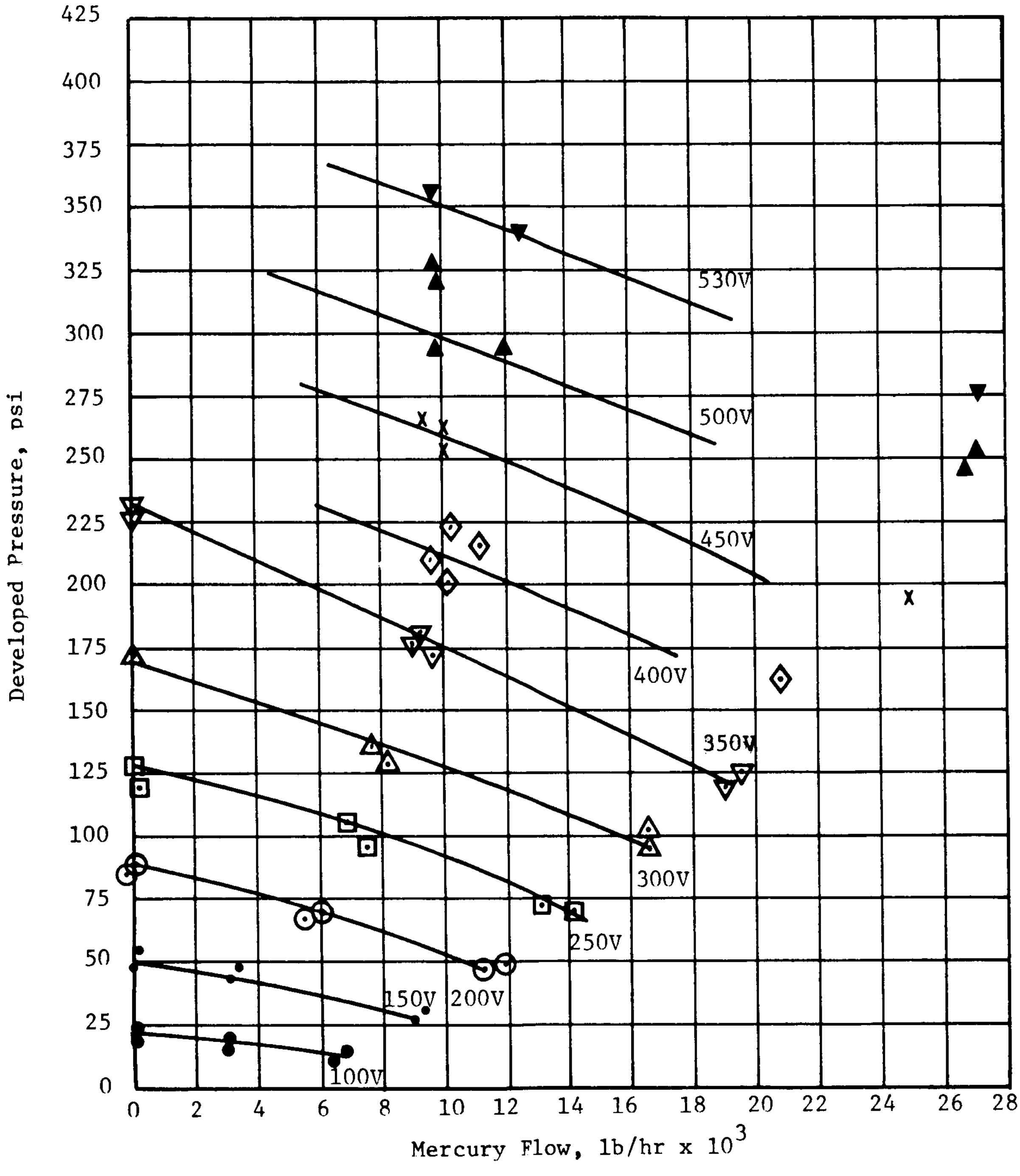

Figure 22. SNAP-8 Centrifugal EM Pump - Modification #7 - Developed Pressure Versus Flow at Several Voltages.

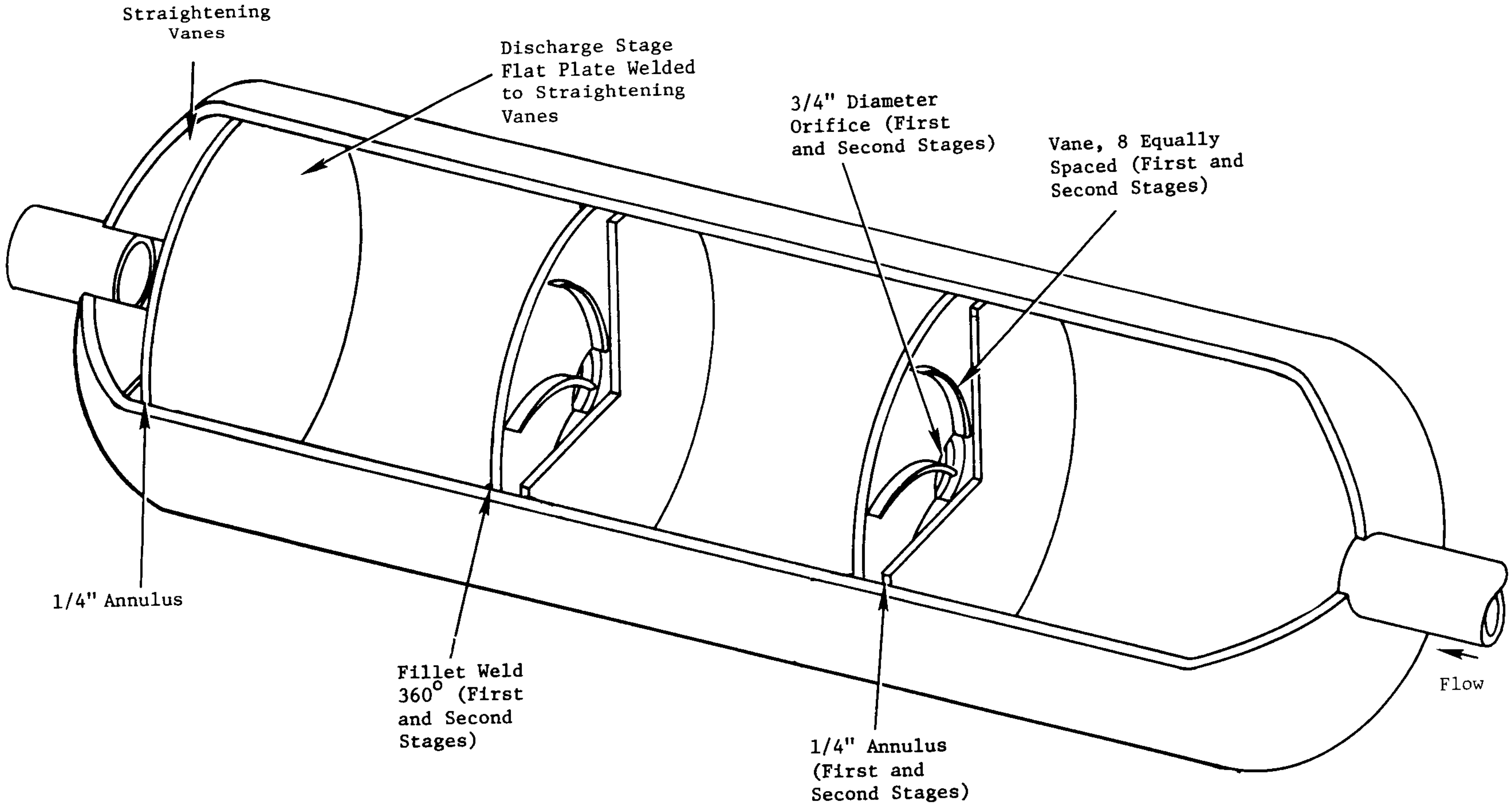

Figure 23. Pump Duct Modification No. 8

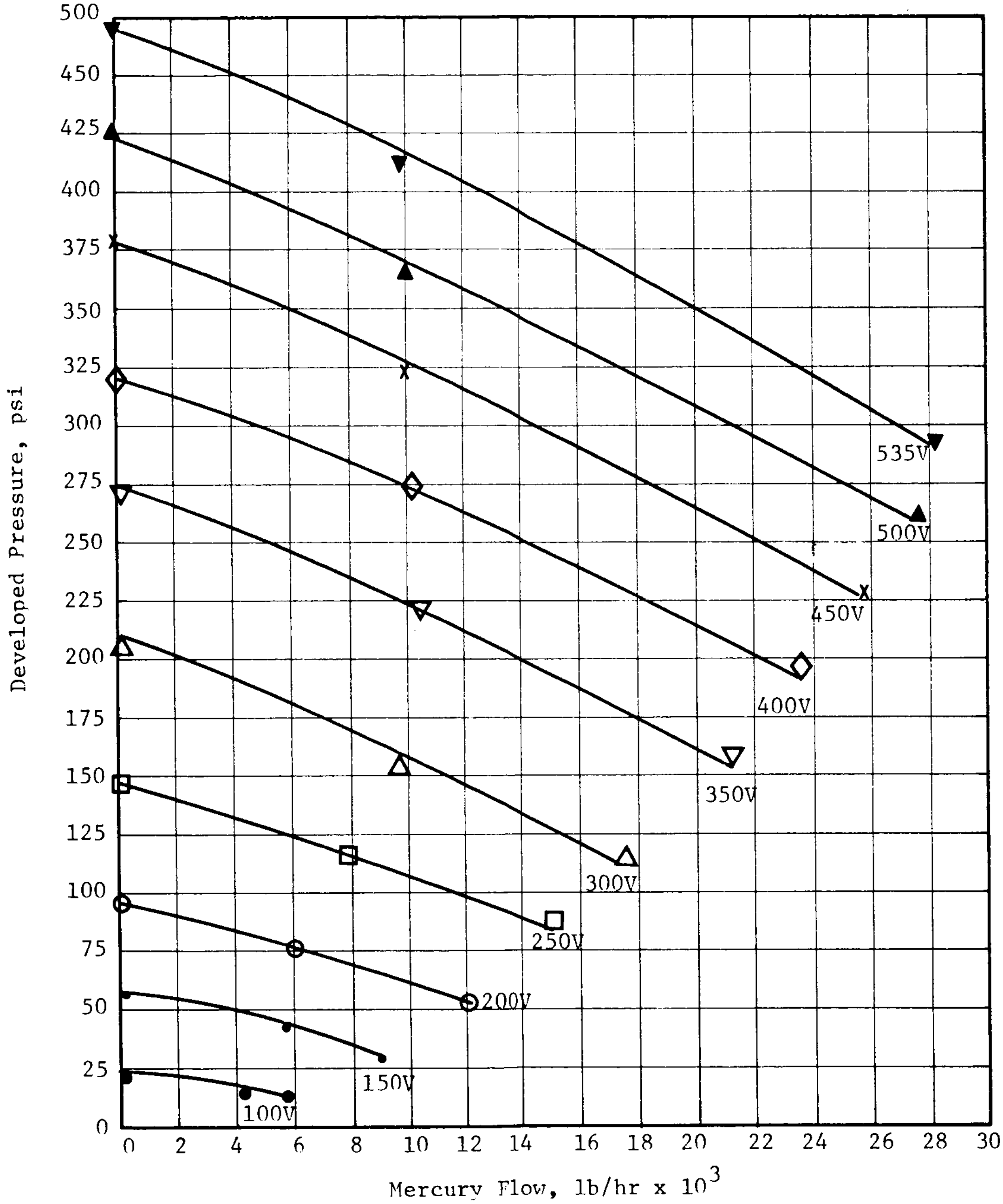

Figure 24. SNAP-8 Centrifugal EM Pump - Modification # 8 - Developed Pressure Versus Flow at Several Voltages.

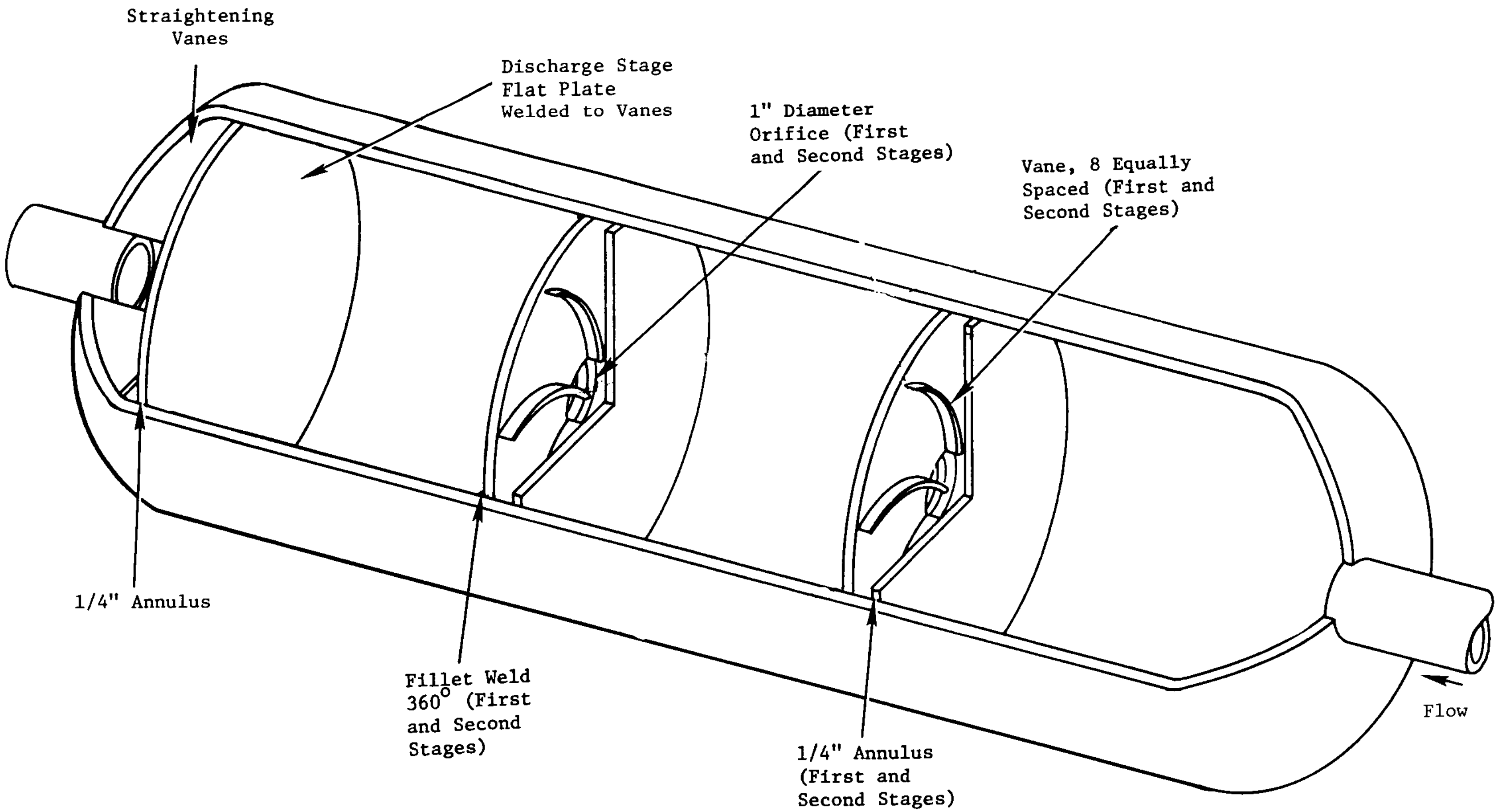

Figure 25. Pump Duct Modification No. 9

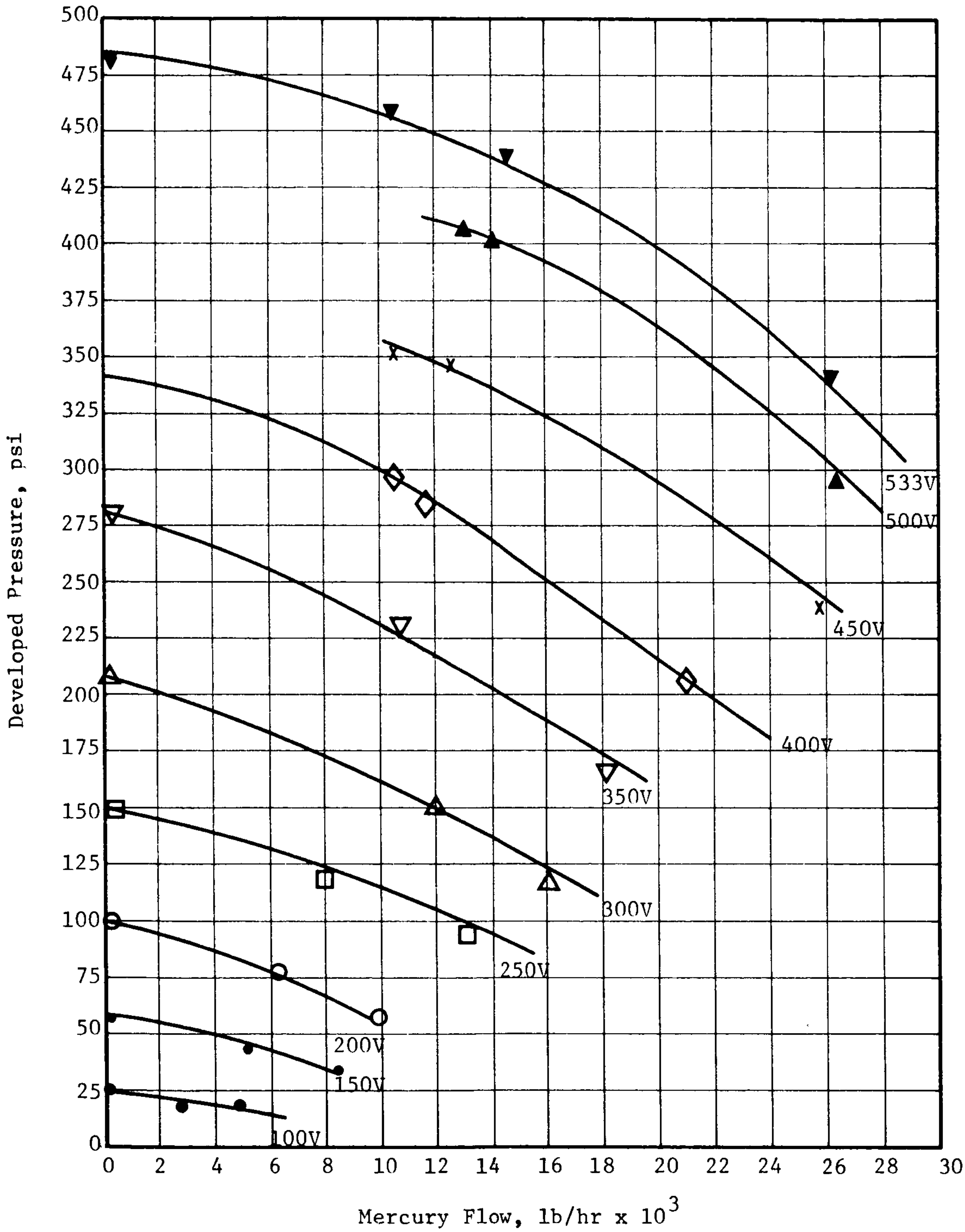

Figure 26. SNAP-8 Centrifugal EM Pump - Modification #9 - Developed Pressure Versus Flow at Several Voltages.

PUMP DUCT MODIFICATION NO. 10

Pump duct modification No. 10, shown in Figure 27, is a three-stage impeller type pump. An impeller was installed on the discharge end. The performance curve, shown in Figure 28, indicates that a current path must be provided for the current generated in the mercury. Therefore, a flat head is not desirable.

FINAL DUCT DESIGN

The final duct design is shown in Figure 29. The primary difference between this configuration and modification No. 9 is that the vanes have been reduced from 1/4 inch to 3/16 inch thickness.

CONCLUSIONS

Mercury can be pumped by the electromagnetic centrifugal principle. This indicates that problems of sealing and lubrication are eliminated and one of the sources of contamination of the refractory metal boiler being tested is eliminated. Pump performance could be improved with further studies on materials of duct construction which mercury would wet and possibly improving the hydraulic losses within the pump.

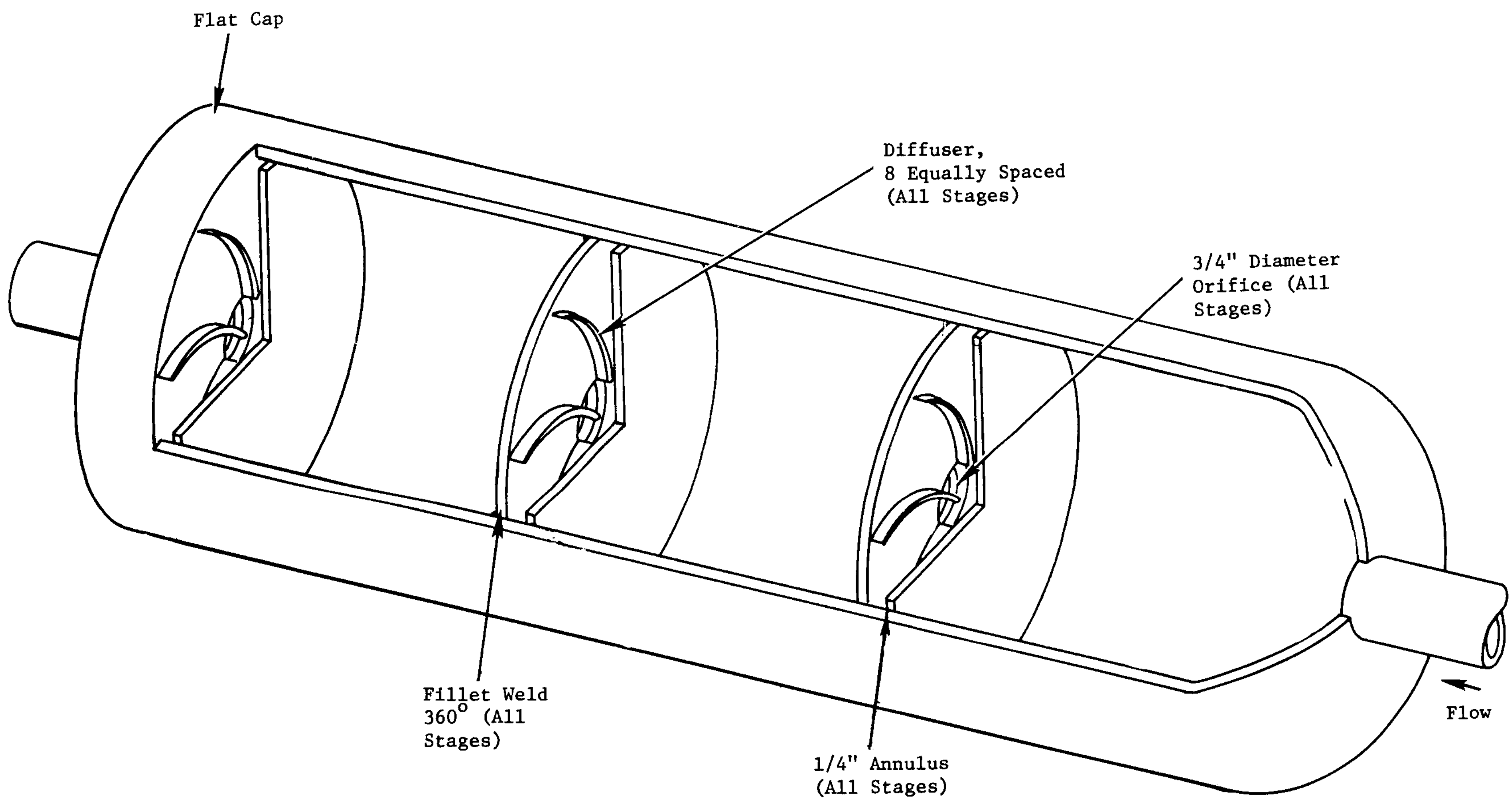

Figure 27. Pump Duct Modification No. 10

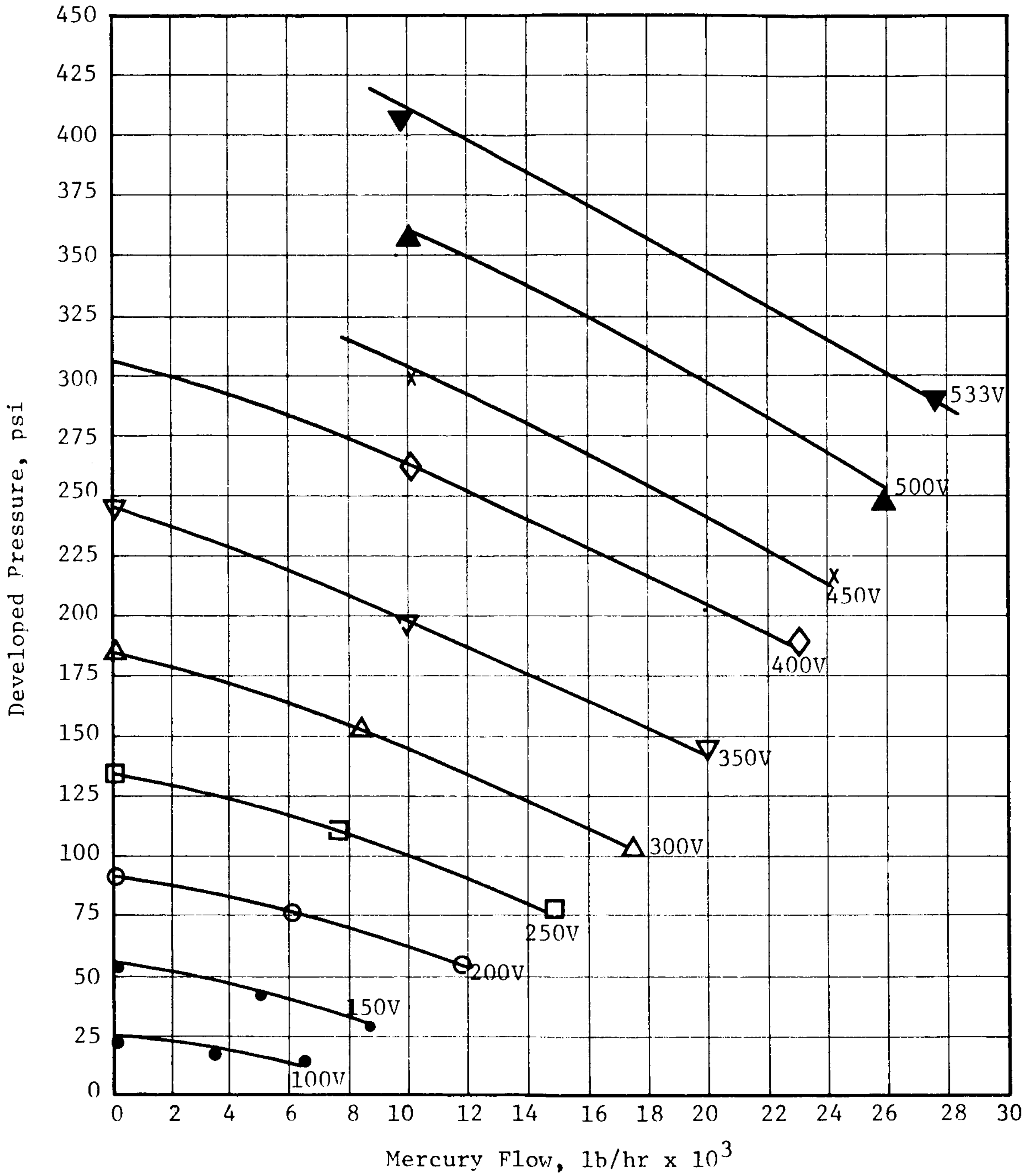

Figure 28. SNAP-8 Centrifugal EM Pump - Modification #10 - Developed Pressure Versus Flow at Several Voltages.

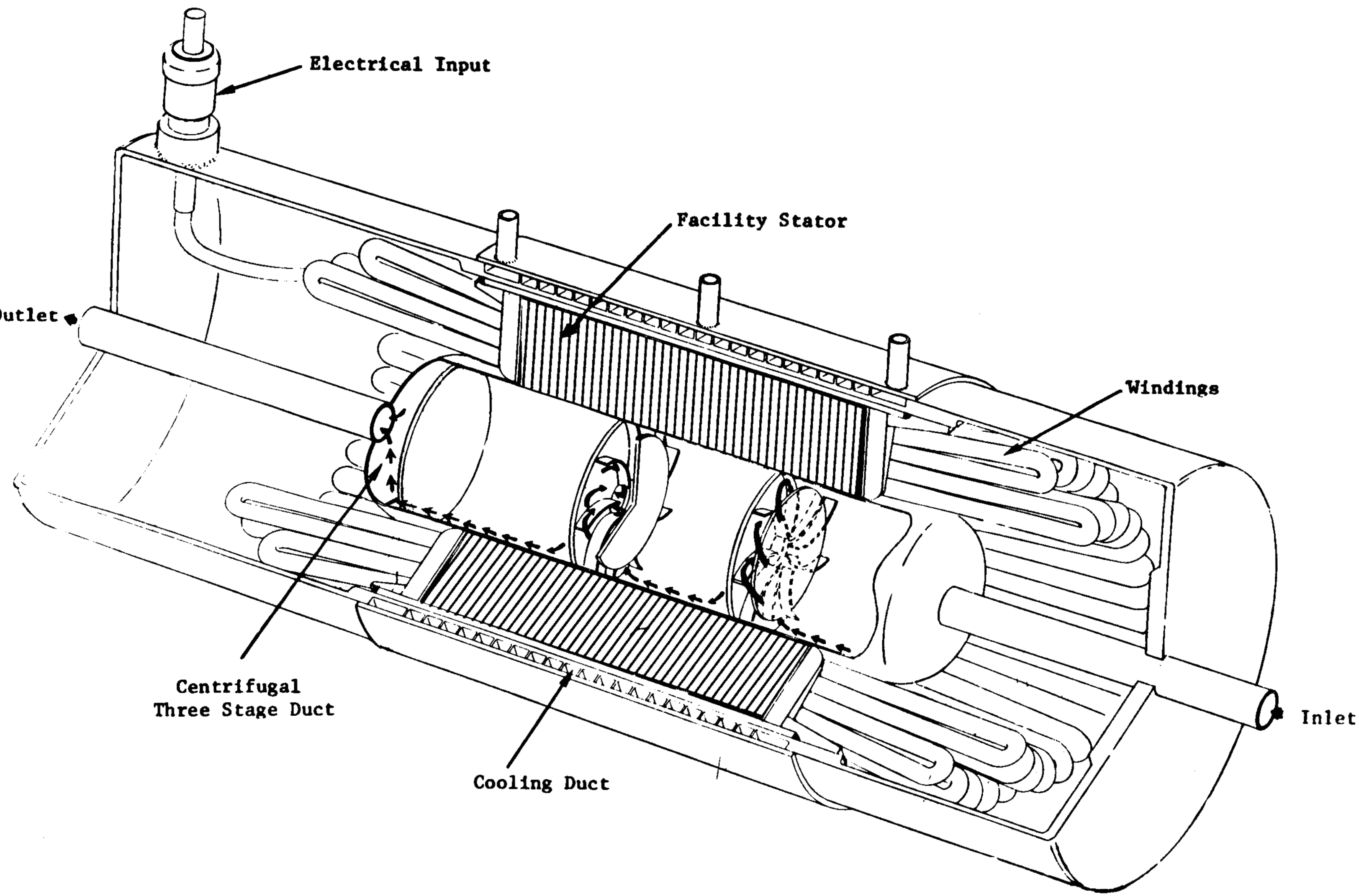

Figure 29. - Three stage mercury centrifugal EM pump.

V. ANALYSIS OF MERCURY EM PUMP LOSSES

The mercury EM pump has a very low efficiency (less than 1%). The major losses which can be identified include the following:

1. Pump duct wall eddy current loss
2. Mercury eddy current loss
3. Hydraulic losses
4. Pump winding I^2R loss
5. Pump core loss
6. Miscellaneous eddy current loss (largely in end regions of the pump containment vessel and enclosed mercury and stainless steel structure).

The recorded data for a typical test point, taken on the three stage 15-inch stator configuration, will be analyzed to determine an approximate distribution of the measured input power among the above-listed loss components.

1. Pump Design Data (Modification No. 9)

Stator stack ID	6.625 inch
Stator stack OD	16.72 inch
Stack length	15 inch
Slot depth	3.182 inch
Number of poles	2
Number of phases	3
Winding pitch	1.0
No. of slots	24
Winding type	Double layer
No. circuits in parallel	2
No. turns per coil	16
Conductor dimensions	10 strands (0.0571-in.-dia. wire)
Winding connection	delta

2. Pump Test Data (Modification No. 9)

Three stage pump pressure rise (shut off)	480 psi
Line voltage (phase voltage)	535 V
Line current	346 amps
Phase current	200 amps
Input power (3 phases)	86 KW

Note: Variation of measured electrical parameters with pump flow was found to be negligible.

VECTOR DIAGRAM

Figure 30 shows the pump vector diagram based on the measured data. The diagram applies to one of the two parallel circuits in each phase.

In Reference 5, pp. 226-235, it is shown that for a 2-pole stator with no inner magnetic structure the total flux crossing the non-magnetic space from pole to pole is given by:

$$\rho_p = 6.38 \text{ AL} \quad (1)$$

where A is the peak ampere turns per pole for a sinusoidally distributed mmf, and L is the stack length in inches.

It is also shown that for a 2-pole stator the flux density in the non-magnetic space is constant in magnitude and direction (directed along a line joining the pole centers) and of magnitude given by

$$B = \frac{3.19A}{R} \quad (2)$$

where R is the stator core inner radius.

The vector diagram of Figure 30 was determined by establishing consistency between the useful flux per pole as given by equation (1) above and the pump voltage equation relating the effective (air gap) voltage and the useful flux per pole. This equation is:

$$V = 4.44 \times f \times N \times K_d K_p \times \rho_p \times 10^{-8} \quad (3)$$

For the diagram of Figure 30, this equation becomes

$$\rho_p = \frac{224}{4.44 \times 60 \times 64 \times 0.96} \times 10^8$$

$$= 1.37 \times 10^6 \text{ lines}$$

VECTOR DIAGRAM

Figure 30 shows the pump vector diagram based on the measured data. The diagram applies to one of the two parallel circuits in each phase.

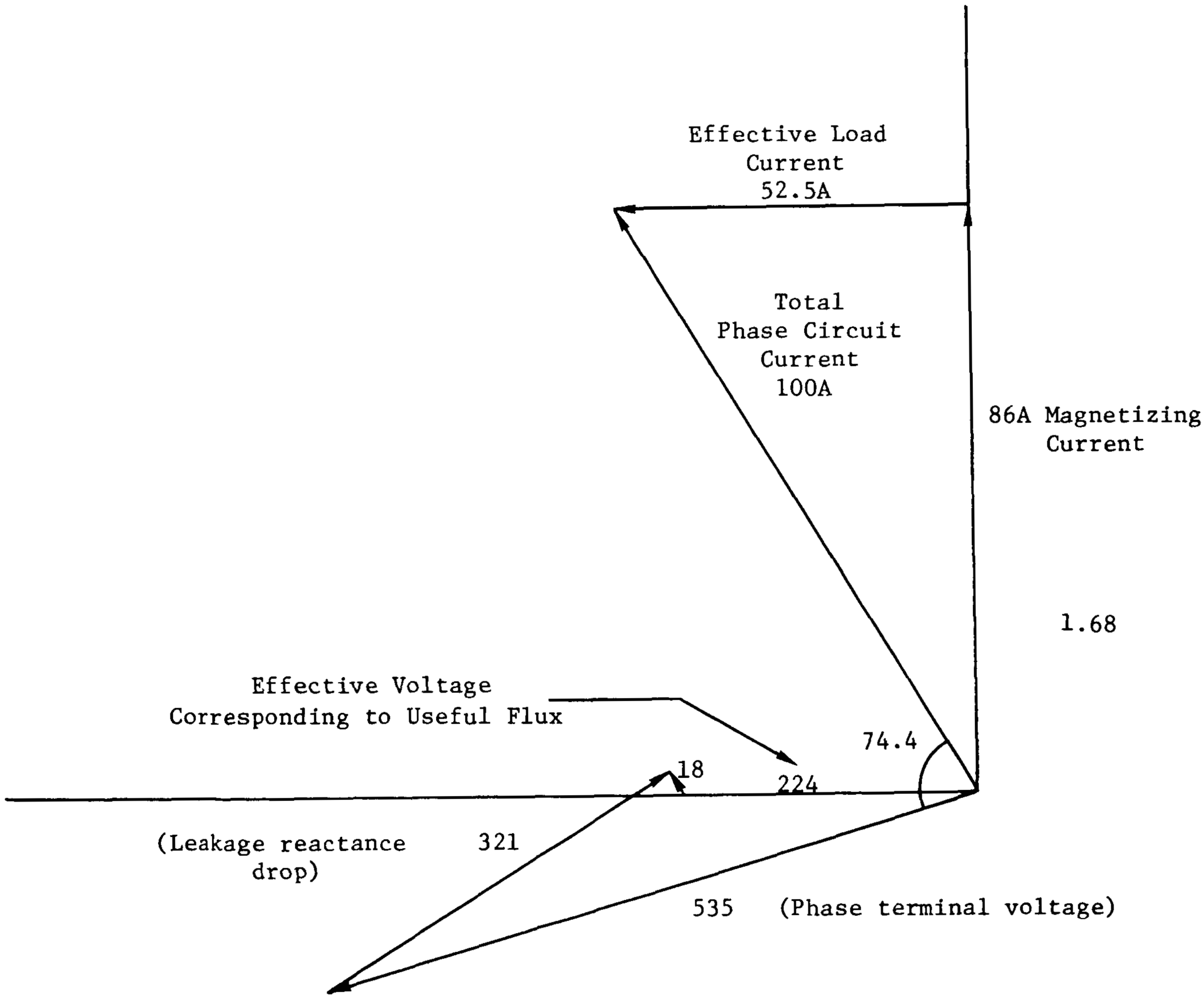

Figure 30. Pump Vector Diagram.

Consistency with equation (1) is shown as follows:

$$\rho_p = 6.38\ AL$$
$$= 6.38 \times 2.7 \times 64 \times 86 \times 0.96 \times 15$$
$$= 1.37 \times 10^6 \text{ lines}$$

A is given by the usual expression for peak fundamental ampere turns per pole,

$$A = 2.7 \times NI \times K_d K_p \tag{4}$$

where N is the turns in series per pole and I is the magnetizing component of the current carried by these turns.

The resistance of the portion of the winding correspondence to one of the two parallel circuits per phase can be calculated from the pump design data given above. This resistance is (approximately) 0.18 ohms. From this value the winding I^2R loss can be determined.

$$\text{Winding } I^2R \text{ loss} = 0.18 \times (100)^2 \times 2 \times 3$$
$$= \text{(approximately) } 11 \text{ KW}$$

Note: This includes only a minimal correction for armature winding skin effect, and may therefore be somewhat low.

The product of the effective voltage and the load current gives the sum of the losses occurring in the pump plus the pump output (which is, relatively speaking, negligible).

That is

$$\text{Loss} = 224 \times 52.5 \times 2 \times 3 = 70.5 \text{ KW} \tag{5}$$

This total includes the sum of the pump duct eddy current loss, the liquid metal eddy current loss, and the hydraulic loss. In order to break these losses down further, and also to further check the validity of the vector diagram, the duct wall loss and the liquid metal eddy current loss will be independently calculated.

DUCT WALL EDDY CURRENT LOSS

In Reference 6, it is shown that eddy current loss per unit volume due to a magnetic field of flux density B revolving through a solid piece of stationary metal is given by:

$$\text{Loss/unit volume} = \frac{B^2 r^2\ \omega^2\ \sin^2\theta}{\rho_c} \tag{6}$$

where r is the radius of the element, ω is the field angular velocity, B is the flux density, ρ_c is the duct wall resistivity and θ is the angle between the field direction and the direction of relative motion between field and metal element. Since the field is produced by a 2 pole 60 cps mmf, ω = 3600 rpm or = 378 radians/sec, B [from equations (2) and (4)], is 13,800 lines/sq.in., and ρ_c is estimated to be 37 x 10^{-6} ohm in., then total duct loss is given by the following expression:

$$\begin{aligned} \text{Duct Wall Loss} &= 2\int_0^{\pi} \frac{B^2 R^2\ \omega^2\ \sin^2\theta\ Rt\ L'd\theta}{\rho_c} \\ &= \frac{2\ B^2 R^3\ \omega^2\ tL'}{\rho_c}\int_0^{\pi} \sin^2\theta\ d\theta \end{aligned} \tag{7}$$

t is the thickness of the duct wall, and L' has been selected at the value 16 inch to allow for loss generated in the duct wall beyond the end of the stack. From (5) the duct wall loss is 30.5 KW.

LIQUID METAL EDDY CURRENT LOSS

The liquid metal eddy current loss can be calculated in a manner similar to the duct loss, starting from the expression for loss in a volume element. The angular velocity, ω, however, to be used in this calculation, will be the angular velocity of the field relative to the rotating liquid metal mass. It is assumed that the liquid metal rotates as a solid body. It is also assumed that the liquid metal angular velocity can be determined from the pressure rise per stage, calculated as the difference in liquid metal static pressure between the duct center and the duct peripnery. This calculation is as follows:

$$\frac{g}{\rho}\frac{dP}{dr} = r\ \omega^2$$

$$\Delta P = \frac{\rho}{g}\ \omega^2 \int_0^R r dr$$

For mercury ρ = 810 lb/ft^3

The pressure rise per stage, from the measured data, is $\frac{480}{3} = 160$ psi. Thus:

$$160 \times 144 = \frac{810}{32.2} \times \omega^2 \times \left(\frac{3.1}{0.2}\right)^2 \times \frac{1}{2}$$

$$\text{and } \omega = 166 \text{ radians/sec} = 1580 \text{ rpm}$$

The field angular velocity relative to the rotating liquid metal is 3600 - 1580 = 2020 rpm = 212 radians/sec. Referring to (6) the liquid metal eddy current loss given by

$$W_f = 2 \int_0^{\pi} \int_0^{R} \frac{B^2 r^3 \omega^2 \sin^2\theta \, L' dr d\theta}{\rho_f}$$

$$= \frac{B^2 \omega^2 \pi R^4 L'}{4 \rho_f}$$

substituting values for B, ω, R, L' (again 16 in.) and ρ_f (44×10^{-6} ohm in.), then:

$$W_f = 21.2 \text{ KW}$$

The hydraulic loss (plus the useful output) can now be calculated as the difference of the (7), and the sum of the liquid metal eddy current loss and the duct wall eddy current loss:

$$W_H = 70.5 - (21.2 + 30.5) = 18.8 \text{ KW}$$

STATOR CORE LOSS

From the stator core weight, the frequency, and estimated values of flux density in the stator teeth and back iron rising core loss curves versus flux density and frequency, the stator core loss is estimated at approximately 1.5 KW.

SUMMARY OF LOSS BREAKDOWN

Winding I^2R loss	11.0 KW
Stator Core loss	1.5 KW
Duct Wall loss	30.5 KW
Liquid Metal Eddy Current loss	21.2 KW
Hydraulic loss	18.8 KW
	83.0 KW
Total measures loss (from test data)	86 KW
Miscellaneous loss unaccounted for	3 KW

In view of the approximate nature of the calculations this appears to provide a satisfactory estimate of the pump loss distribution. The two losses most subject to reduction by design refinement are the duct wall loss (reducible by using a thinner duct of higher resistivity material) and the hydraulic loss.

REFERENCES

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APPENDIX A

ORIGINAL RECORDED DATA

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
Original Pump Configuration	115	1.42	.018	40	34	46	35	17.5	37.5	40	153	159	222	100	100	165	165	68	68	78									
				35	23	26	23	18.5	33.5	40																			
				45	18	23	18	18.3	39.0	40																			
	164	1.97	.035	45	26	31	26.5	19	26.5	40	157	162	210	100	100	155	157	85	91	78									
				51	40	44	40	17.5	32.5	40																			
				55	30	33	29	18	31.0	40																			
				62	20	23	18	18.5	39.5	40	210	220	278	105	103	175	95	65	78	78									
	210	2.52	.055	68	51	56	52	17.5	29.5	40	232	242	340	115	111	230	232	100	105	78									
				60	40	44	40	19	23.5	40																			
				55	30	35	32	19.5	19.5	40																			
				83	20	23	19.5	18.7	39.5	40																			
	404	4.71	.188	107	55	58	55	23.5	0	42																			
				175	158	158	158	16	25	42	418	520	692	138	132	365	400	145	-	78									
				200	20	23	20	19.5	40	42																			
	301	3.55	.107	115	102	112	102	15.5	31.8	42	425	442	653	170	160	400	403	122	130	79									
				101	80	84	80	17	21.5	42																			
				80	42	47	43	21	3.5	42																			
				132	20	24	20	19.5	40	42																			
	0	0	0	26	20	24	20	19.5	39.5	41																			
Modification # 1	160	2.05	.028	37	20	24	20	3.3	24.5	26				85	85	155	160	70	70	-	-	143	125	175	180	180	185	-	-
	200	2.55	.045	38	30	33	30	2.8	24.5	26				87	85	172	190	75	75	-	80	164	210	215	217	220	220	-	-
	250	3.15	.065	51	40	46	43	1.2	24.5	26				90	85	210	225	85	85	-	80	190	250	255	260	260	260	-	-
	300	3.73	.100	70	60	63	60	1.0	24.5	26.5				95	90	270	290	100	100	-	80	235	320	325	325	330	330	335	-
	350	4.30	.133	95	75	83	79	0.5	24.5	26.5				105	100	350	370	120	125	-	80	290	400	400	410	408	412	414	-
	400	4.85	.175	115	100	105	102	1.0	24.5	26.5				115	110	405	430	145	150	-	80	330	463	457	473	470	476	480	-
	450	195	.225	150	133	143	132	0	24.5	27				133	125	495	525	168	170	-	80	395	555	550	570	568	564	580	-
	450	195	.225	160	0	5	6.0	6.0	26	27				-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	450	220	.235	135	58	62	58	10	22.5	27				172	163	351	370	210	235	-	80	317	417	410	420	420	425	-	-
	400	4.85	.183	105	45	50	46	8.5	23	27				180	170	385	398	210	385	-	80	320	405	400	410	410	412	412	-
	350	4.30	.137	85	35	40	37	8.5	23.5	27				185	175	382	397	220	380	-	80	315	375	382	390	388	392	390	-
	300	3.75	.105	62	30	33	30	7	24	27				184	180	345	340	170	190	-	80	272	330	338	344	343	345	344	-
	250	3.18	.073	52	22	25	22	6.5	24.5	27				180	180	322	315	147	165	-	80	243	293	305	310	310	312	310	-
	200	2.56	.045	40	15	20	16	5.7	24.5	27				178	175	292	280	145	140	-	80	214	252	268	273	273	275	273	-
	150	1.90	.025	25	10	15	11	5.1	24.8	27				172	172	240	251	109	112	-	80	185	215	234	236	236	240	240	-

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
Modification #1	150	1.60	.028	27	12	15	11	4	23.5	26	-	-	-	80	78	110	119	78	80	-	78	100	120	-	127	130	130	130	130
	200	2.15	.050	40	18	21	16	5	23.5	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	250	2.70	.078	55	25	27	23	5	23	25.5	-	-	-	88	82	168	188	109	115	-	150	195	-	202	209	209	209	210	210
	300	3.23	.110	74	32	33	30	6	23	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	350	3.75	.145	90	40	42	37	7	22.5	25.5	-	-	-	101	91	267	291	160	175	-	78	215	302	-	312	322	322	326	326
	400	4.27	.187	100	47	50	45	7.5	23	26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	450	4.82	.232	125	55	58	54	9	22.5	26	-	-	-	150	125	387	410	225	250	-	78	337	405	-	420	435	435	-	-
	150			30				4.5																					
	200			45				4.5																					
	250			65				4.5																					
	300			85				4.5																					
	350			95	90	93	88	2	25	26	-	-	-	130	119	340	372	120	125	-	78	268	387	-	400	415	415	419	420
	350			100	-	-	-	5	-	-																			
	400			115	110	110	113	4	25	26.5																			
	400			120	-	-	-	5.5	-	-																			
	450			140	125	131	126	1.5	25	26.5	-	-	-	155	136	500	530	168	177	-	78	365	535	-	550	577	570	575	575
	450			150	-	-	-	6	-	-																			
Modification #2	102	1.15	.01	24	10	13	9	2.5	23	24.5	-	-	-	88	81	155	150	85	90	-	78	133	130	145	145	143	143	135	133
	102	1.15	.01	28	20	24	20	1.8	23.2	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	102	1.15	.01	35	0	0	0	2.7	23.2	24.5	-	-	-	88	82	121	85	67	70	-	78	122	122	128	128	130	130	130	130
	151	1.68	.02	38	15	18	15	3.6	22.5	24.5	-	-	-	90	85	125	125	85	90	-	78	115	115	128	128	128	128	125	126
	150	1.68	.02	47	36	41	37	0	23.2	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	150	1.69	.02	55	0	0	0	2.9	23.5	24.5	-	-	-	92	85	125	90	69	75	-	78	140	140	147	145	150	150	149	150
	200	2.30	.036	60	25	28	24	5.0	22.0	25	-	-	-	96	89	147	148	100	105	-	78	142	140	156	155	156	155	154	156
	202	2.28	.038	70	60	65	60	0	23.0	24.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	204	2.30	.039	88	0	0	0	3.1	23.5	24.5	-	-	-	105	95	155	95	72	86	-	79	190	192	200	198	205	205	203	206
	252	2.86	.060	80	33	37	33	5.5	22.0	24.5	-	-	-	107	98	195	196	122	133	-	79	185	181	203	200	203	201	200	201
	253	2.87	.058	98	85	88	85	0	23.5	24.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	255	2.88	.060	118	0	0	6	3.5	23.5	25	-	-	-	115	102	210	163	75	102	-	79	255	260	272	265	270	278	278	282
	300	3.42	.080	105	42	47	43	6.0	21.5	25	-	-	-	125	109	251	253	150	167	-	79	235	231	259	255	257	255	252	255
	304	3.45	.083	125	110	113	109	0.5	23.5	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	307	3.48	.085	148	0	0	6	3.6	24.0	25	-	-	-	138	125	255	105	78	120	-	78	340	345	247	349	365	365	364	370
	353	4.20	.110	137	55	60	55	8.5	21.5	25	-	-	-	143	125	250	260	165	179	-	79	250	250	275	272	275	275	273	278
	350	4.20	.110	155	140	145	140	5.0	27.5	29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	350	4.20	.110	180	0	12	7	7.5	28.0	29	-	-	-	150	130	263	122	82	78	-	79	340	352	360	351	370	370	370	376
	400	190	.138	158	66	73	67	13.5	24.5	29	-	-	-	169	145	319	320	195	215	-	78	310	305	335	330	335	332	330	335
	400	190	.138	185	175	175	-	7.5	30	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	400	190	.138	215	12	15	-	11	31.5	33	-	-	-	175	150	318	170	100	150	-	78	367	385	390	385	400	400	400	400

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
Modification #2				190	80	85	-	17.5	27.5	32	-	-	-	158	153	235	266	171	188	-	78	278	278	298	295	302	302	302	305
				220	200	205	-	5	30	32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
				250	10	15	-	11.5	30	32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	443	212	.185	200	90	90	-	18	27.5	32	-	-	-	102	105	150	200	136	146	-	78	238	242	242	245	258	262	263	268
	445	212	.175	225	205	210	-	6	30	32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	445	210	.170	250	12	15	-	11.5	30	33	-	-	-	126	120	278	145	95	140	-	78	420	435	435	410	450	455	455	465
M dification #3	0	0	0	10	0	8	5	4.5	25	26.5	-	-	-	80	80	87	62	61	78	-	83	78	80	80	80	80	80	80	80
	100	1.34	.014	15	10	10	6	4.8	25	26.5	-	-	-	88	88	102	105	67	68	-	83	112	110	110	110	110	112	113	113
	100	1.35	.014	15	10	12	9	4.5	25	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	100	1.35	.013	16	0	8	5	4.8	25	26.5	-	-	-	90	89	109	85	62	68	-	83	131	127	128	125	129	130	130	130
	15C	2.01	.030	20	10	13	9	5.2	25	27	-	-	-	95	91	142	150	71	82	-	82	160	155	161	160	160	160	162	162
	150	2.01	.030	20	15	17	13	4.5	25.5	27	-	-	-	99	93	155	160	67	70	-	83	189	180	187	185	186	188	189	189
	151	2.03	.030	22	0	8	5	5	25.5	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	202	2.66	.050	25	12	15	11	5.7	25.5	27	-	-	-	112	109	223	228	102	107	-	85	235	225	237	236	235	235	236	236
	202	2.66	.050	27	20	24	20	4.5	25.5	27	-	-	-	119	110	225	226	75	85	-	85	260	250	260	260	260	260	262	263
	205	2.69	.051	30	0	9	5	5.2	25	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	435	-	235	72	0	10	5	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	200	2.62	.050	29	20	24	20	5	26.5	28	-	-	-	140	130	350	400	105	105	-	88	490	-	-	-	-	-	-	-
	433	210*	.230	60	55	60	55	4.5	26	38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	438	205*	.228	72	10	15	11	11	30	33	-	-	-	172	140	480	530	110	100	-	88	600	575	610	610	612	615	605	610
	400	4.8	.175	60	50	57	51	9.5	31	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	404	4.85	.178	65	12	15	12	11	31	33	-	-	-	200	155	585	595	105	107	-	85	620	585	630	625	625	625	615	620
	350	4.27	.135	52	43	48	44	9.5	31.5	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	347	4.25	.133	55	12	15	11	11	31.5	33	-	-	-	220	160	575	575	100	100	-	85	580	550	590	585	585	585	585	585
	300	3.73	.100	45	36	41	37	9.5	31.5	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	296	3.70	.099	49	10	15	11	11	33	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	249	3.17	.072	36	20	24	19	11	32	33	-	-	-	225	170	505	460	156	168	-	87	430	400	440	433	430	430	425	423
	242	3.13	.070	40	30	33	30	9.8	31.5	33	-	-	-	220	170	408	400	90	100	-	88	418	397	418	397	418	418	417	417
	245	3.15	.071	40	10	15	11	10.5	31	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Modification #3-A	155	2.02	.028	35	15	18	14	5.5	24.5	27	-	-	-	112	111	152	152	90	100	-	90	175	152	161	160	160	161	161	161
	152	2.02	.028	37	27	32	28	2.1	25	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	153	2.03	.028	40	0	8	5	4.6	25	27	-	-	-	111	111	153	95	72	75	-	85	200	190	191	190	192	195	195	195
	200	2.60	.046	49	20	25	20	5.5	24.5	27	-	-	-	115	115	185	190	108	115	-	90	210	188	200	199	198	198	195	195
	200	2.60	.046	52	42	47	42	3.5	25.5	27	-	-	-	117	115	193	200	80	82	-	83	232	218	223	225	225	227	229	230
	202	2.64	.049	57	0	8	3	4.8	25.2	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	250	3.23	.074	66	26	32	27	6.2	24.0	27	-	-	-	120	118	230	232	129	140	-	85	263	233	245	243	243	249	245	245
	253	3.25	.074	73	60	72	61	3.0	25.0	27	-	-	-	122	120	240	250	93	100	-	90	292	272	280	282	280	285	285	287
	259	3.30	.076	78	0	8	3	5.0	25.0	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
Modification #3-A	300	3.78	.100	84	38	41	35	8.2	23	26.5	-	-	-	140	138	290	290	165	175	-	95	345	295	305	305	309	309	305	312
	305	3.82	.105	95	80	86	81	1.0	25.5	27	-	-	-	148	145	300	320	115	120	-	87	372	342	352	352	352	352	357	360
	310	3.86	.107	100	0	8	5	5.2	25.5	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	349	4.30	.135	105	45	48	44	9.0	23.5	27	-	-	-	158	140	357	355	195	215	-	88	407	350	370	365	365	369	367	369
	355	4.35	.140	115	99	102	98	3.0	25.5	27	-	-	-	165	146	325	400	139	149	-	89	450	413	430	429	430	433	433	437
	363	4.40	.145	122	0	8	5	5.5	25.5	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	395	4.77	.173	122	50	57	51	10	23.5	27.5	-	-	-	189	160	400	400	215	240	-	88	465	392	412	410	410	412	412	412
	398	4.80	.175	134	115	120	115	6	25.5	27.5	-	-	-	195	166	400	430	150	160	-	85	515	470	488	488	489	492	493	497
	410	4.85	.180	138	0	10	6	6	25.5	27.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	440	200*	.220	142	60	65	60	6.5	23	27.5	-	-	-	215	180	450	448	240	272	-	89	520	445	468	463	468	468	468	469
	440	200*	.220	150	135	138	130	2.5	25	27.5	-	-	-	230	190	465	505	172	180	-	90	575	530	550	550	550	553	553	558
	443	200*	.220	155	0	11	7	6.2	25.5	27.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Modification #4	200	2.69	.035	49	18	22	18	5.5	24.5	26	-	-	-	115	109	152	155	99	103	-	90	191	135	163	162	160	162	162	162
	200	2.69	.035	55	40	43	40	1.5	25	26	-	-	-	115	110	155	157	78	80	-	90	200	150	175	172	172	175	175	175
	200	2.70	.035	62	0	8	5	4.5	25	26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	250	3.39	.055	65	25	29	26	6.2	24	26.5	-	-	-	119	112	180	185	112	121	-	90	228	160	198	195	192	195	198	197
	250	3.40	.055	76	60	64	60	0.5	25	26.5	-	-	-	121	115	185	192	88	93	-	90	245	181	217	215	215	220	220	220
	254	3.43	.055	82	0	8	5	4.5	25	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	299	4.05	.08	90	35	39	35	7	23.5	26.5	-	-	-	130	120	221	226	135	146	-	90	285	193	242	240	238	240	241	240
	302	4.08	.082	103	85	88	84	0.5	25	26.5	-	-	-	136	123	232	249	103	109	-	90	315	225	285	275	278	283	283	283
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	350	4.68	.110	115	45	50	45	8.6	22.5	26.5	-	-	-	152	135	268	270	165	179	-	91	352	229	288	285	282	288	288	285
	353	4.70	.112	135	115	119	113	1.5	25.5	26.5	-	-	-	155	138	279	300	122	132	-	91	385	265	332	330	330	335	335	335
	353	4.70	.112	150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	402	210	.145	145	60	63	60	10	22.5	27	-	-	-	178	151	370	319	189	210	-	91	428	265	336	336	330	335	335	335
	410	212	.150	170	146	150	145	0.5	25	27.5	-	-	-	190	160	335	360	148	158	-	90	465	312	393	395	395	400	400	400
	200	2.57	.032	45	35	37	35	3.5	25.5	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	250	3.16	.047	60	45	50	45	2.5	25	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	300	3.76	.069	78	65	80	60	1	25	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	350	4.35	.095	105	85	90	85	1	25	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	300	4.10	.083	102	85	90	86	1.0	23	25.4	-	-	-	100	88	250	272	105	110	-	80	320	240	305	305	305	310	310	310
	304	4.08	.082	102	85	88	85	1	23.5	26	-	-	-	155	130	320	330	112	120	-	80	395	265	345	345	345	345	348	345
	300	4.03	.080	100	85	86	83	1	23	26	-	-	-	180	155	320	330	110	120	-	80	390	262	345	345	345	345	345	340
	298	4.00	.078	100	85	86	82	1	24	26	-	-	-	190	170	320	328	111	118	-	80	388	262	342	340	340	345	345	340
	295	3.97	.075	99	84	85	81	1	25	26.5	-	-	-	195	180	320	325	110	115	-	80	385	262	340	340	338	340	340	338
	294	3.96	.075	98	82	84	80	1	24.5	26.5	-	-	-	200	185	320	325	110	115	-	80	382	260	338	338	338	338	340	338
	292	3.93	.074	97	81	83	80	1	24.5	26.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	291	3.92	.074	96	81	83	80	1	24.5	26.5	-	-	-	205	192	312	320	108	112	-	81	378	260	335	335	335	335	338	335
	289	3.92	.074	96	81	83	80	1	24.5	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}	Comments
	289	3.90	.073	95	80	82	78	1.5	25.5	27	-	-	-	210	198	312	320	108	112	-	85	375	260	335	335	332	332	335	332	Bypass Open
	289	3.90	.073	95	81	83	78	1.5	24.5	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	287	3.88	.073	94	80	82	77	1.5	24.0	27	-	-	-	214	203	315	320	108	112	-	88	375	262	335	335	332	335	335	332	
	298	4.00	.078	103	85	88	85	3.7	24.0	27.5	-	-	-	228	218	325	322	110	118	-	90	388	272	348	348	345	348	348	348	
	300	4.03	.080	103	87	88	84	3.7	26.5	28	-	-	-	232	222	325	332	110	118	-	91	390	285	348	348	345	348	350	348	
Modification #5																														
	202	2.76	.04	66	25	28	25	4.5	23	25	-	-	-	102	107	148	153	102	110	-	91	135	159	162	160	160	163	162	162	Bypass open
	201	2.77	.04	80	65	67	64	0.5	24	25	-	-	-	115	110	157	165	85	89	-	91	150	178	182	182	180	185	185	185	Bypass closed
	202	2.77	.04	95	0	8	4	3.2	24	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Shutoff
	250	3.44	.06	96	40	43	39	6	22.5	25	-	-	-	120	115	185	190	122	133	-	91	163	195	200	199	197	203	200	201	BPO
	250	3.44	.06	115	95	100	95	0	23.5	25	-	-	-	122	115	190	201	100	104	-	91	182	218	223	220	220	228	226	228	BPC
	252	3.45	.061	135	0	8	5	3.5	23.5	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O
	300	4.08	.088	132	55	57	54	9	22	25	-	-	-	130	122	240	237	149	165	-	92	205	241	250	247	245	255	250	251	BPO
	300	4.10	.090	157	135	138	135	0.5	23.5	25	-	-	-	140	130	245	262	119	128	-	92	225	272	285	282	283	295	290	290	BPC
	300	4.10	.090	180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O
	350	4.70	.120	170	69	73	68	8.5	21	25	-	-	-	143	137	275	275	177	195	-	92	235	282	295	290	288	305	298	300	BPO
	352	4.75	.120	210	185	187	-	0	24	25.5	-	-	-	160	145	300	320	142	155	-	92	265	328	343	345	345	360	352	352	BPC
	352	4.75	.120	240	-	-	-	4.5	-	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O
	400	210*	.155	210	85	89	83	11.5	22	25.5	-	-	-	185	160	320	328	210	230	-	93	275	328	345	340	339	360	349	349	BPO
	400	210*	.155	255	225	225	-	0	24	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	BPC
	400	210*	.155	295	0	8	-	4.5	25	26	-	-	-	-	-	-	-	-	-	-	-									
	429	210*	.165	220	92	95	89	12.5	20.5	25.5	-	-	-	210	180	330	345	220	245	-	95	290	340	342	355	355	375	366	365	BPO
	429	210*	.165	265	240	240	-	0	24	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	BPC
	429	210*	.165	310	0	8	-	4.5	25	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O
Reverse Field Rotation	0	0	0	15	6	10	6	5.3	26	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	BPC
	200	2.75	.039	82	65	72	67	1	26	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O
	202	2.76	.039	95	0	8	6	5.5	26	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	BPC
	300	4.10	.088	160	149	142	138	1.5	25.5	27.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O
	420	215*	.170	270	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	S/O

Modification #5

Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
202	2.76	.04	66	25	28	25	4.5	23	25	-	-	-	102	107	148	153	102	110	-	91	135	159	162	160	160	163	162	162
201	2.77	.04	80	65	67	64	0.5	24	25	-	-	-	115	110	157	165	85	89	-	91	150	178	182	182	180	185	185	185
202	2.77	.04	95	0	8	4	3.2	24	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
250	3.44	.06	96	40	43	39	6	22.5	25	-	-	-	120	115	185	190	122	133	-	91	163	195	200	199	197	203	200	201
250	3.44	.06	115	95	100	95	0	23.5	25	-	-	-	122	115	190	201	100	104	-	91	182	218	223	220	220	228	226	228
252	3.45	.061	135	0	8	5	3.5	23.5	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
300	4.08	.088	132	55	57	54	9	22	25	-	-	-	130	122	240	237	149	165	-	92	205	241	250	247	245	255	250	251
300	4.10	.090	157	135	138	135	0.5	23.5	25	-	-	-	140	130	245	262	119	128	-	92	225	272	285	282	283	295	290	290
300	4.10	.090	180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
350	4.70	.120	170	69	73	68	8.5	21	25	-	-	-	143	137	275	275	177	195	-	92	235	282	295	290	288	305	298	300
352	4.75	.120	210	185	187	-	0	24	25.5	-	-	-	160	145	300	320	142	155	-	92	265	328	343	345	345	360	352	352
352	4.75	.120	240	-	-	-	4.5	-	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
400	210	.155	210	85	89	83	11.5	22	25.5	-	-	-	185	160	320	328	210	230	-	93	275	328	345	340	339	360	349	349
400	210	.155	255	225	225	-	0	24	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
400	210	.155	295	0	8	-	4.5	25	26	-	-	-	-	-	-	-	-	-	-	-								
429	210	.165	220	92	95	89	12.5	20.5	25.5	-	-	-	210	180	330	345	220	245	-	95	290	340	342	355	355	375	366	365
429	210	.165	265	240	240	-	0	24	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
429	210	.165	310	0	8	-	4.5	25	25.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0	0	0	15	6	10	6	5.3	26	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
200	2.75	.039	82	65	72	67	1	26	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
202	2.76	.039	95	0	8	6	5.5	26	27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
300	4.10	.088	160	149	142	138	1.5	25.5	27.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
420	215*	.170	270	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
Modification #6	100	1.21	.010	25	10	13	9	4	24	25	-	-	-	82	83	90	95	70	72	-	77	75	90	98	98	95	88	100	98
	100	1.21	.010	30	20	24	20	2.8	24	25.2	-	-	-	83	85	95	97	65	68	-	78	81	97	100	101	100	95	102	101
	100	1.21	.010	35	0	5	4	3.6	24	25.2	-	-	-							-									
	200	2.55	.040	70	30	32	28	5.5	22.5	25.2	-	-	-	88	85	111	120	87	92	-	78	80	120	135	135	130	120	138	130
	204	2.58	.043	86	71	76	73	0	24	25.2	-	-	-	100	92	160	168	82	85	-	79	110	157	188	188	180	160	180	183
	205	2.60	.044	105	0	5	4	4	24	25.2	-	-	-							-									
	300	3.77	.090	135	55	62	58	11.5	25.5	29.8	-	-	-	107	100	165	183	122	131	-	78	115	175	210	208	200	182	200	200
	310	3.90	.095	166	149	150	148	5.0	28	29.8	-	-	-	118	105	219	242	110	118	-	78	147	223	272	272	262	230	260	265
	310	3.88	.095	190	10	15	8	9	28	30	-	-	-							-									
	405	210	.155	207	90	90	S/O	15.5	24	30	-	-	-	135	119	248	265	162	188	-	80	157	245	298	295	285	260	288	282
	400	212	.153	245	225	225	S/O	0	28	30	-	-	-	149	125	300	328	142	152	-	80	190	300	365	365	410	305	350	355
	400	212	.153	280	10	15	S/O	9.5		30	-	-	-							-									
	437	220	.178	260	50	55	S/O	11.5	27	30	-	-	-	167	141	365	370	201	221	-	80	210	322	395	392	378	332	375	375
	437	220	.177	290	255	258	S/O	5.5	29	30	-	-	-	180	150	375	410	152	162	-	80	235	365	450	438	495	375	430	435
	437	220	.177	330	0	18	S/O	9.5		30	-	-	-							-									
Modification #7	0	0	0	16	5	12	7.5	6.2	26.6	44.0	-	-	-	86	86	86	82	60	-	-	86	82	82	82	82	82	82	82	82
	100	0.8	.006	30	12	15	12	6.7	26	45	-	-	-	98	99	107	113	85	-	-	81	110	114	110	102	112	110	110	112
	100	0.8	.008	35	23	25	21	5.5	26	44.5	-	-	-						-	-									
	100	0.8	.008	38	5	10	6.5	6.3	26.5	45	-	-	-						-	-									
	153	1.26	.017	46	20	23	20	7.3	26	44.5	-	-	-	98	98	115	119	90	-	-	88	128	129	134	120	130	120	122	125
	153	1.26	.018	55	43	47	42	4.5	26.5	44.3	-	-	-						-	-									
	153	1.26	.018	65	10	11	7	6.5	26.5	44.3	-	-	-						-	-									
	205	1.68	.023	65	29	32	28	8.5	26	45	-	-	-	98	98	165	169	105	-	-	95	172	162	174	150	176	141	165	169
	205	1.68	.022	85	70	75	70	4.5	27	45	-	-	-						-	-									
	205	1.68	.022	105	10	11	7	7	27	45	-	-	-						-	-									
	250	2.03	.031	89	36	40	36	10	26	45	-	-	-	92	92	190	195	125	-	-	90	210	187	200	182	219	154	201	203
	250	2.03	.031	115	95	100	95	1	27	45	-	-	-						-	-									
	250	2.03	.031	145	10	12	7.5	7.2	27	45	-	-	-						-	-									
	300	2.45	.045	115	50	52	48	11	25	45	-	-	-	105	105	245	250	151	-	-	90	270	260	265	231	280	204	255	261
	300	2.45	.051	150	126	130	124	5	27	45	-	-	-						-	-									
	302	2.45	.051	188	10	12	7.5	7.5	27	45	-	-	-						-	-									
	350	2.80	.070	140	60	63	60	12	25	45	-	-	-	102	102	105													
	350	2.85	.070	188	165	165	-	4	27.5	45.5																			
	350	2.85	.070	240	10	12	8	7.9	28	46																			
	350	2.85	.071	205	185	185	-	15	38	56																			
	350	2.85	.071	260	20	23	-	18	38	56																			
	400	3.25	.090	245	220	220	-	13.5	39	56																			
	460	3.72	.120	310	250	250	-	11	37	56																			
	400	3.3	-	230	200	225	-	11	34	53	-	-	-	90	93	305	343	143	-	-	82	397	188	367	285	415	402	376	350
	400	3.27	-	225	210	210	-	11	34	53.3	-	-	-						-	-									
	450	3.65	-	270	250	250	-	8	35	53.8	-	-	-	112	114	445	472	185	-	-	82	512	285	463	356	527	540	540	485
	450	3.67	-	275	210	210	-	9	35	54	-	-	-						-	-									
	500	4.06	-	310	290	300	-	3	36	54	-	-	-						-	-									
	500	4.06	-	310	210	210	-	11	36	54.5	-	-	-	130	130	527	552	185	-	-	82	597	486	550	416	622	-	582	578
	529	4.28	-	350	310	-	-	0	36	54.8	-	-	-	147	143	534	592	209	-	-	83	624	508	567	431	645	-	605	621
	0	0	-	28	2C	23	19	17.3	38	55	-	-	-																

	Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
Modification #7A	0	0	-	23	15	18	13	13.7	34	51.5	-	-	-	70	67	70	68	65	-	-	68	72	72	73	73	73	Out	72	71
	100	0.82	-	37	20	23	20	14.4	34	53	-	-	-						-	-							-		
	100	0.82	-	41	31	35	31	13	34	53	-	-	-						-	-							-		
	100	0.82	-	45	15	18	14	13.8	34	53	-	-	-						-	-							-		
	150	1.25	-	75	15	18	14	13.8	15	51.8	-	-	-						-	-							-		
	150	1.25	-	64	51	54	51	12	34	53	-	-	-						-	-							-		
	150	1.25	-	55	27	31	27	15	33.5	53	-	-	-	70	67	128	143	90	-	-	69	147	145	137	116	145	-	138	132
	200	1.66	-	78	37	41	37	15.5	32.5	52	-	-	-						-	-							-		
	200	1.66	-	92	78	82	73	10.5	33	52	-	-	-	74	69	158	178	82	-	-	68	198	197	192	167	201	-	187	171
	200	1.66	-	105	15	18	15	14	33	52	-	-	-						-	-							-		
	250	2.05	-	140	15	16	17	14	32	52	-	-	-						-	-							-		
	250	2.05	-	120	110	112	109	12	39	52	-	-	-	78	74	239	275	107	-	-	69	298	298	282	215	300	-	279	252
	250	2.06	-	105	60	62	49	17	37	52	-	-	-						-	-							-		
	300	2.47	-	132	64	66	65	18	37	52	-	-	-						-	-							-		
	300	2.47	-	155	145	147	145	13	38	52	-	-	-	86	81	262	274	116	-	-	70	306	305	295	233	312	-	288	265
	300	2.47	-								-	-	-						-	-							-		
	350	2.88	-	190	185	187	-	12	37	53	-	-	-	92	87	333	350	143	-	-	70	338	379	353	280	387	-	360	341
	350	2.89	-	163	78	81	77	20	36	53	-	-	-						-	-							-		
	400	3.30	-	200	92	95	94	22	35	53	-	-	-						-	-							-		
	400	3.30	-	245	220	225	-	10	38	53	-	-	-	107	99	368	406	164	-	-	70	443	446	420	328	457	-	440	395
	450	3.68	-	295	200	208	-	12	38	53.5	-	-	-						-	-							-		
	450	3.68	-	240	105	111	110	25	37	53.5	-	-	-						-	-							-		
	500	4.09	-	285	125	127	131	25	34	53.5	-	-	-						-	-							-		
	500	4.07	-	350	200	205	-	13	40	54	-	-	-	133	120	481	535	182	-	-	71	588	598	561	432	609	-	565	562
	534	4.32	-	385	210	210	-	11	40	54.5	-	-	-						-	-							-		
	533	4.34	-	308	140	140	138	27	35	54	-	-	-						-	-							-		
	500	4.10	-	290	125	132	127	26	36	54	-	-	-						-	-							-		
	500	4.06	-	370	205	205	-	13	42	54.5	-	-	-	113	102	407	473	173	-	-	75	542	547	519	394	565	-	516	464
Modification #8	0	0	0	17	17	17	17	17	42.5	55	-	-	-	73	71	74	73	62	-	-	76	76	75	75	73	74	74	74	-
	100	0.80	.008	31	24	24	23	17.5	42	55	-	-	-						-	-									
	100	0.80	.008	35	34	34	34	16.2	42.5	55	-	-	-	75	73	95	99	64	-	-	75	106	104	104	93	106	107	104	-
	100	0.80	.008	40	17	17	17	17	42.8	55	-	-	-						-	-									
	150	1.23	.017	75	18	18	18	17.2	42.5	55	-	-	-						-	-									
	150	1.23	.017	60	57	57	57	15	42.5	55	-	-	-						-	-									
	150	1.23	.017	50	32	32	32	18	42	55	-	-	-						-	-									
	200	1.64	.030	72	40	40	40	19.5	41.5	55	-	-	-						-	-									
	200	1.64	.030	90	85	85	85	16	42.5	55	-	-	-	79	75	158	164	79	-	-	76	178	176	177	149	179	184	175	-
	200	1.64	.030	113	18	18	18	17.4	42.5	55	-	-	-						-	-									
	250	2.09	.047	164	18	18	18	17.6	42.5	55	-	-	-						-	-									
	250	2.09	.047	130	126	126	126	13	42.5	55.5	-	-	-						-	-									
	250	2.09	.047	105	55	55	55	20.5	41	55.5	-	-	-						-	-									
	300	2.46	.068	136	68	68	68	22	40	55.5	-	-	-						-	-									
	300	2.46	.068	170	166	166	-	13	42.5	55.5	-	-	-	90	85	256	277	120	-	-	76	300	394	288	225	298	304	294	-
	300	2.46	.068	230	18	18	18	18	43	55.5	-	-	-						-	-									
	350	2.85	.093	290	19	19	19	18.4	42.5	56	-	-	-						-	-									
	350	2.85	.093	232	217	217	-	14	42.5	56	-	-	-						-	-									
	350	2.85	.093	180	86	86	85	23	40	56	-	-	-						-	-									
	400	3.27	.120	220	105	105	105	25	39	56	-	-	-						-	-									
	400	3.27	.120	283	212	212	-	14	42.5	56	-	-	-	113	104	391	423	158	-	-	75	447	439	417	321	444	448	434	-
	450	3.67	.154	338	214	214	-	15	43	56.5	-	-	-						-	-									
	450	3.67	.154	260	118	118	118	29	38	56.5	-	-	-						-	-									
	500	4.06	.188	295	134	134	134	30	38	57	-	-	-						-	-									
	500	4.06	.188	375	215	215	-	15	44	57	-	-	-	139	124	479	532	182	-	-	76	581	574	543	408	587	592	570	-
	537	4.31	.214	420	214	214	-	14	44	58	-	-	-																
	535	4.31	.214	325	147	147	147	32	38.5	58	-	-	-						-	-									

Modification #9

Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
0	0	0	15	15	15	15	14.5	40	52.3	-	-	-	83	80	86	67	62	-	-	87	82	81	83	83	82	82	80	81
100	0.80	.008	30	21	21	21	15	39.8	52.3	-	-	-						-	-									
100	0.80	.008	35	34	34	33	13.5	40	52.3	-	-	-						-	-									
100	0.80	.008	40	15	15	15	14.5	40	52.3	-	-	-						-	-									
150	1.25	.018	75	15	15	15	14.5	40	52.3	-	-	-						-	-									
150	1.25	.018	63	58	58	58	12.5	40	52.3	-	-	-						-	-									
150	1.25	.018	45	30	30	30	15.5	39	52.3	-	-	-	81	76	143	150	92	-	-	87	148	145	133	115	145	145	142	138
200	1.65	.031	73	39	39	39	16.5	39	52.3	-	-	-						-	-									
200	1.65	.031	90	88	88	88	13	39.5	52.3	-	-	-						-	-									
200	1.65	.031	115	15	15	15	14.7	40	52.5	-	-	-						-	-									
250	2.05	.048	165	15	15	15	14.8	40	52.8	-	-	-						-	-									
250	2.05	.048	135	120	120	120	14.8	40	52.8	-	-	-						-	-									
250	2.05	.048	105	52	52	52	18	38	52.8	-	-	-						-	-									
300	2.47	.068	135	65	65	65	19	38	52.8	-	-	-						-	-									
300	2.46	.068	175	164	164	164	13	39.5	52.8	-	-	-						-	-									
300	2.46	.068	225	15	15	15	15	40	52.8	-	-	-						-	-									
350	2.87	.094	295	15	15	15	15	40	53	-	-	-						-	-									
350	2.87	.094	240	225	225	-	10	40	53	-	-	-						-	-									
350	2.87	.094	185	88	88	88	22	37	53	-	-	-	106	96	382	355	210	-	-	86	352	348	335	282	347	343	330	320
400	3.29	.123	230	105	105	105	24	36	53	-	-	-						-	-									
400	3.29	.123	295	275	275	-	5	40	53.5	-	-	-						-	-									
450	3.68	.154	345	320	-	-	1	40	54	-	-	-						-	-									
450	3.68	.154	270	123	123	123	25	35	54	-	-	-	130	115	428	415	248	-	-	86	425	418	410	343	425	421	400	388
500	4.08	.190	315	142	142	142	28	35	54	-	-	-						-	-									
500	4.08	.190	400	370	-	-	0	40	54	-	-	-						-	-									
533	4.31	.214	435	405	-	-	0	40	54.5	-	-	-						-	-									
533	4.32	.214	340	155	155	155	30	35	54.5	-	-	-						-	-									
400	3.28	.123	305	215	215	-	13	41	54.8	-	-	-						-	-									
450	3.67	.154	365	215	215	-	13	41	55	-	-	-	134	110	477	500	177	-	-	87	530	523	497	385	537	533	515	491
500	4.06	.189	425	215	215	-	13	42	55.2	-	-	-						-	-									
535	4.33	.215	470	215	215	-	13	42	55.3	-	-	-						-	-									
535	4.33	.215	495	-	-	-	15	42	55.4	-	-	-																

Modification #10

Volts	Amps	KW	P_1	P_2	P_3	P_4	P_5	P_6	P_7	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}	T_{17}	T_{18}	T_{19}
0	0	0	15	15	15	15	15	40.3	52.6	-	-	-	75	78	83	64	60	-	-	87	74	74	72	71	74	73	77	77
100	0.82	.007	30	21	21	21	15.5	40.2	52.8	-	-	-						-	-									
100	0.82	.007	35	33	33	33	14	40.5	52.8	-	-	-						-	-									
100	0.82	.007	40	15	15	15	15	40.5	52.8	-	-	-						-	-									
150	1.23	.017	70	15	15	15	15	40.5	53.0	-	-	-						-	-									
150	1.23	.017	57	54	54	54	13	40.5	53.0	-	-	-						-	-									
150	1.23	.017	45	28	28	28	16	40.0	53.0	-	-	-	82	83	127	142	87	-	-	87	143	142	129	109	140	142	138	137
200	1.64	.031	70	38	38	38	17	39	53.0	-	-	-						-	-									
200	1.64	.031	87	82	82	82	12	40.5	53.2	-	-	-						-	-									
200	1.64	.031	107	16	16	16	16	40.5	53.2	-	-	-						-	-									
250	2.03	.048	150	16	16	16	16	41.0	53.5	-	-	-						-	-									
250	2.03	.048	123	116	116	116	11	41.0	53.5	-	-	-						-	-									
250	2.03	.048	95	50	50	50	19.5	39.5	53.5	-	-	-	93	93	288	275	152	-	-	86	252	249	238	202	244	249	241	237
300	2.45	.069	125	62	62	62	20	39	53.8	-	-	-						-	-									
300	2.45	.069	163	153	153	153	13	40.5	53.8	-	-	-						-	-									
300	2.45	.069	200	16	16	16	15	41.0	54.0	-	-	-						-	-									
350	2.84	.094	260	17	17	17	17	42.0	54.3	-	-	-						-	-									
350	2.84	.093	210	195	195	-	13	41.5	54.5	-	-	-						-	-									
350	2.85	.094	165	80	80	80	22.5	38.5	54.3	-	-	-	114	110	368	346	202	-	-	87	349	343	335	279	340	344	330	323
400	3.27	.121	205	97	97	97	24	38	54.5	-	-	-						-	-									
400	3.26	.121	269	215	215	-	13	41.5	55	-	-	-						-	-									
450	3.66	.154	320	215	215	-	14	42.0	55.2	-	-	-						-	-									
450	3.66	.154	235	112	112	112	26	38.0	55.2	-	-	-	138	127	425	415	240	-	-	87	424	418	415	344	414	422	398	393
500	4.04	.188	280	128	128	128	28	38.0	55.5	-	-	-						-	-									
500	4.04	.188	373	217	217	-	15	43.0	55.8	-	-	-						-	-									
540	4.35	.218	415	218	218	-	15	43.0	56.2	-	-	-						-	-									
538	4.33	.215	320	144	144	144	30	38.0	56.2	-	-	-						-	-									

APPENDIX B

REDUCED DATA

ORIGINAL PUMP DUCT DESIGN

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
115	56.8	3.6	.3183	2,900	16.5	0.233
115	56.8	3.6	.3183	1,450	10.0	0.097
115	56.8	3.6	.3183	0	20.2	-
164	78.8	7.0	.3128	1,850	19.5	0.080
164	78.8	7.0	.3128	3,300	27.0	0.153
164	78.8	7.0	.3128	2,400	30.5	0.130
164	78.8	7.0	.3128	0	37.0	-
210	100.8	11.0	.3000	4,100	44.0	0.174
210	100.8	11.0	.3000	3,200	34.5	0.118
210	100.8	11.0	.3000	2,250	29.0	0.075
210	100.8	11.0	.3000	0	57.8	-
404	188.4	37.6	.2852	3,950	85.0	0.066
404	188.4	37.6	.2852	8,400	162.5	0.256
404	188.4	37.6	.2852	0	174.0	-
301	142.0	21.4	.2891	6,600	93.0	0.246
301	142.0	21.4	.2891	5,600	77.0	0.180
301	142.0	21.4	.2891	3,200	52.5	0.078
301	142.0	21.4	.2891	0	106.0	-

PUMP DUCT MODIFICATION NO. 1

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
160	82.0	5.6	.2465	2,325	27.7	0.077
200	102.0	9.0	.2547	3,260	29.2	0.071
250	126.0	13.0	.2383	4,220	44.8	0.097
300	149.2	20.0	.2580	5,150	63.0	0.108
350	172.0	26.6	.2551	6,000	88.5	0.134
400	194.0	35.0	.2604	6,900	108.0	0.146
450	195.0	45.0	.2961	7.900	143.0	0.168
450	195.0	45.0	.2961	0	148.0	-
450	220.0	47.0	.2741	18,000	119.0	0.305
400	194.0	36.6	.2723	15,500	90.5	0.256
350	172.0	27.4	.2628	14,000	71.5	0.244
300	150.0	21.0	.2694	11,500	49.0	0.180
250	127.2	14.6	.2651	10,500	39.5	0.190
200	102.4	9.0	.2537	9,000	28.3	0.189
150	76.0	5.0	.2533	6,000	13.9	0.111
150	64.0	5.6	.3674	6,700	17.0	0.136
200	86.0	10.0	.3357	8,700	29.0	0.169
250	108.0	15.6	.3336	11,500	44.0	0.217
300	129.2	22.0	.3277	13,000	62.0	0.245
350	150.0	29.0	.3189	14,500	77.0	0.257
400	170.8	37.4	.3161	14,900	86.5	0.230
450	192.8	46.4	.3088	17,300	110.0	0.274
150	64.0	5.6	.3674	0	19.5	-
200	102.4	10.0	.2537	0	34.5	-
250	108.0	15.6	.3336	0	54.5	-
300	129.2	22.0	.3277	0	74.5	-
350	150.0	29.0	.3189	6,600	87.0	0.132
350	150.0	29.0	.3189	0	89.0	-
400	170.8	37.4	.3161	7,200	105.0	0.135
400	170.8	37.4	.3161	0	108.5	-
450	192.8	46.4	.3088	7,900	132.5	0.142
450	192.8	46.4	.3088	0	138.0	-

PUMP DUCT MODIFICATION NO. 2

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
102	46.0	2.0	.1581	6,000	15.5	0.311
102	46.0	2.0	.1581	3,100	20.2	0.210
102	46.0	2.0	.1581	0	29.0	-
151	67.2	4.0	.2271	8,800	29.3	0.431
150	67.2	4.0	.2291	4,100	37.5	0.257
150	67.4	4.0	.2284	0	49.0	-
200	92.0	7.2	.2259	11,500	51.1	0.546
202	91.2	7.6	.2381	5,250	59.0	0.273
204	92.0	7.8	.2399	0	82.0	-
252	114.4	12.0	.2403	13,800	70.9	0.546
253	114.8	11.6	.2306	6,300	86.5	0.314
255	115.2	12.0	.2358	0	112.0	-
300	136.8	16.0	.2251	16,000	95.5	0.639
304	137.6	16.6	.2291	7,200	113.0	0.328
307	138.4	17.0	.2310	0	142.0	-
353	168.0	22.0	.2142	18,000	132.4	0.725
350	168.0	22.0	.2160	8,500	145.5	0.566
350	168.0	22.0	.2160	0	172.0	-
400	190.0	27.6	.2097	21,000	149.5	0.761
400	190.0	27.6	.2097	9,200	187.5	0.407
400	190.0	27.6	.2097	0	209.0	-
450	212.0	37.0	.2239	23,000	167.5	0.696
450	212.0	37.0	.2239	9,900	210.0	0.562
450	212.0	37.0	.2239	0	234.5	-
443	212.0	37.0	.2275	23,500	180.0	0.765
445	212.0	35.0	.2142	10,000	214.0	0.611
445	210.0	34.0	.2100	0	234.5	-

PUMP DUCT MODIFICATION NO. 3

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
100	53.6	2.8	.3016	4,200	4.7	0.047
100	54.0	2.8	.3016	1,430	5.0	0.017
100	54.0	2.6	.3016	-	5.7	-
150	80.4	6.0	.2872	4,800	9.3	0.050
150	80.4	6.0	.2872	2,000	10.0	0.022
151	81.2	6.0	.2813	0	11.5	-
202	106.4	10.0	.2686	6,000	13.8	0.065
202	106.4	10.0	.2686	3,200	17.0	0.036
205	107.6	10.2	.2670	0	19.3	-
435		47.0		0	60.5	
200	104.8	10.0	.2754	2,350	18.5	0.029
433	210.0	46.0	.2921	5,100	50.0	0.037
438	205.0	45.6	.2932	0	54.0	-
400	192.0	35.0	.2631	4,550	45.5	0.040
404	194.0	35.6	.2622	0	49.0	-
350	170.8	27.0	.2607	4,150	37.5	0.058
347	170.0	26.6	.2603	0	39.0	-
300	149.2	20.0	.2580	3,700	30.5	0.038
296	148.0	19.8	.2610	0	23.0	-
249	126.8	14.4	.2633	7,000	20.0	0.044
242	125.2	14.0	.2668	3,200	25.2	0.031
245	126.0	14.2	.2656	0	24.5	-

PUMP DUCT MODIFICATION NO. 3A

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
155	80.8	5.6	.2582	7,900	23.1	0.218
152	80.8	5.6	.2582	3,650	28.5	0.124
153	81.2	5.6	.2602	0	29.0	-
200	104.0	9.2	.2554	10,000	38.7	0.281
200	104.0	9.2	.2554	4,450	42.3	0.136
202	105.6	9.8	.2652	0	46.0	-
250	129.2	14.8	.2646	11,500	53.8	0.280
253	130.0	14.8	.2598	5,750	64.0	0.166
259	132.0	15.2	.2567	0	67.0	-
300	151.2	20.0	.2546	13,000	70.0	0.323
305	152.8	20.1	.2490	6,350	88.2	0.186
310	154.4	21.4	.2581	0	89.0	-
349	172.0	27.0	.2597	15,500	89.5	0.344
355	174.0	28.0	.2617	6,900	106.5	0.176
363	176.0	29.0	.2621	0	111.0	-
395	190.8	34.6	.2651	16,600	107.0	0.343
398	192.0	35.0	.2644	7,400	123.0	0.174
410	194.0	36.0	.2613	0	127.0	-
440	200.0	44.0	.2887	18,500	130.7	0.368
440	200.0	44.0	.2887	8,000	142.7	0.236
443	200.0	44.0	.2867	0	144.0	-

PUMP DUCT MODIFICATION NO. 4

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
200	107.6	7.0	.1878	10,500	37.0	0.354
200	107.6	7.0	.1878	4,400	47.0	0.198
200	108.0	7.0	.1871	0	51.0	-
250	135.6	11.0	.1873	12,000	52.3	0.382
250	136.0	11.0	.1868	5,700	69.0	0.239
254	137.2	11.0	.1823	0	71.0	-
299	162.0	16.0	.1907	15,000	76.5	0.479
302	163.2	16.4	.1921	6,300	96.0	0.247
350	187.2	22.0	.1939	17,000	99.9	0.516
353	188.0	22.4	.1949	7,600	127.0	0.288
353	188.0	22.4	.1949	0	139.0	-
402	210.0	29.0	.1983	19,000	129.5	0.848
410	212.0	30.0	.1993	8,600	163.0	0.313
200	102.8	6.4	.1797	4,000	35.0	0.146
250	126.4	9.4	.2975	4,700	51.0	0.171
300	150.4	13.8	.1766	5,500	70.5	0.188
350	174.0	19.0	.1801	6,500	97.5	0.223

PUMP DUCT MODIFICATION NO. 5

VOLTS	AMPS	KW	Power Factor	Flow #/Hr.	Δ P Psi	Efficiency %
202	110.4	8.0	.2071	13,000	49.7	0.540
201	110.8	8.0	.2074	5,500	67.7	0.466
202	110.8	8.0	.2064	0	80.0	-
250	137.6	12.0	.2014	14,500	78.5	0.634
250	137.6	12.0	.2014	6,800	103.5	0.392
252	138.0	12.2	.2026	0	120.0	-
300	163.2	17.6	.2075	17,500	111.5	0.742
300	164.0	18.0	.2112	8,400	145.0	0.453
300	164.0	18.0	.2112	0	165.0	-
350	188.0	24.0	.2106	21.500	151.0	0.905
352	190.0	24.0	.2072	9,600	199.5	0.534
352	190.0	24.0	.2072	0	225.0	-
400	210.0	31.0	.2131	23,000	188.0	0.933
400	210.0	31.0	.2131	10,500	244.5	0.544
400	210.0	31.0	.2131	0	280.0	-
429	210.0	33.0	.2115	26,000	197.0	1.038
429	210.0	33.0	.2115	10,900	254.5	0.562
429	210.0	33.0	.2115	0	295.0	-
-	-	-	-	-	-	-
200	110.0	7.8	.2047	5,800	67.5	0.311
202	110.4	7.8	.2020	0	80.0	-
300	164.0	17.6	.2065	8,200	149.0	0.423
420	215.0	34.0	.2124	0	255.0	-

PUMP DUCT MODIFICATION NO. 6

VOLTS	AMPS	KW	Power Factor	Flow #/Hr	Δ P Psi	Efficiency %
100	48.4	2.0	.2386	4,650	13.6	0.212
100	48.4	2.0	.2386	3,100	19.8	0.206
100	48.4	2.0	.2386	0	24.0	-
200	102.0	8.0	.2264	11,500	57.5	0.553
204	103.2	8.6	.2360	6,100	79.0	0.375
205	104.0	8.8	.2383	0	94.0	-
300	150.8	18.0	.2297	18,000	116.5	0.779
310	156.0	19.0	.2268	8,400	154.0	0.681
310	155.2	19.0	.2280	0	174.0	-
405	210.0	31.0	.2104	22,600	185.0	0.902
400	212.0	30.6	.2083	10,500	238.0	0.546
400	212.0	30.6	.2083	0	264.0	-
437	220.0	35.6	.2138	30,000	242.0	1.364
437	220.0	35.4	.2138	12,000	278.0	0.630
437	220.0	35.4	.2138	0	314.0	-

PUMP DUCT MODIFICATION NO. 7

VOLTS	AMPS	KW	Power Factor	Flow #/Hr	Δ P Psi	Efficiency %
100	64.0	2.4	.2165	6,800	13.6	0.258
100	64.0	3.2	.2887	3,100	19.8	0.128
100	64.0	3.2	.2887	0	22.0	-
153	100.8	6.8	.2546	9,000	29.2	0.258
153	100.8	7.2	.2546	4,300	41.0	0.164
153	100.8	7.2	.2546	0	49.0	-
205	134.4	9.2	.1928	11,100	47.5	0.383
205	134.4	8.8	.1844	5,750	71.5	0.312
205	134.4	8.8	.1844	0	89.0	-
250	162.4	12.4	.1763	14,200	70.2	0.538
250	162.4	12.4	.1763	6,800	105.2	0.386
250	162.4	12.4	.1763	0	129.0	-
300	196.0	18.0	.1767	16,000	95.5	0.586
300	196.0	20.4	.2003	7,600	136.0	0.339
302	198.4	20.4	.1966	0	172.0	-
350	224.0	28.0	.2062	19,000	119.5	0.542
350	228.0	28.0	.2026	8,900	175.9	0.374
350	228.0	28.0	.2026	0	226.0	-
350	228.0	28.4	.2055	9,100	181.3	0.387
350	228.0	28.4	.2055	0	232.7	-
400	260.0	36.0	.1998	10,100	222.8	0.418
460	297.6	48.0	.2024	10,900	290.3	0.441
400	264.0			9,600	210.3	
400	261.6			9,800	205.3	
450	292.0			10,900	252.5	
450	293.6			10,000	258.5	
500	324.8			11,900	299.3	
500	324.8			9,800	291.3	
529	342.4			12,200	341.3	

PUMP DUCT MODIFICATION NO. 7A

VOLTS	AMPS	KW	Power Factor	Flow #/Hr	Δ P Psi	Efficiency %
100	65.6			6,300	13.3	
100	65.6			3,000	17.8	
100	65.6			0	22.0	
150	100.0			0	52.0	
150	100.0			5,100	42.8	
150	100.0			9,700	30.8	
200	132.8			12,500	53.3	
200	132.8			5,800	72.3	
200	132.8			0	82.0	
250	164.0			0	117.0	
250	164.8			7,500	98.8	
250	164.8			13,000	78.8	
300	197.6			16,500	104.8	
300	197.6			8,000	132.8	
300	197.6			0	-	
350	230.4			9,200	167.8	
350	231.2			18,900	133.8	
400	264.0			21,500	168.8	
400	264.0			10,100	225.8	
450	294.4			9,800	273.8	
450	294.4			24,000	205.8	
500	327.2			26,500	250.8	
500	325.6			9,600	327.8	
534	345.6			9,800	364.8	
533	344.0			26,500	262.8	
500	328.0			26,900	254.8	
500	324.0			9,800	347.8	

PUMP DUCT MODIFICATION NO. 8

VOLTS	AMPS	KW	Power Factor	Flow #/Hr	Δ P Psi	Efficiency %
100	64.0	3.2	.2887	5,600	13.5	0.158
100	64.0	3.2	.2887	4,200	19.3	0.169
100	64.0	3.2	.2887	0	23.0	-
150	98.4	6.8	.2784	0	58.0	-
150	98.4	6.8	.2784	5,400	45.0	0.239
150	98.4	6.8	.2784	9,000	32.0	0.283
200	131.2	12.0	.2640	12,000	52.5	0.351
200	131.2	12.0	.2640	5,900	74.0	0.364
200	131.2	12.0	.2640	0	96.0	-
250	167.2	18.8	.2597	0	147.0	-
250	167.2	18.8	.2597	7,600	117.0	0.316
250	167.2	18.8	.2597	15,000	84.5	0.451
300	196.8	27.2	.2652	17,500	114.0	0.491
300	196.8	27.2	.2652	8,800	149.0	0.322
300	196.8	27.2	.2652	0	213.0	-
350	228.0	37.2	.2691	0	273.0	-
350	228.0	37.2	.2691	10,100	218.0	0.396
350	228.0	37.2	.2691	21,000	160.0	0.604
400	261.6	48.0	.2648	24,000	195.0	0.652
400	261.6	48.0	.2648	9,800	269.0	0.367
450	293.6	61.6	.2692	9,900	323.0	0.347
450	293.6	61.6	.2692	26,000	231.0	0.652
500	324.8	75.2	.2674	27,500	265.0	0.648
500	324.8	75.2	.2674	10,000	360.0	0.320
537	344.8	85.6	.2669	10,000	406.0	0.322
535	344.8	85.6	.2669	28,500	293.0	0.653

PUMP DUCT MODIFICATION NO. 9

VOLTS	AMPS	KW	Power Factor	Flow #/Hr	Δ P Psi	Efficiency %
100	64.0	3.2	.2887	5,200	14.5	0.151
100	64.0	3.2	.2887	3,000	21.0	0.126
100	64.0	3.2	.2887	-	25.0	-
150	100.0	7.2	.2771	-	60.0	-
150	100.0	7.2	.2771	4,900	50.0	0.217
150	100.0	7.2	.2771	8,500	29.0	0.219
200	132.0	12.4	.2712	9,000	56.0	0.260
200	132.0	12.4	.2712	6,100	76.5	0.241
200	132.0	12.4	.2712	-	99.8	-
250	164.0	19.2	.2704	-	149.7	-
250	164.0	19.2	.2704	7,200	119.7	0.287
250	164.0	19.2	.2704	12,300	86.5	0.354
300	197.6	27.2	.2649	14,500	115.5	0.395
300	197.6	27.2	.2649	11,500	151.5	0.328
300	197.6	27.2	.2649	-	209.5	-
350	229.6	37.6	.2701	-	279.5	-
350	229.6	37.6	.2701	10,900	229.5	0.426
350	229.6	37.6	.2701	17,200	162.5	0.476
400	263.2	49.2	.2698	21,000	205.5	0.509
400	263.2	49.2	.2698	11,500	279.5	0.382
450	294.4	61.6	.2685	12,500	343.5	0.446
450	294.4	61.6	.2685	20,400	244.5	0.518
500	326.4	76.0	.2689	22,000	294.5	0.546
500	326.4	76.0	.2689	13,000	399.5	0.438
533	344.8	85.6	.2689	14,300	434.5	0.465
533	345.6	85.6	.2689	26,000	340.5	0.686
400	262.4	49.2	.2706	10,500	291.5	0.400
450	293.6	61.6	.2692	10,500	351.5	0.384
500	324.8	75.6	.2688	10,500	411.5	0.366
535	346.8	86.0	.2691	10,500	456.5	0.357
535	346.8	86.0	.2691	-	480.0	-

PUMP DUCT MODIFICATION NO. 10

VOLTS	AMPS	KW	Power Factor	Flow #/Hr	Δ P Psi	Efficiency %
100	65.6	2.8	.2464	6,300	14.5	0.218
100	65.6	2.8	.2464	3,100	21.0	0.156
100	65.6	2.8	.2464	0	25.0	-
150	98.4	6.8	.2660	0	55.0	-
150	98.4	6.8	.2660	4,600	45.0	0.204
150	98.4	6.8	.2660	8,700	30.0	0.257
200	131.2	12.4	.2728	12,000	54.0	0.350
200	131.2	12.4	.2728	5,900	76.0	0.242
200	131.2	12.4	.2728	0	92.0	-
250	162.4	19.2	.2730	0	135.0	-
250	162.4	19.2	.2730	7,200	113.0	0.283
250	162.4	19.2	.2730	14,500	76.5	0.386
300	196.0	27.6	.2710	17,000	106.0	0.437
350	196.0	27.6	.2710	8,200	151.0	0.300
300	196.0	27.6	.2710	0	185.0	-
350	227.2	37.6	.2730	0	245.0	-
350	227.2	37.2	.2701	9,500	198.0	0.338
350	228.0	37.6	.2720	20,000	143.5	0.511
400	261.6	48.4	.2670	23,000	197.0	0.626
400	260.8	48.4	.2679	10,000	257.0	0.355
450	292.8	61.6	.2699	10,000	307.0	0.333
450	292.8	61.6	.2699	24,000	210.0	0.547
500	323.2	75.2	.2687	26,000	253.0	0.585
500	323.2	75.2	.2687	10,000	358.0	0.318
540	348.0	87.2	.2679	10,000	400.0	0.306
538	346.4	86.0	.2664	28,500	291.0	0.645

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