AN EXPERIMENTAL INVESTIGATION OF CENTRIFUGAL COMPRESSOR SURGE AND STALL PHENOMENA IN TURBOCHARGERS

by

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ABSTRACT

This report documents the 2nd phase of an ongoing experimental research project in stall and surge phenomena in turbocharger centrifugal compressors. To explore the effects of system parameters on centrifugal compressor operation, a new test facility was built which featured a large plenum chamber which would lower the Helmholtz resonator frequency to 7 Hz and slow down the transient surge behavior. Facility design, construction, and data acquisition hardware are discussed initially followed by a presentation of steady and unsteady compressor surge data taken on a turbocharger compressor with a vaneless diffuser. Results indicated that the surge line position was strongly dependent on system volume(B-Parameter dependent). It was also found that large massflow oscillations were also present in the region near the surge breakdown limit whose amplitudes diminished at higher speeds. Time averaged measurements of the diffuser Cp in these regions indicated a severe drop in the diffuser characteristic which in the small B system was reasonably flat and well behaved. Phase measurements of high response casing static pressure probes close to surge indicated an asymmetric flow in the vaneless diffuser. Surge occured at a time averaged diffuser Cp value of approximately .4. Unsteady pressure and massflow time traces of a surge cycle showed that prior to surge blowdown, the compression system exhibited an unstable nonlinear diverging oscillation in massflow and pressure. This behavior emphasized the system nature of the surge process. Evidence is presented that suggests that the system instability is triggered by a momentary vaneless diffuser stall.

Thesis and Faculty Supervisor: Edward M. Greitzer
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BIOGRAPHICAL NOTE

David Allan Fink was born on August 28, 1953 in Meriden, Connecticut to Allan K. and Ruth M. Fink. He graduated from Orville H. Platt H. S. in June 1971. He received his Bachelor of Science in Mechanical Engineering from the Massachusetts Institute of Technology in June 1975. He accepted full time employment as a development engineer in the engine technology department of the Thermo Electron Corporation where he spent a number of years engineering turbomachinery components for cogeneration applications. He returned to M.I.T. in June 1982 as a research assistant at the Gas Turbine and Plasma Dynamics Laboratory in the Department of Aeronautics and Astronautics.

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Symbols

a	=	speed of sound
A_C	=	equivilent compressor duct area
B	=	B-Parameter defined in equation (2)
$\tilde{C}$	=	non-dimensional compressor pressure rise coefficient
	=	$\Delta P_C/(1/2\rho U^2)$
Cp	=	specific heat
Cp_D	=	diffuser pressure rise coefficient
	=	$(P_2-P_1)/(P_{01}-P_1)$
$<Cp_D>$	=	time averaged diffuser pressure rise coefficient
	=	$(<P_2>-<P_1>)/(<P_{01}>-<P_1>)$
C_X	=	flow velocity in equivilent duct
$\tilde{F}$	=	non-dimensional throttle pressure drop
	=	$\Delta P_t/(1/2\rho_{ref}U^2)$
F_C	=	compressor pressure forces on duct fluid
F_I	=	inertial pressure forces on duct fluid
f	=	frequency
G	=	G-Parameter as defined in Greitzer{19}
K	=	constant
L_C	=	equivilent length of compressor-duct model
$\dot{m}$	=	massflow
$\dot{m}_{cor}$	=	corrected massflow
	=	$\dot{m}\sqrt{\theta}/\delta$
$\tilde{\dot{m}}$	=	non-dimensional massflow
	=	$\dot{m}/(\rho U A_C)$
MR	=	impeller Mach ratio
	=	$M_{tip\ rel\ in}/M_{isentropic\ rel\ exit\ jet}$
N	=	RPM
$N_{\tau C}$	=	number of rotor revolutions
N_{Cor}	=	corrected speed
	=	$RPM/\sqrt{\theta}$
P	=	static pressure
$\mathbb{P}$	=	power
ΔP_C	=	compressor pressure rise(total to static)
R	=	compressor tip radius
$\vec{r}$	=	radius vector
Re_X	=	inlet tube Reynolds Number
	=	$\rho C_X X/\mu$
s	=	meridional casing length of impeller
T	=	temperature
t	=	time
U	=	blade tip velocity
u	=	flow velocity in relative frame
V_P	=	plenum volume
X	=	distance from inlet entrance

x = meridional distance from inducer leading edge
$\tilde{\gamma}$ = non-dimensonal damping coefficient
δ = non-dimensional pressure
= P/P_{ref}
δ^* = inlet tube displacement thickness
θ = non-dimensional temperature
= T/T_{ref}
μ = absolute viscosity
ν = kinematic viscosity
ρ = density
τ_C = compressor response time constant
τ_H = Helmholtz resonator period
ϕ = phase angle
Ω = angular speed of rotation
ω = angular frequency
ω_H = Helmholtz angular frequency
= $2\pi f_H$
$\tilde{\omega}_0$ = non dimensional angular frequency
= ω_0/ω_H

Subscripts

C = compressor
cor = corrected value
F = mixed-out condition
H = Helmholtz
I = inertial
ref = reference condition value
T = turbine
t = throttle
X = characteristic length of X
0 = total condition or y-intercept value
τC = compressor response value

Other

| | = magnitude of
~ = non-dimensional quantity
< > = time averaged quantity

1.1 INTRODUCTION

Centrifugal compressors presently enjoy wide popularity for a range of applications due to their unique combination of high pressure ratio per stage, reasonable efficiency, increased surge margin and low cost. These turbomachines first received substantial study in the early 1900's when they were developed for supercharging aircraft engines. A significant later application was in 1936 when Whittle successfully applied a centrifugal compressor in his first experimental jet engine. In subsequent aircraft engine developement, the multistage axial flow compressor became dominant due to its greater maximum massflow/frontal area ratio. Because of this inherent advantage and through very large R&D investments over the years, the multistage axial compressor has evolved into its present highly developed form. The centrifugal compressor's development on the other hand seems to have been stunted a bit due to the axial's popularity and stands today much less understood. However some of the advantages of centrifugal compressors over axials has sustained interest in their development. In smaller aviation applications such as helicopter engines where the max massflow/frontal area ratio is less critical, centrifugals are the most common form and are currently under extensive development. Their improved surge characteristics over axial compressors has stimulated renewed study for use in large aircraft gas turbine engines in the high pressure compressor section. In the automotive, motorcycle, and trucking industry, turbocharging is becoming popular in improving an engine's maximum specific power output and efficiency and centrifugals are used almost exclusively for these applications. The major reasons for this are low cost, low weight, mechanical simplicity, and high efficiency. In future applications such as adiabatic diesels which require higher pressure ratio turbocharger components, the efficiency and range demands will become more critical and will require a more complete understanding of the stability aspects of the centrifugal compressor.

As in axial compressors, a centrifugal compressor can be perturbed by throttling into an unsteady regime of large oscillating massflows(surge), or a regime of periodic flow disturbances which travel around the compressor case(rotating stall). These two phenomena were observed by Emmons{11} in the early 1950's in a centrifugal machine and were then first clearly recognized as two distinctly different behaviors. A classification of the surge as "mild" or "deep" depending on the amplitude of the massflow fluctuation was also given. In this report, mild surge will be in reference to surge which is occuring when the compressor appears to operating stably at constant rpm and no reverse flow is evident. This oscillation frequency is usually of the order of the Helmholtz frequency. Deep surge, surge breakdown, and simple surge are terms which will be used in reference to surge behavior typified by violent reverse flows and blowdown through the compressor, large pressure variations in the connecting plenum, and frequencies lower than those of mild surge. The onset of this violent instability usually terminates the useful range of the compressor. Deep surge is demarcated on the compressor map as the surge limit line.

Besides producing large mechanical stresses in the compressor and high acoustic noise levels, deep surge represents a fundamental limitation in applications which require a wide stable operating flow. In one such application, the matching of turbochargers to diesel engines, it is desirable to have a compressor performance map that is sufficiently broad so that an engine can operate over its entire rpm and throttle range without compressor surge and/or choking. It is also desirable thermodynamically to run the compressor in the region of highest compressor thermal efficiency. A cutaway view of a typical diesel turbocharger is shown in Figure 1 on page 95. A performance map of a current Cummins turbocharger centrifugal compressor overlayed on a set of typical diesel engine air demand lines is shown in Figure 2 on page 96 and illustrates some of the problems an engineer is faced with in the matching process{14}. From this diagram one can see that the current compressor map width represents a constraint on engine drivability in the 1200 rpm upper power region(compressor surge) and the 2100 rpm upper power region (low compressor efficiency). Since most currently designed turbocharger centrifugal compressors have basically geometrically similar performance maps, the ratio of surge massflow to low compressor efficiency massflow for these compressors is not necessarily optimal and with development could be improved upon. If the surge line for this compressor could be shifted to the left without effecting the right hand region, the compressor would have sufficient range to be well matched to the engine. The objective is then to avoid surge altogether in the engine operating range. It is interesting to note that in fighter aircraft axial gas turbine engines deep surge is the preferred mode of instability(recoverable stall), a reversal in design goals.

With the concept of developing wide range centrifugal compressors for future applications and a desire to increase surge margin in their present line of turbochargers, the Cummins Engine Company embarked on an experimental research program with G.T.L. to determine the fundamental cause of surge and stall in a turbocharger centrifugal compressor. This work is to complement their work in wide range compressors some of which is discussed in detail in Flynn and Weber{14}. The G.T.L research is aimed at providing a more fundamental understanding of the complex unsteady fluid phenomena occuring during surge and surge breakdown.

In the first phase of the project under Vincent Capece, a turbocharger test facility was designed and built. Essential features of the hardware construction included the design and testing of an air ejector to drive the turbocharger using the G.T.L. oil free air supply and steam ejector, installation of steady and unsteady pressure instrumentation in the compressor casing, construction of a high response amplifier for Kulite probes, and loop plumbing. Details of this work are found in Capece's thesis{5}. Using a MINC-11 minicomputer for data acquisition, a steady state performance map was constructed, and a surge line was defined. Some static pressure high response Kulite probe data of the pressure signal at the inducer tip was obtained as the compressor was throttled. FFT results of these traces taken at a corrected speed of 51000 rpm indicated that several subsynchronous frequencies predominated consisting of the mild surge frequency of 28 Hz and several possible rotating stall frequencies ranging from 94 Hz to 269 Hz. No phase information was then available to determine number of stall cells occurring in this regime but the results were very encouraging and seem to indicate that rotating stall in the impeller was present prior to surge. Another significant point discovered was the surge limit line appeared to depend on throttle position and other system parameters.

From the first phase of work, it was evident that many unresolved points remained. Previous centrifugal compressor work in surge concentrated on examining particular flow details inside the compressor (inducer and diffuser rotating stall) with less or no attention to the effects that large changes in system parameters(volume,throttle setting, duct geometry) might have on these details. Capece's work seemed to indicate some throttle dependence on the surge limit and the work of Greitzer in axial compressors showed the large effect of system parameters as quantified in the well known B-parameter on post stall behavior. With these points in mind, it was deemed appropiate that an experimental effort should concentrate on centrifugal compressor surge as a behavior influenced by the entire compression system. A set of research questions was formulated to be addressed in the experimental work. These are:

- How important are test facility system parameters such as plenum volume, throttle area, and air ejector performance on the surge line?
- Does rotating stall and/or full stall in the inducer at high positive incidence angles preceed and/or trigger compressor surge?
- Does a major local flow reversal begin in some other portion of the compressor impeller leading to surge?
- Is diffuser stall occuring and if so how critical is diffuser performance to the surge process?
- Is the surge process due to a system instability, perhaps initiated by the stalling of a particular portion of the compressor?
- Is surge breakdown an axisymmetric phenomena?

1.2 LITERATURE REVIEW

1.2.1 REVIEW OF CENTRIFUGAL FLOW PROCESSES

Before one can understand the mechanisms of stall and surge in a centrifugal compressor, a brief review of the normal flow patterns in a typical unstalled centrifugal compressor is in order. These flows are extremely complex and difficult to model mathematically but some of the main flows are understood at least qualitatively.

In the inlet duct, the main core flow is essentially straight and irrotational. A converging section in the compressor housing accelerates this flow into the axial inducer section of the impeller. The inducer, consisting of a number of thin, sharp edged relatively straight vanes, is designed as an axial compressor diffuser as described in Dean{7}. This constant inner and outer radius passage is usually designed for maximum pressure recovery of the relative inlet velocity. The flow, unlike that in a 2-D diffuser however, is rotating in the passage due to the zero vorticity in the absolute frame of reference along the compressor axis. The diffused rotational flow leaves the inducer and enters the radial section of the machine. The flow is then carried out through a radial centrifugal force field where the angular momentum of the fluid is increased. Part of the compression is achieved via a conversion of potential energy in the c.f. field to pressure rather than by a pure diffusion process as in an axial compressor. This is a rather important point and explains why a centrifugal compressor is less limited by diffusion losses in producing a given pressure rise than an axial compressor. The radial c.f field induced pressure rise can be large at low or zero massflows making the centrifugal compressor characteristic less positively sloped in this region which is favorable for system stability as will be discussed later. The tangential acceleration(Coriolis acceleration) of the fluid particles, which occurs as the fluid particles move radially outward and increase their tangential velocity and angular momentum, is achieved by the pressure gradient across the radial passage set up in the loaded blading.

This is more clearly understood if one examines the terms of the equation for the substantial derivative in the rotating frame as given in {41}

$$\left(\frac{Du}{Dt}\right)_R = -\frac{\nabla p}{\rho} - \Omega\times(\Omega\times\vec{r}) - 2\Omega\times\vec{u} + \nu\nabla^2\vec{u} \qquad (1)$$

pressure centrifugal Coriolis viscous

A convenient way of thinking of equilibrium in the circumferential direction in the rotating frame is by requiring a force balance between a pressure forces and the Coriolis "force". This is mathematically equivalent to thinking of the flow as accelerating tangentially in the absolute reference frame at exactly the rate denoted by the Coriolis acceleration from the pressure forces. These forces and the radial forces present on a fluid particle in a rotating passage for inviscid flow are shown in Figure 3 on page 97.

The origin of the pressure gradient across the passage which provides the tangential acceleration of the fluid particles can be explained by thinking of the flow as the sum of two superimposed flows assuming inviscid unseparated flow{23}. The main part, a radially outward moving flow is superimposed upon a circulating flow, which is a consequence(as in the inducer) of the air molecules tendency to preserve zero vorticity in the absolute frame. This superposition is also shown in Figure 3 on page 97 and leads to a velocity and pressure gradient across the radial passage. This explanation is somewhat oversimplified but illustrates the main feature of the flow. The radial outward flow velocity is reduced on the pressure side and increased on the suction side. Some early computations in an NACA paper by Stanitz{38} in 1949 illustrates this quite clearly and also shows the slip factor effect at the exit of the channel and the relative eddy formation on the channel pressure side blade surface.

As discussed in Dean{7}, the flow out of the inducer is often designed to be separated on the suction surface. This region and a separation region on the convex shroud surface are the most typical areas of separation in a centrifugal compressor. An illustration of the separation zones in a shrouded impeller from Fowler{15} is shown in Figure 4 on page 98. Separated flow present in the impeller can vastly alter the flow field from the inviscid unseparated flow described previously. This separated flow consists of a jet region and a wake region. A separation bubble on the impeller blade suction surface acts as a flow blockage and causes a high speed jet of fluid to exist closer to the pressure surface. The velocity profile across this passage will be different from the inviscid case in that higher speed flow exists near the pressure surface area of the impeller rather than on the suction surface. The size of the separation bubble will determine how altered this jet-wake flow will be from the ideal unseparated one. The same sort of altered flow can be present when discussing the velocity distribution existing across the channel passage from hub to shroud. However in an unschrouded impeller the wake region will be modified by the moving casing wall induced secondary flow.

Turbulence and secondary phenomena also exerts an extremely significant effect on impeller flow. Turbulence acts as to separate the high speed fluid particles from the low speed particles. Since the average pressure gradient across the passage is a result of the mean flow conditions, high velocity particles will be accelerated by the larger Coriolis forces, and low velocity particles will be accelerated by larger pressure forces. This action causes the fast particles to move up the pressure surface while slow ones will accumulate on the suction surface. Hence this enhances the jet-wake flow descibed previously. Effects of turbulence from Balje'{1} are also illustrated qualitatively in Figure 4 on page 98.

The turbulence and secondary flow effects in wake formation are discussed in Balje'{1} but are not very well understood. The secondary flows set up in the impeller is generated when the initial axial vorticity present in the flow at the inducer(in the rotating reference frame) is turned both radially outward and tangentially in the impeller. The main secondary flow generated is the circulating flow in the axial direction as shown in Figure 3 on page 97 but vorticity in both the radial and circumferential directions is also generated due the fact that vorticity vectors are convected with streamlines and stretch and change in the same manner as a fluid line in the flow. The main effect of the vorticity present in the impeller passage is to sweep flow from the hub region up the suction surface to the schroud region. This is enhanced by the moving casing wall in unschrouded impellers.

A secondary flow effect which is very influential on compressor performance occurs when the flow leaves the impeller, the circulatory flow causes the tangential leaving velocity to be slightly lower than the blade tip speed. This "slippage" in tangential velocity is quantified by the slip factor. Further complications due to the blade wake and leakage from the pressure side tip region(high pressure jet area) to the suction side wake region are present in this exit region and increase the flow slippage at the exit. The exit region also interacts with the downstream diffuser region to produce an extremely complicated flow. This flow region is unsteady in both the rotating frame and stationary frame and is probably the least understood flow in centrifugal compressors. Some of these effects and others including supersonic flow, shocks, tip vortices, and skew boundary layers are shown in Figure 5 on page 99, a NASA pictorial{2} of some of the more interesting centrifugal flow phenomena earmarked for future research efforts.

The diffuser's effect on a centrifugal compressor is critical but the highly unsteady flow entering this region makes flow understanding difficult. The subsonic and/or supersonic flow leaves the impeller and enters a radial diffuser where the high velocity flow is decelerated. Several types of diffusers exist with the vaneless being the most popular in turbocharger compressors. The flow exits the radial diffuser and enters a collection scroll where some additional diffusion takes place and then exits the machine. A more thorough description of all of the previously discussed processes is available in {1},{2},{6},{7},{15},{24},{27},{28},{32},{38},{39}, and {41} for the interested reader.

1.2.2 REVIEW OF SURGE AND STALL RESEARCH

A literature review of stall and surge research in centrifugal compressors yielded a multitude of investigators with varying opinions as to the surge triggering mechanism. Most of the material in the literature can be divided into three general classifications. One class models the compressor as part of a compression system and establishes various slope dependent stability criteria which predict surge onset and stall behavior. A second class examines details of rotating stall in the impeller and diffuser prior to surge. A third group investigates experimentally or analytically the effect various modifications such as casing treatments or impeller modifications have on the compressor surge behavior.

Emmons, Pearson, and Grant{11} conducted a thorough experimental and analytical investigation of surge and stall in both an axial and centrifugal machine and clearly differentiated the non-axisymmetric rotating stall from the annulus averaged oscillating massflow of surge. With their hotwire anemometer installed in the axial gap behind the rotating inducer section, they discovered groups of 3 to 5 stall cells rotating around the compressor case at about 25% of the wheel speed. Two regions of surge oscillations were reported, a mild surge region occuring on the positively sloped portion of the compressor characteristic near the peak at 10.5 Hz, and a second deep surge region of lower frequency at 9.5 Hz. At low speeds, these two surge regions were separated by a quiet surge-free region but at higher speeds, the surge regions expanded in flow width and coalesced thereby eliminating the quiet zone. In the mild surge region, it was also observed that inducer stall cells would form in bursts during the diminishing positive flow part of the oscillation.

The report also presents a mathematical surge model which predicts that surge will occur when the compressor useful work per unit mass curve slope vanishes. This linearized model lacked a dissipating throttle which as pointed out by Huppert{11} would add complexity to their simple dynamic stability criterion. It, being a linearized analysis, also only predicted the surge onset point not the behavior once surge was established.

Taylor{39} considered the stability of a compressor operating in a duct attached to a single plenum with an exit throttle valve. The linearized analysis assumed the compressor characteristic was unaffected by transient massflow changes(quasisteady assumption) and also that massflow at all points in the compressor duct are constant. Two criterion of stability are derived, a static and a dynamic one which depends on both the throttle slope characteristic and two characteristic time parameters associated with the compressor, its related duct geometry, and the plenum. A interesting point brought out is that as plenum size becomes large, dynamic stability is only assured on the negatively sloped part of the pressure ratio curve. The static criterion of compressor stability requires the compressor slope to be less positive than the throttle characteristic. Also pointed out is that the compressor characteristics near the region of violent stall(deep surge) are probably discontinuous or steeply positively sloped.

A particularly important point was brought out in Emmons, Kronauer, and Rockett{12} which explained how rotating stall might be connected to surge stability. The order(or orders) of magnitude difference in frequency between surge and rotating stall are such that it is generally agreed that rotating stall disturbances can not drive surge oscillations directly. They stated:"Thus there is no connection between stall propagation and surge except that the falling pressure characteristic which is necessary for surge excitation may originate in the stall propagation regime".

Toyama, Runstadler, and Dean{40} conducted experimental work on a 9:1 pressure ratio centrifugal stage with a vaned diffuser and reported large oscillating massflows in "stable" region and then surge breakdown. Also observed was the fact that the surge occurred when the diffuser inlet pressure recovery coefficient dropped to .4. Also significant in their results was the finding that diffuser reverse flow did not occur prior to surge breakdown. They concluded that a successful surge prediction model would be more system oriented and should include an entire system analysis of all piping, plenums, and so forth.

In Dean and Young{8}, it is suggested the mild surge oscillation behavior in the stable region of Toyama's experiment is stable as long as the instantaneous diffuser inlet recovery factor is above .4. Some system modeling of Toyama's results was done based on a modified form of Taylor's analysis with a non constant value of compressor slope. The analysis failed to duplicate the Toyama stable oscillations and several possible explainations were given. The major question centered on how to model the instantaneous compressor characteristic. The characteristic used was quasisteady and no time lags were assumed. It was suggested that progress would be made if the instantaneous characteristic could be measured experimentally.

Greitzer{19} considered low pressure ratio axial compression systems and while the details of the compressor characteristics are different from centrifugal machines, much of the system type behavior might be similar. In a break from previous work, Greitzer modeled the instantaneous compressor characteristic as a first order system(i.e. with a time lag). The significant time constant in the compressor was the time associated with the formation of stall cells in the compressor. The non-linear computation which is verified by experiment in Greitzer[20] demonstrated the dependence of system behavior on the well known B-parameter which is defined as

$$B = \frac{U}{2\omega_H L_C} = \frac{U}{2a} \frac{\sqrt{V_P}}{A_C L_C} \tag{2}$$

It is the major influencing parameter on surge cycle behavior and can be thought of physically as being related to the ratio of compressor pressure rise forces to the inertia forces in the compressor and the system ducting. This is more clear if one considers sinusoidal oscillations of duct massflow and compressor pressure rise in a system as shown in Figure 6 on page 100 given by

$$C_X = |C_X| \sin\omega t \tag{3}$$

and

$$\Delta P_C = |\Delta P_C| \sin(\omega t + \phi) \tag{4}$$

Then B can be expressed by

$$B = \left\{ \frac{|F_C|}{|F_I|} \frac{1}{|\widetilde{C}|} \right\} \frac{|C_X|}{U} \tag{5}$$

where

$$|F_C| = A_C|\Delta P_C| = \frac{1}{2}\rho U^2 A_C|\tilde{C}| \tag{6}$$

and

$$|F_I| = \rho\omega L_C A_C U\frac{|C_X|}{U} \tag{7}$$

For a system in which massflow oscillations are driven by compressor with a given pressure rise, then for $|F_C| = |F_I|$ in equation (5) and B will be proportional to $|C_X|$. Hence large B systems will have necessarily large velocity fluctuations to maintain a balance between pressure and inertia forces.

It can also be expressed as being proportional to the ratio of two time constants. This is shown by expressing (2) as

$$\frac{\tau_H}{\tau_C} = \left(\frac{L_C}{\pi R}\right)\frac{B}{N_{\tau C}} \tag{8}$$

where

$$\tau_H = \frac{1}{\omega_H} = \frac{1}{a}\left[\frac{L_C V_P}{A_C}\right]^{1/2} \tag{9}$$

and

$$\tau_C = \frac{N_{\tau C}}{RPS} = \frac{N_{\tau C}2\pi R}{U} \tag{10}$$

One time constant is the Helmholtz resonator period and is related to system parameters as shown in equation (9). The second time constant is the compressor response time which when the compressor is operating in the rotating stall regime is dependent on the stall cell formation time as given by equation (10). The constant of proportionality is dependent on system geometry and $N_{\tau C}$ which is the response of the compressor in terms of rotor revolutions. At small B values, the ability of the compressor to accelerate fluid in the duct via its pressure rise is small(large inertia effect) and its time constant is very large relative to the Helmholtz resonator period. For a given compressor at a given speed, increasing the Helmholtz resonator period by increasing plenum volume constant or the ducting length will increase B. The ratio of compressor response time to the duct-plenum system response time becomes relatively smaller and at large values the compressor will operate essentially quasi-steadily.

The dramatic effect of various B-parameter values is illustrated in Figure 6 on page 100. For small B values of roughly .5, a compressor which steps over the surge breakdown line will seek a new equilibrium point on the compressor characteristic. For B values of .7 oscillatory behavior is shown on the order of the Helmholtz frequency. This is significant in that it may explain the Toyama oscillation{40} as a consequence of time lags in the instantaneous compressor characteristic. These time lags could be due to rotating stall formation either in the compressor impeller or the diffuser. For larger B values of roughly 1.5, the compressor will not seek a new equilibrium point but will instead undergo a limit cycle oscillation in massflow and pressure ratio. At very large B values of 5 or greater this limit cycle oscillation traces part of the steady state operating characteristic line of the compressor. It must be emphasized that this non-linear model is strongly dependent on the shape of the axial compressor characteristics which are substantially different in centrifugal machinery for reasons cited previously but the concepts introduced in the model may be of equal validity for surge prediction purposes.

Flynn and Weber{14} investigate experimentally the effects of various impeller modifications on the surge limit and an interesting mechanism of surge is postulated. Because the inducer section of an impeller is made up of thin relatively straight axial blades, the flow in this section can remain attached to the blading only over a very limited range of flow coefficients. Once this stall range is exceeded, the inducer enters a stall mode and separated flow regions appear in the inducer tip region. At low throttle values, actual tip reverse flows have been measured{29}. Along the flowpath region downstream of the inducer, these separated flows may reattach or not depending on the pressure gradients present. The essential features of the downstream velocity field are shown in results of their streamline curvature program which show a blade surface velocity diagram of a centrifugal compressor impeller at a surge flowrate. This diagram shows a velocity gradient across the channel which becomes quite extreme in the purely radial section of the machine. Extremely low velocities at the pressure surface at the 80% meridional position are predicted. This can be understood by the superposition argument presented previously where, at a point near surge, the radial flow part of the flow is greatly reduced but the circulating part remains essentially unchanged in magnitude being a function of rpm.

Flynn and Weber contend that as surge is reached, the zone of relatively stagnant fluid on the pressure surface grows toward the inducer and via secondary flows is swept to the suction side of the impeller where it adds stagnant fluid to the suction surface wake. As the wake grows larger it begins further upstream where it eventially interacts with the stall region at the inducer suction surface. The initial suction surface wake as discussed in Balje'{1} is formed by both separation and enhanced by the turbulence phenomena described in Section 1.2.1 whereby low energy fluid tends to accumulate on the suction surface. When the inducer stall zone and the wake regions intersect, a major flow reversal in the impeller occurs and surge is precipitated. Again note that inferred in this reasoning is that the surge is precipitated by a sudden drop in the overall pressure ratio curve caused by the "local" flow reversal in the impeller which perhaps leads to the overall system instability. Thus it is reasoned that surge is initiated in the impeller. They conclude that the separation regions set up by the inducer in the impeller and the geometry of the impeller exit and diffuser are the major factors in surge behavior. In their impeller #2 compressor map, which had the best surge performance, it is important to note that the map has characteristics of unusually flat or negative slopes at low flows, a general requirement of system stability which is also a consequence of the large amount of backsweep they employed in their impeller.

Other researchers believe that the surge breakdown is dominated by the diffuser performance. Braembussche and Frigne{4},{16} documented various types of vaneless diffuser stall present in their test compressor. Senoo and Kinoshita{35} derived a critical inlet swirl angle for the developement of rotating stall cells in a vaneless diffuser. They found that the ratio of inlet diffuser width to inlet diffuser radius had a strong effect on the critical angle.

All of these effects discussed may be important in the surge process and it was not clear which were in fact present in the Cummins turbochargers. The importance of the experimental work in sorting the significant from the unimportant became clear.

1.4 EFFECT OF LARGE PLENUM ON COMPRESSOR OPERATION

A large plenum has a couple of advantages which are utilized in the experiments. Since the experimentation was to concentrate on system effects on the surge limit, it was appropiate to vary the volume of the plenum and observe its effect on system behavior. The first system had a small plenum and a high surge frequency. Since B parameter is proportional to the squareroot of plenum volume, a very large plenum would lower the system Helmholtz frequency, increase B, and hopefully make the compressor operate during the surge process in the limit cycle as shown in Figure 6 on page 100. This would be a simple test of the effect of B-parameter on system behavior. More importantly since inertia pressures are low relative to the compressor pressure rise, the compressor would operate nearly quasisteadily with the compressor pressure ratio closely following the plenum pressure ratio.

Since the compressor predictably should operate in and out of surge in a slow, cyclical, and continuous basis and approaches surge in a quasi-steady manner, a large B-parameter cycle provides a second advantage. It allows one to obtain <u>continuous</u> time data via high response instrumentation of the events occuring in the compressor case prior to surge breakdown. The large plenum also slows the instability process down considerably, thus allowing more high response time data to be acquired with the lab A/D system and also adds a degree of safety to the experiment by decreasing the number of surge stress cycles on the compressor. This approach was originally suggested by Prof N. A. Cumpsty of Churchill College in England and forms a major concept of the experiment.

1.5 EXPERIMENTAL APPROACH,WORK AND TESTPLAN

Having selected a primarily experimental approach to the surge phenomena, a major portion of the project envolved building a new turbocharger test facility with a large plenum for turbocharger testing in surge. The original facility was quite cramped, in a very electrically noisy area, and also quite distant from the lab LSI-11 minicomputer and so was disassembled and moved to the second floor to an area alongside the other compressor test rigs. The first phase of this thesis deals with design and construction of a new facility. This work is described in Chapter 2. In Chapter 3, the compressor instrumentation and data acquisition system work is described in detail.

Major goals in the test program then include:

- Generation of a compressor map with surge limit to show the effect of the change in B-parameter

- Measurement of casing wall pressures and diffusion parameters in the compressor as throttle down occured to determine diffuser and/or impeller stall

- Time records and FFT's of the unsteady wall pressures and massflows in the complete compressor during non-surge operation, in mild surge, and in deep surge with particular attention to stall cell presence in the diffuser and inducer and asymmetric flow behavior

- Time records of unsteady pressures and massflow during a deep surge cycle

The testing as described in Chapter 4 includes the results of four separate tests. In the first test, low response data for a steady state map of the compressor was acquired. In the second test, time averaged low response results to resolve the compressor diffusion parameters close to the surge breakdown line was obtained. The third test results document an effort to resolve inducer, impeller, and diffuser stall utilizing the high response probes on the compressor case and the spectral analyzer. In the last tests, high speed A/D time traces of casing pressure and inlet massflow for a surge cycle initiated from the surge limit at 48K are presented.

2.1 NEW FACILITY AND OVERALL PIPING ARRANGEMENT

A facility flow schematic is shown in Figure 7 on page 101 and illustrates the means for driving the turbocharger compressor. Side views of the new turbocharger test facility as designed is shown in Figure 8 on page 102. An overhead view of the facility is shown in Figure 9 on page 103. The essential features of this rig include:

- Turbocharger mounted on a vibration isolated Unistrut stand.
- Large plenum ≈7.5 cubic foot volume at compressor exit.
- Air ejector for driving the turbocharger turbine.
- 3 motorized valves and actuators for throttling the compressor, controlling high pressure primary air to the air ejector, and adjusting the steam ejector vacuum at the turbocharger turbine exit.
- Oil system with tank, cooler, pump, and filter for turbocharger bearing lubrication.
- Manual high pressure air and steam ejector valves for emergency shutdown and backup control.

A photograph of the facility as built is shown in Photograph A on page 159.

2.2 PLENUM CHAMBER DESIGN AND SUPPORTING STRUCTURES

The plenum as designed is show in Appendix A-1. Generally the requirements were:

- Largest volume possible for both a low Helmholtz resonator frequency and a large B-parameter value.

• Maximum length and diameter constraints determined by the original facility floorplan and turbocharger Unistrut stand.

• Long fatigue life of plenum in surge.

• Adjustable volume capability to vary surge frequency and possibly to simulate various turbocharger-engine configurations in future testing.

The original turbocharger facility surge frequency was 28 Hz and it was desired to drop this to between 5-10 Hz. The largest feasible pipe which would fit directly under the turbocharger as shown in Figure 8 on page 102 was a 14 inch diameter schedule 30 pipe. The maximum length was selected to be 97 inches which was the maximum allowable length in the originally planned floor area. The plenum interior volume was calculated to be 7.34 cubic feet. Using this volume, an approximate B-parameter at 33K and at the maximum 69K speedline were calculated. The results of these calculations is shown in Table A on page 41.

The equivalent $(L/A)_{model}$ was estimated by summing the $(L/A)_{equivalent}$ for the compressor inlet, compressor flowpath, scroll, and the compressor exit duct. It was difficult to calculate (L/A) for the compressor and especially the scroll due the complex internal geometry but using estimates a Helmholtz resonator frequency of 7 Hz was predicted at the 33K operating point. A B-parameter value ranging from .755 @ 33K to 1.337 @ 69K is calculated and this falls in the range of values > .7 which produces the desired oscillatory limit cycle behavior as shown in Figure 6 on page 100.

Stress levels in the plenum were calculated and found to be extremely low due to the large .375 inch wall thickness. A longitudinal stress of 338 psi and hoop stress level of 675 psi were calculated based on a maximum

Table A B-Parameter & Helmholtz Frequency Calculation Summary

Plenum Volume=7.341 ft^3 (large plenum)
=.255 ft^3 (small plenum)

$$\left(\frac{L}{A}\right)_{model} = \int \frac{dl}{A_{inlet\ tube}} + \int \frac{dl}{A_{compressor}} + \int \frac{dl}{A_{exit\ tube}}$$

$$= 21.8ft^{-1} + 46.5ft^{-1} + 36.2^{-1} = 104.5ft^{-1} \text{ (large plenum)}$$
$$= 21.8ft^{-1} + 46.5ft^{-1} + 96.8^{-1} = 165.0ft^{-1} \text{ (small plenum)}$$

$A = A_{inlet} = .104ft^2$

Variable	33K Small Plenum	33K Large Plenum	69K Small Plenum	69K Large Plenum
B	.112	.755	.197	1.327
f_H(Hz)	56.4	7.01	67.0	8.34
U(ft/sec)	725.	725.	1516.	1516.
a(ft/sec)	1220.	1220.	1452.	1452.
τ_H(msec)	2.83	22.7	2.37	19.0
τ_C(msec)	3.64	3.64	1.74	1.74
N	2	2	2	2

compressor ratio of 3.6. These are well below the fatigue limit of the plenum cast iron material and hence fatigue life is essentially infinite.

The Unistrut plenum frame was constructed to be capable of holding the plenum when filled with water or oil(≈ 1000 lbm combined total). It was thought at the time that in a future experiment it may be desirable to reduce plenum volume by adding a fluid in the bottom of the plenum. The four crossbraces in the frame are of adequate size to safely bear the load of a full plenum(worst case).

2.3 TURBOCHARGER LUBRICATION SYSTEM

Several changes in the oil system that provides bearing lubrication were made in the new facility. The original cylindrical oil tank was discarded due to the fact that the oil coolers were too high in the tank to heat the oil at a satisfactory rate. A new rectangular tank with a capacity of 4.3 gallons was constructed. A drawing of this appears in Appendix A-2. The original Sercke oil cooler as supplied by Cummins was found to be leaking and was replaced with a Young one pass shell and tube cooler #HF-202-HY-1P. The cooler, hooked in counterflow arrangement, receives cooling water from a water pipe plumbed into a water main in the G.T.L. basement. The drain line also runs downstairs to a drain near the large compressor. The cooler was sized based on an estimated maximum cooling requirement of 26000 Btu's per hour(≈10 hp bearing loss) occuring at 69K operating speed. Since all present operation is limited to speeds below 52K, this cooler is a bit oversized and a small water flowrate(<.5 GPM) is used. Oil heaters are left on during running to make oil stabilization less sensitive to water flowrate adjustment.

2.4 FLOW CONTROL SYSTEM

A great deal of time and effort went into obtaining and installing motorized remote control valves so that a testpoint could be set without stepping away from the instrument panel and computer terminal area. The position of the valves and their associated actuators in the facility plumbing are shown in Figure 9 on page 103. The characteristics of these valves which were purchased from S.M.A Controls in Medfield, MA is shown in Table B.

In the first arrangement in the new facility, the throttle valve was installed in parallel with a hand gate valve, so that if sufficient

Table B Motorized Valve and Actuator Summary

<u>Compressor Throttle Valve</u>	
Type	3 inch Tri-Pak Ball Valve
Actuator	W-K-M ER-10 reversible with 1K potentiometer,60 second close time,120 VAC
<u>Steam Ejector Control Valve</u>	
Type	4 inch Weco Butterfly Valve
Actuator	W-K-M ER-24 reversible with 1K potentiometer,30 second close time,120 VAC
<u>Oil Free High Pressure Air Valve</u>	
Type	2 inch Tri-Pak Ball Valve
Actuator	W-K-M ER-10 reversible with 1K potentiometer,10 second close time,120 VAC

sensitivity could not be obtained with the motorized valve alone, the gate valve could be opened partially to lower the motorized valve sensitivity. Also it served as a backup in the event of actuator failure. This arrangement was later changed to a configuration featuring a compressor bypass to atmosphere so that more of the compressor speedline could be obtained. This will be discussed more fully in section 2.5.

Pressurized air from the basement oil-free compressor passes through a regulator which is pressurized via a high pressure nitrogen bottle with regulator and a control valve on the instrument panel. This air passes through a second ball valve which serves as an emergency shutoff and then through a motorized 2 inch ball valve and on into the primary nozzle of the air ejector. A second hand valve in parallel with the motorized valve provides a backup or means of fine flow adjustment. The 6 inch steam ejector line has a motorized butterfly valve in series with an emergency hand operated gate valve. The gate valve also was useful for fine adjustments of operating point close to the surge breakdown line.

A valve controller box was designed and built to operate the valve actuators. The controller box displays valve position in percent of full open for each valve on digital panel meters in the controller. Valve position is read by measuring the voltage drop across a 1K feedback potentiometer mounted in each valve actuator. The power supply for the feedback pot and a small power supply for the panel meters are present in the controller box as well as panel lights which indicate whether a valve is opening or closing. Control box machine work details is shown in Appendix A-3 and its associated electronics appears in a schematic in Appendix B-1. Operation of the valves is achieved by manual operation of a self centering toggle switch on the controller corresponding to the desired valve. A voltage (0-10 volts) corresponding to valve position is available on the back panel for A/D data. A picture of the assembled controller is shown in Photograph B on page 159

2.5 SYSTEM FLOW MODELING

In the initial shakedown runs, it was found that one could not cover very much of the compressor map with the 3 inch air ejector. At a N_{Ccor} (corrected flow) of 33K, the compressor was limited to a m_{Ccor} of 38 lbm/min and at 51K, one was limited to 47 lbm/min. It was desirable to increase the speedline widths especially at the higher speeds to look at points far from stall and compare with points which were close to surge breakdown. In an effort to increase the maximum attainable corrected flow on the map, several changes were considered for the rig. These were:

- Change to 2 inch air ejector mixing tube
- Increase oil-free air compressor supply pressure
- Increase compressor corrected flow with inlet screen
- Add compressor flow bypass if turbine choking is occuring
- Bore out air ejector primary nozzle for increased massflow

To examine the effect of each of these changes on the overall system operating point, an approximate system model was developed. Rather than develop a complicated model in which all turbocharger matching conditions were satisfied(RPM, massflow, and work) along with an ejector prediction to determine operating point, a simpler method was used. It was reasoned that a facility operating point could be attained if sufficient turbine power were available to drive the compressor + losses. As one increases compressor corrected flow on a given corrected speed line, a larger compressor power is required and hence more turbine work is needed. Since it was most desired to increase the range covered on the 51K speedline, all calculations were performed for the compressor and turbine operating on this speedline. For the compressor using stations numbered as shown in Figure 7 on page 101, the power is given by

$$\mathbb{P}_C = \dot{m}_C(C_P T_O(\frac{T_{O1}}{T_O} - 1)) \qquad (11)$$

For the 51K speedline in the region of interest, the compressor temperature ratio is approximately constant so

$$\mathbb{P}_C = K_1 \dot{m}_C \qquad (12)$$

Then compressor power is proportional to massflow. For the turbine, a similar expression can be written

$$\mathbb{P}_T = \dot{m}_T C_P T_{O4}(1 - \frac{T_{O5}}{T_{O4}}) \tag{13}$$

A more convenient form of this in terms of turbine corrected flow is

$$\mathbb{P}_T = \dot{m}_{Tcor}\left[\frac{P_{O4}}{P_{ref}}\frac{\sqrt{T_{O4}}}{T_{ref}}\right]\left[C_P T_{ref}(1 - \frac{TO5}{TO4})\right] \tag{14}$$

where

$$\dot{m}_{Tcor} = \frac{\dot{m}_T\sqrt{T_{O4}/T_{ref}}}{P_{O4}/P_{ref}} \tag{15}$$

For the turbine, it is also reasonable to assume its temperature ratio is also approximately constant in the region of interest and thus turbine power is then

$$\mathbb{P}_T = K_2\dot{m}_{Tcor}(\frac{P_{O4}}{Pref}\frac{\sqrt{T_{O4}}}{Tref}) \tag{16}$$

Turbine power increases then can be accomplished by increasing corrected inlet flow thru the turbine and/or increasing ejector performance. For feasible operation at a given point on the 51K line then

$$\mathbb{P}_T \geq \mathbb{P}_C + K_3 \tag{17}$$

where

$$K_3 = \mathbb{P}_{loss} \text{ @ } 51K \tag{18}$$

To evaluate $\mathbb{P}_T$ and $\mathbb{P}_C$, the three constants K_1, K_2, and K_3 were obtained from shakedown experimental data at the rightmost 51K point attainable. Then an ejector calculation was performed to determine the values of m_{Tcor} and $(P_{04}/P_{ref})(T_{04}/T_{ref})^{1/2}$. A computer program EJECTOR was written to calculate the performance of an ejector with prescribed geometry. It uses the mixed-out calculation method of Weatherston{42} also used by Capece{5}.

In Figure 10 on page 104, the effects of ejector mixtube diameter and primary supply pressure are presented. The primary parameter of importance is one of the quantities in equation (14), $(P_{04}/P_{ref})(T_{04}/T_{ref})^{1/2}$ which for a given turbine corrected flow $\dot{m}_{Tcor}$, is proportional to turbine power as shown in equation (16). If turbine choking is occuring, then $\dot{m}_{Tcor}$ will reach a maximum choking value and any power increases will come from increases in $(P_{04}/P_{ref})(T_{04}/T_{ref})^{1/2}$. From data presented in results, the turbine is nearly choked at $\dot{m}_{Tcor} \simeq 33$ lbm/min and so this method of comparing various ejector configurations is reasonable. Each curve is generated by a variation of the compressor massflow(secondary ejector inlet flow) and calculating ejector mixed out conditions $P_F(=P_{04})$ and $T_F(=T_{04})$ and $(P_F/P_{ref})(T_F/T_{ref})^{1/2}$ and $\dot{m}_{Fcor}(=\dot{m}_{Tcor})$.

From Figure 10 on page 104 for a 33 lbm/min choking flowrate, a 2 inch ejector with a 110 psig primary nozzle would effectively increase turbine power $\simeq$ 11.5 % over the current 3 inch ejector operated at 60 psig. 60 psig was the current maximum compressor pressure available in the lab. It was felt that the maximum pressure of 110 psig could be obtained in the lab if the compressor governor was adjusted upwards and only one user was on the system. Clearly then the 2 inch air ejector as recommended in Capece {5} was beneficial. Evaluating $\mathbb{P}_T$ and $\mathbb{P}_C$ and using an estimated 8 hp power loss from the 51K measured point, the results of this calculation are shown in Figure 11 on page 105. At 110 psig primary air pressure, the turbine power is ≈ 10 hp greater than that required to run the compressor. This suggests that the compressor will not run at 51K but will accelerate to some higher speed and power level. To run the system at 51K would require some sort of bypass of compressor flow around the turbine. The predicted maximum compressor corrected flow obtainable with a 2 inch ejector is 55 lbm/min using a bypass. This is a 17% improvement over the maximum measured value of 47 lbm/min achievable with the 3 inch ejector. Figure 11 on page 105 also shows results for the same 2 inch ejector operating at 60 psig. 50 lbm/min without a bypass is predicted for a 12.8% improvement in maximum flow range.

A second approach which seemed reasonable initially was to install a choking screen at the inlet to increase corrected flow by dropping P_O by a factor of 2. If massflow was not greatly effected then this would produce the desired increased corrected flow. Using an inlet screen which dropped inlet P_O to 7.5 psia while maintaining the original T_O(unaffected by screen), the calculations were repeated and the results are presented in Figure 12 on page 106 and Figure 13 on page 107. Figure 12 shows the effect of supply air pressure increases on $(P_F/P_{ref})(T_F/T_{ref})^{1/2}$. With turbine choking at 33 lbm/min the maximum turbine power increase is 13.5% for an increase in primary air supply pressure clearly a gain as in the no-screen case. Looking at power in Figure 13, a maximum corrected flow of

47 lbm/min at 60 psig with bypass is predicted and 55 lbm/min at 110 psig. These results indicate no gain in corrected flow at 110 psig and a loss at 60 psig compared to no-screen case. The effect of the inlet screen is to cause the turbine to choke at a much lower value of turbine massflow(not corrected) and hence maximum massflow and turbine power are greatly reduced. The gain in corrected flow at the compressor is lost by greatly reduced power turbine power.

From this set of calculations, it was concluded that worthwhile improvements would include changing the mixing tube to 2 inches, adding a compressor bypass, and increasing primary air pressure to 110 psig.

2.6 TWO INCH AIR EJECTOR AND BYPASS DESIGN

The 3 inch air ejector was modified for a 2 inch diameter mixing tube. A new axisymmetric contraction section designed by the method outlined in Morel{34} was used to generate the convergent section profile. The profile is shown in Appendix A-4. The details of the design proceedure are presented in a UROP report by Warren Katz{30}. In addition to the ejector modifications, a new expansion round to rectangle transition duct was designed and fabricated to mate the mixing tube to the turbocharger turbine inlet flange. A piece of high temperature marine hose connected the mixing tube to the transition duct. The complete 2 inch air ejector is shown in Photograph C on page 160.

The compressor bypass was made by modifying the hand throttle valve leg which runs in parallel with the motorized throttle valve. The leg ahead of the motorized throttle valve was opened up and the plenum side capped off. The resultant bypass then consisted of a single pipe downstream of the motorized throttle with a hand valve on the end open to atmosphere. These modifications are shown in the flow schematic in Figure 7 on page 101.

2.7 FACILITY OPERATION

Facility operation is discussed in Appendix G

CHAPTER 3 DETAILED FACILITY DESCRIPTION

3.1 TURBOCHARGER

The turbocharger compressor studied in the experiments is a Cummins ST-50 centrifugal compressor with a #3002729 vaneless diffuser case. There are no inlet guide vanes and the impeller has 20 blade passages that are unsplit at inducer and have no backsweep at exit. Tip diameter is 5.035 inches and the inlet hub to tip ratio is .428. Vaneless diffuser parameters include a width/inlet radius ratio of .092 and a outer/inner radius ratio of 1.619. The compressor operates at speeds up to 70000 RPM at pressure ratios of over 3. A picture of the impeller is shown in Photograph D on page 160.

3.2 FACILITY INSTRUMENTATION

3.2.1 INLET

The Inlet instrumentation is shown in detail in Figure 14 on page 108. For calibration of the inlet, a 3 holed cobra probe mounted on a traverse was used to measure the velocity profile. Two traverse mount locations at 90 degrees were made at approximately 1.5 diameters downstream of the inlet entrance. This allowed traversing of inlet at 4 locations which were 90 degrees apart. Two static wall taps 180 degrees apart are present at this location. At 2 diameters downstream a single platinum hotwire(TSI #1210T1.5) is mounted to monitor unsteady velocity in the inlet. It is approximately five impeller inlet diameters upstream of the inducer leading edge out of the local region of unsteadiness which exists in front of the inducer. A shielded type K thermocouple is mounted 180 degrees from the hotwire location to measure the total inlet temperature. Two Dwyer flow manometers with a range of 0-10 inches H_2O are used to measure the static inlet wall pressure which provides a steady state measure of inlet massflow when the inlet is calibrated. The total temperature is read via an Analog Devices microprocessor controlled μMAC-4000 temperature multiplexer.

3.2.2 COMPRESSOR INSTRUMENTATION

Figure 15 on page 109 is a scale drawing of the compressor flowpath and shows casing instrumentation positions. There are seven static wall tap positions in a plane denoted by S1-S7, six Kulite high response tap positions K1-K6, one cobra probe position KL1, and one 3 holed cobra probe position C1. Figure 16 on page 110 shows circumferential positioning of these taps planes on the compressor. Two sets of taps are in the case at -45 degrees and 135 degrees. Kulite tap sets K1-K6 are drilled in 3 planes on the case at 0, 30, 90 degrees. All of these planes were not used simultaneously for any one test. For the inducer tests, three Kulites were installed at the K2 position at 0, 30, and 90 degrees. A fourth Kulite was installed at the plenum location. The taps at 30 degrees were added to the case so that phase measurements of multiple rotating stall cells could be made and the number of stall cells calculated without ambiguity. The multiple taps provide two independent phase angles which serve as a check of the measurement. For the complete compressor tests, eight Kulites were installed at K2, K3, K4, and K6 positions at 0 and 90 degrees. The ninth was the plenum location. The S7 scroll position has 14 static taps placed around it at 22.5 degrees. A Kiel total pressure probe is mounted at the

125 degree circumferential position pointing at an angle 70 degrees from radial in the flow direction to measure the diffuser pressure rise coefficient. This angle was calculated as an average flow direction for the diffuser entrance. Because of the large yaw angle insensitivity of the Kiel probe($\geq$ 40 degrees) the probe angle should not be of any significance and no correction need be applied. The angle probe mounted in the diffuser was not used for the tests discussed in this report.

At the compressor exit, an additional pipe section contains two Kiel probes for total exit pressure measurement, a K-type thermocouple, and four static pressure taps. All compressor static and total pressures are read thru a 48 channel Scanivalve. The compressor exit total pressure is also measured by a 0-60 inch mercury manometer which was also used for Kulite calibration. All temperatures are read by the μMAC-4000 multiplexer. This and other data acquisition hardware is covered in the section 3.3.

3.2.3 MISCELLANEOUS FACILITY INSTRUMENTATION

The air ejector, turbine, and various points in the system are also instrumented with static taps, total pressure Kiel probes, and total temperature K-type thermocouples. A complete list of instrumentation appears in Appendix C. Most of the panel instrumentation remained as V. Capece had originally laid out. The second manometer however was moved onto the panel with the first and the panel leveled. A bearing oil drain thermocouple was added with a panel pyrometer to monitor the bearing exit oil temperature. This thermocouple was added for safety reasons as any oil or bearing problem will tend to cause a high or low reading here. A photo of the instrumentation panel is shown in Photograph E on page 161.

3.3 DATA ACQUISTION HARDWARE

A complete schematic of the data acquisition system is shown in Figure 17 on page 111. The heart of the system is a Digital LSI-11/23 minicomputer which operates several DRV-11 driver boards, a GPIB parallel interface bus(IEEE-488), a Versatec, and several terminals using the multiuser operating system RSX-11. A floppy disc and a Winchester hard disc are used for storing data and the computer program files.

Steady state and low response pressure data are taken by a 48 channel Scanivalve. The Scanivalve is stepped remotely thru an interface by one of the two DRV-11 boards(non isolated DT-2768). A second DRV-11 board operates an A/D converter system previously constructed based on an Analogic MP6912 12 bit data acquisition module and reads the pressure transducer voltage output after a strobing pulse is received from the Scanivalve interface.

The Scanivalve interface was built following an earlier lab design used by T. Eastland{10}. The DRV-11 board has two 40 pin connectors, computer output J1 and input J2. A schematic of this circuit appears in Appendix B-2. A photo of the interface box is shown in Photograph F on page 161. A stepping pulse output from the computer at J1 actuates the interface to step the Scanivalve. The channel # is read by the computer from J2 thru the interface where it is presented as output from an optical encoder in the Scanivalve unit. The pressure transducer voltage output is input to one channel of the A/D and a reading occurs after a strobe pulse appears at the A/D. The strobing pulse was provided in one of two ways for my experiments. For single readings a strobing pulse is output from the Scanivalve interface. For pressure time averaging, the interface output pulse triggers a pulse generator which outputs a gating pulse of long duration(1-5 seconds). This pulse is used to gate a second pulse generator which provides a high frequency square wave(=1000 Hz) pulse train to the A/D. To provide for example a 1000 point average of pressure readings, a one second gating pulse triggered on the first pulse generator is necessary to produce 1000 square pulses at the output of the second pulse generator. This output triggers the A/D 1000 times and then pauses. All data taken in this manner is acquired after the Scanivalve RTR(ready to read) pulse has been output and hence will have no stepping or settling transient in it. The software DATAL3 to operate the Scanivalve as described in the time averaging mode is covered in section 3.4 and a listing appears in Appendix D.

Line drivers were built for the A/D because the computer was over 50 feet from the A/D and in an electrically noisy area. Short duration square pulses quickly lose their higher harmonics via dispersion effects over long lines and can cause erroneous data especially at high data transfer rates. A schematic of the line drivers as built are discussed in Appendix B-3 and a photo is shown in Photograph G on page 162. In this type of line driver, a pair of circuits are required to operate a data line, a transmitter and a receiver. This circuit design was based on one recommended in Horowitz and Hill{24}. With this set of line drivers, error free A/D operation was obtained in the non-scan mode for sampling rates up to 50KHz. A test sampling of a 1 KHz sine wave shows this and breakdown at higher sampling rates.

The RPM signal comes from a magnetic plug placed on the impeller. The 1/rev rotating magnetic field is detected by an induction coil which is placed around the compressor case. The detected 1/rev voltage is amplified and input in an HP frequency counter which is setup for remote operation. The GPIB bus is used to read the counter with subroutine SPEED which appears in Appendix D.

Temperatures on the K-type thermocouples are read using the μMAC-4000 multiplexer. This device is operated via one RS-232 terminal line which is set up as a slave terminal in RSX-11. The terminal driver board #DLV-11 was reconfigured via wire wrap jumpers to provide the proper number of stop bits(2) for operation as it is a non-standard setting. The slave terminal must also have the proper # of fill characters for operation to be successful. Command file SLAVE is used to set the terminal line up and is in Appendix D. Subroutine TEMP operates the multiplexer and a listing appears in Appendix D.

The inlet hotwire signal is conditioned and amplified in a TSI amplifier without linearizer and the output signal can then either be spectral analyzed or recorded using the A/D. The A/D is currently computer memory limited to about 17000 points per trace. The Kulite outputs for the tests were amplified in both the original 4 channel amplifier built for the project and another 5 channel "GTL-Epstein Standard" Kulite amplifier.

The spectral data analysis is performed by an HP-3582A two channel spectrum analyzer. Capabilities of this 25KHz range analyzer include amplitude, phase, amplitude and phase transfer functions, coherance function and time functions. Various types of averaging can also be employed as well as various types of filter passband shapes. The desired high response probe for each of the two available spectral analyzer channels is selected in a manual switch box built for the purpose. A schematic and a picture of this switch network appears in Appendix B-4. The spectral analyzer is operated both manually and in remote operation with the GPIB. Remote mode is used currently to record the spectral data in a data file for later plotting and inspection. Program IBPROG2 is written to read the analyzer data on the GPIB bus and store in a data file and IBPLOT2 is used for Versatec plotting of the spectral results. Both listings are shown in Appendix D.

A Tektronix storage scope with GPIB bus is used to monitor the spectrum analyzer input channels. Records of the screen for a single trace are made by running IBSCOPE2 and then plotting the result with PNTPL4(512 points). Tektronix bandpass filters were used to verify phase measurements of the HP-3582A spectrum analyzer.

3.4 CALIBRATION AND DATA ACQUISITION SOFTWARE

A summary of the important computer programs written for various calibration, data acquisition, and data reduction functions in the project is given in Table C on page 58.
Some of these programs and their associated subroutines is given in Appendix D.

For massflow calibration of inlet, program INCAL was written to integrate the velocity profile measured at each position along a radius in the inlet tube and then calculate δ^* and Re_x where X=3.85 in, the distance from the tube opening to the traverse position. The program was written to accomodate unevenly spaced traverse stations so that many closely spaced points could be taken in the boundary layer and fewer taken in the freestream. Since a linear velocity distribution is assummed between two

Table C Software Summary

Program	Function Description
INCAL	Calibrate inlet using traverse and Cobra probe
HWCAL	Calibrate inlet hotwire
KULCAL	Calibrate Kulites and Scanivalve transducer
PLOTCAL	Plot calibration results of KULCAL
SETAMB	Sets ambient and reference test conditions
SET	Calculates testpoint position on compressor map
DATAL2	Low response data acquisition
DATAL3	Low response time averaged data acquisition
TEMP	Subroutine for temperature multiplexer operation
SPEED	Subroutine for speed counter operation
FILELOW3	Reads data files of DATAL2,DATAL3 and creates plot files
IBPROG2	Reads spectrum analyzer on GPIB and creates plot files
IBPLOT2	Plots IBPROG2 plot files
IBSCOPE2	Reads Tektronix Scope on GPIB and creates plot file for PNTPL4
FREQ2	Operates Analogic A/D in sequential mode and can collect up to 17000 points in one sampling for a data file
DMPLEX4	Demultiplexes A/D scanned time trace data files
PLOTMANY	Plots time trace channel files and other files
SWIRL	Calculates diffuser inlet swirl angle

traverse stations, accuracy of the integration is dependent on the number and their spacing to resolve a region of high shear such as in the boundary layer. Static pressure across the duct is assumed constant and equal to the average of the two wall tap measurements. A compressible flow formulation is used where ρC_X at each station is calculated from measured total pressure and wall static and then integrated over the entire radius. A value of δ^* is obtained by assuming an axisymmetric distribution of ρC_X . To account for non axisymmetric flow blockage, a δ^* at each of four 90 degree stations is calculated(for equal Re_x) and then averaged for a final δ^*.

Hotwire calibration is performed so that during unsteady massflow oscillations, an approximate alternating massflow amplitude can be determined. Roughly 5% hotwire accuracy in velocity is achievable and massflow is somewhat more uncertain since only one inlet hotwire is currently used. This hotwire was intended more as an indicator of massflow fluctuations rather than an accurate measure of them. Since the hotwire is about 5 diameters upstream of the impeller, flow should be mixed out in reverse flow during surge breakdown and undistorted in forward flow. With the small displacement thicknesses in the inlet tube and high enough massflow oscillation frequencies a reasonable linear relationship between hotwire velocity measured and actual massflow should exist.

All Kulite probes and the Scanivalve are calibrated with program KULCAL which averages a number of A/D readings of the transducer output voltage. The mercury manometer head is input into the program for various input pressures provided by a nitrogen bottle. Results of KULCAL are plotted on PLOTCAL.

SETAMB and READAMB are used to set and read ambient conditions for the low response data which includes Scanivalve pressures, inlet flow, and temperature data. The testpoint position on the compressor map and other parameters are calculated by program SET before running DATAL which actually takes the low response data and creates the data file for each point taken. The data file can be read back at terminal or the Versatec using program FILELOW3. This program also organizes and reduces data into plot files for multiple map plots etc. Plotting is accomplished by PLOTMANY.

For high response data acquisition several programs are used. For spectral records of the display of the HP spectral analyzer FFT results, IBPROG2 is used as mentioned in section 3.3. This program instructs the spectrum analyzer to dump the display information from its own internal memory onto a floppy or hard disc. The record can be looked at later by running IBPLOT2 and the results can be Versatec plotted with scaling and a grid. For high speed A/D up to 50 KHz sampling rates, FREQ2 can be used to operate the Analogic A/D. The program creates a disc data file DATA.DAT. DMPLEX4 reads DATA.DAT and sorts the scanned data by channel # for plotting with PLOTMANY. For higher speed A/D operation, traces can be recorded with the Tektronix storage scope and output thru the GPIB and collected on discs with IBSCOPE2.

4.1 PRELIMINARY RESULTS

4.1.1 INLET CALIBRATIONS

The calculated inlet wall displacement thicknesses as measured utilizing the cobra probe traverse are shown in Figure 18 on page 112. These are calculated from the integration of the measured velocity profiles. The δ^* values are plotted vs $1/Re_x^{1/2}$ which for a laminar flat plate solution appears as a straight line passing thru the origin. A linear curvefit with $1/Re_x^{1/2}$ was used to derive a single δ^*_{avg} value for each value of Re_x and is shown also in Figure 18. For the inlet configuration used in all tests, δ^* at 3.85 inches is given by the equation shown in Figure 19 on page 113. The large circumferential variation in δ^* at each flowrate is due to a circumferential distortion in the inlet. This was verified by two measurements taken with the inlet physically rotated 90 degrees and δ^* remeasured at the same radial line. In both of these measurements, the distortion traveled with the rotation and hence were not caused by external room effects. The effective area for each of the 16 measured δ^* values is also shown in Figure 18. The effective area of the inlet at low flowrates is $\simeq$ 96% of the geometric area and increases to $\simeq$ 97% at high flowrates. Using the δ^* curvefit function an inlet calibration curve of corrected massflow vs manometer head was generated and is shown in Figure 19 on page 113. Massflow measurements are corrected to an atmospheric pressure of 14.69 psia and temperature of 545 deg R.

4.1.2 INSTRUMENTATION CALIBRATION AND TESTING

The Scanivalve transducer was calibrated with a 0-60 inch mercury manometer with .1 inch divisions. Maximum error was small and found to be within ± .05 inch of Hg or ±.025 psi. The calibration curve for the transducer is shown in Appendix E. The μMAC-4000 was also checked against a precision laboratory thermometer at several temperatures ranging from 32 deg F to 212 deg F and found accurate to within ±.5% or ±1 deg F. The results of these measurements are also shown in Appendix E. The speed counter was checked with a strobotac and accuracy is ±.2% or ±1 revolution/sec. Kulites were calibrated with the mercury manometer in the same manner as the Scanivalve transducer.

4.1.3 FACILITY OPERATION RESULTS

Steam ejector capacity was measured in the shakedown runs of the completed facility and is shown in Figure 20 on page 114. The upper plot is turbine back pressure and the lower plot represents steam ejector pressure downstream of the 3 inch butterfly control valve. There was no primary massflow in the air ejector for these tests. As seen in the figure, a maximum compressor corrected flow of 52 lbm/min is obtained with the butterfly fully open. The static pressure drop thru the valve and piping at 52 lbm/min is ≃ 1.6 psi which is small compared with the large pressure drop thru the system particularly the turbine.

Near turbine choking is indicated in Figure 21 on page 115 and is a major limitation on operation of the compressor at the speeds above 52K and at higher more unstalled flowrate points on the compressor map. At the choke condition, turbine corrected flow reaches a maximum and any further increases in pressure ratio across the turbine will not affect the corrected flow. The figure shows a leveling off of turbine corrected flow to a maximum value as the pressure ratio is greatly increased. With turbine choking, higher turbine powers can only be accomplished by raising P_{O4} and T_{O4} thru increased ejector performance or by the addition of an inlet flow heater as shown in equation (16).

The two inch mix tube air ejector was instrumented to compare its performance with the original 3 inch ejector. In Figure 22 on page 116, total pressure rise of the pumped secondary stream thru the ejector vs massflow ratio is shown for both air ejectors. The performance of both ejectors are similar at $\dot{m}_O/\dot{m}_1$ values greater than 2.3 but the 3 inch seems to suffer in performance at lower $\dot{m}_O/\dot{m}_1$ values. No data below an $\dot{m}_O/\dot{m}_1$ value of 2 for the 3 inch was available but the data indicated the 2 inch ejector would be an improvement. Mixed out Mach #'s as measured with the pitot tube centered at the turbine inlet are also shown in Figure 22. The 2 inch ejector has a significantly lower mixed out Mach # indicating more complete mixing of the secondary and primary stream. As predicted in the flow modeling in section 2.5, the 2 inch mixtube offers some improvement in performance at 60 psig. Larger improvements should be evident at higher primary pressures but no additional data was obtained to examine this.

4.1.4 COMPRESSOR MAPS

Data points taken in the testing which define a performance map of pressure ratio vs $\dot{m}_{ccor}$ is shown in Figure 23 on page 117. Compressor exit pressure for this map is measured directly by the mercury manometer. Corrected flow is determined by the calibrated inlet flowrate manometer pressure drop. At 33K, the maximum error of the pressure ratio is within .12% of the nominal value and at higher pressure ratios is less. However low frequency unsteadiness in the pressure reading at higher flowrates considerably increases maximum error to typically ±.2 in Hg giving a ±.1 psi accuracy or approximately .5% for pressure ratio.

The maximum flowrate error is determined mainly by the maximum error of the δ^* measurement in the calibration results. Uncertainty in this measurement depends on Re_x but from data presented is less than +.010 inches in all cases. Maximum flow error for a ± .010 inch δ^* variation is approximately ±1% and thus flowrate accuracy is better than ±.23 lbm/min at a flowrate of 23 lbm/min.

The wide speedlines obtained at lower speeds were obtained utilizing the compressor bypass valve discussed in section 2.5. The right point of each speedline is the facility dependent maximum power point. The surge breakdown limits defined in the map are the lowest flow points at which the compressor could be operated at constant speed. To the left of this line, compressor operation was a surge cycle of varying periods depending on speed. At 48K this period was about 2 seconds. Features of the surge cycle obtained included a very audible compressor surge breakdown phase with reverse flow in the inlet, a several thousand RPM drop in compressor speed, and large pressure ratio variations. The surge breakdown line was well defined and repeatable at each RPM. No throttle dependence was noted. A mild surge oscillation of approximately 6-7 Hz begins at points to the right of the compressor pressure peak and grows in amplitude as throttle down continues to the breakdown point. Unsteady hotwire and Kulite measurements of this phenomena will be discussed in section 4.3.1.

The surge breakdown points from the data collected all occur on the positively sloped part of the pressure ratio curve near the peak. Figure 24 on page 118 shows compressor pressure ratio vs mean inlet C_x/U at inducer inlet. C_x is an averaged value calculated based on the known measured massflow and the annulus flow area at x/s = 0 shown in Figure 19 on page 113. The flow is assumed to occupy the full annulus area from r_{max} = 1.4665 inch to r_{min} = .6202 inch. Compressible isentropic flow is assumed. As will be seen this method neglects important details of the inlet flow including possible tip reverse flow and separation bubble regions, circumferential distortions, and rotating stall cells but gives an approximate measure of the average flow angle. The mean incidence angles for the inducer are also shown in Figure 24. At 33K surge point mean inducer incidence angle is +23.6 deg based on a mean blade angle of 42.2 deg measured from the axial direction. At the 51K surge point the incidence angle is +19.0 deg.

Because of the sharp corner which exists in the #3002729 compressor case ahead of the inducer as shown in Figure 15 on page 109, separated flow exists ahead of impeller in the tip region. The wake region after the corner enters the impeller tip area at a velocity much less than the freestream C_x calculated previously. With greatly reduced C_x and large tip speed U, the relative inlet flow angle is very large(almost in the circumferential direction) and the blade tips operate in a stalled condition over most of the compressor operating range. The case precipitates inducer stall much earlier and at higher levels than if the inlet flowpath were more smoothly contoured. Evidence of this will be shown in the FFT results of the Kulite pressure signals in sections 4.3.4

and in section 4.3.2 which presents static pressures on the compressor case walls.

Figure 25 on page 119 presents the compressor performance in terms of pressure rise coefficient Cp_C vs C_x/U which is the form often used for axial compressor maps at lower pressure ratios(incompressible flow). Compressibility effects make the characteristics functions of speed as well as flow coefficient as the figure indicates.

Figure 26 on page 120 presents compressor adiabatic efficiency for the compressor. A fair amount of scatter exists in the data close to surge point but at all surge points efficiency is above 70 percent. The scatter is partly due to the surge massflow oscillation which will be discussed in 4.3.1.

4.2 EFFECT OF B-PARAMETER ON COMPRESSOR SURGE LIMIT

4.2.1 SMALL B VS LARGE B SURGE LIMIT

The substantial effect of a large change in system volume on the surge limit is shown in Figure 27 on page 121. The data of map in the figure has been plotted along with surge limit data from the original system as tested and discussed by Capece{5}. The small plenum system had a substantially larger operating range than the present large plenum system. The B-parameter calculated for the large plenum system ranges from .755 to 1.3 @ 69K while the small system B was calculated as approximately 1/7 of these values. The range improvement seems to be reduced at higher speeds of 51K and higher. Also noteworthy is some scatter in characteristic as the surge limit is reached in the large B system data. This is again due to a large unsteadiness in massflow discussed in section 4.3.1.

4.2.2 DISCUSSION AND COMPARISON WITH LINEARIZED STABILITY ANALYSIS

The shift in surge point can be explained qualitatively by considering a linearized stability analysis of the compressor-duct system as shown in Figure 6 on page 100. For simplicity, the flow in the compressor is assummed incompressible, the compressor inlet and exit duct are of constant area, and the compressor is modeled as an actuator disc. This is the model analyzed in a nonlinear fashion by Greitzer{19} and I will employ the same nomenclature. If we further assume that the throttle duct length is small(equivalently a G-parameter = 0) and the compressor characteristic has no time lag we obtain the following three equations:

$$\frac{d\dot{\tilde{m}}_C}{d\tilde{t}} = B(\tilde{C} - \Delta\tilde{P}) \tag{19}$$

$$\Delta\tilde{P} = \tilde{F} \tag{20}$$

$$\frac{d\Delta\tilde{P}}{d\tilde{t}} = \frac{1}{B}(\dot{\tilde{m}}_C - \dot{\tilde{m}}_t) \tag{21}$$

which are equivilent to (11), (12), and (13) in {19}. If we further assume that both the throttle and compressor characteristic may be modeled as linear in a small region around the steady state operating point then it can be shown that the equation for compressor massflow is

$$\frac{d^2\tilde{\dot{m}}_c}{d\tilde{t}^2} + \left(\frac{1}{B\tilde{F}'} - B\tilde{C}'\right)\frac{d\tilde{\dot{m}}_c}{dt} + \left(1 - \frac{\tilde{C}'}{\tilde{F}'}\right)\tilde{\dot{m}}_c = \frac{\tilde{C}_0 - \tilde{F}_0}{\tilde{F}'} \qquad (22)$$

where

$$\tilde{C} = \tilde{C}'\tilde{\dot{m}}_c + \tilde{C}_0 \qquad (23)$$

$$\tilde{F} = \tilde{F}'\tilde{\dot{m}}_t + \tilde{F}_0 \qquad (24)$$

A derivation of this is shown in Appendix F. The transient solution of this equation is the response of a classic second order system harmonic oscillator with damping. The nondimensional natural frequency is given by

$$\tilde{\omega}_0 = \left(1 - \frac{\tilde{C}'}{\tilde{F}'}\right)^{1/2} \qquad (25)$$

and the damping term is

$$\tilde{\gamma} = \left(\frac{1}{B\tilde{F}'} - B\tilde{C}'\right) \qquad (26)$$

Two stability criteria are essential for the transient solution to be bounded with time. These are

$$\tilde{C}' \le \tilde{F}' \qquad (27)$$

and

$$\tilde{C}' \leq \frac{1}{B^2\tilde{F}'} \tag{28}$$

which are respectively the static and dynamic stability criterion. Since throttle lines are normally quite steep in the region of interest, the dynamic criterion is usually violated first. The dynamic stability condition is equivalently one where the damping of the system vanishes. At slightly more positive values of $\tilde{C}'$, the damping term in equation (22) becomes negative causing a net energy input to occur over a cycle and the transient solution grows with time. The three possible conditions are shown in Figure 28 on page 122. Surge onset occurs when $\tilde{C}'=1/B^2\tilde{F}'$.

Several interesting trends can be observed from this simple model which can be applied to the results of Figure 27 on page 121. Since $\tilde{F}'$ is usually much greater than 1, then for large B in equation (28), the dynamically neutral point becomes $\tilde{C}' \simeq 0$. This finding is similar to the result of Taylor's stability analysis and is also confirmed in the results of Figure 27 on page 121. The second interesting point as shown by equation (25), is that the frequency of the initial instability will for this large plenum system approach the Helmholtz oscillator frequency as C' approaches 0.

This analysis demonstrates qualitatively the major effect of B but it is limited for several reasons. First it can only predict where an instability (surge) occurs. Once the instability point is reached and the oscillations grow with time, the equation becomes nonlinear due to coefficient dependence on instantaneous values of $\tilde{\dot{m}}_c$ and $\tilde{\dot{m}}_t$. The behavior after surge onset is highly dependent on the characteristic curve shapes in the region around the operating point and various effects such as surge oscillations of finite bounded amplitude are not predicted by this linearized treatment. As pointed out by Greitzer{19}, a periodic surge cycle of finite amplitude can be maintained if the compressor characteristic $\tilde{C}(\dot{\tilde{m}}_c)$ satisfies

$$\tilde{C}(\dot{\tilde{m}}_C) > \frac{1}{B^2\tilde{F}'(\dot{\tilde{m}}_t)} \tag{29}$$

over part of the cycle. The existence of just such a surge oscillation will be discussed in the next section. This is a nonlinear effect dependent on conditions around the instability point rather than at the instability point.

The linear treatment also does not consider time lags in the compressor characteristic due to the formation or collapsing of rotating stall cells in the inducer or diffuser. Adding such a lag has the effect of decreasing the instantaneous compressor slope which has a stabilizing effect on the surge oscillation. The $\tilde{C}'$ becomes smaller hence the negative damping term in equation (22) becomes smaller. The effect of time lags in the compressor response will become apparent in the unsteady time response data of section 4.4.1.

4.3 COMPRESSOR STEADY STATE HIGH RESPONSE RESULTS

4.3.1 MILD SURGE OSCILLATION RESULTS AND DISCUSSION

To quickly pinpoint frequencies and phenomena of interest, the spectrum analyzer was used to examine the hotwire and Kulite pressure output amplitudes and phases as throttling proceeded. Accordingly, a series of test point locations were chosen for these FFT tests. These test point locations on the compressor map are shown in Figure 29 on page 123. Points 1 thru 4 and 6 thru 9 refer to test conditions in which compressor RPM and low response pressure ratio are stable. Points 5 and 10 denote FFT data taken to left of the surge limit line which are not really "points" but are in the surge regime where "steady" compressor operation is no longer possible.

The presence of large amplitude low frequency massflow oscillations when operating in the region close to the surge limit is shown in Figure 30 on page 124. This figure shows an FFT of hotwire voltage and plenum amplitude as one throttles down the compressor. The FFT sampling was a 4 point RMS average taken over a 12.5 second period. At points 1 and 6 there is no oscillation as the compressor operates on the negative sloped part of the characteristic and is stable. At points 3 and 8 which correspond closely with the peak of the pressure ratio curve, the onset of surge is detected. At points 4 and 9, a large amplitude massflow and plenum pressure oscillation is observed. This is mild surge. At 33K, this surge frequency is 6.2 Hz. At 48K the frequency shifts upward to 7.2 Hz. This is close to an f_H of 7.5 Hz if calculated by the method used for the results shown in Table A on page 41. Points 4 and 9 represent closest operation to the surge limit without simple surge. These points will be refered to as neutral stability points. Enlargements of the point 4 and 9 FFT results are shown in Figure 31 on page 125 and also a phase measurement in Figure 32 on page 126. The phase measurement clearly shows a 90 degree phase angle between the massflow fluctuation and the plenum pressure. In the spectral analyzer sign convention, minus phase angles are indicated when the reference channel(hotwire voltage) leads the second channel(plenum pressure voltage). Since the A/D was not operational for these tests an estimate was made of the operation path on the compressor map based on the measurements and the calibrated hotwire and plenum Kulite. The operation path for two sinusoid signals of identical frequency with a phase angle of 90 degrees is an ellipse with the semi major and minor axis dimensions determined by the ratio of amplitudes of the two signals. The estimated operation path at the neutral stability points is shown in Figure 33 on page 127.

It is important to remember that this is plenum pressure vs flow rather than instantaneous compressor pressure ratio which would require an inertial correction. However inertia forces are small in this high B system. For example, at 48K a 10 lbm/min peak to peak oscillation at 7.3 Hz will require a ΔP across the entire duct of only .6% of the ΔP across the compressor. Therefore this path should closely track the instantaneous compressor operation path.

The presence of the orbits as shown in Figure 33 on page 127 illustrates some interesting points and brings up a few questions. The speed of the compressor was monitored with a counter type RPM meter that sums 1/rev pulses over a 1 second period and so is not sensitive to rapidly fluctuating speeds. If speed were varying at the surge rate then the excursions of the compressor above and below the steady characteristic can be explained as compressor speed fluctuations. If however the speed is constant over the 7 Hz oscillation, then these excursions above and below the compressor steady state characteristic can be explained as due to both an inertial correction term and/or a compressor characteristic which is also a function of time(i.e. with a time lag). If the inertial term is small, then the compressor characteristic is mainly dependent on time. This is essentially the sort of lag effect discussed in detail in Greitzer{19}. The source of the lag in this compressor is most likely the presence of rotating stall in the inducer. Evidence of this will be presented in sections 4.3.4 and 4.4. Additional evidence will also be shown that suggests that further lag in the compressor response is introduced when the diffuser begins forming rotating stall cells as would occur during the minimum massflow part of the surge oscillation described in Figure 32 on page 126. This can potentially lead to an instability which causes violent stall of the stage. This will become more clear when the unsteady time traces are presented in section 4.4.1.

Upon a slight closing of the compressor throttle, the compressor-system undergoes deep surge, the characteristic Helmholtz frequency becomes less dominant, and the frequency drops. The dramatic change in the character of the FFT signature in deep surge is shown in Figure 34 on page 128 and Figure 35 on page 129. In Figure 34, the presence of a low frequency ≃ 1/2 Hz and its higher harmonics is shown. This indicates a surge cycle of approximately 2 seconds in duration. Phase angles are shown in Figure 35.

The effects of the mild surge oscillation on the pressure field thru the compressor case was also investigated with 8 Kulite pressure probes at locations in the case as described in section 3.2.2. The 90 degree angle between the two probes at each meridional station allowed a quick method of examining the asymmetry of the pressure field. Using the same 4 point RMS sampling technique as for the hotwire and plenum pressure FFT, the Kulite pressure signals were spectrally analyzed. Figure 36 on page 130 shows low frequency FFT results at points 1 and 6 in the non-surge region thru the compressor. Top charts are inducer disturbances and bottom charts represent diffuser exit fluctuations. By reading top to bottom, a spatial picture of flow disturbances is obtained as one travels meridionally thru the machine. No significant surge like frequencies are evident at this stable operating point. As one throttles the compressor down and surge oscillations are encountered, the picture changes substantially. At the neutral stability points 4 and 9 pressure fluctuations corresponding to the surge frequency are seen in Figure 37 on page 131 which further demonstrates the surge oscillation throughout the entire compressor. This also confirms the hotwire and plenum FFT's presented previously.

However an interesting and unexpected result of phase measurements taken of the pressure disturbances between the 0 and 90 deg circumferential locations is shown in Figure 38 on page 132. This figure shows phase angles of data presented in Figure 37 on page 131 at the neutral stability points 4 and 9. Also shown in each chart is the amplitude of the reference Kulite at the 0 deg location. At the inducer(x/s=.09), the surge pressure oscillations are in phase indicative that the oscillation in this flow region is axisymmetric. At the mid-impeller location(x/s=.54), the pressure oscillation is becoming more asymmetric especially at 48K with a 90 degree pressure phase lag. In the diffuser inlet(x/s=1.02) the pressure fluctuations are 180 degrees out of phase which is evidence of a very asymmetric flow field. This is indicative of perhaps some sort of diffuser transitory stalling process whose frequency is the surge frequency. Since the diffuser has a volute section of increasing flow area, it is possible that this asymmetry is a consequence of the scroll geometry.

4.3.2 TIME AVERAGE RESULTS

From the spectral data presented in the last section, it was evident that large oscillations in the compressor point were occuring in a mild surge region near the surge limit as shown in Figure 33 on page 127. In an effort to resolve the average pressures in the compressor case in this region and particularly to resolve the diffuser Cp close to stall, a set of time averaged data sets were obtained with the Scanivalve. In time average mode, the Scanivalve transducer read each static pressure port several hundred times over an integral number of surge cycles(in this case 2 cycles were used). The frequency was observed from the hotwire output displayed on the spectrum analyzer. Employing this approach, time averaged performance maps at 33K and 48K are shown in Figure 39 on page 133 thru Figure 42 on page 136. Some of the scatter in the previous maps is eliminated in these maps particularly in the adiabatic efficiency vs corrected flow. This scatter is probably due to the diffuser flow asymmetry and the surge oscillations. The positively sloped region immediately prior to surge breakdown is well resolved in both speedlines.

Figure 43 on page 137 and Figure 44 on page 138 present time averaged casing static pressures for two speedlines 33K and 48K. For each speedline, two series of curves which correspond to the two circumferential static tap positions S1-S6 at -45 degrees and 135 degrees as shown in Figure 16 on page 110. Throttle down corresponds to moving upwards on the plots from high to low massflow.

Several points may be observed from these curves. the 33K speedline has an asymmetry in casing pressure which is large in the inducer region at high flowrates. At the surge flowrate(upper curve), the asymmetry becomes negligable. This could possibly be some sort of geometric distortion in the case or a case not concentric with the rotor centerline. A 4 mil radial clearance variation was measured which could via reverse leakage flows cause uneven blockage at the tip area just ahead of the inducer. Another possibility is that the asymmetry in wall pressure is introduced by the collection scroll which has circumferentially varying area. The pressures at x/s=2.25 which correspond to the scroll are fairly close in pressure however.

The most plausible explaination of the asymmetry is inducer inlet flow distortion introduced by the converging section which ends in a sharp corner ahead of the inducer in combination with the radial clearance variation. This unmachined converging section is part of the casing casting and typically large tolerances of the casting could lead to a nonconcentric or irregularly shaped inlet section. A nonconcentric inlet section would for example introduce more flow to one side of the inducer then the other creating a pressure difference between the two sides. The wider spread of pressures at S1 at -45 deg could be a result of such a distorted flow introducing more massflow on this side than at the 135 deg location.

The distorted inlet flow hypothesis also supported by the much larger pressure drop which is incurred in the inducer at flowrates of 37 lbm/min and above. In this area of the map, the inducer no longer acts as a diffuser because incidence angles are negative and the passage appears as an area reduction. Larger than mean C_x values from a distortion would manifest themselves as a greater pressure drop. Blade blockage is also responsible for some of the pressure drop however. At higher wheel speeds C_x variations are less noticable as incidence is at more positive angles. Figure 44 on page 138 shows the casing pressure distribution at 48K. The -45 degree location again shows lower pressure at S1 and higher pressure at S7 as at 33K.

The diffusion parameters as measured in the time averaged Scanivalve mode are presented in Figure 45 on page 139 thru Figure 47 on page 141. The Mach ratio MR is an important impeller diffusion parameter and is defined as the ratio of the inducer relative inlet tip Mach Number divided by the isentropic relative exit jet Mach Number. The inducer tip Mach Number was estimated assuming an area averaged axial Mach Number and then calculating from the tip velocity triangle the relative tip inlet Mach Number. The exit jet Mach Number is the Mach Number attained in an isentropic expansion to the measured exit static pressure from the relative inlet condition. The resulting Mach Number's are plotted in Figure 45 and the ratio of the two in Figure 46. A rather odd knee develops in the 33K Mach ratio curve, the significance of which is not clear. Both stall points occur at similar Mach ratios of approximately 1.75. A great deal of scatter is observed in the Mach ratio near the surge limit.

Of more interest and significance are the time averaged results of the diffuser pressure rise coefficients shown in Figure 47 on page 141. Two <Cp>'s are shown, an overall value which includes the scroll, and a radial diffuser value which refers only to the pressure rise in the radial section of the diffuser. From our FFT phase results of the diffuser, an asymmetric diffuser flow is occuring. The time averaged diffuser <Cp> results in Figure 47 show a dramatic peak in <Cp> occuring at the compressor pressure ratio peak and then as throttling continues a precipitous plunge in diffuser performance. The steeply positively sloped portion of the <Cp> curves is the region of surge oscillations. At the surge limit, the vaneless diffuser pressure rise coefficient is approximately .4. There severely degraded diffusion is occuring in the diffuser prior to surge.

The effect of B-parameter on vaneless diffuser Cp is shown in Figure 48 on page 142. Diffuser data of the small plenum system is compared with the large plenum system at identical speeds and corrected flowrates. At 33K the diffuser Cp peaks much earlier in the large B data and plummets to the stall flowrate. The small B diffuser Cp peaks later and then falls off and stall occurs. The small B data was not time averaged but clearly indicates the markedly different performance the diffuser has when a system parameter is changed. At 51K, the highest practical speed obtained in the system again markedly different diffuser trends are again in evidence depending on B. The remarkable difference in diffuser Cp is due to the large surge oscillation present in the massflow. This is a consequence of the instability considerations presented in section 4.2 which relate surge onset and post surge onset behavior with B. Slight surge oscillations may in fact improve diffuser performance as evidenced by Cp peaking before the Cp drop occuring at large massflow oscillations near surge breakdown. This could be a boundary layer effect similar to that in wing flow where oscillations in angle of attack tend to stabilize the boundary layer and delay separation of flow to steeper angles of attack. Very little data exists on unsteady massflow effects on the diffuser performance which appear to be important here.

Because of the strong influence diffuser Cp has on the shape of the compressor characteristics, an estimate of the centrifugal compressor pressure ratio at near shutoff conditions was made for values of diffuser Cp of 0 and .4. The results are shown in Figure 49 on page 143. The calculation assumed that the inducer had no pressure recovery(fully stalled) and that the total pressure rise was due to centrifugal pressure rise in the radial part of the impeller and diffusion in the radial diffuser. The large slope difference in the small flow region illustrates how significant the diffuser performance is to overall compressor stability(slope and B-parameter dependent).

4.3.3 CRITICAL DIFFUSER SWIRL ANGLE

As the diffuser Cp data indicated in section 4.3.2, diffuser performance degraded rapidly in the surge oscillation region near the surge limit. The work of Senoo{35} has identified critical swirl angles at which rotating stall in the diffuser appears so a calculation of diffuser inlet swirl angle was performed to see if a critical swirl angle was associated with surge breakdown. The calculation used data from both the time averaged runs and the earlier performance map data presented in 4.1.4. Two methods were employed to calculate the average diffuser inlet velocity vector and the swirl angle. The swirl calculation made the assumptions of axisymmetric, compressible, and uniformly mixed out flow at the inlet. Measured imput parameters to program SWIRL for both methods include the measured m_{Ccor}, RPS, T_{01}, T_{02}, and P_{01}.For method A, the diffuser inlet stagnation pressure as measured by KL1 is input. In method B, which is used as a check, the static pressure as measured at this location is used. A summary of the results is shown in Table D on page 80 in which average swirl angle at all surge limit points are calculated. No swirl data was available for the small B system. Program SWIRL is shown in Appendix D.

Table D Average Diffuser Inlet Swirl Angle at Surge Limit

Point #	RPM	m_{Ccor}(Lbm/Min)	Angle(Deg)$_A$	Angle(Deg)$_B$
1 Time Av	33K	22.7	74.6	75.1
2	33K	23.0	73.8	74.5
3	39K	29.7	72.9	73.3
4	45K	35.5	73.3	73.4
5 Time Av	48K	39.5	73.4	73.7
6	48K	39.0	73.8	74.0
7	51K	42.8	73.9	74.1

It should be emphasized that the swirl angle in the table is an average value as the real swirl angle oscillates due to the large surge massflow fluctuation present near the surge point. The results of table D show the average swirl angle for method at 73.7 degrees from the radial with a standard deviation of .5 degree. Method B swirl angles are at slightly higher levels averaging 74 degrees, the difference almost insignificant. The important point here is the very small standard deviation between critical swirl angles and the almost negligable difference between A and B. This appears to support the previous evidence for diffuser stall as being of major importance in the stage stall event in this compression system.

As stated previously, the real swirl angle oscillates and it might be expected then that surge breakdown would be initiated when the minimum swirl angle reached the critical level during the flow oscillation rather than a dependence on an average angle. For small oscillations, there would be no distinctions between the two criteria. In the present test results, the massflow oscillation amplitudes are of decreasing size as speed is increased so swirl angle oscillation amplitudes are also decreased.

4.3.4 STALL CELL FFT RESULTS

Frequencies which appeared to indicate inducer stall cells were detected by Capece but no phase was measured to determine number of cells and propagation speed if these disturbances were rotating stall cells. In an effort to document rotating stall-like phenomena on the map, two experiments were performed utilizing the Kulites.

In the first experiment, three Kulites were installed at the K2 inducer location at 0, 30, and 90 degrees as shown in Figure 16 on page 110. The 30 degree probe would serve as a check of phase angle if multiple stall cells were detected. The results of these are presented in Figure 51 on page 145 and Figure 52 on page 146. Calculated tip incidence angle based on an area average axial velocity is shown in Figure 50 on page 144 for reference. In Figure 51, the results of a 32 point average FFT shows two frequencies of interest, a 1/rev frequency and a lower 220 Hz stall cell frequency. The 1/rev signal is believed to be caused by a geometric abnormality in the impeller blading or perhaps by mechanical vibration induced Kulite excitation. The stall cell frequency is confirmed as a rotating disturbance by the phase results shown in Figure 52. From this phasing information, at 33K the inducer has a single stall cell rotating around the case at approximately 42% of rotor speed. The pressure amplitude of this cell varied with flow in a curious manner. At high flows a single cell seemed to be present which disappeared at slightly lower flows. The sharp edge in the compressor case as mentioned in section 4.1.4 probably helps promote inducer stall cell formation at this high flowrate. As throttling continued, the cell reappeared and rapidly reaches a peak in amplitude near the pressure peak. At flowrates less than 26 lbm/min the cell amplitude remains fairly constant but the surrounding frequencies rise up and tend to drown out the stall cell signal. This is due to the large oscillations of flow in this range which make the stall cell a highly transient phenomena. The stall cell is not of constant amplitude but is being modulated with massflow i.e. is forming and collapsing in time. This transient nature will be made clearer in section 4.4 and was not recognized at the time the tests were made.

The second rotating stall cell experiments were performed in an identical manner to those described in section 4.3.1 only with a 0-1000 Hz frequency range selected on the spectrum analyzer. The keyed test points are those shown in Figure 29 on page 123. Phase angle between each of the Kulite probes was 90 degrees at all meridional stations.

Figure 53 on page 147 thru Figure 55 on page 149 present the plenum and hotwire results during throttle down. Of interest in Figure 53 is the presense of the 1/rev signal at point 9 which is small at point 6. The 1/rev frequency could be an unsteady flow field effect of a geometric rotor assymmetry or possibly due to mechanical vibration of the turbocharger that induces aerodynamic excitation of the hotwire.

The results of the rotating stall FFT's are presented in Figure 56 on page 150 thru Figure 59 on page 153. Figure 56 is stall cell like frequencies thru the entire compressor at high flow(points 1 and 6) and

Figure 58 is at the low flow neutral stability points(points 4 and 9). Of particular interest is the 48K speedline at both high and flow. At high flow, the inducer has several rotating stall frequencies including a small disturbance at 90 Hz, a second at 280 Hz(approximately 35% of wheel speed),a third at 500 Hz, a fourth at 560 Hz(a harmonic of the second), and a 1/rev seen in most of the data. The 280 Hz rotating stall extends to the mid-meridional position(x/s=.54) as shown in Figure 56 on page 150. A slight amount of activity at the diffuser at this frequency is also shown. The phase measurements for these points are shown in Figure 57 on page 151. Again a phase angle of 90 degrees is shown indicating a single stall cell in the inducer(x/s=.09) and mid-impeller area(x/s=.54). At the low flow neutral stability points FFT results in Figure 58 on page 152 show the single 280 Hz stall cell frequency present throughout the machine at 48K. This does not suggest that a rotating stall cell of this frequency is present in the whole machine but indicates that the inducer stall cell is driving and creating 280 Hz disturbances in the diffuser entrance and exit(x/s=1.63). Phase information is presented in Figure 59 and is quite erratic due to the transient nature of the stall cells.

4.4 SYSTEM INSTABILITY IN A SURGE CYCLE

4.4.1 UNSTEADY A/D TIME TRACES OF A SURGE CYCLE

In the last experiment, unsteady A/D data of the massflow and pressure events in the compressor case were acquired during a deep surge cycle. The Kulite transducers and inlet hotwire are again in positions as shown in Figure 15 on page 109 and Figure 16 on page 110 identical to the positioning in previous tests. Surge breakdown is caused by a slight throttle closing while the compressor is operating at the neutral stability point(surge limit) at 48K. After the initial perturbation the system enters a deep surge cycle of approximately two seconds duration. Once the periodic behavior of the surge cycle was established an A/D record of the cycle was obtained. The resulting time histories are shown in Figure 60 on page 154 thru Figure 62 on page 156.

In Figure 60, massflow and plenum pressure vs time are shown. Due to computer memory limitations the full 2 second surge cycle was not recorded as it was desired to sample the 10 channels at 1000 Hz/channel to resolve rotating stall cell frequencies on the order of several hundred Hz. Also due to the coupling between the turbine drive system and the compressor, the speed was not constant over much of the cycle. However in the final approach to surge, the speed was slowly increasing towards 48K and is fairly constant with most significant speed change occuring after the surge breakdown phase when the plenum is being pressurized again.

The massflow as shown in Figure 60 on page 154 is calculated based on the known hotwire voltage output vs inlet massflow for steady flow in the inlet. Inlet massflow is obtained from the inlet calibration data presented earlier. The effects of unsteady boundary layer activity from oscillating flow and flow reversal are not corrected for in this calculation. The magnitude of these effects is not accurately known and therefore the massflow as plotted may have significant error associated with these effects. The hotwire output serves only as an approximation rather than an accurate measurement of massflow.

As a single hotwire does not distinguish forward from reverse flow, the trace was corrected for this. The high frequency components of velocity shown in reverse flow which coincides with the blowdown phase of the plenum allowed a good estimate of the extent of this region. The high frequencies are due to rotating stall and other non axisymmetric flow which create large velocity fluctuations as they pass out thru the inlet. This reverse flow was confirmed by both plenum pressure drops and by a hand placed near the inlet during the surge cycle. Substantial puffs of air could be felt during the blowdown part of the cycle.

From t=0 to t=300msec, one can observe a massflow oscillation which is roughly constant in amplitude and nearly sinusoidal. The waveform is nonlinear however in that the time interval from valley to peak is shorter than the interval from peak to valley. The frequency of the oscillation also drops slightly with time between peaks getting longer. At t=400msec, the oscillation period has lengthened and the amplitude continues to drop and reaches a new low at t=460msec($\dot{m} \simeq 10$ lbm/min). Note how far to the left of the nominal surge limit line the massflow is (39.5 lbm/min) and yet surge has not yet occured!. The oscillation becomes more nonlinear with the increasing massflow portions becoming much more steeply sloped and the decreasing massflow sections also steepening but at a slower rate. The massflow recovers very quickly into an overshoot condition perhaps a consequence of the high positive compressor slope existing in the small flow region which greatly increases the system damping (as expressed in equation (26) to large <u>negative</u> values. This effectively causes a large increase in the rate of mechanical energy addition into the system by the compressor which cannot be dissipated as quickly in the throttle. At t=520msec, the flow turns around and decreases to the reverse flow range at t=680msec. The crash to reverse flow starts at a very slow rate after the overshoot and is controlled by the dissipating effect of the throttle as the compressor slope is small in the large flow region of the map. The negative part of the damping term as given by equation (26) is small. The massflow trace however steepens considerably as the crash progresses and, decelerating rapidly, is nearly vertical as reverse flow is encountered. This is due to the increasing negative damping contribution of the compressor as the compressor operation point moves during the crash to more positively sloped areas of the performance map.

The period of the unstable oscillation is seen to increase as the compressor moves towards flow reversal. Most of the increase in period occurs in peak to valley portion of the oscillation. One reason for this is that as the oscillations increase in amplitude more mechanical energy per cycle is inputed which since throttle dissipation occurs at a relatively constant rate then requires more time for dissipation. A second is that the compressor operates in an average sense on more positive compressor slopes which therefore lowers $\tilde{\omega}_0$ via equation (25).

Increases in τ_C also occur due to increased stall activity(stall cell formation) in the diffuser. Such activity would have the effect of lengthening τ_C and thus effectivily increasing $N_{\tau C}$ in equation (8) in the Greitzer model. The reason for this is that since the speed is gradually increasing in the approach phase to surge blowdown, the inlet swirl angle in the diffuser is on the average becoming more tangential. When the critical swirl angle is reached, the the formation or collapse of stall cells in the diffuser will add to the overall compressor τ_C and tend to slow down the oscillation by adding lag in the system. Detailed nonlinear modeling of these effects will be needed to verify this. Also a better method of speed measurement is needed to monitor the speed change in the oscillatory approach and surge blowdown phases of the cycle.

At approximately t=680msec reverse flow is underway with the associated large pressure drop in the plenum from mass continuity considerations. The high frequency content of the hotwire signal is evidence of substantial rotating stall passing out through the inlet. At t=840msec, the flow recovers to positive flow conditions. Acceleration of the flow is very rapid appearing almost vertical on the plot. Overshoot is again in evidence in flow. At t=1.2sec, the flow is again constant after a settling period. The time constant associated with recovery is the fill up time for the plenum which is emptying thru the throttle(and the turbocharger turbine). At t=1.5sec, there is still no evidence of Helmholtz oscillations. These build up in the missing portion of the cycle.

The question in these results concerns the mechanism which causes the downward swing of massflow at t=.4sec to continue to lower values and thus trigger the general system instability. Clearly since the period of the oscillation has increased it might be associated with a sudden increase in system damping. This, as mentioned earlier, may be associated with the sudden increase in the compressor τ_C associated with the formation of diffuser stall cells. Such an increase in τ_C would make the instantaneous value of $\tilde{C}'$ smaller thereby adding damping in equation (26). Evidence of this activity is shown in Figure 61 on page 155 and Figure 62 on page 156.

In Figure 61, the behavior of K4 which is the diffuser inlet location appears to have some unusual behavior. The frequency of the oscillations appears to be modulated by the massflow oscillation. In the 0-400msec range, if you note where the minimum massflow occurs in each massflow oscillation cycle, the frequency of K4 drops a short time later to a lower frequency. It would appear that rotating stall is occuring in the diffuser and is changing the number of stall cells in response to the massflow oscillation but with a time lag. The same behavior to a lessor extent is shown in traces of K2 and K3. Also clearly seen on K2, K3, and K4 is the formation of cells starting at t=1.2sec.

At t = 400msec, the character of the diffuser pressure traces at K4 and K6 in Figure 61 appears to change. At K6(the diffuser exit), small downward spikes of pressure begin appearing and at K4 the rotating stall disturbance appears to have collapsed. Previous to this moment, the K4 trace appeared to be highly modulated both in frequency and amplitude. This appears to be a momentary diffuser stall. Contrarily the impeller pressure ratio as shown by K4 does not appear to suffer any appreciable drop from stalling prior to reverse flow. Hence an impeller stall does not appear to trigger the instability.

Considering the events as an imbalance in pressure forces via equation (19) coupled with equation (21) is helpful in explaining the time trace behavior. In equation (19), B serves as an amplification factor of any transient changes in compressor or plenum pressure rises $\tilde{C}$ and $\widetilde{\Delta P}$. The output variable is massflow acceleration. In a large B system, the amplification of pressure rise disturbances is large and necessarily large fluctations in massflow are required for a balance between inertial and pressure forces. Conversely in equation (21), B is an attenuation factor for time rate changes in plenum $\widetilde{\Delta P}$ from changing values of $\dot{\tilde{m}}_C$ and $\dot{\tilde{m}}_t$.

The apparent drop in instantaneous compressor pressure rise $\tilde{C}$ relative to the plenum $\widetilde{\Delta P}$ induced by the diffuser stall causes a sudden imbalance in pressure forces on duct fluid and $d\tilde{\dot{m}}_C/dt$ is driven negative for a short time. At t = 460msec, rotating stall grows at inducer and appears to propagate through the machine. Rotating stall appears at the inlet hotwire also as higher frequency components. Here the massflow time trace slope is again flat as is shown in Figure 61. This suggests that again a balance of $\tilde{C}$ and $\widetilde{\Delta P}$ has occured. However the plenum pressure which responds more slowly than the compressor to large changes in massflow is still falling.

At t=480msec, the plenum pressure has dropped sufficiently so that the compressor pressure rise $\tilde{C}$ becomes larger than the plenum $\widetilde{\Delta P}$ contribution. Thus the massflow changes direction moving toward higher massflow. As the flow increases, the compressor quickly recovers pressure rise and both the diffuser and inducer appear to recover. This creates more pressure driving force on the duct fluid and the flow accelerates positi·ely. The plenum pressure responding to the steplike increase in massflow slowly via equation (21) increases again until some balance between $\tilde{C}$ and $\widetilde{\Delta P}$ is again achieved. This balance is temporary however. The massflow time trace appears then to slowly steepen negatively in slope as plenum pressure continues rising. The duct pressure forces get larger decelerating flow again towards low flow. Because of the high mass flowrate during the overshoot period, a longer period is required for plenum to drop in pressure. The large $\widetilde{\Delta P}$ pressure imbalance forces $d\tilde{\dot{m}}_C/dt$ to higher negative values. Rotating stall appears again at the inducer which causes $\tilde{C}$ to drop more. Because this drop in $\tilde{C}$ occurs so much more quickly the pressure imbalance becomes extreme and reverse flow results.

The surge is then initiated by a slight drop in diffuser Cp from a momentary stall condition which has the net effect of driving the entire compression system unstable. From the initial diffuser Cp drop to surge is slightly larger then 1 cycle or ≃ 280msec. The pressure rise in the diffuser has not collapsed completely to initiate the surge but has merely dropped a bit due to stall cell formation at the diffuser exit. After the stall a recovery then takes place in which the massflow swings wildly up and quickly reverses itself to a final crash. The data indicates that the diffuser $\Delta\tilde{P}$ does not dissappear until $\dot{m}=0$. Thus the overall area averaged diffuser flow reversal occurs when $\dot{m} = 0$ rather than prior to it. Toyama{40} also concludes this in their 9:1 pressure ratio compressor.

Also notable in the Figure 61 is the 180 degree phase difference of the inducer pressure trace(K2) with the massflow oscillation. This is a result of the small inertia pressure forces and the area contraction at the inducer. The contraction point pressure in the inlet tube for steady massflow is lower than ambient from the Bernoulli equation. If this massflow is then allowed to vary slowly with time then the pressure at the contraction is minimum at a massflow peak and maximum at a massflow minimum.

Figure 62 shows K2, K3, K4, and K6 at the 90 degree circumferential location. K4 illustrates similar high frequency modulation in the surge approach phase superimposed upon a Helmholtz order low frequency due to the mild surge massflow oscillation. Also shown is the mild temporary diffuser stall preceeding the surge breakdown at t = 460msec. The stall is unusual in that K4 tends to move up in pressure ratio approaching K6. The diffuser appears to recover but to reiterate, the diffuser off-on behavior drives the system more unstable.

In Figure 63 on page 157, the data is presented superimposed upon the compressor map as obtained in earlier experiments. The path of the process is indicated by arrows. It has not been inertially corrected. Each point represents a 5msec time interval. At t=0 operation is at the intersection of the 48K speedline and the small B surge limit. The large density of points on a horizontal line around this point are the massflow orbits building up amplitude. These are like the orbits of Figure 33 on page 127. At a critical point, perhaps due to a critical diffuser swirl angle being reached, the massflow orbit size in less than one orbit becomes quite large. This new orbit is extremely transitory as the large space between the points of equal time intervals indicates. At the minimum massflow point, the diffuser has stalled temporarily. But recovery occurs which sends the massflow back into the right of the surge limit at a high rate of speed. This pre-surge orbit however is short-lived. The highly nonlinear oscillation is dynamically unstable and the compressor operation point surges, overshooting and then settling on the stable backflow compressor characteristic. The speed of this change to negative flow is indicative of the low duct inertia and high acceleration of duct fluid typical of high B systems.

4.4.2 DRUNK ANALOGY

The drunk analogy stated by Dean{8} appears to be somewhat applicable to the system surge behavior presented. The drunk represents the wandering massflow operating point of the compressor near the surge point or cliff.

However important modifications of this analogy are required to correctly describe the behavior of the compression system as presented in section 4.4.1. The lefthand "cliff" is not a discontinuity but is an area of continuously increasing slope. Moving to the left, this slope gets steeper(compressor and throttle characteristic behavior). Also as one moves left on the steepening slope, increasing amounts of rocks and debris are present which can trip up the drunk(transient diffuser and/or impeller stall). If the man is only mildly inebriated(small B-parameter), then his weaving amplitude will be small and some of the debris will be no more than a nuisance. If he trips, he will be able to recover and continue on his way. As he ventures onto the steeper pitch of the slope, recovery from such a stumble becomes more difficult. A completely sober individual($B = 0$) could perhaps negotiate far to the left(to shutoff condition $m = 0$). If on the otherhand, he is heavily intoxicated(high B-parameter), his weaving amplitude will be large and the smallest rocks and debris on the slightest slope will trip him, increase the wildness of his meanderings, and eventually cause an irrecoverable slide down the slope(surge!).

5.1 SUMMARY AND CONCLUSIONS

Several points were discussed in the data presented in chapter 4 which will be reiterated here. These are:

- The surge point is substantially affected by the B-parameter.
- Large massflow oscillations are present in the apparently stable compression system operation close to the surge limit.
- Large changes in B-parameter can cause large changes in vaneless diffuser Cp at equal operating points.
- Diffuser flow is degraded and non-axisymmetric in the region close to the surge limit for the large B system.
- A critical average diffuser inlet swirl angle appears to be associated with surge breakdown which also appears to depend on B.
- Surge breakdown appears to be a dynamic system instability precipitated by a momentary stall in the vaneless diffuser flow field.
- A single inducer stall cell which is present at the inducer at both large and small flows does not appear to precipitate surge breakdown.
- An overall impeller stall does not seem to occur prior to surge and thus is not a triggering mechanism for surge breakdown instability for the range of speeds tested.
- The stall cell behavior in the diffuser is highly transient emphasizing the importance of examining the diffuser in the time domain.
- A nonlinear lumped parameter model appears to be applicable to predicting centrifugal compressor surge behavior with modifications that

properly define the characteristics, time lags, and compressibility effects.

5.2 RECOMMENDATIONS

Several areas of follow on activity in the project should include:

- Rebuild system with a very small B to investigate performance near shutoff with particular interest paid to the diffuser behavior.

- Investigate modifications of the nonlinear model of surge for an accurate numerical simulation of the system instability. Such items as compressibility, transient diffuser and inducer stall, etc. should be included. Such a predictive model would be quite useful to predict the surge point of a centrifugal compressor in any arbitrary system and the time history of the surge event.

- Run the surge cycle experiments with a faster more accurate method of transient speed measurement to determine RPM behavior during the stall event.

- Acquire more time resolved data with both casing Kulites and hotwire probes installed in the diffuser. This would help in understanding the flow behavior during the highly transient surge process.

- Investigate compressor modifications which could alter system response and improve surge margin. Such modifications might include a variable width diffuser, damping to stabilize the system, and possibly casing treatments.

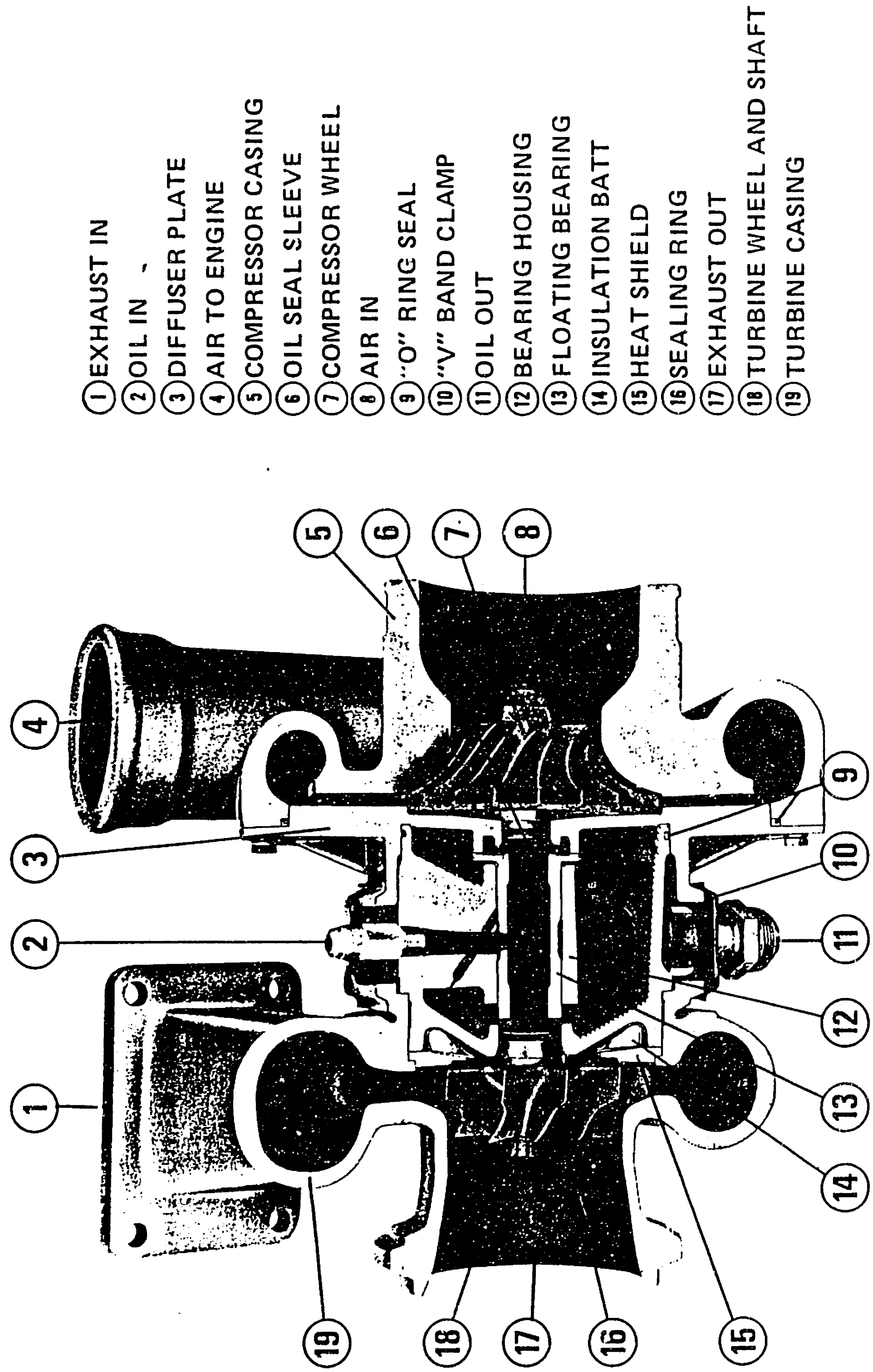


Figure 1 Turbocharger Cutaway

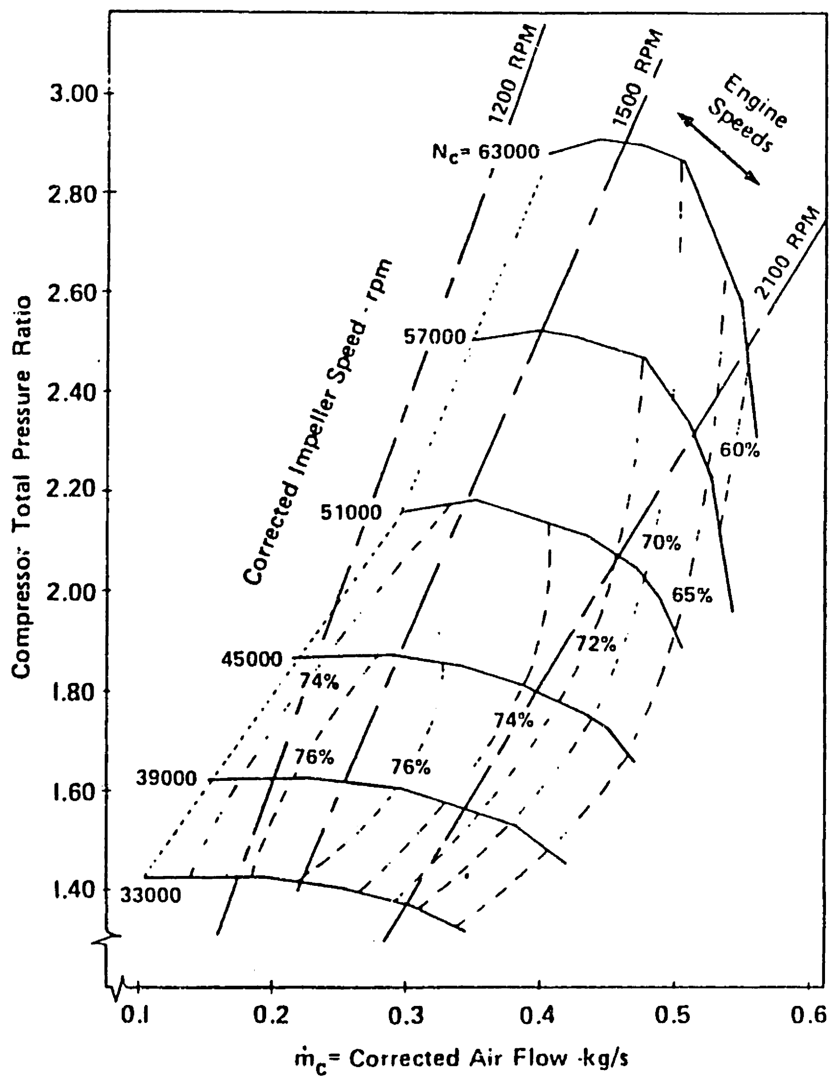


Figure 2 Cummins Diesel-Turbocharger Map

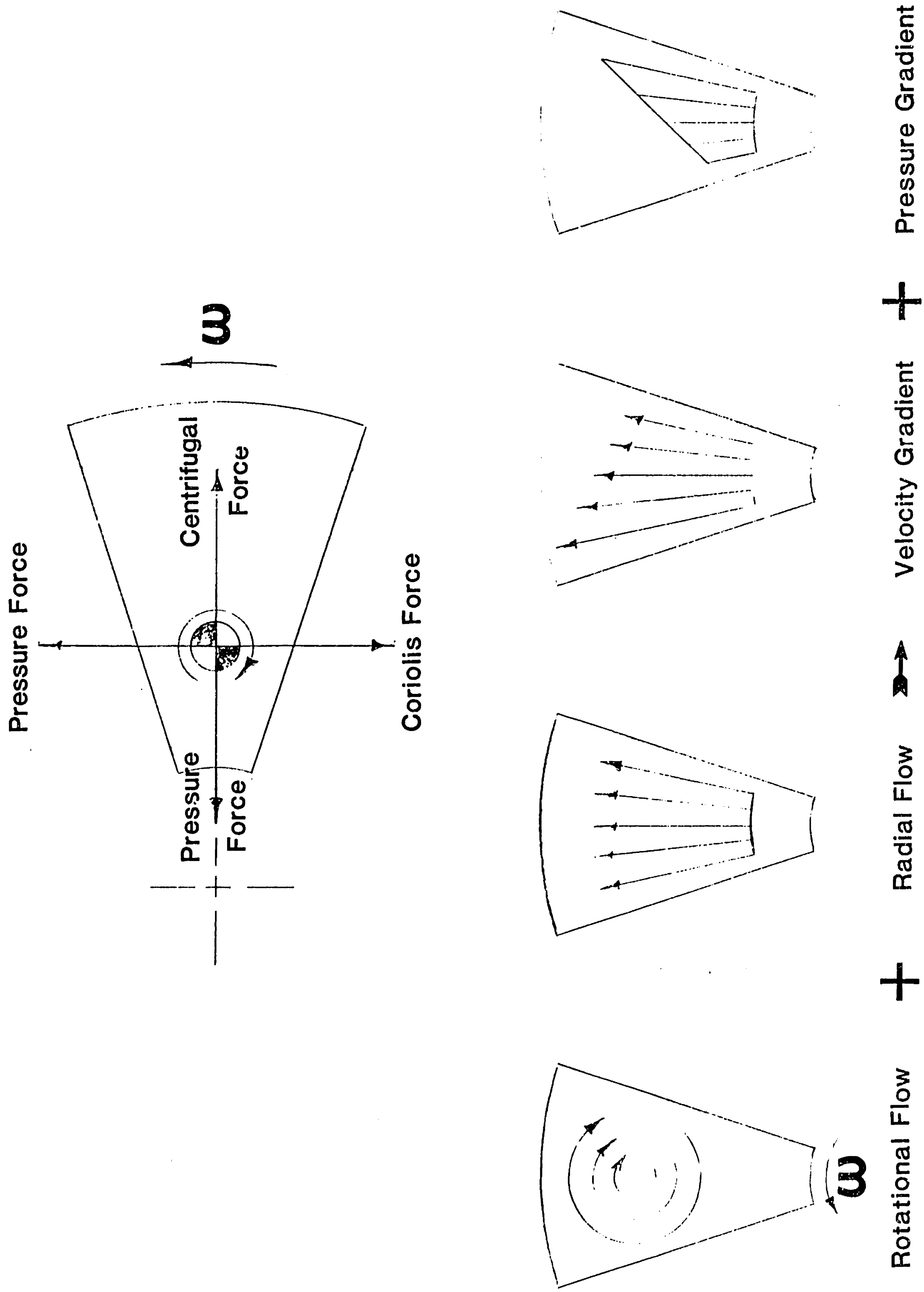
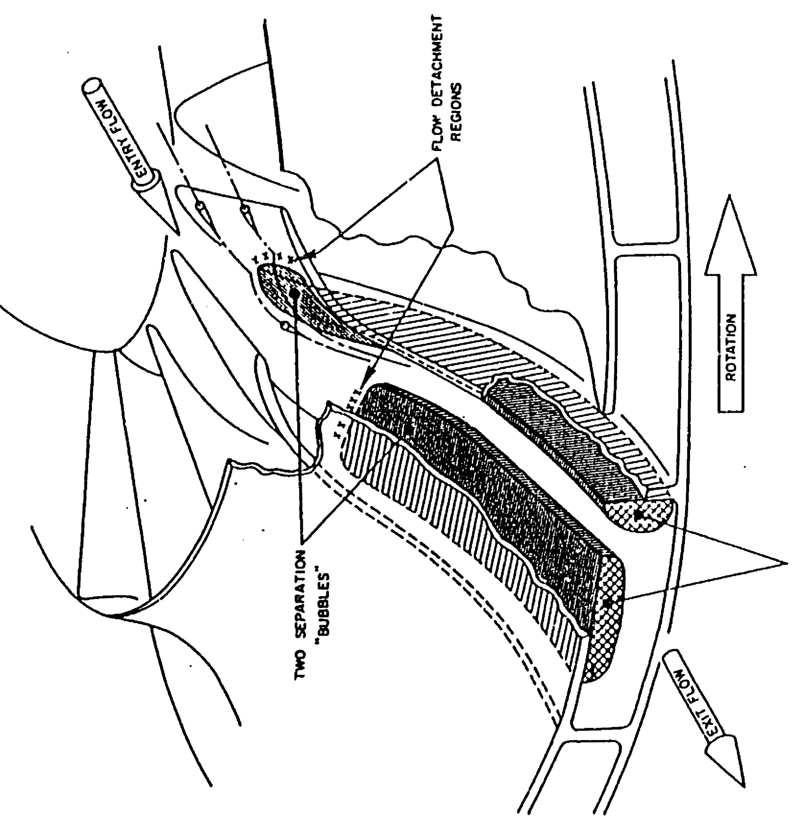
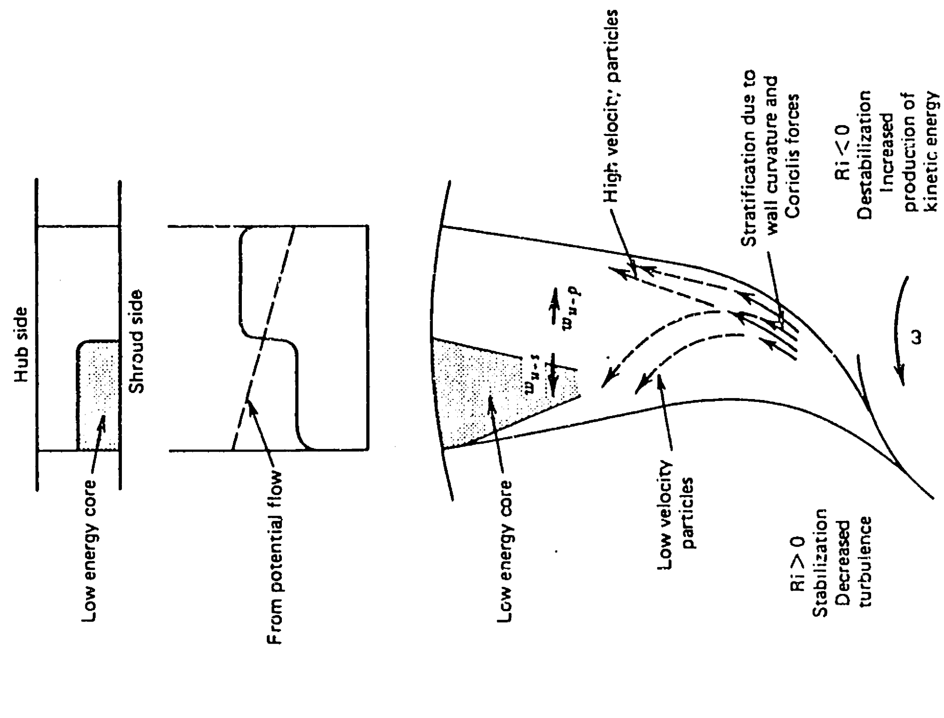


Figure 3 Inviscid Flow in a Rotating Radial Passage



from Fowler{15}



from Balje'{1}

Figure 4 Viscous and Turbulence Effects on Impeller Flows

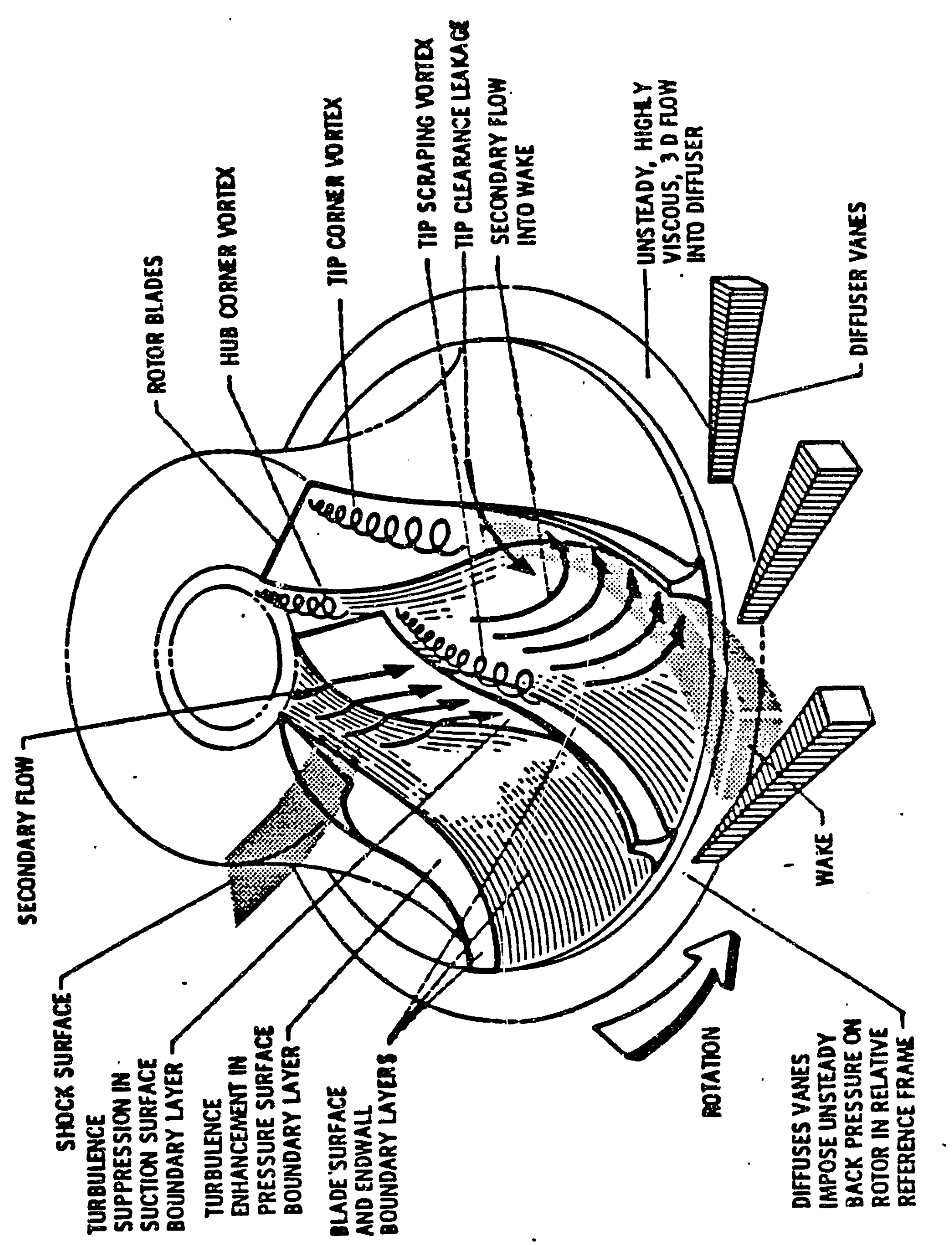


Figure 5 NASA Pictoral of Centrifugal Compressor Fluid Dynamics

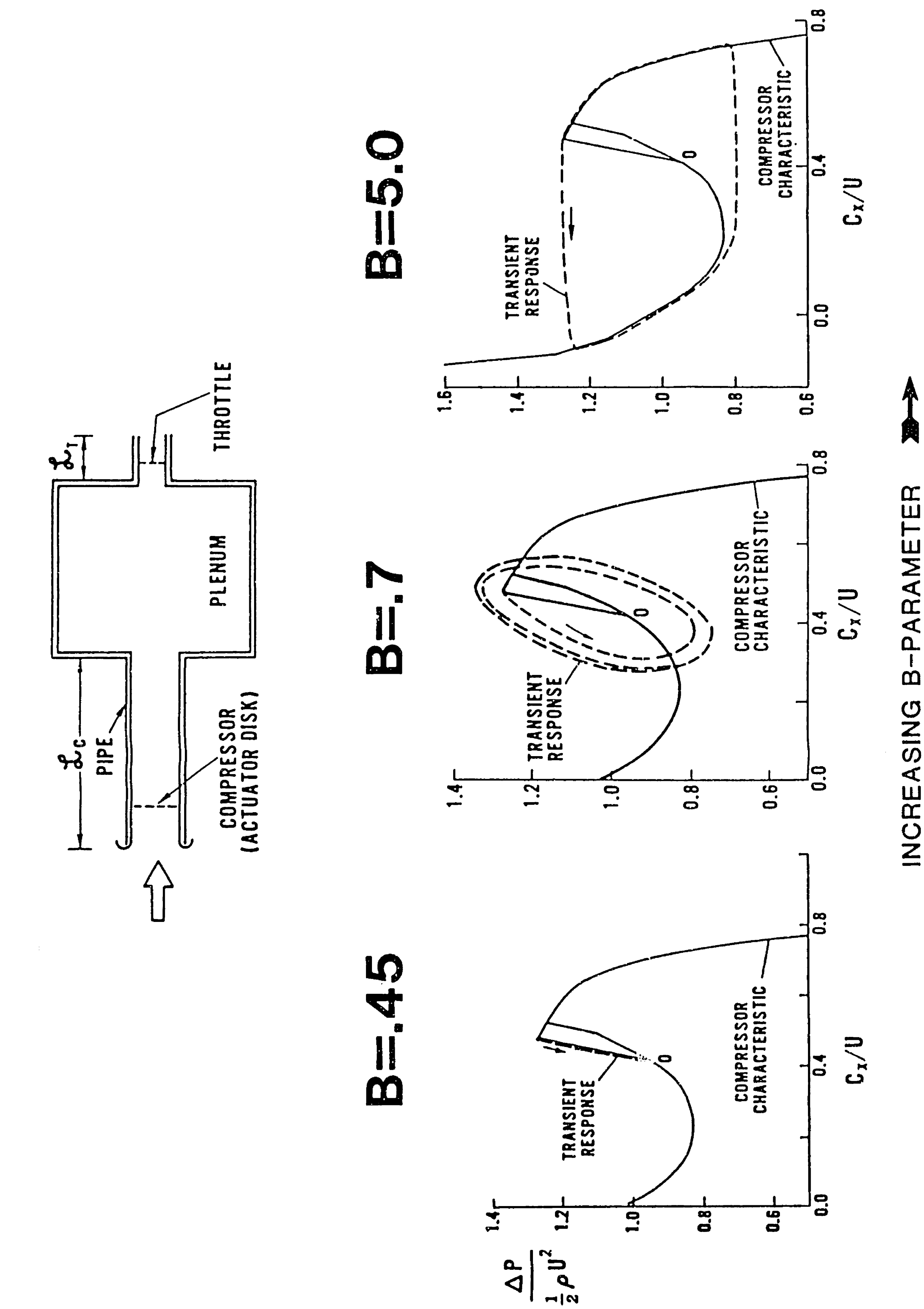


Figure 6 B-Parameter Effect on Compressor Surge Cycle Behavior

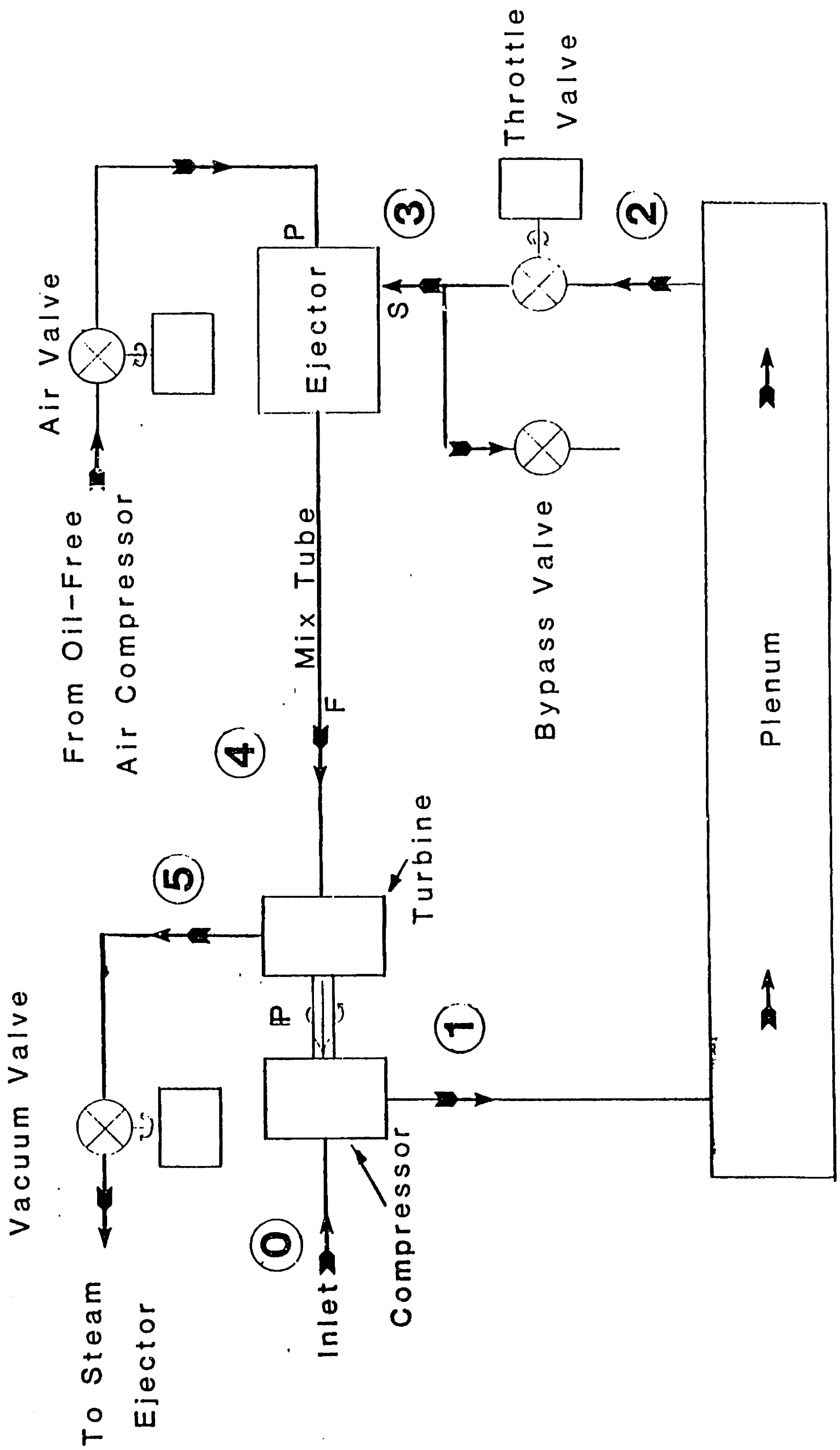


Figure 7 Facility Flow Schematic

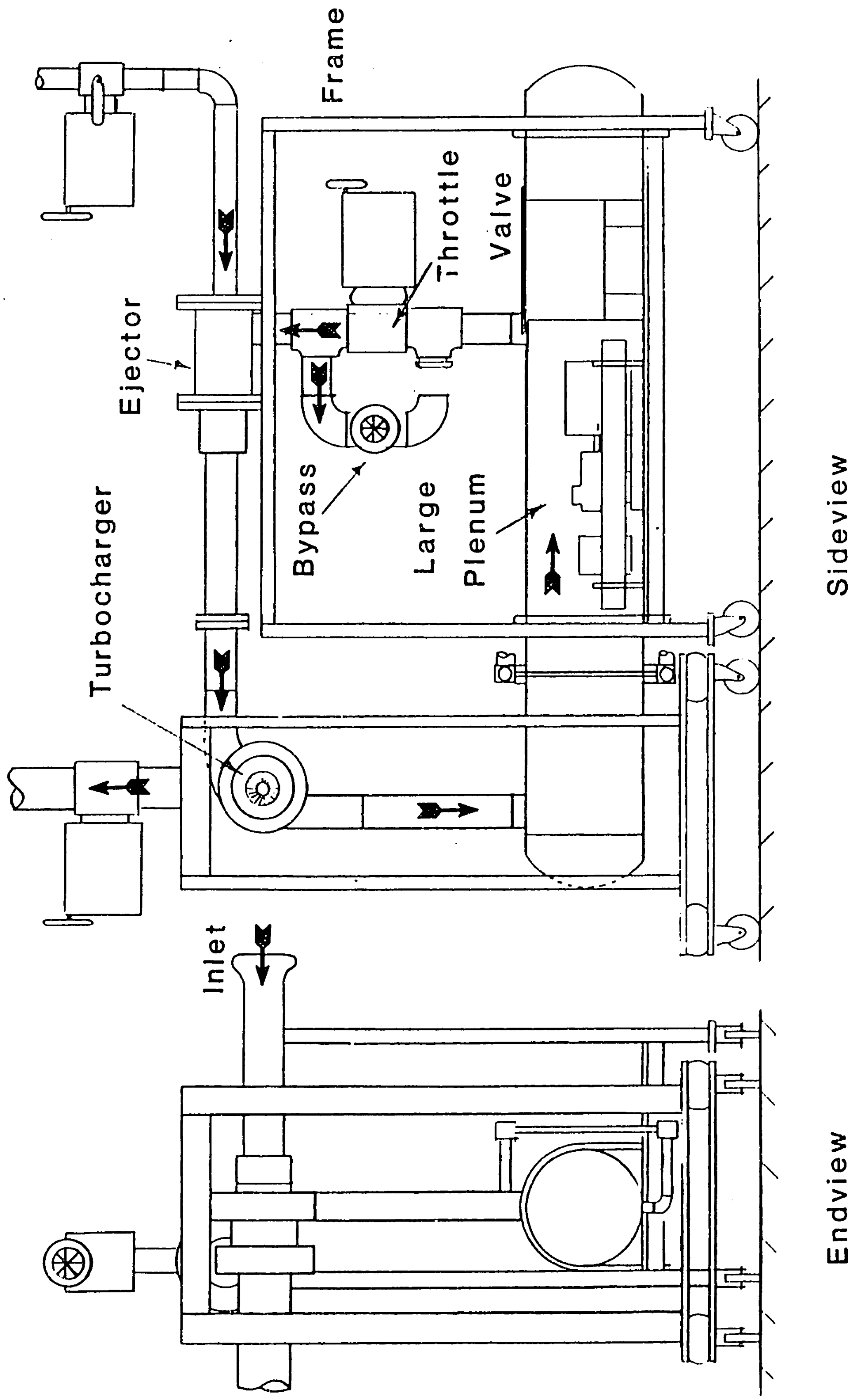


Figure 8 Sideview of Turbocharger and Plenum Arrangement

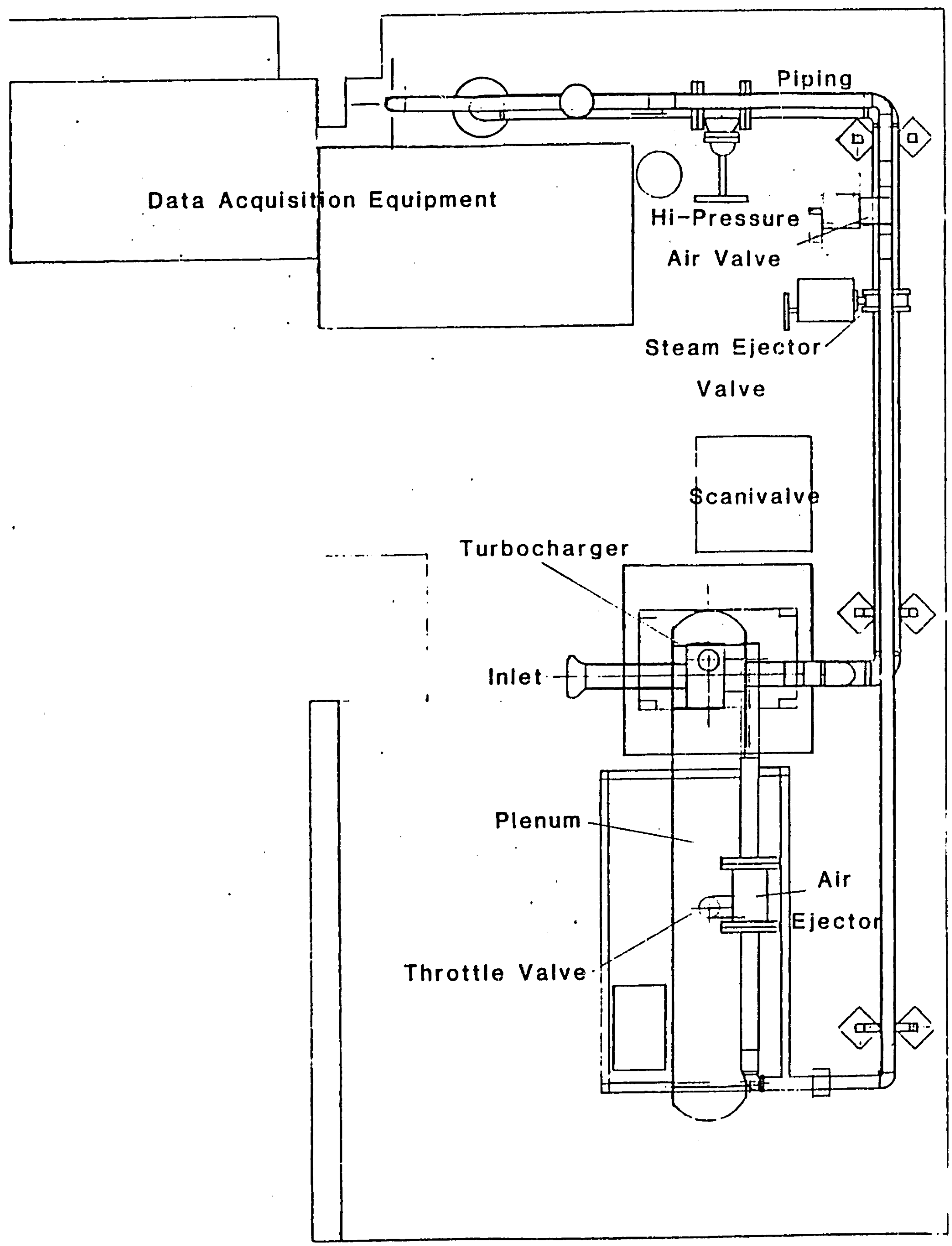


Figure 9 Overall Lab Layout

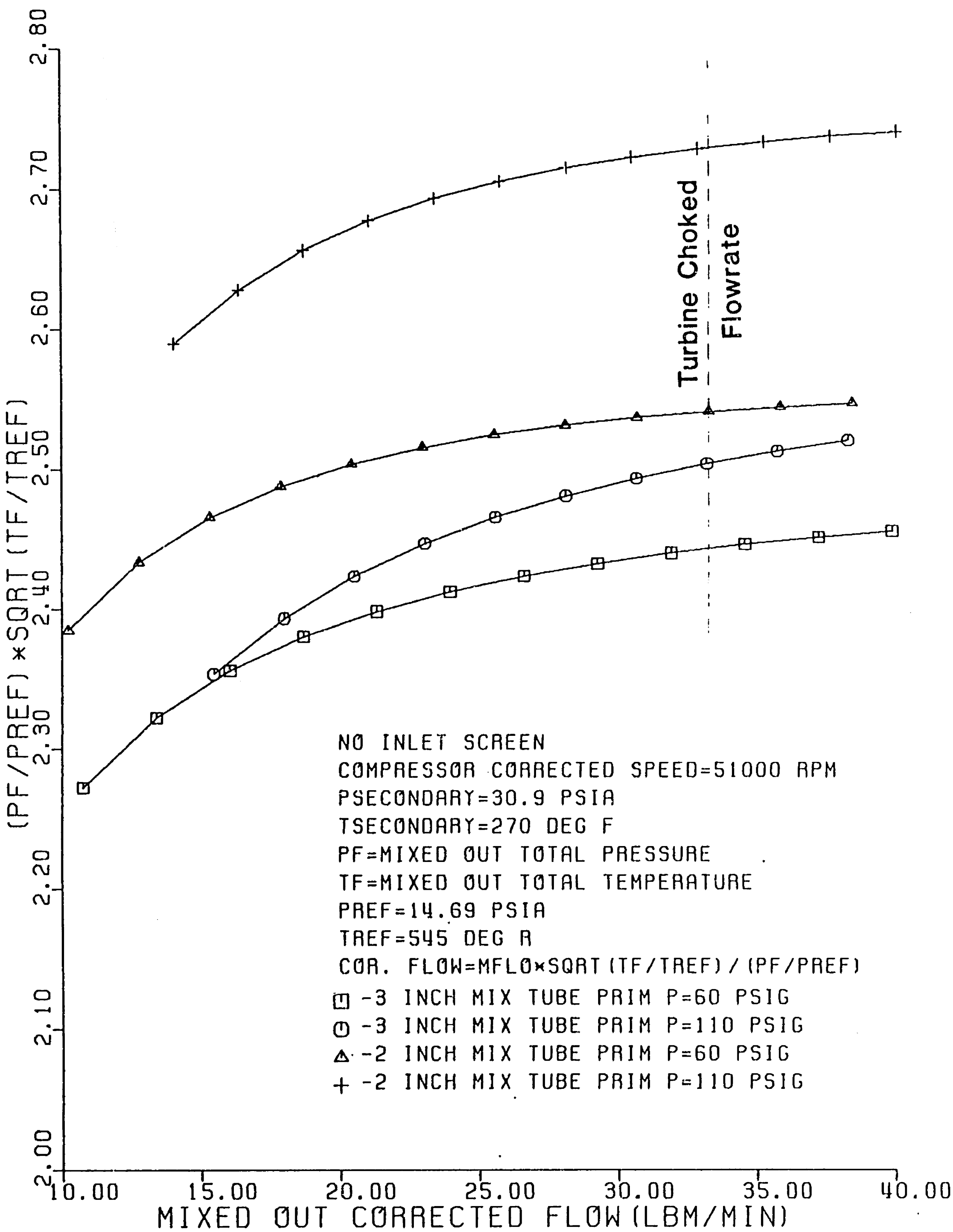
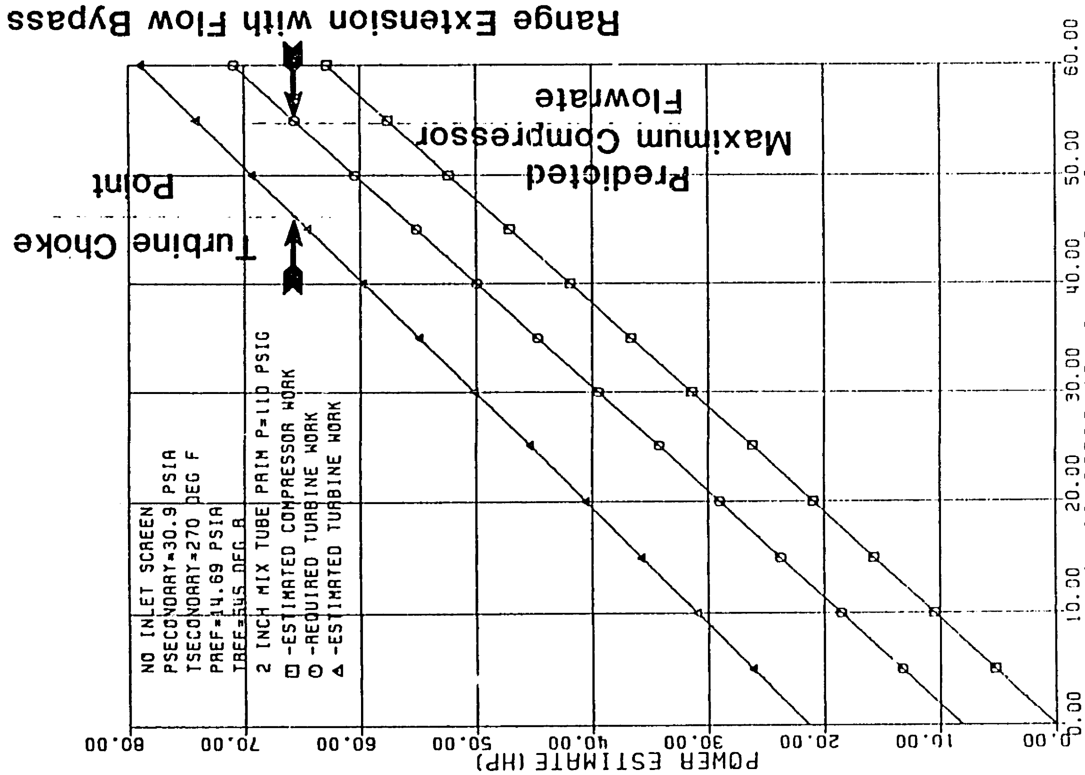


Figure 10 2 and 3 Inch Ejector Prediction without Inlet Screen



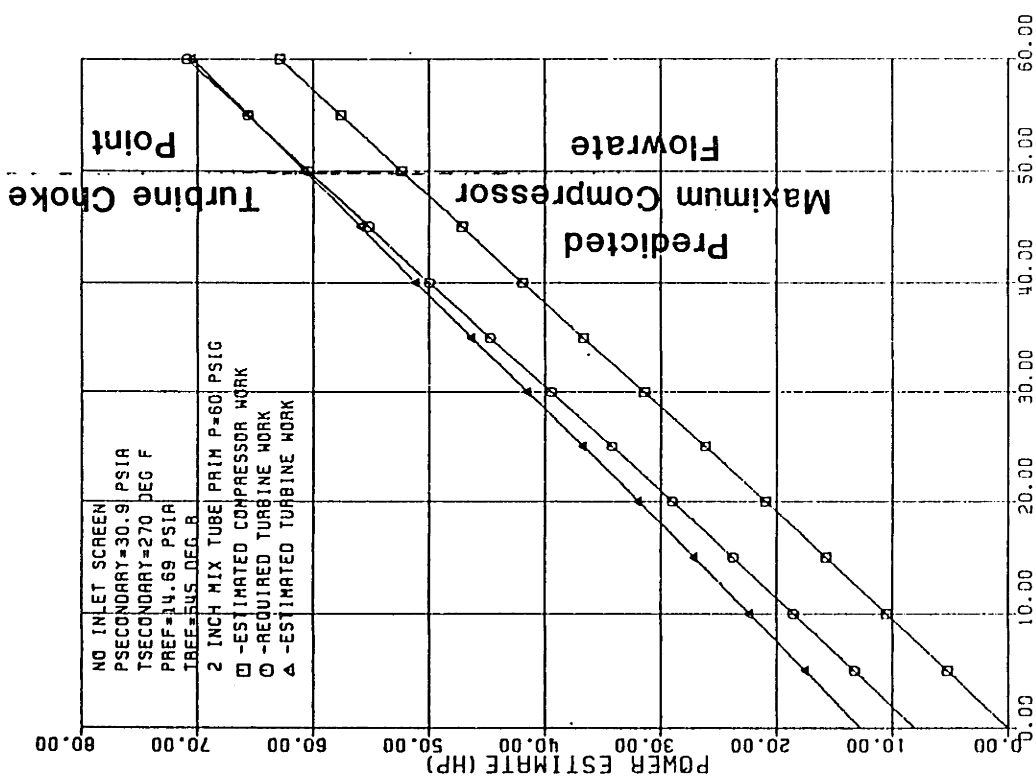


Figure 11 2 Inch Ejector Power Estimate with No Inlet Screen

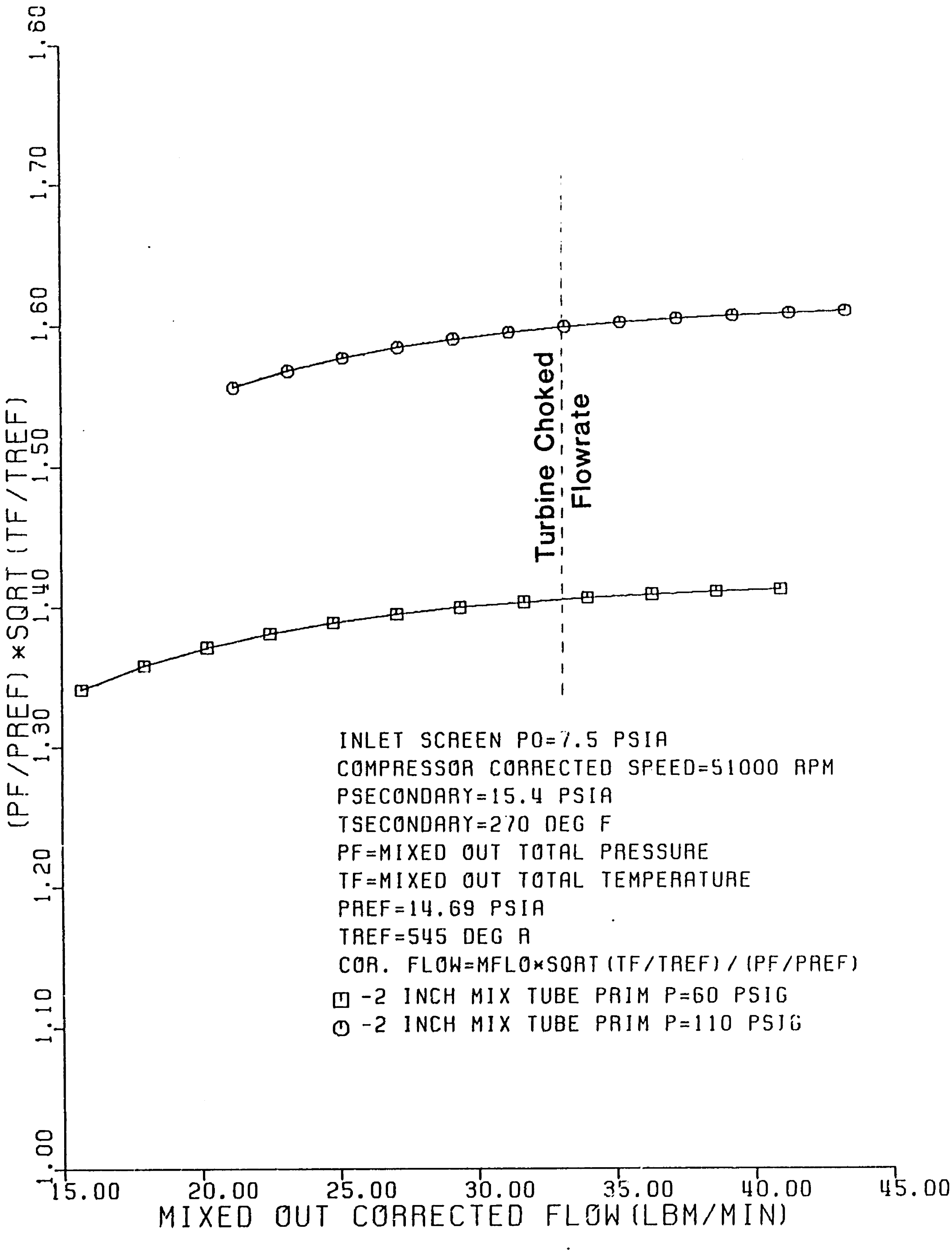
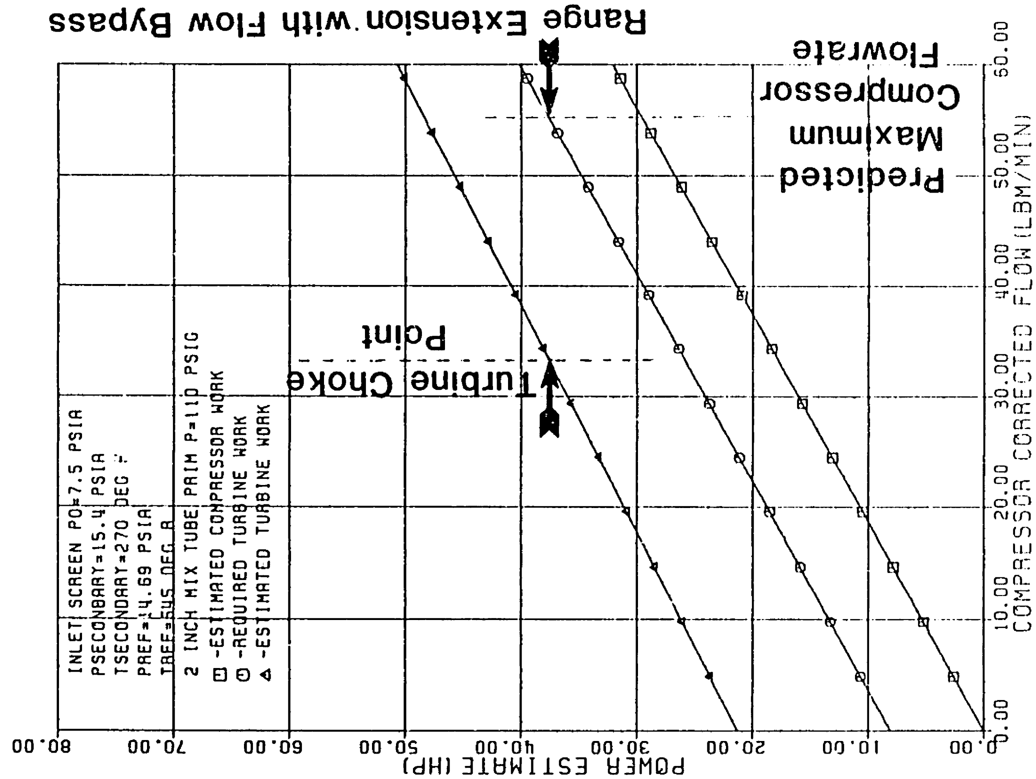


Figure 12 2 Inch Ejector Performance with Choking Inlet Screen



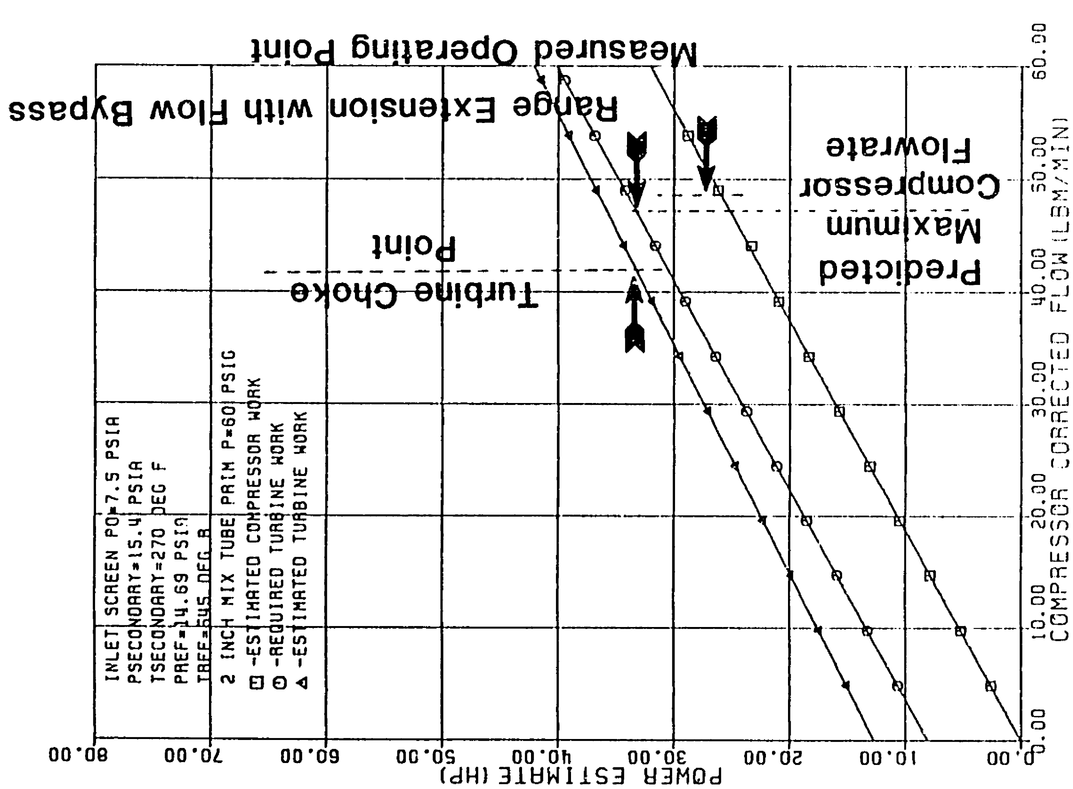


Figure 13 2 Inch Ejector Power Estimate with Choking Inlet Screen

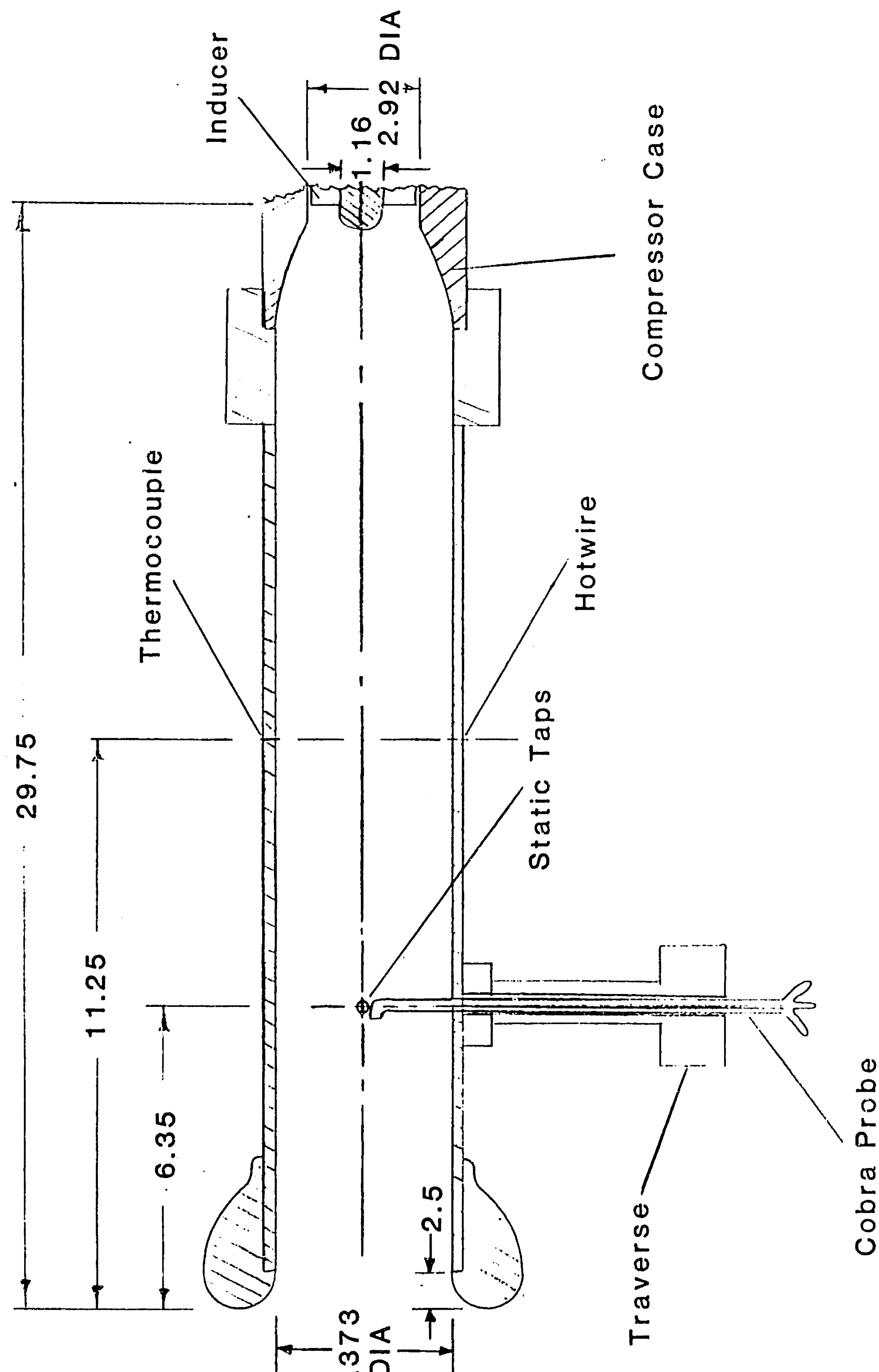


Figure 14 Inlet Instrumentation

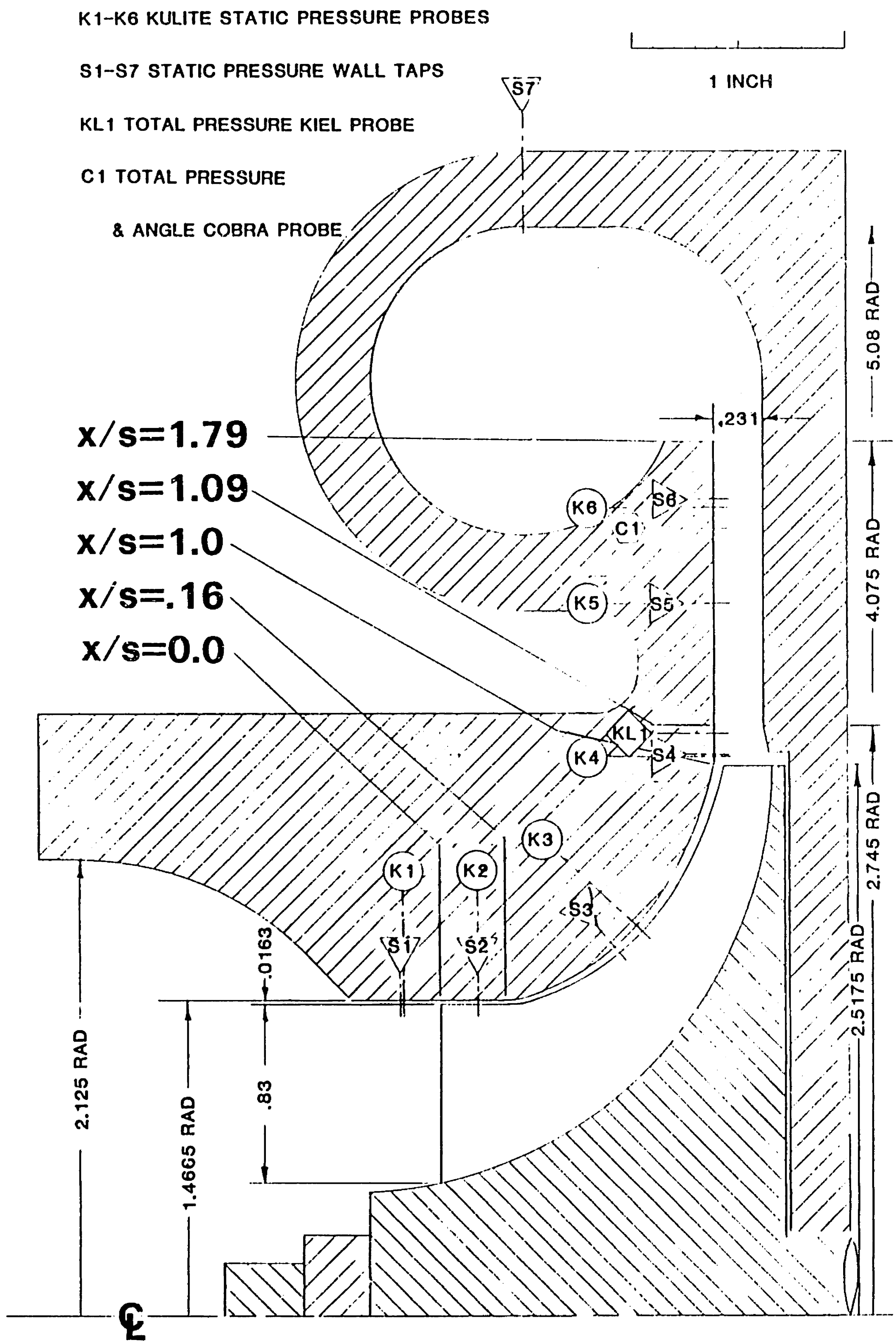
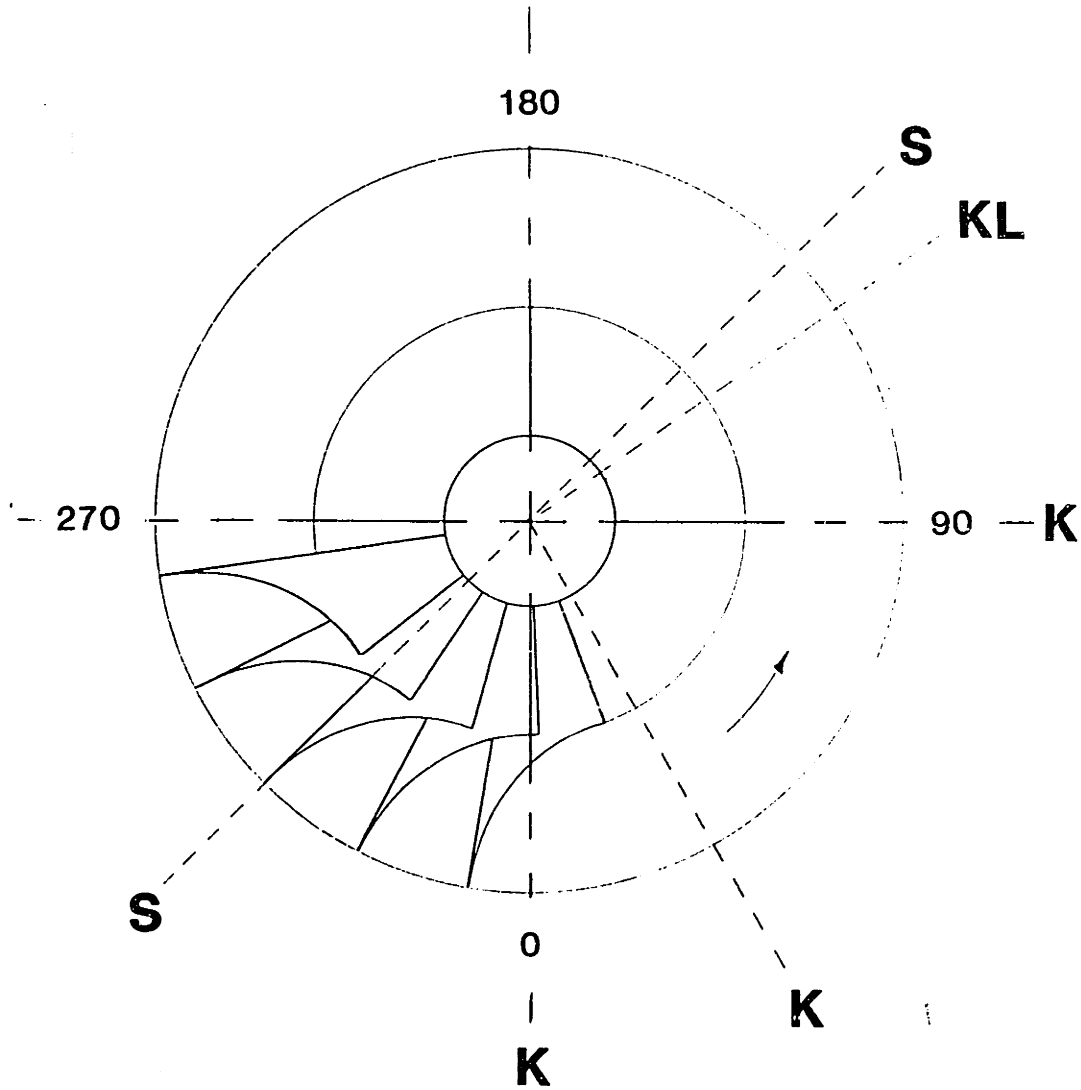


Figure 15 Compressor Instrumentation(Meridional Positions)



S- Casing Static Pressure Taps(S1-S6) at -45 Deg, 135 Deg

K- Kulite Static Pressure Probes(K1-K6) at 0 Deg, 30 Deg, 90 Deg

KL- Total Pressure Kiel Probe(KL1) at 125 Deg

Figure 16 Compressor Instrumentation(Circumferential Positions)

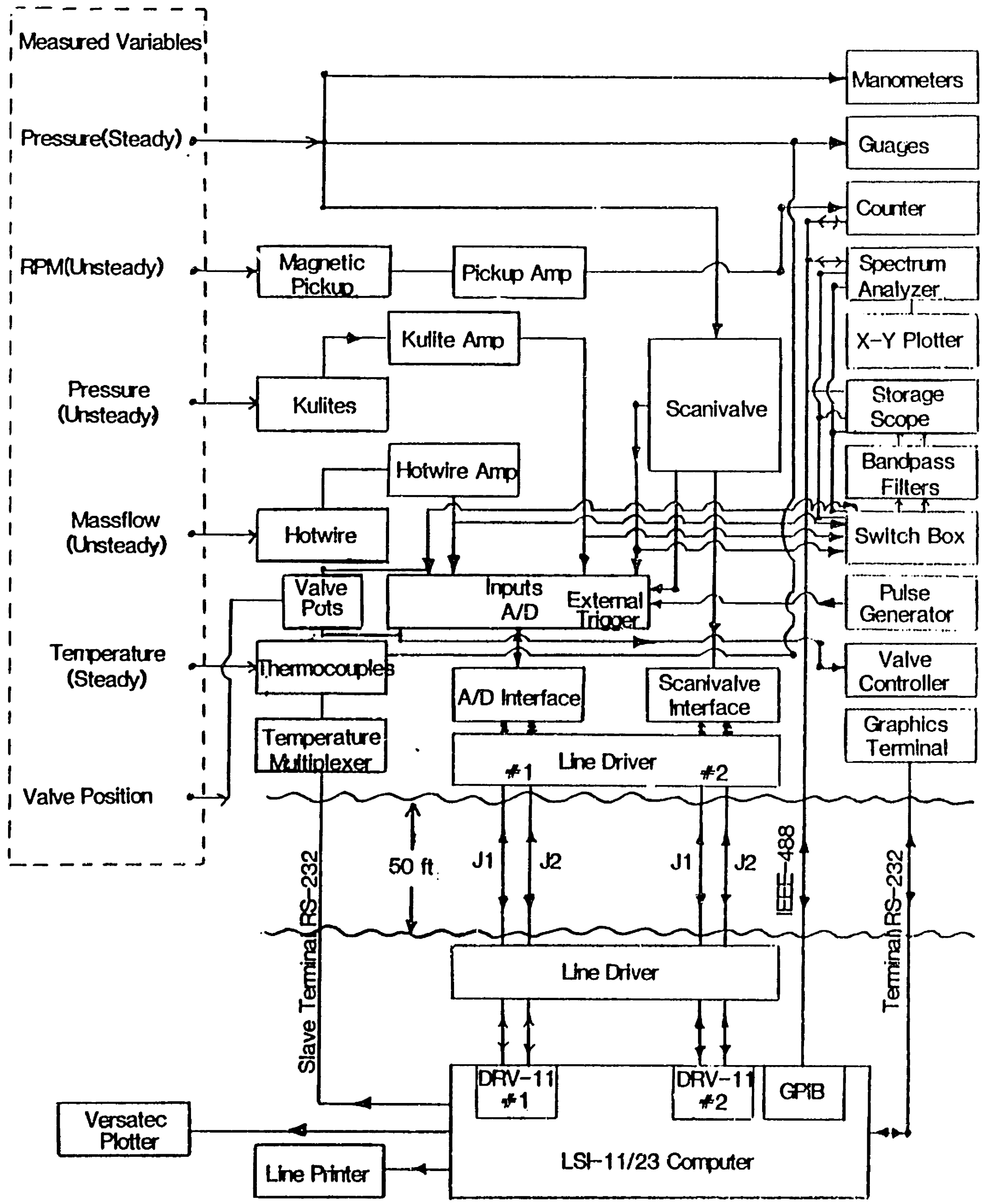


Figure 17 Data Acquisition Schematic

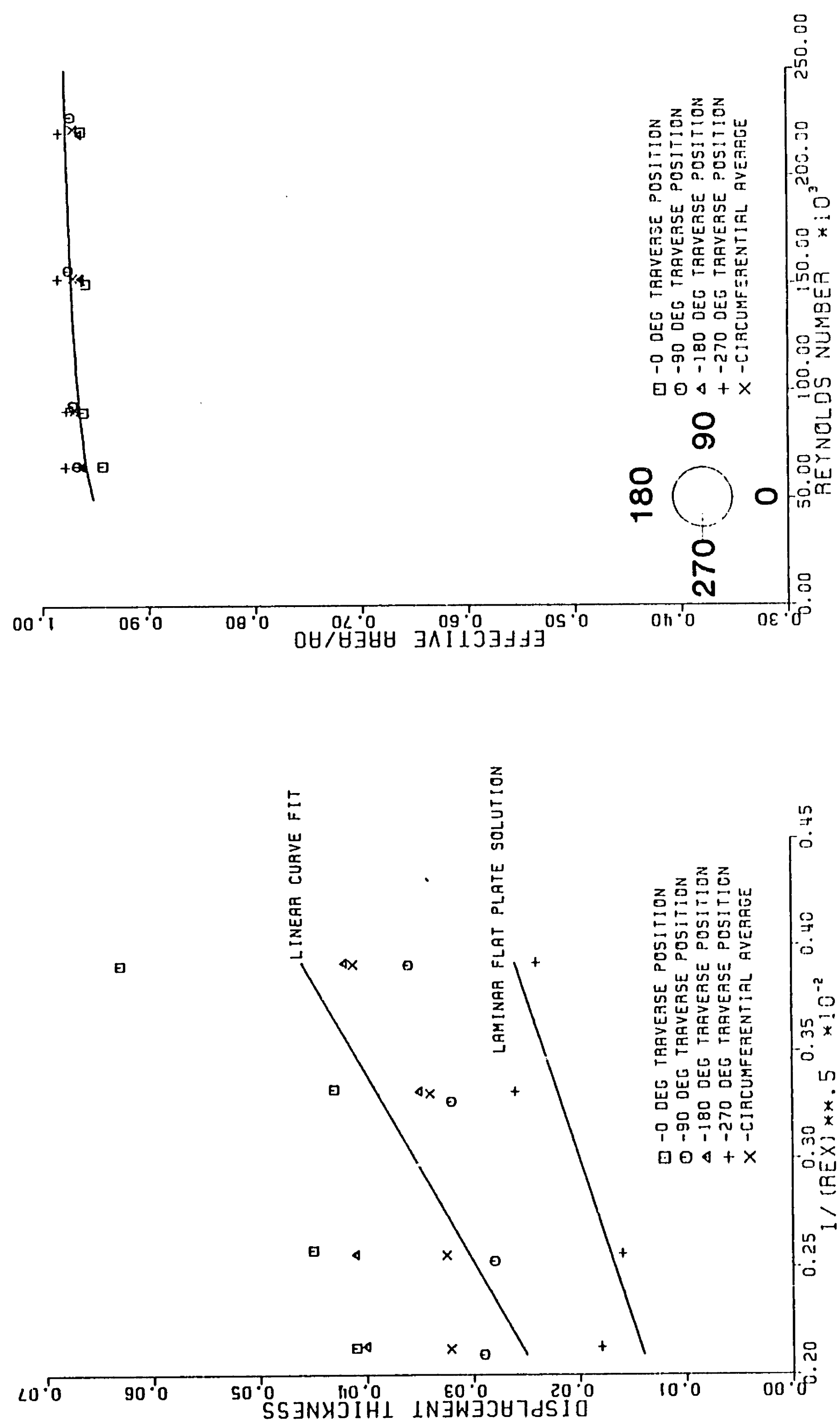


Figure 18 Inlet Calibration Results

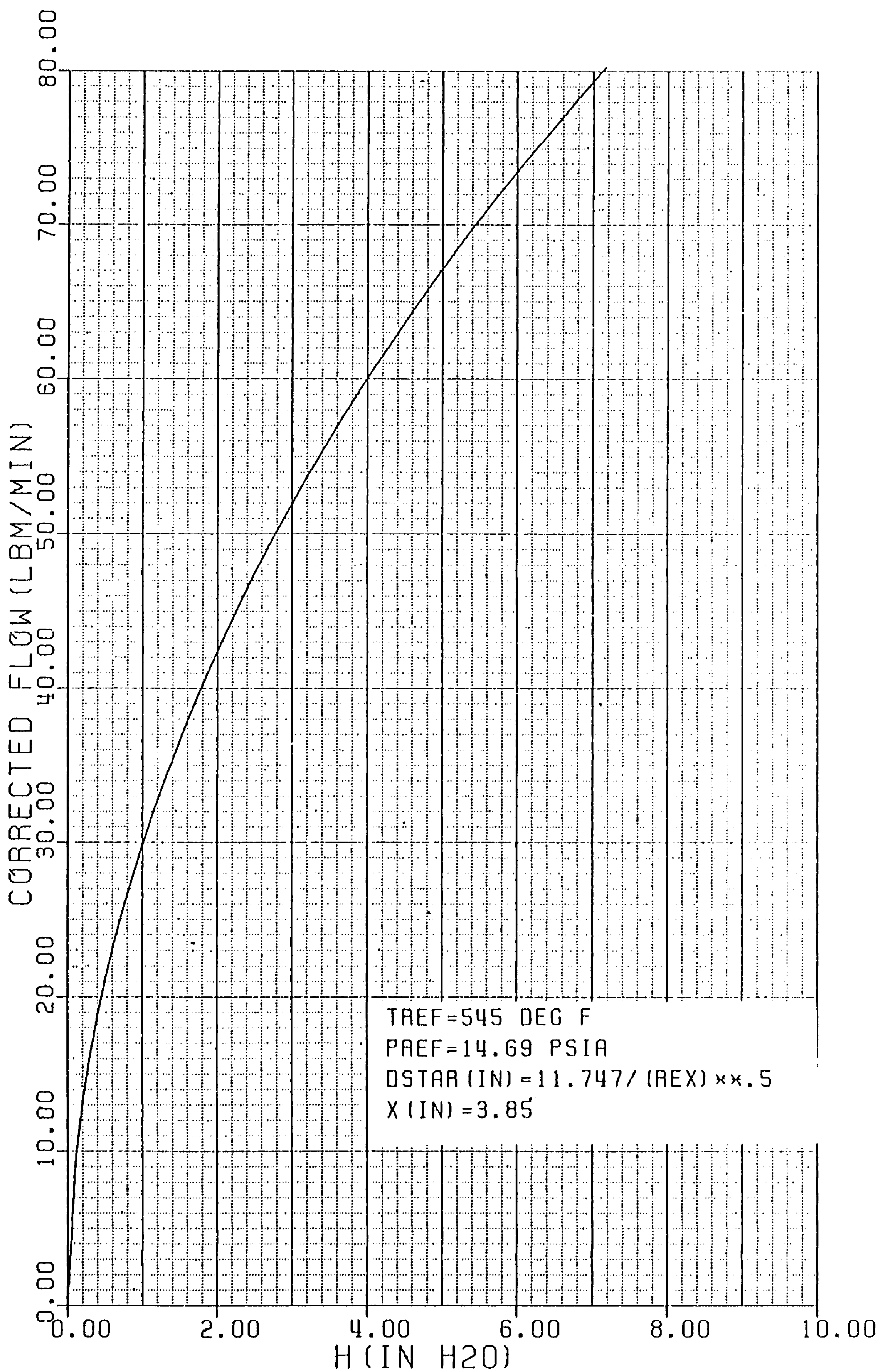


Figure 19 Inlet Corrected Flow vs Manometer Head

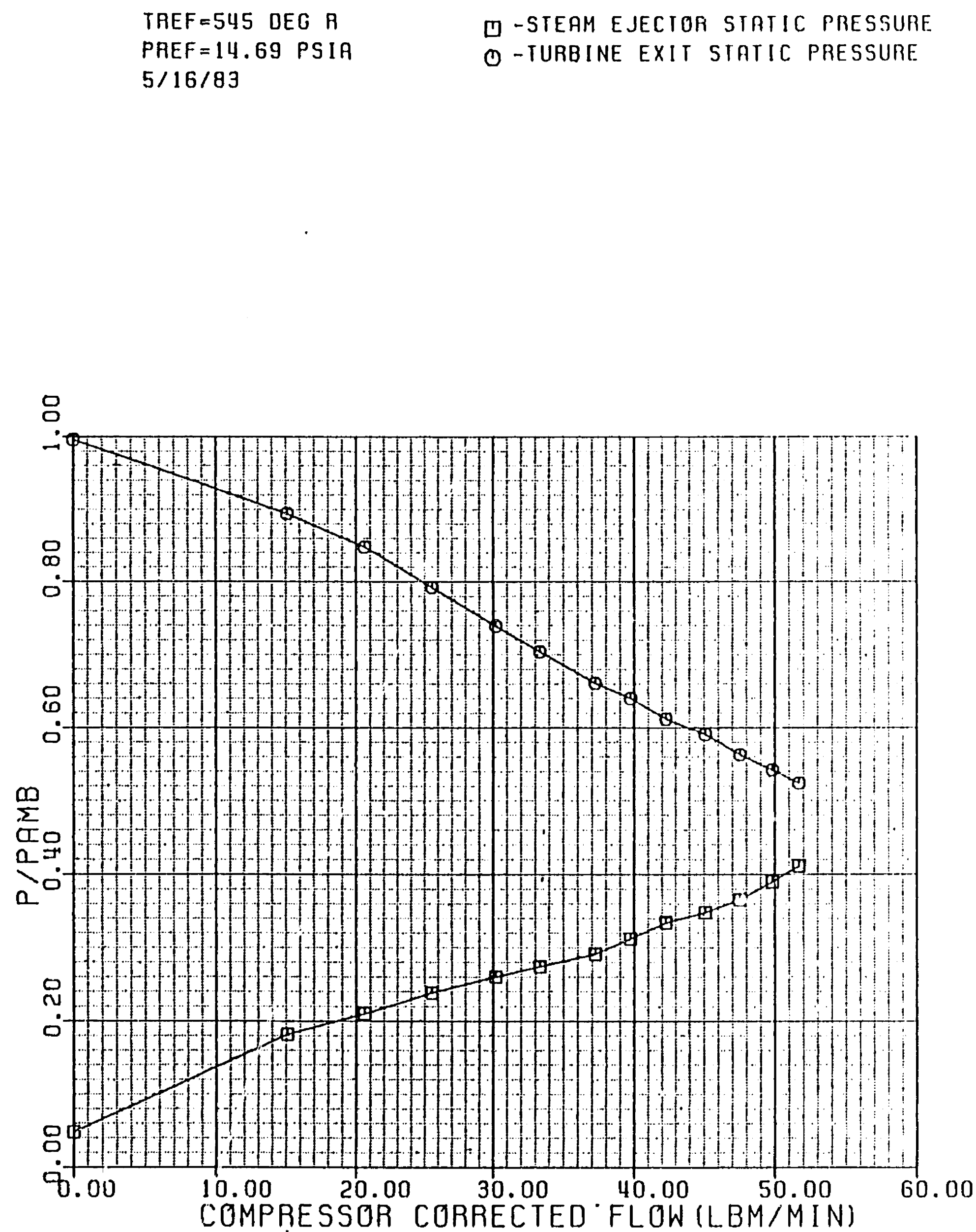
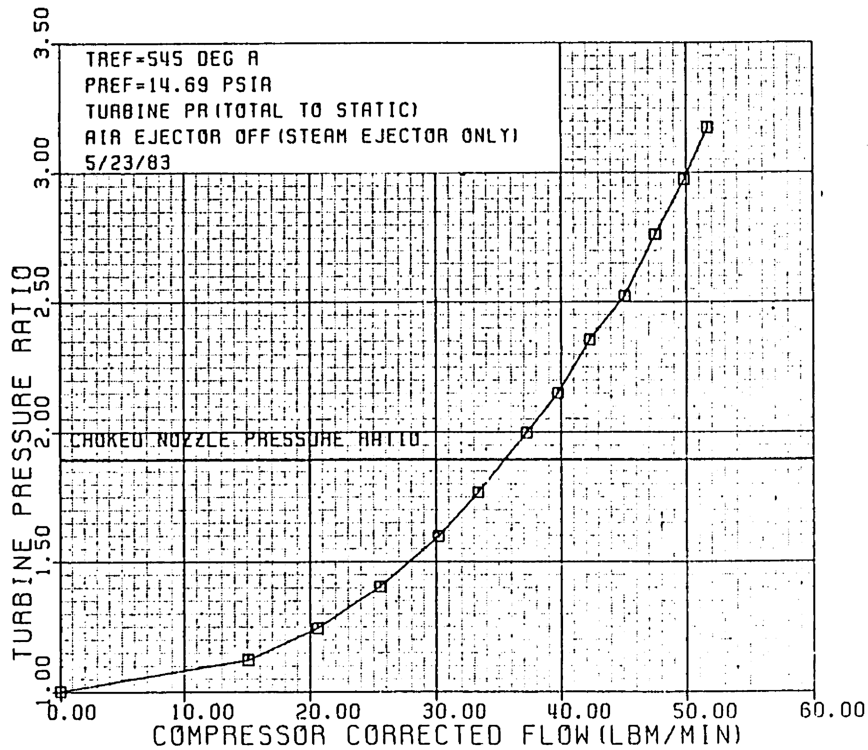


Figure 20 Steam Ejector Performance



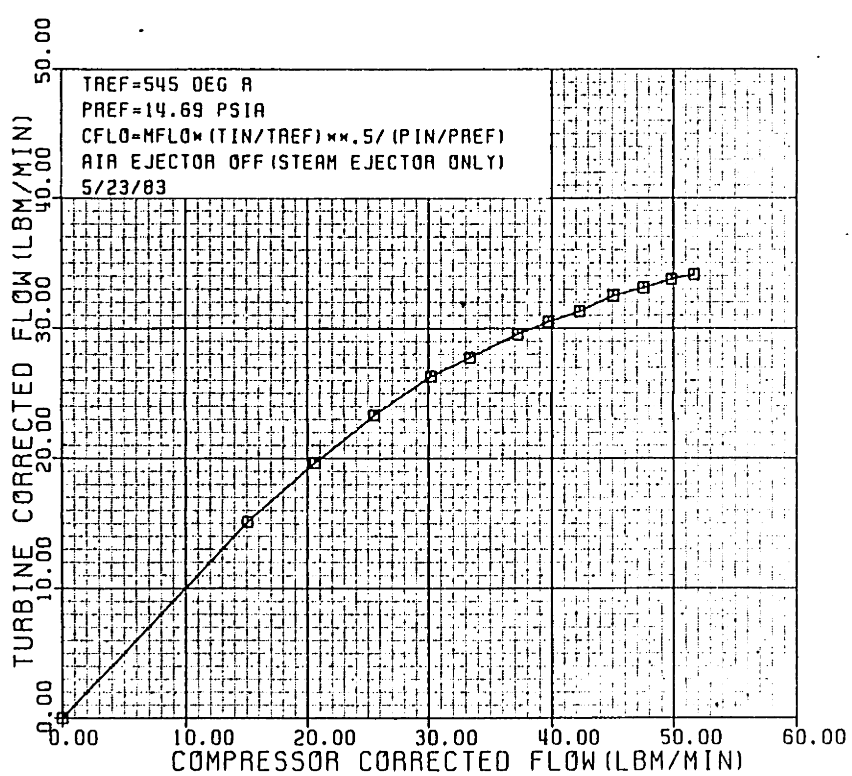
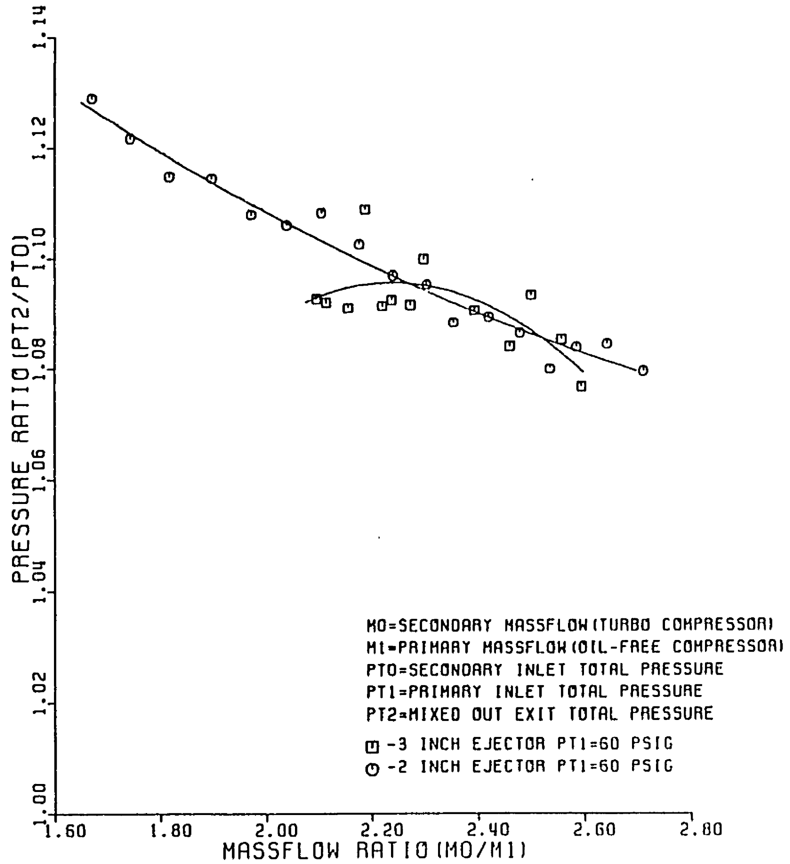


Figure 21 Turbine Performance



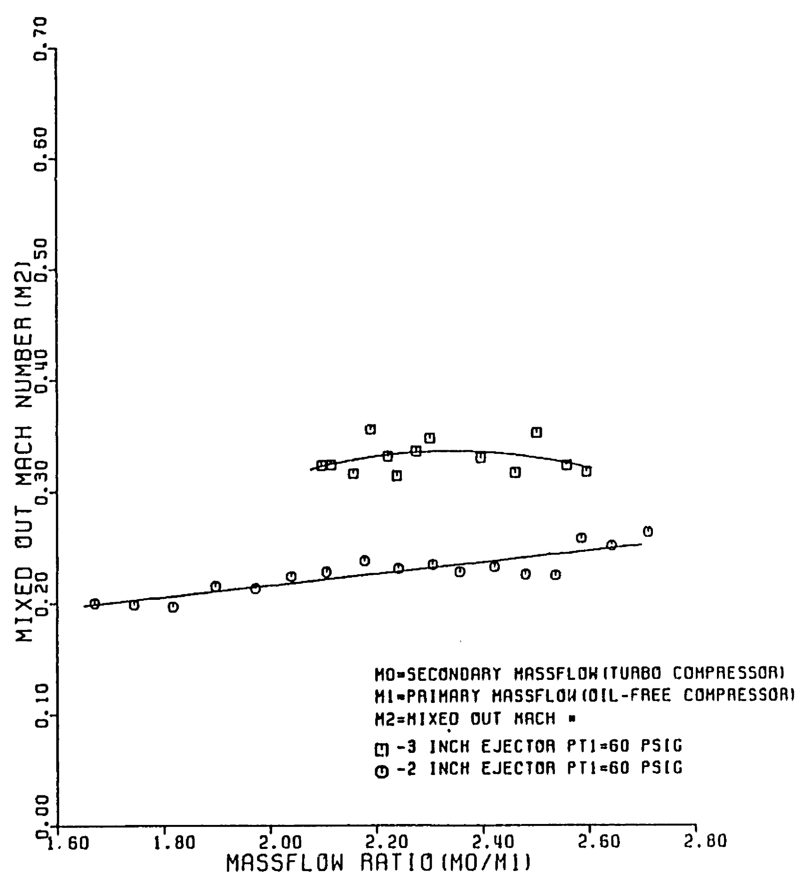


Figure 22 Air Ejector Performance

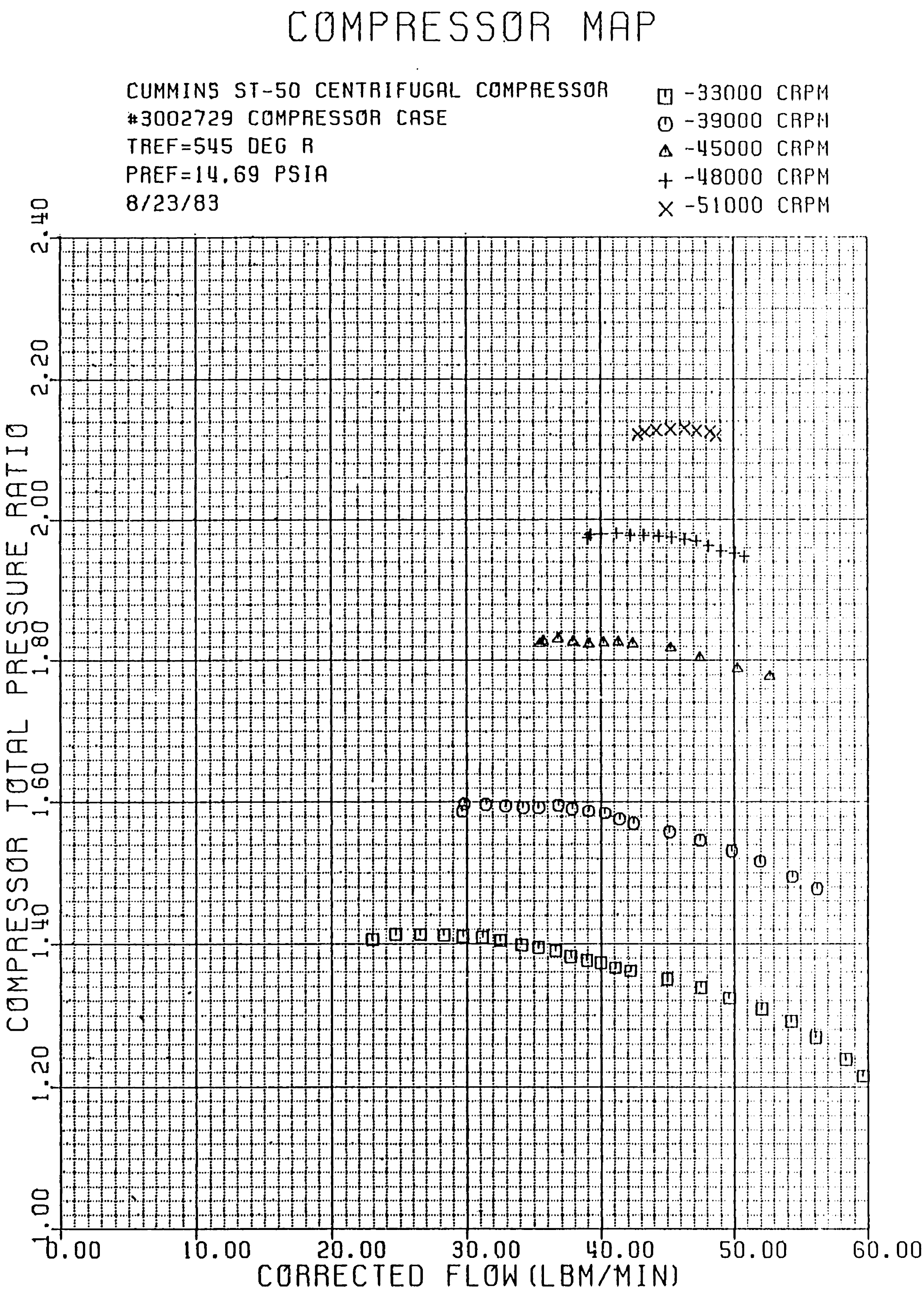


Figure 23 Total Pressure Ratio vs Corrected Flow

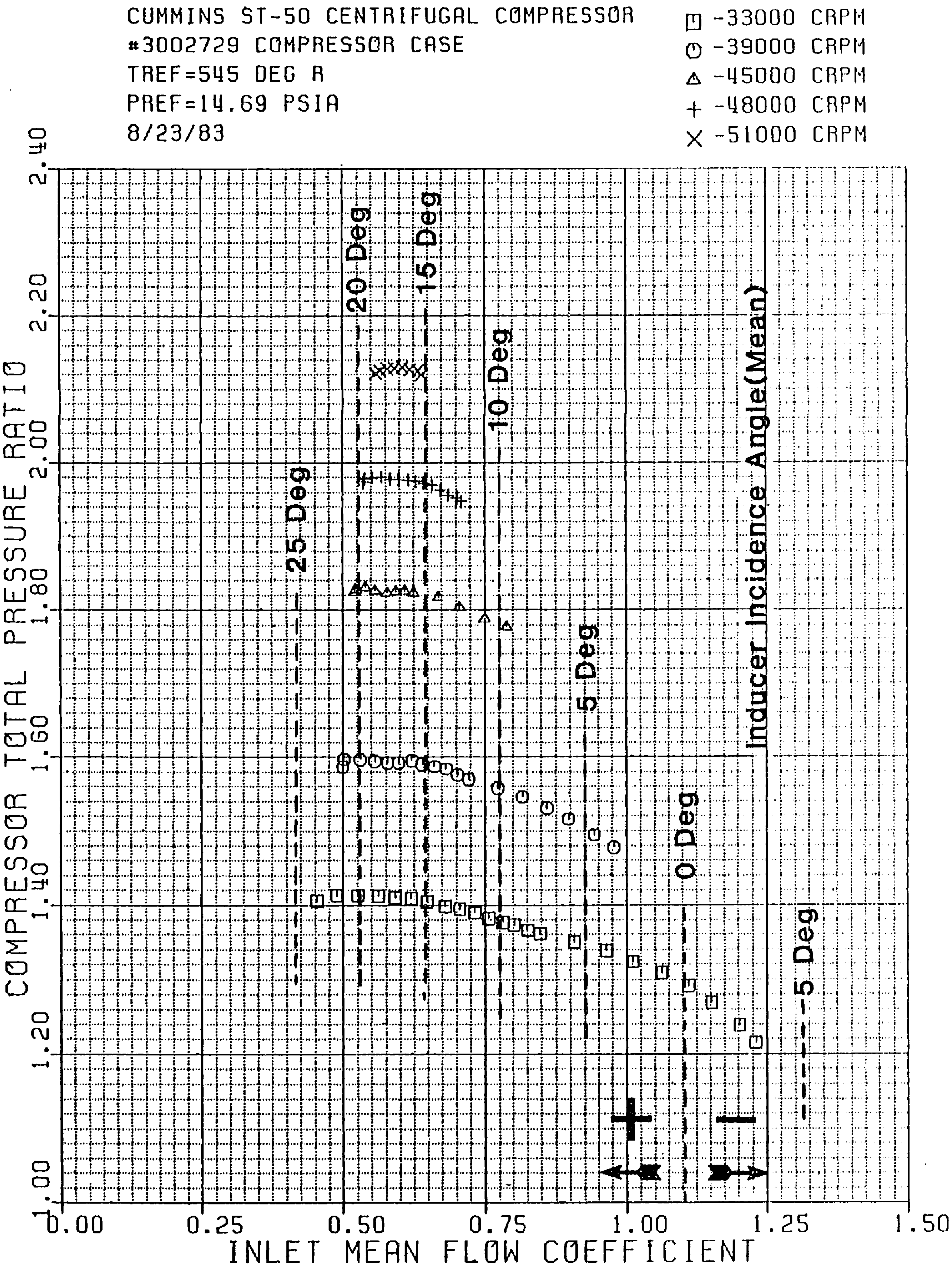


Figure 24 Total Pressure Ratio vs Flow Coefficient

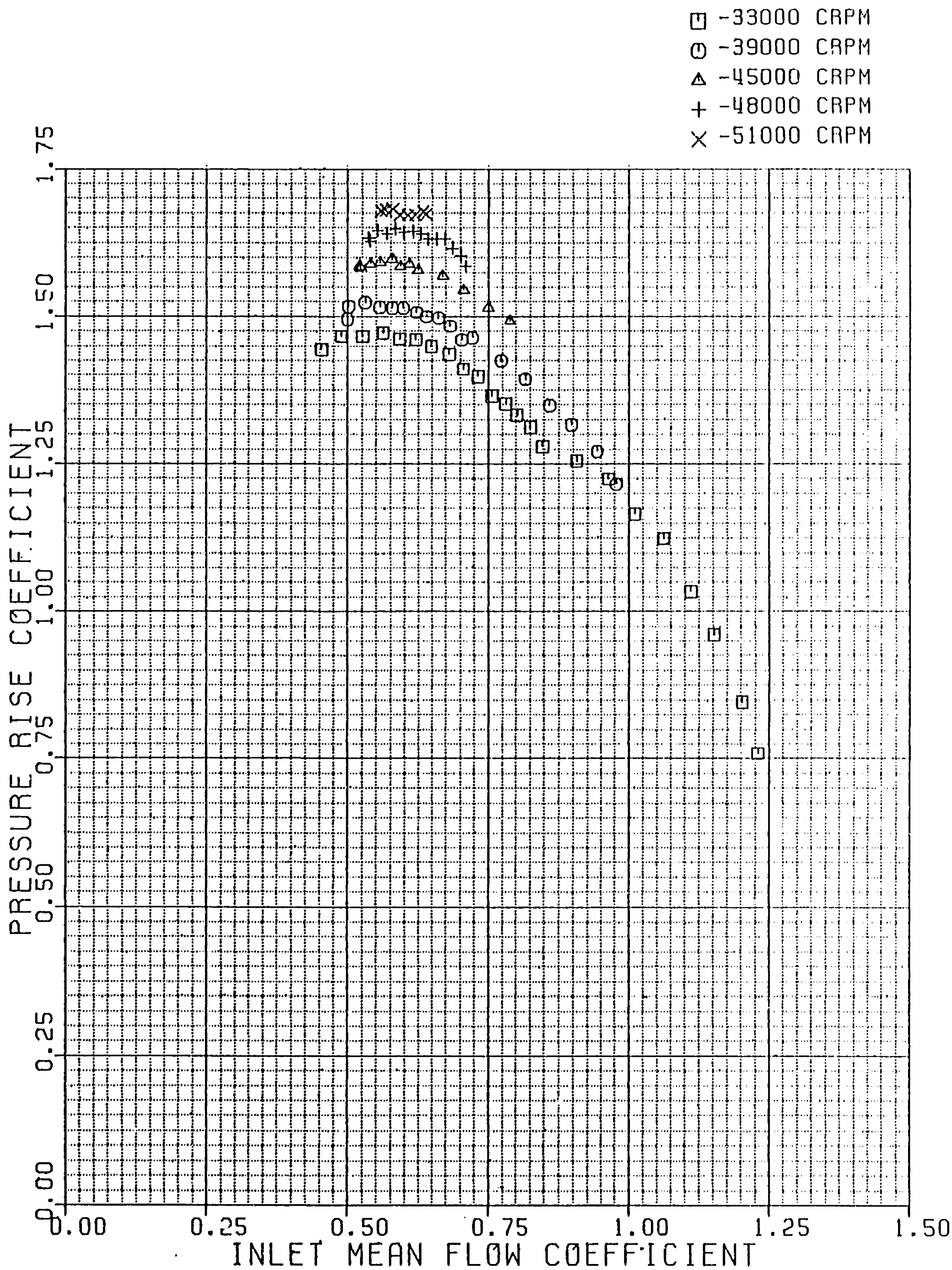


Figure 25 Pressure Rise Coefficient vs Flow Coefficient

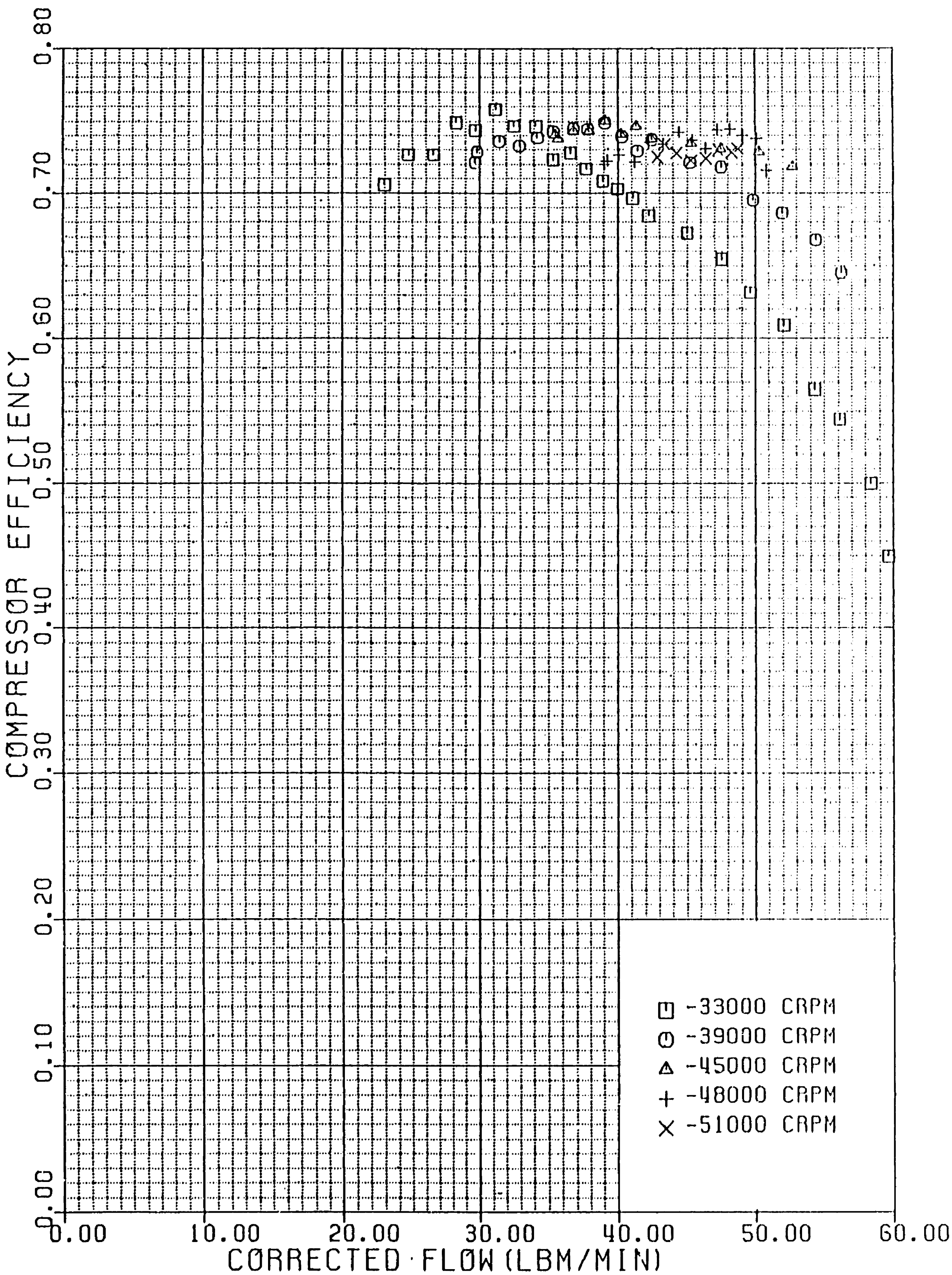


Figure 26 Adiabatic Efficiency vs Corrected Flow

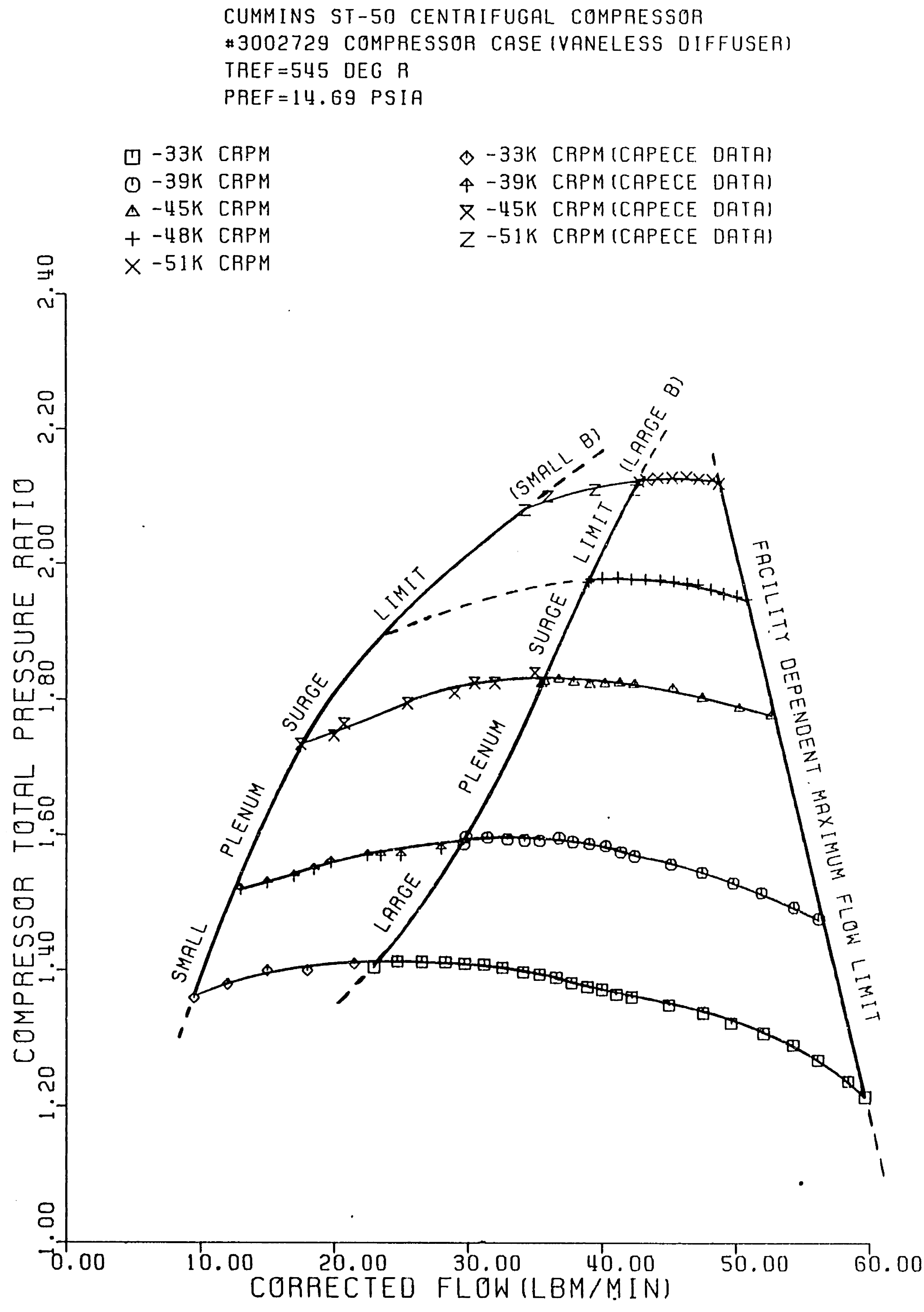


Figure 27 Effect of System B-Parameter on Compressor Performance Map

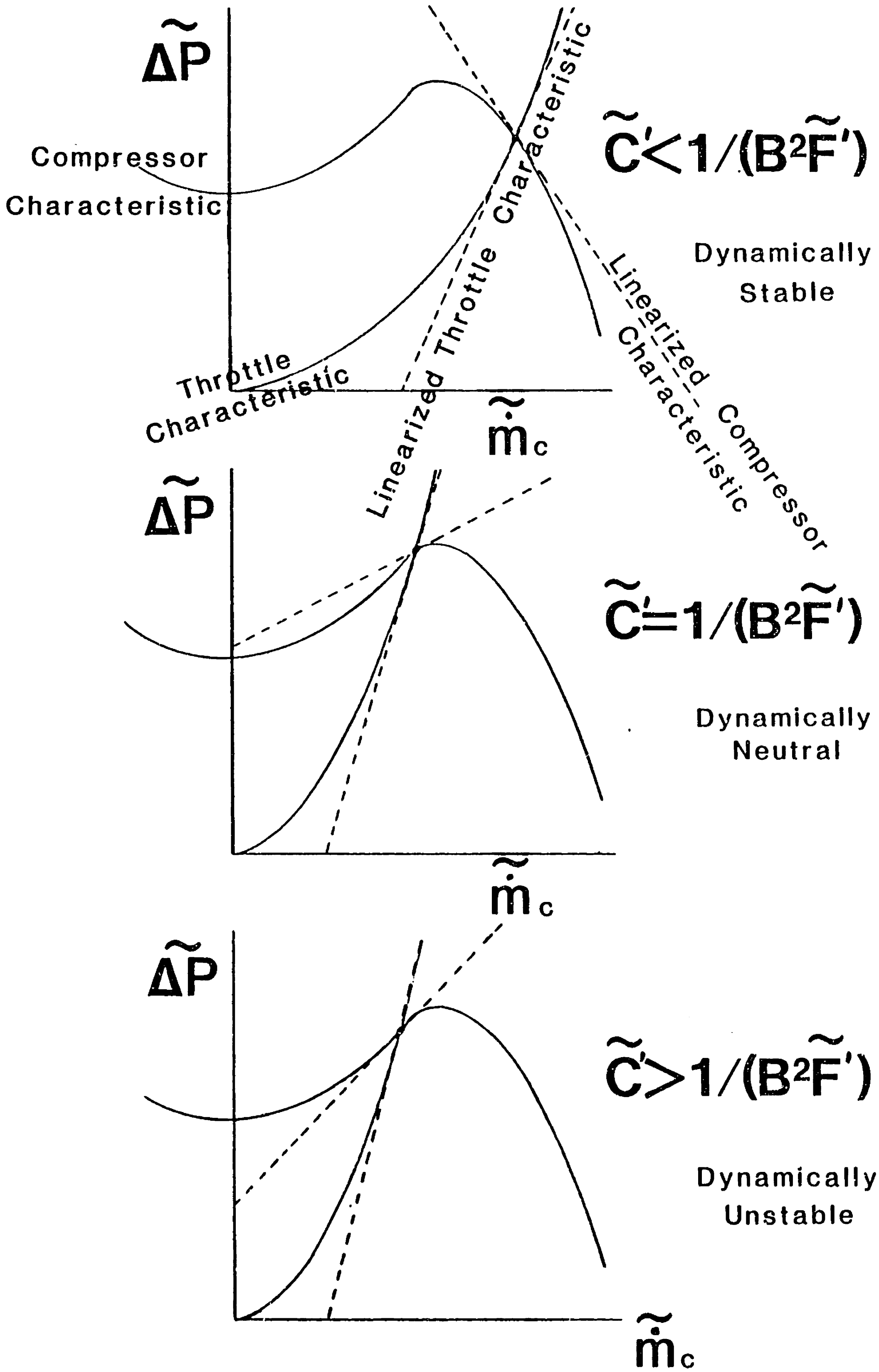


Figure 28 Surge Onset Criteria

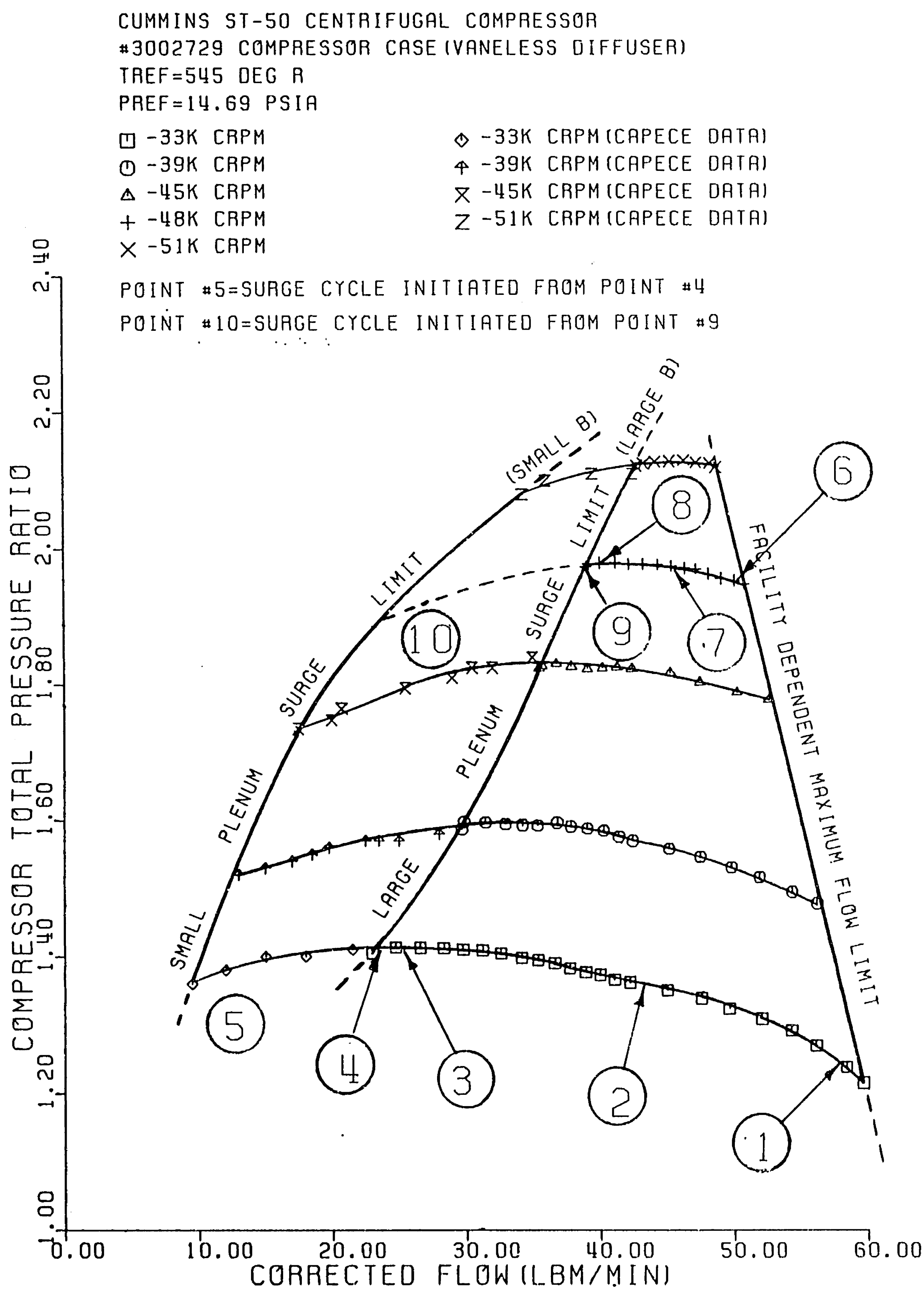


Figure 29 Compressor FFT Test Point Key

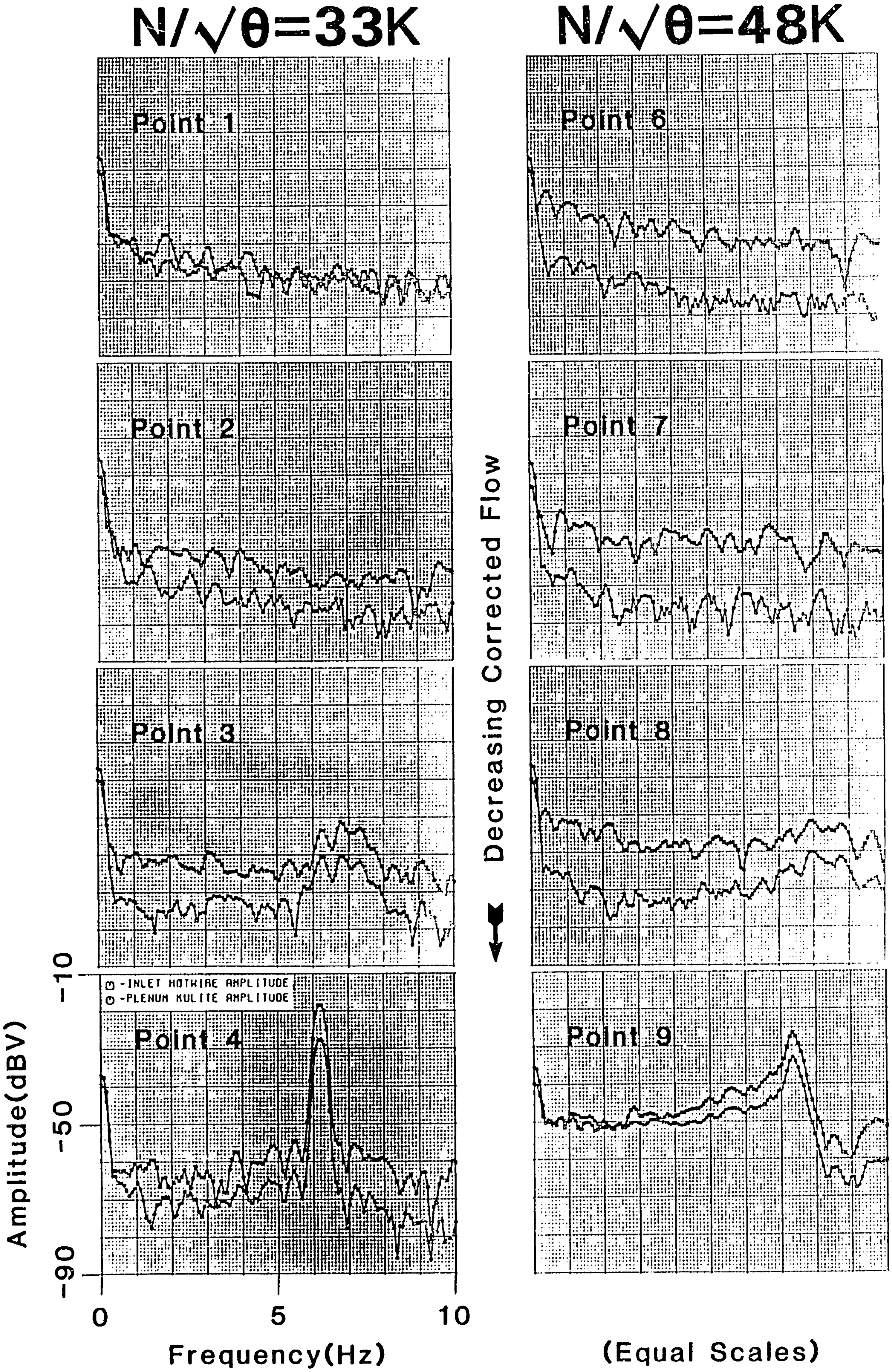
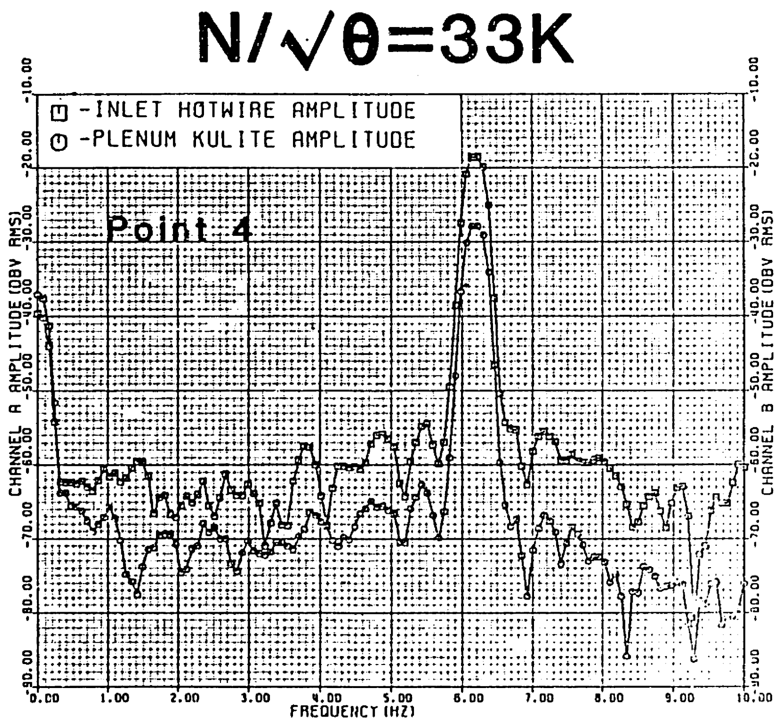


Figure 30 Massflow and Plenum Pressure FFT(0-10Hz) vs Flow



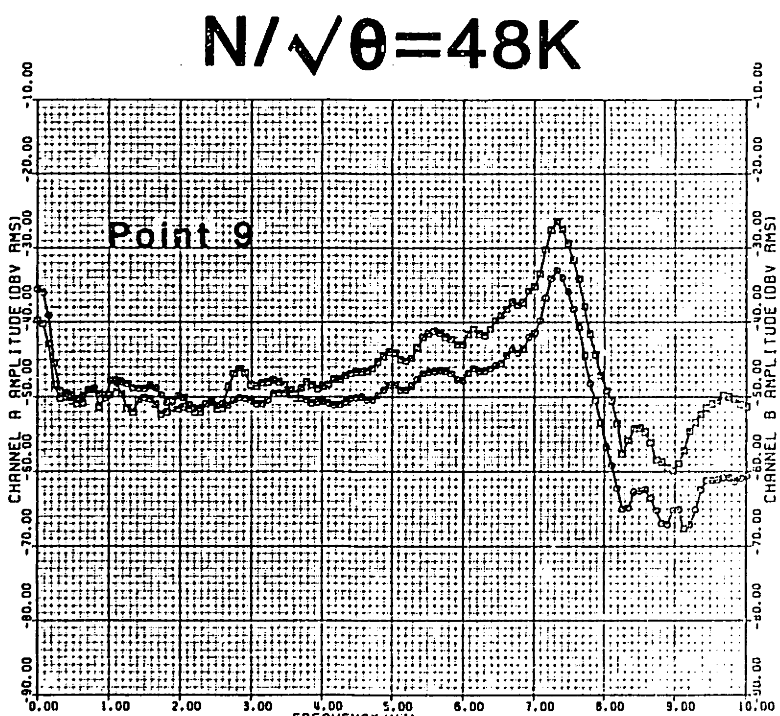
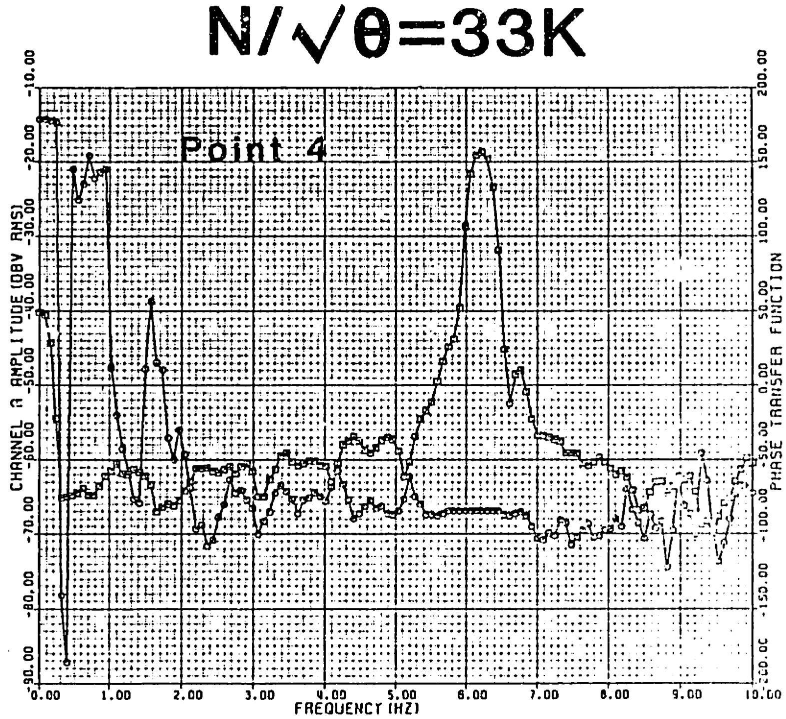


Figure 31 Massflow and Plenum Pressure FFT(0-10Hz) at Surge Limit



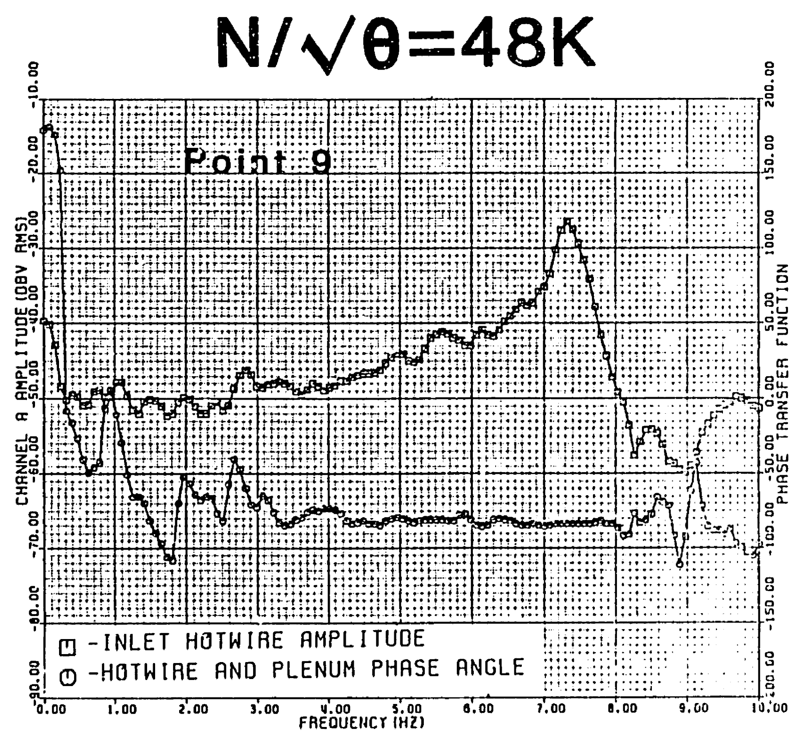


Figure 32 Massflow and Plenum Pressure FFT Phases at Surge Limit

Estimated Compressor Operation Paths (Orbits)

at Neutral Stability Points

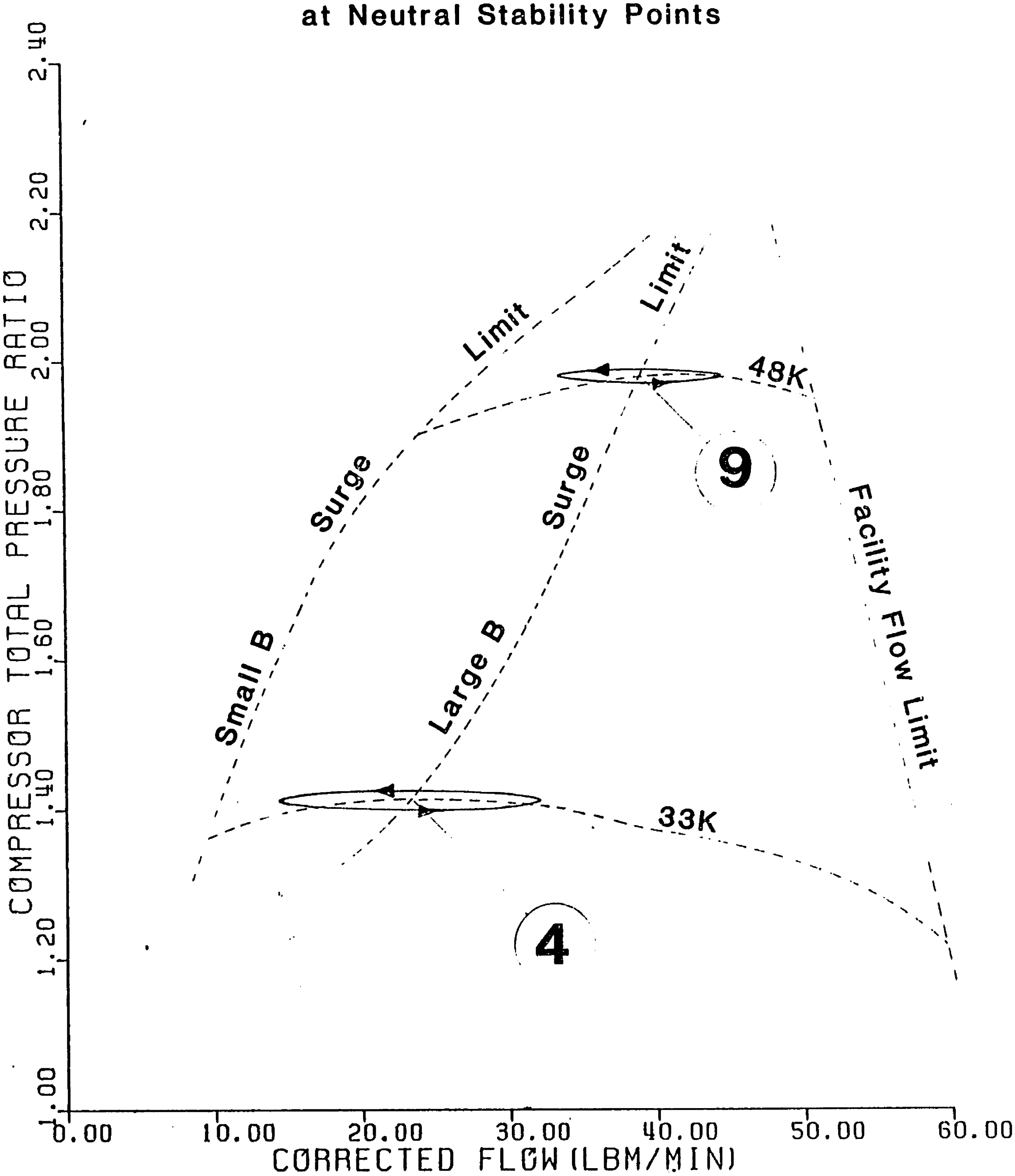


Figure 33 Estimated Compressor Operation Orbits

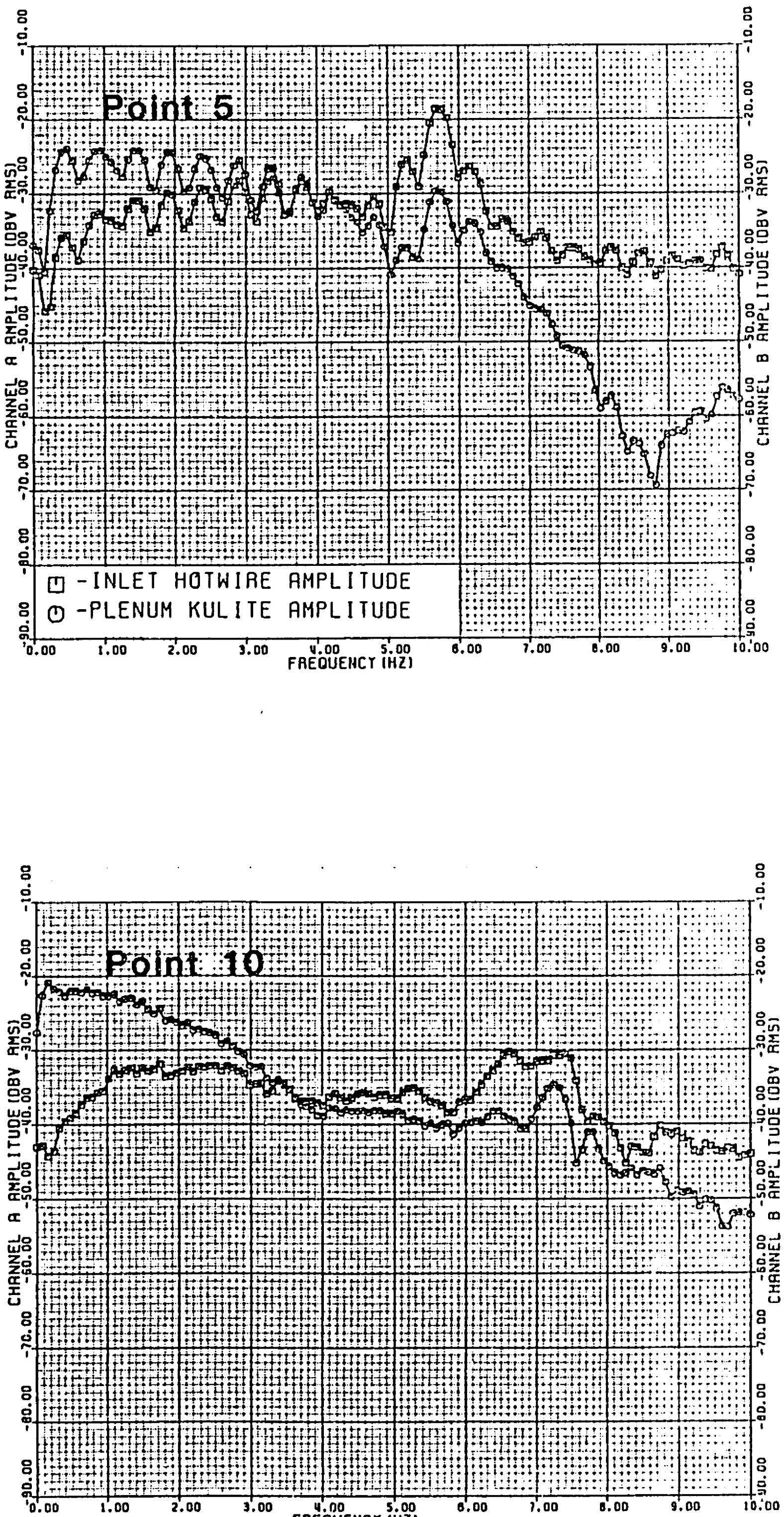


Figure 34 Massflow and Plenum Pressure FFT(0-10Hz) at Surge Breakdown

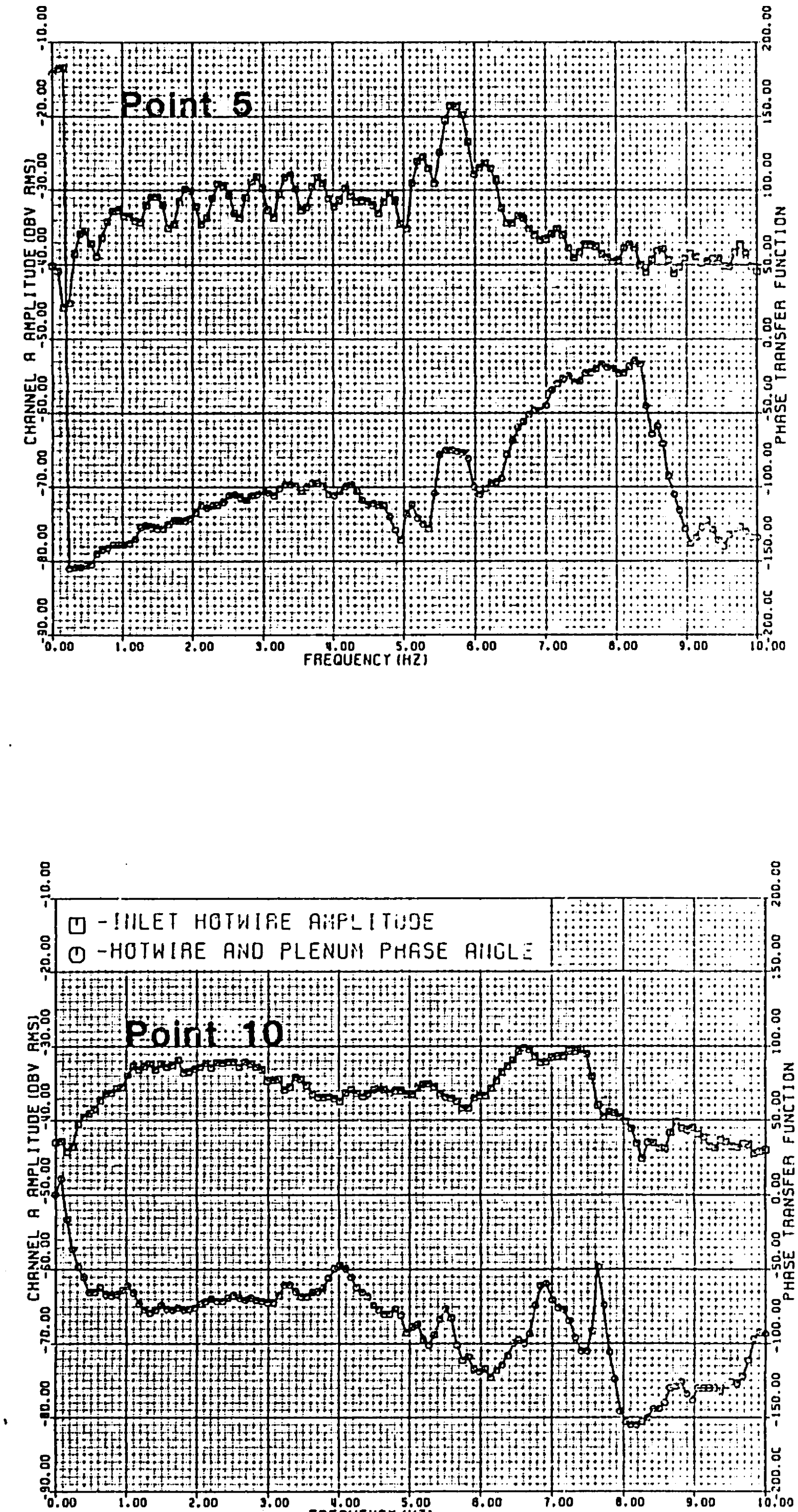


Figure 35' Massflow and Plenum Pressure FFT Phases at Surge Breakdown

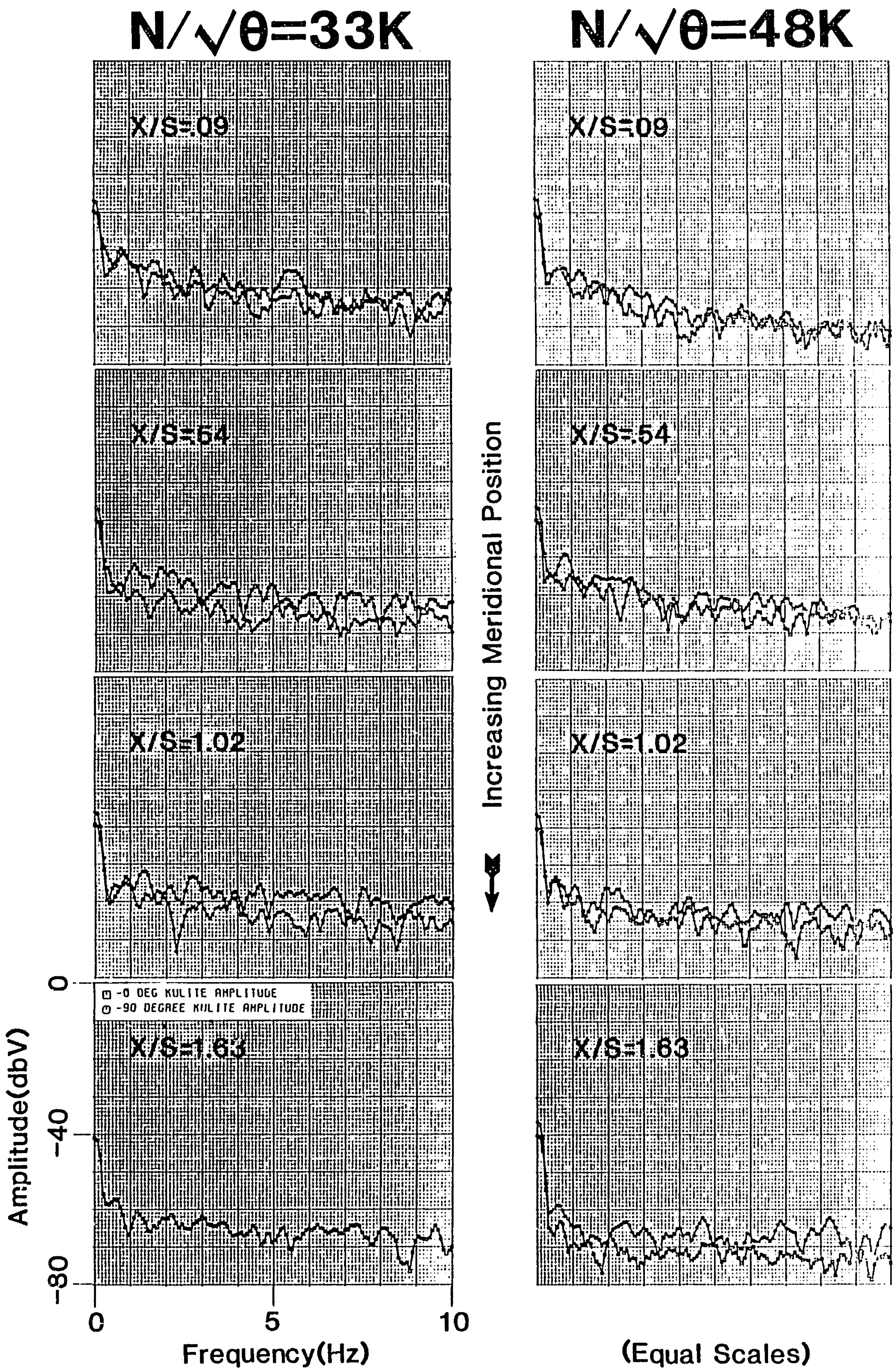


Figure 36 Casing Pressure FFTs(0-10Hz) in Non-Surge region

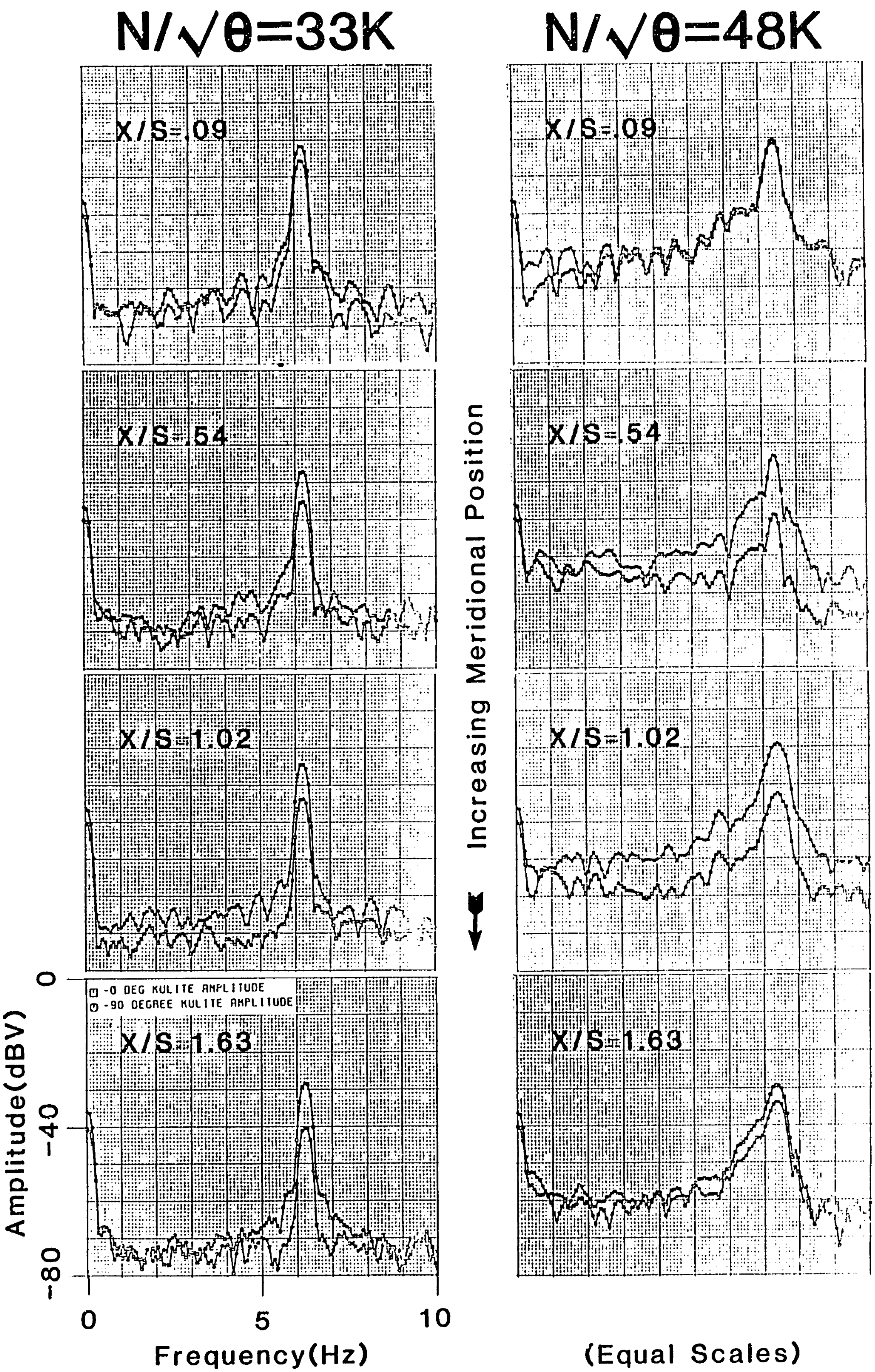


Figure 37 Casing Pressure FFTs(0-10Hz) at Surge Limit

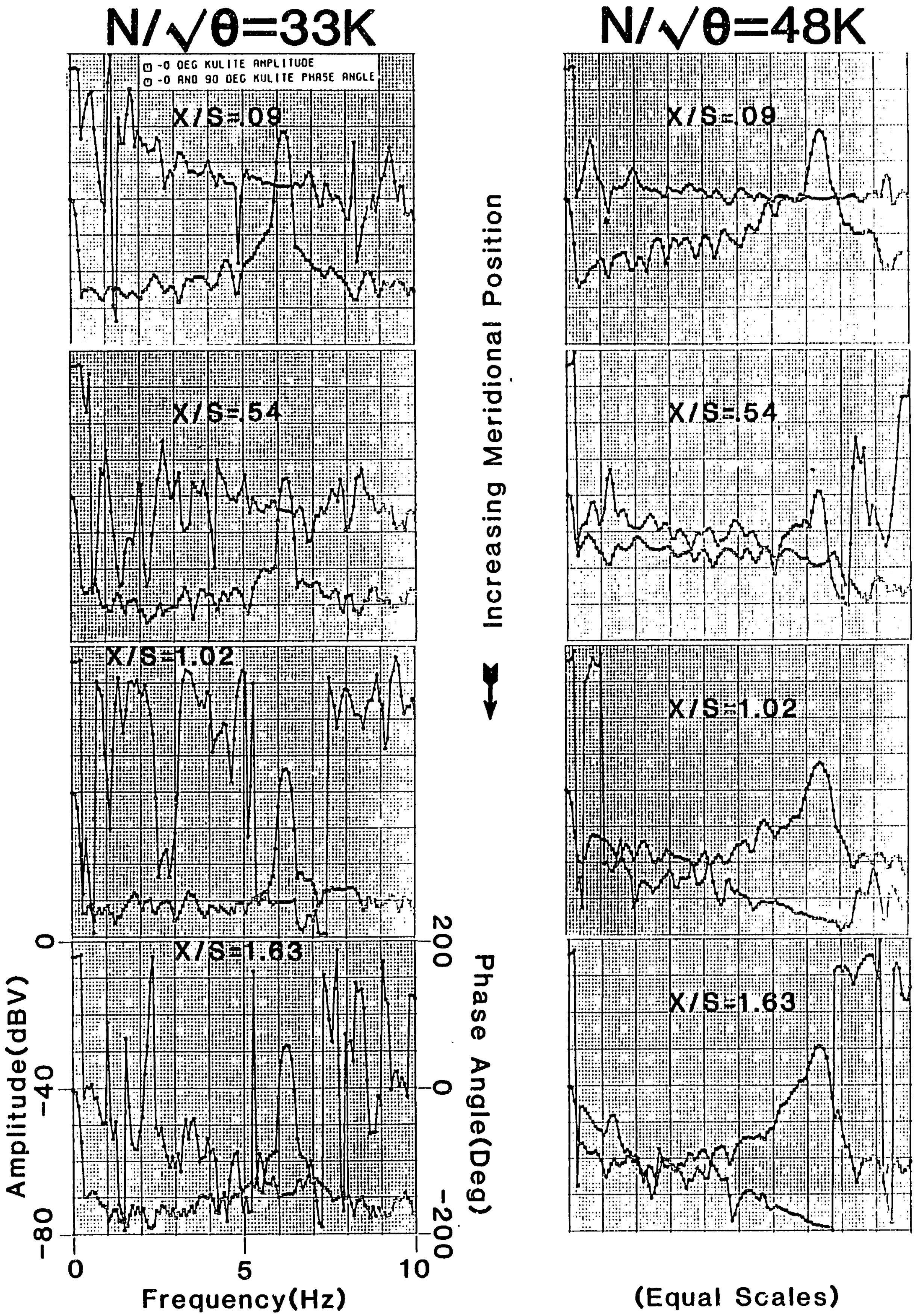


Figure 38 Casing Pressure FFT Phases at Surge Limit

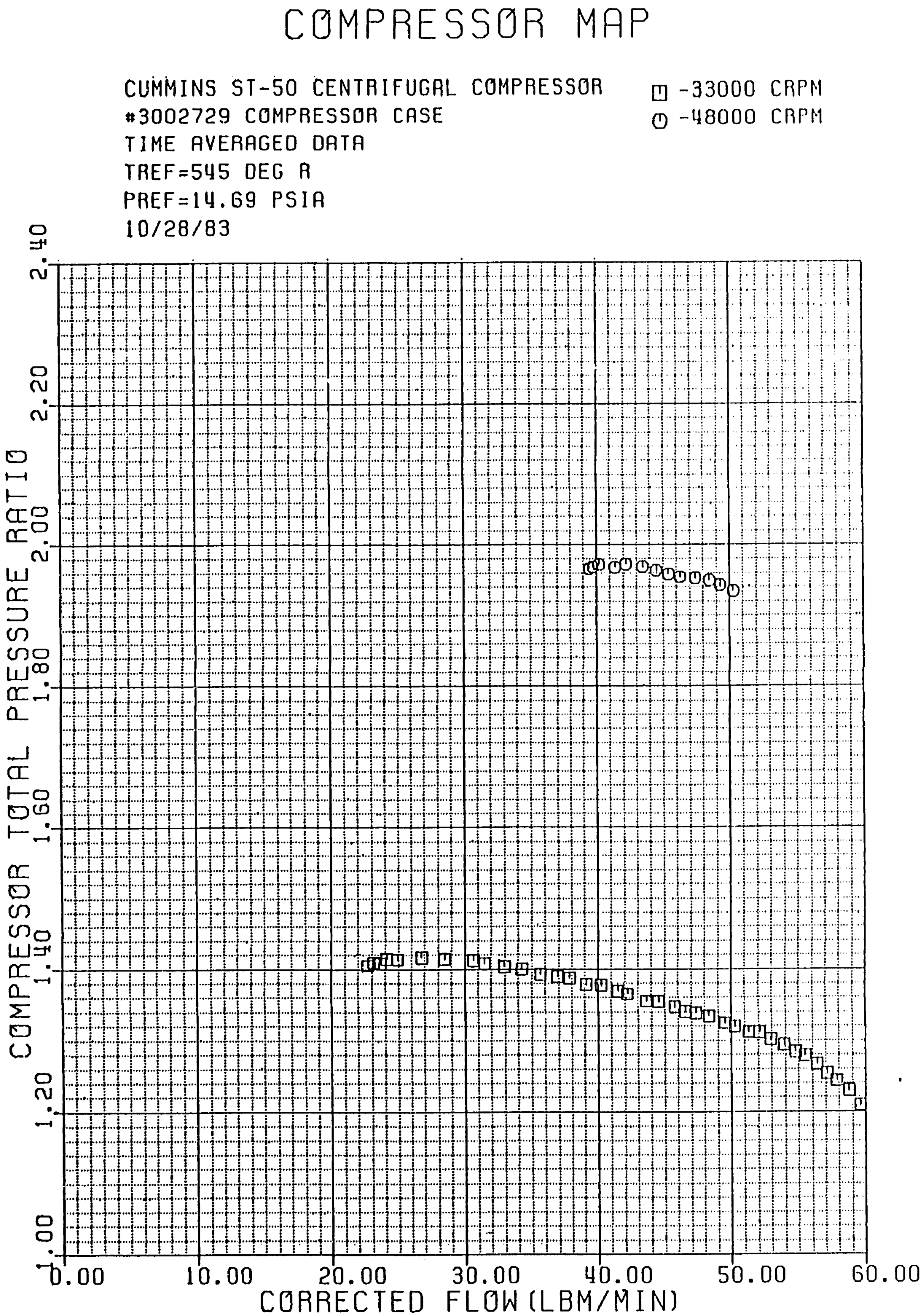


Figure 39 Time Average Total Pressure Ratio vs Corrected Flow

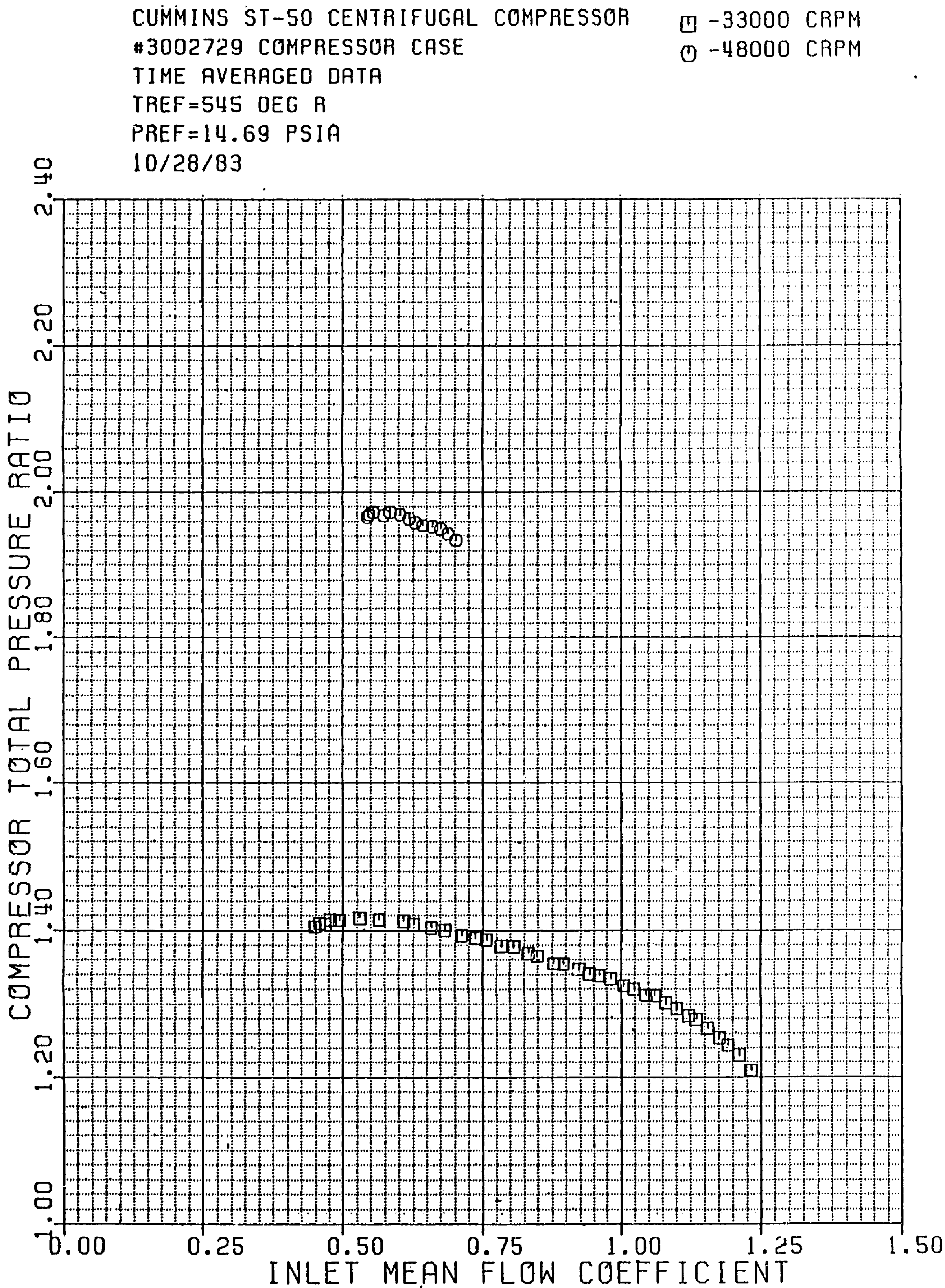


Figure 40 Time Average Total Pressure Ratio vs Flow Coefficient

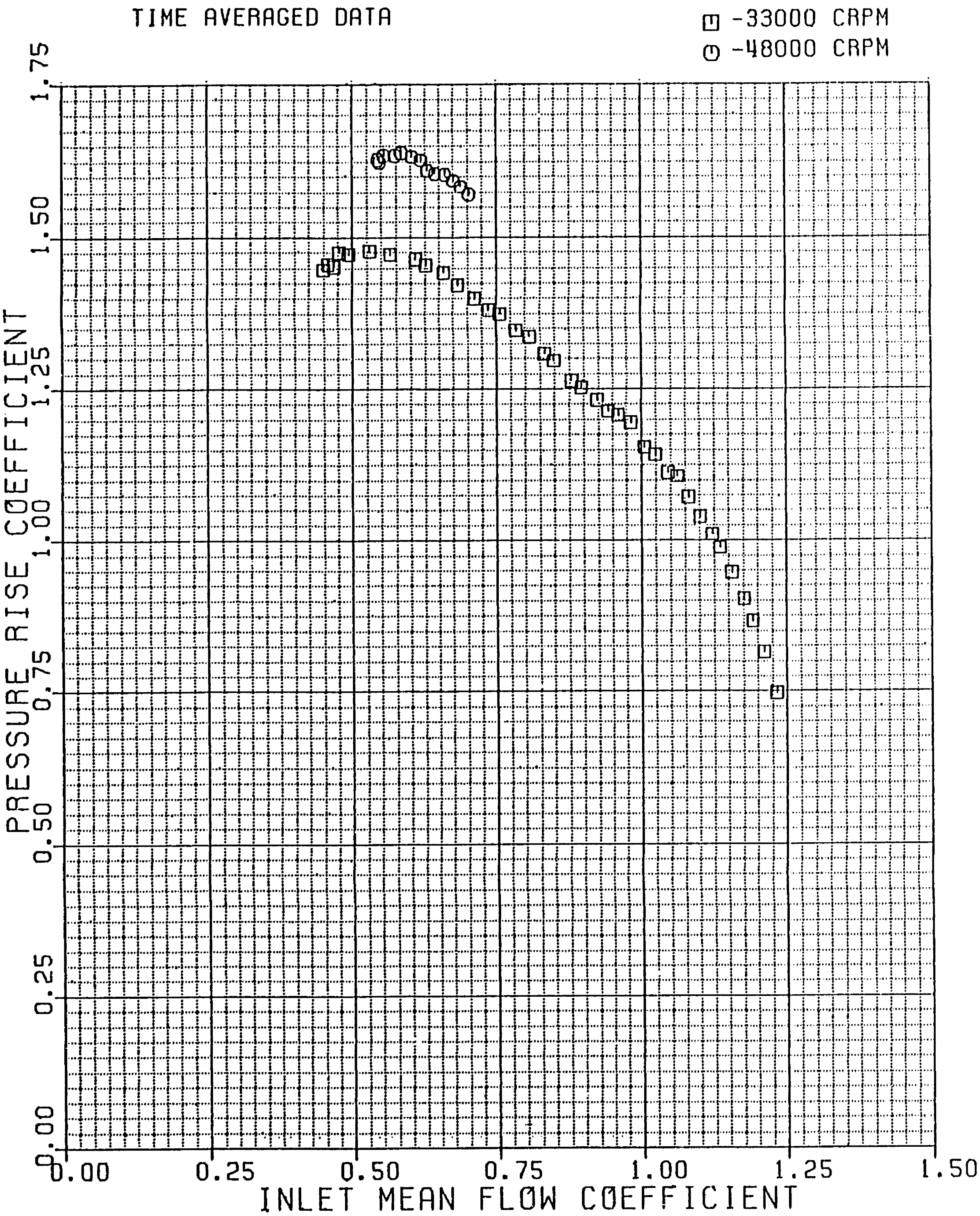


Figure 41 Time Average Pressure Rise Coefficient vs Flow Coefficient

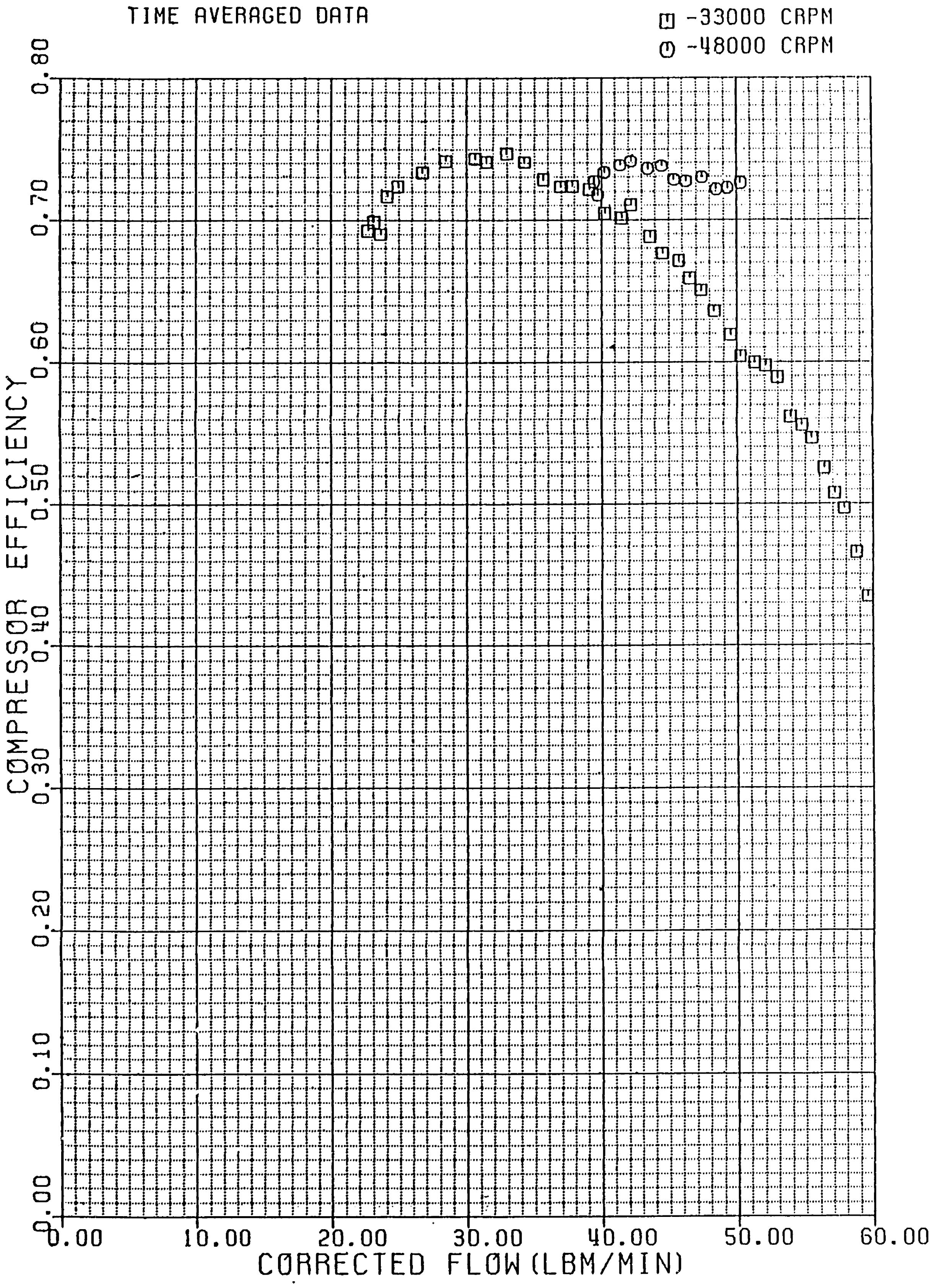


Figure 42 Time Average Adiabatic Efficiency vs Corrected Flow

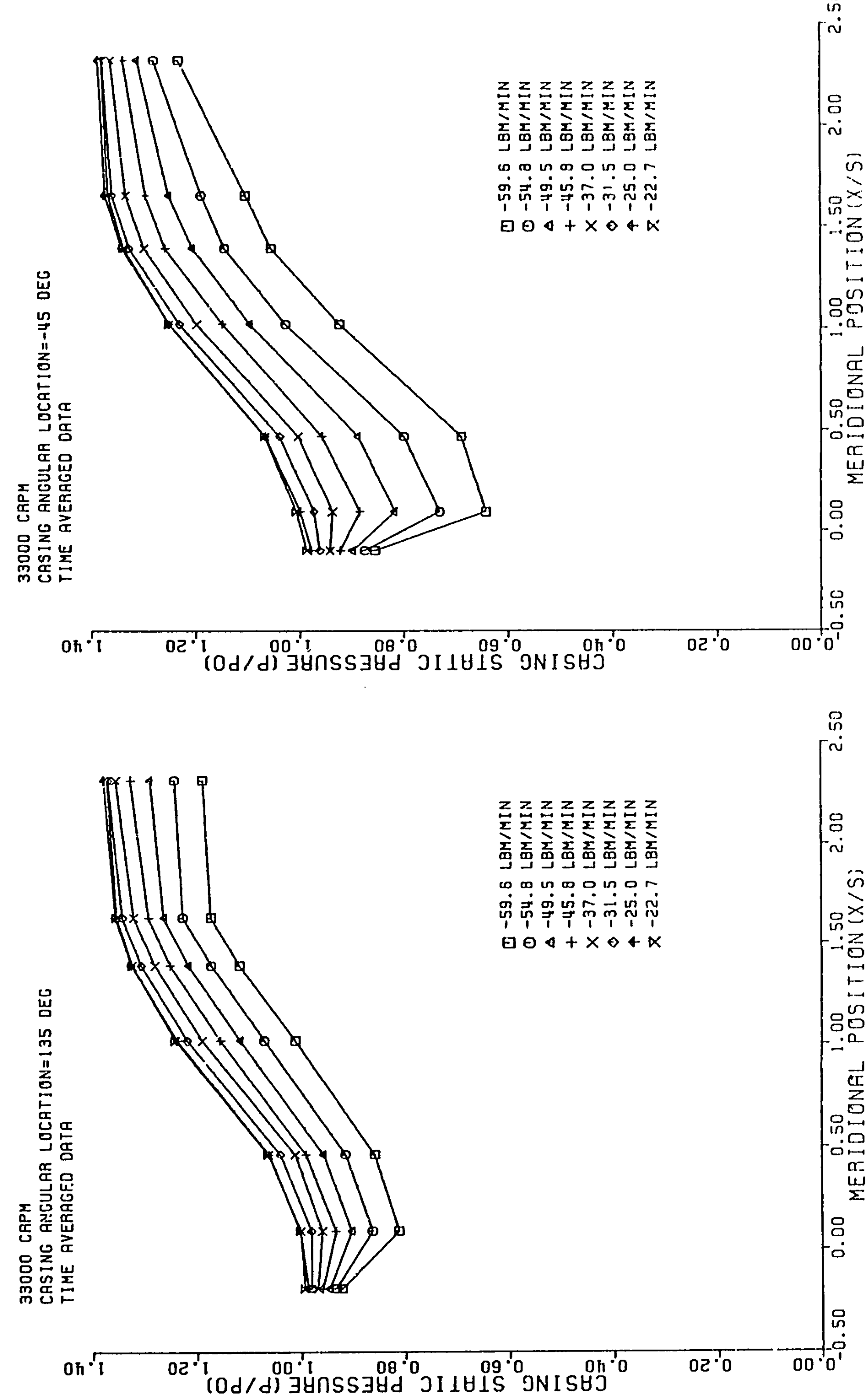


Figure 43 Time Average Casing P/PO vs x/s @ 33K

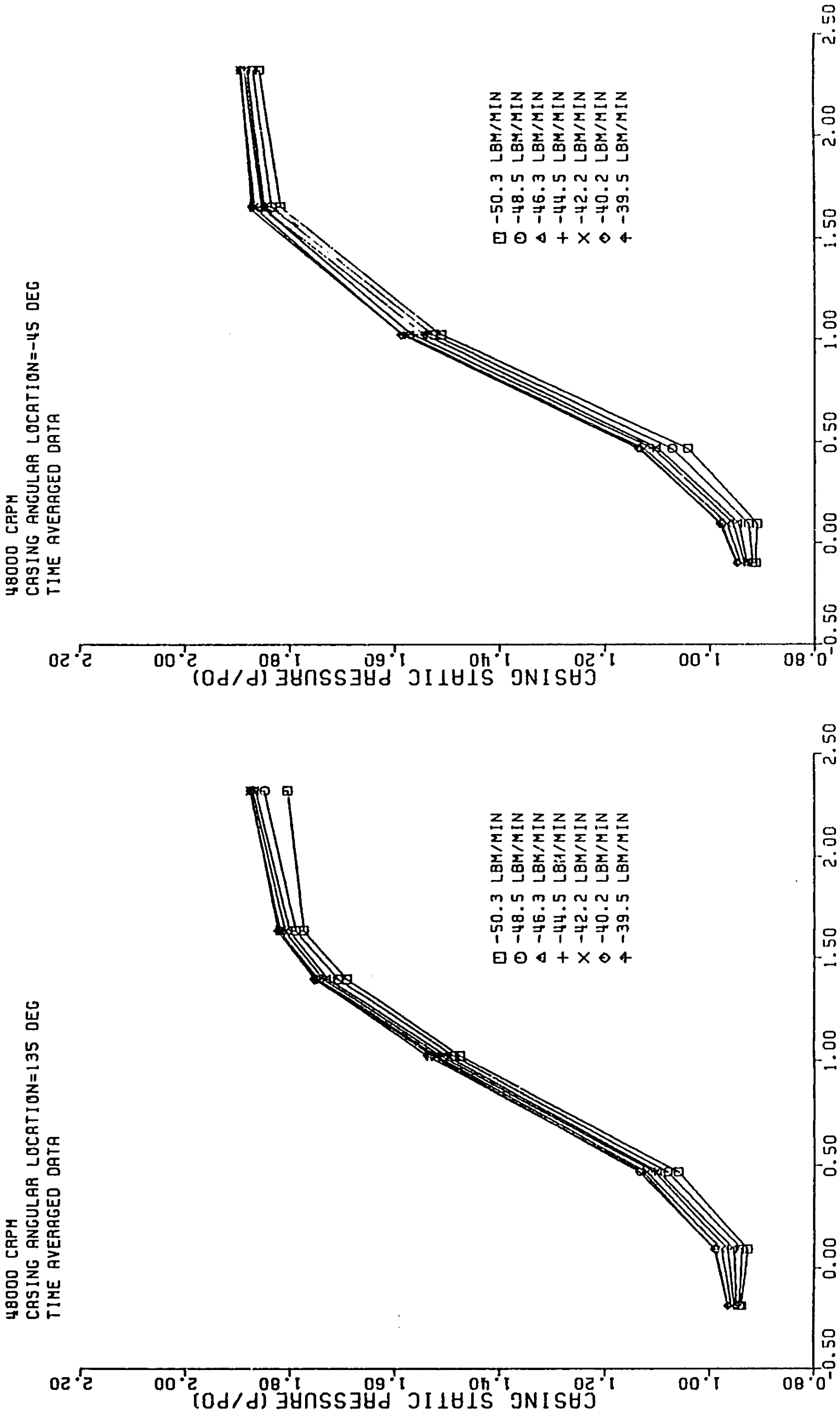


Figure 44 Time Average Casing P/PO vs x/s @ 48K

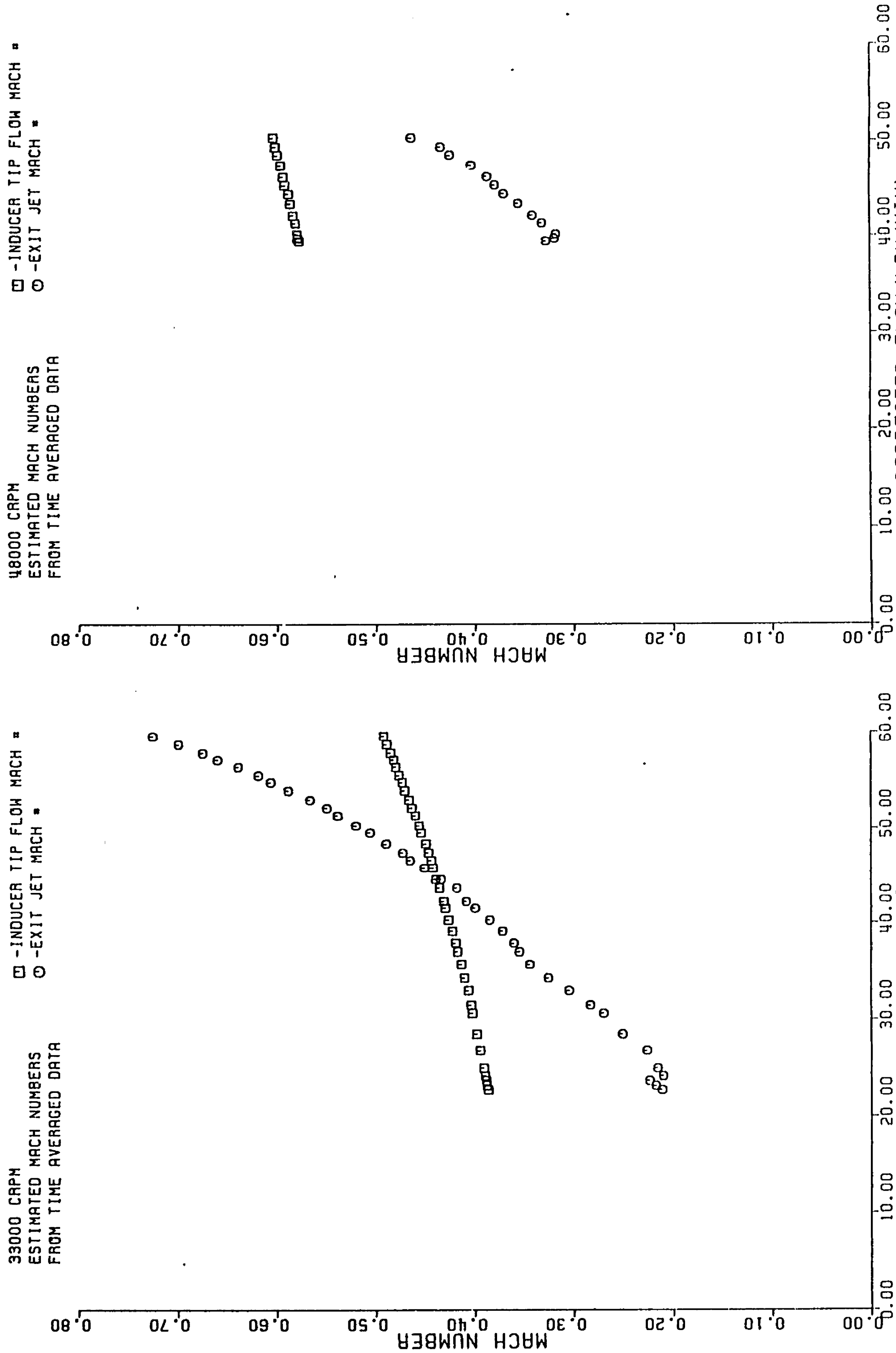


Figure 45 Impeller Estimated Mach Numbers vs Corrected Flow

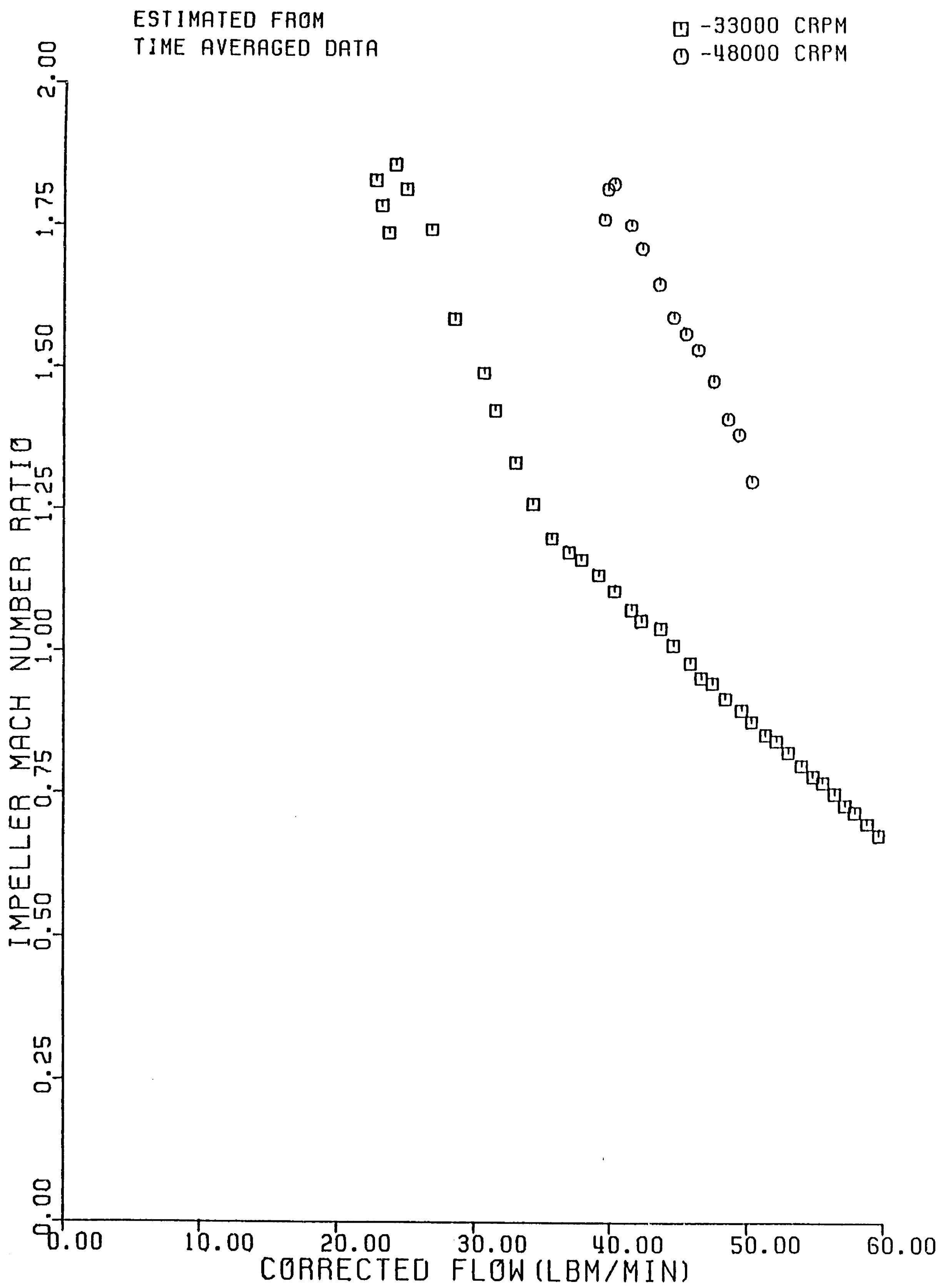


Figure 46 Impeller Estimated Mach Ratio vs Corrected Flow

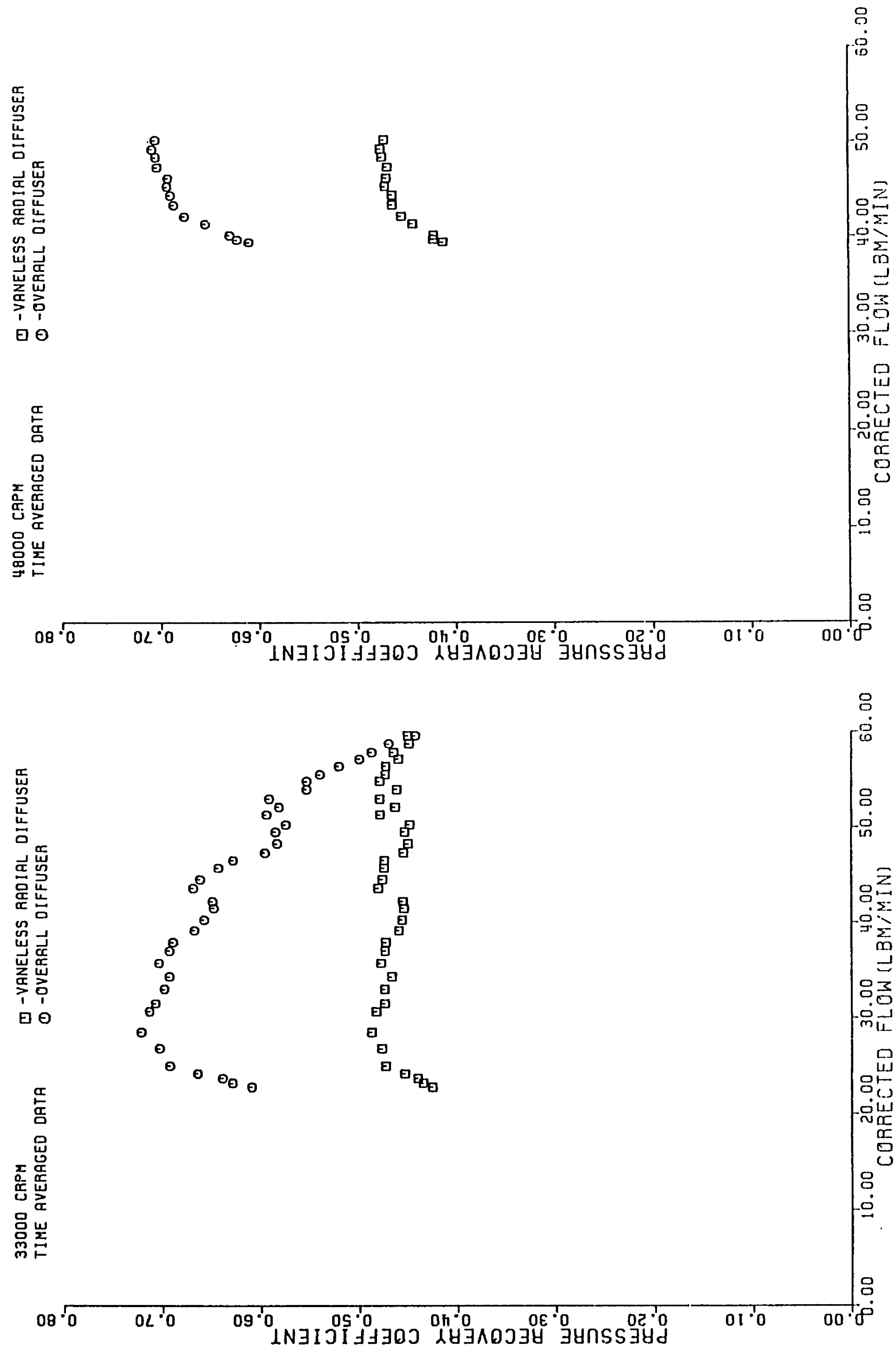


Figure 47 Time Average Diffuser Cp vs Corrected Flow

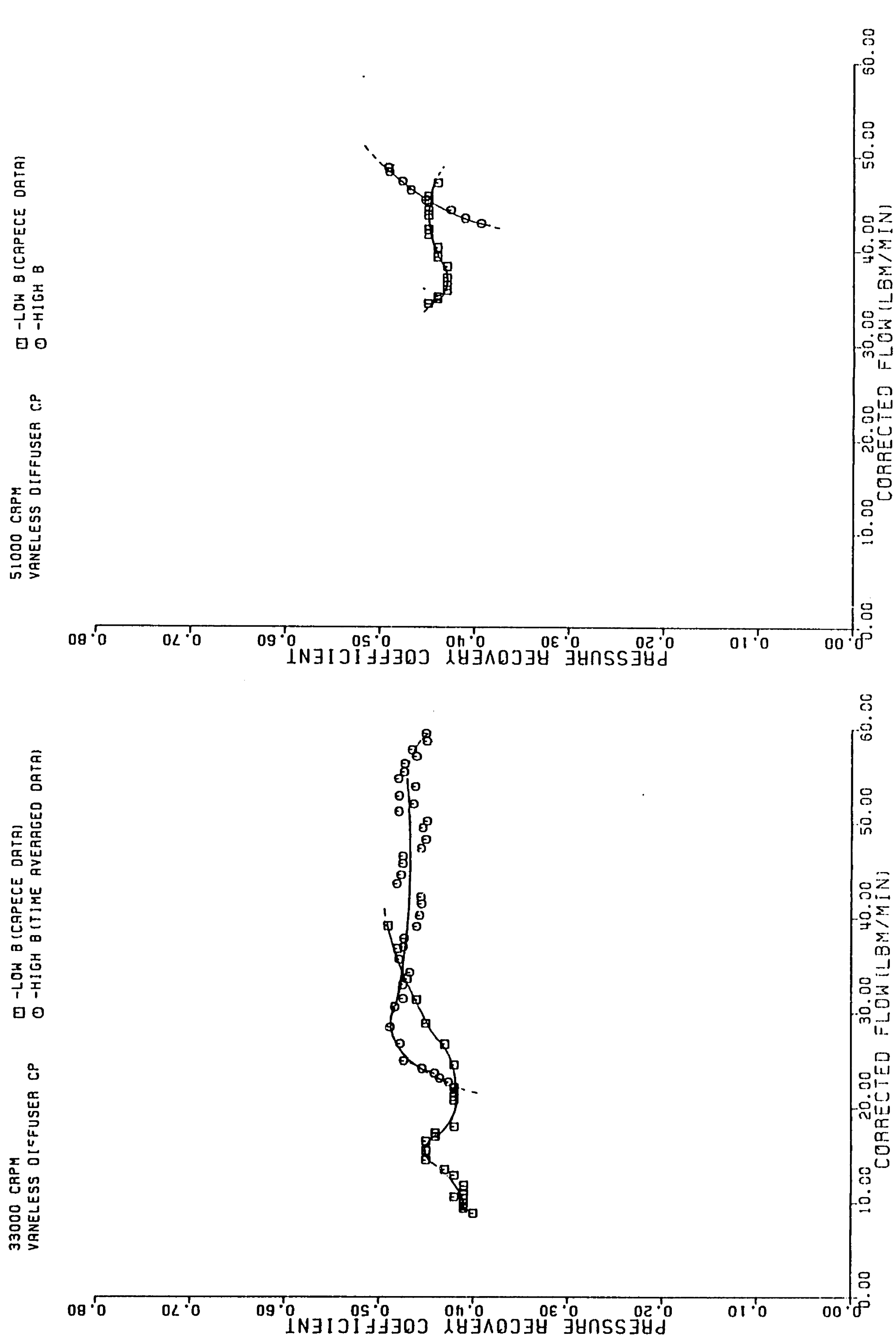


Figure 48 Effect of System B-Parameter on Diffuser Performance

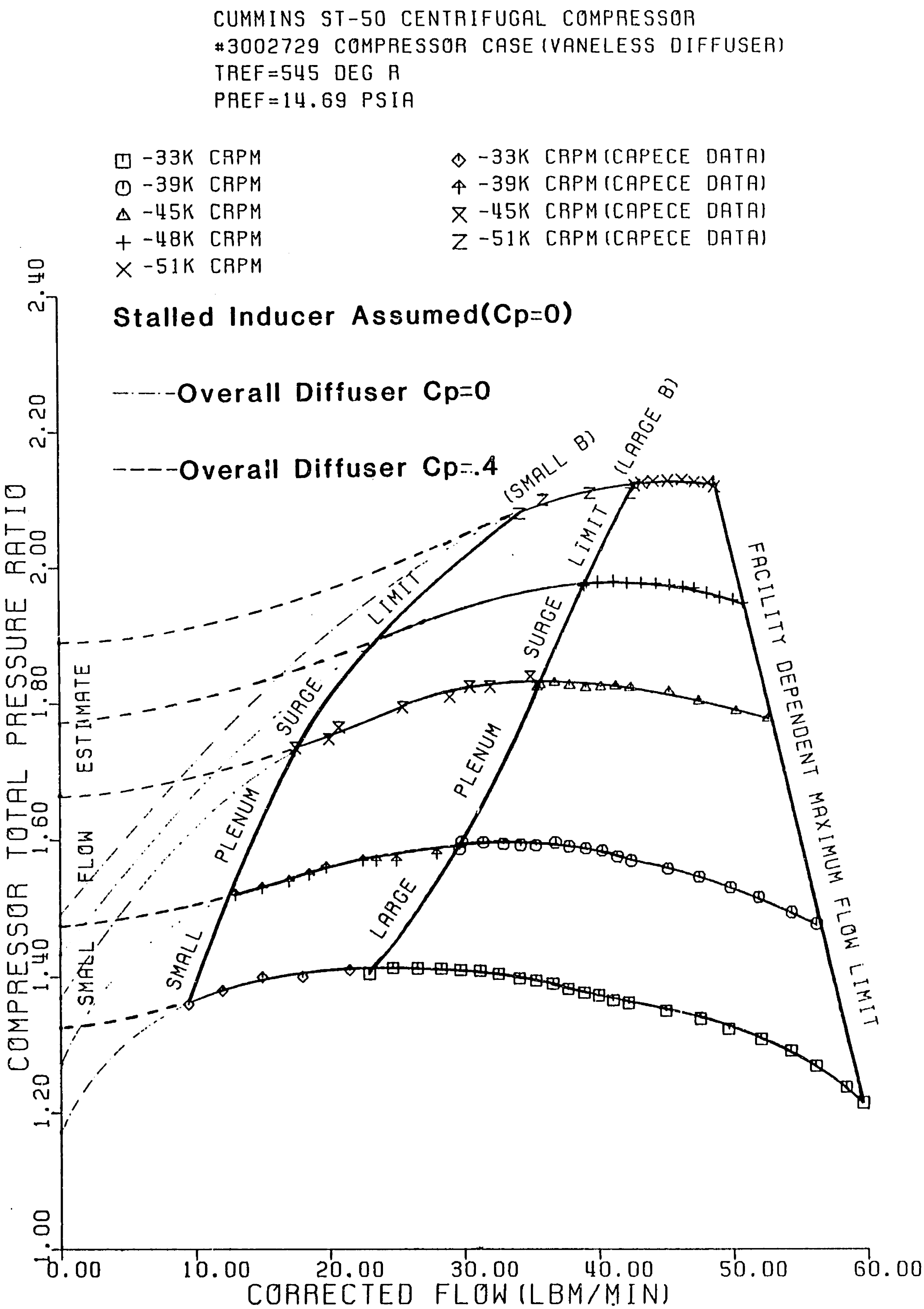


Figure 49 Effect of Diffuser on Characteristics at Low Flows

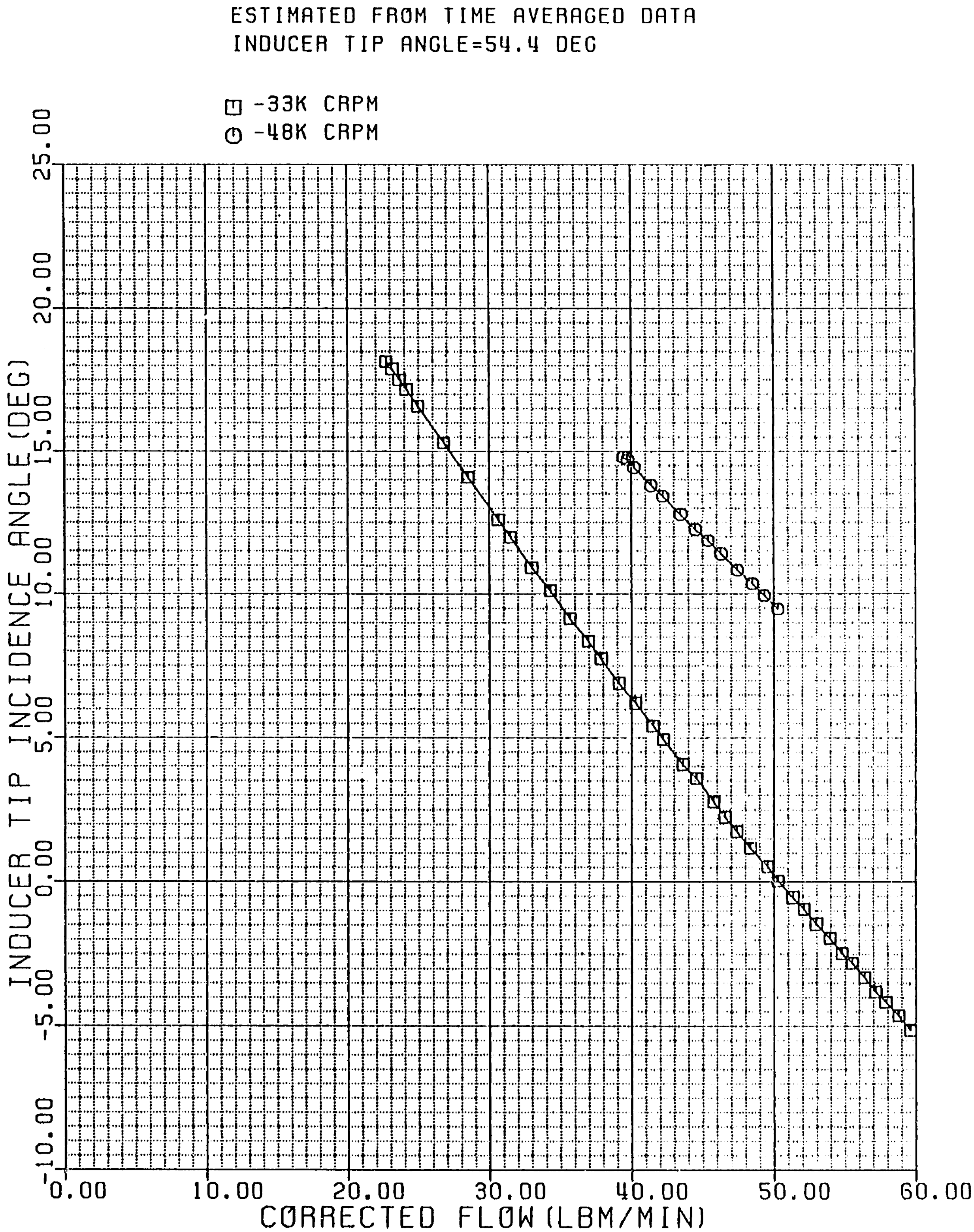


Figure 50 Impeller Flow Angle vs Corrected Flow

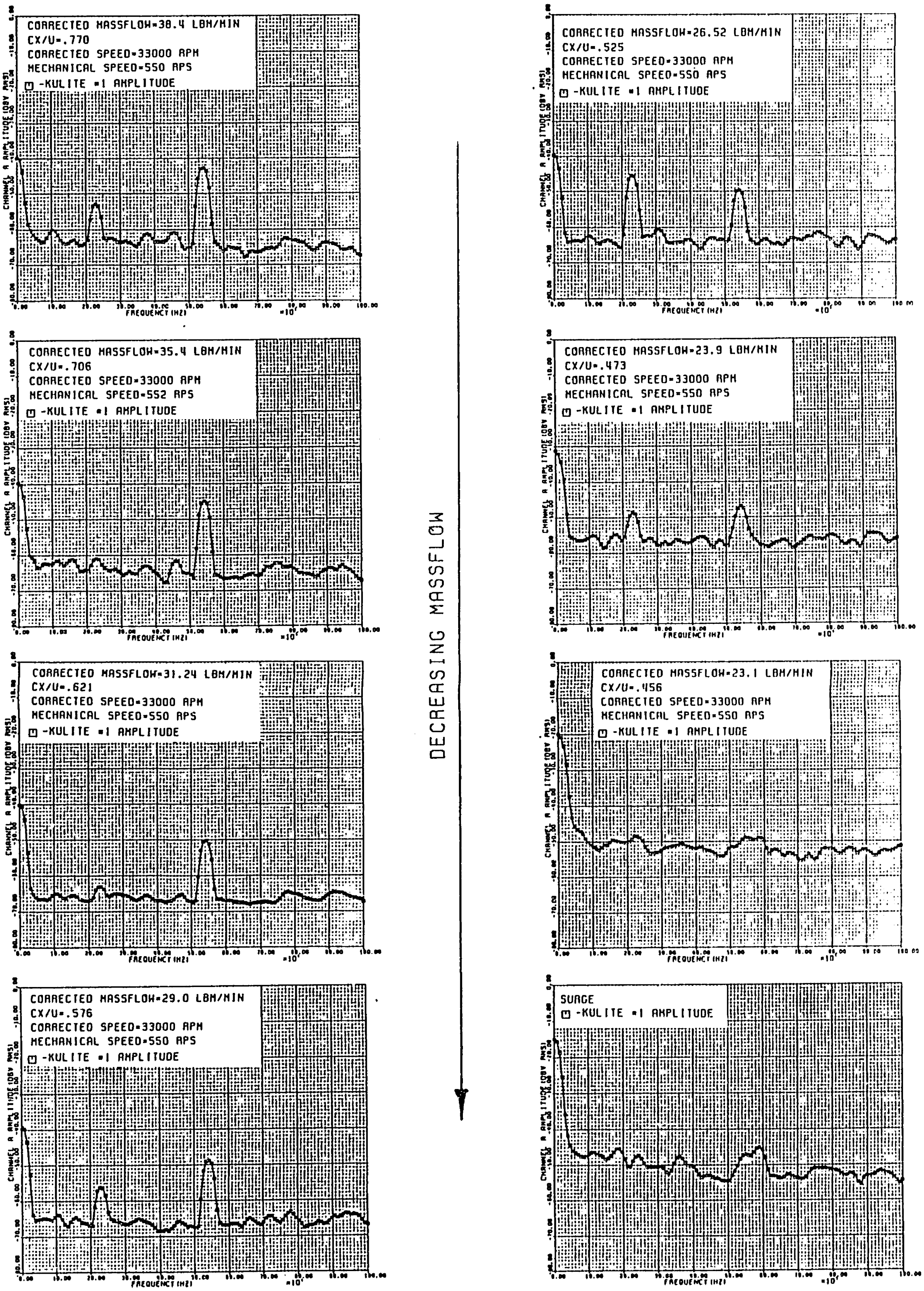


Figure 51 Inducer Stall Cell Amplitude vs Flow

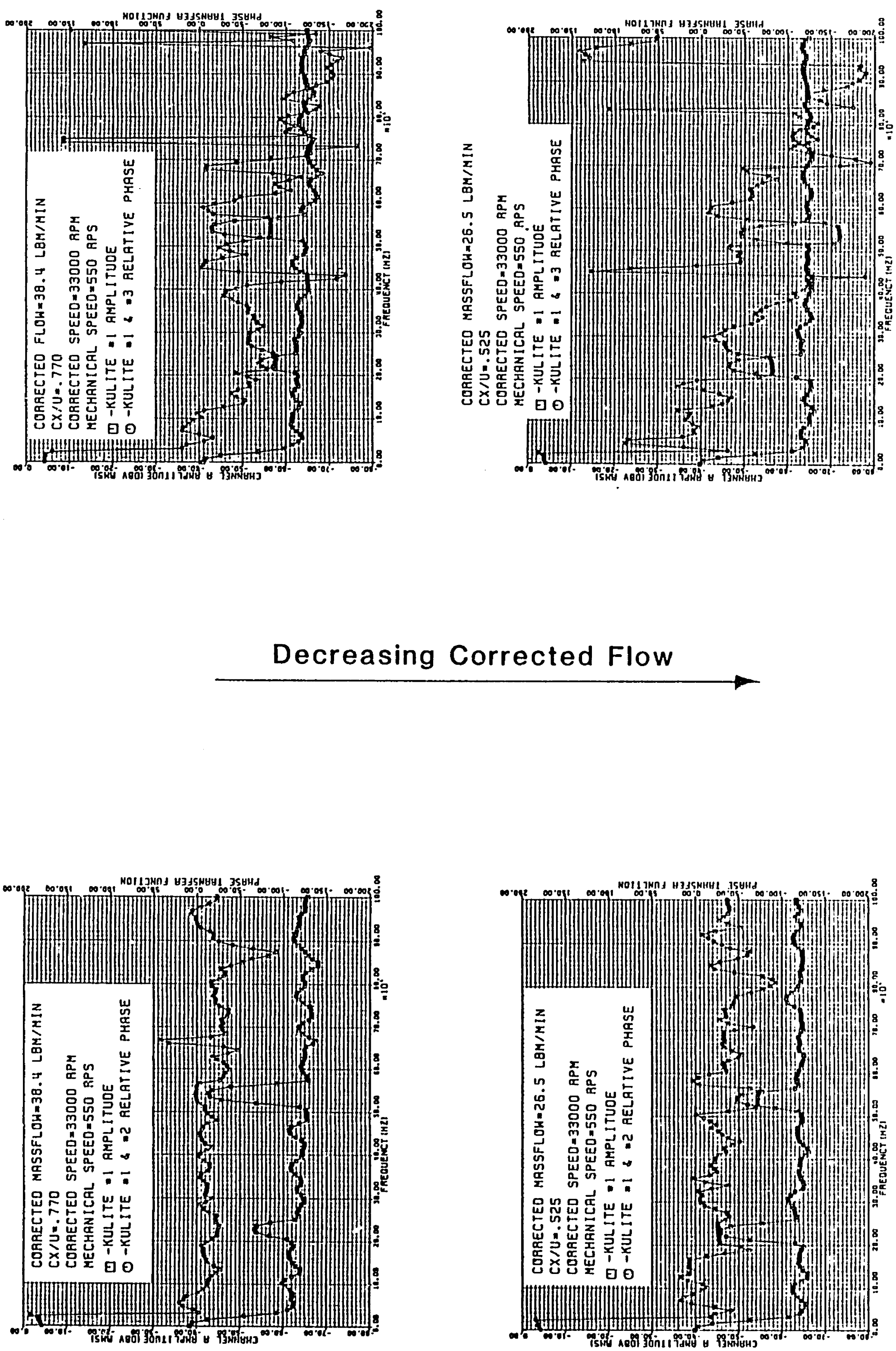


Figure 52 Inducer Stall Cell Verification

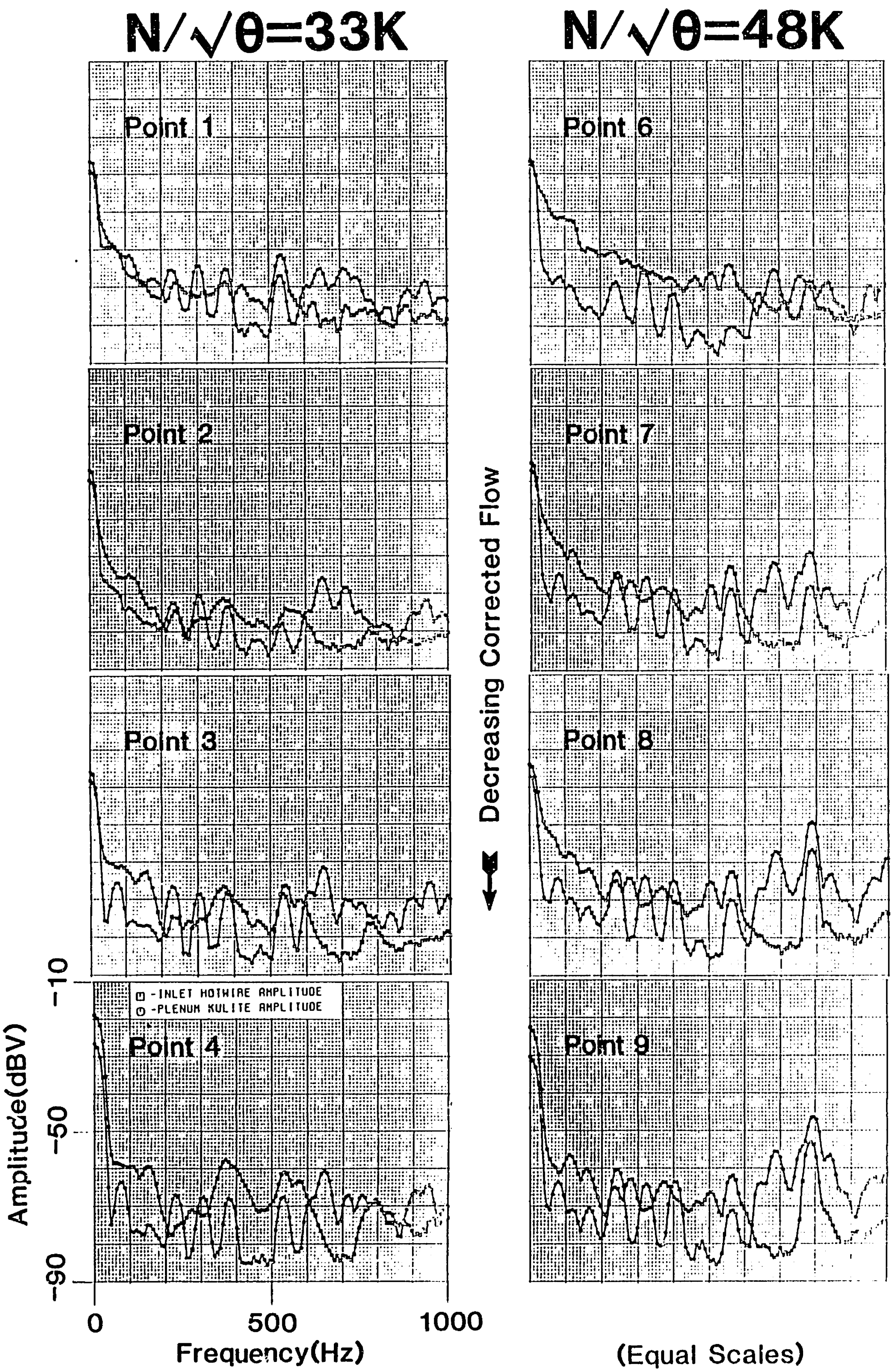
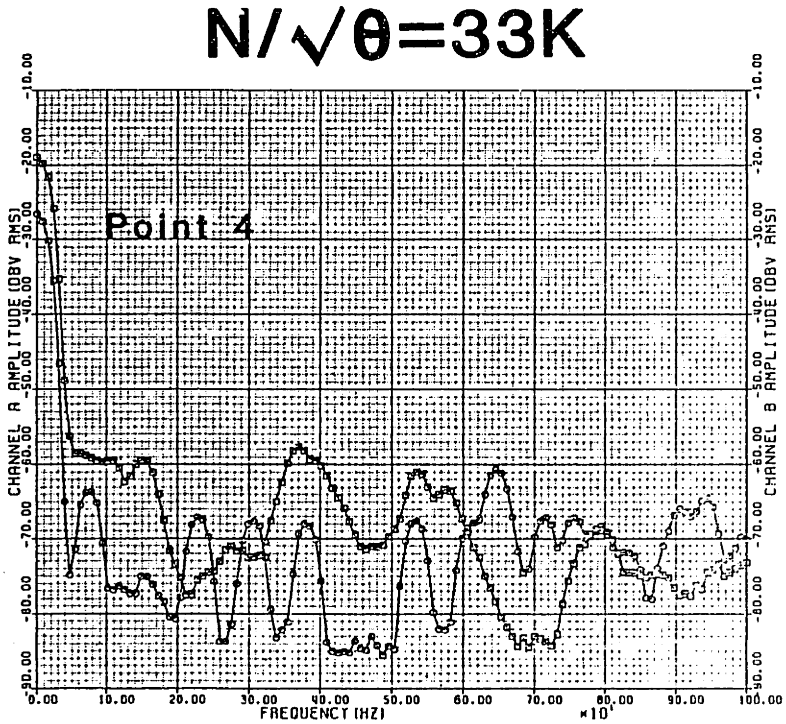


Figure 53 Massflow and Plenum Pressure FFT(0-1000Hz) vs Flow



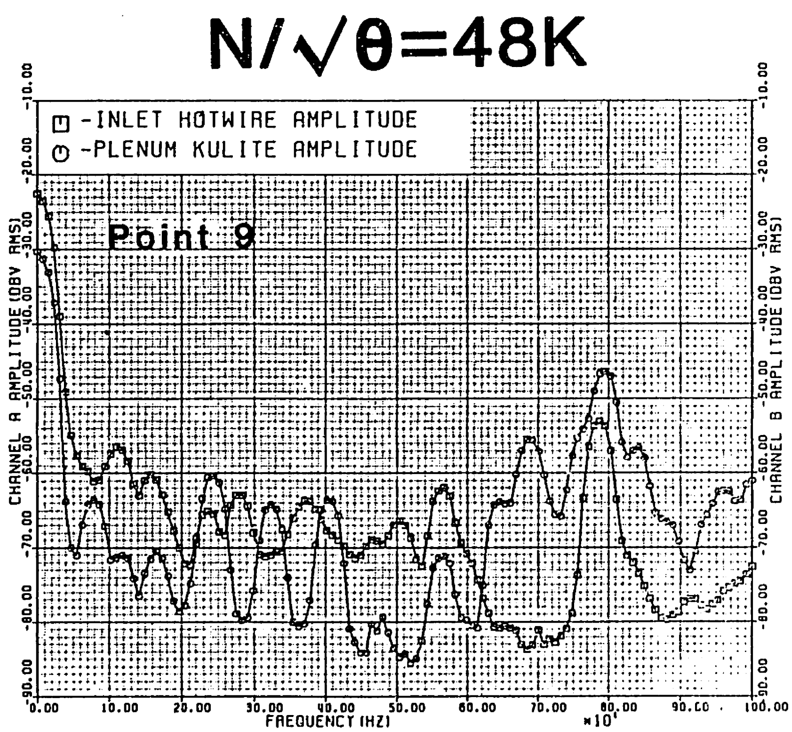
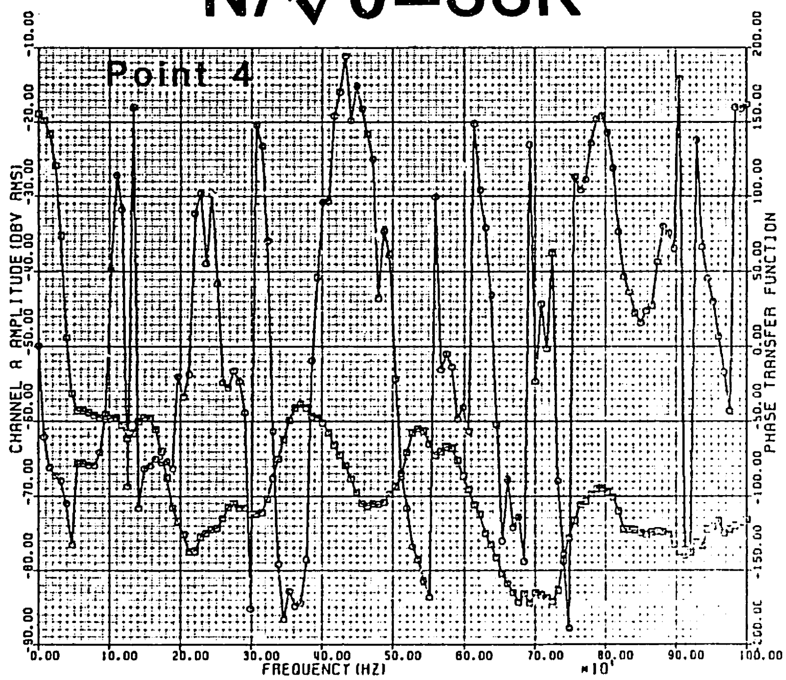


Figure 54 Massflow and Plenum Pressure FFT(0-1000Hz) at Surge Limit

N/√θ=33K



N/√θ=48K

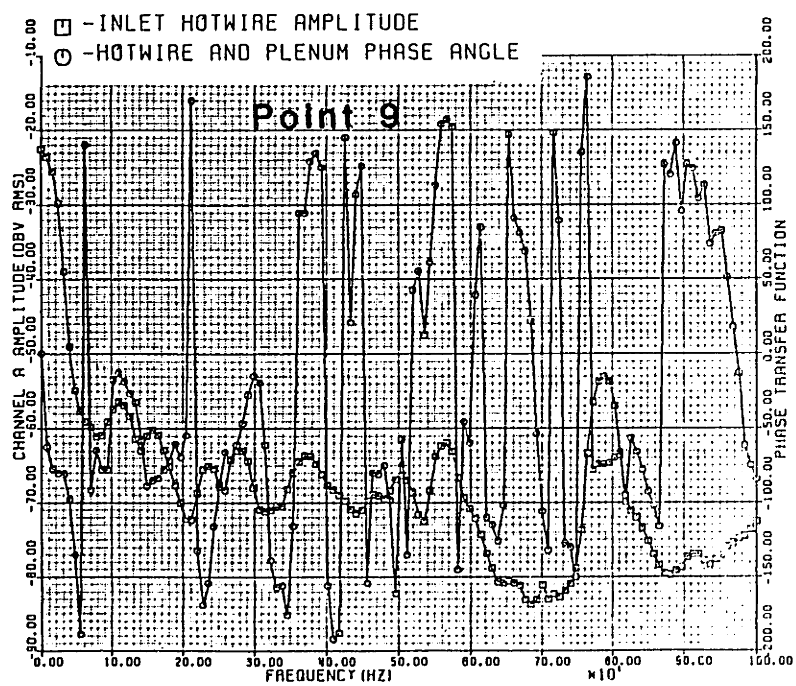


Figure 55 Massflow and Plenum Pressure FFT Phases at Surge Limit

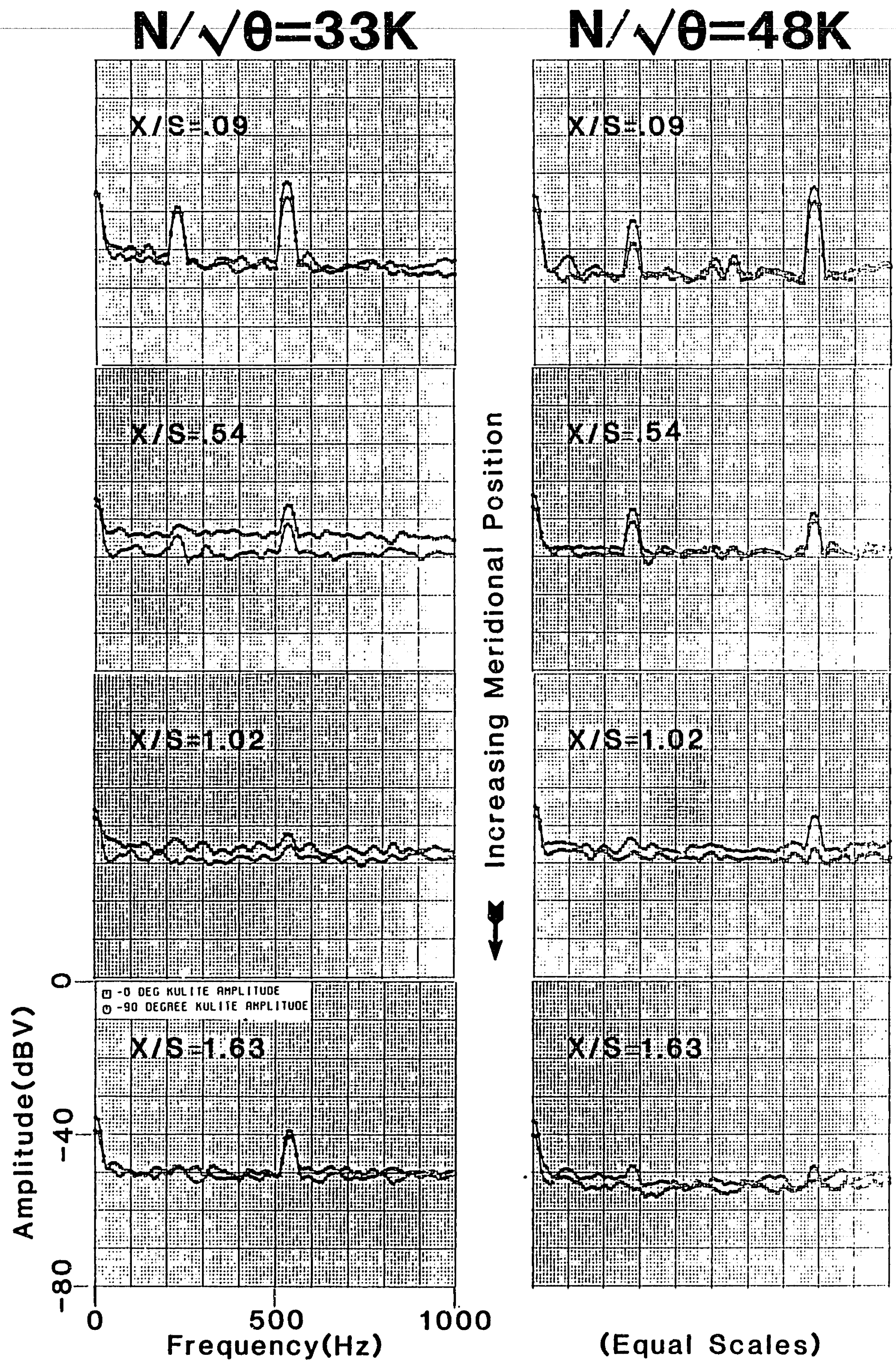


Figure 56 Casing Pressure FFTs(0-1000Hz) vs x/s in Non-Surge

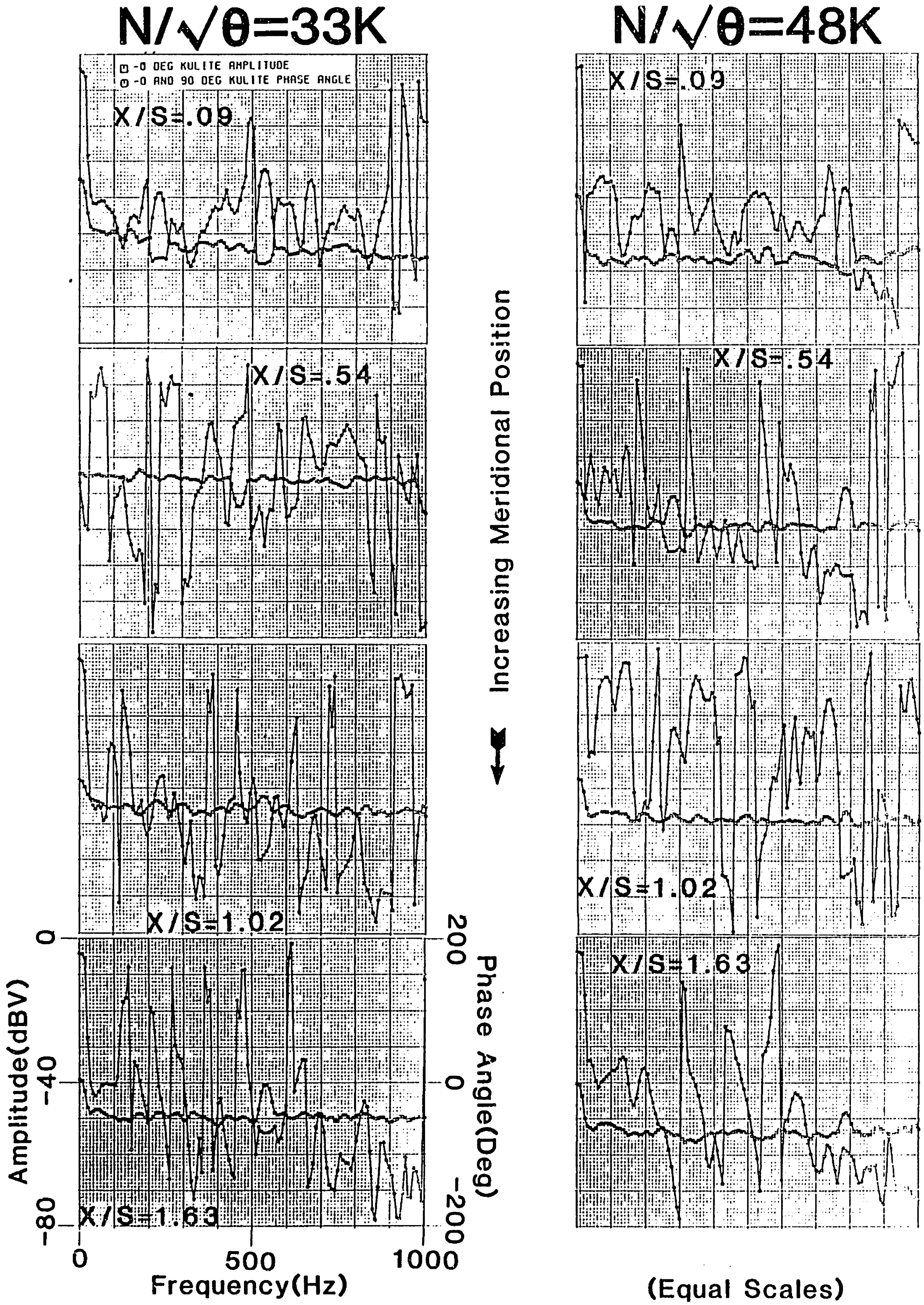


Figure 57 Casing Pressure FFT Phases vs x/s in Non-surge

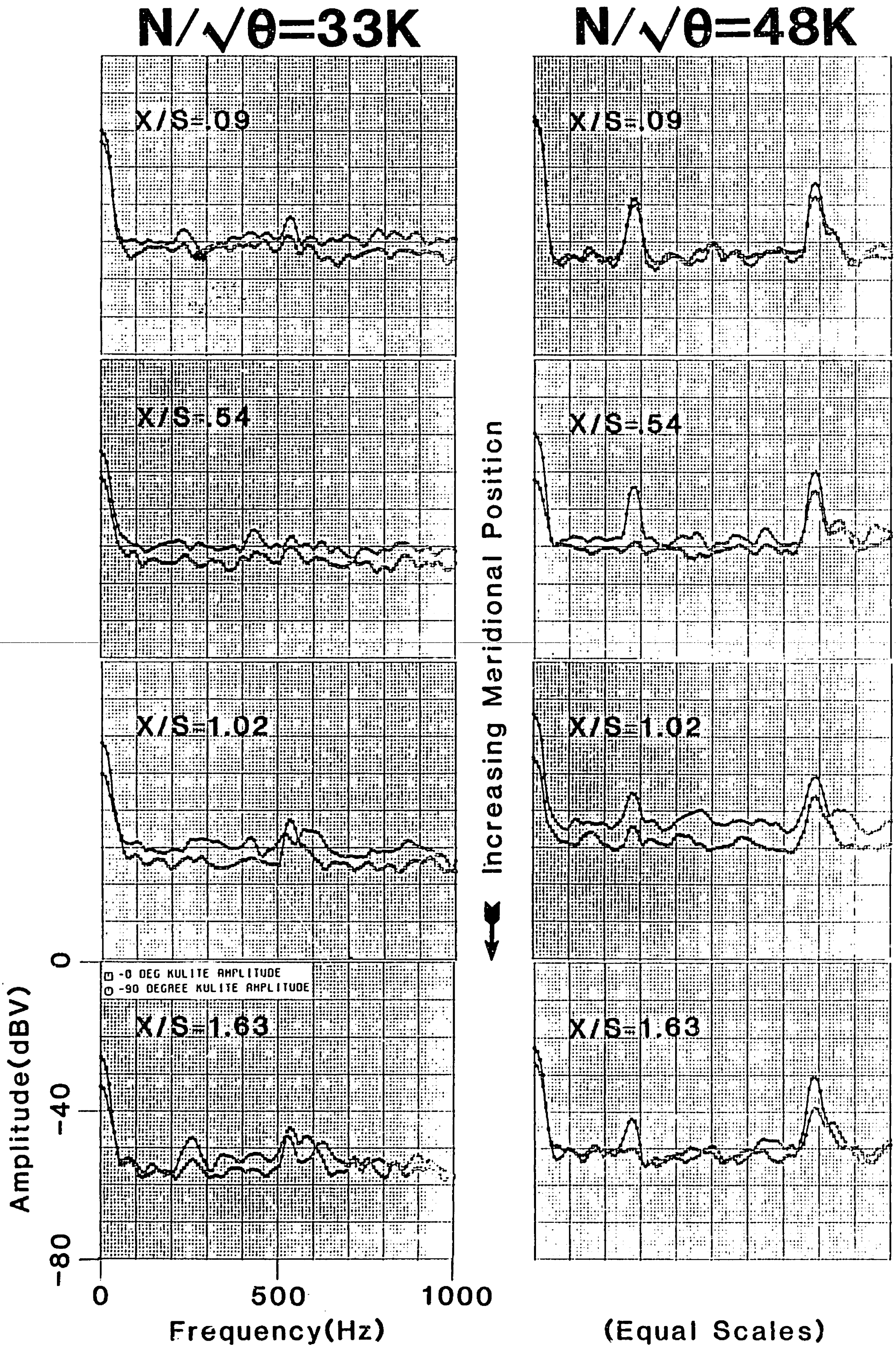


Figure 58 Casing Pressure FFTs(0-1000Hz) vs x/s at Surge Limit

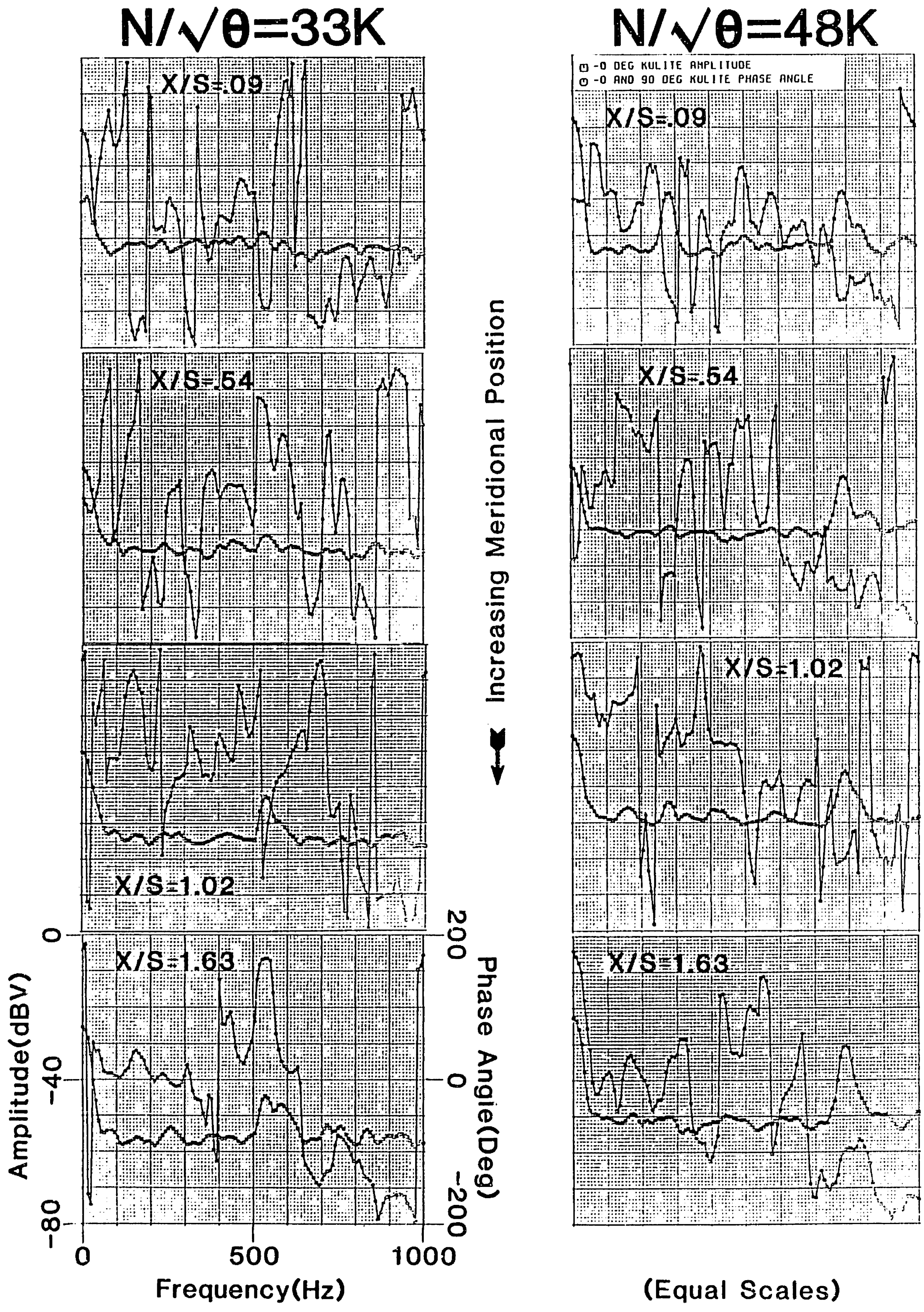


Figure 59 Casing Pressure FFT Phases vs x/s at Surge Limit

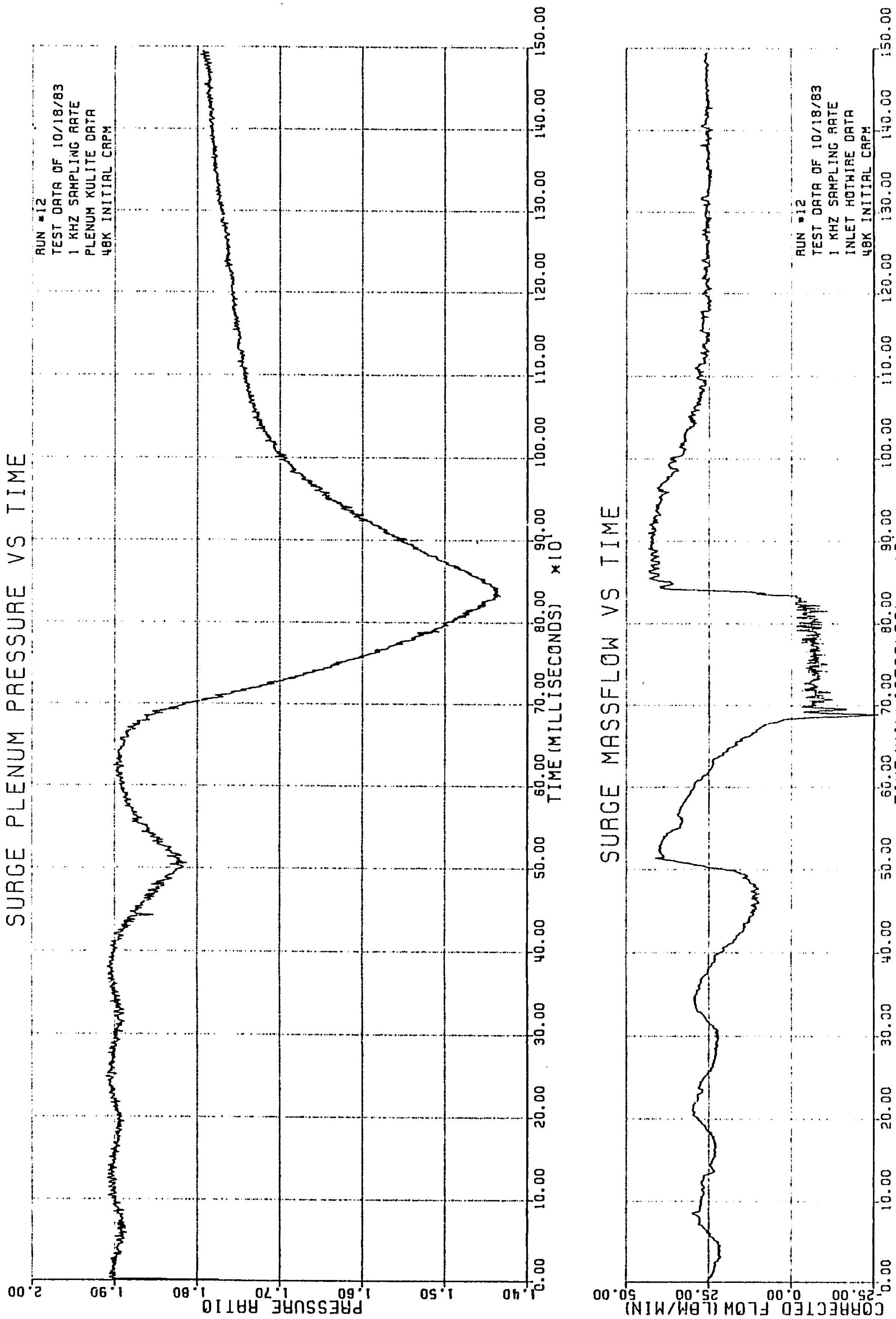


Figure 60 Plenum Pressure and Massflow vs Time during Surge Cycle

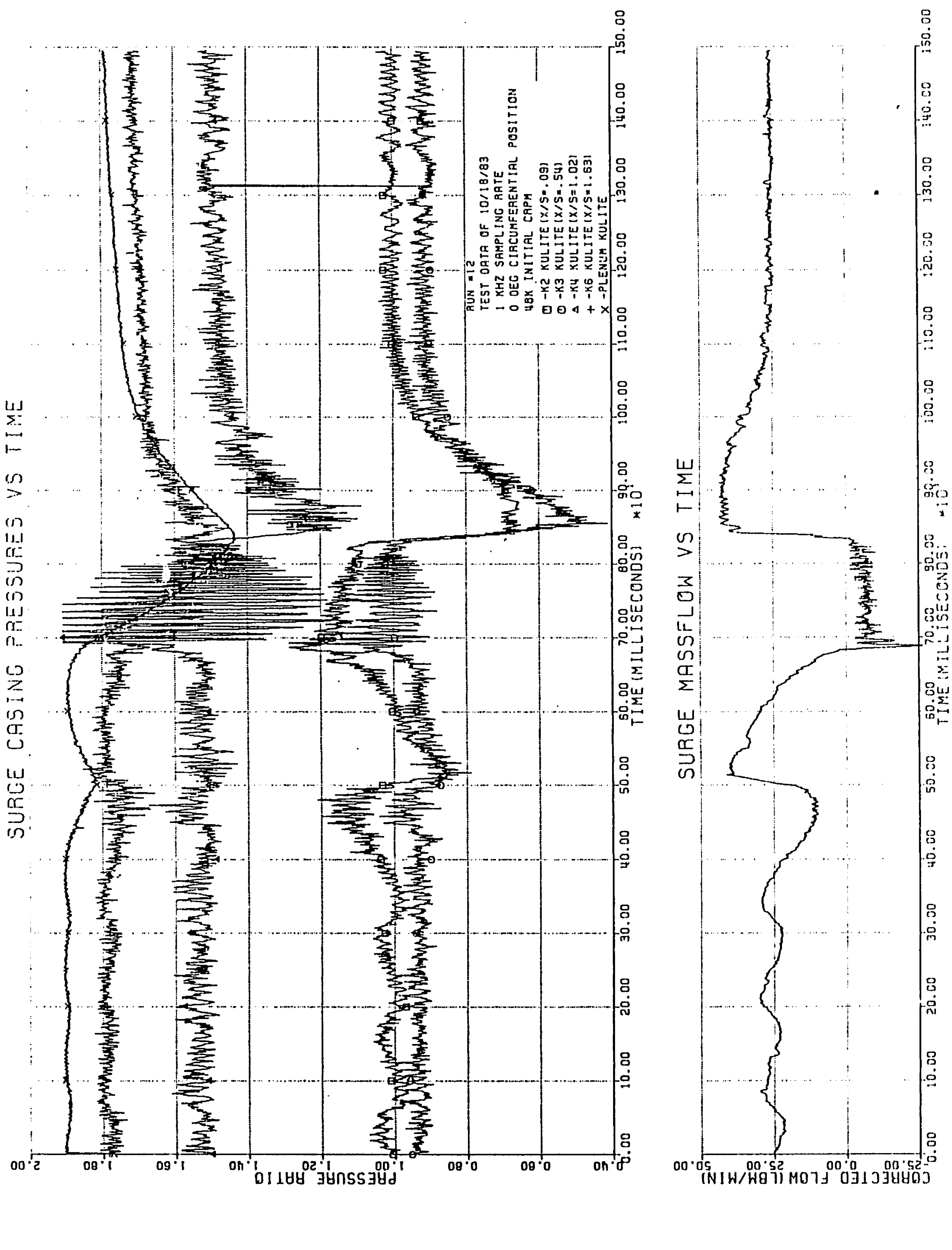


Figure 61 Casing P/PO at 0 Deg vs Time during Surge Cycle

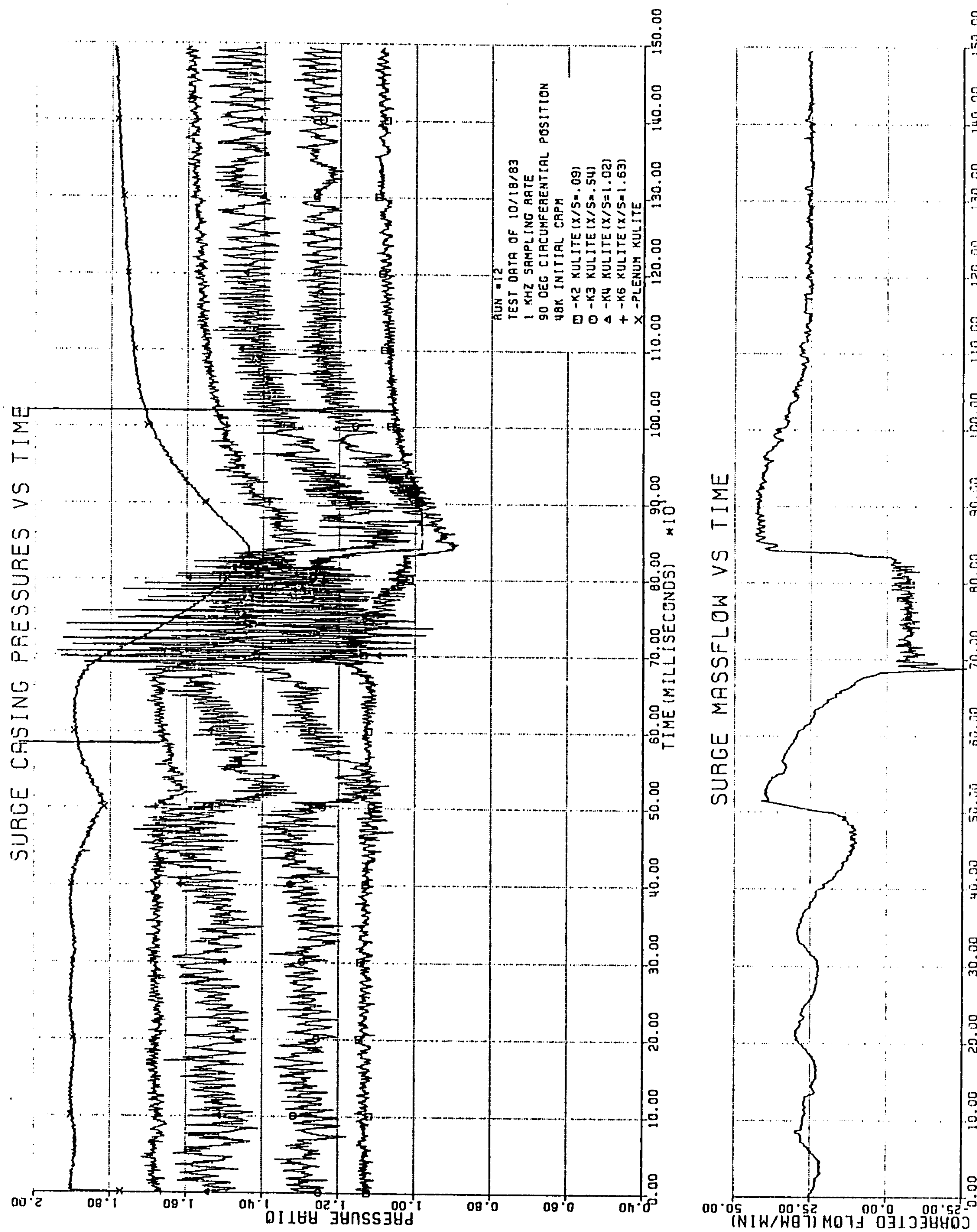


Figure 62 Casing P/P0 at 90 Deg vs Time during Surge Cycle

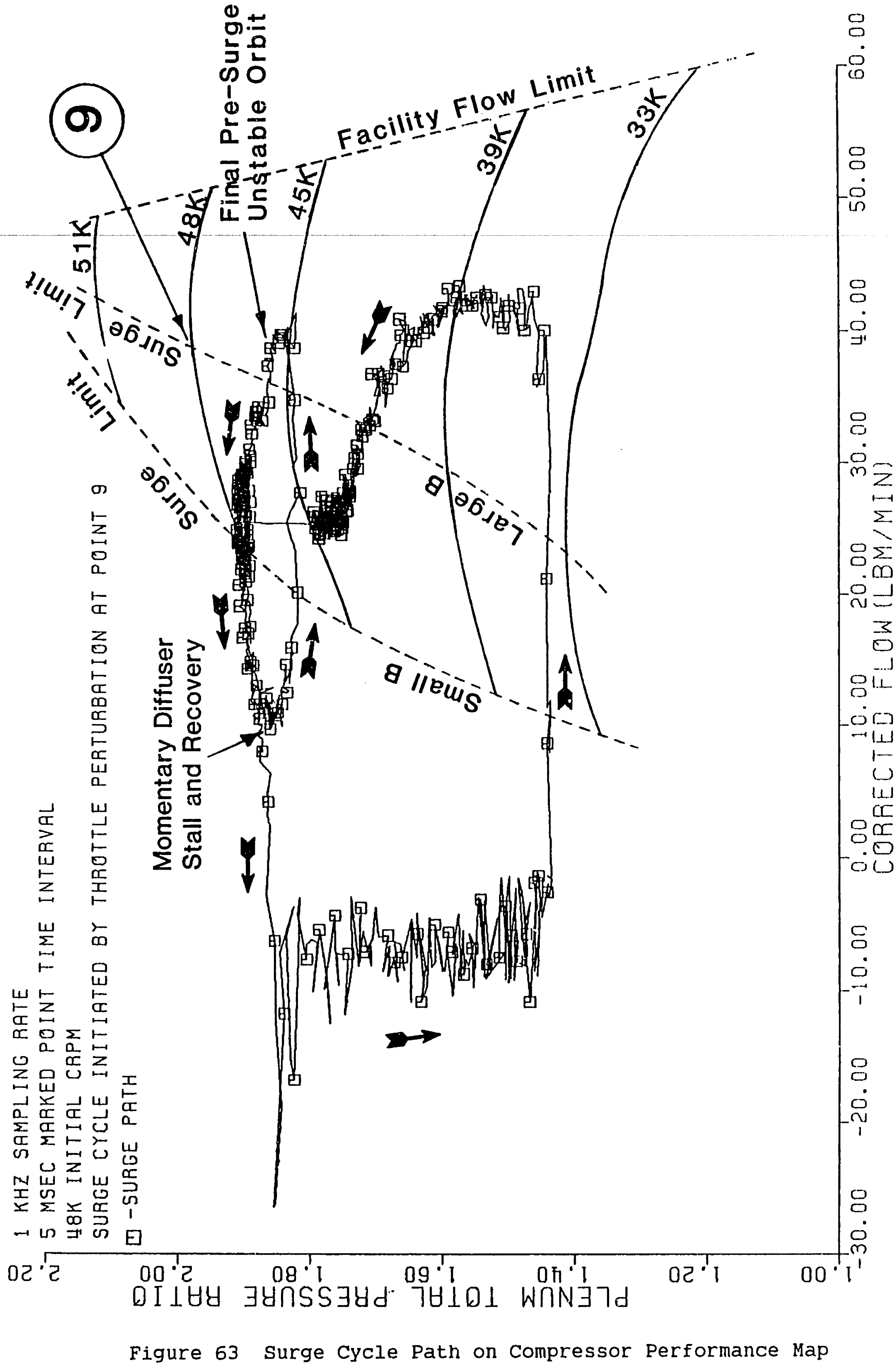
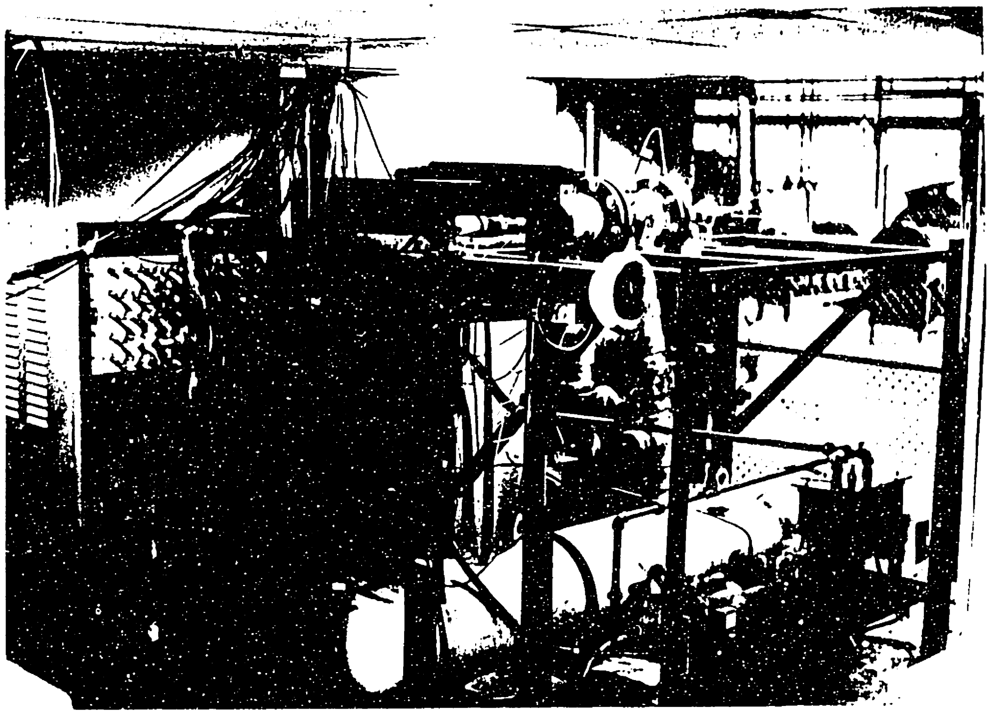
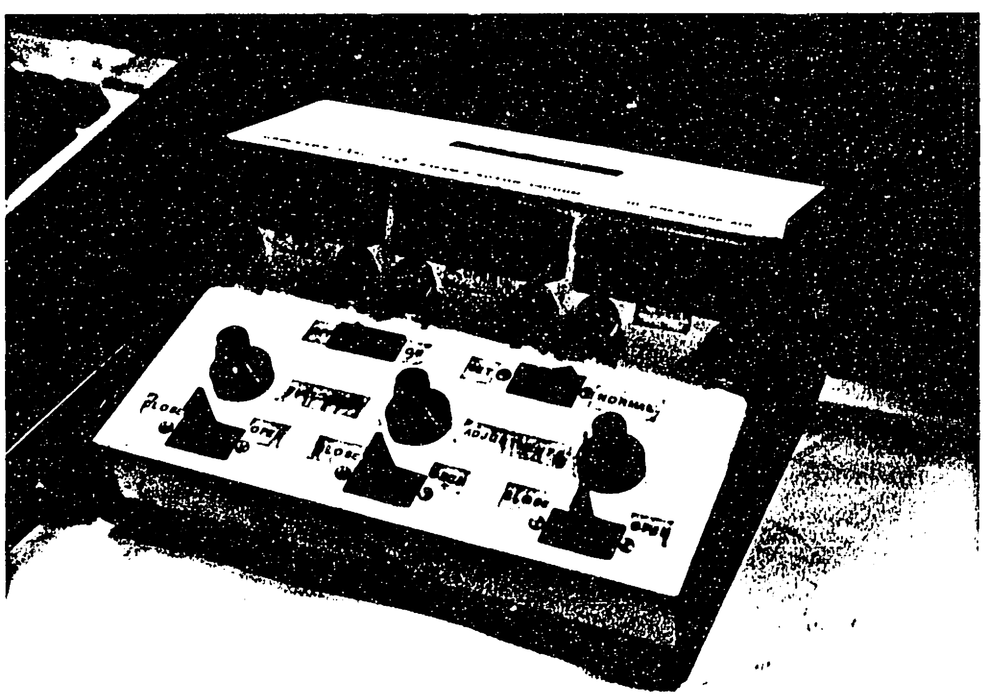


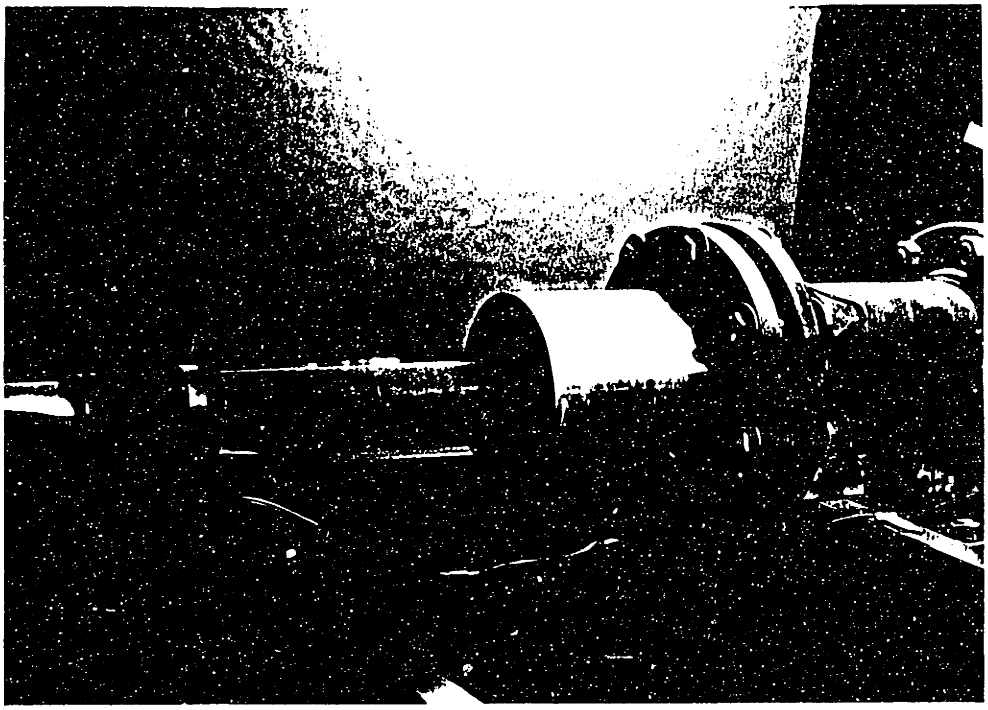
Figure 63 Surge Cycle Path on Compressor Performance Map



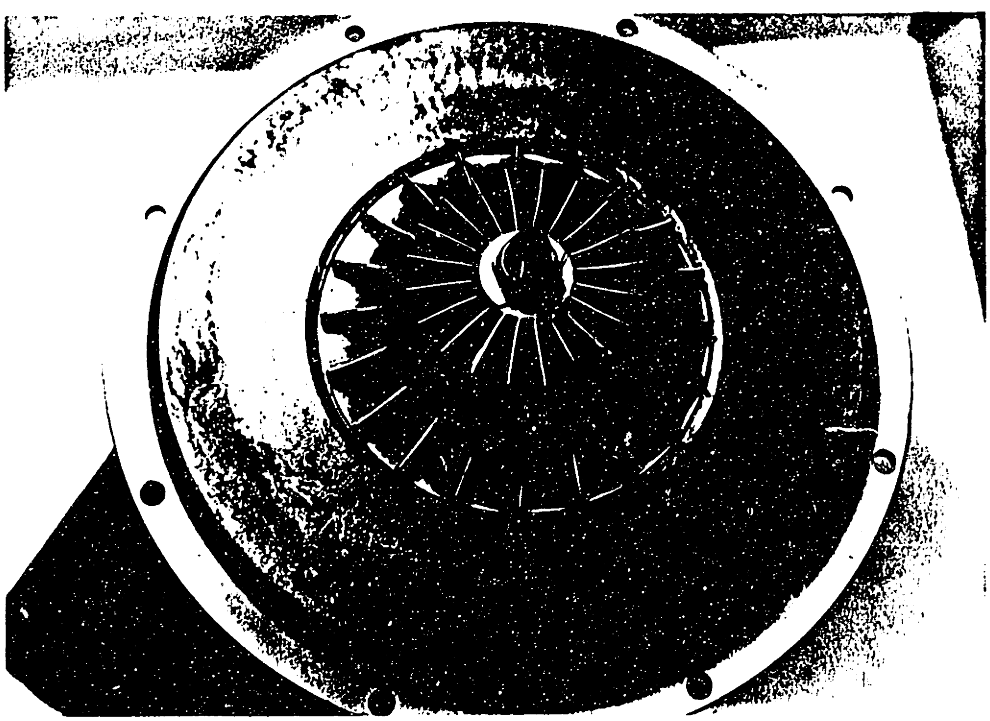
Photograph A Overall Facility



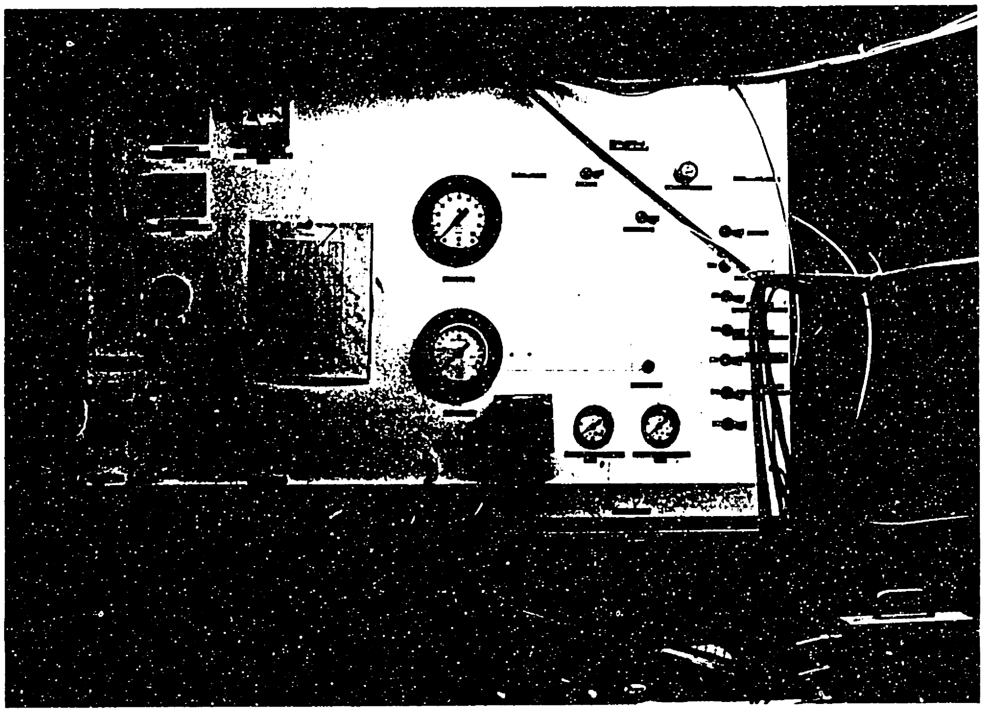
Photograph B Valve Controller Box



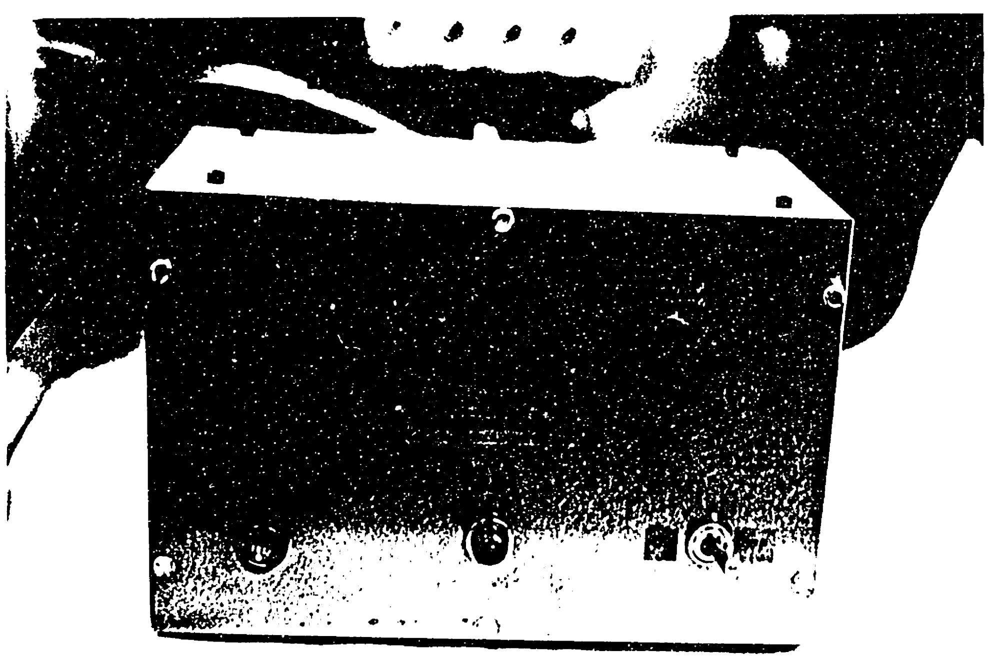
Photograph C 2 Inch Air Ejector



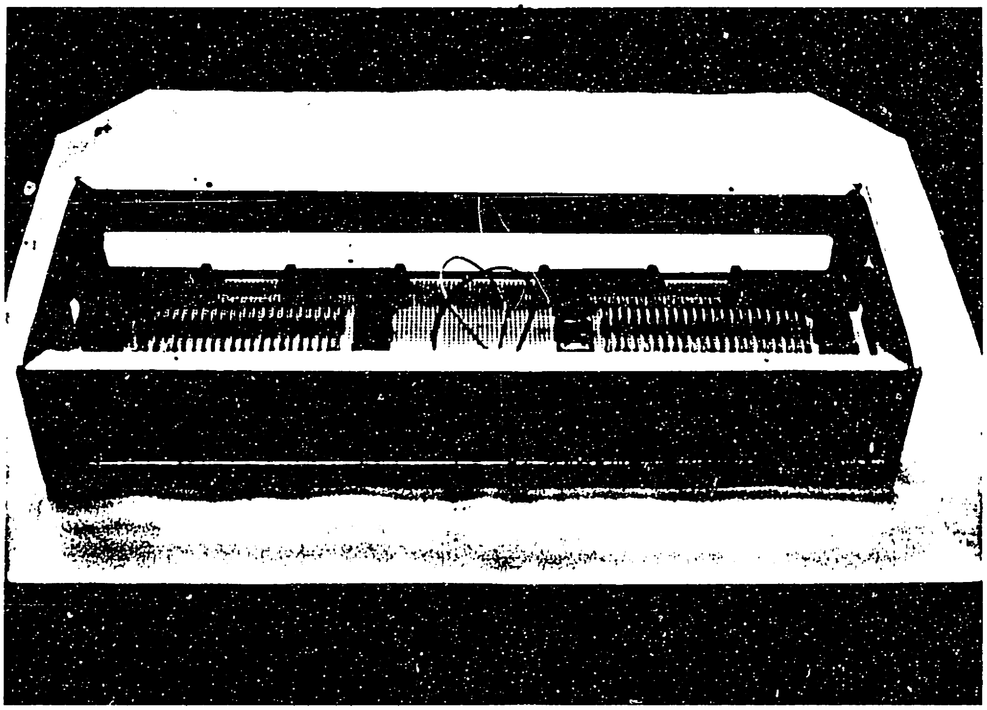
Photograph D Turbocharger Impeller



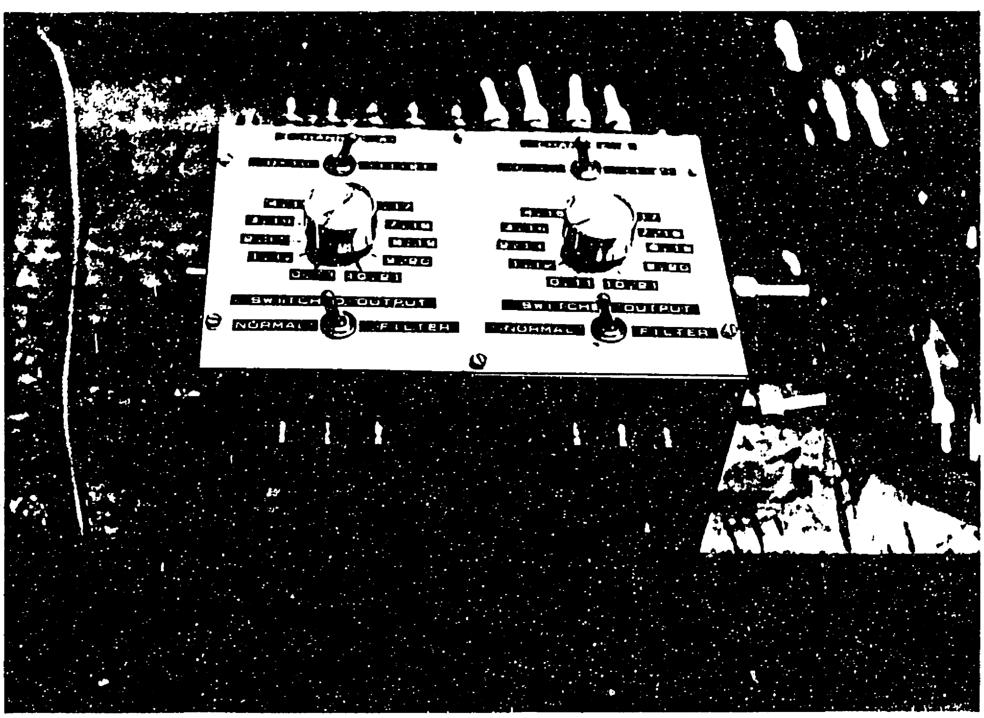
Photograph E Instrumentation Panel



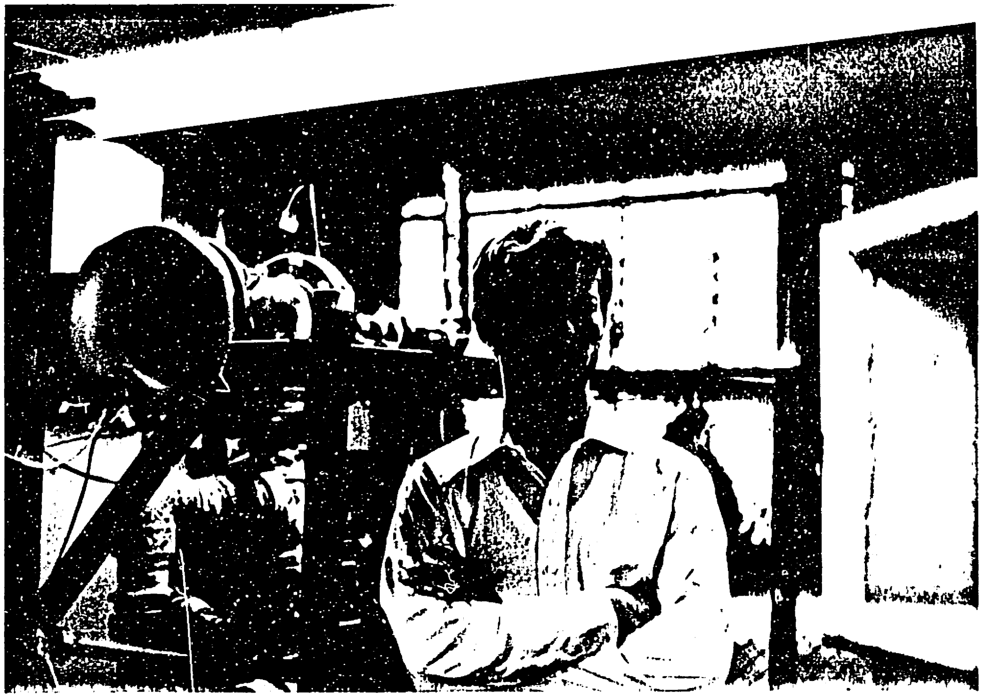
Photograph F Scanivalve Interface



Photograph G A/D Line Drivers



Photograph H Switch Network



Photograph I The Author

1 Balje', O. E., Turbomachines-A Guide to Design, Selection and Theory, John Wiley and Sons, New York, 1981, pp.375-440

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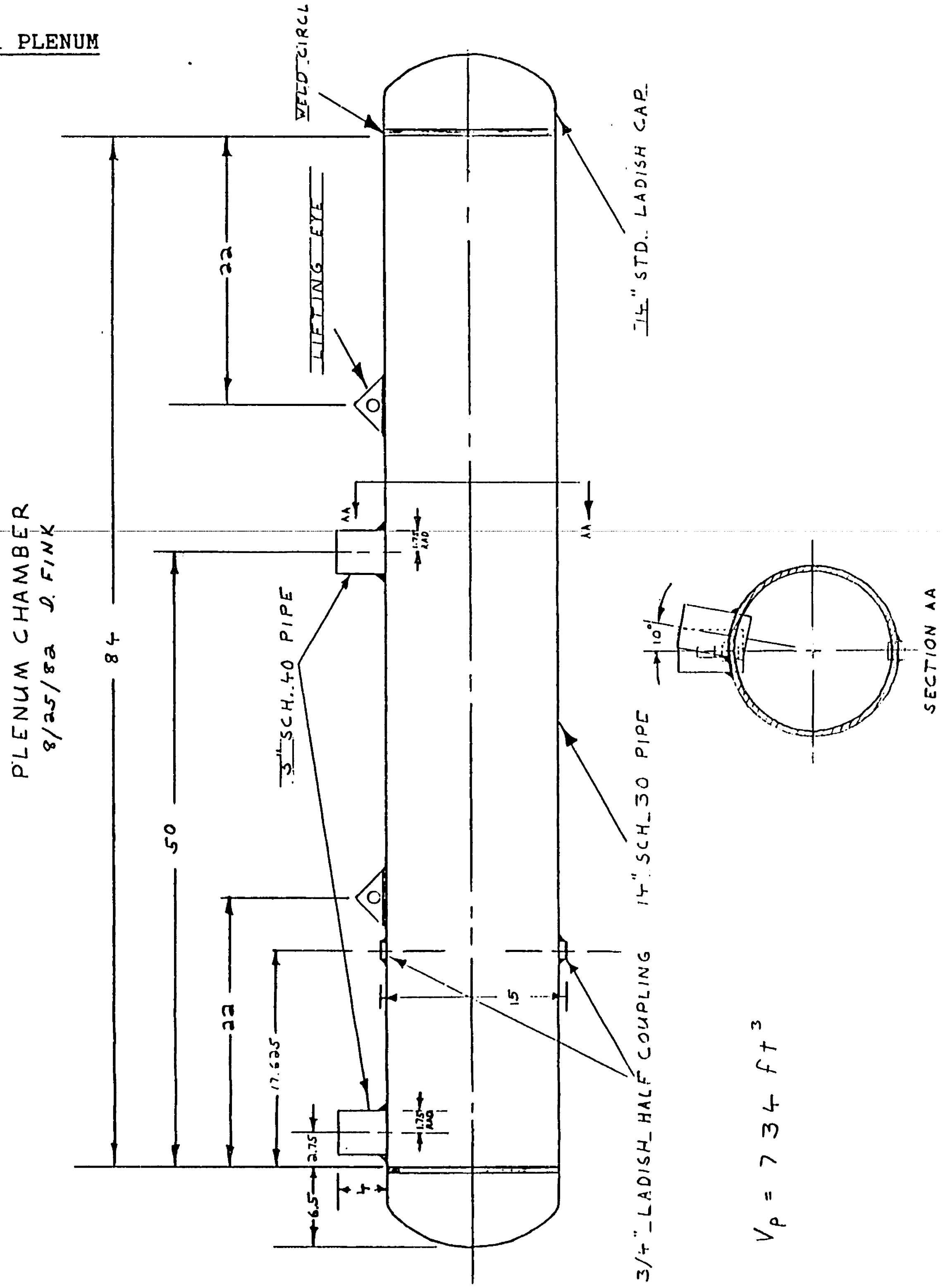
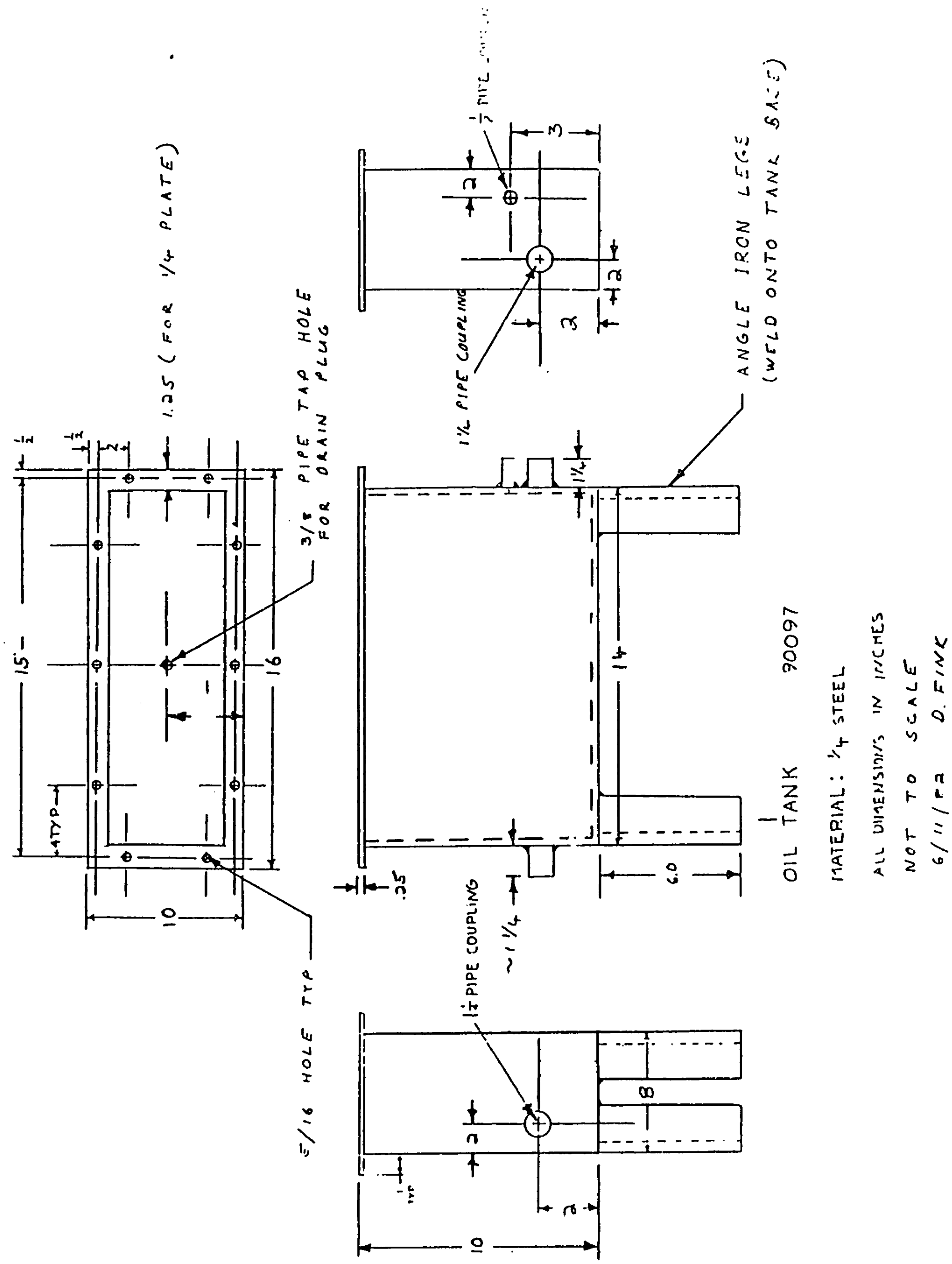
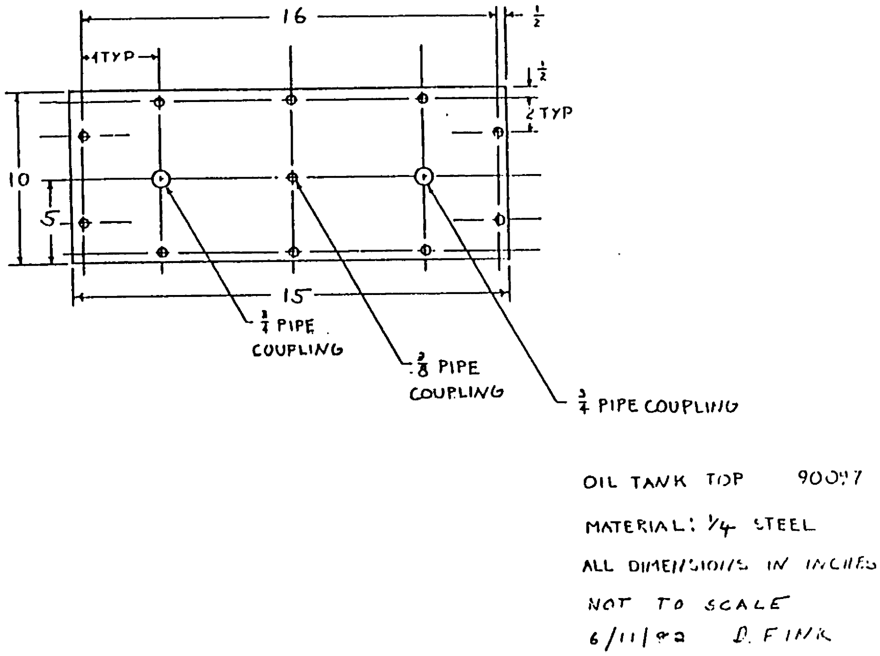
A-1 PLENUM


PLENUM CHAMBER
8/25/82 D. FINK
WELD CIRCLE
LIFTING EYE
14" STD. LADISH CAP
3" SCH. 40 PIPE
14" SCH. 30 PIPE
3/4" LADISH HALF COUPLING
SECTION AA
84
50
22
22
15
17.625
6.5
4
2.75
1.75 RAD
10°
AA

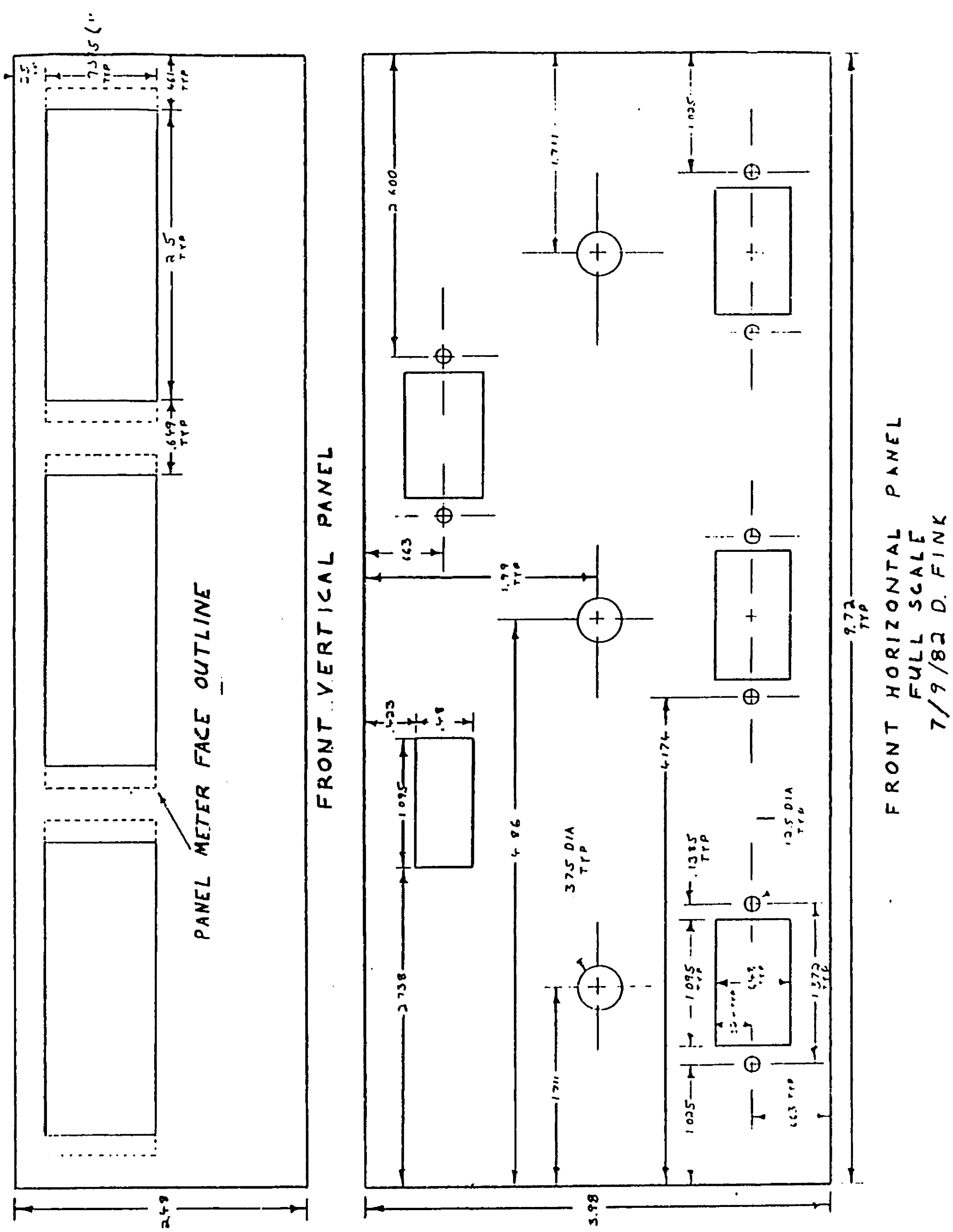
A-2 OIL TANK

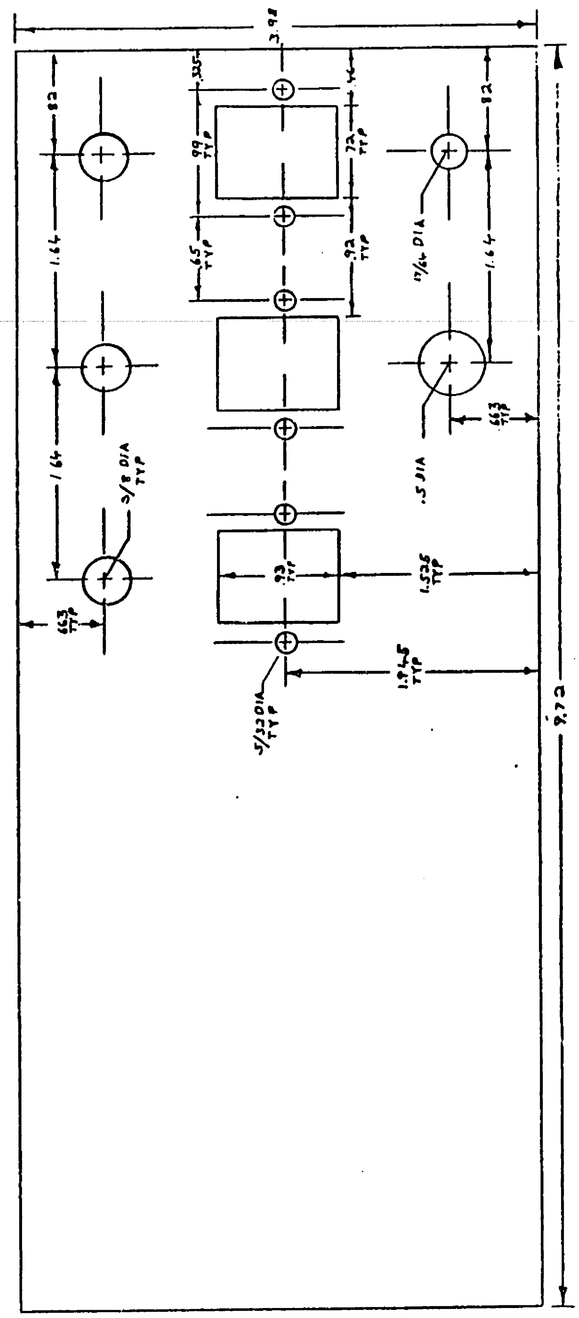


1.25 (FOR 1/4 PLATE)
3/8 PIPE TAP HOLE FOR DRAIN PLUG
5/16 HOLE TYP
1 1/4 PIPE COUPLING
ANGLE IRON LEGS (WELD ONTO TANK BASE)
OIL TANK 90097
MATERIAL: 1/4 STEEL
ALL DIMENSIONS IN INCHES
NOT TO SCALE
D. FINK


16
1/2
1 TYP
1/2
2 TYP
10
5
15
3/4 PIPE COUPLING
3/8 PIPE COUPLING
3/4 PIPE COUPLING
OIL TANK TOP 90097
MATERIAL: 1/4 STEEL
ALL DIMENSIONS IN INCHES
NOT TO SCALE
6/11/92 D. FINK

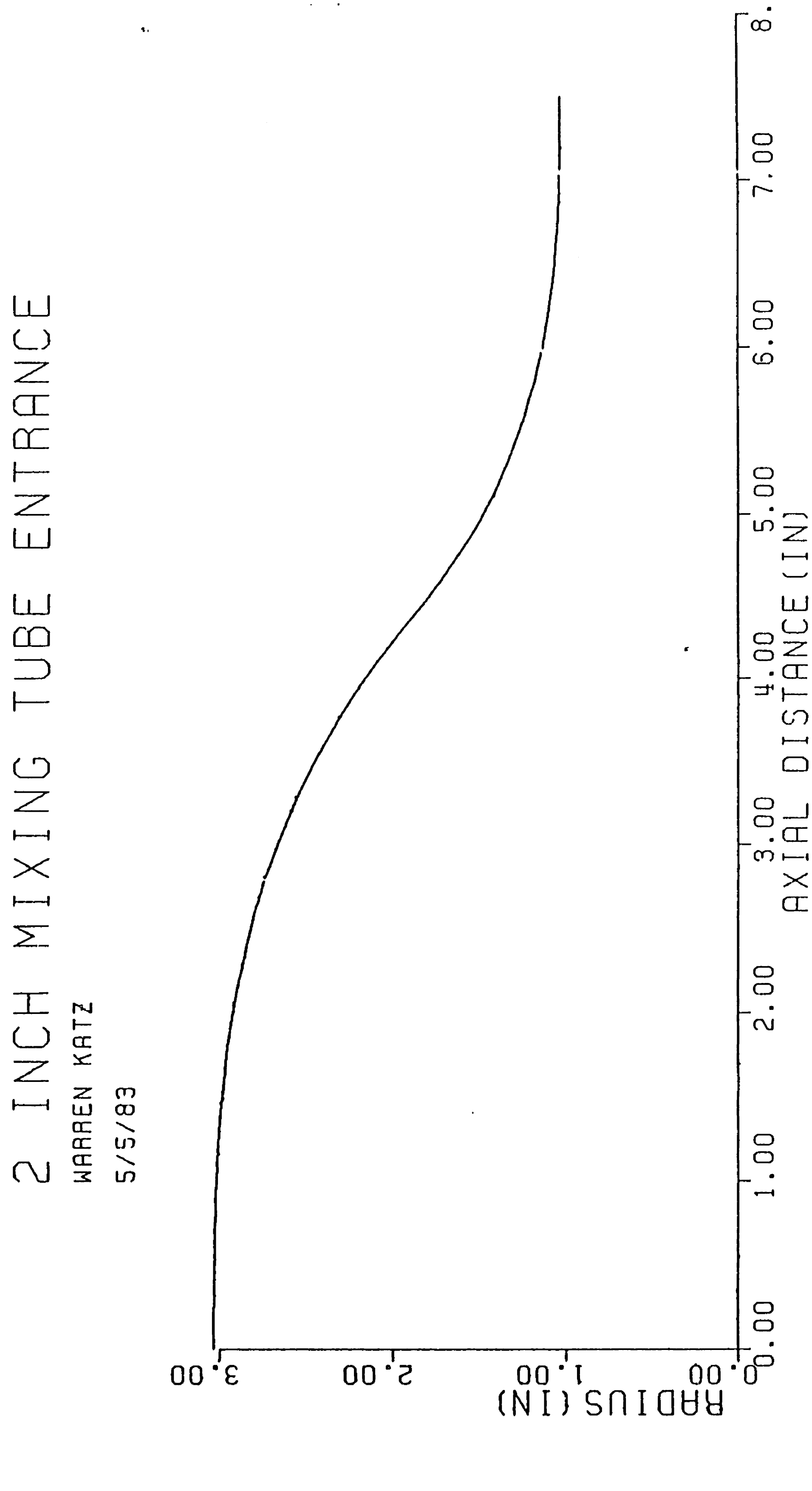
A-3 VALVE CONTROLLER BOX



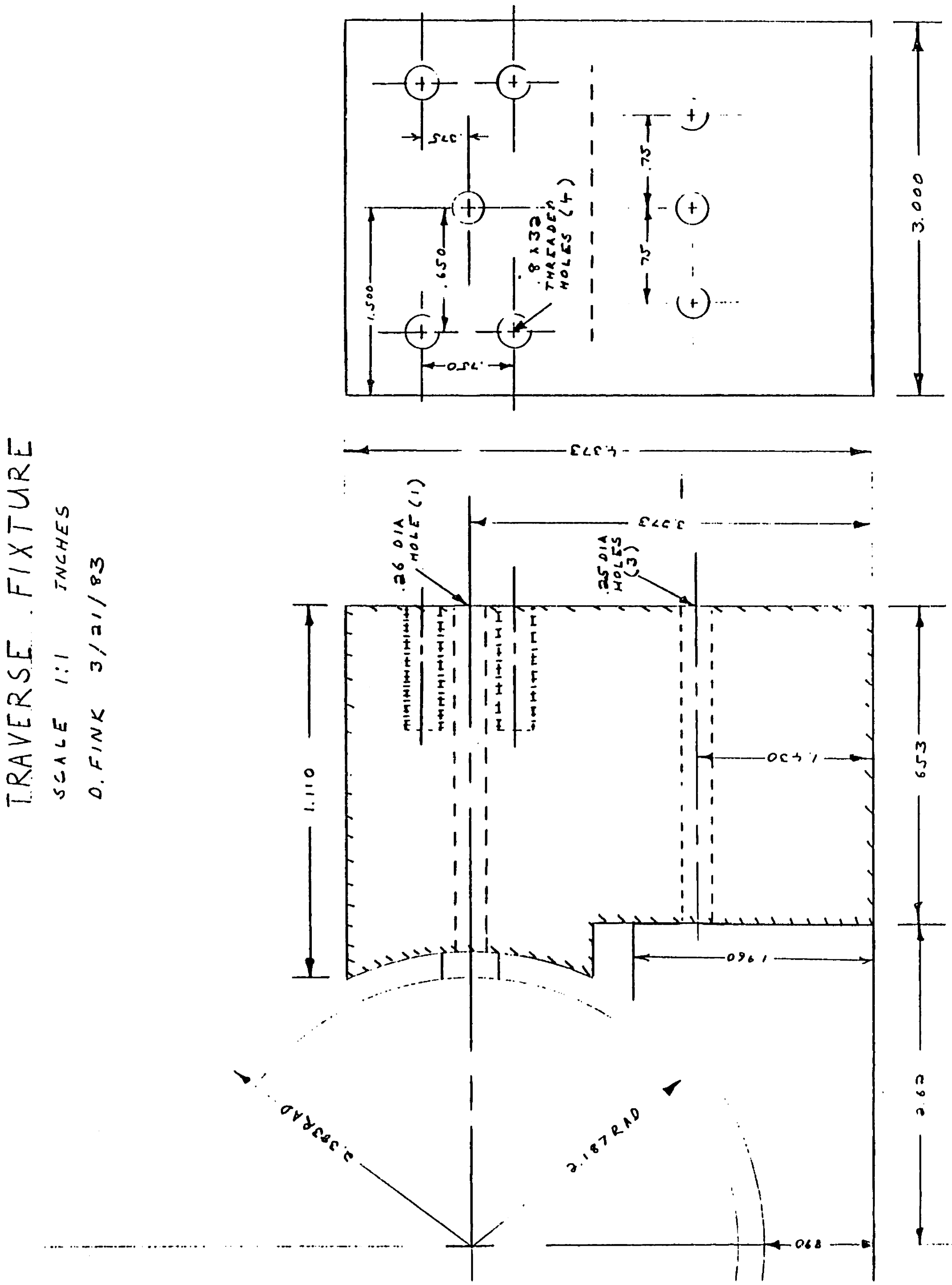


REAR VERTICAL PANEL
FULL SCALE
7/12/82 D. FINK

A-4 2 INCH AIR EJECTOR

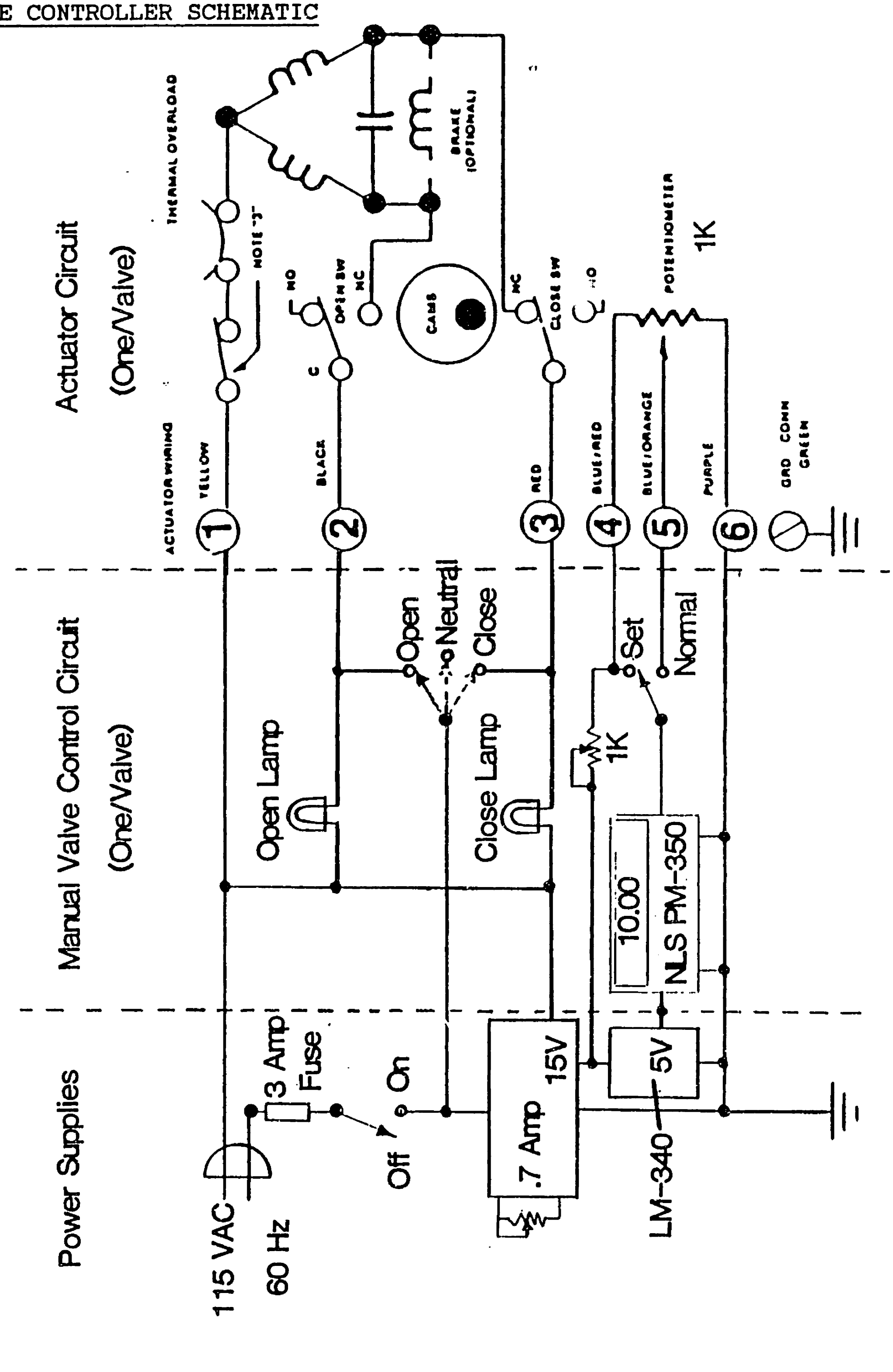


A-5 INLET TRAVERSE FIXTURE

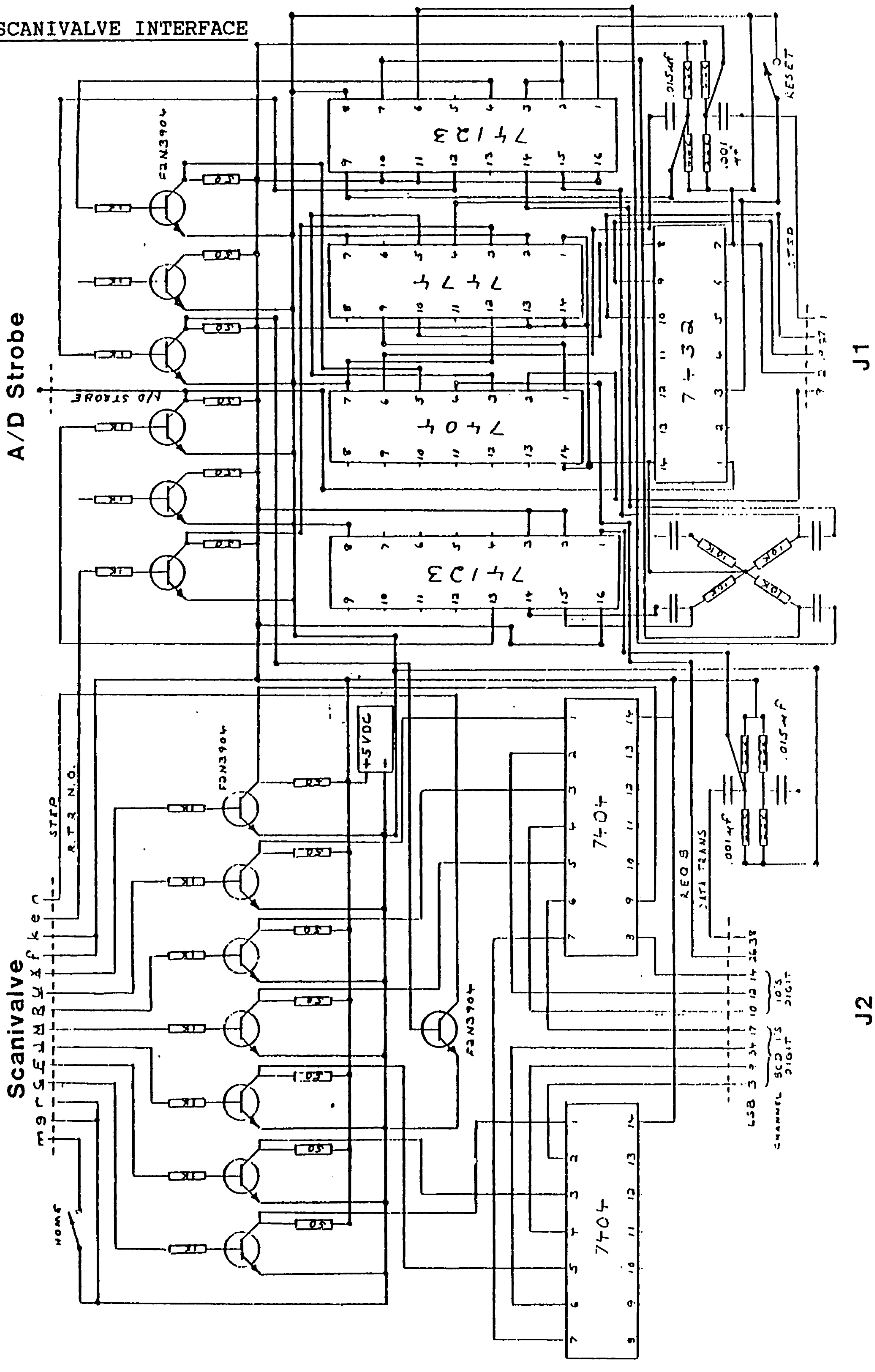


APPENDIX B ELECTRONIC HARDWARE

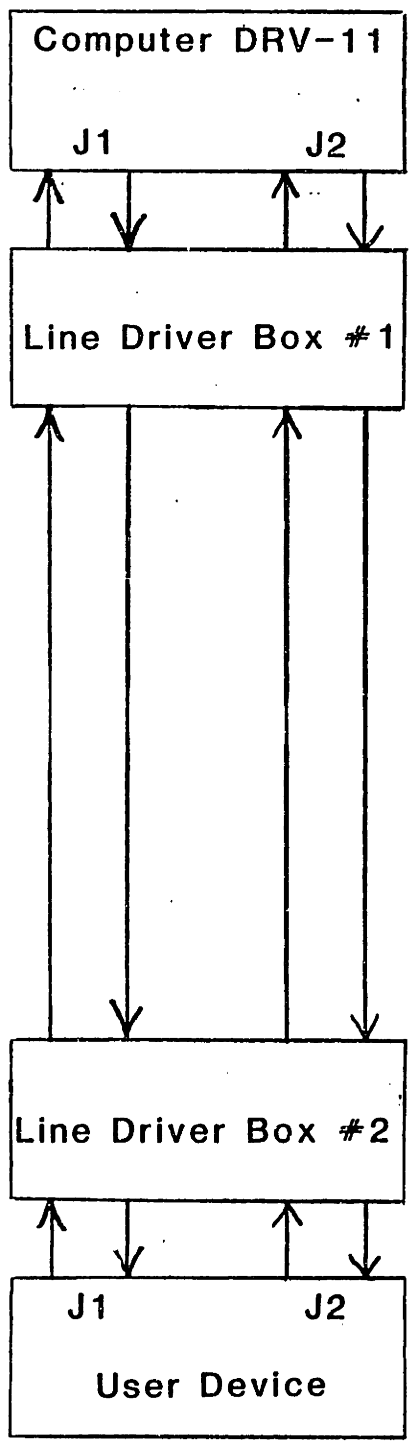
B-1 VALVE CONTROLLER SCHEMATIC

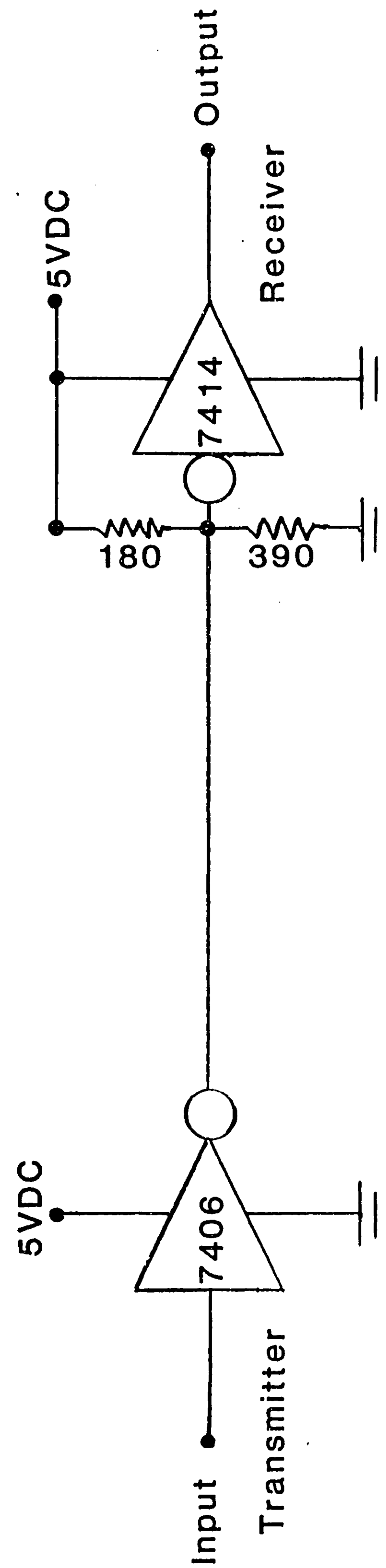


B-2 SCANIVALVE INTERFACE

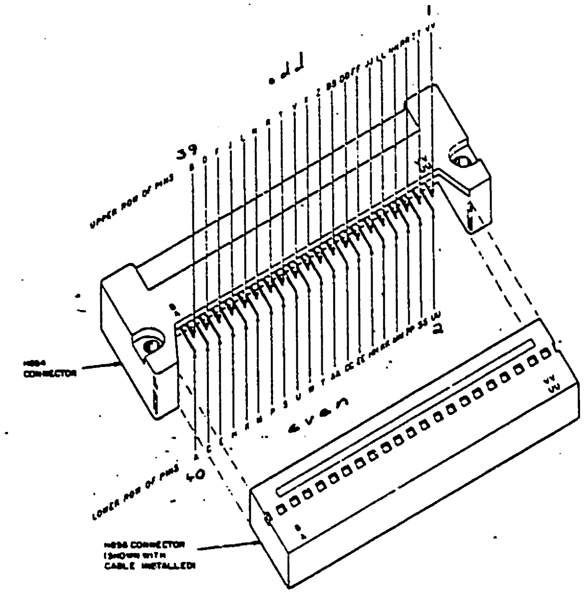


B-3 LINE DRIVERS





Line Driver Circuit(1/Line)



J2 CONNECTOR PIN CONFIGURATION
(DT 2768)

DRV11 Input and Output Signal Pins

Inputs			Outputs		
Signal	Connector	Pin	Signal	Connector	Pin
IN00	J2	TT	OUT00	J1	C
IN01	J2	LL	OUT01	J1	K
IN02	J2	H, E	OUT02	J1	NN
IN03	J2	BB	OUT03	J1	U
IN04	J2	KK	OUT04	J1	L
IN05	J2	HH	OUT05	J1	N
IN06	J2	EE	OUT06	J1	R
IN07	J2	CC	OUT07	J1	T
IN08	J2	Z	OUT08	J1	W
IN09	J2	Y	OUT09	J1	X
IN10	J2	W	OUT10	J1	Z
IN11	J2	V	OUT11	J1	AA
IN12	J2	U	OUT12	J1	BB
IN13	J2	P	OUT13	J1	FF
IN14	J2	N	OUT14	J1	HH
IN15	J2	M	OUT15	J1	JJ
REQ A	J1	LL	NEW DATA RDY*	J1	VV
REQ B	J2	S	DATA TRANS*	J2	C
			CSR0	J2	K
			CSR1	J1	DD
			INIT	J1	P
			INIT	J2	RR, NN

*Pulse signals, approximately 750 ns wide. Width can be changed by user.

J1 CONNECTOR PIN CONFIGURATION
(DT 2768)

SIGNAL NAME	3M CONNECTOR PIN #		SIGNAL NAME
Reserved	1	2	Gnd
IN 00	3	4	Gnd
BINITH	5	6	Gnd
~~OCNTLB~~ BINITH	7	8	Gnd
IN 01	9	10	IN 04
Gnd	11	12	IN 05
NC	13	14	IN 06
Gnd	15	16	IN 07
IN 03	17	18	Gnd
IN 08	19	20	IN 09
Gnd	21	22	IN 10
IN 11	23	24	IN 12
Gnd	25	26	REQ B
Gnd	27	28	IN 13
IN 14	29	30	IN 15
Gnd	31	32	CSR 0
Gnd	33	34	IN 02
NC	35	36	IN 02
Reserved	37	38	DATA TRANS
Reserved	39	40	NC

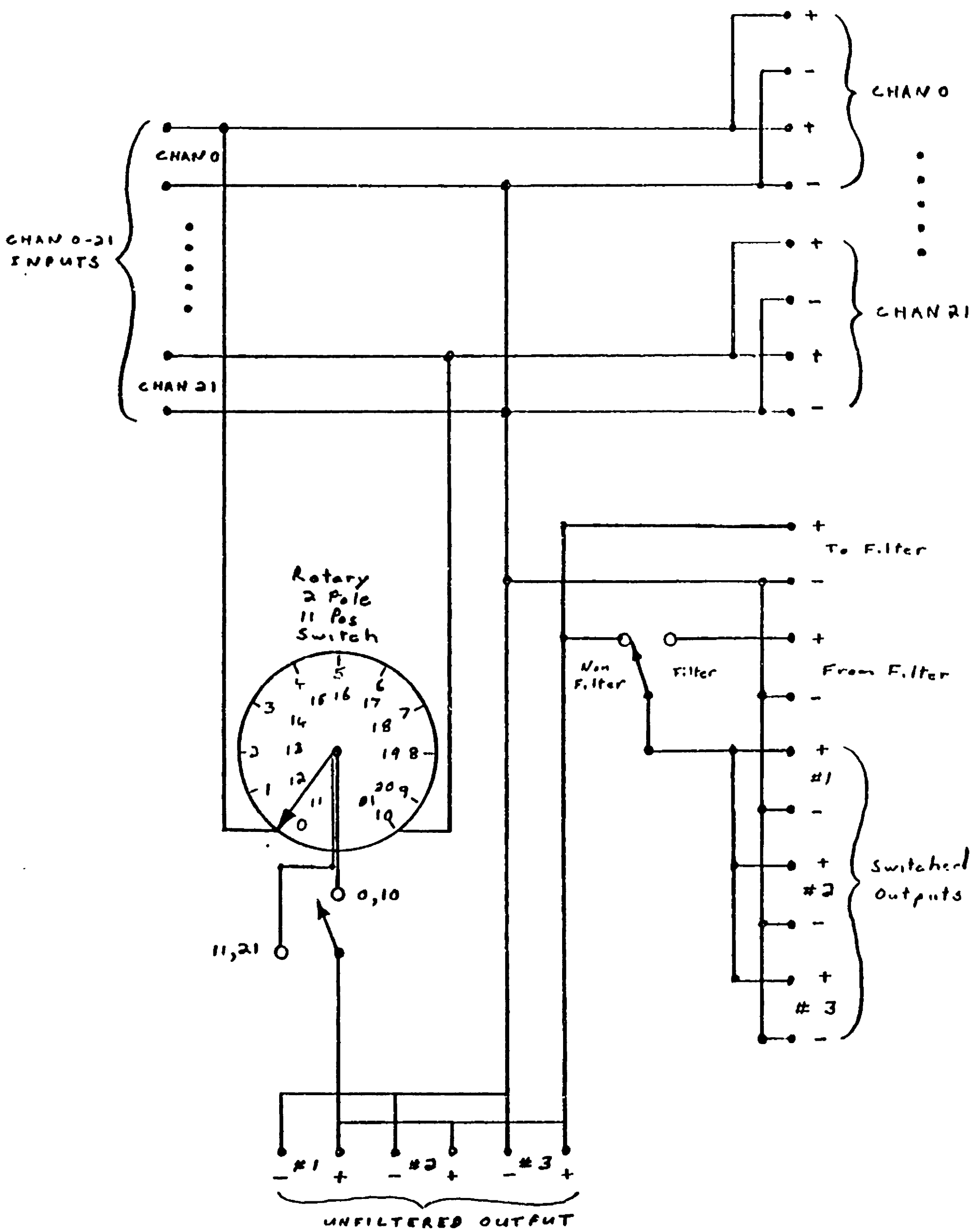
NC = not connected

SIGNAL NAME	3M CONNECTOR PIN #		SIGNAL NAME
NEW DATA RDY	1	2	GND
Reserved	3	4	GND
Reserved	5	6	GND
OUT 02	7	8	GND
REQ A	9	10	GND
OUT 15	11	12	OUT 14
OUT 13	13	14	GND
CSR 1	15	16	GND
OUT 12	17	18	OUT 11
OUT 10	19	20	GND
OUT 09	21	22	OUT 08
GND	23	24	OUT 03
OUT 07	25	26	GND
OUT 06	27	28	AINITH
OUT 05	29	30	GND
OUT 04	31	32	OUT 01
GND	33	34	NC
Reserved	35	36	NC
Reserved	37	38	OUT 00
Reserved	39	40	Reserved

NC = not connected

Pin Convention

B-4 SWITCH NETWORK



Switch Network

```
***INSTRUMENTATION LIST*********************************************************

THE FOLLOWING IS A LIST OF CURRENT INSTRUMENTATION.

SCANIVALVE PRESSURE CHANNELS(PSIA)
--------------------------------------------------------------------------------
P1 STATIC INDUCER INLET(S1)       THETA=-45 DEG, X/S=-.Ø983
P2 STATIC OVER INDUCER INLET(S2) THETA=-45 DEG, X/S= .Ø936
P3 STATIC MID-MERIDIONAL(S3)      THETA=-45 DEG, X/S= .4664
P4 STATIC DIFFUSER INLET(S4)      THETA=-45 DEG, X/S=1.Ø219
P5 STATIC MID-DIFFUSER(S5)        THETA=-45 DEG, X/S=1.3921
P6 STATIC DIFFUSER EXIT(S6)       THETA=-45 DEG, X/S=1.6519
P7 STATIC INDUCER INLET(S1)       THETA=135 DEG, X/S=-.1878
P8 STATIC OVER INDUCER INLET(S2) THETA=135 DEG, X/S= .Ø918
P9 STATIC MID-MERIDIONAL(S3)      THETA=135 DEG, X/S= .4664
P1Ø STATIC DIFFUSER INLET(S4)     THETA=135 DEG, X/S=1.Ø219
P11 STATIC MID-DIFFUSER(S5)       THETA=135 DEG, X/S=1.3937
P12 STATIC DIFFUSER EXIT(S6)      THETA=135 DEG, X/S=1.6313
P13-P26 STATIC SCROLL CASE(S7)    THETA= Ø,22.5,45,...,292.5 DEG
P27-P3Ø STATIC COMPRESSOR EXIT
P31 TOTAL COMPRESSOR OUTLET(2 INTO 1)
P32 TOTAL SECONDARY EJECTOR INLET
P33 STATIC EJECTOR COLLECTION CHAMBER(3 INTO 1)
P34 *****
P35 TOTAL TURBINE INLET PITOT TUBE
P36 STATIC TURBINE INLET PITOT TUBE
P37 STATIC TURBINE ROTOR INLET(4 INTO 1)
P38 STATIC TURBINE ROTOR EXIT(4 INTO 1)
P39 TOTAL TURBINE DIFFUSER EXIT(2 INTO 1)
P4Ø-P43 *****
P44 *****
P45 TOTAL DIFFUSER INLET KIEL   THETA=125 DEG, X/S=1.Ø731
P46 TOTAL STEAM EJECTOR PIPING EXIT
P47 STATIC STEAM EJECTOR PIPING EXIT
P48 TOTAL AMBIENT


PANEL PRESSURE GUAGES
--------------------------------------------------------------------------------
G1 TOTAL NOZZLE INLET(PSIG)
G2 STATIC NOZZLE INLET AT Ø DEG(PSIG)
G3 STATIC NOZZLE INLET AT 18Ø DEG(PSIG)
G4 TOTAL SECONDARY INLET(PSIG)
G5 TOTAL OIL-FREE HI-PRESSURE AIR INLET(PSIG)
G6 *****

V1 STATIC TURBINE EXIT(IN HG VACUUM)
V2 TOTAL STEAM EJECTOR AT PIPING EXIT(IN HG VACUUM)

O1 TURBOCHARGER OIL PRESSURE(PSIG)
O2 OIL PUMP PRESSURE(PSIG)
```

MANOMETERS(IN)

M1 DELTA BETWEEN STATIC INLET AT 9Ø DEG AND 27Ø DEG AND AMBIENT(IN H2Ø)
M2 DELTA FOR COBRA-PROBE ANGLE ZEROING(IN H2Ø)
DELTA BETWEEN TOTAL INLET CALIBRATION PROBE AND STATIC INLET(IN H2Ø)
DELTA BETWEEN STATIC INLET AT 9Ø DEG AND 27Ø DEG AND AMBIENT(IN H2Ø)
M3 COMPRESSOR EXIT TOTAL(IN HG)

uMAC-4ØØØ TEMPERATURE MULTIPLEXER CHANNELS(VOLTS)

K-TYPE THERMOCOUPLES

TT1 TOTAL INLET AIR
TT2 TOTAL COMPRESSOR EXIT
TT3 TOTAL PRIMARY EJECTOR AIR INLET
TT4 TOTAL TURBINE INLET
TT5 TOTAL TURBINE EXIT
TT6 OIL TANK
TT7 TURBOCHARGER OIL INLET
TT8 TURBOCHARGER OIL DRAIN
TT9 TOTAL PLENUM AIR
TT1Ø TOTAL MIXING TUBE AT 12 INCH LOCATION
TT11 TOTAL EJECTOR SECONDARY AIR INLET
TT12 TOTAL TEST CELL

PANEL TEMPERATURE GUAGES

J-TYPE THERMOCOUPLES

T1 OIL TANK(DEG F)
T2 TURBOCHARGER OIL INLET(DEG F)
T3 TURBOCHARGER OIL DRAIN(DEG F)

A/D CONVERTER CHANNELS(VOLTS)

VØ	SCANIVALVE PRESSURE TRANSDUCER INLET HOTWIRE	
V1	INDUCER KULITE(K2)	THETA= Ø DEG, X/S= .Ø926
V2	MID-MERIDIONAL KULITE(K3)	THETA= Ø DEG, X/S= .5432
V3	DIFFUSER INLET KULITE(K4)	THETA= Ø DEG, X/S=1.Ø161
V4	DIFFUSER EXIT KULITE(K6)	THETA= Ø DEG, X/S=1.6313
V5	INDUCER KULITE(K2)	THETA=9Ø DEG, X/S= .Ø926
V6	MID-MERIDIONAL KULITE(K3)	THETA=9Ø DEG, X/S= .5432
V7	DIFFUSER INLET KULITE(K4)	THETA=9Ø DEG, X/S=1.Ø161
V8	DIFFUSER EXIT KULITE(K6)	THETA=9Ø DEG, X/S=1.6313
V9	PLENUM PRESSURE KULITE	
V1Ø-V15	*****	

```
C       PROGRAM INCAL
C       THIS PROGRAM IS USED TO CALCULATE THE MASSFLOW OF THE
C       TURBOCHARGER FROM A TOTAL PRESSURE TRAVERSE OF THE INLET DIAMETER.
C       TRAVERSE IS STARTED FROM CENTER OF INLET AND MOVED TOWARD INLET
C       WALL. FOR NMAX-1 TEST POINTS TWO ARRAYS R(NMAX) AND P(NMAX) ARE
C       CREATED WHICH ARE USED AS INPUT TO AN INTEGRATION ROUTINE FOR MASS
C       FLOW.R(NMAX)=INLET RADIUS=RØ
        DIMENSION R1(1ØØ),PT1(1ØØ),M(1ØØ),RHOV(1ØØ),H(1ØØ),V(1ØØ),T(1ØØ)
        DIMENSION SLOPE(1ØØ)
        REAL K,M1,M,MU1,NU1
        INTEGER MM,DD,YY
        BYTE TM(8),DT(9),FNAME(16),RN(5)
        DATA FNAME/' ','D','Y','Ø',':','I','N','C','A','L','D','.',3*'X',Ø/
        DATA RN/' ',3*'X',Ø/
        D1=4.373/12.
        PI=3.1415927
        A1=PI*D1**2./4.
        TREF=545.
        PREF=14.69*144.
        G=32.174Ø5
        R=53.3*G
        K=1.4
        WRITE(5,*)'NEW DATA? 1=YES Ø=NO'
        ACCEPT*,LN
        IF(LN .EQ. Ø) GO TO 45
5       WRITE(5,*)'INPUT RUN #(3 DIGITS)'
        ACCEPT 9Ø6,(FNAME(N),N=13,15)
9Ø6     FORMAT(3A1)
        RN(2)=FNAME(13)
        RN(3)=FNAME(14)
        RN(4)=FNAME(15)
        CALL DATE(DT)
        CALL TIME(TM)
        WRITE(5,*)'INPUT AMBIENT TEMPERATURE IN DEG C'
        ACCEPT*,TØ
        TØ=1.8*TØ+32.+459.67
        WRITE(5,*) 'INPUT AMBIENT PRESSURE IN PSIA'
        ACCEPT*,PØ
        PØ=PØ*144.
        RHO=-2.6419E-Ø4*(TØ-459.67)+1.9544
        RHOØ=PØ/(R*TØ)
        WRITE(5,*)'SET AND INPUT DESIRED FLOWRATE HEAD(IN H2Ø)'
        ACCEPT*,H1
        WRITE(5,*)'CENTER TRAVERSE PROBE IN INLET'
        N=1
        R1(1)=Ø.
        WRITE(5,*)'INPUT CENTER TOTAL PRESSURE HEAD(IN H2Ø)'
        ACCEPT*,H(1)
1Ø      N=N+1
2Ø      WRITE(5,*)'MOVE PROBE AND INPUT NEW RADIAL LOCATION(IN)'
        ACCEPT*,R1(N)
        WRITE(5,*)'INPUT NEW TOTAL PRESSURE HEAD(IN H2Ø)'
        ACCEPT*,H(N)
        WRITE(5,*) ' '
        WRITE(5,*)'N=',N
        WRITE(5,*) 'RADIUS(IN)=',R1(N)
        WRITE(5,*) 'MANOMETER HEAD(IN H2Ø)=',H(N)
        WRITE(5,*) ' '
        R1(N)=R1(N)/12.
        WRITE(5,*)'IS POINT O.K.? 1=YES,Ø=NO'
        ACCEPT*,I
        IF(I .EQ. Ø) GO TO 2Ø
        WRITE(5,*)'MORE POINTS? 1=YES,Ø=NO'
        ACCEPT*,I
```

```
      IF(I .EQ. 1) GO TO 1Ø
      NMAX=N+1
      WRITE(5,*)'WITHDRAW PROBE AND INPUT FLOW MANOMETER READING(IN H2Ø)'
      ACCEPT*,H2
      H1=(H1+H2)/2.
      DP1=H1*G*RHO/12.
      P1=PØ-DP1
      M1=SQRT(((PØ/P1)**((K-1)/K)-1)*2./(K-1))
      T1=TØ/(1+(K-1)*M1**2./2.)
      V1=M1*SQRT(K*R*T1)
      RHOV1=SQRT(K/R)*P1/SQRT(TØ)*M1*SQRT(TØ/T1)
      WRITE(5,*)'INPUT PROBE AXIAL LOCATION FROM INLET(IN)'
      ACCEPT*,X1
      X1=X1/12.
C     CALCULATE FLAT PLATE DISPLACEMENT THICKNESS DSTAR1
      RHO1=P1/(R*T1)
      MU1=.317Ø*T1**1.5*(734.7/(T1+216.))*1E-1Ø
      NU1=MU1/RHO1
      ReX1=V1*X1/NU1
      DLAM=1.72Ø8*X1/SQRT(ReX1)
      DTURB=.Ø4625*X/ReX1**.2
      IF(ReX1 .GT. 6.75E+Ø5) GO TO 24
      DSTAR1=DLAM
      GO TO 25
24    DSTAR1=DTURB
C     DSTAR1=Ø.
25    A=PI*D1**2./4.-PI*(D1-DSTAR1)*DSTAR1
      CFLO1=A*SQRT(K/R)*M1/(TØ/T1)**((K+1)/(K-1)/2.)*PREF/SQRT(TREF)
C     CALCULATE MASSFLOW PARAMETER AT EACH TRAVERSE POINT
      J=NMAX-1
      DO 3Ø N=1,J
      PT1(N)=PØ-H(N)*G*RHO/12.
      M(N)=SQRT(((PT1(N)/P1)**((K-1)/K)-1)*2./(K-1))
      T(N)=TØ/(1.+(K-1.)*M(N)**2./2.)
      V(N)=M(N)*SQRT(K*R*T(N))
      RHOV(N)=SQRT(K/R)*P1/SQRT(TØ)*M(N)*SQRT(1.+(K-1)*M(N)**2./2.)
3Ø    CONTINUE
      PT1(NMAX)=P1
      M(NMAX)=Ø.
      T(NMAX)=TØ
      V(NMAX)=Ø.
      RHOV(NMAX)=Ø.
C     RHOV(NMAX)=RHOV1
      R1(NMAX)=D1/2.
      H(NMAX)=H2
C     INTEGRATE VELOCITY PROFILE TO OBTAIN CORRECTED FLOWRATE(LBM/MIN)
      SUM=Ø.
      DO 4Ø N=1,J
      SLOPE(N)=(RHOV(N+1)-RHOV(N))/(R1(N+1)-R1(N))
      DR=R1(N+1)-R1(N)
      SUM=SUM+2.*PI*RHOV(N)*R1(N)*DR+PI*(SLOPE(N)*R1(N)+
     1 RHOV(N))*DR**2.+2.*PI*SLOPE(N)*DR**3./3.
C     SUM=SUM+2.*PI*(R1(N+1)**3.-R1(N)**3.)*SLOPE(N)/3.
C    1 +PI*RHOV(N)*(R1(N+1)**2.-R1(N)**2.)
C    2 -PI*R1(N)*(R1(N+1)**2.-R1(N)**2.)*SLOPE(N)
4Ø    CONTINUE
C     CALCULATE MEASURED VALUE OF DSTAR
      DSTAR2=(D1-SQRT(4.*SUM/(PI*RHOV1)))/2.
C     CALCULATE MEASURED VALUE OF CORRECTED MASSFLOW
      CFLO2=SUM*SQRT(TØ/TREF)/(PØ/PREF)
C     PRINT CALCULATED RESULTS
45    IF(LN .EQ. 1) GO TO 46
      WRITE(5,*) 'INPUT RUN NUMBER(3 DIGITS)'
      ACCEPT 9Ø8,(FNAME(N),N=13,15)
```

```
908       FORMAT(3A1)
          RN(2)=FNAME(13)
          RN(3)=FNAME(14)
          RN(4)=FNAME(15)
          OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1    FORM='UNFORMATTED',RECORDSIZE=500,INITIALSIZE=1)
          READ(4'1,ERR=43) DT,TM,T0,P0,H1,V1,X1,NU1,ReX1,DSTAR1,CFLO1
     1    ,NMAX,DSTAR2,SUM,CFLO2,(N,R1(N),H(N),V(N),M(N),N=1,NMAX)
          GO TO 44
43        WRITE(5,*)'I/O ERROR AT STATEMENT 43'
44        CLOSE(UNIT=4)
46        WRITE(5,*) ' '
          WRITE(5,*) 'INLET CALIBRATAION CALCULATIONS'
          WRITE(5,*) ' '
          WRITE(5,907) (FNAME(N),N=13,15)
907       FORMAT(1H ,'RUN NUMBER=',3A1)
          WRITE(5,904) (DT(N),N=1,9)
904       FORMAT(1H ,'DATE=',9A1)
          WRITE(5,905) (TM(N),N=1,8)
905       FORMAT(1H ,'TIME=',8A1)
          WRITE(5,*) 'T0(DEG F)=',T0-459.67
          WRITE(5,*) 'P0(PSIA)=',P0/144.
          WRITE(5,*) 'FLOWRATE MANOMETER HEAD(IN H20)=',H1
          WRITE(5,*)'FREE STREAM VELOCITY(FT/SEC)=',V1
          WRITE(5,*)'AXIAL LOCATION(IN)=',X1*12.
          WRITE(5,*)'AIR NU(FT**2/SEC)=',NU1
          WRITE(5,902) ReX1
902       FORMAT(1H ,'ReX=',E12.4)
          WRITE(5,*) 'X/SQRT(ReX)(IN)=',X1*12./SQRT(ReX1)
          IF(ReX1 .GT. 6.75E+05) GO TO 28
          WRITE(5,*)'ESTIMATED LAMINAR DISPLACEMENT THICKNESS(IN)=',DSTAR1*12.
          GO TO 29
28        WRITE(5,*)'ESTIMATED TURBULENT DISPLACEMENT THICKNESS(IN)=',DSTAR1*12.
29        WRITE(5,*)'ESTIMATED CORRECTED FLOW(LBM/MIN)=',CFLO1*G*60.
          AE=(D1-2.*DSTAR1)**2./D1**2.
          BE=1-AE
          WRITE(5,*)'ESTIMATED Aeff/A0=',AE
          WRITE(5,*)'ESTIMATED BLOCKAGE=',BE
          WRITE(5,*) 'NMAX=',NMAX
          WRITE(5,*)'MEASURED DISPLACEMENT THICKNESS(IN)=',DSTAR2*12.
          WRITE(5,*)'MEASURED MASSFLOW(LBM/MIN)=',SUM*G*60.
          WRITE(5,*)'MEASURED CORRECTED MASSFLOW(LBM/MIN)',CFLO2*G*60.
          AM=(D1-2.*DSTAR2)**2./D1**2.
          BM=1-AM
          WRITE(5,*)'MEASURED Aeff/A0=',AM
          WRITE(5,*)'MEASURED BLOCKAGE=',BM
          WRITE(5,900)
900       FORMAT(1H0,3X,'N',5X,'R(IN)',6X,'R/R0',5X,'H(IN)',1X,'V(FT/SEC)',5X,
     1    'V/V1s',4X,'MACH #')
          DO 50 N=1,NMAX
          PT1(N)=PT1(N)*144.
          WRITE(5,901) N,R1(N)*12.,R1(N)*2./D1,H(N),V(N),V(N)/V1,M(N)
901       FORMAT(1H ,I4,F10.4,F10.4,F10.4,F10.2,2F10.4)
50        CONTINUE
          WRITE(5,*) 'DO YOU WANT A PRINTED COPY? 1=YES 0=N0'
          ACCEPT*,I
          IF(I .EQ. 0) GO TO 81
          WRITE(6,903)
903       FORMAT(1H1)
          WRITE(6,*) 'INLET CALIBRATION CALCULATIONS'
          WRITE(6,*) ' '
          WRITE(6,907) (FNAME(N),N=13,15)
          WRITE(6,904) (DT(N),N=1,9)
          WRITE(6,905) (TM(N),N=1,8)
```

```
      WRITE(6,*) 'TØ(DEG F)=',TØ-459.67
      WRITE(6,*) 'PØ(PSIA)=',PØ/144.
      WRITE(6,*) 'FLOWRATE MANOMETER HEAD(IN H2Ø)=',H1
      WRITE(6,*)'FREE STREAM VELOCITY(FT/SEC)=',V1
      WRITE(6,*)'AXIAL LOCATION(IN)=',X1*12.
      WRITE(6,*)'NU(FT**2/SEC)=',NU1
      WRITE(6,9Ø2) ReX1
      WRITE(6,*) 'X/SQRT(ReX)(IN)=',X1*12./SQRT(ReX1)
      IF(ReX1 .GT. 6.75E+Ø5) GO TO 6Ø
      WRITE(6,*)'ESTIMATED LAMINAR DISPLACEMENT THICKNESS(IN)=',DSTAR1*12.
      GO TO 7Ø
6Ø    WRITE(6,*)'ESTIMATED TURBULENT DISPLACEMENT THICKNESS(IN)=',DSTAR1*12.
7Ø    WRITE(6,*)'ESTIMATED CORRECTED FLOW(LBM/MIN)=',CFLO1*G*6Ø.
      WRITE(6,*)'ESTIMATED Aeff/AØ=',AE
      WRITE(6,*)'ESTIMATED BLOCKAGE=',BE
      WRITE(6,*)'NMAX=',NMAX
      WRITE(6,*)'MEASURED DISPLACEMENT THICKNESS(IN)=',DSTAR2*12.
      WRITE(6,*)'MEASURED MASSFLOW(LBM/MIN)=',SUM*G*6Ø.
      WRITE(6,*)'MEASURED CORRECTED MASSFLOW(LBM/MIN)=',CFLO2*G*6Ø.
      WRITE(6,*)'MEASURED Aeff/AØ=',AM
      WRITE(6,*)'MEASURED BLOCKAGE=',BM
      WRITE(6,9ØØ)
      DO 8Ø N=1,NMAX
      WRITE(6,9Ø1) N,R1(N)*12.,R1(N)*2./D1,H(N),V(N),V(N)/V1,M(N)
8Ø    CONTINUE
C     STORE RESULTS ON FLOPPY DISC
81    IF(LN .EQ. Ø) GO TO 9Ø
      WRITE(5,*)'DO YOU WANT TO STORE DATA? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 9Ø
      OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='NEW',FORM=
     1 'UNFORMATTED',RECORDSIZE=5ØØ,INITIALSIZE=1)
      WRITE(4'1,ERR=1Ø8) DT,TM,TØ,PØ,H1,V1,X1,NU1,ReX1,DSTAR1
     1 ,CFLO1,NMAX,DSTAR2,SUM,CFLO2,(N,R1(N),H(N),V(N),M(N),N=
     2 1,NMAX)
      GO TO 1Ø9
1Ø8   WRITE(5,*)'I/O WRITE ERROR AT STATEMENT 1Ø9'
1Ø9   CLOSE(UNIT=4)
9Ø    DO 1ØØ N=1,NMAX
      R1(N)=R1(N)*2./D1
      V(N)=V(N)/V1
1ØØ   CONTINUE
      R1(NMAX+1)=Ø.
      R1(NMAX+2)=Ø.
      V(NMAX+1)=Ø.
      V(NMAX+2)=Ø.
C     PLOT RESULTS
      WRITE(5,*) 'DO YOU WANT A VELOCITY PLOT? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 11Ø
      WRITE(5,*) 'INPUT PLOTTING UNIT:5=TERMINAL,6=X-Y PLOTTER'
      ACCEPT*,NUNIT
      CALL PLOTS(Ø,Ø,NUNIT)
      CALL PLOT(1.75,2.,-3)
      CALL SYMBOL(1.,8.25,.2,23H INLET VELOCITY PROFILE,Ø.,+23)
      CALL SYMBOL(1.,7.75,.15,12H RUN NUMBER=,Ø.,+12)
      CALL SYMBOL(999.Ø,999.Ø,.15,RN,Ø.,+5)
      CALL SCALE(R1,5.,NMAX,+1)
      CALL SCALE(V,5.,NMAX,+1)
      CALL AXIS(Ø.,Ø.,5HV/VIS,+5,5.,9Ø.,V(NMAX+1),V(NMAX+2))
      CALL AXIS(Ø.,Ø.,4HR/RØ,-4,5.,Ø.,R1(NMAX+1),R1(NMAX+2))
      CALL LINE(R1,V,NMAX,1,+1,Ø)
      CALL PLOT(Ø.,Ø.,+999)
11Ø   STOP
      END
```

```
C        PROGRAM HWCAL
C        THIS PROGRAM IS USED FOR CALIBRATING THE INLET HOT WIRE PROBE WITH
C        THE FLOWRATE  MANOMETER.THE VOLTAGE OUTPUT FROM THE HOTWIRE AMPLIFIER
C        IS READ WITH THE ANALOGIC 16 CHANNEL MP6912 A/D CONVERTER ON CHANNEL
C        1. 100 SAMPLINGS OF CHANNEL 1 ARE AVERAGED TO GIVE ONE CALIBRATION
C        POINT ON A CALIBRATION CURVE.THE CALIBRATION POINTS CAN THEN BE STORED
C        ON A FLOPPY DISC,DISPLAYED ON THE TERMINAL, OR WRITTEN OUT ON THE LINE
C        PRINTER. SETTINGS FOR THE A/D CONVERTER ARE:
C        OUT CODE: 1 0
C        RANGE SELECT: 0 1 1  (-10.24 TO +10.24 VOLTS)
C                      0 0 1  (-5.12 TO +5.12 VOLTS)
C        SEQUENTIAL
C        SCAN SELECT: 0 0 0 0
C        SAMPLE RATE: 10000HZ
C
         REAL*4 V(102),X1(102),MFLO(102)
         DIMENSION X(102),IOUT(1000),DATA(1000),ERROR(100),HC(100),COF(4)
         DIMENSION X2(102),Y2(102)
         COMMON/DATAFL/X2,Y2,NMAX,COF
         COMMON/T/T(12)
         COMMON/AMB/ PAMB,TAMB,PREF,TREF
         BYTE TM(8),DT(9),INFO(72),FNAME(16)
         DATA NUL/0/
         DATA FNAME/' ','D','L','2',':',6*'X','.',3*'X',0/
         G=32.17405
         WRITE(5,*)'NEW DATA TO BE IMPUT? 1=YES 0=NO'
         ACCEPT*,I
         IF(I .EQ. 0) GO TO 25
         WRITE(5,*)'INPUT INSTRUMENTATION INFO(72 CHARACTERS OR LESS)'
         ACCEPT 900,(INFO(N),N=1,72)
900      FORMAT(72A1)
         CALL DATE(DT)
         CALL TIME(TM)
C        WRITE(5,*)'INPUT AMBIENT TEMPERATURE(DEG C)'
C        ACCEPT*,T0
C        T0=1.8*T0+32.+459.67
C        WRITE(5,*)'INPUT AMBIENT PRESSURE(IN HG)'
C        ACCEPT*,P0
C        P0=P0*.4911543
C        CALCULATE DENSITY OF MERCURY(SLUG/FT**3)
C        RHO=-2.5533E-03*(T0-459.67)+26.51067
         WRITE(5,*) 'INPUT DESIRED NUMBER OF A/D SAMPLINGS(<1000)'
         ACCEPT*,NPT
         N=0
10       N=N+1
20       WRITE(5,*)'SET AND INPUT DESIRED FLOWRATE HEAD(IN H20)'
         ACCEPT*,X(N)
C        CALCULATE CORRECTED MASSFLOW
         CALL CFLOC(X(N),X1(N),MFLO(N))
C        READ CHANNEL 0 OF A/D CONVERTER FOR VOLTAGE AND AVERAGE
C        WRITE(5,*) 'INPUT NUMBER OF A/D SAMPLINGS FOR AVERAGING(<1000)'
C        ACCEPT*,NPT
         CALL SAMPLE(1000,IOUT)
         SUM=0.
         DO 22 J=1,NPT
         I=IOUT(J)
         CALL RETRVA(I,IADDR,IDATA)
         DATA(J)=FLOAT(IDATA-2048)
C        RANGE: -10.24 VOLTS TO 10.24 VOLTS
C        DATA(J)=DATA(J)*10.24/2048.
C        RANGE: -5.12 VOLTS TO 5.12 VOLTS
         DATA(J)=DATA(J)*5.12/2048.
         SUM=SUM+DATA(J)
22       CONTINUE
```

```
      V(N)=SUM/FLOAT(NPT)
C     CALCULATE NON DIM PARAMETERS FOR CURVE FIT
C     250 DEG C OPERATING TEMP ASSUMED
      TS=482.
      X2(N)=V(N)**2./(TS-T(1))
      Y2(N)=MFLO(N)**.5
      WRITE(5,*)' '
      WRITE(5,*)'POINT #=',N
      WRITE(5,*)'MANOMETER HEAD(IN H20)=',X(N)
      WRITE(5,*)'INLET FLOW TEMP(DEG F)=',T(1)
      WRITE(5,*)'AMBIENT PRESSURE(PSIA)=',PAMB/144.
      WRITE(5,*)'AMBIENT TEMPERATURE(DEG F)=',TAMB-459.688
      WRITE(5,*)'CFLO(LBM/MIN)=',X1(N)
      WRITE(5,*)'OUTPUT VOLTAGE=',V(N)
      WRITE(5,*)' '
      WRITE(5,*)'IS THIS POINT O.K.? 1=YES,0=N0'
      ACCEPT*,I
      IF(I .EQ. 0) GO TO 20
      WRITE(5,*)'MORE POINTS? 1=YES 0=NO'
      ACCEPT*,I
      IF(I .EQ. 1) GO TO 10
      NMAX=N
      GO TO 30
25    WRITE(5,*) 'ENTER DATA FILE NAME (XXX:XXXXXX.XXX)'
      ACCEPT 907, (FNAME(I),I=2,15)
907   FORMAT(14A1)
      OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1 FORM='UNFORMATTED',RECORDSIZE=400,INITIALSIZE=1)
      READ(4'1,ERR=26) INFO,DT,TM,PAMB,TAMB,NMAX,(X(N),X1(N),V(N),
     1 X2(N),Y2(N),N=1,NMAX)
      CLOSE(UNIT=4)
      GO TO 30
26    WRITE(5,*)'I/O ERROR AT STATEMENT 26'
C     OUTPUT RESULTS ON TERMINAL
30    WRITE(5,*)'CALIBRATION DATA'
      WRITE(5,*)' '
      WRITE(5,905) (INFO(N),N=1,72)
905   FORMAT(1H ,72A1)
      WRITE(5,901) (DT(N),N=1,9)
901   FORMAT(1H ,'DATE=',9A1)
      WRITE(5,902) (TM(N),N=1,8)
902   FORMAT(1H ,'TIME=',8A1)
      WRITE(5,*)'AMBIENT PRESSURE(PSIA)=',PAMB/144.
      WRITE(5,*)'AMBIENT TEMPERATURE(DEG F)=',TAMB-459.688
      WRITE(5,*)'NUMBER OF POINTS=',NMAX
      WRITE(5,*)' '
      WRITE(5,903)
903   FORMAT(1H ,3X,'N',6X,'H(IN H20)',2X,'CFLO(LBM/MIN)',10X,'VOLTS',
     1 14X,'X',14X,'Y')
      WRITE(5,904) (N,X(N),X1(N),V(N),X2(N),Y2(N),N=1,NMAX)
904   FORMAT(1H ,I4,3F15.4,2E15.4)
40    WRITE(5,*)'DO YOU WANT A PRINTOUT OF THIS DATA? 1=YES 0=NO'
      ACCEPT*,I
      IF(I .EQ. 0) GO TO 60
      WRITE(6,906)
906   FORMAT(1H1)
      WRITE(6,*)'CALIBRATION DATA'
      WRITE(6,*)' '
      WRITE(6,905) (INFO(N),N=1,72)
      WRITE(6,901) (DT(N),N=1,9)
      WRITE(6,902) (TM(N),N=1,8)
      WRITE(6,*)'AMBIENT PRESSURE(PSIA)=',PAMB/144.
      WRITE(6,*)'AMBIENT TEMPERATURE(DEG F)=',TAMB-459.688
      WRITE(6,*)' '
```

```
      WRITE(6,9Ø3)
      WRITE(6,9Ø4) (N,X(N),X1(N),V(N),X2(N),Y2(N),N=1,NMAX)
C5Ø   WRITE(5,*)'DO YOU WANT A PLOT OF THIS DATA? 1=YES Ø=NO'
C     ACCEPT*,I
C     IF(I .EQ.Ø) GO TO 6Ø
C     PLOT DATA
C     X1(NMAX+1)=.Ø
C     X1(NMAX+2)=.Ø
C     V(NMAX+1)=.Ø
C     V(NMAX+2)=.Ø
C     WRITE(5,*) 'INPUT PLOTTING UNIT 5=TERMINAL,6=X Y PLOTTER'
C     ACCEPT*,NUNIT
C     CALL PLOTS(Ø,Ø,NUNIT)
C     CALL PLOT(1.75,2.,-3)
C     CALL SYMBOL(1.,8.25,.2,24H KULITE CALIBRATION DATA,Ø.,+24)
C     CALL SYMBOL(1.,7.75,.15,19H KULITE #4361-4-123,Ø.,+19)
C     CALL SYMBOL(1.,7.5,.15,37H AMP CHAN #4,GAIN=5ØØ,6.44 VDC SOURCE,
C    1 Ø.,+37)
C     CALL SYMBOL(1.,7.25,.15,6H DATE=,Ø.,+6)
C     CALL SYMBOL(999.Ø,999.Ø,.15,DT,Ø.,+9)
C     CALL SYMBOL(1.,7.,.15,6H TIME=,Ø.,+6)
C     CALL SYMBOL(999.Ø,999.Ø,.15,TM,Ø.,+8)
C     CALL SYMBOL(1.,6.75,.15,24H AMBIENT PRESSURE(PSIA)=,Ø.,+24)
C     CALL NUMBER(999.Ø,999.Ø,.15,PØ,Ø.,+4)
C     CALL SYMBOL(1.,6.5,.15,28H AMBIENT TEMPERATURE(DEG F)=,Ø.,+28)
C     CALL NUMBER(999.Ø,999.Ø,.15,TØ-459.67,Ø.,+2)
C     CALL SCALE(V,5.,NMAX,1)
C     CALL SCALE(X1,7.,NMAX,1)
C     CALL AXIS(Ø.,Ø.,5HVOLTS,-5,5.,Ø.,V(NMAX+1),V(NMAX+2))
C     CALL AXIS(Ø.,Ø.,3HPSI,+3,7.,9Ø.,X1(NMAX+1),X1(NMAX+2))
C     CALL LINE(V,X1,NMAX,1,+1,Ø)
6Ø    WRITE(5,*)'DO YOU WANT TO STORE THIS DATA? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 7Ø
C     STORE DATA ON FLOPPY DISC
      WRITE(5,*) 'ENTER DATA FILE NAME (XXX:XXXXXX.XXX)'
      ACCEPT 9Ø7,(FNAME(I),I=2,15)
      OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='NEW',FORM=
     1 'UNFORMATTED',RECORDSIZE=4ØØ,INITIALSIZE=1)
      WRITE(4'1,ERR=64) INFO,DT,TM,PAMB,TAMB,NMAX,(X(N),X1(N),V(N),X2(N),
     1 Y2(N),N=1,NMAX)
      GO TO 65
64    WRITE(5,*) 'I/O ERROR AT 65'
65    CLOSE(UNIT=4)
7Ø    WRITE(5,*) 'DO YOU WANT TO CURVEFIT THIS DATA? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 75
      CALL CURFIT
      WRITE(6,9Ø9)
9Ø9   FORMAT(1H1)
      WRITE(6,*) 'CURVE FIT RESULTS'
      WRITE(6,*) ' '
      WRITE(6,*) 'COEFFICIENTS'
      WRITE(6,91Ø)
91Ø   FORMAT(1HØ,12X,'C1',12X,'C2',12X,'C3',12X,'C4')
      WRITE(6,9Ø8) (COF(N),N=1,4)
9Ø8   FORMAT(1H ,4E14.7)
      WRITE(5,911)
      WRITE(6,911)
911   FORMAT(1HØ,2X,'N',1ØX,'VOLTS',14X,'X',7X,'MFLOMEAS',7X,
     1 'MFLOCALC',7X,'ERROR(%)')
      DO 74 N=1,NMAX
      IF(X2(N) .EQ. Ø.) GO TO 79
C     HC(N)=COF(1)+COF(2)*X2(N)+COF(3)*X2(N)**2.+COF(4)*X2(N)**3.
```

```
      HC(N)=COF(1)+COF(2)*X2(N)+COF(3)*X2(N)*X2(N)+COF(4)*X2(N)*
     1 X2(N)*X2(N)
      GO TO 8Ø
79    HC(N)=COF(1)
8Ø    IF(X2(N) .EQ. Ø.) GO TO 73
      ERROR(N)=(HC(N)**2.-Y2(N)**2.)/Y2(N)**2.*1ØØ.
      GO TO 74
73    ERROR(N)=999999999999.9
74    CONTINUE
      DUM=1.
      WRITE(5,921) (N,V(N),X2(N),Y2(N)**2.,HC(N)**2.,
     1 ERROR(N),N=1,NMAX)
      WRITE(6,921) (N,V(N),X2(N),Y2(N)**2.,HC(N)**2.,ERROR(N),N=1,NMAX)
921   FORMAT(1H ,I3,1F15.4,E15.4,2F15.4,F15.2)
75    STOP
      END
```

```
      SUBROUTINE CURFIT
C
C     XX = REAL ARRAY OF HORIZENTAL VALUES FOR DATA
C     YY = REAL ARRAY OF VERTICAL VALUES
C     NPTS = NUMBER OF POINTS IN X AND Y ARRAYS
C     X = REAL ARRAY OF HORIZANTAL VALUES FOR CURVE FITTED DATA
C     Y = REAL ARRAY OF VETICAL VALUES FOR CURVE FITTED DATA
C
C     THIS PROGRAM IS MADE FOR SECOND OR THIRD POLYNOMIAL CURVE
C     FITTING BY USING LEAST SQUARE CURVE FITTING METHOD.
C
C     DATA SRE READ FROM FILES. YOU CAN READ SEVERAL FILES AT
C     ONCE.
C
C     THIS IS FIRST VERSION - DEC. 2Ø, 1982 -- HWS
C
      REAL*4 XX(1Ø2),YY(1Ø2)
      DIMENSION A(5,5),COF(4)
      COMMON/DATAFL/XX,YY,NPTS,COF
      DO 2Ø I=1,4
      DO 3Ø J=1,5
      A(I,J)=Ø
3Ø    CONTINUE
2Ø    CONTINUE
      A(1,1)=NPTS
      DO 4Ø K=1,NPTS
              A(1,2)=A(1,2)+XX(K)
              A(1,3)=A(1,3)+XX(K)**2
              A(1,4)=A(1,4)+XX(K)**3
              A(1,5)=A(1,5)+YY(K)
              A(2,4)=A(2,4)+XX(K)**4
              A(2,5)=A(2,5)+XX(K)*YY(K)
              A(3,4)=A(3,4)+XX(K)**5
              A(3,5)=A(3,5)+XX(K)*XX(K)*YY(K)
              A(4,4)=A(4,4)+XX(K)**6
              A(4,5)=A(4,5)+YY(K)*XX(K)**3
4Ø    CONTINUE
      A(2,1)=A(1,2)
      A(2,2)=A(1,3)
      A(2,3)=A(1,4)
      A(3,1)=A(1,3)
      A(3,2)=A(1,4)
      A(3,3)=A(2,4)
      A(4,1)=A(1,4)
      A(4,2)=A(2,4)
      A(4,3)=A(3,4)
      TYPE 2ØØ
2ØØ   FORMAT(' DO YOU WANT 2 OR 3 POLYNOMIAL CURVE FIT? --- ENTER :',/,
      1       ' 2 ---> FOR SECOND POLINOMIAL CURVE FITTING.',/,
      2       ' 3 ---> FOR THIRD POLINOMIAL CURVE FITTING')
      ACCEPT*,MD
      MD=MD+1
      MMD=MD+1
      IF(MD.EQ.4) GO TO 1ØØ
      DO 3ØØ J=1,3
      A(J,4)=A(J,5)
3ØØ   CONTINUE
C
C  SOLVE THE POLYNOMIAL EQUATION
C
1ØØ   DO 11 I1=1,MD
              C=A(I1,I1)
      DO 12 I2=1,MMD
              A(I1,I2)=A(I1,I2)/C
```

```
12        CONTINUE
          DO 13 I3=1,MD
                  IF(I1-I3)15,13,15
15                FACT=A(I3,I1)
          DO 14 I4=1,MMD
                  A(I3,I4)=A(I3,I4)-FACT*A(I1,I4)
14        CONTINUE
13        CONTINUE
11        CONTINUE
          DO 16 KL=1,MD
          COF(KL)=A(KL,MMD)
16        CONTINUE
          WRITE(5,*)  'C1=',COF(1)
          WRITE(5,*)  'C2=',COF(2)
          WRITE(5,*)  'C3=',COF(3)
          WRITE(5,*)  'C4=',COF(4)
          RETURN
          END
```

```
      SUBROUTINE CFLOC(H1,CFLO,MFLO)
C     THIS PROGRAM WILL CALCULATE CORRECTED MASSFLOW(LBM/MIN)
C     FOR A TEST POINT FROM INPUTED FLOWRATE MANOMETER
C     READING(IN H2Ø).
      REAL K,M,MOLD,M1,M2,NU,MU,MFLO
      COMMON/T/TT(12)
      COMMON/AMB/ PAMB,TAMB,PREF,TREF
      DSTAR=.Ø1/12.
C     INLET DIAMETER
      D1=4.373/12.
C     COMPRESSOR CASING I.D.
      DT=2.933/12.
C     IMPELLER HUB/CASING I.D.
      HTR=.3965
      PI=3.1415927
      AØ=PI*D1**2./4.
      A1=PI*(D1-2.*DSTAR)**2./4.
      A2=PI*(1.-HTR**2.)*DT**2./4.
      TREF=545.
      PREF=14.69*144.
      G=32.174Ø5
      R=53.3*G
      K=1.4
C     READ REFERENCE AND AMBIENT TEST CONDITIONS
      OPEN(UNIT=2,NAME='AMB.DAT',TYPE='OLD',FORM='UNFORMATTED')
      READ(2) PAMB,TAMB,PREF,TREF
      CLOSE(UNIT=2)
C     CALCULATE TEST POINT STEADY STATE PARAMETERS
C     WRITE(5,*)'INPUT AMBIENT TEMPERATURE(DEG R)'
C     ACCEPT*,TØ
C     TØ=1.8*TØ+32.+459.688
C     READ TEST CELL TEMPERATURE
C     TØ=TAMB
      CALL TEMP(12,12)
      TØ=TT(12)+459.688
C     CALCULATE DENSITY OF H2Ø AT TEST CELL TEMPERATURE
      RHO1=-2.6419E-Ø4*(TØ-459.688)+1.9544
C     CALCULATE DENSITY OF HG AT TEST CELL TEMPERATURE
C     RHO2=-2.5533E-Ø3*(TØ-459.688)+26.51Ø67
C     WRITE(5,*)'INPUT AMBIENT PRESSURE(IN HG)'
C     ACCEPT*,PØ
C     CONVERT PRESSURE(IN HG) TO PSF
C     PØ=PØ*G*RHO2/12.
      PØ=PAMB
C9    WRITE(5,*)'INPUT DESIRED CORRECTED SPEED LINE(RPM)'
C     ACCEPT*,CRPMS
C     READ INLET TEMPERATURE(DEG F)
1Ø    CALL TEMP(1,1)
C     TT(1)=TAMB-459.688
C     CALCULATE FLOW VARIABLES AT INLET CONDITIONS
      TØ=TT(1)+459.688
C     TØ=TAMB
C     HZ=CRPMS*SQRT(TØ/TREF)/6Ø.
C     WRITE(5,*)'SET MECHANICAL SPEED(HZ)=',HZ
C11   WRITE(5,*)'INPUT FLOWRATE MANOMETER HEAD(IN H2Ø)'
C     ACCEPT*,H1
      IF(H1 .EQ. Ø) GO TO 25
12    DELP=H1*G*RHO1/12.
      P=PØ-DELP
      M1=SQRT(((PØ/P)**((K-1)/K)-1)*2./(K-1))
      FM=M1/(1+(K-1)*M1**2./2.)**((K+1)/(K-1)/2.)
C     CALCULATE INLET REYNOLDS NUMBER FOR DSTAR CALCULATION
C     CFLO=A1*SQRT(K/R)*FM*PREF/SQRT(TREF)
      T1=TØ/(1+(K-1)*M1**2./2.)
```

```
      V1=M1*SQRT(K*R*T1)
      RHO=P/(R*T1)
      MU=.317Ø*T1**1.5*(734.7/(T1+216.))*1E-1Ø
      NU=MU/RHO
      X=3.85/12.
      ReX=V1*X/NU
      DSTAR=11.7467/(ReX)**.5/12.
      A1=PI*(D1-2.*DSTAR)**2./4.
      CFLO=A1*SQRT(K/R)*FM*PREF/SQRT(TREF)
      CFLO=CFLO*G*6Ø
      MFLO=CFLO*(PØ/PREF)/( Ø/TREF)**.5
      GO TO 26
25    CFLO=Ø.
26    WRITE(5,*) 'H1=',H1
      WRITE(5,*) 'TAMB(DEG F)=',TAMB-459.688
      WRITE(5,*) 'PAMB(PSIA)=',PAMB/144.
      WRITE(5,*) 'CFLO(LBM/MIN)=',CFLO
      WRITE(5,*) 'MFLO(LBM/MIN)=',MFLO
      RETURN
      END
```

```
      SUBROUTINE TEMP(NF,NL)
C     THIS PROGRAM OPERATES THE UMAC-4ØØØ TEMPERATURE MULTIPLEXER WITH
C     C PROTOCOL.THE CODE WILL READ THE TEMPERATURE CHANNELS Ø-11
C     AND OUTPUT THE RESULTS ON THE TERMINAL.TERMINAL TT5 IS SET
C     AS A SLAVE TERMINAL AND THE UMAC-4ØØØ IS CONNECTED TO IT.
C     USE ASG=TT5:3 FOR TASK BUILDING.
C     TERMINAL TT5: SETTINGS ARE:
C     SLAVE,NOECHO,96ØØ BAUD,HFILL=1
C     DLV11-J INTERFACE BOARD #2 CHANNEL #2 RECONFIGURED:
C     7 DATA BITS,2 STOP BITS,PARITY ENABLED,ODD PARITY
C     NOTE:ON FIRST RUN AFTER POWER UP ONE WILL GET AN ERROR
C     WHICH GOES AWAY UPON RERUNNING.
      BYTE CR(1),LF(1),X(1),CH(2),V(7),CJT(7),ERR(7)
      BYTE COM1(7),REP1(7),COM2(7),REP2(7),COM3(1Ø),REP3(14)
      BYTE COM4(1Ø),REP4(14),COM5(9),REP5(7)
      COMMON /T/ TT(12)
      DIMENSION CJTEMP(12)
      INTEGER*2 J
      DATA COM1/'*','Ø'.':','S','T','A',':'/
      DATA COM2/'*','Ø',':','R','E','S',':'/
      DATA COM3/'*','Ø',':','C','H','A','/',2*'Ø',':'/
      DATA COM4/'*','Ø',':','T','E','M','/','Ø'.'Ø',':'/
      DATA COM5/'*','Ø',':','D','E','G','/','F',':'/
      DATA. ERR/'9','9','9','9','.','9','9'/
      DATA CR/13/
C
C     RESET UMAC-4ØØØ
      WRITE(3,9ØØ) CR,COM2,CR
      WRITE(5,9Ø1) COM2
9ØØ   FORMAT(9A1)
9Ø1   FORMAT(9HØCOMMAND=,7A1)
      READ(3,9ØØ) LF,REP2,X
      WRITE(5,9Ø2) REP2
9Ø2   FORMAT(7H REPLY=,7A1)
C
C     CHECK UMAC-4ØØØ STATUS
      WRITE(3,9ØØ) LF,COM1,CR
      WRITE(5,9Ø1) COM1
      READ(3,9ØØ) LF,REP1,X
      WRITE(5,9Ø2) REP1
C
C     SET TEMPERATURE TO DEG F
      WRITE(3,91Ø) LF,COM5,CR
91Ø   FORMAT(11A1)
      WRITE(5,911) COM5
911   FORMAT(9HØCOMMAND=,9A1)
      READ(3,9ØØ) LF,REP5,X
      WRITE(5,9Ø2) REP5
      DO 1ØØ J=Ø,11
      IF(J .LT. (NF-1)) GO TO 1ØØ
      IF(J .GT. (NL-1)) GO TO 1ØØ
      ENCODE(2,912,CH) J
912   FORMAT(I2)
      COM3(8)=CH(1)
      COM3(9)=CH(2)
      COM4(8)=CH(1)
      COM4(9)=CH(2)
C
C     READ DATA ON CHANNEL J
      WRITE(3,9Ø3) LF,COM3,CR
9Ø3   FORMAT(12A1)
      WRITE(5,9Ø6) COM3
9Ø6   FORMAT(9HØCOMMAND=,1ØA1)
      READ(3,9Ø4) LF,REP3,X
```

```
904     FORMAT(16A1)
        WRITE(5,905) REP3
905     FORMAT(7H REPLY=,14A1)
        IF(REP3(6) .EQ. 'O') GO TO 60
        GO TO 70
60      DO 65 L=1,7
        REP3(L+4)=ERR(L)
65      CONTINUE
C
C       READ COLD JUNCTION REFERENCE TEMPERATURE ON CHANNEL J
70      WRITE(3,907) LF,COM4,CR
907     FORMAT(1A1,10A1,1A1)
        WRITE(5,906) COM4
        READ(3,908) LF,REP4,X
908     FORMAT(16A1)
        WRITE(5,909) REP4
909     FORMAT(7H REPLY=,14A1)
        DO 90 K=1,7
        V(K)=REP3(K+4)
        CJT(K)=REP4(K+4)
90      CONTINUE
        DECODE(7,913,V) TT(J+1)
        DECODE(7,914,CJT) CJTEMP(J+1)
913     FORMAT(F7.2)
914     FORMAT(F7.2)
        WRITE(5,915) J+1,TT(J+1),CJTEMP(J+1)
915     FORMAT(1H0,'CHANNEL=',I2,5X,'TEMP=',F7.2,5X,'CJTEMP=',F7.2)
100     CONTINUE
        RETURN
        END
```

```
;
        .TITLE ADCVTDRV
;
; A set of fortran callable routines for using the Analogic Device analog-
; to-digital converter interface to the Dec DRV-11 at Q-bus address 171770.
;
        .PSECT SAMPLE,RW,I,GBL,REL,CON
;
;Subroutine SAMPLE enables the analog-to-digital converter to convert
;the voltages in SEQUENTIAL and EXT. TRIG. MODE. To use this, use
;  CALL SAMPLE(IC,IOUT), where IC denotes the number of data points to
;be converted and IOUT is the OUTPUT ARRAY.
;
SAMPLE::        TST (R5)+               ;SKIP NO OF ARGUMENTS
                MOV @(R5)+,R0           ;LOAD NO. OF DATA PTS TO BE COLLECTED
                                        ;IN REG. R0
                MOV (R5)+,R3            ;LOAD R3 WITH ADDRESS POINTER FOR
                                        ;OUTPUT ARRAY
LOOP2:          TST $DR1CS              ;LOOK FOR END OF CONVERSION
                BPL LOOP2               ;END OF CONVERSION ?
                MOV $DR1IN,(R3)+        ;GET DATA AND UPDATE ADDRESS POINTER
                DEC R0                  ;UPDATE DATA PT POINTER BY 1
                BNE LOOP2               ;IF NOT DONE CONTINUE
                RETURN
                .END


.TITLE RETRVA
;THIS SUBROUTINE RETRIEVES ADDRESS AND DATA
;FROM 16-BIT WORD.
.GLOBL RETRVA
;
RETRVA: TST     (R5)+           ;(R5)+2.
        MOV     (R5)+,R1        ;INPUT ADDRESS AT R1.
        MOV     (R5)+,R2        ;ADDRESS OF DATA ADDRESS AT R2.
        MOV (R5),R3             ;DATA ADDRESS AT R3.
;
;RETRIVE THE ADDRESS.
        MOV     (R1),(R2)
        SWAB    (R2)
        ROR     (R2)
        ROR     (R2)
        ROR     (R2)
        ROR     (R2)
;1 111 111 111 110 000=177760 OCTAL.
        BIC     #177760,(R2)
;
;RETRIVE THE DATA.
        MOV     (R1),(R3)
;1 111 000 000 000 000=170000 OCTAL.
        BIC     #170000,(R3)
        RTS     PC
        .END
```

```
C       PROGRAM SETAMB
C       THIS PROGRAM CALCULATES ATMOSPHERIC PRESSURE FROM UNCORRECTED
C       BAROMETER READING(IN HG) AND SETS UP AMBIENT CONDITION FILE.
C       UNITS IN AMB.DAT ARE T(DEG R),P(LBF/FT**2)
        G=32.17405
        WRITE(5,*) 'INPUT UNCORRECTED AMBIENT BAROMETRIC PRESSURE(IN HG)'
        ACCEPT*,P0
        WRITE(5,*) 'INPUT BAROMETER TEMPERATURE READING(DEG F)'
        ACCEPT*,T0
C       CALCULATE DENSITY OF HG AT BAROMETER TEMPERATURE(SLUG/FT**3)
        RHO=-2.5533E-3*T0+26.51067
C       CONVERT TEMPERATURE TO DEG R
        T0=T0+459.688
C       CONVERT PRESSURE TO PSF
        P0=P0*G*RHO/12.
C       SET REFERENCE ATMOSPHERIC CONDITIONS
        WRITE(5,*) 'INPUT REFERENCE TEMPERATURE(DEG F)'
        ACCEPT*,TREF
        TREF=TREF+459.688
        WRITE(5,*) 'INPUT REFERENCE PRESSURE(PSIA)'
        ACCEPT*,PREF
        PREF=PREF*144.
        OPEN(UNIT=2,NAME='AMB.DAT',TYPE='NEW',FORM='UNFORMATTED')
        WRITE(2) P0,T0,PREF,TREF
        CLOSE(UNIT=2)
        STOP
        END
```

```
C         PROGRAM SET
C         THIS PROGRAM WILL CALCULATE CORRECTED MASSFLOW
C         (LBM/MIN),COMPRESSOR TOTAL PRESSURE RATIO, AND
C         SPEED(HZ) FOR A TEST POINT FROM INPUTED FLOWRATE MANOMETER
C         READING(IN H2Ø),COMPRESSOR OUTLET TOTAL
C         PRESSURE(IN HG GUAGE), AND CORRECTED SPEED(HZ).
          REAL K,M,MOLD,M1,M2,NU,MU
          COMMON /T/ TT(12)
          DSTAR=.Ø1/12.
C         INLET DIAMETER
          D1=4.373/12.
C         COMPRESSOR CASING I.D.
          DT=2.933/12.
C         IMPELLER HUB/CASING I.D.
          HTR=.3965
          PI=3.1415927
          AØ=PI*D1**2./4.
          A1=PI*(D1-2.*DSTAR)**2./4.
          A2=PI*(1.-HTR**2.)*DT**2./4.
          TREF=545.
          PREF=14.69*144.
          G=32.174Ø5
          R=53.3*G
          K=1.4
C         READ REFERENCE AND AMBIENT TEST CONDITIONS
          OPEN(UNIT=2,NAME='AMB.DAT',TYPE='OLD',FORM='UNFORMATTED')
          READ(2) PAMB,TAMB,PREF,TREF
          CLOSE(UNIT=2)
C         CALCULATE TEST POINT STEADY STATE PARAMETERS
C         WRITE(5,*)'INPUT AMBIENT TEMPERATURE(DEG C)'
C         ACCEPT*,TØ
C         TØ=1.8*TØ+32.+459.688
C         READ TEST CELL TEMPERATURE
          CALL TEMP(12,12)
          TØ=TT(12)+459.688
C         CALCULATE DENSITY OF H2Ø AT TEST CELL TEMPERATURE
          RHO1=-2.6419E-Ø4*(TØ-459.688)+1.9544
C         CALCULATE DENSITY OF HG AT TEST CELL TEMPERATURE
          RHO2=-2.5533E-Ø3*(TØ-459.688)+26.51Ø67
C         WRITE(5,*)'INPUT AMBIENT PRESSURE(IN HG)'
C         ACCEPT*,PØ
C         CONVERT PRESSURE(IN HG) TO PSF
C         PØ=PØ*G*RHO2/12.
          PØ=PAMB
9         WRITE(5,*)'INPUT DESIRED CORRECTED SPEED LINE(RPM)'
          ACCEPT*,CRPMS
C         READ INLET TEMPERATURE(DEG F)
1Ø        CALL TEMP(1,1)
C         CALCULATE FLOW VARIABLES AT INLET CONDITIONS
          TØ=TT(1)+459.688
          HZ=CRPMS*SQRT(TØ/TREF)/6Ø.
          WRITE(5,*)'SET MECHANICAL SPEED(HZ)=',HZ
11        WRITE(5,*)'INPUT FLOWRATE MANOMETER HEAD(IN H2Ø)'
          ACCEPT*,H1
          IF(H1 .EQ. Ø) GO TO 25
12        DELP=H1*G*RHO1/12.
          P=PØ-DELP
          M1=SQRT(((PØ/P)**((K-1)/K)-1)*2./(K-1))
          FM=M1/(1+(K-1)*M1**2./2.)**((K+1)/(K-1)/2.)
C         CALCULATE INLET REYNOLDS NUMBER FOR DSTAR CALCULATION
C         CFLO=A1*SQRT(K/R)*FM*PREF/SQRT(TREF)
          T1=TØ/(1+(K-1)*M1**2./2.)
          V1=M1*SQRT(K*R*T1)
          RHO=P/(R*T1)
```

```
      MU=.317Ø*T1**1.5*(734.7/(T1+216.))*1E-1Ø
      NU=MU/RHO
      X=3.85/12.
      ReX=V1*X/NU
      DSTAR=11.7467/(ReX)**.5/12.
      A1=PI*(D1-2.*DSTAR)**2./4.
      CFLO=A1*SQRT(K/R)*FM*PREF/SQRT(TREF)
      WRITE(5,*)'INPUT COMPRESSOR OUTLET MANOMETER HEAD(IN HG)'
      ACCEPT*,H2
C     READ ACTUAL SPEED ON SPEED COUNTER
      CALL SPEED(HZ)
C     CALCULATE ACTUAL CORRECTED SPEED
      CRPM=HZ*6Ø./SQRT(TØ/TREF)
13    DELP=G*H2*RHO2/12.
      PRT=1.+DELP/PØ
C     CALCULATE AXIAL MACH # AND VELOCITY OF FLOW
C     AT IMPELLER INLET ANNULUS
      B=CFLO*SQRT(TREF)/PREF*SQRT(R/K)/A2
      M2=B
2Ø    F=M2**(2.*(K-1)/(K+1))-(K-1)*B**(2.*(K-1)/(K+1))*M2**2./
     1 2.-B**(2.*(K-1)/(K+1))
      SLOPE=2.*(K-1)*M2**((K-3)/(K+1))/(K+1)-(K-1)*B**(2.*(K-1
     1 )/(K+1))*M2
      MOLD=M2
      M2=M2-F/SLOPE
      IF(ABS(M2/MOLD-1.) .GT. .ØØØØ1) GO TO 2Ø
      WRITE(5,*)' '
      T2=TØ/(1.+(K-1)*M2**2./2.)
      V2=M2*SQRT(K*R*T2)
C     CALCULATE MEAN IMPELLER WHEEL SPEED
      U2=PI*(1.+HTR)*DT/2.*HZ
      PHI2=V2/U2
      BETA2=ATAN(1./PHI2)*36Ø./2./PI
      CFLO=CFLO*G*6Ø.
C     WRITE STEADY STATE TEST POINT VALUES
      WRITE(5,*)'TEST POINT CALCULATIONS'
      WRITE(5,*)' '
      WRITE(5,*)'CORRECTED SPEED(RPM)=',CRPM
      WRITE(5,*)'CORRECTED FLOWRATE(LBM/MIN)=',CFLO
      WRITE(5,*)'COMPRESSOR TOTAL PRESSURE RATIO=',PRT
      WRITE(5,*)'IMPELLER INLET FLOW COEFFICIENT=',PHI2
      WRITE(5,*)'REFERENCE TEMP(DEG F)=',TREF-459.688
      WRITE(5,*)'REFERENCE PRESSURE(PSIA)=',PREF/144.
      WRITE(5,*)'BAROMETRIC PRESSURE(PSIA)=',PAMB/144.
      WRITE(5,*)'INLET FLOW TEMP(DEG F)=',TT(1)
      WRITE(5,*)'FLOWRATE MANOMETER HEAD(IN H2Ø)=',H1
      WRITE(5,*)'COMPRESSOR OUTLET MANOMETER HEAD(IN HG)=',H2
      WRITE(5,*)'COMPRESSOR SPEED(HZ)=',HZ
      WRITE(5,*)'INLET MACH #=',M1
      WRITE(5,*)'INLET VELOCITY(FT/SEC)=',V1
      WRITE(5,*)'INLET ReX=',ReX
      WRITE(5,*)'INLET AVERAGE DSTAR(IN)=',DSTAR*12.
      WRITE(5,*)'INLET AVERAGE Aeff/AØ=',A1/AØ
      WRITE(5,*)'IMPELLER AXIAL INLET MACH #=',M2
      WRITE(5,*)'IMPELLER AXIAL INLET VELOCITY(FT/SEC)=',V2
      WRITE(5,*)'IMPELLER RELATIVE INLET FLOW ANGLE(DEG)=',BETA2
      WRITE(5,*)'BAROMETER CORRECTION TEMP(DEG F)=',TAMB-459.688
      WRITE(5,*)'TEST CELL CORRECTION TEMP(DEG F)=',TT(12)
      WRITE(5,*)' '
      WRITE(5,*)'DO YOU WANT DATA AT THIS POINT? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 1Ø
25    STOP
      END
```

```
      SUBROUTINE SPEED(HZ)
C     THIS SUBROUTINE READS THE HP 5300B COUNTER VIA THE HPIB BUS
C     AND RETURNS THE READING IN RPS.
      BYTE ARRAY(20),COUNT(10)
      EQUIVALENCE (COUNT(1),ARRAY(6))
C     THIS CLEARS BUS
      J=IBUP(10)
      IF(J .LT. 0) WRITE(5,*) 'UNABLE TO CLEAR GPIB BEFORE USE:J=',J
      J=IBUP(2,-1)
C     SET SPEED COUNTER IN REMOTE MODE
      J=IBUP(4,1)
C     TRIGGER SPEED COUNTER
      J=IBUP(3,1)
C     READ SPEED
      J=IBUP(1,1,ARRAY,20)
      DECODE(10,111,COUNT)HZ
111   FORMAT(E10.0)
C     SET SPEED COUNTER IN LOCAL MODE
      J=IBUP(5,1)
C     UNADDRESS COUNTER
      RETURN
      END
```

```
C       PROGRAM   DATAL2
C       THIS PROGRAM ACQUIRES LOW RESPONSE DATA FROM THE 5300B
C       COUNTER,SCANIVALVE,UMAC-4000 TEMPERATURE MULTIPLEXER, AND
C       MANUALLY ENTERED VALUES.
        REAL M1,M2,M3,M4
        INTEGER RN
        BYTE TM(8),DT(9),INFO(72),FNAME(18)
        COMMON /A/ P(48)
        COMMON /T/ TT(12)
        DATA NUL/0/
        DATA FNAME/' ','D','Y','0',':',6*'X','.',3*'X',';','1',0/
        CALL DATE(DT)
        CALL TIME(TM)
        WRITE(5,*) 'INPUT POINT #'
        ACCEPT*,RN
        WRITE(5,*) 'INPUT INFORMATION ON DATA(72 CHARACTERS)'
        ACCEPT 900,(INFO(I),I=1,72)
900     FORMAT(72A1)
C       WRITE(5,*) 'INPUT AMBIENT TEMPERATURE(DEG C)'
C       ACCEPT*,T0
C       WRITE(5,*) 'INPUT AMBIENT PRESSURE(IN HG)'
C       ACCEPT*,P0
C       READ AMBIENT CONDITIONS
        OPEN(UNIT=2,NAME='AMB.DAT',TYPE='OLD',FORM='UNFORMATTED')
        READ(2) PAMB,TAMB,PREF,TREF
        CLOSE(UNIT=2)
        WRITE(5,*) 'INPUT MANOMETER FLOWRATE HEAD(IN H20)'
        ACCEPT*,M1
C       WRITE(5,*) 'INPUT EJECTOR NOZZLE TOTAL PRESSURE(PSI GUAGE)'
C       ACCEPT*,G1
        G1=0.
        WRITE(5,*) 'HOME AND RESET SCANIVALVE'
C       WRITE(5,*) 'INPUT COMPRESSOR OUTLET MANOMETER HEAD(IN HG)'
C       ACCEPT*,M3
        M3=0.
        WRITE(5,*) 'INPUT ANY NUMBER TO START'
        ACCEPT*,START
        CALL SPEED(HZ1)
        WRITE(5,*) 'SPEED1(RPS)=',HZ1
C       FOR UNAVERAGED SCANIVALVE DATA USE VALVE
        CALL VALVE
C       FOR AVERAGING USE VALVE2
C       CALL VALVE2
C       WRITE(5,902) (I,P(I),I=1,48)
902     FORMAT(1H ,I2,10X,F10.4)
        CALL TEMP(1,12)
C       CALL COBRA
        CALL SPEED(HZ2)
        WRITE(5,*) 'SPEED2(RPS)=',HZ2
        HZ=(HZ1+HZ2)/2.
C       WRITE(5,*) 'INPUT COMPRESSOR OUTLET MANOMETER HEAD(IN HG)'
C       ACCEPT*,M4
        M4=0.
C       WRITE(5,*) 'INPUT EJECTOR NOZZLE TOTAL PRESSURE(PSI GUAGE)'
C       ACCEPT*,G2
        G2=0.
        WRITE(5,*) 'INPUT MANOMETER FLOWRATE HEAD(IN H20)'
        ACCEPT*,M2
        M3=(M3+M4)/2.
        WRITE(5,*) 'AVERAGE COMPRESSOR SPEED(RPS)=',HZ
C       WRITE(5,*) 'AVERAGE COMPRESSOR OUTLET MANOMETER HEAD(IN HG)=',M3
        G1=(G1+G2)/2.
C       WRITE(5,*) 'AVERAGE EJECTOR NOZZLE TOTAL PRESSURE(PSI GUAGE)=',G1
        M1=(M1+M2)/2.
        WRITE(5,*) 'AVERAGE FLOWRATE MANOMETER HEAD=',M1
```

```
      WRITE(5,*) 'INPUT FILENAME FOR DATA STORAGE(XXXXXX.XXX)'
      ACCEPT 9Ø1,(FNAME(I),I=6,15)
9Ø1   FORMAT(1ØA1)
      IF(RN .EQ. 1) GO TO 5
      OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1 FORM='UNFORMATTED',RECORDSIZE=1ØØ,INITIALSIZE=1ØØ)
      GO TO 1Ø
5     OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='NEW',
     1 FORM='UNFORMATTED',RECORDSIZE=1ØØ,INITIALSIZE=1ØØ)
1Ø    WRITE(4'RN,ERR=2Ø) INFO,DT,TM,PAMB,TAMB,PREF,TREF,M1,G1,M3,HZ,P,TT
      GO TO 3Ø
2Ø    WRITE(5,*) 'WRITE ERROR AT STATEMENT 1Ø'
3Ø    CLOSE(UNIT=4)
      STOP
      END
```

```
      SUBROUTINE VALVE
C     THIS PROGRAM STEPS THE SCANIVALVE WITH THE DRV-11 #2
C     AND READS THE ANALOGIC MP6912 A/D WITH DRV-11 #1.THE A/D
C     IS TRIGGERED VIA RTR N.O. SIGNAL OBTAINED FROM BACK OF INTERFACE
C     BOX.SCANIVALVE TRANSDUCER OUTPUT IS INPUT ON A/D CHANNEL Ø
C     NO POINT AVERAGING USED
      COMMON /A/ P(48)
      KL=5
      DO 1 I=1,48
      DO 2 J=1,1ØØØØ
      AA=5.**2.
2     CONTINUE
      CALL SCAN(KL,IPOS)
      CALL CLRDR1
      CALL SAMPLE(1,ID)
      CALL RETRVA(ID,IADDR,IDATA)
C     A/D RANGE:-1Ø.24 TO 1Ø.24 VOLTS
C     DATA=FLOAT(IDATA-2Ø48)*1Ø.24/2Ø48.
C     A/D RANGE:-5.12 TO 5.12 VOLTS
      DATA=FLOAT(IDATA-2Ø48)*5.12/2Ø48.
      CALL CHAN(IPOS,ICHN)
      WRITE(5,*)'ICHN=',ICHN
      WRITE(5,*)'DATA=',DATA
      P(I)=DATA
1     CONTINUE
      RETURN
      END

C THIS PROGRAM CALCULATES S/V CHANNEL NO. (ICHN) FROM S/V DATA (IPOS)
      SUBROUTINE CHAN(IPOS,ICHN)
      IF(IPOS.LT.1Ø)GO TO 4Ø
      IF(IPOS.GT.3Ø)GO TO 1Ø
      ICHN=IPOS-6
      GO TO 5Ø
1Ø    IF(IPOS.GT.42)GO TO 2Ø
      ICHN=IPOS-12
      GO TO 5Ø .
2Ø    IF(IPOS.GT.6Ø)GO TO 3Ø
      ICHN=IPOS-18
      GO TO 5Ø
3Ø    ICHN=IPOS-24
      GO TO 5Ø
4Ø    ICHN=IPOS
5Ø    CONTINUE
      RETURN
      END

        .GLOBL CLRDR1
CLRDR1: CLR $DR1CS
        RETURN
        .END


        .GLOBL SCAN
SCAN:   MOV (R5)+,RØ
        CLR $DR3CS
        MOV @(R5)+,$DR3OU
        CLR R1
ADDRES: TST $DR3CS
        BPL ADDRES
        MOV $DR3IN,@(R5)+
        MOV (R5)+,R3
        RTS PC
        .END
```

```
C       PROGRAM KULCAL
C       THIS PROGRAM IS USED FOR CALIBRATING KULITE HIGH RESPONSE PROBES
C       WITH A MERCURY MANOMETER.THE VOLTAGE OUTPUT FROM THE KULITE AMPLIFIER
C       IS READ WITH THE ANALOGIC 16 CHANNEL MP6912 A/D CONVERTER ON CHANNEL
C       1. 1ØØ SAMPLINGS OF CHANNEL 1 ARE AVERAGED TO GIVE ONE CALIBRATION
C       POINT ON A CALIBRATION CURVE.THE CALIBRATION POINTS CAN THEN BE STORED
C       ON A FLOPPY DISC,DISPLAYED ON THE TERMINAL, OR WRITTEN OUT ON THE LINE
C       PRINTER. SETTINGS FOR THE A/D CONVERTER ARE:
C       OUT CODE: 1 Ø
C       RANGE SELECT: Ø 1 1  (-1Ø.24 TO +1Ø.24 VOLTS)
C                     Ø Ø 1  (-5.12 TO +5.12 VOLTS)
C       SEQUENTIAL
C       SCAN SELECT: Ø Ø Ø Ø
C       SAMPLE RATE: 1ØØØØHZ
C
        REAL*4 V(1Ø2),X1(1Ø2)
        DIMENSION X(1Ø2),IOUT(1ØØ),DATA(1ØØ),ERROR(1ØØ),HC(1ØØ),COF(4)
        COMMON/DATAFL/V,X1,NMAX,COF
        BYTE TM(8),DT(9),INFO(72),FNAME(16)
        DATA NUL/Ø/
        DATA FNAME/' ','D','L','2',':',6*'X','.',3*'X',Ø/
        G=32.174Ø5
        WRITE(5,*)'NEW DATA TO BE IMPUT? 1=YES Ø=NO'
        ACCEPT*,I
        IF(I .EQ. Ø) GO TO 25
        WRITE(5,*)'INPUT INSTRUMENTATION INFO(72 CHARACTERS OR LESS)'
        ACCEPT 9ØØ,(INFO(N),N=1,72)
9ØØ     FORMAT(72A1)
        CALL DATE(DT)
        CALL TIME(TM)
        WRITE(5,*)'INPUT AMBIENT TEMPERATURE(DEG C)'
        ACCEPT*,TØ
        TØ=1.8*TØ+32.+459.67
        WRITE(5,*)'INPUT AMBIENT PRESSURE(IN HG)'
        ACCEPT*,PØ
        PØ=PØ*.4911543
C       CALCULATE DENSITY OF MERCURY(SLUG/FT**3)
        RHO=-2.5533E-Ø3*(TØ-459.67)+26.51Ø67
        N=Ø
1Ø      N=N+1
2Ø      WRITE(5,*)'SET AND INPUT DESIRED MANOMETER HEAD(IN HG)'
        ACCEPT*,X(N)
        X1(N)=X(N)*G*RHO/12./144.
C       READ CHANNEL Ø OF A/D CONVERTER FOR VOLTAGE AND AVERAGE
        CALL SAMPLE(1ØØ,IOUT)
        SUM=Ø.
        DO 22 J=1,1ØØ
        I=IOUT(J)
        CALL RETRVA(I,IADDR,IDATA)
        DATA(J)=FLOAT(IDATA-2Ø48)
C       RANGE: -1Ø.24 VOLTS TO 1Ø.24 VOLTS
C       DATA(J)=DATA(J)*1Ø.24/2Ø48.
C       RANGE: -5.12 VOLTS TO 5.12 VOLTS
        DATA(J)=DATA(J)*5.12/2Ø48.
        SUM=SUM+DATA(J)
22      CONTINUE
        V(N)=SUM/1ØØ.
        WRITE(5,*)' '
        WRITE(5,*)'POINT #=',N
        WRITE(5,*)'MANOMETER HEAD(IN HG)=',X(N)
        WRITE(5,*)'MANOMETER HEAD(PSI)=',X1(N)
        WRITE(5,*)'OUTPUT VOLTAGE=',V(N)
        WRITE(5,*)' '
        WRITE(5,*)'IS THIS POINT O.K.? 1=YES,Ø=NØ'
```

```
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 2Ø
      WRITE(5,*)'MORE POINTS? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. 1) GO TO 1Ø
      NMAX=N
      GO TO 3Ø
25    WRITE(5,*) 'ENTER DATA FILE NAME (XXX:XXXXXX.XXX)'
      ACCEPT 9Ø7, (FNAME(I),I=2,15)
9Ø7   FORMAT(14A1)
      OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1 FORM='UNFORMATTED',RECORDSIZE=4ØØ,INITIALSIZE=1)
      READ(4'1,ERR=26) INFO,DT,TM,PØ,TØ,NMAX,(X(N),X1(N),V(N),N=1,NMAX)
      CLOSE(UNIT=4)
      GO TO 3Ø
26    WRITE(5,*)'I/O ERROR AT STATEMENT 26'
C     OUTPUT RESULTS ON TERMINAL
3Ø    WRITE(5,*)'CALIBRATION DATA'
      WRITE(5,*)' '
      WRITE(5,9Ø5) (INFO(N),N=1,72)
9Ø5   FORMAT(1H ,72A1)
      WRITE(5,9Ø1) (DT(N),N=1,9)
9Ø1   FORMAT(1H ,'DATE=',9A1)
      WRITE(5,9Ø2) (TM(N),N=1,8)
9Ø2   FORMAT(1H ,'TIME=',8A1)
      WRITE(5,*)'AMBIENT PRESSURE(PSIA)=',PØ
      WRITE(5,*)'AMBIENT TEMPERATURE(DEG F)=',TØ-459.67
      WRITE(5,*)'NUMBER OF POINTS=',NMAX
      WRITE(5,*)' '
      WRITE(5,9Ø3)
9Ø3   FORMAT(1H ,3X,'N',2X,'H(IN HG)',4X,'H(PSI)',5X,'VOLTS')
      WRITE(5,9Ø4) (N,X(N),X1(N),V(N),N=1,NMAX)
9Ø4   FORMAT(1H ,I4,3F1Ø.4)
4Ø    WRITE(5,*)'DO YOU WANT A PRINTOUT OF THIS DATA? 1=YES Ø=NO'
      ACCEPT*,I
      IF(I .EQ. Ø) GO TO 6Ø
      WRITE(6,9Ø6)
9Ø6   FORMAT(1H1)
      WRITE(6,*)'CALIBRATION DATA'
      WRITE(6,*)' '
      WRITE(6,9Ø5) (INFO(N),N=1,72)
      WRITE(6,9Ø1) (DT(N),N=1,9)
      WRITE(6,9Ø2) (TM(N),N=1,8)
      WRITE(6,*)'AMBIENT PRESSURE(PSIA)=',PØ
      WRITE(6,*)'AMBIENT TEMPERATURE(DEG F)=',TØ-459.67
      WRITE(6,*)' '
      WRITE(6,9Ø3)
      WRITE(6,9Ø4) (N,X(N),X1(N),V(N),N=1,NMAX)
C5Ø   WRITE(5,*)'DO YOU WANT A PLOT OF THIS DATA? 1=YES Ø=NO'
C     ACCEPT*,I
C     IF(I .EQ.Ø) GO TO 6Ø
C     PLOT DATA
C     X1(NMAX+1)=.Ø
C     X1(NMAX+2)=.Ø
C     V(NMAX+1)=.Ø
C     V(NMAX+2)=.Ø
C     WRITE(5,*) 'INPUT PLOTTING UNIT 5=TERMINAL,6=X Y PLOTTER'
C     ACCEPT*,NUNIT
C     CALL PLOTS(Ø,Ø,NUNIT)
C     CALL PLOT(1.75,2.,-3)
C     CALL SYMBOL(1.,8.25,.2,24H KULITE CALIBRATION DATA,Ø.,+24)
C     CALL SYMBOL(1.,7.75,.15,19H KULITE #4361-4-123,Ø.,+19)
C     CALL SYMBOL(1.,7.5,.15,37H AMP CHAN #4,GAIN=5ØØ,6.44 VDC SOURCE,
C    1 Ø.,+37)
```

```
C       CALL SYMBOL(1.,7.25,.15,6H DATE=,Ø.,+6)
C       CALL SYMBOL(999.Ø,999.Ø,.15,DT,Ø.,+9)
C       CALL SYMBOL(1.,7.,.15,6H TIME=,Ø.,+6)
C       CALL SYMBOL(999.Ø,999.Ø,.15,TM,Ø.,+8)
C       CALL SYMBOL(1.,6.75,.15,24H AMBIENT PRESSURE(PSIA)=,Ø.,+24)
C       CALL NUMBER(999.Ø,999.Ø,.15,PØ,Ø.,+4)
C       CALL SYMBOL(1.,6.5,.15,28H AMBIENT TEMPERATURE(DEG F)=,Ø.,+28)
C       CALL NUMBER(999.Ø,999.Ø,.15,TØ-459.67,Ø.,+2)
C       CALL SCALE(V,5.,NMAX,1)
C       CALL SCALE(X1,7.,NMAX,1)
C       CALL AXIS(Ø.,Ø.,5HVOLTS,-5,5.,Ø.,V(NMAX+1),V(NMAX+2))
C       CALL AXIS(Ø.,Ø.,3HPSI,+3,7.,9Ø.,X1(NMAX+1),X1(NMAX+2))
C       CALL LINE(V,X1,NMAX,1,+1,Ø)
6Ø      WRITE(5,*)'DO YOU WANT TO STORE THIS DATA? 1=YES Ø=NO'
        ACCEPT*,I
        IF(I .EQ. Ø) GO TO 7Ø
C       STORE DATA ON FLOPPY DISC
        WRITE(5,*) 'ENTER DATA FILE NAME (XXX:XXXXXX.XXX)'
        ACCEPT 9Ø7,(FNAME(I),I=2,15)
        OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='NEW',FORM=
     1  'UNFORMATTED',RECORDSIZE=4ØØ,INITIALSIZE=1)
        WRITE(4'1,ERR=64) INFO,DT,TM,PØ,TØ,NMAX,(X(N),X1(N),V(N),N=1,NMAX)
        GO TO 65
64      WRITE(5,*) 'I/O ERROR AT 65'
65      CLOSE(UNIT=4)
7Ø      WRITE(5,*) 'DO YOU WANT TO CURVEFIT THIS DATA? 1=YES Ø=NO'
        ACCEPT*,I
        IF(I .EQ. Ø) GO TO 75
        CALL CURFIT
        WRITE(6,9Ø9)
9Ø9     FORMAT(1H1)
        WRITE(6,*) 'CURVE FIT RESULTS'
        WRITE(6,*) ' '
        WRITE(6,*) 'COEFFICIENTS'
        WRITE(6,91Ø)
91Ø     FORMAT(1HØ,12X,'C1',12X,'C2',12X,'C3',12X,'C4')
        WRITE(6,9Ø8) (COF(N),N=1,4)
9Ø8     FORMAT(1H ,4E14.7)
        WRITE(5,911)
        WRITE(6,911)
911     FORMAT(1HØ,2X,'N',5X,'VOLTS',3X,'HM(PSI)',3X,'HC(PSI)',2X,
     1  'ERROR(%)')
        DO 74 N=1,NMAX
        IF(V(N) .EQ. Ø.) GO TO 79
C       HC(N)=COF(1)+COF(2)*V(N)+COF(3)*V(N)**2.+COF(4)*V(N)**3.
        HC(N)=COF(1)+COF(2)*V(N)+COF(3)*V(N)*V(N)+COF(4)*V(N)*
     1  V(N)*V(N)
        GO TO 8Ø
79      HC(N)=COF(1)
8Ø      IF(X1(N) .EQ. Ø.) GO TO 73
        ERROR(N)=(HC(N)-X1(N))/X1(N)*1ØØ.
        GO TO 74
73      ERROR(N)=99999999.9999
74      CONTINUE
        WRITE(5,921) (N,V(N),X1(N),HC(N),ERROR(N),N=1,NMAX)
        WRITE(6,921) (N,V(N),X1(N),HC(N),ERROR(N),N=1,NMAX)
921     FORMAT(1H ,I3,4F1Ø.4)
75      STOP
        END
```

```
C         PROGRAM PLOTCAL
C         THIS PROGRAM IS USED FOR PLOTTING THE CALIBRATION OUTPUT OF PROGRAM
C         KULCAL. THE OUTPUT IS READ FROM DATA FILES ON DYØ:.
          REAL*4 V(1Ø2),X1(1Ø2),X(1Ø2),XTEX(1Ø)
          BYTE TM(8),DT(9),INFO(72),FNAME(16)
          DATA NUL/Ø/
          DATA FNAME/' ','D','L','2',':',6*'X','.',3*'X',Ø/
          G=32.174Ø5
25        WRITE(5,*) 'ENTER DATA FILE NAME (XXX:XXXXXX.XXX)'
          ACCEPT 9Ø7, (FNAME(I),I=2,15)
9Ø7       FORMAT(14A1)
          OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1    FORM='UNFORMATTED',RECORDSIZE=4ØØ,INITIALSIZE=1)
          READ(4'1,ERR=26) INFO,DT,TM,PØ,TØ,NMAX,(X(N),X1(N),V(N),N=1,NMAX)
          CLOSE(UNIT=4)
          GO TO 3Ø
26        WRITE(5,*)'I/O ERROR AT STATEMENT 26'
C         OUTPUT RESULTS ON TERMINAL
3Ø        WRITE(5,*)'CALIBRATION DATA'
          WRITE(5,*)' '
          WRITE(5,9Ø5) (INFO(N),N=1,72)
9Ø5       FORMAT(1H ,72A1)
          WRITE(5,9Ø1) (DT(N),N=1,9)
9Ø1       FORMAT(1H ,'DATE=',9A1)
          WRITE(5,9Ø2) (TM(N),N=1,8)
9Ø2       FORMAT(1H ,'TIME=',8A1)
          WRITE(5,*)'AMBIENT PRESSURE(PSIA)=',PØ
          WRITE(5,*)'AMBIENT TEMPERATURE(DEG F)=',TØ-459.67
          WRITE(5,*)'NUMBER OF POINTS=',NMAX
          WRITE(5,*)' '
          WRITE(5,9Ø3)
9Ø3       FORMAT(1H ,3X,'N',2X,'H(IN HG)',4X,'H(PSI)',5X,'VOLTS')
          WRITE(5,9Ø4) (N,X(N),X1(N),V(N),N=1,NMAX)
9Ø4       FORMAT(1H ,I4,3F1Ø.4)
C         PLOT DATA
          X1(NMAX+1)=.Ø
          X1(NMAX+2)=.Ø
          V(NMAX+1)=.Ø
          V(NMAX+2)=.Ø
          WRITE(5,*) 'INPUT PLOTTING UNIT 5=TERMINAL,6=X Y PLOTTER'
          ACCEPT*,NUNIT
          CALL PLOTS(Ø,Ø,NUNIT)
          CALL PLOT(1.75,2.,-3)
          WRITE(5,*) 'INPUT TITLE'
          ACCEPT 987,(XTEX(I),I=1,1Ø)
987       FORMAT(1ØA4)
          CALL SYMBOL(1.,8.25,.2,XTEX,Ø.,4Ø)
          WRITE(5,*) 'INPUT CALIBRATION INFO'
          ACCEPT 987,(XTEX(I),I=1,1Ø)
          CALL SYMBOL(1.,7.75,.15,XTEX,Ø.,4Ø)
          WRITE(5,*) 'INPUT CALIBRATION INFO'
          ACCEPT 987,(XTEX(I),I=1,1Ø)
          CALL SYMBOL(1.,7.5,.15,XTEX,Ø.,4Ø)
          CALL SYMBOL(1.,7.25,.15,6H DATE=,Ø.,+6)
          CALL SYMBOL(999.Ø,999.Ø,.15,DT,Ø.,+9)
          CALL SYMBOL(1.,7.Ø,.15,6H TIME=,Ø.,+6)
          CALL SYMBOL(999.Ø,999.Ø,.15,TM,Ø.,+8)
          CALL SYMBOL(1.,6.75,.15,24H AMBIENT PRESSURE(PSIA)=,Ø.,+24)
          CALL NUMBER(999.Ø,999.Ø,.15,PØ,Ø.,+4)
          CALL SYMBOL(1.,6.5,.15,28H AMBIENT TEMPERATURE(DEG F)=,Ø.,+28)
          CALL NUMBER(999.Ø,999.Ø,.15,TØ-459.67,Ø.,+2)
C         CALL SCALE(V,5.,NMAX,1)
C         CALL SCALE(X1,7.,NMAX,1)
          WRITE(5,*) 'ENTER X-AXIS ORIGIN'
```

```
      ACCEPT*,V(NMAX+1)
      WRITE(5,*) 'ENTER X-AXIS INCREMENT'
      ACCEPT*,V(NMAX+2)
      WRITE(5,*) 'ENTER Y-AXIS ORIGIN'
      ACCEPT*,X1(NMAX+1)
      WRITE(5,*) 'ENTER Y-AXIS INCREMENT'
      ACCEPT*,X1(NMAX+2)
      CALL AXIS(Ø.,Ø.,5HVOLTS,-5,5.,Ø.,V(NMAX+1),V(NMAX+2))
      CALL AXIS(Ø.,Ø.,3HPSI,+3,7.,9Ø.,X1(NMAX+1),X1(NMAX+2))
      CALL LINE(V,X1,NMAX,1,+1,Ø)
      CALL PLOT(Ø.,Ø.,+999)
75    STOP
      END
```

```
C       THIS PROGRAM ACQUIRES LOW RESPONSE DATA FROM THE 5300B
C       COUNTER,SCANIVALVE,UMAC-4000 TEMPERATURE MULTIPLEXER, AND
C       MANUALLY ENTERED VALUES.
        REAL M1,M2,M3,M4
        INTEGER RN
        BYTE TM(8),DT(9),INFO(72),FNAME(18)
        COMMON /A/ P(48)
        COMMON /T/ TT(12)
        DATA NUL/0/
        DATA FNAME/' ','D','Y','0',':',6*'X','.',3*'X',';','1',0/
        CALL DATE(DT)
        CALL TIME(TM)
        WRITE(5,*) 'INPUT POINT #'
        ACCEPT*,RN
        WRITE(5,*) 'INPUT INFORMATION ON DATA(72 CHARACTERS)'
        ACCEPT 900,(INFO(I),I=1,72)
900     FORMAT(72A1)
C       WRITE(5,*) 'INPUT AMBIENT TEMPERATURE(DEG C)'
C       ACCEPT*,T0
C       WRITE(5,*) 'INPUT AMBIENT PRESSURE(IN HG)'
C       ACCEPT*,P0
C       READ AMBIENT CONDITIONS
        OPEN(UNIT=2,NAME='AMB.DAT',TYPE='OLD',FORM='UNFORMATTED')
        READ(2) PAMB,TAMB,PREF,TREF
        CLOSE(UNIT=2)
        WRITE(5,*) 'INPUT MANOMETER FLOWRATE HEAD(IN H20)'
        ACCEPT*,M1
C       WRITE(5,*) 'INPUT EJECTOR NOZZLE TOTAL PRESSURE(PSI GUAGE)'
C       ACCEPT*,G1
        G1=0.
        WRITE(5,*) 'HOME AND RESET SCANIVALVE'
C       WRITE(5,*) 'INPUT COMPRESSOR OUTLET MANOMETER HEAD(IN HG)'
C       ACCEPT*,M3
        M3=0.
        WRITE(5,*) 'INPUT ANY NUMBER TO START'
        ACCEPT*,START
        CALL SPEED(HZ1)
        WRITE(5,*) 'SPEED1(RPS)=',HZ1
C       FOR UNAVERAGED SCANIVALVE DATA USE VALVE
C       CALL VALVE
C       FOR AVERAGING USE VALVE2
        CALL VALVE2
C       WRITE(5,902) (I,P(I),I=1,48)
902     FORMAT(1H ,I2,10X,F10.4)
        CALL TEMP(1,12)
C       CALL COBRA
        CALL SPEED(HZ2)
        WRITE(5,*) 'SPEED2(RPS)=',HZ2
        HZ=(HZ1+HZ2)/2.
C       WRITE(5,*) 'INPUT COMPRESSOR OUTLET MANOMETER HEAD(IN HG)'
C       ACCEPT*,M4
        M4=0.
C       WRITE(5,*) 'INPUT EJECTOR NOZZLE TOTAL PRESSURE(PSI GUAGE)'
C       ACCEPT*,G2
        G2=0.
        WRITE(5,*) 'INPUT MANOMETER FLOWRATE HEAD(IN H20)'
        ACCEPT*,M2
        M3=(M3+M4)/2.
        WRITE(5,*) 'AVERAGE COMPRESSOR SPEED(RPS)=',HZ
C       WRITE(5,*) 'AVERAGE COMPRESSOR OUTLET MANOMETER HEAD(IN HG)=',M3
        G1=(G1+G2)/2.
C       WRITE(5,*) 'AVERAGE EJECTOR NOZZLE TOTAL PRESSURE(PSI GUAGE)=',G1
        M1=(M1+M2)/2.
        WRITE(5,*) 'AVERAGE FLOWRATE MANOMETER HEAD=',M1
```

```
      WRITE(5,*) 'INPUT FILENAME FOR DATA STORAGE(XXXXXX.XXX)'
      ACCEPT 901,(FNAME(I),I=6,15)
901   FORMAT(10A1)
      IF(RN .EQ. 1) GO TO 5
      OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1 FORM='UNFORMATTED',RECORDSIZE=100,INITIALSIZE=100)
      GO TO 10
5     OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='NEW',
     1 FORM='UNFORMATTED',RECORDSIZE=100,INITIALSIZE=100)
10    WRITE(4'RN,ERR=20) INFO,DT,TM,PAMB,TAMB,PREF,TREF,M1,G1,M3,HZ,P,TT
      GO TO 30
20    WRITE(5,*) 'WRITE ERROR AT STATEMENT 10'
30    CLOSE(UNIT=4)
      STOP
      END
```

```
      SUBROUTINE VALVE2
C     THIS PROGRAM STEPS THE SCANIVALVE WITH THE DRV-11 #2
C     AND READS THE ANALOGIC MP6912 A/D WITH DRV-11 #1.THE A/D
C     IS TRIGGERED VIA RTR N.O. SIGNAL OBTAINED FROM BACK OF INTERFACE
C     BOX.SCANIVALVE TRANSDUCER OUTPUT IS INPUT ON A/D CHANNEL Ø
C     DATA IS TIME AVERAGED OVER AN INTEGRAL NUMBER OF CYCLES
C     NSAMP=# OF A/D SAMPLES
C     FREQS=A/D SAMPLING FREQUENCY(HZ)
C     NCYCLE=# OF CYCLES FOR AVERAGING
C     FREQD=DESIRED AVERAGING FREQUENCY(HZ)
C     GATET=WAVETEK GATE PULSE WIDTH(SEC)
      INTEGER ITIME
      REAL NCYCLE
      DIMENSION ID(1ØØØ),DATA(1ØØØ)
      COMMON /A/ P(48)
C     INPUT DESIRED AVERAGING FREQ
98    WRITE(5,*) 'INPUT DESIRED AVERAGING FREQUENCY'
      ACCEPT*,FREQD
      NCYCLE=2.
      FREQS=1ØØØ.
      NSAMP=IFIX(FREQS/FREQD*NCYCLE)
      GATET=FLOAT(NSAMP)/FREQS
      WRITE(5,*) '# OF AVERAGING CYCLES=',NCYCLE
      WRITE(5,*) 'A/D SAMPLING FREQUENCY(HZ)=',FREQS
      WRITE(5,*) 'AVERAGING FREQUENCY(HZ)=',FREQD
      WRITE(5,*) 'WAVETEK GATE TIME(SEC)=',GATET
      WRITE(5,*) '# OF A/D POINTS=',NSAMP
      IF(NSAMP .LT. 1ØØØ) GO TO 99
      WRITE(5,*) 'NSAMP > 1ØØØ POINTS'
      GO TO 98
99    KL=5
      DO 1 I=1,48
      DO 2 J=1,1ØØØØ
      A=5.**2
2     CONTINUE
      CALL SCAN(KL,IPOS)
      CALL CLRDR1
C     CALL SAMPLE(1,ID)
C     TAKE NSAMP PRESSURE SAMPLES USING GATED PULSE GENERATOR.
C     OUTPUT TRIGGER SIGNAL FROM SCANIVALVE INTERFACE IS USED TO
C     TRIGGER WAVETEK PULSE OF 1 SECOND DURATION. THIS 1 SECOND
C     PULSE IS USED TO GATE A 1ØØ HZ SQUARE WAVE TO THE A/D.THUS
C     1ØØ TRIGGERING PULSES PER CHANNEL ARE ACHIEVED
      CALL SAMPLE(NSAMP,ID)
      SUM=Ø.
      CALL CHAN(IPOS,ICHN)
      WRITE(5,*) 'CHANNEL #=',ICHN
      DO 3 K=1,NSAMP
      CALL RETRVA(ID(K),IADDR,IDATA)
C     A/D RANGE:-1Ø.24 TO 1Ø.24 VOLTS
C     DATA(K)=FLOAT(IDATA-2Ø48)*1Ø.24/2Ø48.
C     A/D RANGE:-5.12 TO 5.12 VOLTS
      DATA(K)=FLOAT(IDATA-2Ø48)*5.12/2Ø48.
      SUM=SUM+DATA(K)
3     CONTINUE
      WRITE(5,*)'AVERAGE DATA=',SUM/FLOAT(NSAMP)
      P(I)=SUM/FLOAT(NSAMP)
1     CONTINUE
      RETURN
      END
```

```
C         PROGRAM FILELOW3
C         THIS PROGRAM READS THE LOW RESPONSE RAW DATA STORED ON DISCS
C         AND CREATES DATA FILES FOR PLOTTING WITH PNTPL4
          REAL M1,M2,M3,M4,K
          INTEGER RN,RMAX,RMIN
          BYTE TM(8),DT(9),INFO(72),FNAME(16),PFNAME(16)
          DIMENSION P(48),TT(12)
          COMMON /A/ RN,RMAX,P,TT,G1,FLAG,ETAC,PFNAME
          DATA NUL/Ø/
          DATA FNAME/' ','D','L','2',':',6*'X','.',3*'X',Ø/
          DATA PFNAME/' ','D','L','2',':',3*'X','P','L','T','.',3*'X',Ø/
          WRITE(5,*) 'INPUT FILENAME FOR DESIRED DATA(XXX:XXXXXX.XXX)'
          ACCEPT 9ØØ,(FNAME(I),I=2,15)
9ØØ       FORMAT(14A1)
          WRITE(5,*) 'INPUT DESIRED OUTPUT UNIT:5=TERM,6=LP'
          ACCEPT*,NUNIT
          WRITE(5,*) 'DO YOU WANT TO READ FILES OR GENERATE PLOTFILES'
          WRITE(5,*) '(Ø=READ FILES,1=CREATE PLOTFILES)'
          ACCEPT*,FLAG
          IF(FLAG .EQ. Ø) GO TO 5
          WRITE(5,*) 'INPUT PLOTFILE NAME(XXX:XXXXXX)'
          ACCEPT 919,(PFNAME(I),I=2,11)
919       FORMAT(1ØA1)
          WRITE(5,*) 'INPUT TOTAL NUMBER OF RECORDS IN FILE'
          ACCEPT*,RMAX
          RMIN=1
          GO TO 6
5         WRITE(5,*) 'INPUT NUMBER OF FIRST RECORD TO BE READ'
          ACCEPT*,RMIN
          WRITE(5,*) 'INPUT NUMBER OF LAST RECORD TO BE READ'
          ACCEPT*,RMAX
6         DO 45 RN=RMIN,RMAX
          OPEN(UNIT=4,NAME=FNAME,ACCESS='DIRECT',TYPE='OLD',
     1    FORM='UNFORMATTED',RECORDSIZE=1ØØ,INITIALSIZE=1ØØ)
1Ø        READ(4'RN,ERR=2Ø) INFO,DT,TM,PAMB,TAMB,PREF,TREF,M1,G1,M3,HZ,P,TT
          GO TO 3Ø
2Ø        WRITE(5,*) 'READ ERROR AT STATEMENT 1Ø'
3Ø        CLOSE(UNIT=4)
C         WRITE(5,*) 'INPUT OUTPUT DEVICE:5=TERM,6=LP'
C         ACCEPT*,NUNIT
C         NUNIT=6
          WRITE(NUNIT,9Ø1)
9Ø1       FORMAT(1H1)
          WRITE(NUNIT,9Ø2) (INFO(I),I=1,72)
9Ø2       FORMAT(1H ,72A1)
          WRITE(NUNIT,917) RN,(DT(I),I=1,9),(TM(I),I=1,8)
917       FORMAT(1H ,'POINT #=',I3,1ØX,'DATE=',9A1,1ØX,'TIME=',8A1)
          WRITE(NUNIT,9Ø3) (FNAME(I),I=1,18)
9Ø3       FORMAT(1H ,'FILE NAME=',18A1)
C         WRITE(NUNIT,9Ø3) (DT(I),I=1,9)
C9Ø3      FORMAT(1H ,'DATE=',9A1)
C         WRITE(NUNIT,9Ø4) (TM(I),I=1,8)
C9Ø4      FORMAT(1H ,'TIME=',8A1)
C         SCANIVALVE CALIBRATION CURVE TO CONVERT VOLTAGES TO PRESSURES
C         (PSIA)
C         P(48)=AMBIENT=Ø.
C         CALCULATE OFFSET VOLTAGE TO NULL P(48) TO ADJUST FOR TRANSDUCER
C         DRIFT
C         FIRST CALIBRATION
C         OFFSET=-.351374+1Ø.337227*P(48)+.ØØ32*P(48)**2.
C         SECOND CALIBRATION
          OFFSET=.8255996E-Ø2+.9369544E+Ø1*P(48)-.5776125E-Ø2*P(48)**2.
          DO 4Ø I=1,48
C         FIRST CALIBRATION
```

```
C       P(I)=-.351374+1Ø.337227*P(I)+.ØØ32ØØ*P(I)**2.+PAMB/144.-OFFSET
        P(I)=.8255996E-Ø2+.9369544E+Ø1*P(I)-.5776125E-Ø2*P(I)**2.+
     1  PAMB/144.-OFFSET
4Ø      CONTINUE
C       CALCULATE COMPRESSOR EFFICIENCY(TOTAL TO TOTAL)
        K=1.4
        TR=(TT(2)+459.688)/(TT(1)+459.688)
        PR=P(31)/PAMB*144.
        ETAC=(PR**((K-1.)/K)-1.)/(TR-1.)
C       OUTPUT TESTPOINT CALCULATIONS
        TIN=TT(1)+459.688
        TCELL=TT(12)+459.688
        CALL TPCALC(TIN,TCELL,PAMB,TAMB,PREF,TREF,HZ,M1,M3,NUNIT)
C       GUAGE CALIBRATION CURVE
C
        IF(FLAG .EQ. Ø) WRITE(NUNIT,9Ø8) G1
9Ø8     FORMAT(1H ,'EJECTOR NOZZLE FLOWRATE HEAD(PSI GUAGE)=',F1Ø.4)
        IF(FLAG .EQ. Ø) WRITE(NUNIT,918) ETAC
918     FORMAT(1H ,'COMPRESSOR THERMAL EFFICIENCY(TOTAL TO TOTAL)=',F7.4)
        IF(FLAG .EQ. 1) GO TO 45
        WRITE(NUNIT,911)
911     FORMAT(1HØ,'PRESSURES(PSIA)')
        WRITE(NUNIT,912)
912     FORMAT(1HØ,1X,4('N',12X,'P',5X))
        WRITE(NUNIT,913) (I,P(I),I=1,48)
913     FORMAT(4(1H ,I2,3X,F1Ø.4,3X))
        WRITE(NUNIT,914)
914     FORMAT(1HØ,'TEMPERATURES(DEG F)')
        WRITE(NUNIT,915)
915     FORMAT(1HØ,1X,4('N',11X,'TT',5X))
C       TEMPERATURE CALIBRATION CURVE
C
        WRITE(NUNIT,916) (I,TT(I),I=1,12)
916     FORMAT(4(1H ,I2,3X,F1Ø.2,3X))
45      CONTINUE
        STOP
        END
```

```
      SUBROUTINE TPCALC(TIN,TCELL,PAMB,TAMB,PREF,TREF,HZ,H1,H2,NUNIT)
C     THIS PROGRAM WILL CALCULATE CORRECTED MASSFLOW
C     ,COMPRESSOR TOTAL PRESSURE RATIO, AND
C     SPEED FOR A TEST POINT FROM INPUTED FLOWRATE MANOMETER
C     READING,COMPRESSOR OUTLET TOTAL PRESSURE,AND SPEED.
C     INPUT VARIABLES:
C     TIN=INLET DUCT TOTAL TEMPERATURE(DEG R)
C     TCELL=TEST CELL TOTAL TEMPERATURE(DEG R)
C     PAMB=BAROMETRIC PRESSURE(LBF/FT**2)
C     TAMB=BAROMETER TEMPERATURE FOR CORRECTION CALCULATION(DEG R)
C     PREF=REFERENCE PRESSURE(LBF/FT**2)
C     TREF=REFERENCE TEMPERATURE(DEG R)
C     HZ=COMPRESSOR MECHANICAL SPEED(HZ)
C     H1=FLOWRATE MANOMETER HEAD(IN H2Ø)
C     H2=COMPRESSOR EXIT TOTAL PRESSURE(IN HG GUAGE)
C     NUNIT=5 TI:
C     NUNIT=6 LPØ:
      REAL K,M,MOLD,M1,M2,MU,NU,MFLOWØ,MFLOWI
      REAL M1TREL,M2JREL,MRAT
      INTEGER RN,RMAX
C     LOGICAL*1 FNAME(16),COMMNT(68),NUL
      LOGICAL*1 COMMNT(68),FNAME(16),FNUM(3),NUL,PFNAME(16),PLT(3)
      LOGICAL*1 COM(68),COM1(68),COM2(68),COM3(68),COM4(68),COM5(68)
      LOGICAL*1 COM6(68),COM7(68),COM8(68),COM9(68),COM1Ø(68)
      LOGICAL*1 WP1(4),WP2(4)
      DIMENSION PP(48),TT(12),PS(7),S(7)
      COMMON /A/ RN,RMAX,PP,TT,G1,FLAG,ETAC,PFNAME
      DATA NUL/Ø/
      DATA COMMNT/'W','A','L','L',' ','P','R','E','S','S','U','R',
     1 'E','S',54*' '/
      DATA COM1/'P','R',' ','V','S',' ','C','F','L','O',58*' '/
      DATA COM2/'P','R',' ','V','S',' ','C','X','/','U',58*' '/
      DATA COM3/'C','P',' ','V','S',' ','C','X','/','U',58*' '/
      DATA COM4/'E','T','A','C',' ','V','S',' ','C','F','L','O',
     1 56*' '/
      DATA COM5/'C','P','D','1',' ','V','S',' ','C','F','L','O',
     1 56*' '/
      DATA COM6/'C','P','D','2',' ','V','S',' ','C','F','L','O',
     1 56*' '/
      DATA COM7/'M','1','T','R','E','L',' ','V','S',' ','C','F',
     1 'L','O',54*' '/
      DATA COM8/'M','2','J','R','E','L',' ','V','S',' ','C','F',
     1 'L','O',54*' '/
      DATA COM9/'M','R','A','T',' ','V','S',' ','C','F','L','O',
     1 56*' '/
      DATA COM1Ø/'B','E','T','A','2','T',' ','V','S',' ','C','F',
     1 'L','O',54*' '/
      DATA WP1/'W','P','1','.'/
      DATA WP2/'W','P','2','.'/
      DATA PLT/'P','L','T'/
      DSTAR=.Ø1/12.
      D1=4.373/12.
      DT=2.933/12.
      HTR=.3965
      DTEX=5.Ø35/12.
      PI=3.1415927
      A1=PI*(D1-2.*DSTAR)**2./4.
      A2=PI*(1.-HTR**2.)*DT**2./4.
C     TREF=545.
C     PREF=14.69*144.
      G=32.174Ø5
      R=53.3*G
      K=1.4
      TØ=TCELL
```

```
C       CALCULATE DENSITY OF H2Ø AT TEST CELL TEMPERATURE
        RHO1=-2.6419E-Ø4*(TØ-459.688)+1.9544
C       CALCULATE DENSITY OF HG AT TEST CELL TEMPERATURE
        RHO2=-2.5533E-Ø3*(TØ-459.688)+26.51Ø67
        PØ=PAMB
        TØ=TIN
        CRPM=HZ*6Ø./SQRT(TØ/TREF)
        IF(H1 .EQ. Ø) GO TO 14
12      DELP=H1*G*RHO1/12.
        P=PØ-DELP
        M1=SQRT(((PØ/P)**((K-1)/K)-1)*2./(K-1))
        FM=M1/(1+(K-1)*M1**2./2.)**((K+1)/(K-1)/2.)
C       CFLO=A1*SQRT(K/R)*FM*PREF/SQRT(TREF)
C       CALCULATE INLET REYNOLDS NUMBER FOR DSTAR CALCULATION
        T1=TØ/(1+(K-1)*M1**2./2.)
        V1=M1*SQRT(K*R*T1)
        RHO=P/(R*T1)
        MU=.317Ø*T1**1.5*(734.7/(T1+216.))*1E-1Ø
        NU=MU/RHO
        X=3.85/12.
        ReX=V1*X/NU
        DSTAR=11.7467/(ReX)**.5/12.
        A1=PI*(D1-2.*DSTAR)**2./4.
        CFLO=A1*SQRT(K/R)*FM*PREF/SQRT(TREF)
13      DELP=G*H2*RHO2/12.
C       PRT=1.+DELP/PØ
C       CALCULATE AXIAL MACH # AND VELOCITY OF FLOW
C       AT IMPELLER INLET ANNULUS
        B=CFLO*SQRT(TREF)/PREF*SQRT(R/K)/A2
        M2=B
2Ø      F=M2**(2.*(K-1)/(K+1))-(K-1)*B**(2.*(K-1)/(K+1))*M2**2./
     1  2.-B**(2.*(K-1)/(K+1))
        SLOPE=2.*(K-1)*M2**((K-3)/(K+1))/(K+1)-(K-1)*B**(2.*(K-1
     1  )/(K+1))*M2
        MOLD=M2
        M2=M2-F/SLOPE
        IF(ABS(M2/MOLD-1.) .GT. .ØØØØ1) GO TO 2Ø
        T2=TØ/(1.+(K-1)*M2**2./2.)
        V2=M2*SQRT(K*R*T2)
C       CALCULATE MEAN IMPELLER WHEEL SPEED
        U2=PI*(1.+HTR)*DT/2.*HZ
        PHI2=V2/U2
        BETA2=ATAN(1./PHI2)*36Ø./2./PI
        CFLO=CFLO*G*6Ø.
C       CALCULATE IMPELLER MACH # RATIO
        UTIP=PI*DT*HZ
        BETA2T=ATAN(UTIP/V2)
        M1TREL=M2/COS(BETA2T)
        P2=PØ/(TØ/T2)**(K/(K-1.))
        PØ1REL=P2*(1.+(K-1.)*M1TREL**2./2.)**(K/(K-1.))
C       CALCULATE AVERAGE STATIC PRESSURE AT S=.9 INSIDE IMPELLER
        P2=(PP(9)+PP(3))/2.
        M2JREL=SQRT(((PØ1REL/(P2*144.))**((K-1.)/K)-1.)*(2./(K-1.)))
        MRAT=M1TREL/M2JREL
        GO TO 15
14      CFLO=Ø.
        PHI2=Ø.
        M1=Ø.
        V1=Ø.
        ReX=Ø.
        M2=Ø.
        V2=Ø.
C       CALCULATE DIFFUSER CPD AT 135 DEG
15      PØ2=PP(45)
```

```
C       P2STAR=(PP(4)+PP(1Ø))/2.
        P2STAR=PP(1Ø)
C       P3=(PP(6)+PP(12))/2.
        P3=PP(12)
C       WRITE(NUNIT,*)'PØ2=',PP(45)
C       WRITE(NUNIT,*)'P2STAR=',P2STAR
C       WRITE(NUNIT,*)'P3=',P3
        CPD1=(P3-P2STAR)/(PØ2-P2STAR)
        P3=(PP(27)+PP(28)+PP(29)+PP(3Ø))/4.
        CPD2=(P3-P2STAR)/(PØ2-P2STAR)
C       CALCULATE IMPELLER CPC
        UTIPEX=PI*DTEX*HZ
        CPC=(PP(31)-PP(48))*144./(.5*(PØ/(R*TØ))*UTIPEX**2.)
C       CALCULATE COMPRESSOR PRESSURE RATIO
        PRT=PP(31)*144./PØ
C       WRITE STEADY STATE TEST POINT VALUES
        IF(FLAG .EQ. 1) GO TO 24
        WRITE(NUNIT,*)'CORRECTED SPEED(RPM)=',CRPM
        WRITE(NUNIT,*)'CORRECTED FLOWRATE(LBM/MIN)=',CFLO
        WRITE(NUNIT,*)'COMPRESSOR TOTAL PRESSURE RATIO=',PRT
        WRITE(NUNIT,*)'IMPELLER MEAN INLET FLOW COEFFICIENT=',PHI2
        WRITE(NUNIT,*) 'PREF(PSIA)=',PREF/144.
        WRITE(NUNIT,*) 'TREF(DEG F)=',TREF-459.688
        WRITE(NUNIT,*)'BAROMETRIC PRESSURE(PSIA)=',PAMB/144.
        WRITE(NUNIT,*)'INLET TEMP(DEG F)=',TIN-459.688
        WRITE(NUNIT,*)'FLOWRATE MANOMETER HEAD(IN H2Ø)=',H1
        WRITE(NUNIT,*)'COMPRESSOR OUTLET MANOMETER HEAD(IN HG)=',H2
        WRITE(NUNIT,*)'COMPRESSOR SPEED(HZ)=',HZ
C       WRITE(NUNIT,*)'INLET MACH #=',M1
        WRITE(NUNIT,*)'INLET VELOCITY(FT/SEC)=',V1
        WRITE(NUNIT,*)'INLET ReX=',ReX
        WRITE(NUNIT,*)'INLET AVERAGE DSTAR(IN)=',DSTAR*12.
C       WRITE(NUNIT,*)'IMPELLER AXIAL INLET MACH #=',M2
C       WRITE(NUNIT,*)'IMPELLER AXIAL INLET VELOCITY(FT/SEC)=',V2
        WRITE(NUNIT,*)'IMPELLER RELATIVE TIP FLOW ANGLE(DEG)=',
     1  BETA2T*18Ø./PI
        WRITE(NUNIT,*)'IMPELLER RELATIVE INLET TIP MACH #=',M1TREL
        WRITE(NUNIT,*)'IMPELLER RELATIVE EXIT JET MACH #=',M2JREL
        WRITE(NUNIT,*)'IMPELLER MACH # RATIO=',MRAT
        WRITE(NUNIT,*)'VANELESS DIFFUSER CPD=',CPD1
        WRITE(NUNIT,*)'OVERALL DIFFUSER CPD=',CPD2
        WRITE(NUNIT,*)'OVERALL COMPRESSOR PRESSURE RISE COEF=',CPC
C       WRITE(NUNIT,*)'BAROMETER CORRECTION TEMP(DEG F)=',TAMB-459.688
C       WRITE(NUNIT,*)'TEST CELL CORRECTION TEMP(DEG F)=',TCELL-459.688
        IF(FLAG .EQ. Ø) GO TO 26
C       PLOT FILE CREATION SECTION
C       COMPRESSOR PR VS CFLO FILE
24      CALL PFILE(1,COM1,CFLO,PRT)
        CALL PFILE(2,COM2,PHI2,PRT)
        CALL PFILE(3,COM3,PHI2,CPC)
        CALL PFILE(4,COM4,CFLO,ETAC)
        CALL PFILE(5,COM5,CFLO,CPD1)
        CALL PFILE(6,COM6,CFLO,CPD2)
        CALL PFILE(7,COM7,CFLO,M1TREL)
        CALL PFILE(8,COM8,CFLO,M2JREL)
        CALL PFILE(9,COM9,CFLO,MRAT)
        CALL PFILE(1Ø,COM1Ø,CFLO,BETA2T*18Ø./PI)
C       YY=CPC
C       YY=CPD2
C       YY=ETAC
C       YY=CPD1
C       YY=CPD2
C       YY=MRAT
C       WRITE(5,9Ø9) RN,XX,YY
```

```
C9Ø9    FORMAT(1HØ,'RN=',I3,5X,'XX=',E13.7,5X,'YY=',E13.7)
CA      CALL PFILE(XX,YY)
C       AIR EJECTOR DATA REDUCTION FILES
C       XX=PHI2
C       YY=CFLO*(PAMB/PP(35)/144.)*SQRT((TT(4)+459.688)/TIN)
C       YY=PP(35)/PP(38)
C       YY=PRT
C       CALL PFILE(XX,YY)
C       MFLOWØ=CFLO*(PAMB/PREF)/SQRT(TIN/TREF)
C       MFLOWI=.532*6Ø.*.175*(PAMB/144.+G1)/SQRT(TT(3)+459.688)
C       WRITE(5,*) 'MFLOWØ=',MFLOWØ
C       WRITE(5,*) 'MFLOWI=',MFLOWI
C       XX=MFLOWØ/MFLOWI
C       EPR=PP(35)/PP(32)
C       WRITE(5,*) 'TOTAL PRESSURE RATIO=',EPR
C       YY=EPR
C       P2=(PP(4Ø)+PP(41)+PP(42)+PP(43))/4.
C       P2=PP(36)
C       PT2=PP(44)
C       PT2=PP(35)
C       YY=SQRT(((PT2/P2)**((K-1.)/K)-1.)*2./(K-1.))
C       WRITE(5,*) 'MIXED OUT MACH #=',YY
C       WALL PRESSURE PLOTFILES
        DO 97Ø I=1,8
        FNAME(I)=PFNAME(I)
97Ø     CONTINUE
        ENCODE(3,957,FNUM) RN
957     FORMAT(I3)
        DO 958 I=1,3
        FNAME(I+12)=FNUM(I)
        FNAME(16)=PFNAME(16)
958     CONTINUE
        DO 975 I=1,4
        FNAME(I+8)=WP1(I)
975     CONTINUE
C       WALL PRESSURE PROFILE PLOT FILE
C       -45 DEG ANGULAR POSITION
25      S(1)=-.Ø983
        S(2)=.Ø936
        S(3)=.4664
        S(4)=1.Ø219
        S(5)=1.3921
        S(6)=1.6519
        S(7)=2.32Ø5
        DO 3Ø I=1,6
        PS(I)=PP(I)/PP(48)
3Ø      CONTINUE
        PS(7)=PP(19)/PP(48)
        OPEN(UNIT=3,NAME=FNAME,TYPE='NEW',FORM='FORMATTED',
     1  INITIALSIZE=5)
        WRITE(3,955) (COMMNT(I),I=1,68),7
        WRITE(3,956) (S(I),PS(I),I=1,7)
        CLOSE(UNIT=3)
        DO 995 I=1,4
        FNAME(I+8)=WP2(I)
995     CONTINUE
31      S(1)=-.1878
        S(2)=.Ø918
        S(3)=.4664
        S(4)=1.Ø219
        S(5)=1.3937
        S(6)=1.6313
        S(7)=2.32Ø5
        DO 32 I=1,6
```

```
      PS(I)=PP(I+6)/PP(48)
32    CONTINUE
      PS(7)=.5*(PP(13)+PP(26))/PP(48)
      OPEN(UNIT=3,NAME=FNAME,TYPE='NEW',FORM='FORMATTED',
     1 INITIALSIZE=5)
      WRITE(3,955) (COMMNT(I),I=1,68),7
955   FORMAT(68A1,I3)
      WRITE(3,956) (S(I),PS(I),I=1,7)
956   FORMAT(2E13.7)
      CLOSE(UNIT=3)
26    RETURN
      END


      SUBROUTINE PFILE(NPLOT,COMMNT,XX,YY)
      INTEGER RN,RMAX
      LOGICAL*1 PFNAME(16),COMMNT(68),NUL,FNUM(3)
      DIMENSION DUMX(100),DUMY(100)
      COMMON /A/ RN,RMAX,DUM(61),FLAG,DUM1,PFNAME
      DATA NUL/0/
C     THIS PROGRAM CREATES FILES FOR PLOTTING WITH PNTPL4
      IF(FLAG .EQ. 0.) GO TO 25
      ENCODE(3,906,FNUM) NPLOT
906   FORMAT(I3)
      DO 20 I=1,3
      PFNAME(I+12)=FNUM(I)
20    CONTINUE
      IF(RN .GT. 1) GO TO 23
      OPEN(UNIT=3,NAME=PFNAME,TYPE='NEW',FORM='FORMATTED',
     1 INITIALSIZE=5,ERR=21)
      GO TO 22
21    WRITE(5,*) 'I/O ERROR IN TPCALC2'
      RETURN
22    WRITE(3,904) (COMMNT(I),I=1,68),RMAX
904   FORMAT(68A1,I3)
      GO TO 24
23    OPEN(UNIT=3,NAME=PFNAME,TYPE='OLD',FORM='FORMATTED',
     1 ERR=21)
      READ(3,904) (COMMNT(I),I=1,68),RMAX
      READ(3,905) (DUMX(I),DUMY(I),I=1,RN-1)
24    WRITE(3,905) XX,YY
      WRITE(5,*) XX,YY
905   FORMAT(2E13.7)
      CLOSE(UNIT=3)
25    RETURN
      END
```

```
C       PROGRAM IBPROG2
C       PROGRAM TO READ DATA FROM THE 3582A SPECTRUM ANALYZER
C       AND SAVE DATA IN THE FILE SPEC.DAT
C       THE COMMAND J=IBUP(Ø,...) WRITES A COMMAND OVER DATA LINE TO DEVICE
C       THE COMMAND J=IBUP(1,...) READS THE ENSUING DATA.
C       IF J IS NEGATIVE, THERE WAS AN ERROR.
        BYTE LAD(3),LSP(3),LAS(3),LBS(3),LXS(3),LDS(3),COMMA(1),ARRAY(8Ø)
        BYTE POINTS(5121),TEMPX(1Ø),TEMPY(1Ø),FNAME(18),LMK(3),LAN(3),MN1(3)
        BYTE TAØ(3),TA1(3),TBØ(3),TB1(3)
        REAL*4 MARKA,MARKF,LIN1(8),LIN2(8),LIN3(8),LIN4(8),ASCII(33),NOTES(32)
        DIMENSION X(512),Y(512)
C       POSSIBLE COMMANDS...
        DATA LAD/'L','A','D'/
        DATA LMK/'L','M','K'/
        DATA LSP/'L','S','P'/
        DATA LAS/'L','A','S'/
        DATA LBS/'L','B','S'/
        DATA LXS/'L','X','S'/
        DATA LAN/'L','A','N'/
        DATA LDS/'L','D','S'/
        DATA MN1/'M','N','1'/
        DATA TAØ/'T','A','Ø'/
        DATA TA1/'T','A','1'/
        DATA TBØ/'T','B','Ø'/
        DATA TB1/'T','B','1'/
C       FILE NAME TO STORE DATA ON DISK.
        DATA NUL/Ø/
        DATA FNAME/' ',3*'X',':',8*'X','.',3*'X',Ø/
C       GPIB CONTROLLER CLEAR ALL INSTRUMENTS ON GPIB
        J=IBUP(2,-1)
        IF(J.LT.Ø)WRITE(5,*)'UNABLE TO CLEAR GPIB BEFORE USE:J=',J
C       SET SPECTRUM ANALYZER IN REMOTE OPERATION
        J=IBUP(4,2)
        IF(J.LT.Ø)WRITE(5,*)'UNABLE TO SET IN REMOTE'
C       READ FREQUENCY ADJUST VALUE (FAV)
        J=IBUP(Ø,2,LAD,3)
        IF (J.LT.Ø) GOTO 998
        J=IBUP(1,2,ARRAY,9)
        IF (J.LT.Ø) GOTO 998
        DECODE(9,1Ø,ARRAY) FAV
1Ø      FORMAT(F7.1)
        TYPE *,'FREQUENCY ADJUST VALUE = ',FAV
C       TURN ON MARKER IF NOT ALREADY ON
        J=IBUP(Ø,2,MN1,3)
        IF(J.LT.Ø) GO TO 998
C       READ MARKER AMPLITUDE AND FREQUENCY
        J=IBUP(Ø,2,LMK,3)
        IF(J.LT.Ø) GO TO 998
        J=IBUP(1,2,ARRAY,21)
        IF(J.LT.Ø) GO TO 998
        DECODE(1Ø,15,ARRAY) MARKA
15      FORMAT(E1Ø.3)
        WRITE(5,9Ø1) MARKA
9Ø1     FORMAT(1H ,'MARKER AMPLITUDE=',E1Ø.3)
        DO 16 I=12,21
        ARRAY(I-11)=ARRAY(I)
16      CONTINUE
        DECODE(1Ø,17,ARRAY) MARKF
17      FORMAT(F1Ø.3)
        WRITE(5,9Ø2) MARKF
9Ø2     FORMAT(1H ,'MARKER FREQUENCY=',F1Ø.3)
C       READ SPAN IN HZ (ISPAN)
        J=IBUP(Ø,2,LSP,3)
        IF (J.LT.Ø) GOTO 998
```

```
        J=IBUP(1,2,ARRAY,7)
        IF (J.LT.Ø) GOTO 998
        DECODE(5,2Ø,ARRAY) ISPAN
2Ø      FORMAT(I5)
        TYPE *,'SPAN = ',ISPAN
C       READ CHANNEL A SENSITIVITY (CHAS)
        J=IBUP(Ø,2,LAS,3)
        IF (J.LT.Ø) GOTO 998
        J=IBUP(1,2,ARRAY,11)
        IF (J.LT.Ø) GOTO 998
        DECODE(9,3Ø,ARRAY) CHAS
3Ø      FORMAT(E9.2)
        TYPE *,'CHANNEL A SENSITIVITY = ',CHAS
C       READ CHANNEL B SENSITITY (CHBS)
        J=IBUP(Ø,2,LBS,3)
        IF (J.LT.Ø) GOTO 998
        J=IBUP(1,2,ARRAY,11)
        IF (J.LT.Ø) GOTO 998
        DECODE(9,3Ø,ARRAY) CHBS
        TYPE *,'CHANNEL B SENSITITY = ',CHBS
C       READ TRANSFER FUNCTION SENSITIVITY (TXS)
        J=IBUP(Ø,2,LXS,3)
        IF (J.LT.Ø) GOTO 998
        J=IBUP(1,2,ARRAY,11)
        IF (J.LT.Ø) GOTO 998
        DECODE(9,3Ø,ARRAY) TXS
        TYPE *,'TRANSFER FUNCTION SENSITIVITY = ',TXS
C       READ ALPHANUMERIC DISPLAY DATA
        J=IBUP(Ø,2,LAN,3)
        IF(J.LT.Ø) GO TO 998
        J=IBUP(1,2,ASCII,13Ø)
        IF(J .LT.Ø) GO TO 998
        DO 35 I=1,8
        LIN1(I)=ASCII(I)
        LIN2(I)=ASCII(I+8)
        LIN3(I)=ASCII(I+16)
        LIN4(I)=ASCII(I+24)
35      CONTINUE
        WRITE(5,9ØØ) (LIN1(I),I=1,8)
9ØØ     FORMAT(6H LINE=,8A4)
        WRITE(5,9ØØ) (LIN2(I),I=1,8)
        WRITE(5,9ØØ) (LIN3(I),I=1,8)
        WRITE(5,9ØØ) (LIN4(I),I=1,8)
C       ASK USER FOR THE FREQUENCY ADJUST MODE. (IFAD)
61      TYPE *,'FREQUENCY ADJUST MODES:'
        TYPE *,'[1] Ø-25KHZ SPAN'
        TYPE *,'[2] Ø START'
        TYPE *,'[3] SET CENTER'
        TYPE *,'[4] SET START'
        TYPE *,'PLEASE ENTER THE FREQUENCY ADJUST MODE.'
        ACCEPT *, IFAD
        IF (IFAD.LE.4.AND.IFAD.GE.1) GOTO 65
        TYPE *,'YOU ENTERED AN INCORRECT VALUE. PLEASE TRY AGAIN.'
        GOTO 61
65      TYPE *,'FREQENCY ADJUST MODE = ',IFAD
66      TYPE *,'WHICH SCALE IS THE ANALYZER SET ON?'
        WRITE(5,9Ø)
9Ø      FORMAT(1X,'[1] LINEAR [2] 1ØDB/DIV [3] 2DB/DIV : ',$)
        ACCEPT *, ISCALE
        IF (ISCALE.LE.3.AND.ISCALE.GE.1) GOTO 1ØØ
        TYPE *,'YOU ENTERED AN INCORRECT VALUE. PLEASE TRY AGAIN.'
        GO TO 66
1ØØ     TYPE *,'SCALE = ',ISCALE
C       ASK USER FOR CHANNEL MODES
```

```
70      TYPE *,'CHANNEL MODES: '
        TYPE *,'[1] SINGLE TRACE IN DUAL CHANNEL MODE (128 PTS)'
        TYPE *,'[2] SINGLE TRACE IN SINGLE CHANNEL MODE (256 PTS)'
        TYPE *,'[3] DUAL TRACE IN DUAL CHANNEL MODE (128 PTS EACH)'
        TYPE *,'[4] SINGLE TIME TRACE IN DUAL CHANNEL MODE (256 POINTS)'
        TYPE *,'[5] SINGLE TIME TRACE IN SINGLE CHANNEL MODE(512 POINTS)'
        WRITE(5,71)
71      FORMAT(1X,'PLEASE ENTER WHICH MODE YOU WOULD LIKE: ',$)
        ACCEPT *,IMODE
        IF (IMODE.LE.5.AND.IMODE.GE.1) GOTO 72
        TYPE *,'YOU ENTERED AN INCORRECT VALUE. PLEASE TRY AGAIN.'
        GOTO 70
72      IF(IMODE.GT.1) GO TO 74
C       IMODE=1 SINGLE TRACE IN DUAL CHANNEL MODE
        TYPE *,'TRACE TYPES: '
        TYPE *,'[1] AMPLITUDE OF CHANNEL A'
        TYPE *,'[2] AMPLITUDE OF CHANNEL B'
        TYPE *,'[3] AMPLITUDE TRANSFER FUNCTION'
        TYPE *,'[4] PHASE OF CHANNEL A'
        TYPE *,'[5] PHASE OF CHANNEL B'
        TYPE *,'[6] PHASE TRANSFER FUNCTION'
        TYPE *,'[9] COHERENCE FUNCTION'
        TYPE *,'INPUT TRACE TYPE'
        ACCEPT *,ITYPE1
        IF(ITYPE1.GE.1.AND.ITYPE.LE.6) GO TO 73
        IF(ITYPE1.EQ.9) GO TO 73
        TYPE *,'INCORRECT VALUE,REINPUT'
        GO TO 72
73      ITYPE2=0
        INUMP=128
        GO TO 83
74      IF(IMODE.GT.2) GO TO 76
C       IMODE=2 SINGLE TRACE IN SINGLE CHANNEL MODE
        TYPE *,'TRACE TYPES:'
        TYPE *,'[1] AMPLITUDE OF CHANNEL A'
        TYPE *,'[2] AMPLITUDE OF CHANNEL B'
        TYPE *,'[4] PHASE OF CHANNEL A'
        TYPE *,'[5] PHASE OF CHANNEL B'
        TYPE *,'INPUT TRACE TYPE'
        ACCEPT *,ITYPE1
        IF(ITYPE1.EQ.1) GO TO 75
        IF(ITYPE1.EQ.2) GO TO 75
        IF(ITYPE1.EQ.4) GO TO 75
        IF(ITYPE1.EQ.5) GO TO 75
        TYPE *,'INCORRECT VALUE,REINPUT'
        GO TO 74
75      ITYPE2=0
        INUMP=256
        GO TO 83
76      IF(IMODE .GT.3) GO TO 79
        IFLAG=0
C       IMODE=3 DUAL TRACE IN DUAL CHANNEL MODE
102     TYPE *,'TRACE TYPES:'
        TYPE *,'[1] AMPLITUDE OF CHANNEL A'
        TYPE *,'[2] AMPLITUDE OF CHANNEL B'
        TYPE *,'[3] AMPLITUDE TRANSFER FUNCTION'
        TYPE *,'[4] PHASE OF CHANNEL A'
        TYPE *,'[5] PHASE OF CHANNEL B'
        TYPE *,'[6] PHASE TRANSFER FUNCTION'
        TYPE *,'[9] COHERENCE FUNCTION'
        IF(IFLAG.EQ.0) TYPE *,'INPUT TRACE #1 TYPE'
        IF(IFLAG.EQ.1) TYPE *,'INPUT TRACE #2 TYPE'
        ACCEPT *,ITYPE
        IF((ITYPE.GE.1).AND.(ITYPE.LE.6)) GO TO 77
```

```
      IF(ITYPE.EQ.9) GO TO 77
      TYPE *,'INCORRECT VALUE,REINPUT'
      GO TO 102
77    IF(IFLAG.EQ.1) GO TO 78
      ITYPE1=ITYPE
      IFLAG=1
      GO TO 102
78    ITYPE2=ITYPE
      INUMP=256
      GO TO 83
79    IF(IMODE.GT.4) GO TO 81
C     IMODE=4 SINGLE TIME TRACE IN DUAL CHANNEL MODE
      TYPE *,'TRACE TYPES:'
      TYPE *,'[7] TIME TRACE OF CHANNEL A'
      TYPE *,'[8] TIME TRACE OF CHANNEL B'
      ACCEPT *,ITYPE1
      IF(ITYPE1.EQ.7) GO TO 80
      IF(ITYPE1.EQ.8) GO TO 80
      TYPE *,'INCORRECT VALUE,REINPUT'
      GO TO 79
80    ITYPE2=0
      INUMP=256
      GO TO 83
C     IMODE=5 SINGLE TIME TRACE IN SINGLE CHANNEL MODE
81    TYPE *,'TRACE TYPES:'
      TYPE *,'[7] TIME TRACE OF CHANNEL A'
      TYPE *,'[8] TIME TRACE OF CHANNEL B'
      ACCEPT *,ITYPE1
      IF(ITYPE1.EQ.7) GO TO 82
      IF(ITYPE1.EQ.8) GO TO 82
      TYPE *,'INCORRECT VALUE,REINPUT'
      GO TO 81
82    ITYPE2=0
      INUMP=512
C     READ POINTS FROM ANALYZER (INUMP POINTS) (DATA STORED IN ARRAY POINTS)
83    NBYTES=INUMP*10+1
C     NOTE THAT THERE IS NO ERROR CHECKING FOR THIS READ---
C     FOR SOME REASON, THE EXTRA TIME DELAY INVOLVED IN THIS CAUSES
C     A TIME-OUT ERROR ON THE BUS READ.
C     IF IMODE=4,5 THEN SET TIME FUNCTION ON
      IF(ITYPE1.EQ.7) J=IBUP(0,2,TA1,3)
      IF(ITYPE1.EQ.8) J=IBUP(0,2,TB1,3)
      J=IBUP(0,2,LDS,3)
C     J=IBUP(6,2)
C     WRITE(5,*)'J=',J
C     READ RETURNED ARRAY
      J=IBUP(1,2,POINTS,NBYTES)
      WRITE(5,*) '# OF BYTES READ=',J
C     TURN OFF TIME FUNCTION
      IF(ITYPE1.EQ.7) J=IBUP(0,2,TA0,3)
      IF(ITYPE1.EQ.8) J=IBUP(0,2,TB0,3)
C     FINISH USE OF GPIB BUS
      J=IBUP(10)
      IF(J.LT.0)WRITE(5,*)'UNABLE TO TERMINATE USAGE OF GPIB AFTER USE'
C     TRACE CONVERSION OF POINTS TO AN ARRAY OF NUMBERS
      ICOUNT = 0
      DO 101 I=1,INUMP
C     XPART IS THE PERCENTAGE OF THE DISTANCE GONE ON THE X-AXIS
      IF(IMODE.EQ.3) GO TO 221
      XPART =FLOAT(I-1)/FLOAT(INUMP-1)
      GO TO 222
221   IF(I.LE.128) XPART=FLOAT(I-1)/127.
      IF(I.GT.128) XPART=FLOAT(I-129)/127.
C     ASSIGN BYATES TO SPECIAL ARRAY TO BE DECODED.
```

```
222     DO 11Ø J=1,9
        TEMPY(J)=POINTS(ICOUNT+J)
11Ø     CONTINUE
C       INCREMENT COUNT OF BYTES ALREADY DECODED.
        ICOUNT=ICOUNT + 1Ø
        DECODE(9,2ØØ,TEMPY) YPART
2ØØ     FORMAT(E1Ø.3)
        X(I) = XPART
        Y(I) = YPART
1Ø1     CONTINUE
C25Ø     TYPE *,'POINTS DATA = '
C       DO 3ØØ I= 1,INUMP
C3ØØ     TYPE *,I,' X = ',X(I),' Y = ',Y(I)
C       CALCULATE SCALING INFORMATION FOR PLOTTING
C       HORIZONTAL SCALING
        IF(IMODE.GE.4) GO TO 325
C       IFAD=1,2
        IF(IFAD.GT.2) GO TO 31Ø
        FX=Ø.
        DX=FLOAT(ISPAN)/5./2.
        GO TO 33Ø
C       IFAD=3
31Ø     IF(IFAD.GT.3) GO TO 32Ø
        FX=FAV-FLOAT(ISPAN)/2.
        DX=FLOAT(ISPAN)/5./2.
        GO TO 33Ø
C       IFAD=4
32Ø     FX=FAV
        DX=FLOAT(ISPAN)/5./2.
        GO TO 33Ø
C       HORIZONTAL TIME SCALING(IN MILLISECONDS)
325     IF(IMODE.EQ.5) GO TO 326
        FX=Ø.
        DX=25./FLOAT(ISPAN)/2.*1ØØØ.
        GO TO 33Ø
326     FX=Ø.
        DX=5Ø./FLOAT(ISPAN)/2.*1ØØØ.
C       VERTICAL SCALING
33Ø     IFLAG=Ø
331     IF(IFLAG.EQ.Ø) ITYPE=ITYPE1
        IF(IFLAG.EQ.1) ITYPE=ITYPE2
        IF(ISCALE.GT.1) GO TO 34Ø
C       LINEAR SCALING
        IF(ITYPE.LE.3) FY=Ø.
        IF(ITYPE.GE.4) FY=-2ØØ.
        IF(ITYPE.GE.7) FY=-1.
        IF(ITYPE.EQ.9) FY=Ø.
        IF(ITYPE.EQ.Ø) DY=Ø.
        IF(ITYPE.EQ.1) DY=CHAS/8.
        IF(ITYPE.EQ.2) DY=CHBS/8.
        IF(ITYPE.EQ.3) DY=TXS/8.
        IF(ITYPE.GT.3) DY=5Ø.
        IF(ITYPE.GE.7) DY=.25
        IF(ITYPE.EQ.9) DY=.125
        GO TO 36Ø
C       1ØdB SCALING
34Ø     IF(ISCALE.GT.2) GO TO 35Ø
        IF(ITYPE.EQ.Ø) FY=Ø.
        IF(ITYPE.EQ.1) FY=CHAS-8Ø.
        IF(ITYPE.EQ.2) FY=CHBS-8Ø.
        IF(ITYPE.EQ.3) FY=TXS-8Ø.
        IF(ITYPE.GE.4) FY=-2ØØ.
        IF(ITYPE.GE.7) FY=-1.
        IF(ITYPE.EQ.9) FY=Ø.
```

```
      IF(ITYPE.EQ.Ø) DY=Ø.
      IF(ITYPE.EQ.1) DY=1Ø.
      IF(ITYPE.EQ.2) DY=1Ø.
      IF(ITYPE.EQ.3) DY=1Ø.
      IF(ITYPE.GE.4) DY=5Ø.
      IF(ITYPE.GE.7) DY=.25
      IF(ITYPE.EQ.9) DY=.125
      GO TO 36Ø
C     2dB SCALING
35Ø   IF(ITYPE.EQ.Ø) FY=Ø.
      IF(ITYPE.EQ.1) FY=CHAS-16.
      IF(ITYPE.EQ.2) FY=CHBS-16.
      IF(ITYPE.EQ.3) FY=TXS-16
      IF(ITYPE.GE.4) FY=-2ØØ.
      IF(ITYPE.GE.7) FY=-1.
      IF(ITYPE.EQ.9) FY=Ø.
      IF(ITYPE.EQ.Ø) DY=Ø.
      IF(ITYPE.EQ.1) DY=2.
      IF(ITYPE.EQ.2) DY=2.
      IF(ITYPE.EQ.3) DY=2.
      IF(ITYPE.GE.4) DY=5Ø.
      IF(ITYPE.GE.7) DY=.25
      IF(ITYPE.EQ.9) DY=.125
36Ø   IF(IFLAG.EQ.Ø) FY1=FY
      IF(IFLAG.EQ.1) FY2=FY
      IF(IFLAG.EQ.Ø) DY1=DY
      IF(IFLAG.EQ.1) DY2=DY
      IF(IFLAG.EQ.1) GO TO 361
      IF(IFLAG.EQ.Ø) IFLAG=1
      GO TO 331
361   WRITE(5,*) 'PLOTTING SCALING PARAMETERS'
      WRITE(5,*) 'FX=',FX
      WRITE(5,*) 'DX=',DX
      WRITE(5,*) 'FY1=',FY1
      WRITE(5,*) 'DY1=',DY1
      WRITE(5,*) 'FY2=',FY2
      WRITE(5,*) 'DY2=',DY2
C     RESCALE HORIZONTAL STATIONS
      IF(IMODE.EQ.3) GO TO 37Ø
      DO 365 I=1,INUMP
      X(I)=FX+X(I)*(5.*DX*2.)
C     TYPE *,I,'   ','X=',X(I),'   ','Y=',Y(I)
365   CONTINUE
      GO TO 38Ø
37Ø   DO 375 I=1,128
      X(I)=FX+X(I)*(5.*DX*2.)
      X(I+128)=X(I)
375   CONTINUE
      DO 376 I=1,INUMP
C     TYPE *,I,'   ','X=',X(I),'   ','Y=',Y(I)
376   CONTINUE
38Ø   TYPE *,'INPUT NOTES ON DATA(<128 CHARACTERS)'
      ACCEPT 9Ø8,(NOTES(I),I=1,32)
9Ø8   FORMAT(32A4)
      TYPE *,'INPUT FILENAME FOR STORAGE(XXX:XXXXXXXX.XXX)'
      ACCEPT 9Ø7,(FNAME(I),I=2,17)
9Ø7   FORMAT(16A1)
C     STORE DATA IN FILE XXX:XXXXXXXX.XXX
      OPEN(UNIT=4,NAME=FNAME,TYPE='NEW')
      WRITE(4,*) FAV
      WRITE(4,*) ISPAN
      WRITE(4,*) CHAS
      WRITE(4,*) CHBS
      WRITE(4,*) TXS
```

```
      WRITE(4,*) IFAD
      WRITE(4,*) IMODE
      WRITE(4,*) ICHAN
      WRITE(4,*) INUMP
      WRITE(4,*) ISCALE
      WRITE(4,*) ITYPE1,ITYPE2
      WRITE(4,*) MARKA,MARKFB
      WRITE(4,978) LIN1,LIN2,LIN3,LIN4
978   FORMAT(32A4)
      WRITE(4,978) NOTES
      WRITE(4,*) FX,DX
      WRITE(4,*) FY1,DY1,FY2,DY2
      DO 800 I = 1, INUMP
800   WRITE(4,*) I,X(I), Y(I)
      CLOSE(UNIT=4)
C     FINISH
C     RETURN ANALYZER TO LOCAL CONTROL AND CLEAR BUS LINES.
      J=ICLR([illegible]
      J=IBUP(10)
      GOTO 999
C     IN CASE OF ERRORS....
C     (MOST COMMON ERROR INVOLVES TIMING PROBLEMS--- IN THIS CASE,
C     YOU WILL GET AN INPUT CONVERSION ERROR BECAUSE DATA WAS NOT
C     READ COMPLETELY BY DEVICE DRIVER.)
998   TYPE*,'THERE WAS AN ERROR INVOLVING THE SPECTRUM ANALYZER.'
      TYPE*,'ERROR NUMBER = ',J
      TYPE*,'PLEASE TRY RUNNING THIS PROGRAM AGAIN.'
999   STOP
      END
```

```
C       PROGRAM IBPLOT2
C       PROGRAM READS DATA STORED IN FILE SPEC.DAT FROM SPECTRUM ANALYZER
C       AND PLOTS IT USING VERSAPLOT SOFTWARE
        DIMENSION X(514),Y(514),X1(258),Y1(258),Y2(258),X2(258)
C       FILE NAME FOR DATA.
        REAL*4 MARKA,MARKF,LIN1(8),LIN2(8),LIN3(8),LIN4(8),NOTES(32)
        REAL*4 XTEX(10)
        BYTE XLAB(40),XLAB1(40),XLAB2(40),YLAB(40),YLAB1(40),YLAB2(40)
        BYTE YLAB3(40),YLAB4(40),YLAB5(40),YLAB6(40),YLAB7(40),YLAB8(40)
        BYTE FNAME(18),DB(11),TF(40),CYN,YLAB9(40)
        DATA NUL/0/
        DATA FNAME/' ',3*'X',':',8*'X','.',3*'X',0/
        DATA XLAB1/10*' ','F','R','E','Q','U','E','N','C','Y','(',
     1  'H','Z',')',17*' '/
        DATA XLAB2/10*' ','T','I','M','E','(','M','I','L','L',
     1  'I','S','E','C','O','N','D','S',')',12*' '/
        DATA YLAB1/10*' ','C','H','A','N','N','E','L',' ','A',' ','A',
     1  'M','P','L','I','T','U','D','E','(','V','O','L','T','S',' ','R',
     2  'M','S',')'/
        DATA YLAB2/10*' ','C','H','A','N','N','E','L',' ','B',' ','A',
     1  'M','P','L','I','T','U','D','E','(','V','O','L','T','S',' ','R',
     2  'M','S',')'/
        DATA YLAB3/10*' ','A','M','P','L','I','T','U','D','E',' ','T','R',
     1  'A','N','S','F','E','R',' ','F','U','N','C','T','I','O','N',
     2  3*' '/
        DATA YLAB4/10*' ','C','H','A','N','N','E','L',' ','A',' ','P','H',
     1  'A','S','E','(','D','E','G','R','E','E','S',')',6*' '/
        DATA YLAB5/10*' ','C','H','A','N','N','E','L',' ','B',' ','P','H',
     1  'A','S','E','(','D','E','G','R','E','E','S',')',6*' '/
        DATA YLAB6/10*' ','P','H','A','S','E',' ','T','R','A','N','S','F',
     1  'E','R',' ','F','U','N','C','T','I','O','N',7*' '/
        DATA DB/'(','D','B','V',' ','R','M','S',')',2*' '/
        DATA TF/10*' ','T','I','M','E',' ','F','U','N','C','T','I','O','N',
     1  ' ','A','M','P','L','I','T','U','D','E',7*' '/
        DATA YLAB9/10*' ','C','O','H','E','R','E','N','C','E',' ','F','U',
     1  'N','C','T','I','O','N',12*' '/
        DATA LMASK1/"104210/,LMASK2/"125252/
        TYPE *,'ENTER FILENAME OF SPECTRUM ANALYZER DATA(XXX:XXXXXXXX.XXX)'
        ACCEPT 907,(FNAME(I),I=2,17)
907     FORMAT(16A1)
C       READ THE DATA FROM THE DATA FILE
        OPEN(UNIT=4,NAME=FNAME,TYPE='OLD')
C       SET-UP VARIABLES: (SEE IBPROG2.FTN)
        READ(4,*) FAV
        READ(4,*) ISPAN
        READ(4,*) CHAS
        READ(4,*) CHBS
        READ(4,*) TXS
        READ(4,*) IFAD
        READ(4,*) IMODE
        READ(4,*) ICHAN
        READ(4,*) INUMP
        READ(4,*) ISCALE
        READ(4,*) ITYPE1,ITYPE2
        READ(4,*) MARKA,MARKF
        READ(4,947) LIN1,LIN2,LIN3,LIN4
947     FORMAT(32A4)
        READ(4,947) NOTES
        READ(4,*) FX,DX
        READ(4,*) FY1,DY1,FY2,DY2
C       READ DATA POINTS
        DO 800 I = 1, INUMP
800     READ(4,*) INC,X(I), Y(I)
        CLOSE(UNIT=4)
```

```
C       TYPE OUT DATA
        TYPE 9Ø9,(NOTES(I),I=1,32)
9Ø9     FORMAT(1H ,32A4)
        TYPE *,'FREQUENCY ADJUST VALUE = ',FAV
        TYPE *,'SPAN = ',ISPAN
        TYPE *,'CHANNEL A SENSITIVITY = ',CHAS
        TYPE *,'CHANNEL B SENSITITY = ',CHBS
        TYPE *,'TRANSFER FUNCTION SENSITIVITY = ',TXS
        TYPE *,'FREQENCY ADJUST MODE = ',IFAD
        TYPE *,'MODE = ',IMODE,'  CHANNEL = ',ICHAN
        TYPE *,'NUMBER OF POINTS = ',INUMP
        TYPE *,'SCALE = ',ISCALE
        TYPE *,'ITYPE1= ',ITYPE1
        TYPE *,'ITYPE2= ',ITYPE2
        TYPE *,'MARKER AMPLITUDE= ',MARKA
        TYPE *,'MARKER FREQUENCY= ',MARKF
        WRITE(5,9Ø4) (LIN1(I),I=1,8)
9Ø4     FORMAT(6H LINE=,8A4)
        WRITE(5,9Ø4) (LIN2(I),I=1,8)
        WRITE(5,9Ø4) (LIN3(I),I=1,8)
        WRITE(5,9Ø4) (LIN4(I),I=1,8)
        TYPE *,'FX=',FX,'  DX=',DX
        TYPE *,'FY1=',FY1,'  DY1=',DY1
        TYPE *,'FY2=',FY2,'  DY2=',DY2
        TYPE 792
792     FORMAT(' DO YOU WANT TO PLOT THIS RECORD?',$)
        ACCEPT 7Ø1, CYN
        IF(CYN.NE.'Y') GO TO 791
C       CONVERT TO DECIBEL UNIT LABELS IF REQUIRED
        IF(ISCALE.EQ.1) GO TO 38
        DO 35 I=1,11
        YLAB1(29+I)=DB(I)
        YLAB2(29+I)=DB(I)
35      CONTINUE
C       PLOT SECTION
38      INUM = INUMP
C       IF TWO CHANNELS, ONLY 128 POINTS EACH.
        IF (IMODE.EQ.3) INUM = 128
        IF (IMODE.NE.3) GOTO 11
C       IF TWO CHANNELS, SPLIT DATA INTO TWO SEPARATE ARRAYS.
        DO 277 I = 1, INUM
        X1(I)= X(I)
        X2(I)= X(I)
        Y1(I) = Y(I)
277     Y2(I) = Y(I+128)
11      TYPE 278
278     FORMAT(1H ,'DO YOU WANT THE DATA TYPED OUT?',$)
        ACCEPT 7Ø1,CYN
        IF(CYN.EQ.'N') GO TO 2Ø5
28Ø     TYPE *,'POINTS DATA = '
        DO 3Ø2 I= 1,INUM
        IF (IMODE.NE.3) GOTO 3Ø3
        TYPE *,I,' XA=',X1(I),' YA=',Y1(I),' XB=',X2(I),' YB=',Y2(I)
        GOTO 3Ø2
3Ø3     TYPE *,I,' X =',X(I),' Y =',Y(I)
3Ø2     CONTINUE
2Ø5     WRITE(5,22Ø)
22Ø     FORMAT(1X,'PLEASE ENTER THE PLOTTING DEVICE NUMBER (Ø-6): ',$)
C       (3) = VT1ØØ
C       (5) = VISUAL 5ØØ
C       (6) = PEN-PLOTTER.
        ACCEPT *, ILDEV
        IF (ILDEV.GE.Ø.AND.ILDEV.LE.6) GOTO 225
        TYPE *,'YOU ENTERED AN INCORRECT VALUE. PLEASE TRY AGAIN.'
```

```
      GOTO 2Ø5
225   XLEN=1Ø.
      YLEN=8.
      TYPE *,'INPUT PLOTTING SCALE FACTOR(USE 1=TERMINAL,.575=VERSATEC)'
      ACCEPT *,SFACT
      CALL PLOTS(Ø,Ø,ILDEV)
C     MOVE FROM EDGE OF SCREEN
      CALL PLOT(1.28,1.25,-3)
      CALL FACTOR(SFACT)
C     TWO CHANNELS--REQUIRES DIFFERENT AXES.
      IF (IMODE.EQ.3) GOTO 5ØØ
C     SINGLE TRACE SCALING
      X(INUM+1) = FX
      X(INUM+2) = DX
      Y(INUM+1) = FY1
      Y(INUM+2) = DY1
C     SINGLE TRACE LABELING
      DO 121 I=1,4Ø
      IF(ITYPE1.EQ.1) YLAB(I)=YLAB1(I)
      IF(ITYPE1.EQ.2) YLAB(I)=YLAB2(I)
      IF(ITYPE1.EQ.3) YLAB(I)=YLAB3(I)
      IF(ITYPE1.EQ.4) YLAB(I)=YLAB4(I)
      IF(ITYPE1.EQ.5) YLAB(I)=YLAB5(I)
      IF(ITYPE1.EQ.6) YLAB(I)=YLAB6(I)
      IF(ITYPE1.EQ.7) YLAB(I)=TF(I)
      IF(ITYPE1.EQ.8) YLAB(I)=TF(I)
      IF(ITYPE1.EQ.9) YLAB(I)=YLAB9(I)
      IF(IMODE.GE.4) XLAB(I)=XLAB2(I)
      IF(IMODE.LT.4) XLAB(I)=XLAB1(I)
121   CONTINUE
C     DRAW SINGLE TRACE AXIS
      CALL AXIS(Ø.,Ø.,XLAB,-4Ø,XLEN,Ø.,X(INUM+1),X(INUM+2))
      CALL AXIS(Ø.,Ø.,YLAB,4Ø,YLEN,9Ø.,Y(INUM+1),Y(INUM+2))
C     DRAW DATA POINTS FOR SINGLE TRACE
13Ø   CALL LINE(X,Y,INUM,1,1,Ø)
      GOTO 999
C     DUAL TRACE SCALING
5ØØ   X1(INUM+1)=FX
      X1(INUM+2)=DX
      Y1(INUM+1)=FY1
      Y1(INUM+2)=DY1
      Y2(INUM+1)=FY2
      Y2(INUM+2)=DY2
C     DUAL TRACE X-AXIS
      CALL AXIS(Ø.,Ø.,XLAB1,-4Ø,XLEN,Ø.,X1(INUM+1),X1(INUM+2))
C     IF (ISCALE.GE.2) GOTO 399
C     DUAL TRACE AXIS LABELING
      DO 5Ø1 I=1,4Ø
      IF(ITYPE1.EQ.1) YLAB(I)=YLAB1(I)
      IF(ITYPE1.EQ.2) YLAB(I)=YLAB2(I)
      IF(ITYPE1.EQ.3) YLAB(I)=YLAB3(I)
      IF(ITYPE1.EQ.4) YLAB(I)=YLAB4(I)
      IF(ITYPE1.EQ.5) YLAB(I)=YLAB5(I)
      IF(ITYPE1.EQ.6) YLAB(I)=YLAB6(I)
      IF(ITYPE1.EQ.9) YLAB(I)=YLAB9(I)
5Ø1   CONTINUE
C     DRAW VERTICAL AXIS #1
      CALL AXIS(Ø.,Ø.,YLAB,4Ø,8.Ø,9Ø.,Y1(INUM+1),Y1(INUM+2))
      DO 5Ø2 I=1,4Ø
      IF(ITYPE2.EQ.1) YLAB(I)=YLAB1(I)
      IF(ITYPE2.EQ.2) YLAB(I)=YLAB2(I)
      IF(ITYPE2.EQ.3) YLAB(I)=YLAB3(I)
      IF(ITYPE2.EQ.4) YLAB(I)=YLAB4(I)
      IF(ITYPE2.EQ.5) YLAB(I)=YLAB5(I)
```

```
      IF(ITYPE2.EQ.6) YLAB(I)=YLAB6(I)
      IF(ITYPE2.EQ.9) YLAB(I)=YLAB9(I)
502   CONTINUE
C     DRAW VERTICAL AXIS #2
      CALL AXIS(10.,0.,YLAB,-40,8.0,90.,Y2(INUM+1),Y2(INUM+2))
C     PLOT DUAL TRACE DATA (SEE VERSAPLOT MANUAL FOR DETAILS.)
400   CALL LINE(X1,Y1,128,1,1,0)
      CALL LINE(X1,Y2,128,1,1,1)
      GOTO 999
998   TYPE *,'THERE WAS AN ERROR IN READING THE DATAFILE'
      TYPE *,'PLEASE TRY AGAIN OR VERIFY THAT THE FILE EXISTS.'
C     FINISH
999   CONTINUE
C     ADD NOTES TO PLOT
699   TYPE 700
700   FORMAT(' DO YOU WANT TO ADD A LINE OF TEXT TO PLOT ?',$)
      ACCEPT 701,CYN
701   FORMAT(A1)
      IF(CYN.NE.'Y') GO TO 750
      TYPE 702
702   FORMAT(' ENTER TEXT')
      ACCEPT 703,(XTEX(I),I=1,10)
703   FORMAT(10A4)
      TYPE 704
704   FORMAT(' ENTER TEXT POSITION(PLOTTING UNITS):X,Y=',$)
      ACCEPT *,XPOS,YPOS
      TYPE 705
705   FORMAT(' ENTER TEXT HEIGHT(PLOTTING UNITS): ',$)
      ACCEPT *,TEXHT
      CALL SYMBOL(XPOS,YPOS,TEXHT,XTEX,0.,40)
      GO TO 699
C     SYMBOL KEY SECTION
750   WRITE(5,751)
751   FORMAT(1H ,'DO YOU WANT A SYMBOL KEY ON GRAPH?',$)
      ACCEPT 701,CYN
      IF(CYN.NE.'Y') GO TO 790
      WRITE(5,752)
752   FORMAT(1H ,'INPUT KEY TEXT HEIGHT(PLOTTING UNITS):',$)
      ACCEPT *,TEXHT
      ISYM=0
753   WRITE(5,754)
754   FORMAT(1H ,'ENTER KEY LABEL POSITION(PLOTTING UNITS):X,Y',$)
      ACCEPT *,XPOS,YPOS
      CALL SYMBOL(XPOS,YPOS,TEXHT,ISYM,0.,-1)
      CALL SYMBOL(999.,999.,TEXHT,1H-,0.,0)
      WRITE(5,755) ISYM+1
755   FORMAT(1H ,'ENTER LABEL #',I2,':',$)
      ACCEPT 703,(XTEX(I),I=1,10)
      CALL SYMBOL(999.0,999.0,TEXHT,XTEX,0.,40)
      ISYM=ISYM+1
      IF((ISYM.EQ.1).AND.(IMODE.EQ.3)) GO TO 753
C     ADD GRID ON PLOT
      WRITE(5,793)
793   FORMAT(1H ,'DO YOU WANT A GRID?',$)
      ACCEPT 701,CYN
      IF(CYN.EQ.'N') GO TO 790
      XPOS=0.
      YPOS=0.
      NX=10
      NY=8
      XD=1.
      YD=1.
      LMASK=LMASK2
      CALL GRID(XPOS,YPOS,NX,XD,NY,YD,LMASK)
```

```
      XPOS=Ø.
      YPOS=Ø.
      NX=1ØØ
      NY=8Ø
      XD=.1
      YD=.1
      LMASK=LMASK1
      CALL GRID(XPOS,YPOS,NX,XD,NY,YD,LMASK)
C     TERMINATE PLOTTING.
79Ø   CALL PLOT(Ø.,Ø.,+999)
791   STOP
      END
```

```
C THIS PROGRAM SAMPLES THE DATA AT A FREQUENCY PROVIDED BY THE EXTERNAL
C CLOCK.
        DIMENSION IOUT(17000)
        WRITE(5,*)'ENTER DESIRED NO. OF DATA PTS TO BE COLLECTED(<17000)'
        READ(5,*)IN
        WRITE(5,*)'IN BEFORE A/D:',IN
        CALL SAMPLE(IN,IOUT)
        WRITE(5,*)'IN AFTER A/D:',IN
        OPEN(UNIT=4,NAME='DATA.DAT',TYPE='NEW',FORM='UNFORMATTED')
        WRITE(4)IN,(IOUT(I),I=1,IN)
        CLOSE(UNIT=4)
        END
```

```
C       PROGRAM RETDATA2
C       DECODES OUTPUT OF A/D PROGRAM FREQ
C       17000 POINTS MAX SIZE
        INTEGER IN*2
        VIRTUAL IN(17000)
        OPEN(UNIT=4,NAME='DATA.DAT',TYPE='OLD',FORM='UNFORMATTED')
        READ(4) NPT,(IN(I),I=1,NPT)
        CLOSE(UNIT=4)
        WRITE(5,*) 'NO. OF DATA POINTS:',NPT
        WRITE(5,*) 'DO YOU WANT NUMBERS OUTPUT(1=YES,0=NO)'
        ACCEPT*,NW
        DO 10 I=1,NPT
        IOUT=IN(I)
        CALL RETRVA(IOUT,IADDR,IDATA)
C       A/D RANGE:-5.12 TO 5.12 VOLTS
C       CONVERT A/D OUTPUT TO VOLTS
        DATA=(IDATA-2048)*5.12/2048
C       CONVERT A/D OUTPUT TO .5 MILLIVOLT UNITS(.5mV=1)
        IN(I)=(IDATA-2048)*5
        IF(NW .EQ. 1) WRITE(5,900) I,IADDR,DATA
900     FORMAT(1H ,' NPT=',I5,5X,'CHANNEL=',I3,5X,'DATA(VOLTS)=',F8.4)
10      CONTINUE
        OPEN(UNIT=4,NAME='OUT.DAT',TYPE='NEW',FORM='UNFORMATTED')
        WRITE(4) NPT,(IN(I),I=1,NPT)
        CLOSE(UNIT=4)
        STOP
        END
```

```
C        PROGRAM DMPLEX4
C        F77
C        THIS PROGRAM READS FILE DATA.DAT CREATED BY FREQ2 AND
C        DEMULTIPLEXES IT TO OBTAIN THE DESIRED CHANNEL VOLTAGES FROM
C        THE ANALOGIC MP6912 HIGH SPEED DATA ACQUISITION MODULE.
C        THE ORIGINAL VERSION DMPLEX WORKS ONLY IF THERE ARE NO
C        A/D CHANNEL SKIPPING OR OTHER PROBLEMS.  THIS VERSION
C        WILL USE CHANNEL INFO IN DATA FILE TO SORT DATA INTO PLOT FILES.
C        THE PLOT FILES ARE FORMATTED AND USE PLOTMANY FOR PLOTTING
C        TWO PLOT FILES ARE CREATED:
C          a)DL2:ADCPLT[ICHAN].[IRUN] - CHANNEL VARIABLE VS TIME PLOT FILES
C          b)DL2:ADSURGE.[IRUN] - SURGE CYCLE PLOT FILE
C        IF SKIPPING ERRORS ARE OCCURING THEN TIMING INFORMATION WILL
C        BE SOMEWHAT IN ERROR BUT OVERALL DATA SET WILL BE USABLE AS
C        LONG AS THE A/D STROBING RATE IS NOT A MULTIPLE OF THE 6Ø HZ
C        FREQUENCY.  THE SKIPPING SEEMS TO OCCUR AT THIS FREQUENCY
C        VARIABLES:
C        NCHAN=# OF DESIRED A/D CHANNEL(Ø-15)
C        NSCAN=TOTAL NUMBER OF A/D CHANNELS SCANNED(Ø-15)
C        NPT=NUMBER OF POINTS IN INPUT FILE(17ØØØ MAX)
C        FSAMP=A/D STROBING RATE(HZ)
C        JMAX(NCHAN)=NUMBER OF POINTS FOR CHANNEL NCHAN
C        CURVEFIT COEFFICIENTS
C        ARRAY ELEMENT NCHAN=A/D CHANNEL + 1
C        1=HOTWIRE
C        2=KULITE #1
C        3=KULITE #2
C        :
C        :
C        1Ø=KULITE #9
C        WRITTEN 1/25/84 DAVID A. FINK
C        MODIFIED 4/18/84 D. A. FINK
         REAL*4 MFLO,MVDATA(8),CDATA(8),DMIN(16),DMAX(16),RTIME(16)
         VIRTUAL XCF(18ØØ),YPR(18ØØ)
         INTEGER*2 H(25Ø),JMAX(16),ERR(16)
         INTEGER*2 FTAG(1Ø),NAME(5),IDATE(5),ITIME(4)
         BYTE FILE(3Ø),ANSWER,ANS2,CCHAN(2),CRUN(3),SCFILE(3Ø)
         BYTE COMMNT(68),SRUN(3),CHRUN(3),ADCHAN(2),CHFILE(3Ø)
         CHARACTER*68 COM2(1Ø),COM3
         LOGICAL*2 ANS
         VIRTUAL IN(17ØØØ)
         COMMON/A/ PØ,TØ,PREF,TREF
         EQUIVALENCE (FTAG(1),H(25))
         EQUIVALENCE (NAME,H),(IDATE(1),H(11)),(ITIME(1),H(21))
         EQUIVALENCE (SCALE,H(4Ø)),(ZERO,H(42)),(CCHAN,FILE(12))
         EQUIVALENCE (CRUN,FILE(15)),(SRUN,SCFILE(14))
         EQUIVALENCE (ADCHAN,CHFILE(12)),(CHRUN,CHFILE(15))
         DATA NUL/Ø/
         DATA FILE/' ','D','L','2',':','A','D','C','H','A','N',
      1  2*' ','.',16*Ø/
         DATA SCFILE/' ','D','L','2',':','A','D','S','U','R',
      1  'G','E','.',3*' ',14*Ø/
         DATA CHFILE/' ','D','L','2',':','A','D','C','P','L','T',
      1  2*' ','.',16*Ø/
         DATA COMMNT/'S','U','R','G','E',' ','C','Y','C','L',
      1  'E',' ','P','A','T','H',52*Ø/
         DATA COM2(1)/
      1  'CORRECTED MASSFLOW(LBM/MIN) VS TIME(MILLISECONDS)'/
         DATA COM2(2)/
      1  'K2 @ Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
         DATA COM2(3)/
      1  'K3 @ Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
         DATA COM2(4)/
      1  'K4 @ Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
```

```
      DATA COM2(5)/
     1 'K6 @ Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
      DATA COM2(6)/
     1 'K2 @ 9Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
      DATA COM2(7)/
     1 'K3 @ 9Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
      DATA COM2(8)/
     1 'K4 @ 9Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
      DATA COM2(9)/
     1 'K6 @ 9Ø DEG STATIC PRESSURE RATIO VS TIME(MILLISECONDS)'/
      DATA COM2(1Ø)/'PLENUM PRESSURE RATIO VS TIME(MILLISECONDS)'/
      DATA COM3/
     1 'CHANNEL VOLTAGE(VOLTS) VS TIME(MILLISECONDS)'/
      DATA JMAX/16*Ø/
      DATA ERR/16*Ø/
      DATA DMIN/16*1.ØE38/
      DATA DMAX/16*-1.ØE38/
C     TREF=545.
C     PREF=14.69*144.
      WRITE(5,*) 'INPUT DATA RUN NUMBER'
      ACCEPT*,IRUN
      WRITE(5,*) 'INPUT NUMBER OF CHANNELS SCANNED'
      ACCEPT*,NSCAN
      WRITE(5,*) 'INPUT CLOCKRATE(HZ)'
      ACCEPT*,FSAMP
      WRITE(5,1ØØØ)
1ØØØ  FORMAT(1H ,'INPUT DESIRED PLOT FILE FORMAT',/,
     1 ' Ø=PLOTMANY COMPATIBLE',/,
     2 ' 1=NEW G.T.L. MTRACE COMPATIBLE(NOT WORKING YET)')
      ACCEPT*,IFORM
      WRITE(5,*) 'DO YOU WANT PLOT VARIABLES SCALED?1=SCALED Ø=VOLTS'
      ACCEPT*,NSCALE
C     WRITE(5,*) 'INPUT AMBIENT PRESSURE(PSIA) FOR RUN'
C     ACCEPT*,PØ
C     PØ=PØ*144.
C     WRITE(5,*) 'INPUT AMBIENT TEMP(DEG F)'
C     ACCEPT*,TØ
C     TØ=TØ+459.688
C     READ AMBIENT TEST INFORMATION
      OPEN(UNIT=4,NAME='AMB.DAT',TYPE='OLD',FORM='UNFORMATTED')
      READ(4) PØ,TØ,PREF,TREF
      CLOSE(UNIT=4)
C     READ A/D DATA FILE
      OPEN(UNIT=4,NAME='DATA.DAT',TYPE='OLD',FORM='UNFORMATTED')
      READ(4) NPT,(IN(I),I=1,NPT)
      CLOSE(UNIT=4)
      LU=5
      WRITE(LU,9Ø7)
9Ø7   FORMAT(1H1)
      WRITE(LU,*) 'RUN #=',IRUN
      WRITE(LU,*) 'A/D RAW DATA(MILLIVOLTS)'
      WRITE(LU,*) 'NUMBER OF POINTS=',NPT
      WRITE(LU,*) '# OF CHANNELS SCANNED=',NSCAN
      WRITE(LU,*) 'CLOCKRATE(HZ)=',FSAMP
      RT=FLOAT(NPT-1)*1ØØØ./FSAMP
      WRITE(LU,*) 'RECORD TIME LENGTH(MILLISECONDS)=',RT
      WRITE(LU,*) 'PØ(PSIA)=',PØ/144.
      WRITE(LU,*) 'TØ(DEG F)=',TØ-459.688
      WRITE(5,*) 'DO YOU WANT DATA TYPED?(Y OR N)'
      ACCEPT 9Ø4,ANS2
9Ø4   FORMAT(A1)
      IF(ANS2.EQ.'N') GO TO 4
C
C     PRINT RAW UNMULTIPLEXED DATA
```

```
        WRITE(5,*) 'INPUT LOGICAL UNIT NUMBER TERM=5,LP=6'
        ACCEPT*,LU
        IF(LU.EQ.5) GO TO 77
        WRITE(LU,907)
        WRITE(LU,*) 'RUN #=';IRUN
        WRITE(L",*) 'A/D RAW DATA(MILLIVOLTS)'
        WRITE(LU,*) 'NUMBER OF POINTS=',NPT
        WRITE(LU,*) '# OF CHANNELS SCANNED=',NSCAN
        WRITE(LU,*) 'CLOCKRATE(HZ)=',FSAMP
        WRITE(LU,*) 'RECORD TIME LENGTH(MILLISECONDS)=',RT
        WRITE(LU,*) 'PØ(PSIA)=',PØ/144.
        WRITE(LU,*) 'TØ(DEG F)=',TØ-459.688
77      WRITE(LU,9Ø5)
9Ø5     FORMAT(1HØ,2X,'PT #',8X,'1',8X,'2',8X,'3',8X,'4',8X
     1  ,'5',8X,'6',8X,'7',8X,'8')
1       DO 3 I=1,NPT,8
        DO 2 J=1,8
        IF(NPT .LT. (I+J-1)) GO TO 2
C       DECODE FREQ2 OUTPUT TO OBTAIN RAW DATA VOLTAGE
        IOUT=IN(I+J-1)
        CALL RTRV2(IOUT,IADDR,IDATA,MVDATA(J))
2       CONTINUE
        JLIM=8
        IF((NPT/8).EQ.((I-1)/8)) JLIM=MOD(NPT,8)
        WRITE(LU,9Ø6) I,(MVDATA(J),J=1,JLIM)
9Ø6     FORMAT(1H ,I6,8F9.1)
3       CONTINUE
C
C       DETERMINE DESIRED CHANNELS TO BE OUTPUT
4       WRITE(5,1Ø1Ø)
1Ø1Ø    FORMAT(1H ,'INPUT A/D CHANNELS[MIN,MAX,INC] Ø-15')
        ACCEPT*,NMIN,NMAX,NINC
        NMIN=NMIN+1
        NMAX=NMAX+1
        WRITE(5,*) 'DO YOU WANT EACH CHANNEL PRINTED?(Y OR N)'
        ACCEPT 9Ø4,ANS2
        DO 1ØØ NCHAN=NMIN,NMAX,NINC
C       READ DATA FILE
        OPEN(UNIT=4,NAME='DATA.DAT',TYPE='OLD',FORM='UNFORMATTED')
        READ(4) NPT,(IN(I),I=1,NPT)
        CLOSE(UNIT=4)
C       SEPARATE DESIRED CHANNEL DATA AND COUNT NUMBER OF POINTS
C       FOR EACH CHANNEL
        DO 1Ø I=1,NPT
        IOUT=IN(I)
        CALL RTRV2(IOUT,IADDR,IDATA,DATA)
        IADDR=IADDR+1
        IF(NCHAN.EQ.IADDR) GO TO 7
        GO TO 1Ø
7       JMAX(NCHAN)=JMAX(NCHAN)+1
C       CHECK FOR MAXIMUM AND MINIMUM VOLTAGE FOR PLOT SCALING
C       PURPOSES
        IF(DATA.GT.DMAX(NCHAN)) DMAX(NCHAN)=DATA
        IF(DATA.LT.DMIN(NCHAN)) DMIN(NCHAN)=DATA
C       STORE DATA IN INTEGER FORMAT(1/2 MILLIVOLT=1)
        IN(JMAX(NCHAN))=IFIX(DATA*2.)
C       CHECK FOR ERROR IN SEQUENCING
        IF((I+NSCAN).GT.NPT) GO TO 1Ø
        IOUT=IN(I+NSCAN)
        CALL RTRV2(IOUT,IADDR,IDATA,DATA)
        IADDR=IADDR+1
        IF(IADDR.EQ.NCHAN) GO TO 1Ø
        ERR(NCHAN)=ERR(NCHAN)+1
1Ø      CONTINUE
```

```
      RTIME(NCHAN)=FLOAT((JMAX(NCHAN)-1)*NSCAN)/FSAMP*1000.
      WRITE(5,956) NCHAN-1
956   FORMAT(1H ,'SORTING COMPLETE FOR CHANNEL ',I2)
      LU=5
      WRITE(LU,907)
      WRITE(LU,*) 'RUN #=',IRUN
      WRITE(LU,*) 'A/D CHANNEL DATA(MILLIVOLTS)'
      WRITE(LU,*) 'CHANNEL #=',NCHAN-1
      WRITE(LU,*) 'NUMBER OF POINTS=',JMAX(NCHAN)
      WRITE(LU,*) 'NUMBER OF SEQUENCING ERRORS=',ERR(NCHAN)
      WRITE(LU,*) 'SCALING INFORMATION'
      WRITE(LU,*) 'MAXIMUM VALUE(MILLIVOLTS)=',DMAX(NCHAN)
      WRITE(LU,*) 'MINIMUM VALUE(MILLIVOLTS)=',DMIN(NCHAN)
      WRITE(LU,*) 'RECORD TIME LENGTH(MILLISECONDS)=',RTIME(NCHAN)
      IF(ANS2.EQ.'N') GO TO 11
      WRITE(5,*) 'INPUT LOGICAL UNIT TERM=5,LP=6'
      ACCEPT*,LU
      IF(LU.EQ.5) GO TO 79
      WRITE(LU,907)
      WRITE(LU,*) 'RUN #=',IRUN
      WRITE(LU,*) 'A/D CHANNEL DATA(MILLIVOLTS)'
      WRITE(LU,*) 'CHANNEL #=',NCHAN-1
      WRITE(LU,*) 'NUMBER OF POINTS=',JMAX(NCHAN)
      WRITE(LU,*) 'NUMBER OF SEQUENCING ERRORS=',ERR(NCHAN)
      WRITE(LU,*) 'SCALING INFORMATION'
      WRITE(LU,*) 'MAXIMUM VALUE(MILLIVOLTS)=',DMAX(NCHAN)
      WRITE(LU,*) 'MINIMUM VALUE(MILLIVOLTS)=',DMIN(NCHAN)
      WRITE(LU,*) 'RECORD TIME LENGTH(MILLISECONDS)=',RTIME(NCHAN)
79    WRITE(LU,905)
      DO 9 I=1,JMAX(NCHAN),8
      DO 8 J=1,8
      IF(JMAX(NCHAN).LT.(I+J-1)) GO TO 8
C     DATA FROM RETDATA2 IS IN HALF MILLIVOLTS SO CONVERT
      MVDATA(J)=FLOAT(IN(I+J-1))/2.
8     CONTINUE
      JLIM=8
      IF((JMAX(NCHAN)/8).EQ.((I-1)/8)) JLIM=MOD(JMAX(NCHAN),8)
      WRITE(LU,906) I,(MVDATA(J),J=1,JLIM)
9     CONTINUE
C     CHECK IF SCALING WANTED
11    IF(NSCALE.EQ.0) GO TO 600
C
C     CONVERT DATA TO REQUIRED UNITS BY UTILIZING CALIBRATION CURVES
      WRITE(5,907)
      WRITE(5,*) 'RUN #=',IRUN
      WRITE(5,*) 'A/D CONVERTED CHANNNEL DATA'
      WRITE(5,*) 'CHANNEL #=',NCHAN-1
      WRITE(5,*) 'NUMBER OF POINTS=',JMAX(NCHAN)
      WRITE(5,*) 'NUMBER OF SEQUENCING ERRORS=',ERR(NCHAN)
C     CHANNEL DESCRIPTION
      IF(NCHAN.EQ.1) WRITE(5,*) 'HOTWIRE ESTIMATED MASSFLOW(LBM/MIN)'
      IF(NCHAN.GT.1) WRITE(5,*) 'KULITE OUTPUT PRESSURE(PSIA)'
      DMIN(NCHAN)=1.0E38
      DMAX(NCHAN)=-1.0E38
      DO 13 I=1,JMAX(NCHAN),8
      DO 12 J=1,8
      IF(JMAX(NCHAN).LT.(I+J-1)) GO TO 12
C     CONVERT TO VOLTS
      X=FLOAT(IN(I+J-1))/2000.
C     CONVERT VOLTAGE TO OUTPUT VARIABLE
      IF(NCHAN.EQ.1) GO TO 17
C     KULITE OUTPUT PSIA
      CALL CVERT(NCHAN,X,CDATA(J))
C     WRITE(5,*) 'I',I
```

```
C       WRITE(5,*) 'X=',X,'CDATA(J)=',CDATA(J)
C       STORE PRESSURE RATIO FOR PLOTTING(.ØØ1=1)
        IN(I+J-1)=IFIX(CDATA(J)/(PØ/144.)*1ØØØ.)
C       WRITE(5,*) 'INDEX=',I+J-1,'PR=',FLOAT(IN(I+J-1))/1ØØØ.
C       WRITE(5,*) 'DMIN=',DMIN(NCHAN),'DMAX=',DMAX(NCHAN)
C       CALCULATE MIN AND MAX PR FOR PLOTTING PURPOSES
        IF((FLOAT(IN(I+J-1))/1ØØØ.).GT.DMAX(NCHAN)) DMAX(NCHAN)=
     1  FLOAT(IN(I+J-1))/1ØØØ.
        IF((FLOAT(IN(I+J-1))/1ØØØ.).LT.DMIN(NCHAN)) DMIN(NCHAN)=
     1  FLOAT(IN(I+J-1))/1ØØØ.
C       WRITE(5,*) 'DMIN=',DMIN(NCHAN),'DMAX=',DMAX(NCHAN)
        GO TO 12
C       HOTWIRE OUTPUT CORRECTED FLOW(LBM/MIN)
17      CALL CVERT(NCHAN,X,CDATA(J))
C       STORE CORRECTED MASSFLOW FOR PLOTTING(.Ø1=1)
        IN(I+J-1)=IFIX(CDATA(J)*1ØØ.)
C       WRITE(5,*) 'CFLO=',FLOAT(IN(I+J-1))/1ØØ.
C       CALCULATE MIN AND MAX MCOR FOR PLOTTING PURPOSES
        IF((FLOAT(IN(I+J-1))/1ØØ.).GT.DMAX(NCHAN)) DMAX(NCHAN)=
     1  FLOAT(IN(I+J-1))/1ØØ.
        IF((FLOAT(IN(I+J-1))/1ØØ.).LT.DMIN(NCHAN))
     1  DMIN(NCHAN)=FLOAT(IN(I+J-1))/1ØØ.
C       WRITE(5,*) 'DMIN=',DMIN(NCHAN),'DMAX=',DMAX(NCHAN)
12      CONTINUE
        IF(ANS2.EQ.'N') GO TO 13
        IF(I.GT.1) GO TO 23
        IF(LU.EQ.5) GO TO 8Ø
        WRITE(LU,9Ø7)
        WRITE(LU,*) 'RUN #=',IRUN
        WRITE(LU,*) 'A/D CONVERTED CHANNNEL DATA'
        WRITE(LU,*) 'CHANNEL #=',NCHAN-1
        WRITE(LU,*) 'NUMBER OF POINTS=',JMAX(NCHAN)
        WRITE(LU,*) 'NUMBER OF SEQUENCING ERRORS=',ERR(NCHAN)
C       CHANNEL DESCRIPTION
        IF(NCHAN.EQ.1) WRITE(LU,*) 'HOTWIRE ESTIMATED MASSFLOW(LBM/MIN)'
        IF(NCHAN.GT.1) WRITE(LU,*) 'KULITE OUTPUT PRESSURE(PSIA)'
8Ø      WRITE(LU,9Ø5)
23      JLIM=8
        IF((JMAX(NCHAN)/8).EQ.((I-1)/8)) JLIM=MOD(JMAX(NCHAN),8)
        WRITE(LU,9Ø9) I,(CDATA(J),J=1,JLIM)
9Ø9     FORMAT(1H ,I6,8F9.3)
13      CONTINUE
        WRITE(LU,*) 'SCALING INFORMATION'
        IF(NCHAN.EQ.1) WRITE(LU,*) 'MINIMUM CFLO(LBM/MIN)=',
     1  DMIN(NCHAN)
        IF(NCHAN.GT.1) WRITE(LU,*) 'MINIMUM PRESSURE RATIO=',
     1  DMIN(NCHAN)
        IF(NCHAN.EQ.1) WRITE(LU,*) 'MAXIMUM CFLO(LBM/MIN)=',
     1  DMAX(NCHAN)
        IF(NCHAN.GT.1) WRITE(LU,*) 'MAXIMUM PRESSURE RATIO=',
     1  DMAX(NCHAN)
        WRITE(5,*) 'RECORD TIME LENGTH(MILLISECONDS)=',RTIME(NCHAN)
C
C       CREATE DATAFILE IN EPSTEIN G.T.L. FORMAT FOR PLOTTING
        IF(IFORM.EQ.Ø) GO TO 8ØØ
        WRITE(5,*) 'TYPE TEST DATA TRACE DESCRIPTION(<=1Ø CHARACTERS)'
        READ(5,9Ø1) (NAME(I),I=1,5)
9Ø1     FORMAT(5A2)
        IF(NCHAN.GT.NMIN) GO TO 5Ø
C       WRITE(5,*) 'TYPE DATA FILE NAME FOR PLOTTING'
C       ACCEPT 9ØØ, (FILE(I),I=1,2Ø)
C9ØØ    FORMAT(3ØA1)
        WRITE(5,*) 'TYPE TEST TIME(HH:MMM:SS)'
        READ(5,9Ø2) (ITIME(I),I=1,4)
```

```
902     FORMAT(4A2)
        WRITE(5,*) 'TYPE TEST DATE(DD-MMM-YY)'
        READ(5,901) (IDATE(I),I=1,5)
        WRITE(5,*) 'TYPE PLOT TITLE(<=20 CHARACTERS)'
        READ(5,903) (FTAG(I),I=1,10)
        H(99)=-1
903     FORMAT(10A2)
        WRITE(5,*) 'INPUT SCALE FACTOR'
        ACCEPT*,SCALE
        WRITE(5,*) 'INPUT ZERO SCALING FACTOR'
        ACCEPT*,ZERO
        H(98)=-1
        H(100)=IFIX(1E+06/FSAMP)
        H(94)=NSCAN
        WRITE(5,*) 'INPUT TIME SCALING FACTOR(INTEGER)'
        READ(5,*) H(95)
        H(98)=-1
50      ENCODE(2,950,CCHAN) NCHAN-1
950     FORMAT(I2)
        ENCODE(3,955,CRUN) IRUN
955     FORMAT(I3)
        OPEN(UNIT=1,NAME=FILE,TYPE='NEW',FORM='UNFORMATTED',
     1  ORGANIZATION='SEQUENTIAL',RECL=125,RECORDTYPE='FIXED')
        WRITE(1) H
C       CALCULATE NUMBER OF RECORDS IN PLOTFILE
        NREC=JMAX(NCHAN)/250+2
        IF(MOD(JMAX(NCHAN),250) .EQ. 0) NREC=NREC-1
        WRITE(5,*) 'NUMBER OF RECORDS=',NREC
C       STORE DEMULTIPLEXED NUMBERS IN PLOTFILE
        IRMAX=250
        DO 20 N=2,NREC
        IF(N.EQ.NREC) IRMAX=MOD(JMAX(NCHAN),250)
        IF(MOD(JMAX(NCHAN),250).EQ.0) IRMAX=250
        WRITE(1) (IN(J+(N-2)*250),J=1,IRMAX)
20      CONTINUE
        CLOSE(UNIT=1)
        WRITE(5,957) NCHAN-1
957     FORMAT(1H ,'PLOTFILE COMPLETE FOR CHANNEL ',I2)
C       CREATE VARIABLE VS TIME PLOT FILES FOR PLOTTING WITH PLOTMANY
C       CREATE SURGE PATH PLOT FILE
800     IF((NMIN.EQ.1).AND.(NMAX.EQ.10)) GO TO 95
        WRITE(5,*) 'PR VS CFLO PATH HISTORY PLOT SKIPPED'
        GO TO 600
95      IF(NCHAN.EQ.1) GO TO 96
        IF(NCHAN.EQ.10) GO TO 98
        GO TO 600
96      ENCODE(3,955,SRUN) IRUN
        OPEN(UNIT=3,NAME=SCFILE,TYPE='NEW',FORM='FORMATTED')
        WRITE(3,971) (COMMNT(I),I=1,68),JMAX(1)
971     FORMAT(68A1,I4)
        DUM=0.
        DO 400 I=1,JMAX(1)
        XCF(I)=FLOAT(IN(I))/100.
C       WRITE(5,*) 'I=',I,'XCF(I)=',XCF(I)
        WRITE(3,972) XCF(I),DUM
972     FORMAT(2E13.7)
400     CONTINUE
        CLOSE(UNIT=3)
        GO TO 600
98      OPEN(UNIT=3,NAME=SCFILE,TYPE='OLD',FORM='FORMATTED')
        READ(3,971) (COMMNT(I),I=1,68),JMAX(1)
        READ(3,972) (XCF(I),DUM,I=1,JMAX(1))
        IF(JMAX(10).LT.JMAX(1)) IJMAX=JMAX(10)
        IF(JMAX(10).GE.JMAX(1)) IJMAX=JMAX(1)
```

```
      REWIND(UNIT=3)
      WRITE(3,971) (COMMNT(I),I=1,68),IJMAX
      DO 500 I=1,IJMAX
      YPR(I)=FLOAT(IN(I))/1000.
C     WRITE(5,*) 'XCF(I)=',XCF(I),'YPR(I)=',YPR(I)
      WRITE(3,972) XCF(I),YPR(I)
500   CONTINUE
      CLOSE(UNIT=3)
      WRITE(5,*) 'PR VS CFLO PATH HISTORY PLOT FILE COMPLETE'
C     VARIABLE VS TIME PLOT FILES
600   IF(IFORM.EQ.1) GO TO 100
      ENCODE(2,950,ADCHAN) NCHAN-1
      ENCODE(3,955,CHRUN) IRUN
      OPEN(UNIT=3,NAME=CHFILE,TYPE='NEW',FORM='FORMATTED')
      DT=1000./FSAMP
C     WRITE(5,*) 'DT=',DT
      TST=FLOAT(NCHAN-1)*DT
C     WRITE(5,*) 'TST=',TST,'NCHAN=',NCHAN
C     WRITE(5,*) 'NSCAN=',NSCAN
      IF(NSCALE.EQ.0) GO TO 601
      WRITE(3,973) COM2(NCHAN),JMAX(NCHAN)
973   FORMAT(A68,I4)
      GO TO 602
601   WRITE(3,973) COM3,JMAX(NCHAN)
602   DO 700 K=1,JMAX(NCHAN)
      NT=NSCAN*(K-1)
C     WRITE(5,*) 'NT=',NT
      XCF(K)=TST+DT*FLOAT(NT)
C     WRITE(5,*) 'K=',K,'XCF(K)=',XCF(K)
      IF(NCHAN.EQ.1) GO TO 650
      YPR(K)=FLOAT(IN(K))/1000.
      IF(NSCALE.EQ.0) YPR(K)=FLOAT(IN(K))/2000.
      WRITE(3,972) XCF(K),YPR(K)
      GO TO 700
650   YPR(K)=FLOAT(IN(K))/100.
      IF(NSCALE.EQ.0) YPR(K)=FLOAT(IN(K))/2000.
      WRITE(3,972) XCF(K),YPR(K)
C     WRITE(5,1030) K,XCF(K),YPR(K)
C1030 FORMAT(1H ,'K=',I4,2X,'XCF(K)=',F10.2,2X,'YPR(K)=',F10.2)
700   CONTINUE
      CLOSE(UNIT=3)
      WRITE(5,1020) NCHAN-1
1020  FORMAT(1H ,'CHANNEL ',I2,' VS TIME PLOT FILE COMPLETE')
100   CONTINUE
      STOP
      END
```

```
      SUBROUTINE CVERT(NCHAN,X,CDAT)
C     THIS SUBROUTINE CONVERTS KULITE AND HOTWIRE VOLTAGES
C     TO PSIA AND LBM/MIN(CORRECTED FLOW).
      REAL*4 MFLO
      DIMENSION C1(16),C2(16),C3(16),C4(16)
      COMMON/A/ PØ,TØ,PREF,TREF
      DATA C1/-.1297345E+Ø1,-2.Ø78949,-3.Ø628,-2.732142,-2.741874,
     1 9.174626,13.621858,9.641758,9.6Ø6646,8.379413,6*Ø.Ø/
      DATA C2/.972Ø3Ø8E+Ø2,3.158848,3.Ø27192,3.147719,3.13Ø529,
     1 2.3264Ø1,2.7Ø6134,2.418674,2.283385,2.426997,6*Ø.Ø/
      DATA C3/.362114Ø3E+Ø4,.ØØ2562,.Ø12923,.ØØ2888,.ØØ1Ø29,
     1 .ØØ1Ø16,-.ØØØ411,.ØØ1451,.ØØ1726,.ØØ1942,6*Ø.Ø/
      DATA C4/16*Ø.Ø/
      IF(NCHAN .EQ. 1) GO TO 5
C     KULITE PRESSURE CONVERSIONS(VOLTS TO PSIA)
      PSIG=C1(NCHAN)+C2(NCHAN)*X+C3(NCHAN)*X*X
     1 +C4(NCHAN)*X*X*X
      CDAT=PSIG+PØ/144.
      GO TO 1Ø
C     HOTWIRE MASSFLOW CONVERSIONS(VOLTS TO INLET MASSFLOW(LBM/MIN))
5     X=X**2./(482.-(TØ-459.688))
C     WRITE(5,*) 'NCHAN=',NCHAN,'X=',X
      XMIN=(-C2(1)+SQRT(C2(1)**2.-4.*C3(1)*C1(1)))/(2.*C3(1))
C     WRITE(5,*) 'XMIN=',XMIN
      IF(X .LT. XMIN) GO TO 8
      MFLO=(C1(1)+C2(1)*X+C3(1)*X*X+C4(1)*X*X*X)**2.
      GO TO 9
8     MFLO=Ø.
9     CFLO=MFLO*SQRT(TØ/TREF)/(PØ/PREF)
C     WRITE(5,*) 'CFLO=',CFLO
      CDAT=CFLO
1Ø    RETURN
      END
```

```
      SUBROUTINE RTRV2(IOUT,IADDR,IDATA,DATA)
C     THIS SUBROUTINE DECODES INTEGER A/D DATA FROM DATA FILE
C     'DATA.DAT' WHICH IS CREATED BY PROGRAM FREQ2.  THE A/D USED
C     FOR THESE TESTS IS THE G.T.L ANALOGIC MP6912 DATA-ACQUISITION
C     MODULE.THE 16 BIT INTEGER IS DECODED INTO A 12 BIT INTEGER
C     CORRESPONDING TO THE VOLTAGE AND A 4 BIT INTEGER CORRESPONDING
C     TO THE A/D CHANNEL.
C     VARIABLES:
C     IOUT=DATA.DAT INPUT FILE ELEMENT
C     IADDR=A/D CHANNEL(Ø-15)
C     IDATA=INTEGER OUTPUT IN OFFSET BINARY(+ AND - RANGE)
C     DATA=CONVERTED REAL NUMBER CORRESPONDING TO VOLTAGE(MILLIVOLTS)
      CALL RETRVA(IOUT,IADDR,IDATA)
C     A/D RANGE:-5.12 TO 5.12 VOLTS
C     CONVERT OUTPUT TO MILLIVOLTS
      DATA=FLOAT(IDATA-2Ø48)*2.5
      RETURN
      END
```

```
C       PROGRAM PLOTMANY
C       THIS PROGRAM ALLOWS DATA POINTS TO BE PLOTTED ON THE VISUAL 5ØØ.
C       DATA POINTS ARE IN FORMATTED FILES AS OUTPUT BY DMPLEX2 BUT CAN
C       ALSO BE INPUTTED USING THE KEYBOARD
C       USING THE TERMINAL KEYBOARD, BUT MAY BE STORED ON DISC FILES FOR
C       REPLOTTING AT A LATER DATE. LARGEST ARRAY SIZE=1495 POINTS
        REAL*4 X(1497),Y(1497)
        LOGICAL*1 ASCFIL(16),COMMNT(68),CYN,NUL
        DIMENSION IFLAG(3)
        COMMON/DATAFL/ NPTS,X,Y
        COMMON/F/ IFLAG,FX,DX,FY,DY,INTEQ,DONE
        DATA NUL/Ø/
        DATA ASCFIL/' ',3*'X',':',6*'X','.',3*'X',Ø/
        DATA IFLAG/3*Ø./
        DATA INTEQ/-1/
C
C SET DONE=1 TO INDICATE BEGINNING OF NEW PLOT
C
        DONE=1
C
1       TYPE 2
2       FORMAT(' DO YOU WANT TO: Ø-QUIT, 1-ENTER DATA, 2-READ DISC ',$)
        ACCEPT *,IDO
        IF(IDO.EQ.Ø) CALL EXIT
        IF(IDO.EQ.1) GOTO 1ØØ
4       TYPE 5
5       FORMAT(' ENTER DATA FILE NAME',/,' XXX:XXXXXX.XXX')
        ACCEPT 6,(ASCFIL(I),I=2,15)
6       FORMAT(14A1)
        TYPE 7,ASCFIL
7       FORMAT(' DATA FILE NAME IS ',16A1,' - OK? ',$)
        ACCEPT 8,CYN
8       FORMAT(A1)
C
        CALL CLEAR
C
        IF(CYN.NE.'Y') GOTO 4
        OPEN(UNIT=3,NAME=ASCFIL,TYPE='OLD',FORM='FORMATTED',
     1  ERR=12)
        READ(3,243)(COMMNT(K),K=1,68),NPTS
        DO 1Ø I=1,NPTS
        READ(3,241) X(I),Y(I)
C       X(I)=1./SQRT(X(I))
1Ø      CONTINUE
        CLOSE(UNIT=3)
        TYPE 11,(COMMNT(I),I=1,68),NPTS
11      FORMAT(' FILE = ',68A1,/,' THERE ARE ',I6,' DATA POINTS')
        GO TO 1Ø6
12      TYPE *,' BAD OPEN FILE TO READ'
        GO TO 1Ø6
1ØØ     TYPE 1Ø1
1Ø1     FORMAT('ØENTER X & Y - (X,Y = -999,-999 ===> NO MORE DATA)')
        DO 1Ø4 I=1,256
1Ø2     TYPE 1Ø3,I
1Ø3     FORMAT(' I= ',I3,'  X , Y = ',$)
        ACCEPT *,X(I),Y(I)
        IF(X(I).EQ.-999.Ø.AND.Y(I).EQ.-999.Ø) GOTO 1Ø5
1Ø4     CONTINUE
1Ø5     NPTS=I-1
1Ø6     TYPE 4359
4359    FORMAT(' DO YOU WANT TO TYPE OUT THE DATA? ',$)
        ACCEPT 8,CYN
C
        CALL CLEAR
```

```
C
        IF(CYN.NE.'Y') GOTO 199
        TYPE *,'     I           X              Y'
        DO 1Ø7,I=1,NPTS
C       WRITE(5,991) I,X(I),Y(I)
C991    FORMAT(1H ,'I=',I3,5X,'X=',E13.7,5X,'Y=',E13.7)
1Ø7     TYPE *,I,X(I),Y(I)
        TYPE 1Ø8
1Ø8     FORMAT('ØARE ALL OF THESE VALUES CORRECT? ',$)
        ACCEPT 8,CYN
        IF(CYN.EQ.'Y') GOTO 199
1Ø9     TYPE 11Ø
11Ø     FORMAT(' ENTER CORRECT I, X(I), Y(I) : ',$)
        ACCEPT *,ICORR,X(ICORR),Y(ICORR)
        IF(X(ICORR).EQ.-999.Ø.AND.Y(ICORR).EQ.-999.Ø) NPTS=ICORR-1
        GOTO 1Ø6
199     TYPE 23Ø
23Ø     FORMAT(' DO YOU WANT TO STORE THESE NUMBERS ON DISC? ',$)
        ACCEPT 8,CYN
C
        CALL CLEAR
C
        IF(CYN.NE.'Y') GO TO 21Ø
        TYPE 231
231     FORMAT(' ENTER DATA DESCRIPTION UNDER X MARKS',/,1X,68('X'))
        ACCEPT 232,(COMMNT(I),I=1,68)
232     FORMAT(68A1)
233     TYPE 5
        ACCEPT 6,(ASCFIL(I),I=2,15)
        TYPE 7, ASCFIL
        ACCEPT 8,CYN
        IF(CYN.NE.'Y') GOTO 233
        OPEN(UNIT=3,NAME=ASCFIL,TYPE='NEW',FORM='FORMATTED',
     1  INITIALSIZE=5,ERR=24Ø)
        WRITE(3,243)(COMMNT(K),K=1,68),NPTS
243     FORMAT(68A1,I4)
        DO 242 I=1,NPTS
        WRITE(3,241) X(I),Y(I)
241     FORMAT(2E13.7)
242     CONTINUE
        CLOSE(UNIT=3)
        GO TO 21Ø
24Ø     TYPE *,' BAD OPEN FILE TO WRITE'
        GO TO 1
21Ø     IF(IFLAG(1) .EQ. 1) GO TO 213
        TYPE 9ØØ
9ØØ     FORMAT(1H ,'DO YOU WANT A PLOT?',$)
        ACCEPT 8,CYN
C
        CALL CLEAR
C
        IF(CYN .EQ. 'Y') GO TO 213
        GO TO 1
213     CALL PLTDAT
        GO TO 1
        END
```

```
      SUBROUTINE PLTDAT
C     THIS SUBROUTINE IS PLOTTED DATA ON VISUAL 500 TERMINAL OR X-Y RECORDER.
C     X = X ARRAY
C     Y = Y ARRAY
C     LARGEST ARRAY =1495 POINTS
      REAL*4 X(1497),Y(1497),XTEX(15)
      LOGICAL*1 XLAB(40),YLAB(40),CYN
      DIMENSION IFLAG(3)
      COMMON /F/ IFLAG,FX,DX,FY,DY,INTEQ,DONE
      COMMON /DATAFL/ NPTS,X,Y
      DATA XLAB/40*25/
      DATA YLAB/40*25/
      DATA LMASK1/"104210/,LMASK2/"125252/
      N1=NPTS+1
      N2=NPTS+2
      IF(IFLAG(1) .EQ. 1) GO TO 440
      WRITE(5,*)'INPUT XORG AND YORG'
      READ(5,*)XORG,YORG
      CALL CLEAR
      WRITE(5,*) 'INPUT X-AXIS LENGTH'
      ACCEPT*,XLEN
      WRITE(5,*) 'INPUT Y-AXIS LENGTH'
      ACCEPT*,YLEN
      CALL CLEAR
      WRITE(5,*) 'ENTER PLOTTIMG UNIT; 3=VT100, 5 = VIS500'
      ACCEPT *,NUNIT
      CALL CLEAR
      TYPE 10
10    FORMAT(' ENTER X LABEL ( < or = 40 Charecters) ')
      ACCEPT 20,(XLAB(I),I=1,40)
20    FORMAT(40A1)
C     COUNT NUMBER OF CHARACTERS IN XLAB FOR CENTERING
      DO 21 I=40,1,-1
      IF(XLAB(I).EQ.' ') GO TO 21
      LXLAB=I
      GO TO 22
21    CONTINUE
22    TYPE 15
15    FORMAT(' ENTER Y LABEL ( < or = 40 Charecters) ')
      ACCEPT 25,(YLAB(I),I=1,40)
25    FORMAT(40A1)
C     COUNT NUMBER OF CHARACTERS IN YLAB FOR CENTERING
      DO 26 I=40,1,-1
      IF(YLAB(I).EQ.' ') GO TO 26
      LYLAB=I
      GO TO 27
26    CONTINUE
27    CALL CLEAR
      WRITE(5,*) 'INPUT PLOTTING SCALE FACTOR'
      ACCEPT*,FACT
      CALL CLEAR
      IF(DONE.EQ.1)CALL PLOTS(0,0,NUNIT)
      CALL PLOT(XORG,YORG,-3)
      CALL FACTOR(FACT)
430   CALL SCALE(X,XLEN,NPTS,1)
      FX=X(N1)
      DX=X(N2)
      CALL SCALE(Y,YLEN,NPTS,1)
      FY=Y(N1)
      DY=Y(N2)
      TYPE 905,126,24,FX,DX,FY,DY
905   FORMAT(2A1,'FX=',F12.3,2X,'DX=',F12.3,2X,'FY=',F12.3,2X,
     1 'DY=',F12.3,/,1H ,'INPUT FX,DX,FY,DY')
      ACCEPT*,FX,DX,FY,DY
```

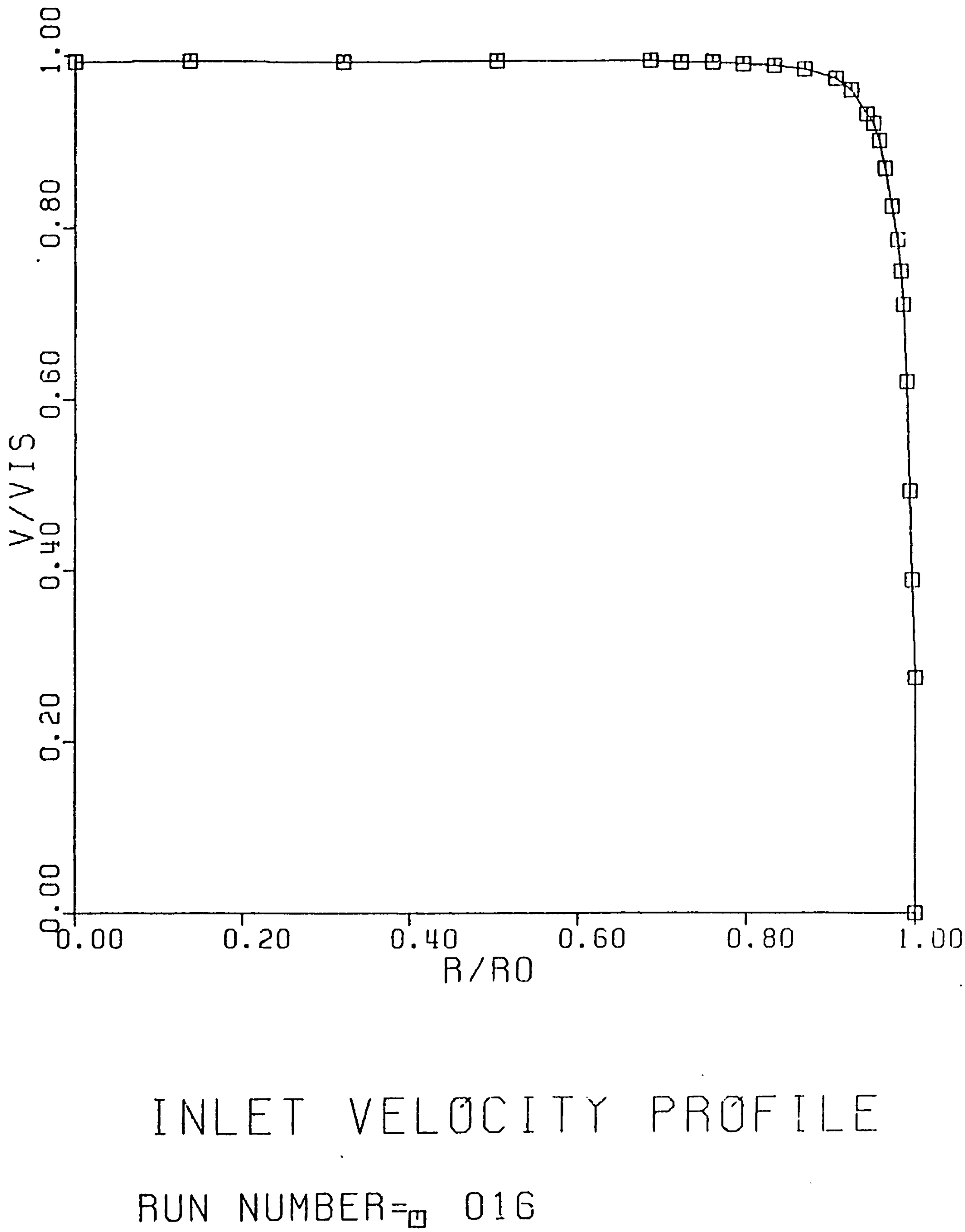
```
      CALL CLEAR
      TYPE 919, 126,31
919   FORMAT(2A1)
      CALL AXIS(Ø.Ø,Ø.Ø,XLAB,-LXLAB,XLEN,Ø.,FX,DX)
      CALL AXIS(Ø.Ø,Ø.Ø,YLAB,LYLAB,YLEN,9Ø.,FY,DY)
44Ø   X(N1) = FX
      X(N2) = DX
      Y(N1) = FY
      Y(N2) = DY
      WRITE(5,29)
29    FORMAT(1H ,'INPUT SYMBOL POINT INCREMENT INTEGER:',$)
      ACCEPT *,INC
      CALL CLEAR
      WRITE(5,3Ø)
3Ø    FORMAT(1H ,'INPUT INTEGER LINTYP FOR LINE/SYMBOL DEFINITION',/
     1 ,1H ,'LINTYP=Ø:STRAIGHT LINES,NO SYMBOLS',/,1H ,
     2 'LINTYP=+N:STRAIGHT LINES,SYMBOLS EVERY Nth POINT',/,1H ,
     3 'LINTYP=-N:NO LINES,SYMBOLS EVERY Nth POINT',/,1H )
      ACCEPT *,LINTYP
      CALL CLEAR
      IF(LINTYP.EQ.Ø) GO TO 4Ø
C     IF(LINTYP.EQ.999) GO TO 41
      INTEQ=INTEQ+1
4Ø    CALL LINE(X,Y,NPTS,INC,LINTYP,INTEQ)
      IF(IFLAG(2) .EQ. 1) GO TO 54
C41   TYPE *,' DO YOU WANT CURVE FIT ?'
C     ACCEPT 5Ø, CYN
C     IF(CYN.NE.'Y') GO TO 54
C     IFLAG(2)=1
C     DO 41Ø J=1,NPTS
C     XX(J) = X(J)
C     YY(J) = Y(J)
C41Ø  CONTINUE
C     CALL CURFIT
C     N1 = NPTS + 1
C     N2 = NPTS + 2
C     X(N1)=FX
C     X(N2)=DX
C     Y(N1)=FY
C     Y(N2)=DY
C     LINTYP=Ø
C     INC=1
C     GO TO 4Ø
54    IFLAG(2)=Ø
      WRITE(5,9ØØ)
9ØØ   FORMAT(1H ,'DO YOU WANT MORE CURVES ON THESE AXIS?',$)
      ACCEPT 5Ø,CYN
      CALL CLEAR
      IF(CYN .NE. 'Y') GO TO 55
      IFLAG(1)=1
      RETURN
55    ITXTN=Ø
49    TYPE 45
45    FORMAT(' DO YOU WANT TO ADD A LINE OF TEXT TO THE PLOT ?',$)
      ACCEPT 5Ø,CYN
5Ø    FORMAT(A1)
      CALL CLEAR
      IF(CYN.NE.'Y') GO TO 6Ø
      TYPE 51
51    FORMAT(' ENTER TEXT ')
      ACCEPT 52,(XTEX(I),I=1,15)
52    FORMAT(15A4)
      DO 67 I=15,1,-1
      IF(XTEX(I).EQ.'    ') GO TO 67
```

```
      LXTEX=I
      GO TO 68
67    CONTINUE
68    IF(ITXTN.GE.1) WRITE(5,*) 'LAST XPOS=',XPOS,'LAST YPOS=',
     1 YPOS
      TYPE 53
53    FORMAT(' ENTER TEXT POSITION(PLOTTING UNITS):(X,Y)',/,
     1 ' USE X=-1 FOR CENTERED TEXT')
      ACCEPT *,XPOS,YPOS
      TYPE 57
57    FORMAT(' ENTER TEXT HEIGHT(PLOTTING UNITS): ')
      ACCEPT *,TEXHT
      CALL CLEAR
C     CALCULATE XPOS FOR CENTERED TEXT
      IF(XPOS.EQ.-1) GO TO 69
      GO TO 7Ø
69    XPOS=XLEN/2.-FLOAT(LXTEX)*TEXHT*2.
      WRITE(5,*) 'XPOS FOR CENTERING=',XPOS
7Ø    CALL SYMBOL(XPOS,YPOS,TEXHT,XTEX,Ø.,6Ø)
      ITXTN=ITXTN+1
      GO TO 49
6Ø    WRITE(5,9Ø1)
9Ø1   FORMAT(1H ,'DO YOU WANT A SYMBOL KEY ON GRAPH?',$)
      ACCEPT 5Ø,CYN
      IF(CYN .NE. 'Y') GO TO 62
      WRITE(5,9Ø4)
9Ø4   FORMAT(1H ,'INPUT KEY TEXT HEIGHT(PLOTTING UNITS):',$)
      ACCEPT *,TEXHT
      ISYM=Ø
61    WRITE(5,9Ø2)
9Ø2   FORMAT(1H ,'ENTER KEY LABEL POSITION(PLOTTING UNITS):X,Y',$)
      ACCEPT *,XPOS,YPOS
      CALL SYMBOL(XPOS,YPOS,TEXHT,ISYM,Ø.,-1)
      CALL SYMBOL(999.,999.,TEXHT,1H-,Ø.,Ø)
      WRITE(5,9Ø3) ISYM+1
9Ø3   FORMAT(1H ,'ENTER LABEL #',I2,':',$)
      ACCEPT 52, (XTEX(I),I=1,15)
      CALL SYMBOL(999.Ø,999.Ø,TEXHT,XTEX,Ø.,6Ø)
      ISYM=ISYM+1
      IF((ISYM-1) .LT. INTEQ) GO TO 61
      CALL CLEAR
C     GRID GENERATION
62    WRITE(5,9Ø6)
9Ø6   FORMAT(1H ,'DO YOU WANT A GRID?',$)
      ACCEPT 5Ø,CYN
      IF(CYN .EQ. 'N') GO TO 6364
63    WRITE(5,9Ø7)
9Ø7   FORMAT(1H ,'INPUT STARTING X,Y:',$)
      ACCEPT *,XPOS,YPOS
      WRITE(5,9Ø8)
9Ø8   FORMAT(1H ,'INPUT TOTAL X,Y INTERVALS:',$)
      ACCEPT *,NX,NY
      WRITE(5,9Ø9)
9Ø9   FORMAT(1H ,'INPUT VALUE OF X,Y INTERVAL(PLOT UNITS):',$)
      ACCEPT *,XD,YD
      WRITE(5,91Ø)
91Ø   FORMAT(1H ,'INPUT S=SOLID LINE,D=DOTTED LINE:',$)
      ACCEPT 5Ø,CYN
      CALL CLEAR
      LMASK=LMASK1
      IF(CYN .EQ. 'S') LMASK=LMASK2
      CALL GRID(XPOS,YPOS,NX,XD,NY,YD,LMASK)
      WRITE(5,911)
911   FORMAT(1H ,'DO YOU WANT ANOTHER GRID?',$)
```

```
        ACCEPT 5Ø,CYN
        CALL CLEAR
        IF(CYN .EQ. 'Y') GO TO 63
6364    WRITE(5,*)'DO YOU WANT TO TERMINATE PLOTTING?'
        ACCEPT 5Ø,CYN
        CALL CLEAR
        IF(CYN .EQ. 'Y') GO TO 64
        DONE=Ø
        IFLAG(1)=Ø
        RETURN
64      CALL PLOT(Ø.Ø,Ø.Ø,999)
        DONE=1
        IFLAG(1)=Ø
        RETURN
        END
C
        SUBROUTINE CLEAR
C ERASE THE SCREEN OF A VT52
        TYPE 1ØØ,126,27,118
1ØØ     FORMAT(3A1)
        RETURN
        END
```

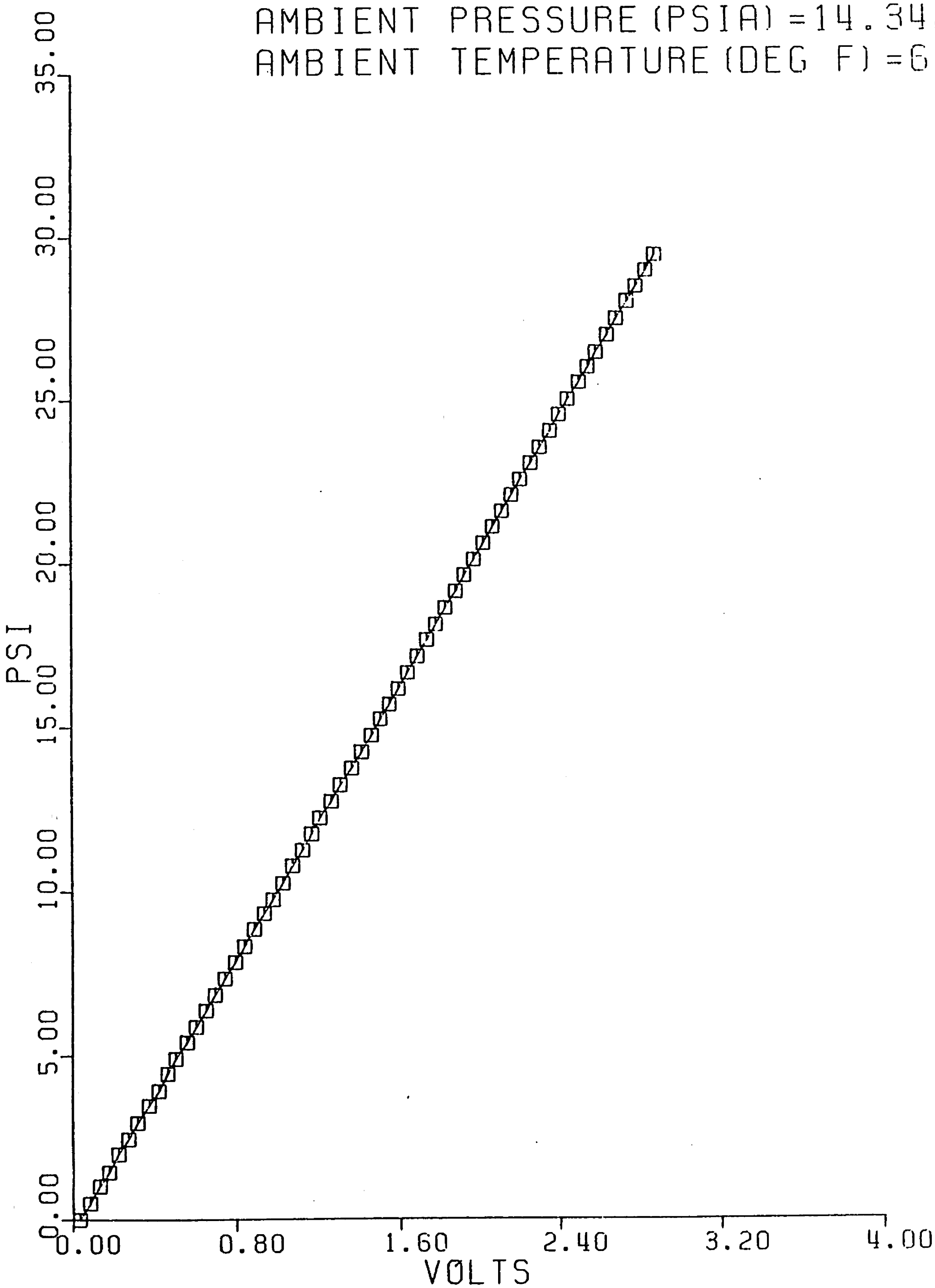
```
C       PROGRAM SWIRL
C       THIS PROGRAM CALCULATES THE SWIRL ANGLE AT THE INLET TO
C       THE DIFFUSER.
C       INPUT VARIABLES ARE:
C       PØ1=COMPRESSOR INLET TOTAL PRESSURE(PSIA)
C       TØ1=COMPRESSOR INLET TOTAL TEMP(DEG F)
C       PØ2=DIFFUSER INLET TOTAL PRESSURE(PSIA)
C       TØ2=DIFFUSER INLET TOTAL TEMP(DEG F)
C       MCOR=CORRECTED MASSFLOW(LBM/MIN)
C       RPS=COMPRESSOR ROTOR SPEED(REV/SEC)
C       CONSTANTS ARE:
C       CP=SPECIFIC HEAT AT CONST PRESSURE(BTU/LBM DEG F)
C       K=RATIO OF SPECIFIC HEATS
C       R2=DIFFUSER INLET RADIUS(IN)
C       WD=DIFFUSER PASSAGE WIDTH
C       AD=DIFFUSER INLET AREA
C       PREF=REFERENCE PRESSURE(PSIA)
C       TREF=REFERENCE TEMPERATURE(DEG F)
C       OUTPUT VARIABLES ARE:
C       VT2=TANGENTIAL VELOCITY(FT/SEC)
C       VR2=RADIAL VELOCITY(FT/SEC)
C       UTIP=IMPELLER TIP SPEED(FT/SEC)
C       MT2=DIFFUSER INLET TANGENTAL MACH NUMBER
C       MR2=DIFFUSER INLET NORMAL MACH NUMBER
C       M2=DIFFUSER INLET MACH NUMBER
C       SWIRL=DIFFUSER SWIRL PARAMETER(=VT2/VN2)
C       ALPHA2=SWIRL ANGLE(DEG FROM AXIAL DIRECTION)
C       MFLO=MASSFLOW(LBM/MIN)
C       Z=NUMBER OF IMPELLER BLADES
C       SLIPV=SLIP VELOCITY(FT/SEC)
C       SLIPP=SLIP PARAMETER
C       STANVT=STANITZ PREDICTED VT2(FT/SEC)
C       STANSV=STANITZ SLIP VELOCITY(FT/SEC)
C       STANSP=STANITZ SLIP PARAMETER(FT/SEC)
        REAL MFLO,MCOR,K,M2,MT2,MR2,MOLD,J,N
        K=1.4
        G=32.174Ø5
        R=53.3*G
        J=778.26
        PI=3.1415927
        CP=R*K/(K-1.)
        DR=459.688
        PREF=14.69*144.
        TREF=545.
        R2=2.5175/12.
        WD=.231/12.
        AD=2*PI*R2*WD
        Z=2Ø
        WRITE(5,*) 'INPUT PØ1(PSIA) TØ1(DEG F) PØ2(PSIA) TØ2(DEG F)'
        READ(5,*) PØ1,TØ1,PØ2,TØ2
        PØ1=PØ1*144.
        TØ1=TØ1+DR
        PØ2=PØ2*144.
        TØ2=TØ2+DR
        WRITE(5,*) 'INPUT MCOR(LBM/MIN) RPS(HZ)'
        READ(5,*) MCOR,RPS
        WRITE(5,*) 'INPUT OUTPUT UNIT(5=TERM 6=PRINTER)'
        READ(5,*) NUNIT
        MCOR=MCOR/(6Ø.*G)
        MFLO=MCOR*(PØ1/PREF)/SQRT(TØ1/TREF)
        VT2=CP*(TØ2/TØ1-1)*TØ1/(2*PI*R2*RPS)
C       INTIAL GUESS FOR VR2
        VR2=MFLO*R*TØ2/(AD*PØ2)
        WRITE(5,*) 'INITIAL VR2 GUESS=',VR2
```

```
C       ITERATE FOR VR2
        X=1.-(VR2**2.+VT2**2.)/(2.*CP*TØ2)
1Ø      FUN=MFLO/AD-PØ2*VR2*X**(1./(K-1.))/(R*TØ2)
        DFUN=-PØ2*(X**(1./(K-1.))-VR2**2.*X**((2.-K)/(K-1.))/((K-1.)
     1  *CP*TØ2))/(R*TØ2)
        VR2OLD=VR2
        VR2=VR2-FUN/DFUN
        WRITE(5,*) 'VR2=',VR2
        IF(ABS(VR2/VR2OLD-1.) .GT. .ØØØØ1) GO TO 1Ø
        SWIRL=VT2/VR2
        ALPHA2=ATAN(SWIRL)
        V2=SQRT(VR2**2.+VT2**2.)
        M2=SQRT((X**-1.-1.)*2./(K-1.))
        UTIP=2*PI*R2*RPS
        SLIPV=UTIP-VT2
        SLIPP=VT2/UTIP
        STANSV=UTIP*(.63*PI/Z)
        STANVT=UTIP-STANSV
        STANSP=STANVT/UTIP
        ERR=1ØØ.*(STANVT-VT2)/VT2
        WRITE(NUNIT,*) 'DIFFUSER INLET CALCULATION'
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'PØ1(PSIA)=',PØ1/144.,'TØ1(DEG F)=',TØ1-DR
        WRITE(NUNIT,*) 'PØ2(PSIA)=',PØ2/144.,'TØ2(DEG F)=',TØ2-DR
        WRITE(NUNIT,*) 'MCOR(LBM/MIN)=',MCOR*G*6Ø.
        WRITE(NUNIT,*) 'RPS(HZ)=',RPS
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'DIFFUSER GEOMETRY'
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'INLET RADIUS(IN)=',R2*12.
        WRITE(NUNIT,*) 'CHANNEL WIDTH(IN)=',WD*12.
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'AIR PROPERTIES'
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'K=',K
        WRITE(NUNIT,*) 'CP(BTU/LBM DEG F)=',CP/G/J
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'CALCULATION RESULTS'
        WRITE(NUNIT,*) ' '
        WRITE(NUNIT,*) 'MFLO(LBM/MIN)=',MFLO*G*6Ø.
        WRITE(NUNIT,*) 'VT2(FT/SEC)=',VT2
        WRITE(NUNIT,*) 'VR2(FT/SEC)=',VR2
        WRITE(NUNIT,*) 'IMPELLER TIP SPEED(FT/SEC)=',UTIP
        WRITE(NUNIT,*) 'SLIP VELOCITY(FT/SEC)=',SLIPV
        WRITE(NUNIT,*) 'SLIP PARAMETER=',SLIPP
        WRITE(NUNIT,*) 'SWIRL PARAMETER=',SWIRL
        WRITE(NUNIT,*) 'INLET FLOW ANGLE(DEG)=',ALPHA2*36Ø./2./PI
        WRITE(NUNIT,*) 'INLET MACH NUMBER=',M2
        WRITE(NUNIT,*) 'STANITZ PREDICTED VT2(FT/SEC)=',STANVT
        WRITE(NUNIT,*) 'STANITZ PREDICTED SLIP VELOCITY(FT/SEC)=',STANSV
        WRITE(NUNIT,*) 'STANITZ PREDICTED SLIP PARAMETER=',STANSP
        WRITE(NUNIT,*) 'STANITZ PREDICTED SLIP VELOCITY ERROR(%)=',ERR
        STOP
        END
```

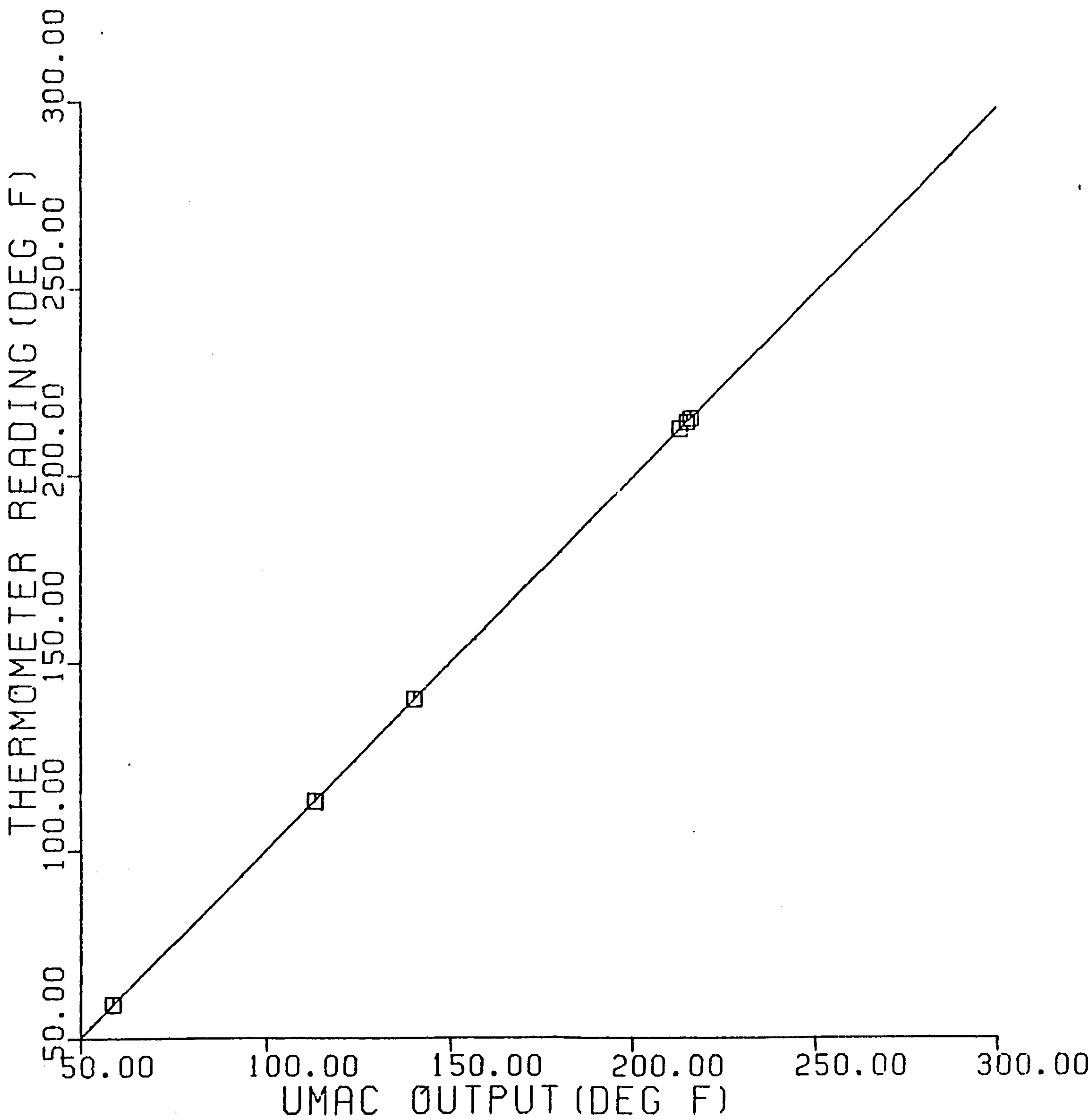

1.00
0.80
0.60
0.40
0.20
0.00
V/VIS
0.00
0.20
0.40
0.60
0.80
1.00
R/RO
INLET VELOCITY PROFILE
RUN NUMBER= 016

SCANIVALVE CALIBRATION

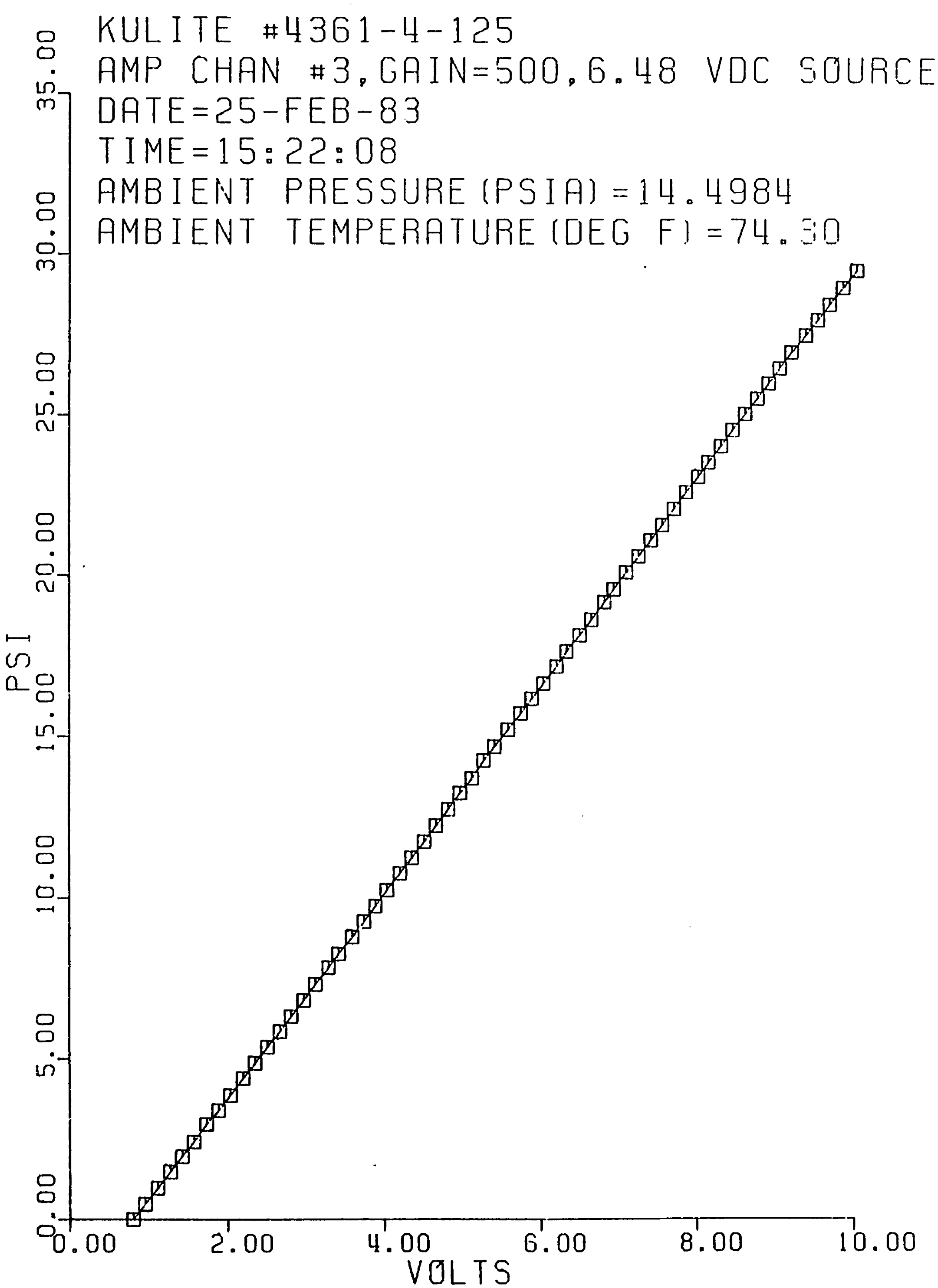
DATE=25-MAR-83
TIME=22:08:08
AMBIENT PRESSURE(PSIA)=14.3427
AMBIENT TEMPERATURE(DEG F)=67.10



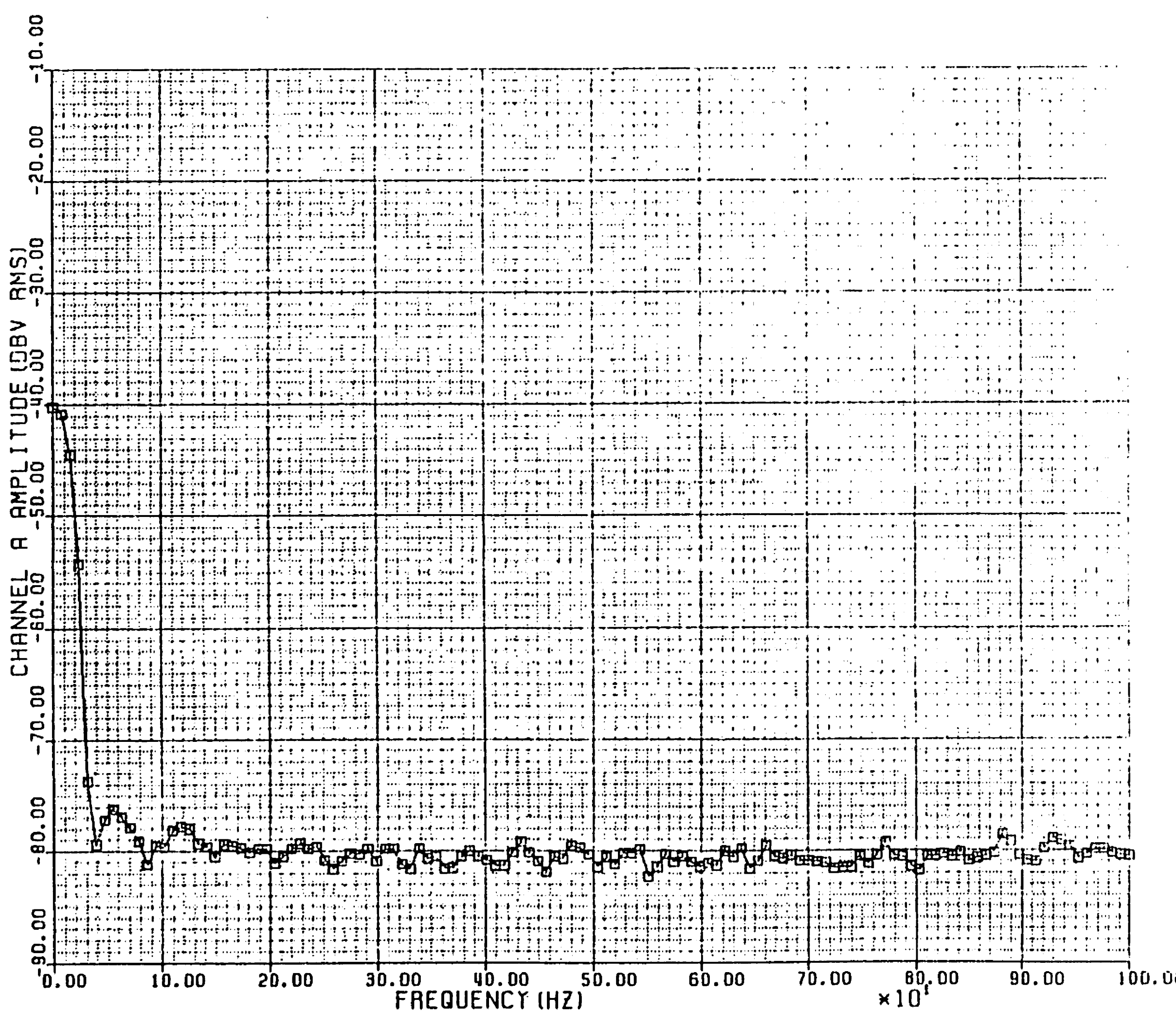
UMAC-4000 CALIBRATION



KULITE CALIBRATION

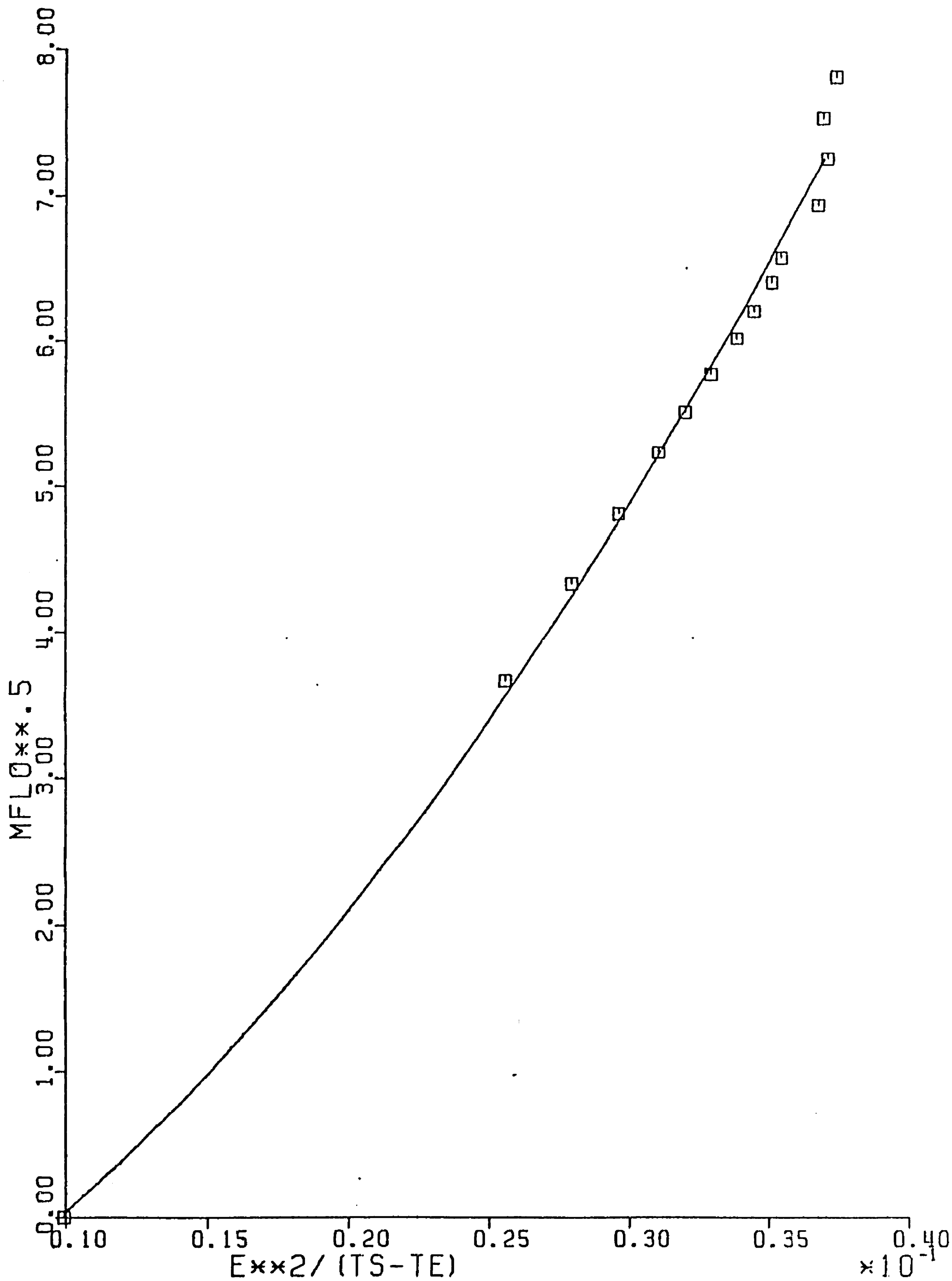


KULITE #3 NØISE
CHANNEL 3
-KULITE #3 AMPLITUDE

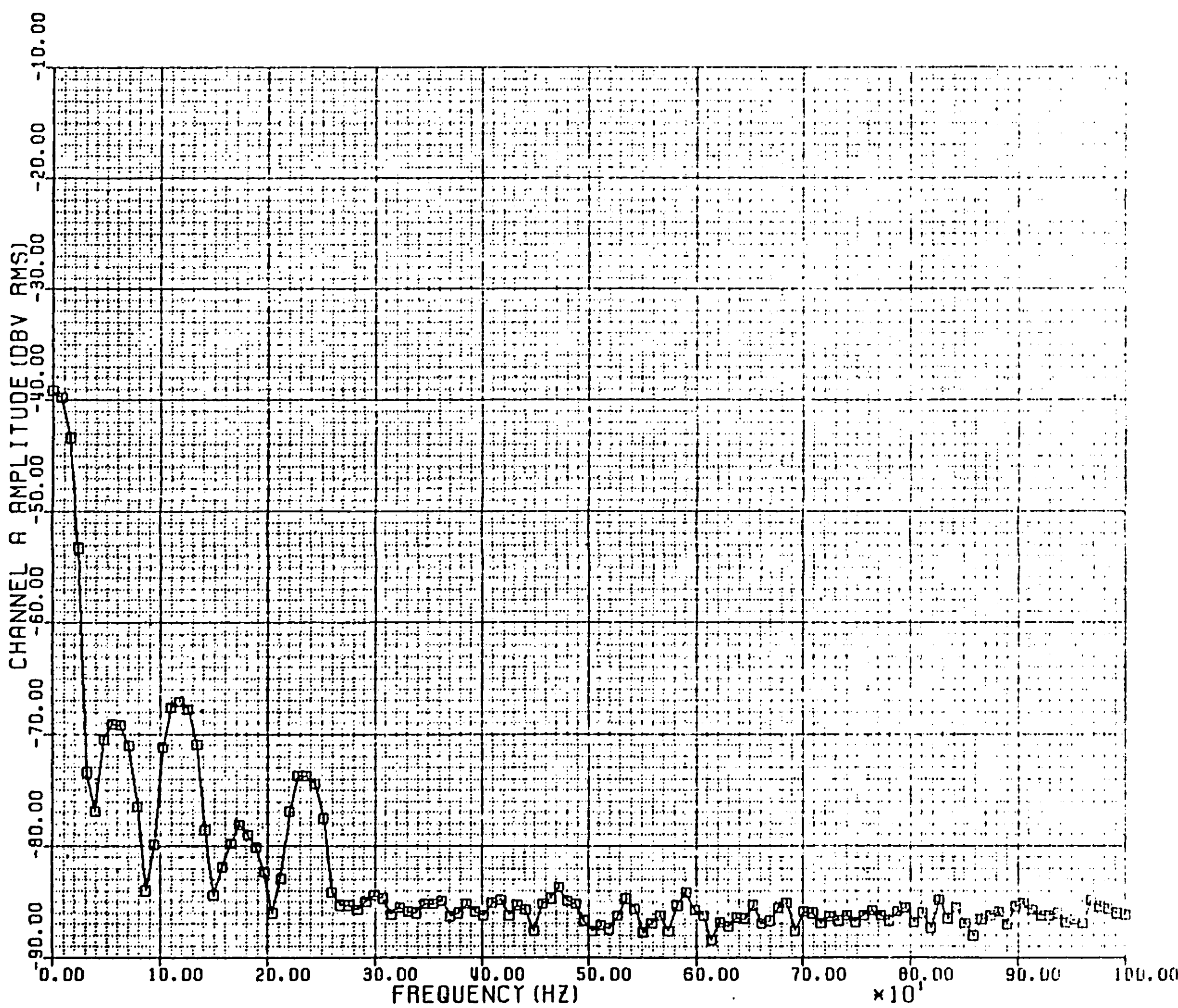


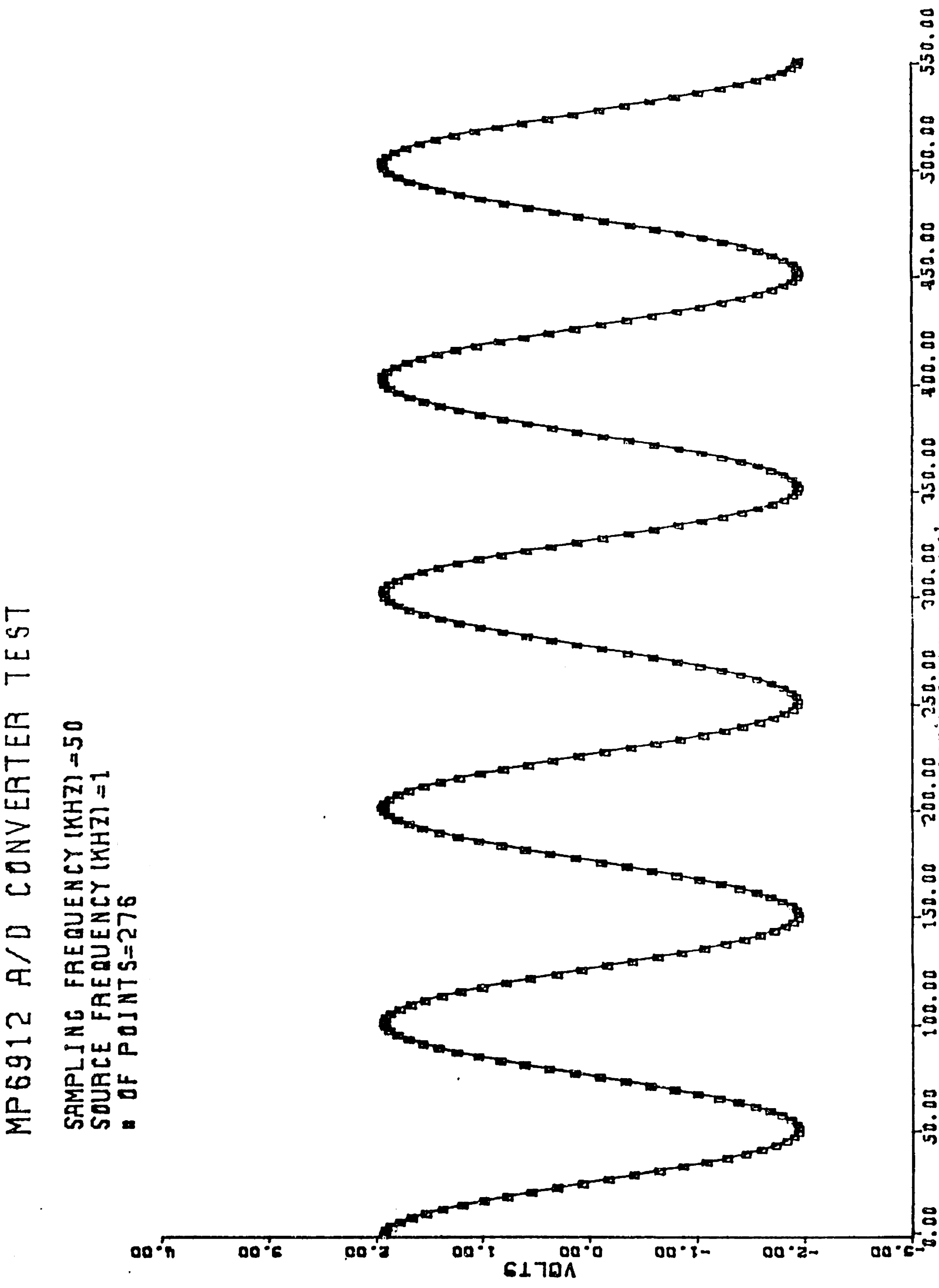
INLET HØTWIRE CALIBRATION

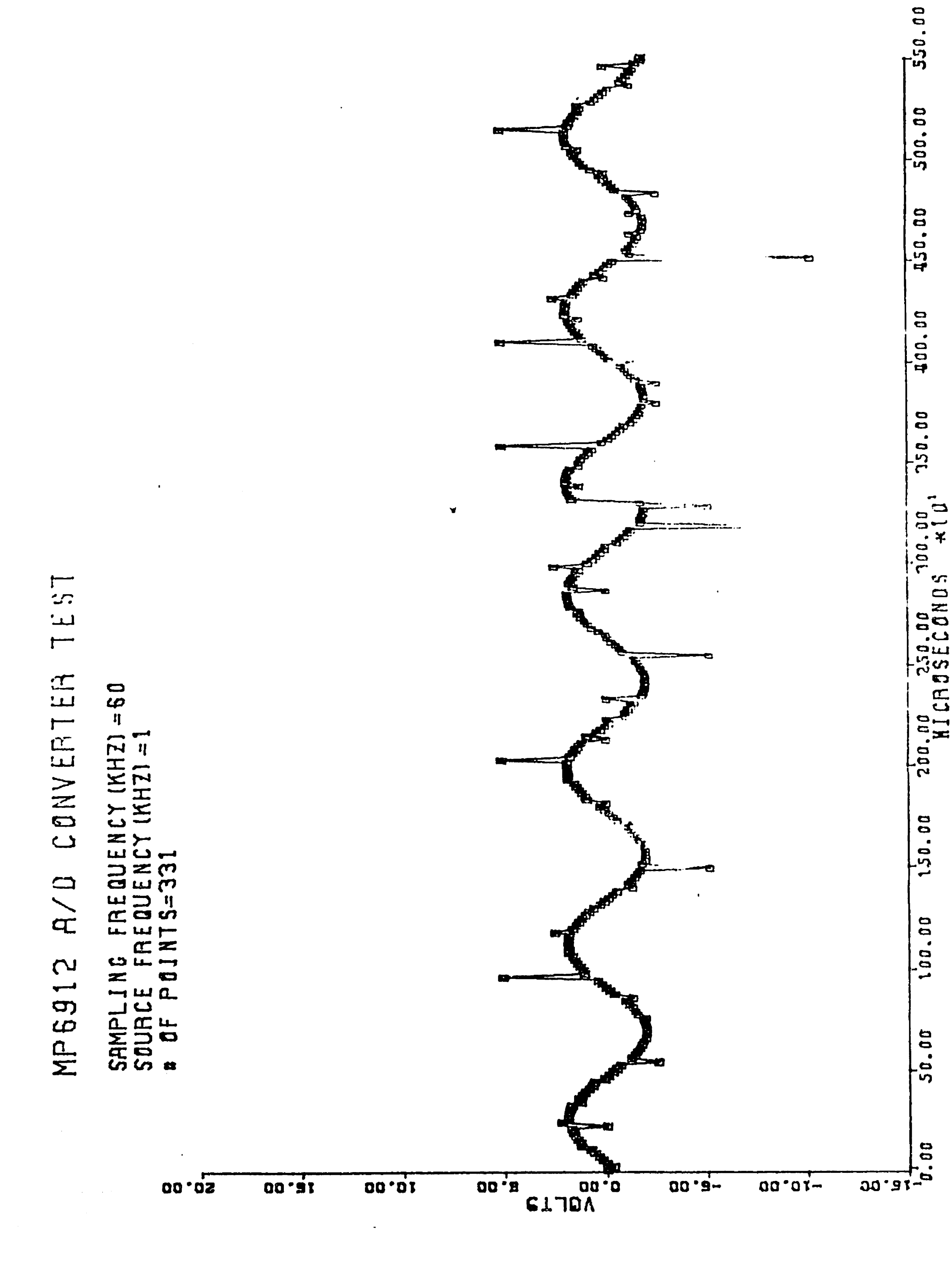
100 POINT AVERAGE AT 50 HZ
HØTWIRE TEMPERATURE (TS) =250 DEG C



INLET HOTWIRE NOISE
CHANNEL 0
□ -INLET HOTWIRE AMPLITUDE




MP6912 A/D CONVERTER TEST
SAMPLING FREQUENCY(KHZ)=50
SOURCE FREQUENCY(KHZ)=1
OF POINTS=276
VOLTS
MICROSECONDS *10^1
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
550.00


MP6912 A/D CONVERTER TEST
SAMPLING FREQUENCY(KHZ)=60
SOURCE FREQUENCY(KHZ)=1
OF POINTS=331
VOLTS
MICROSECONDS *10¹
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
550.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00

$$\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} = B(\tilde{C} - \Delta\tilde{P}) \qquad \text{Eq. (11) of \{19\}} \quad (1)$$

$$\frac{d\tilde{\dot{m}}_t}{d\tilde{t}} = \frac{B}{G}(\Delta\tilde{P} - \tilde{F}) \qquad \text{Eq. (12) of \{19\}} \quad (2)$$

$$\frac{d\Delta\tilde{P}}{d\tilde{t}} = \frac{1}{B}(\tilde{\dot{m}}_c - \tilde{\dot{m}}_t) \qquad \text{Eq. (13) of \{19\}} \quad (3)$$

$$\frac{d\tilde{C}}{d\tilde{t}} = \frac{1}{\tilde{\tau}}(\tilde{C}_{ss} - \tilde{C}) \qquad \text{Eq. (14) of \{19\}} \quad (4)$$

Assume $\tilde{\tau} = 0$ and $G = 0$

Then $\tilde{C}_{ss} = \tilde{C}$ (4a)

and $\Delta\tilde{P} = \tilde{F}$ (2a)

Then we have three equations

$$\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} = B(\tilde{C} - \Delta\tilde{P}) \quad (1)$$

$$\Delta\tilde{P} = \tilde{F} \quad (2a)$$

$$\frac{d\Delta\tilde{P}}{d\tilde{t}} = \frac{1}{B}(\tilde{\dot{m}}_c - \tilde{\dot{m}}_t) \quad (3)$$

Differentiate (2a)

$$\Delta\tilde{P} = \tilde{F}(\tilde{\dot{m}}_t) \qquad \frac{d\Delta\tilde{P}}{d\tilde{t}} = \tilde{F}'\frac{d\tilde{\dot{m}}_t}{d\tilde{t}} \quad (2b)$$

Substitute (2b) into (3) to get

$$\frac{d\tilde{\dot{m}}_t}{d\tilde{t}} = \frac{1}{B\tilde{F}'}\left(\tilde{\dot{m}}_c - \tilde{\dot{m}}_t\right) \qquad (5)$$

Substitute (2a) into (1) to obtain

$$\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} = B\left(\tilde{C} - \tilde{F}\right) \qquad (6)$$

For a stability analysis at point of intersection of characteristics shown in Figure 28 linearize the compressor and throttle characteristics as

$$\tilde{C} = \tilde{C}'\,\tilde{\dot{m}}_c + \tilde{C}_o \qquad (7)$$

and

$$\tilde{F} = \tilde{F}'\,\tilde{\dot{m}}_t + \tilde{F}_o \qquad (8)$$

Substituting (7) and (8) into (6) gives

$$\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} = B\left(\tilde{C}'\tilde{\dot{m}}_c + \tilde{C}_o - \tilde{F}'\tilde{\dot{m}}_t - \tilde{F}_o\right) \qquad (6a)$$

Eliminate $\dot{m}_t$ from equations (5) and (6a) to obtain a linear 2nd order equation in $\tilde{\dot{m}}_c$

Differentiate (6a) to get

$$\frac{d^2 \tilde{\dot{m}}_c}{d\tilde{t}^2} = B\left(\tilde{C}' \frac{d\tilde{\dot{m}}_c}{d\tilde{t}} - \tilde{F}' \frac{d\tilde{\dot{m}}_T}{d\tilde{t}}\right) \quad (6b)$$

Substitute for $\frac{d\tilde{\dot{m}}_t}{d\tilde{t}}$ in (6b) the expression of (5) to give

$$\frac{d^2 \tilde{\dot{m}}_c}{d\tilde{t}^2} = B\left(\tilde{C}' \frac{d\tilde{\dot{m}}_c}{d\tilde{t}} - \frac{(\tilde{\dot{m}}_c - \tilde{\dot{m}}_t)}{B}\right) \quad (9)$$

Solve (6a) for $\tilde{\dot{m}}_t$

$$B\tilde{F}'\tilde{\dot{m}}_t = B(\tilde{C}'\tilde{\dot{m}}_c + \tilde{C}_o - \tilde{F}_o) - \frac{d\tilde{\dot{m}}_c}{d\tilde{t}}$$

or

$$\tilde{\dot{m}}_t = \frac{1}{\tilde{F}'}(\tilde{C}'\tilde{\dot{m}}_c + \tilde{C}_o - \tilde{F}_o) - \frac{1}{B\tilde{F}'}\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} \quad (10)$$

Substitute (10) into (9) to give

$$\frac{d^2 \tilde{\dot{m}}_c}{d\tilde{t}} + \left(\frac{1}{B\tilde{F}'} - B\tilde{C}'\right)\frac{d\tilde{\dot{m}}_c}{d\tilde{t}} + \left(1 - \frac{\tilde{C}'}{\tilde{F}'}\right)\tilde{\dot{m}}_c = \frac{\tilde{C}_o - \tilde{F}_o}{\tilde{F}'}$$

(11)

1) Preheat oil by turning on the heater switch located on the instrumentation panel. Also check oil level in tank.

2) Turn on valve controller and check that steam ejector valve reads closed (0%) as well as the hi-pressure air valve. The hi-pressure air valve in parallel with the motorized valve should also be closed(handle down) along with the compressor throttle valve and bypass valve(manual valve).

3) Turn on oil-free compressor and the 6 inch steam ejector in basement. Call M.I.T. central utilities at ext3-4753 before turning on steam ejector.

4) Shut air regulator valve on panel

5) Open nitrogen bottle valve and adjust bottle regulator pressure to 150 psi.

6) Open air regulator valve on panel.

7) With oil recirculation valve on upper pipe fully open and valve to turbo shut turn on oil pump.

8) Adjust oil pump pressure(guage O2) to 40 psi-60 psi.

9) Open steam ejector valve on the controller until turbo begins to turn over(≈ 19% open)

10) Once RPM is established fully open the turbo bearing valve. Oil pressure(guage O1) should immediately begin to rise. If no pressure is seen turn off immediately and investigate cause(most likely low oil supply level in the tank).

11) Slowly close oil bypass valve until turbo inlet bearing pressure reads 40 psi.

12) To establish flow point envolves adjusting a combination of the compressor throttle, compressor bypass, steam ejector, and oil-free air compressor valves. For high flow lower speeds, compressor bypass valve is opened. For higher speeds, it is left closed or slightly open.

13) For high speeds from 48 to 52K, the oil cooler should be used. The water supply valve is opened slightly. A very small flowrate supplies sufficient cooling for these speeds. Oil temperatures(T2) of about 180-210 deg F should be maintained. Oil temperatures higher than 230 deg F should

be avoided as speed variations become larger making a steady operating point difficult to maintain.

14) Shutdown is accomplished by first shutting the hi-pressure valve and then closing the air ejector valve. When turbo has stopped spinning oil pump can be turned off along with other valves and switches.