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**AN EXPERIMENTAL EVALUATION OF
UNSTEADY FLOW EFFECTS ON AN
AXIAL COMPRESSOR**

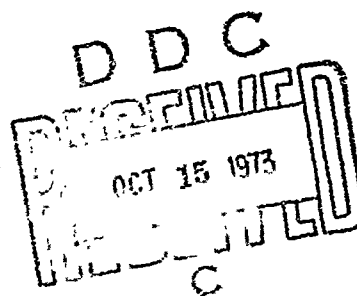
P3 GENERATOR PROGRAM

G. G. REYNOLDS

W. F. VIER

T. P. COLLINS

GENERAL ELECTRIC COMPANY



TECHNICAL REPORT AFAPL-TR-73-43

JULY 1973

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FOREWORD

This report was prepared by the Aircraft Engine Group, General Electric Company for the Air Force Aero Propulsion Laboratory, Air Force Systems Command, under Contract No. F33615-73-C-2001.

The work reported herein was conducted under the technical cognizance of Mr. Richard J. Martin, Turbine Engine Division, Air Force Aero Propulsion Laboratory during the period 1 July 1972 thru 1 July 1973.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


ERNEST C. SIMPSON, Director
Turbine Engine Division
AF Aero Propulsion Laboratory

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A test program has been successfully completed to obtain fundamental information concerning the behavior of a fan compressor unit when subjected to planar pressure and flow pulses. Testing was conducted at two corrected fan speeds over a range of input pressure amplitudes and frequencies. A total of 24 fan surges and approximately fifty-seven "steady-state" data points were obtained. The General Electric developed Planar Pressure Pulse Generator (P³G) was used to produce a sinusoidal type pressure disturbance to a current technology two-stage fan inlet. A thorough complement of dynamic instrumentation, consisting of approximately 45 transducers, was utilized throughout the testing. Data reduction is complete and several fundamental results have been obtained.		

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ABSTRACT

A test program has been successfully completed to obtain fundamental information concerning the behavior of a fan compressor unit when subjected to planar pressure and flow pulses. Testing was conducted at two corrected fan speeds over a range of input pressure amplitudes and frequencies. A total of 24 fan surges and approximately 57 "steady-state" data points was obtained. The General-Electric-developed Planar Pressure Pulse Generator (P³G) was used to produce a sinusoidal-type pressure disturbance to a current technology two-stage fan inlet. A thorough complement of dynamic instrumentation, consisting of approximately 45 transducers, was utilized throughout the testing. Data reduction is complete and several fundamental results have been obtained.

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<u>Name</u>	<u>Description</u>	<u>Units</u>
P_{T25}	Face Average Total Pressure at Plane 25	psia
R-T-S	P^3_G Rotor-to-Stator Spacing	inches
T_{TIGV}	Face Average Total Temperature at IGV	° R
T_{T14}	Face Average Total Temperature at Plane 14	° R
T_{T25}	Face Average Total Temperature at Plane 25	° R
W_A	Physical Airflow	pps
W_{TC} or W_C	Total Corrected Airflow	pps
$W_{14/25}$	Total Corrected Airflow at Surge Based on $P_{R14/25}$	pps
W_{14}	Total Corrected Airflow at Surge Based on P_{R14}	pps
W_{F14}	Bypass Duct Corrected Airflow	pps
W_{F25}	Core Corrected Airflow	pps

1.0 INTRODUCTION

A substantial amount of data reported in the last several years has qualitatively documented the deleterious effects of dynamic distortion on engine stability. However, very little information is available to define the quantitative effects.

The majority of the data available to quantify the effects of dynamic distortion has been obtained with an inlet flow field having a random-type, time-variant pressure distortion. This flow field is produced by actual aircraft inlets, turbulators, random frequency generators, or inlet simulators. Results obtained from this type of data are quite useful but limited by the accuracy of the definition of the clean stall line, the steady-stage distortion correlation, and the operating test conditions. Furthermore, because of the random nature of the disturbance, the results do not provide a basis for establishing detailed compression system response characteristics.

The objective of this program was to obtain fundamental information by subjecting a fan compression unit to planar, discrete frequency pressure pulses in order to provide a systematic basis for establishing the fan component dynamic response and a source of data for correlating and refining analytical models.

This report contains a description and results discussion of the test program undertaken to obtain this type of fundamental information.

2.0 SUMMARY

The General-Electric-developed Planar Pressure Pulse Generator (P³G) was tested with a two-stage fan at Lynn, Massachusetts, in the Large Fan Test Facility on February 6 and February 8, 1973. A total of 24 surges was encountered; 23 were induced in the presence of unsteady flow, and one was a steady-state posttest surge check. Fan and P³G mechanical operations were smooth and no serious problems or structural damage were incurred. Fifty-three data points were taken to monitor operation at 80% and 100% corrected fan rotor speed over a P³G frequency range of 42 to 800 Hz at basically two different levels of pulse amplitude. A full complement of steady-state and dynamic instrumentation and associated signal conditioning equipment was installed to record each data point and surge condition.

The data acquired during this program permitted documentation of planar, unsteady flow effects on the fan. Compressor sensitivities to "dynamic distortion" and "dynamic distortion transfer" characteristics were computed for every pertinent data point. The aerodynamic performance of the planar pulse generator was defined in terms of flow character at the inlet to the fan. Overall system aerodynamic response was recorded.

As much basic engineering data as practicable have been presented in order to provide an in-depth documentation of the test program for future reference.

3.0 TEST HARDWARE DESCRIPTION

3.1 DESCRIPTION OF P³G GENERATOR

The P³G was developed to provide a means of fan inlet flow/pressure throttling in a sinusoidal manner for determination of the dynamic response of a compression unit. The sinusoidal inlet flow/pressure throttling is accomplished by a method very similar to a siren - chopping the airflow with a rotating disk and a stationary disk with mating holes in each. The similarity ends there, because the P³G aerodynamic design is more sophisticated in order to minimize the steady-state pressure losses that do not contribute to the pulse-generating phenomena and to ensure uniform and planar waves that result in good sinusoidal variation in pressure/flow. Furthermore, a choked condition exists at the airflow chopping plane so as to gain a very high output level of fluctuations.

The basic mechanical design is novel and innovative, yet the design levels are conservative. The mechanical design of the system tested consists of triple rotors (all coaxial) with gear-controlled rotor speeds in inverse proportion to the number of holes in the radial rows in each of these rotating disks. Aerodynamic considerations dictated uniform hole sizing in the rotor which, in turn, necessitated the multiple rotor design. An axially translating stationary disk (stator) with mating holes (≈ 2500) to the rotating disks (rotor) provides a variable axial clearance between the rotor and the stator. Thus, the frequency of the air pulses generated is controlled by rotor speed, and the amplitude is controlled by the rotor-to-stator (R-T-S) spacing and the amount of airflow through the holes.

The rotor speed relationships and disk-to-disk hole opening/closing cycle phasing is accomplished in the radial drive assembly. Radial drive was chosen for minimizing the P³G's axial length and airflow blockage. Radial drive also provides compactness and serviceability as shown in Figure 1. This compactness was definitely needed in the Lynn Facility as shown in Figure 2.

The P³G's operational success can be partially attributed to the mechanical reviews and tests conducted throughout the development. The final check-out was a through-flow test that was successfully performed in the actual installation with the fan. The following operational characteristics, fundamental to the program's ultimate success, were demonstrated:

- P³G mechanical and aerodynamic integrity
- Capability to stall the fan component with planar pulses
- Capability to clear fan surge quickly with normal procedures

Photographs of the P³G system are shown in Figures 3 and 4. Figure 3 is a view of the downstream side of the device along with the control consoles for the 75 HP drive motor and the three stator axial positioning synchronous motors (i.e., P³G output frequency and amplitude controls, respectively). Figure 4

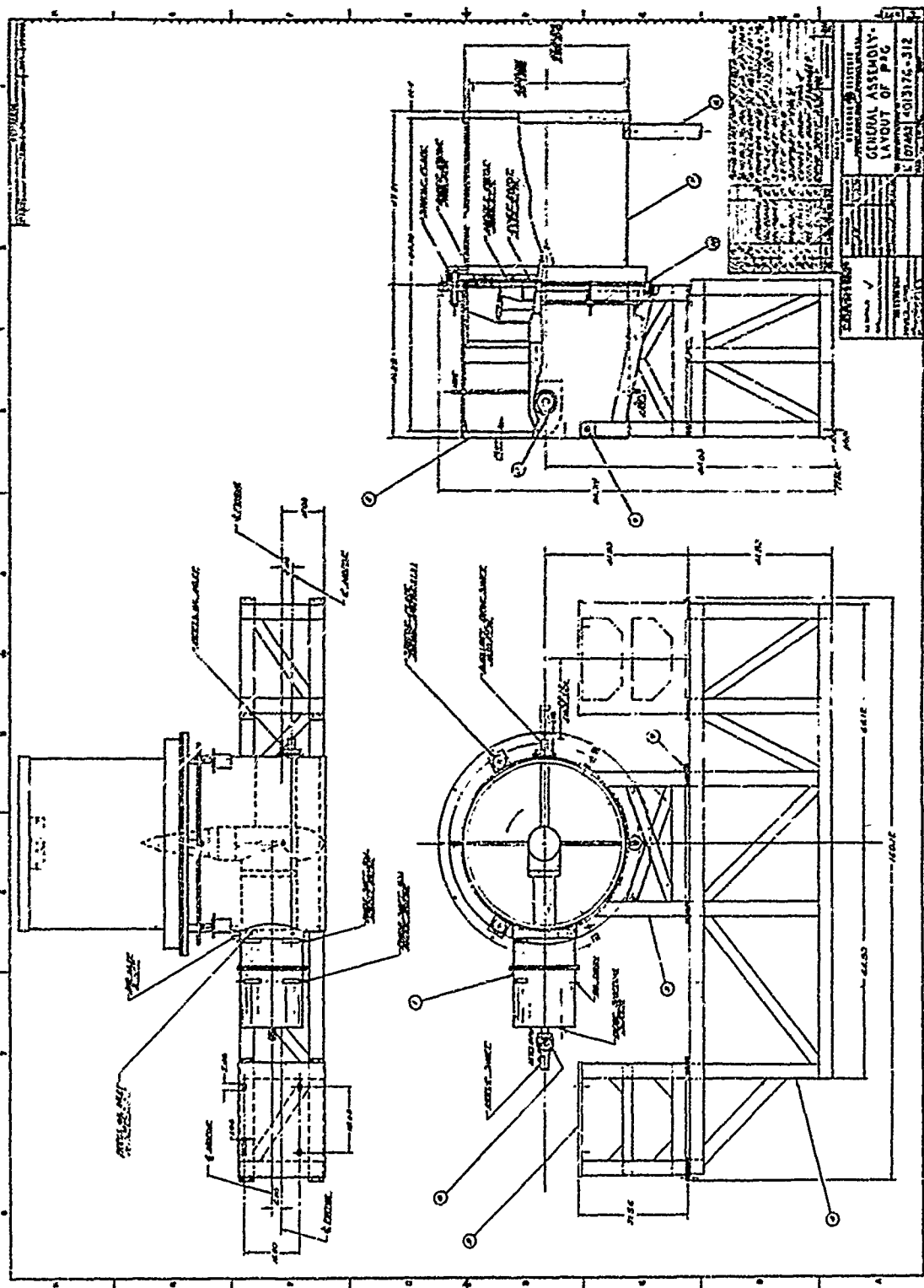


Figure 1. General Assembly of p³G.

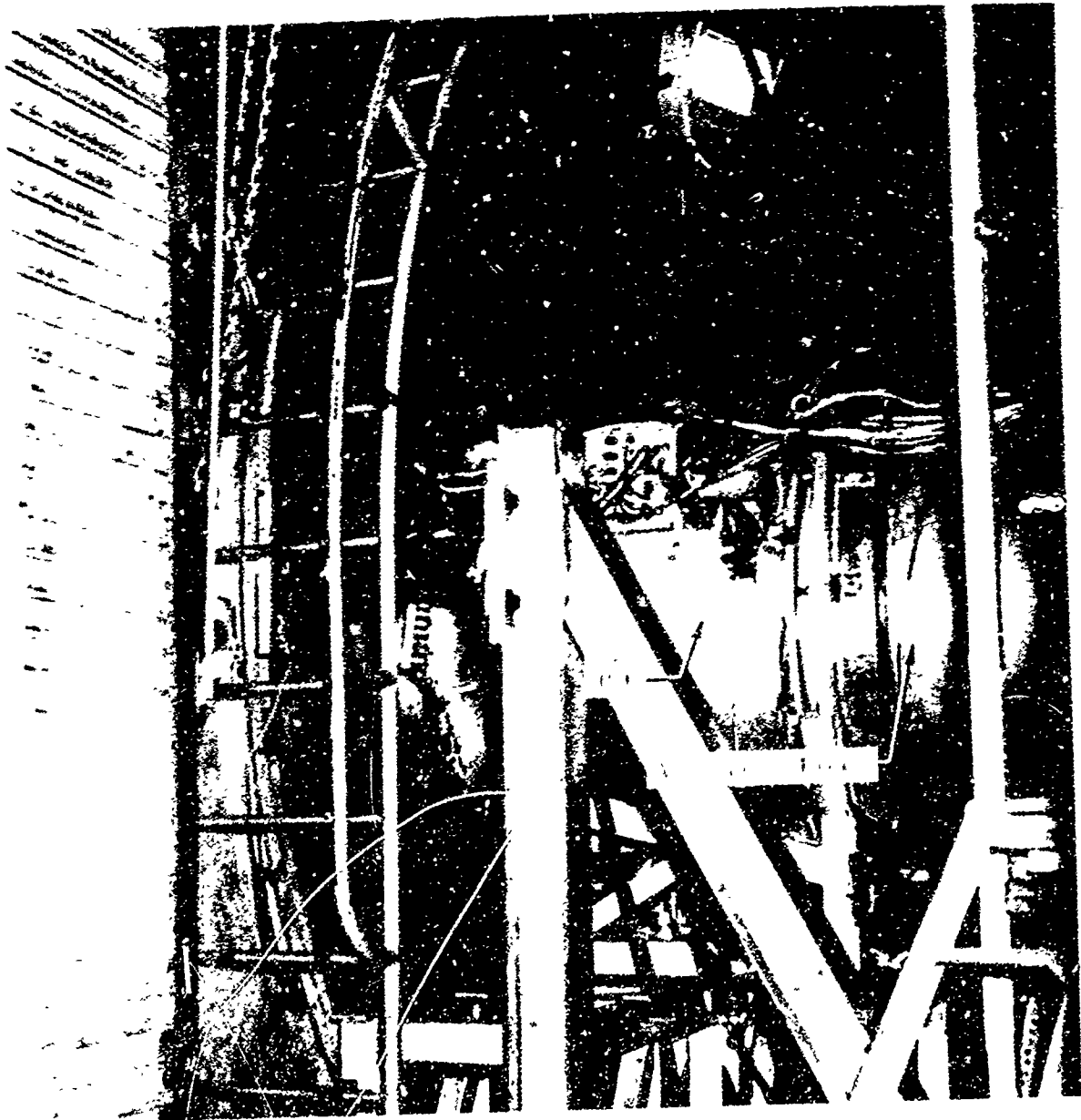


Figure 2. P^3G Installation.

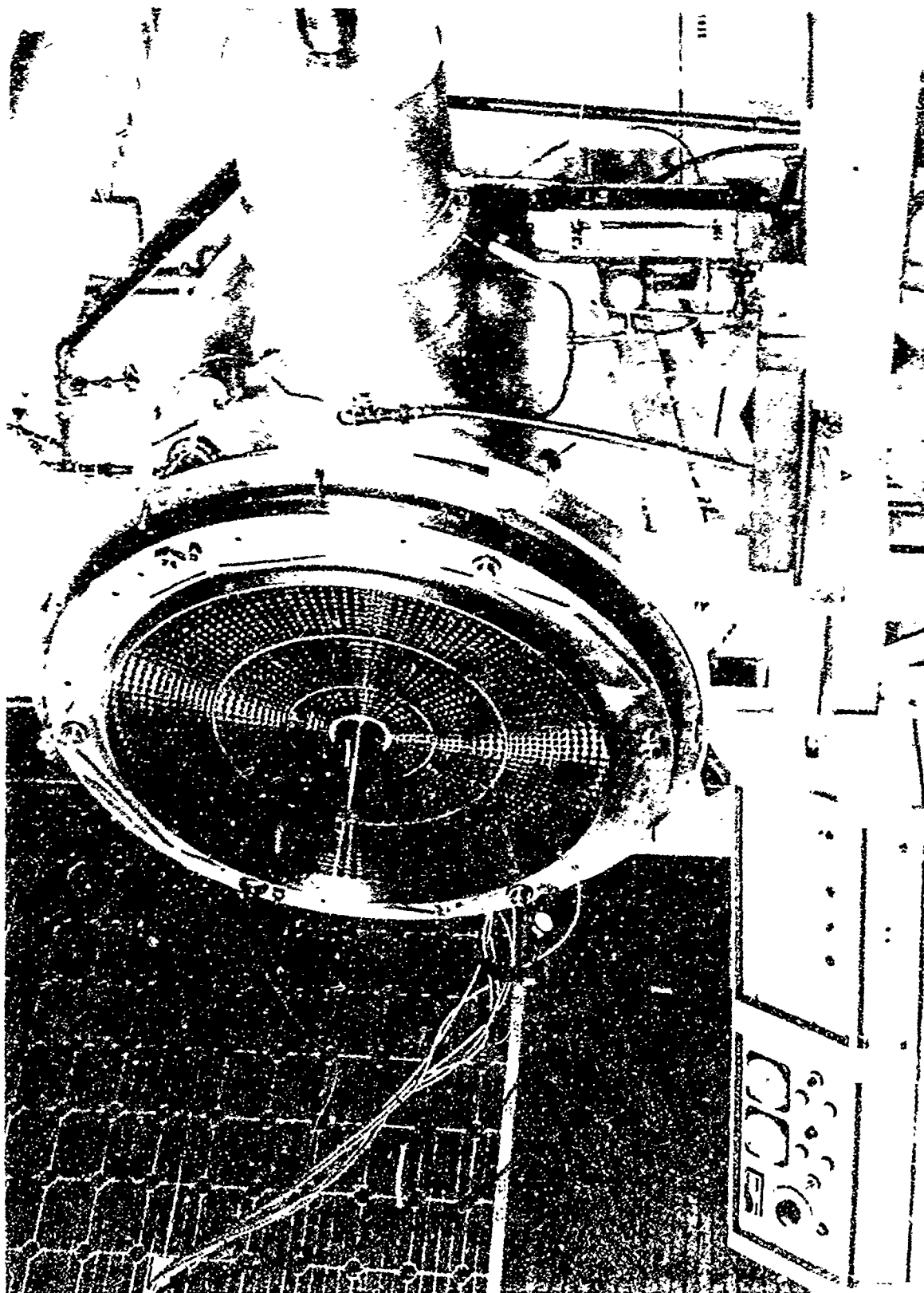


Figure 3. P^3G Downstream Section.

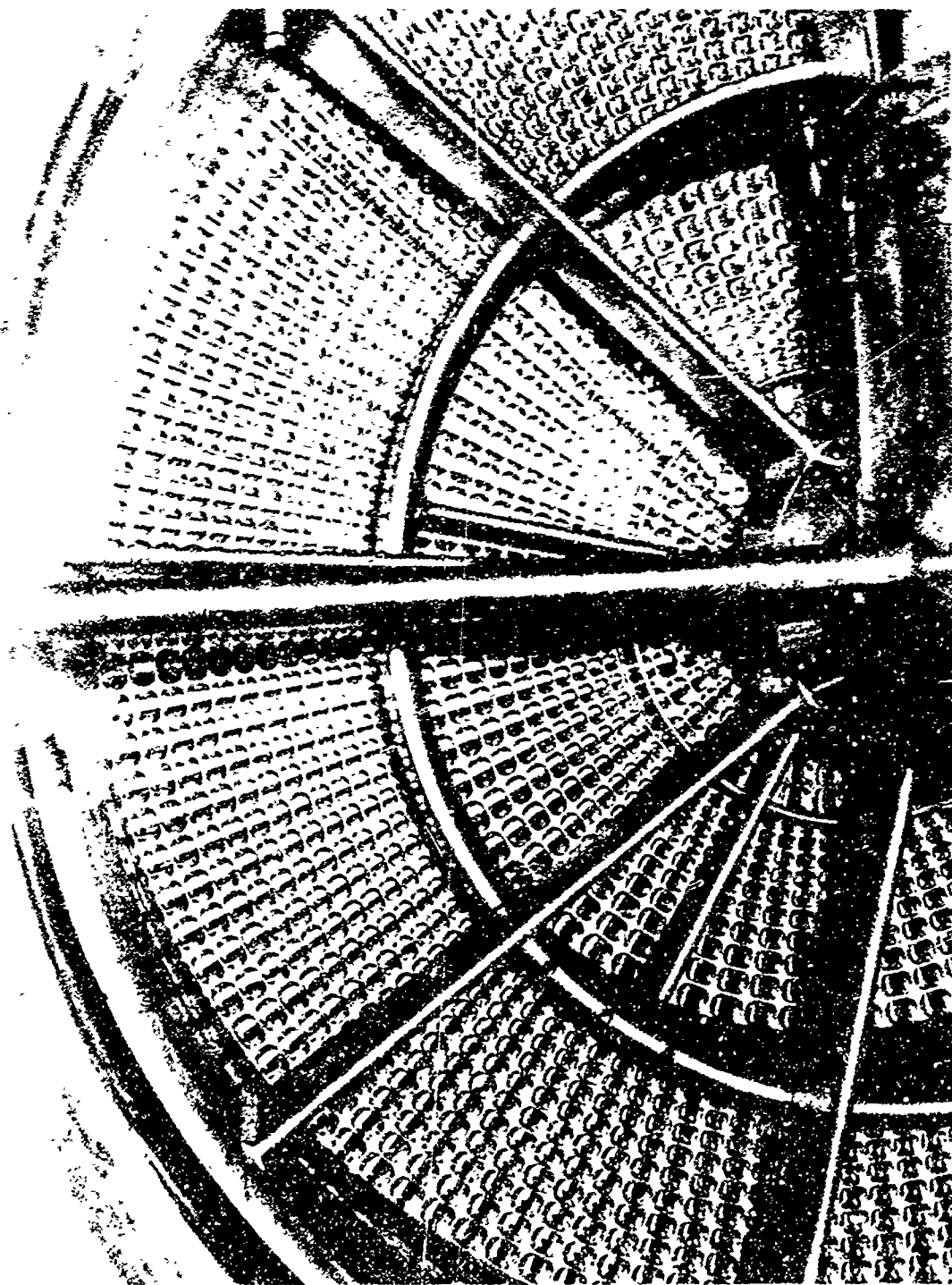


Figure 4. P^3G Inlet View.

is a view into the inlet showing the triple rotor system in the minimum area position of the airflow-chopping cycle.

3.2 FAN COMPONENT VEHICLE DESCRIPTION

The fan component is a two-stage flight-type design with the necessary adaptive hardware for its installation in Lynn's Large Fan Test Facility (LFTF). Tip shrouds (sealing type) are used on both rotors. This vehicle uses variable front frame strut flaps for IGV's and has both vane stages variable. The "design choice" vane schedule was used for the P³G test.

3.3 TEST FACILITY AND INSTALLATION DESCRIPTION

The Large Fan Test Facility (LFTF) is an open-loop flow system located at GE's AEG Plant in Lynn, Massachusetts. A cross-sectional view of this facility in this test setup configuration is seen in Figure 5. Note that the fan is driven from the rear. The facility features inlet protection, silencing, and throttling as well as discharge throttling and airflow measurement. A 33,000 HP steam turbine is the fan's power source.

3.4 INSTRUMENTATION DESCRIPTION

P³G Vehicle Safety. Necessary safety and condition monitoring instrumentation and readout were provided on the P³G. Details of this instrumentation are included in Reference 2.

Aerodynamic Instrumentation. The dynamic instrumentation consists of "Kulite" transducers mounted such that flat amplitude and phase response exist out to 500 Hz. One hot-film probe with response from 0 to well above 500 Hz was used to measure fan inlet flow variation. Location of these probes can best be described by Figure 6 which includes a complete listing of aerodynamic instrumentation and some of the related steady-state instrumentation. Table I summarizes the working dynamic parameters. The steady-state instrumentation is listed in Table II.

3.5 DYNAMIC DATA ACQUISITION SYSTEM

This system, known as the "DCS System," was tailored for acquiring output information from a large number of "Kulite" pressure transducers. Basically, it contains the transducer excitation, transducer bridge and its temperature compensation, signal sensitivity normalizing amplifiers, zero suppression (adjustment), 84-channel multiplexing capability, and a 14-channel tape deck.

A reference pressure system was used for all Kulite transducers. This system is basically a set of solenoid pressure switches and differential

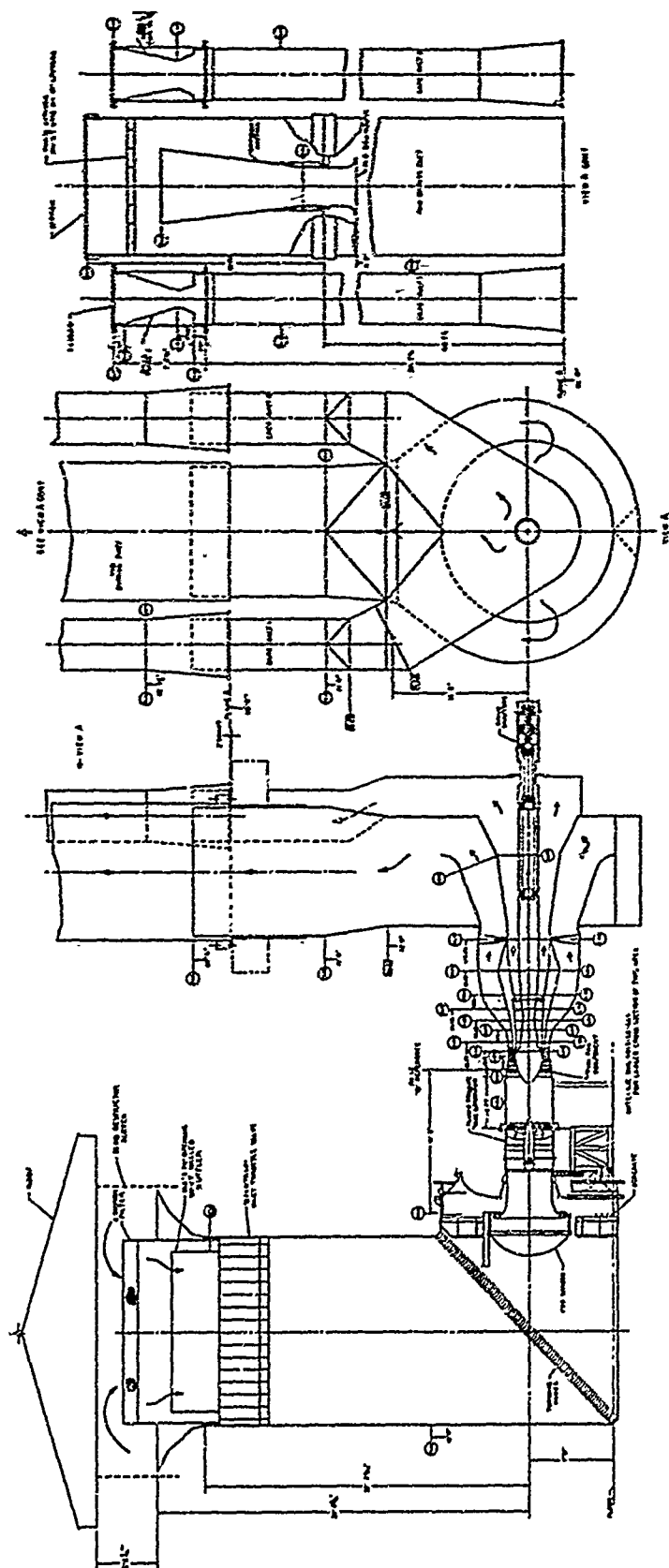


Table I. Aerodynamic Instrumentation, Status Summary of Retrievable Measurements/Planned Measurements.

<u>Run 1 - 2/6/73</u>	<u>Plane</u>	<u>P_T</u>	<u>P_S</u>	<u>P_V</u>	<u>Totals</u>
Prerun	IGV	9/12	0/2	1/1	10/15
	S1	0/1	0/1	---	1/4
	S2	0/1	1/1	---	
	14	4/8	1/2	---	5/10
	25	16/20	1/1	---	17/21
	Misc.	---	5/8	---	5/8
Postrun	IGV	9/12	0/2	0/1	9/15
	S1	0/1	0/1	---	1/4
	S2	0/1	1/1	---	
	14	4/8	1/2	---	5/10
	25	14/20	1/1	---	15/21
	Misc.	---	5/8	---	5/8
<u>Run 2 - 2/8/73</u>					
Prerun	IGV	9/12	0/2	1/1	10/15
	S1	0/1	0/1	---	1/4
	S2	0/1	1/1	---	
	14	4/8	1/2	---	5/10
	25	18/20	1/1	---	19/21
	Misc.	---	5/8	---	5/8
Postrun	IGV	9/12	0/2	1/1	10/15
	S1	0/1	0/1	---	1/4
	S2	0/1	0/1	---	
	14	4/8	1/2	---	5/10
	25	18/20	1/1	---	19/21
	Misc.	---	5/8	---	5/8

Table II. Steady-State Pressure Instrumentation List.

Description	Quantity
Facility Inlet Stack Static Pressures	4
Bellmouth P_T	1
Bellmouth P_S	1
$P^3_G P_S$	1
Spacer Duct P_S	3
IGV Plane P_T	40
IGV Plane P_S	16
R1 Inlet Manifold P_S	6
S1 Leading Edge P_T	15
S1 Inlet P_S	6
S2 Leading Edge P_T	15
S2 Exit P_S	6
Plane 14 P_T	40
Plane 14 P_S	10
Plane 25 P_T	40
Plane 25 P_S	17
Bypass Discharge Duct P_S	2
Bypass Discharge Valve P_S	1
Facility Core Flow Measuring "Dall" Tube P_S	3
Facility Bypass Flow Measuring Bellmouth	4

pressure regulators [used to apply two different pressures to the reference (back) side of the diaphragm for sensitivity calibration]. In the normal mode, one of the pressures becomes the "operate" pressure which biases the output of the transducer for range optimization for a capability of better signal-to-noise ratios of the recorded transducer signals. Banks of these solenoid switches pneumatically "short" the two sides of the "Kulite" transducer diaphragm for zero drift information. A schematic of the system is shown in Figure 7.

Linked with the DCS system was a desk-top ZAI-PACE TR-48 Analog Computer for on-line data analysis. Outputs from this computer were displayed on panel meters and recorded on the light-beam oscillograph and/or Sangamo and DCS tape decks. A sample of the type of on-line reduced data from the oscillograph is shown in Figure 8.

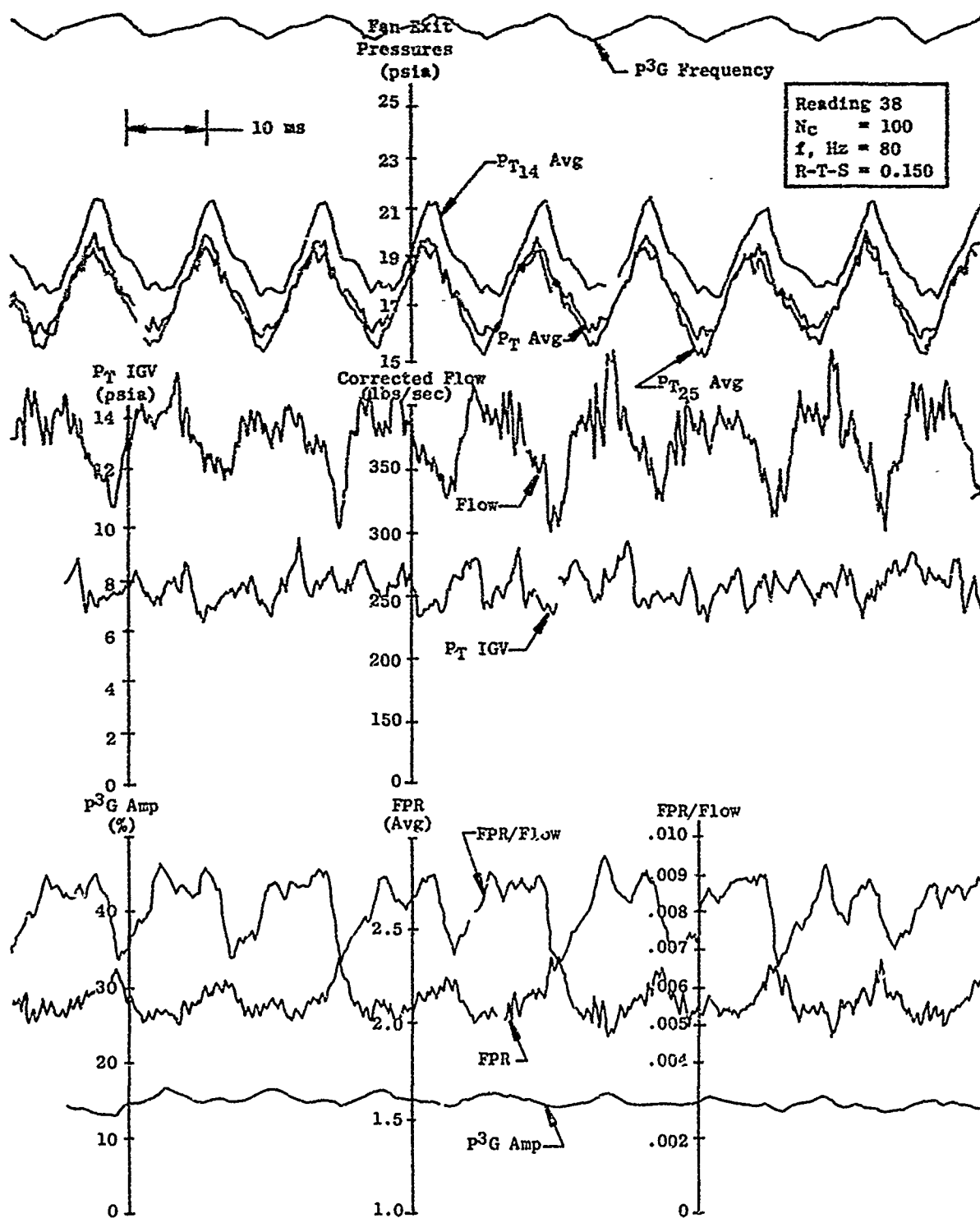


Figure 8. On-Line Data Samples.

4.0 MECHANICAL PERFORMANCE

The mechanical performance of the P³G was outstanding - no hardware failures were experienced and operation of the P³G was smooth and easy. Virtually no oil leaked into the engine airflow or onto the vehicle.

Vibration of the P³G was large in amplitude relative to aircraft engine turbomachinery; however, it was as predicted and presented no major problems. Figure 9 shows the most significant vibration parameter's level versus the generator's fundamental frequency. This parameter is the P³G stator in the axial mode. The stator experiences $\approx 95\%$ of the total dynamic loading which is in the axial direction. Stress levels seemed to be very well correlated with the vibration levels as noted on-line, and these stress levels were maintained below design limits. The remainder of vibration parameters was low (<10 mils), except the vehicle axial which demonstrated a maximum of ≈ 25 mils (peak-to-peak) at the stator critical fundamental of 60 to 65 Hz. A 4 Hz beating was always noted which indicates the critical fundamental of the total P³G system as supported in Lynn's LFTF. The isolation between the P³G and the inlet bellmouth just ahead of the P³G was not intended (probable centerline to centerline misalignment); and, thus, the P³G and bellmouth vertical vibration levels seemed to be well correlated in frequency and waveform and reached as high as 20 mils (peak-to-peak).

The facility showed no signs of damage in a subsequent inspection; however, the P³G in the through-flow check-out run was able to shake loose a sizeable amount of scale and dirt.

The fan's mechanical reaction to the P³G was quite small and did not measurably affect changes in the test plan. The maximum measured fan stress level ever obtained was 65% of limits and generally was 30% or below.

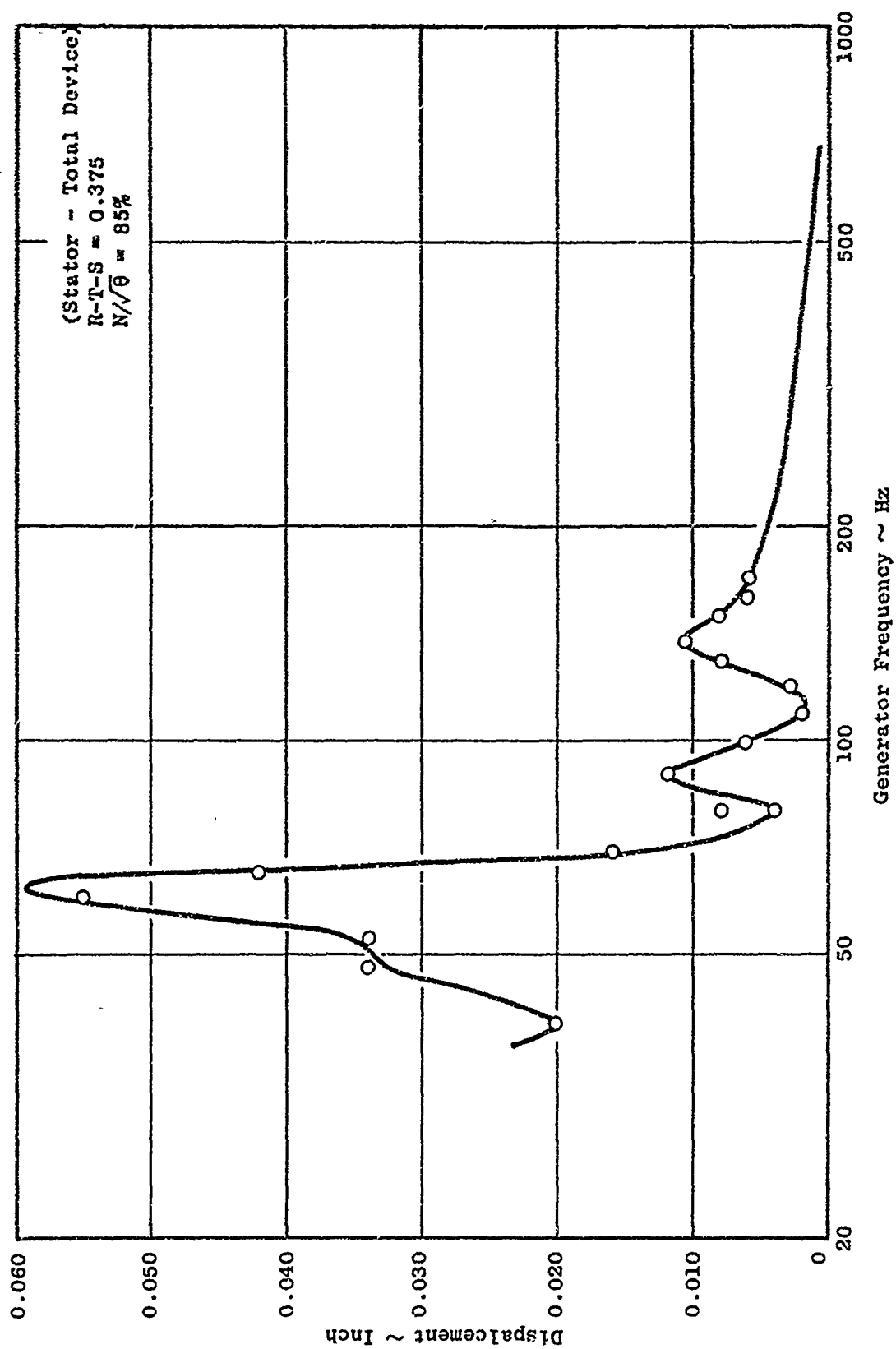


Figure 9. P³G Stator Vibratory Characteristics.

5.0 FAN/P³G AERODYNAMIC PERFORMANCE RESULTS

5.1 GENERAL

An important program to determine the effects of unsteady flow on an axial flow compression unit has been successfully completed. The effects of sinusoidal type pressure oscillations generated by the GE P³G on the fan component are documented in this report. Discussion of the results and analysis is broken into three major categories.

- P³G Aerodynamic Performance
- Fan Aerodynamic Performance
- System Interaction and Boundary Condition Definition

P³G Aerodynamic Performance includes the definition of magnitude and quality of test pressure oscillation as measured at the inlet guide vane leading edge instrumentation station. Fan Aerodynamic Performance is primarily a definition of steady-state and dynamic fan operating conditions existing at a given stable operating point and at surge. The destabilizing effect of the unsteady flow is related to fan stability in a manner analogous to steady-state distortion and discussed in terms of "dynamic distortion" characteristics (time variant instead of spatial distortion). The System Interaction and Boundary Conditions section documents the amplitude of waves existing at several locations throughout the test set-up geometry and provided information to help define the type and location of the boundary conditions influencing the unsteady flow.

Twenty-four surges were obtained during the test operations conducted on February 6 and 8, 1973. Figure 10 shows the matrix of surge points in terms of frequency, fan speed, and P³G amplitude. As indicated, 14 surges were obtained at 100% N/ $\sqrt{\theta}$ and 10 surges were obtained at 80% N/ $\sqrt{\theta}$ over a range of frequencies from 42 to 800 Hz and primarily at R-T-S spacings of 0.150 and 0.090 inch. Two of the 100% speed points, 80 Hz and 350 Hz, were duplicated to determine operational repeatability, and three inadvertent stalls occurred while trying to set a stable operating condition near surge. A system aeromechanical check-out run made on December 21, 1972 was included in this report, since data from this run were extremely limited because of dynamic data acquisition problems.

The general form of the analysis presented in this report is in terms of the standard stability and performance parameters versus frequency. Dynamic distortion sensitivity and transfer are defined in a manner which draws heavily from the spatial distortion concepts. A complete study to determine the fundamental relationships governing dynamically induced surge characteristics is probably within the potential of the data but requires a considerably more detailed analysis.

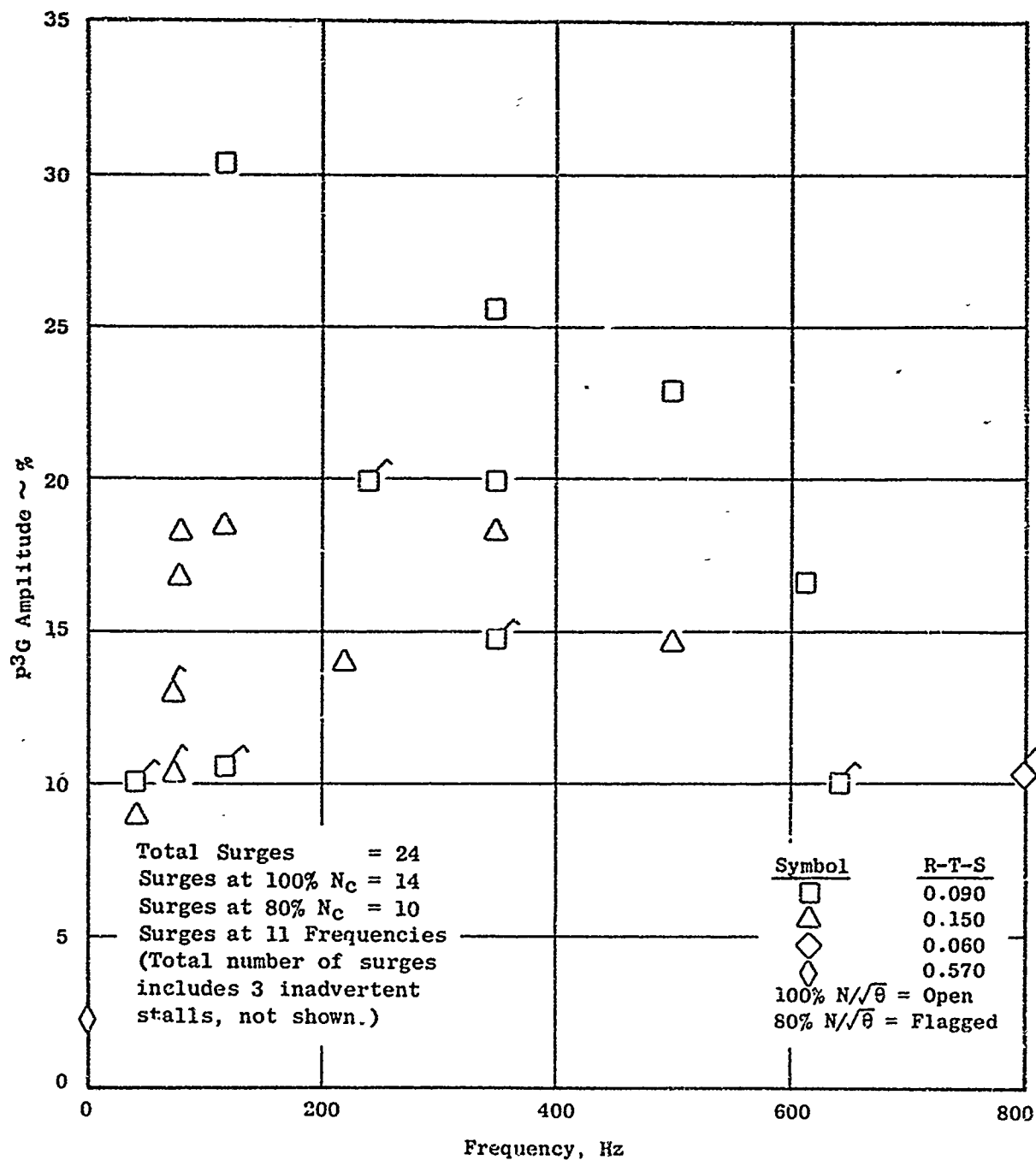


Figure 10. IGV Total Pressure Amplitude Near Stall-Surge Point Matrix.

5.2 P^3G AERODYNAMIC PERFORMANCE

Frequency Range. The P^3G produced high amplitude, near-planar, and sinusoidal pressure and flow oscillation over a frequency range of 42 to 800 Hz during testing.

Amplitude. Amplitudes ranged from 3% (nonpulsing) to 30% while only using partial amplitude capability, i.e., partially closed rotor-to-stator spacing. P^3G output amplitudes were a function of R-T-S spacing, flow, and frequency in that respective order of importance. Actual amplitude performance is compared to predicted performance in Figure 11. The predicted maximum amplitude (minimum R-T-S) compares well with the measured performance at R-T-S = 0.090, indicating that the P^3G has more amplitude capability than anticipated. The data scatter in Figure 11 is due primarily to frequency effects.

Distortion/Planarity. The measured "steady-state" distortions were quite low and compared closely to P^3G model levels, as shown in Figure 12. Figures 13 through 16 illustrate individual waveforms at the B (outer annulus) and D (inner annulus) element measurement locations and the combined rake average waveforms (B - D elements) for the 46° and 226° rakes. The good circumferential waveform relationship can be seen by comparing the corresponding elements on the two rakes. This strong axisymmetric property is further substantiated by the rake average waveforms which compare quite closely in shape, amplitude, and phase. Figure 17 summarizes the excellent circumferential planarity characteristics of the P^3G in terms of phase and amplitude between the rake average waveforms at 46° and 226°. Figures 13 and 15 illustrate the good agreement between individual element measurements at the same radial but different circumferential locations. The D-element waveforms of these readings (especially Figure 13) also illustrate how the shape of the wave at the hub was affected by secondary waveforms apparently caused by acoustic interactions. The typical spectra shown in Figures 18 to 21 indicate that the D-element waveforms have larger harmonic content; spectra for the B-element are very similar to previous model results. The distortion of the waveform produced radial phase shifts, as shown by the ring average values in Figures 22 through 25. Pulse amplitudes for all rings were approximately the same, and the phase between the A and B rings is nearly zero at all times. The hub ring (D), however, had measureable phase shifts relative to A and B. This phase shift results in a reduction of the overall face average amplitude and a radial distortion. The level of the time-variant radial distortion increases with both phase shift and amplitude. Summary plots of the radial (B to D ring average) phase and amplitude ratio for all near-stall points are shown in Figure 26. The amplitudes of the waveforms compare favorable at all but the 641 and 800 Hz frequencies at 80% speed. With the exception of the higher (>300 Hz) and a single low frequency point, the data show little difference in phase. The data in Figure 26 indicate that the higher peak values of the time-variant radial distortion occur at frequencies above 200 Hz and, therefore, have little if any effect on the fan. The peak values of the time-variant radial distortion for the 40 and 80 Hz (100% N/√θ) speed points are approximately 6% and 4%, respectively. These two points are representative of the maximum radial distortion levels at the low frequencies (<300 Hz) and should not cause any significant effects on the fan performance relative to this investigation.

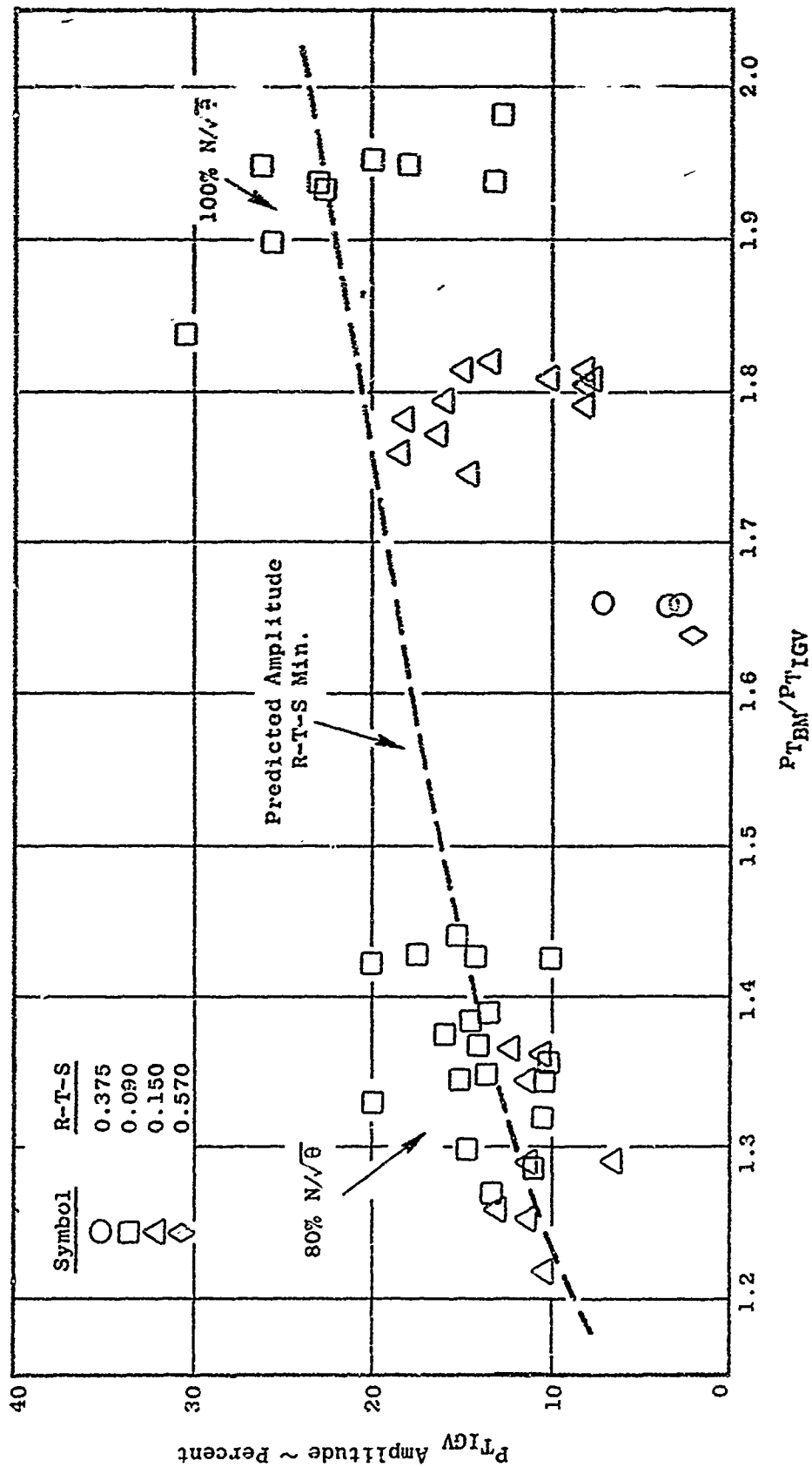


Figure 11. p^3G Amplitude Results Versus Prediction.

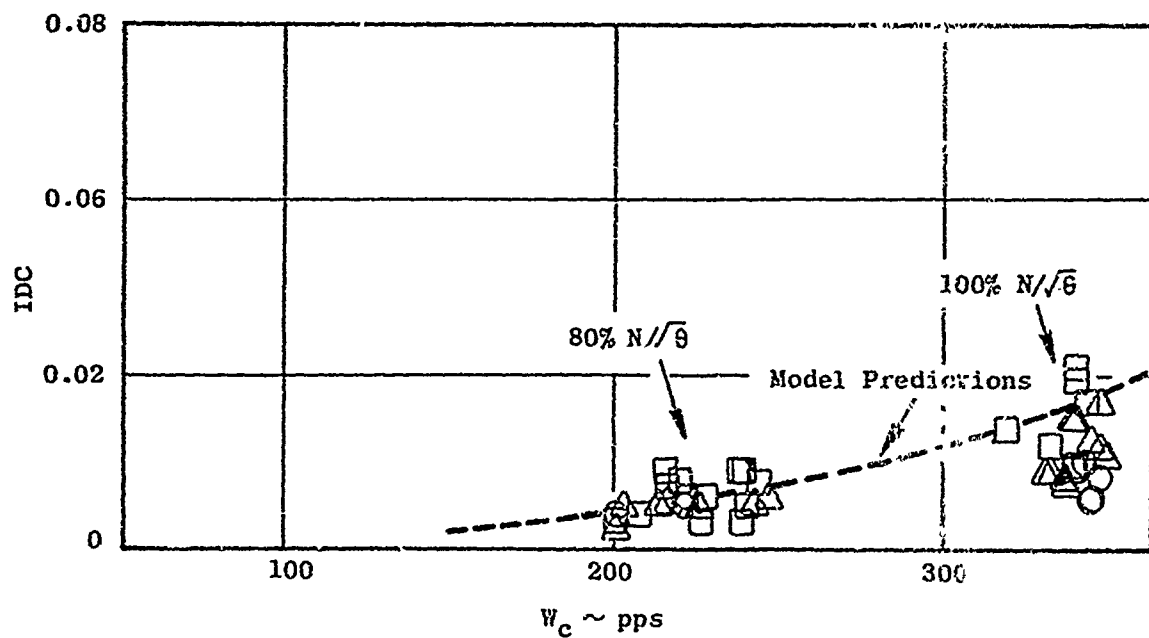
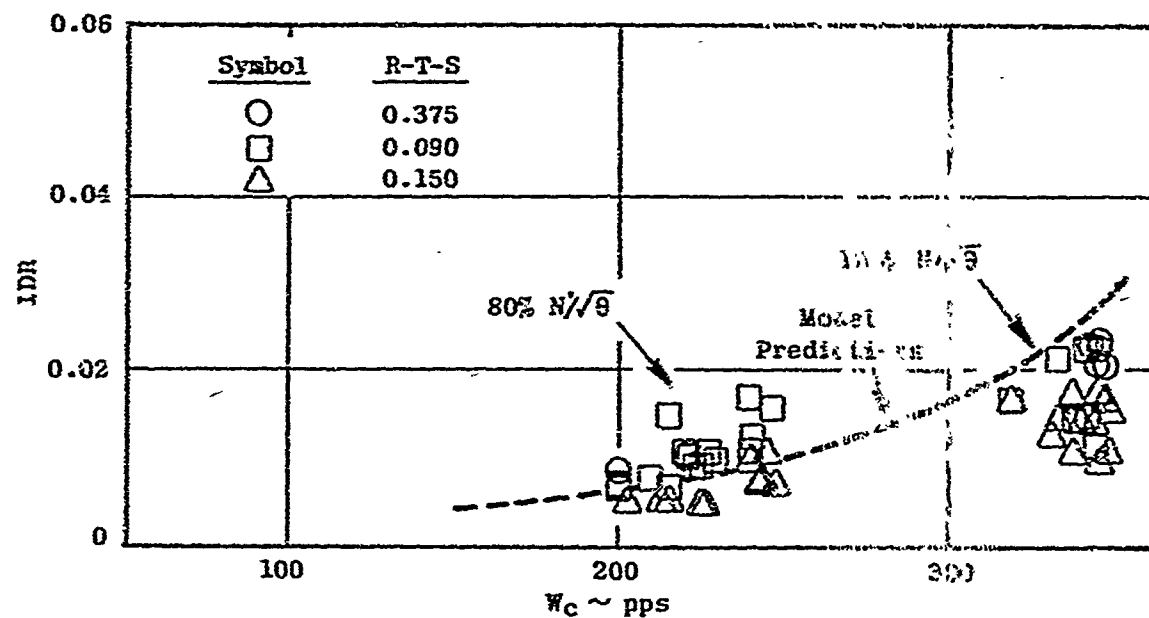


Figure 12. Steady-State Distortion Levels.

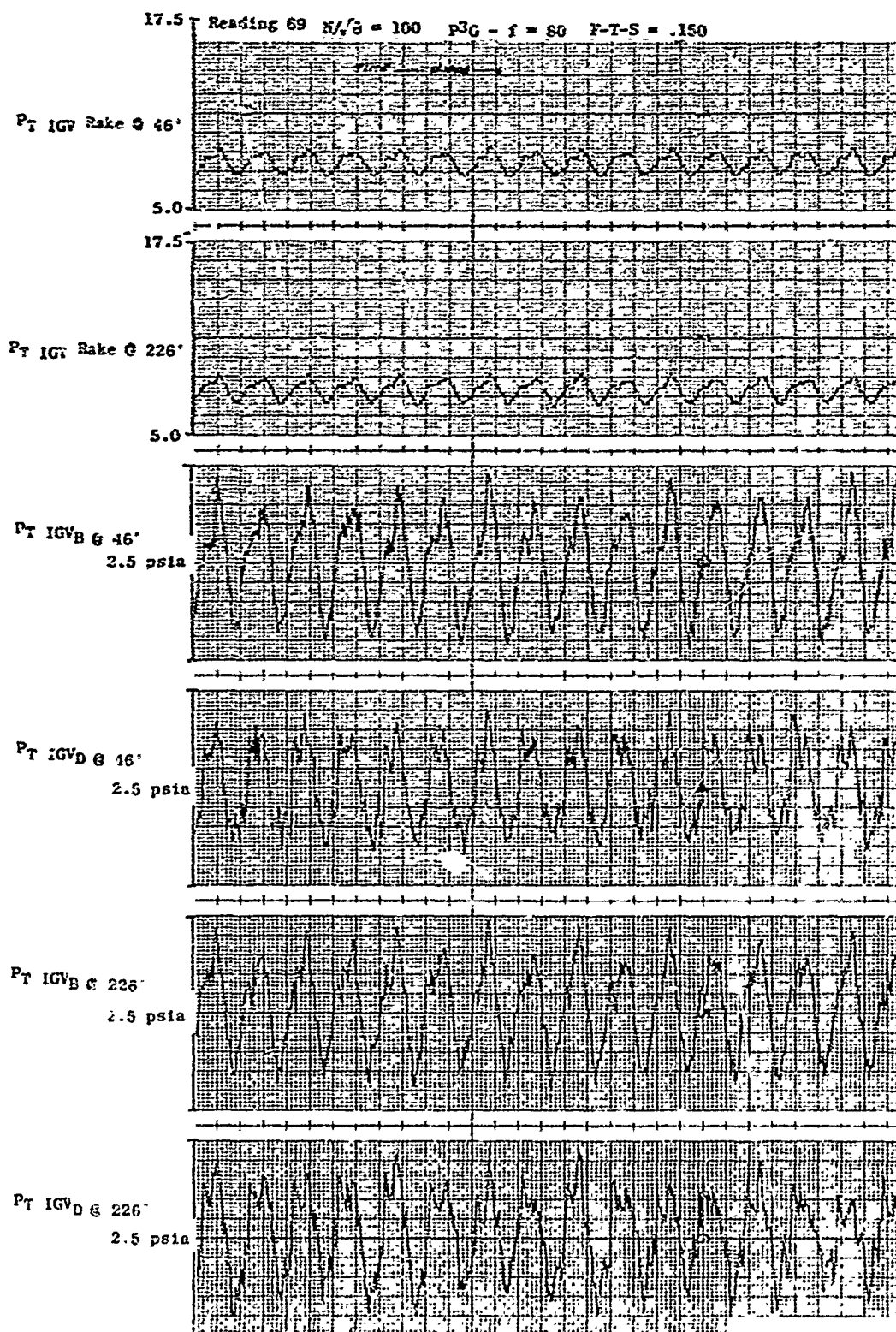


Figure 13. Fan/ P^3G Dynamic Data - Circumferential Planarity Waveforms
- Reading 62.

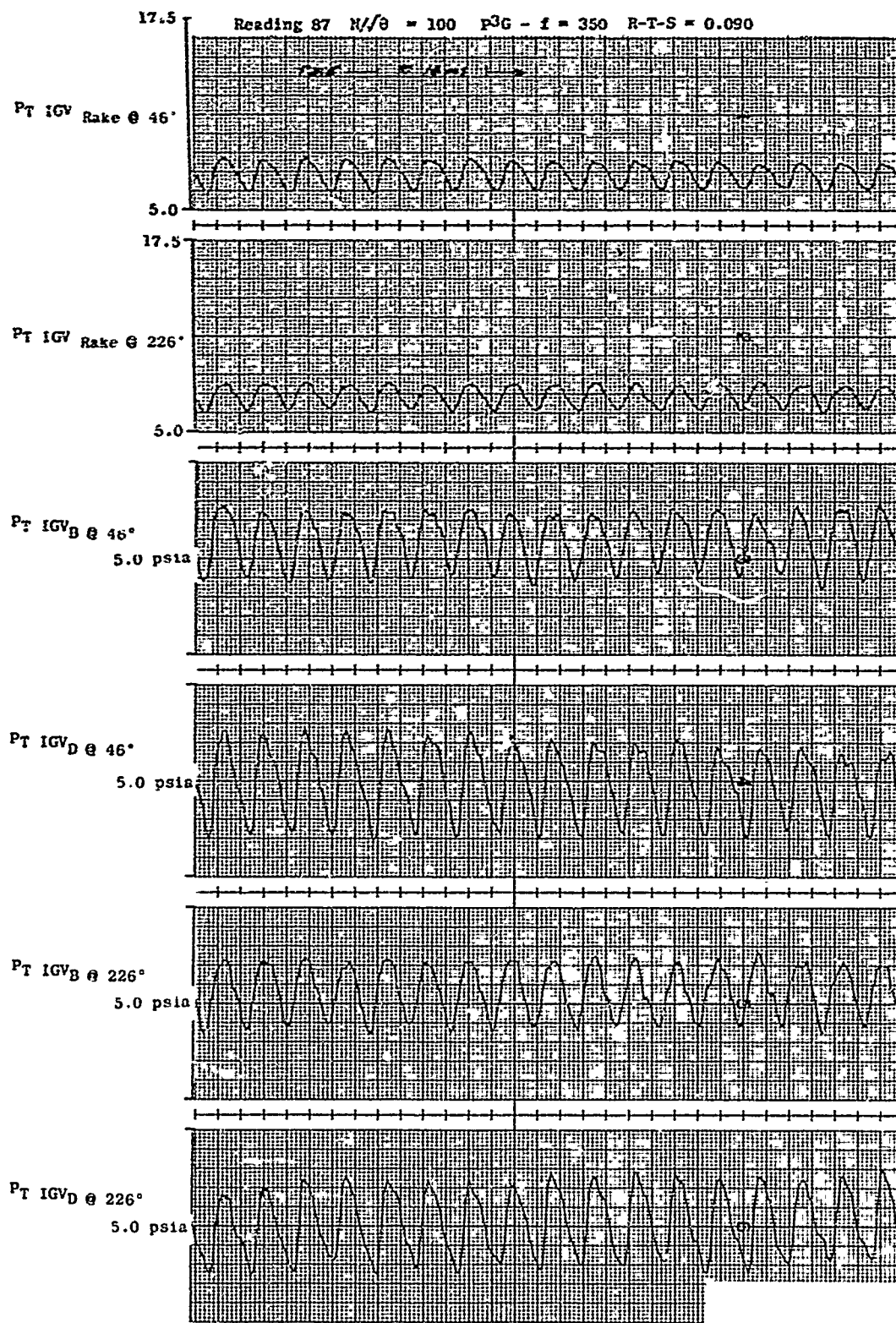


Figure 14. Fan/ P^3G Dynamic Data - Circumferential Planarity Waveforms
- Reading 87.

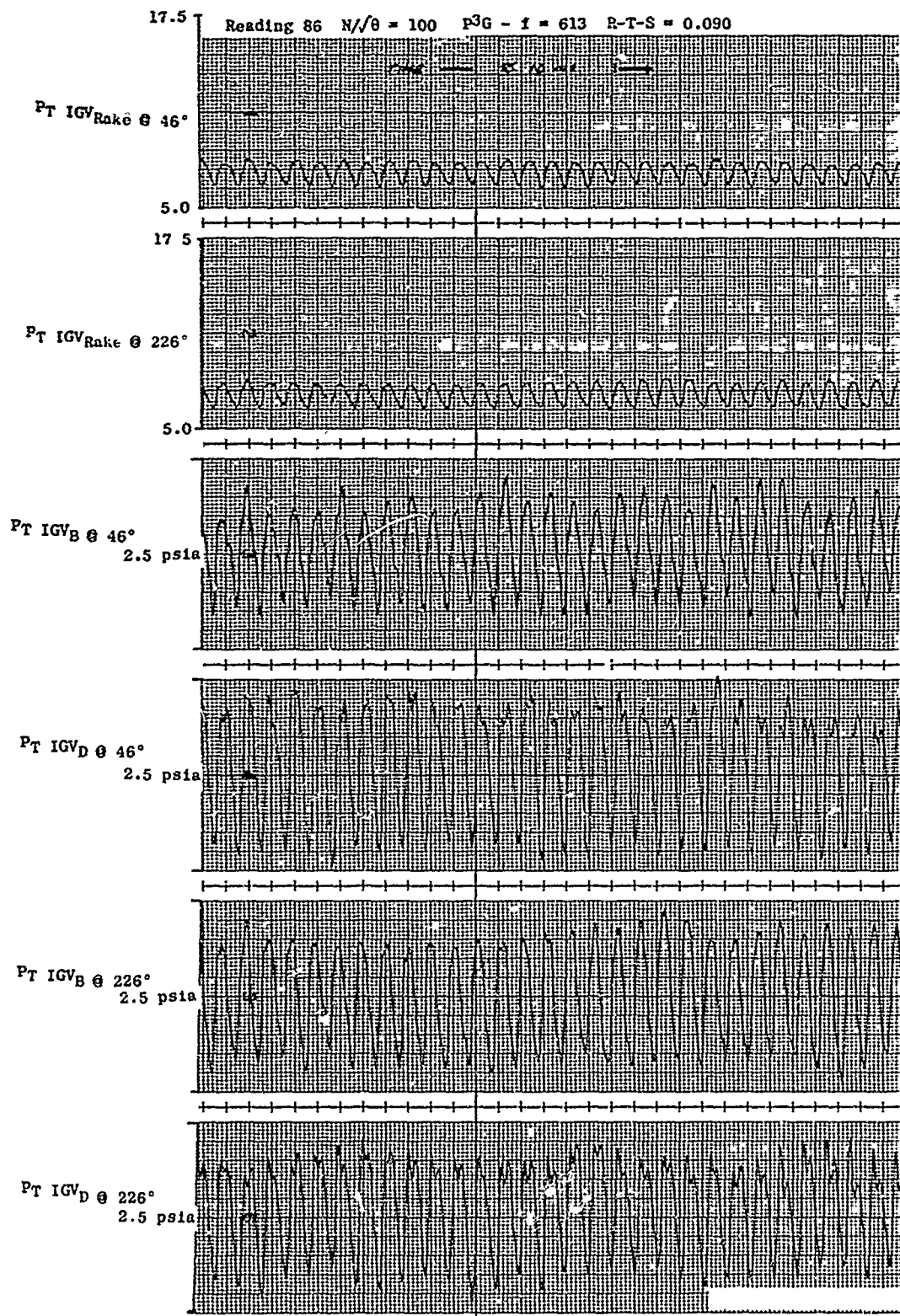


Figure 15. Fan/ P^3G Dynamic Data - Circumferential Planarity Waveforms
- Reading 86.

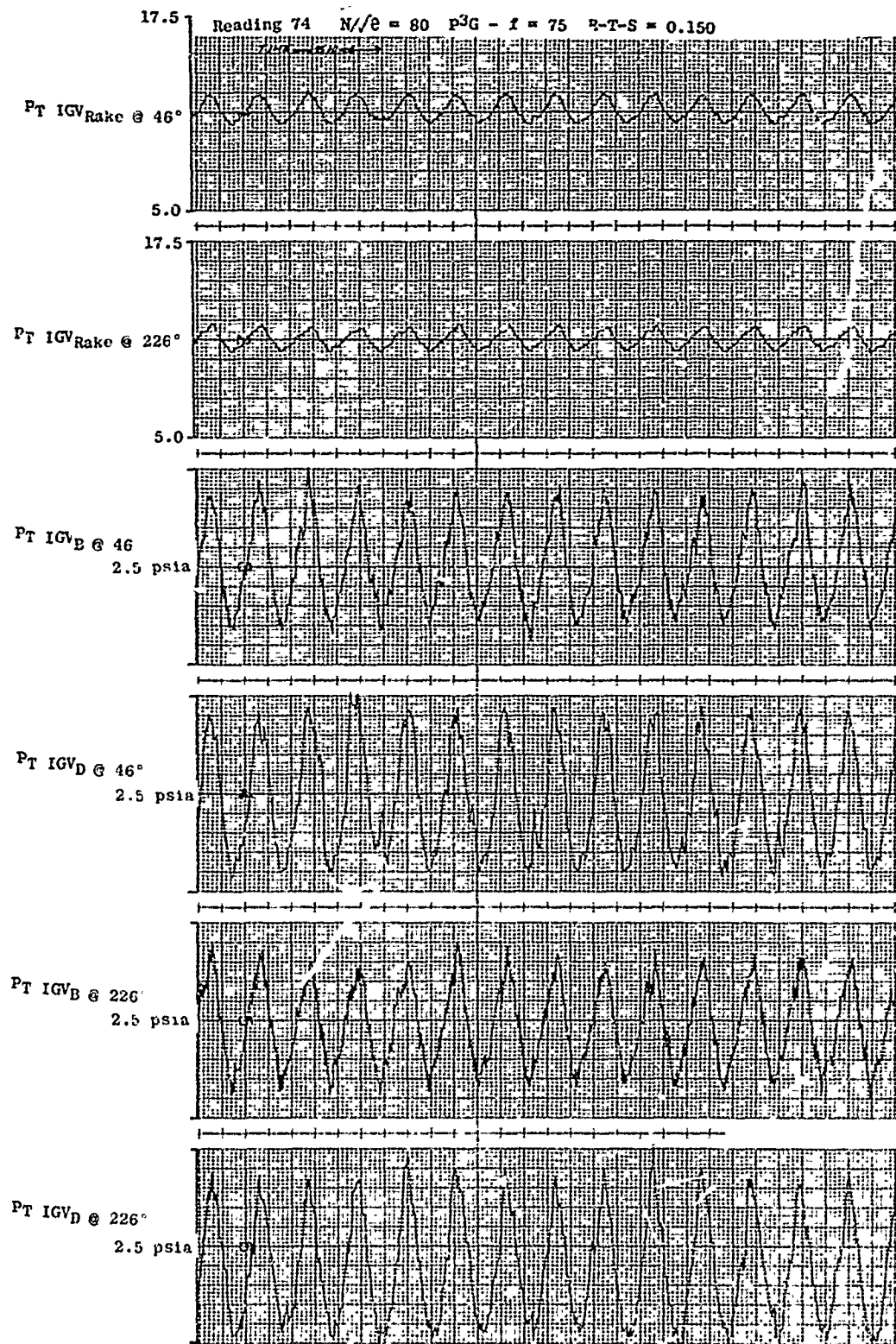


Figure 16. Fan/ P^3G Dynamic Data - Circumferential Planarity Waveforms - Reading 74.

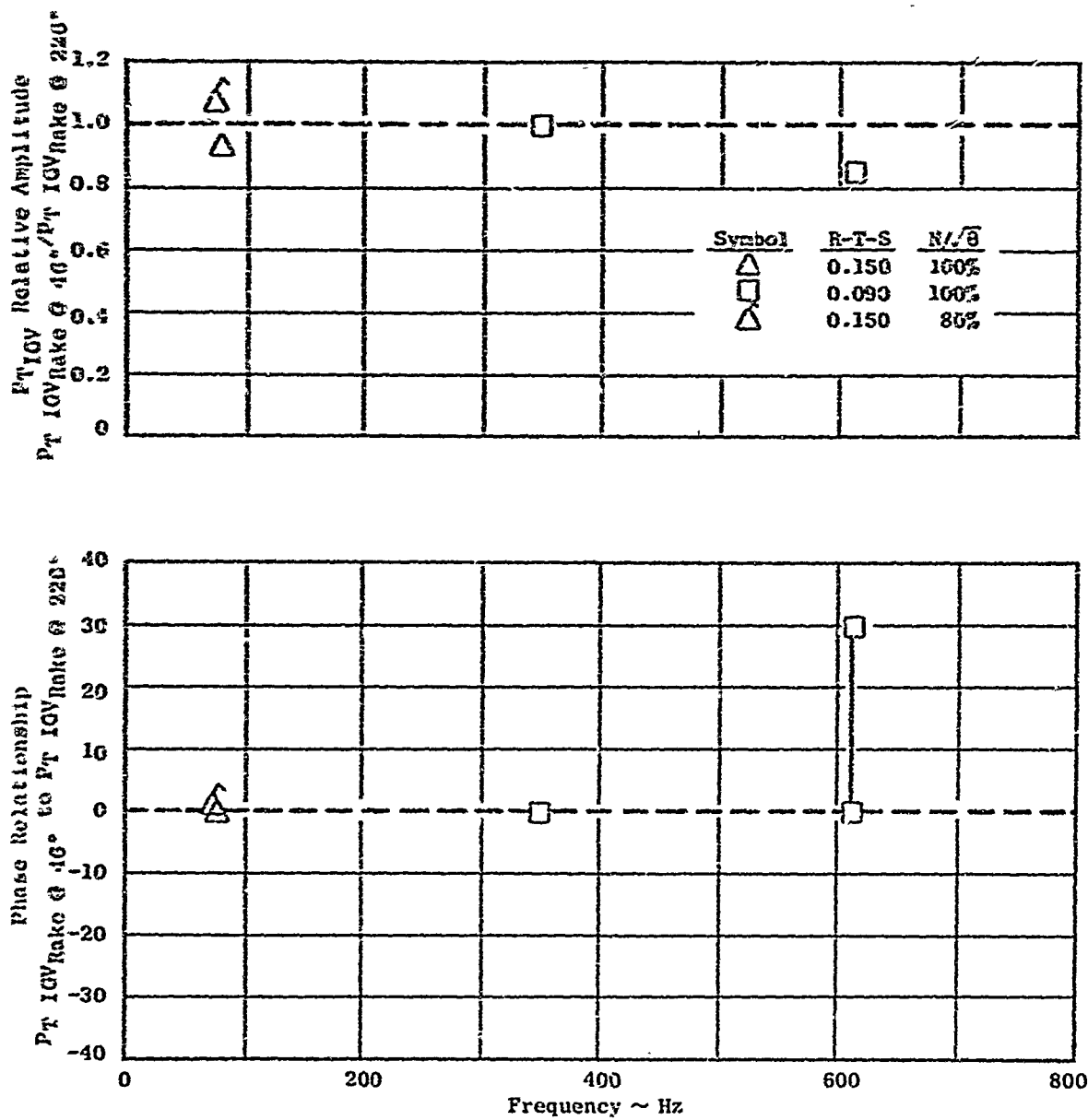


Figure 17. Wave Planarity Summary - Circumferential Mode.

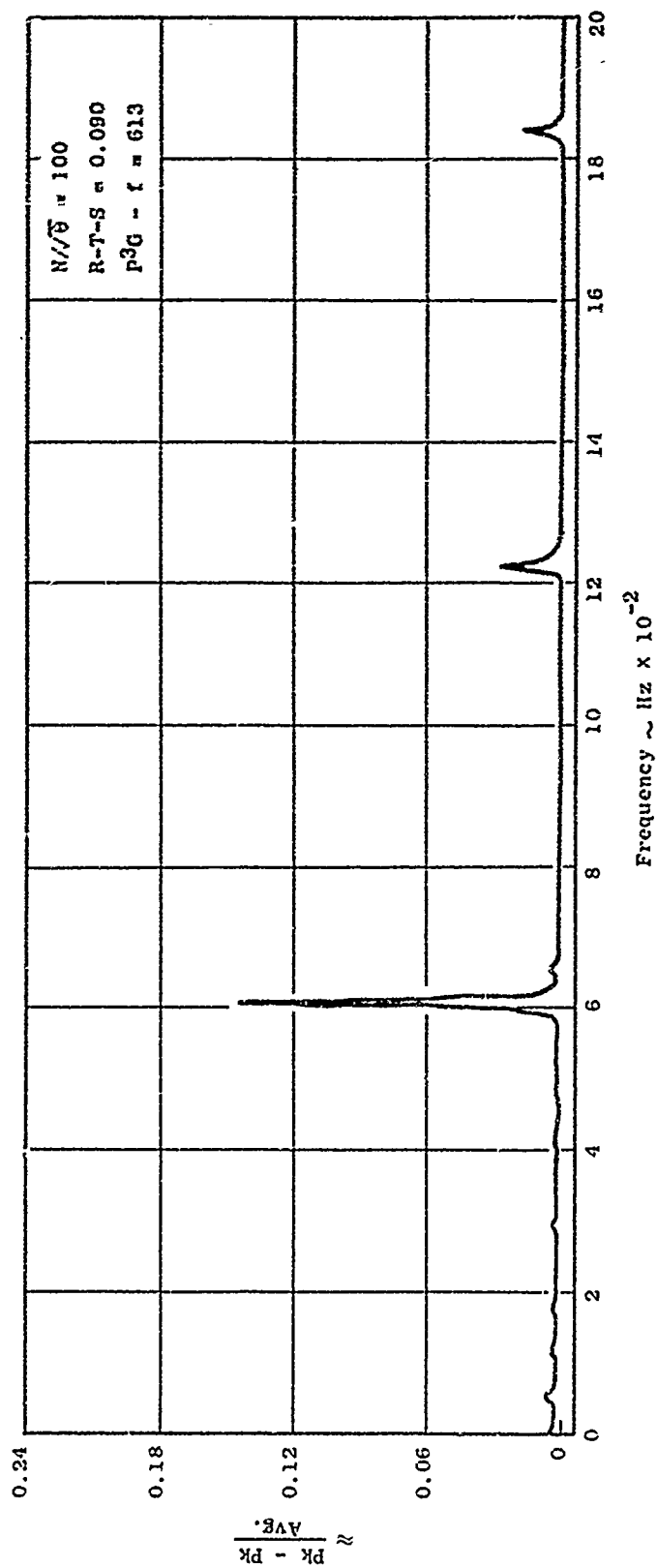


Figure 18. Reading 86 - Spectrum Analysis - P_T IGV B at 46° .

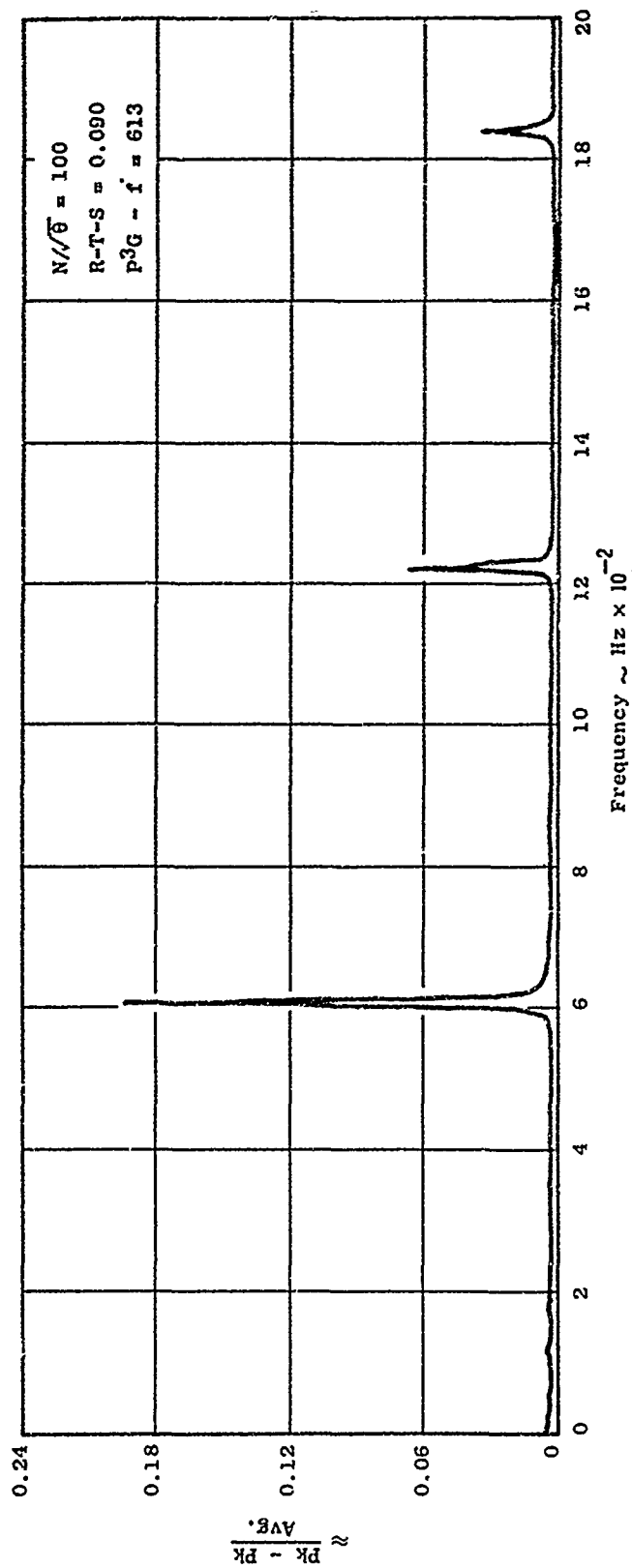


Figure 19. Reading 86 - Spectrum Analysis - P_T IGV D at 46° .

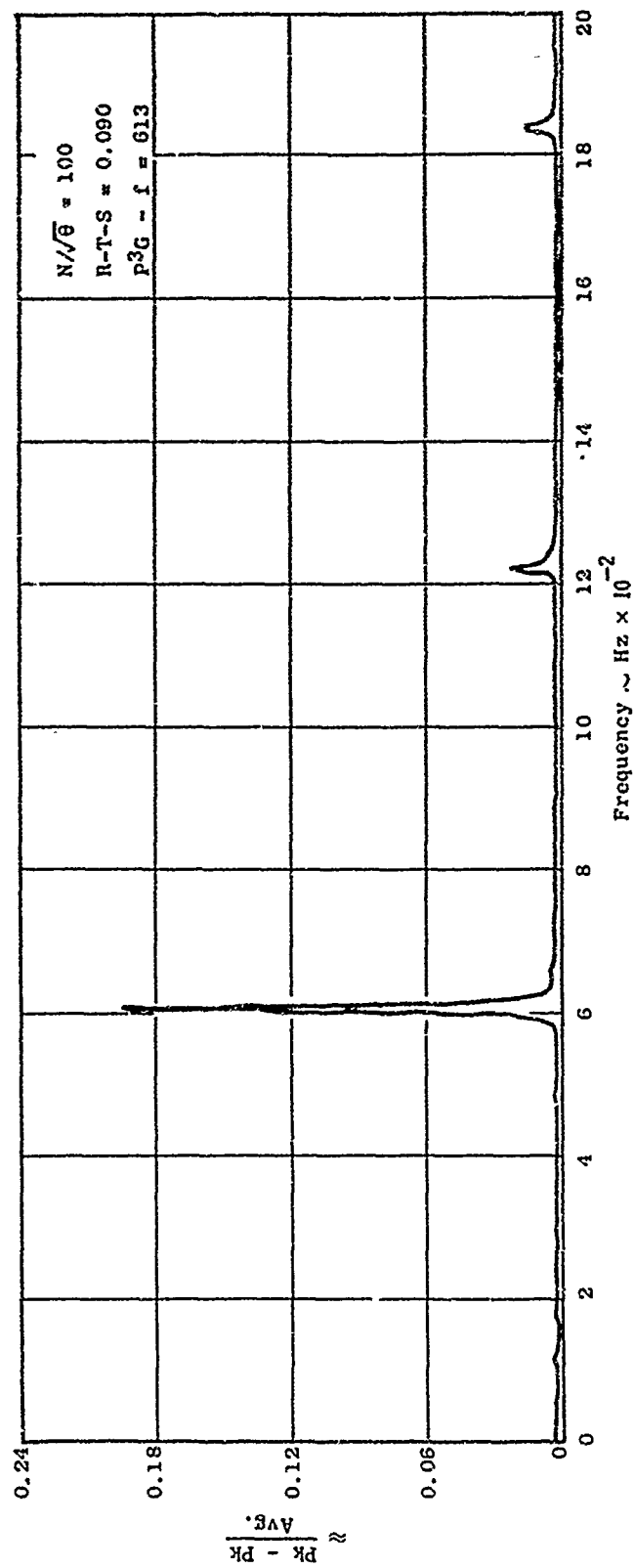


Figure 20. Reading 86 - Spectrum Analysis - P_T IGV B at 226° .

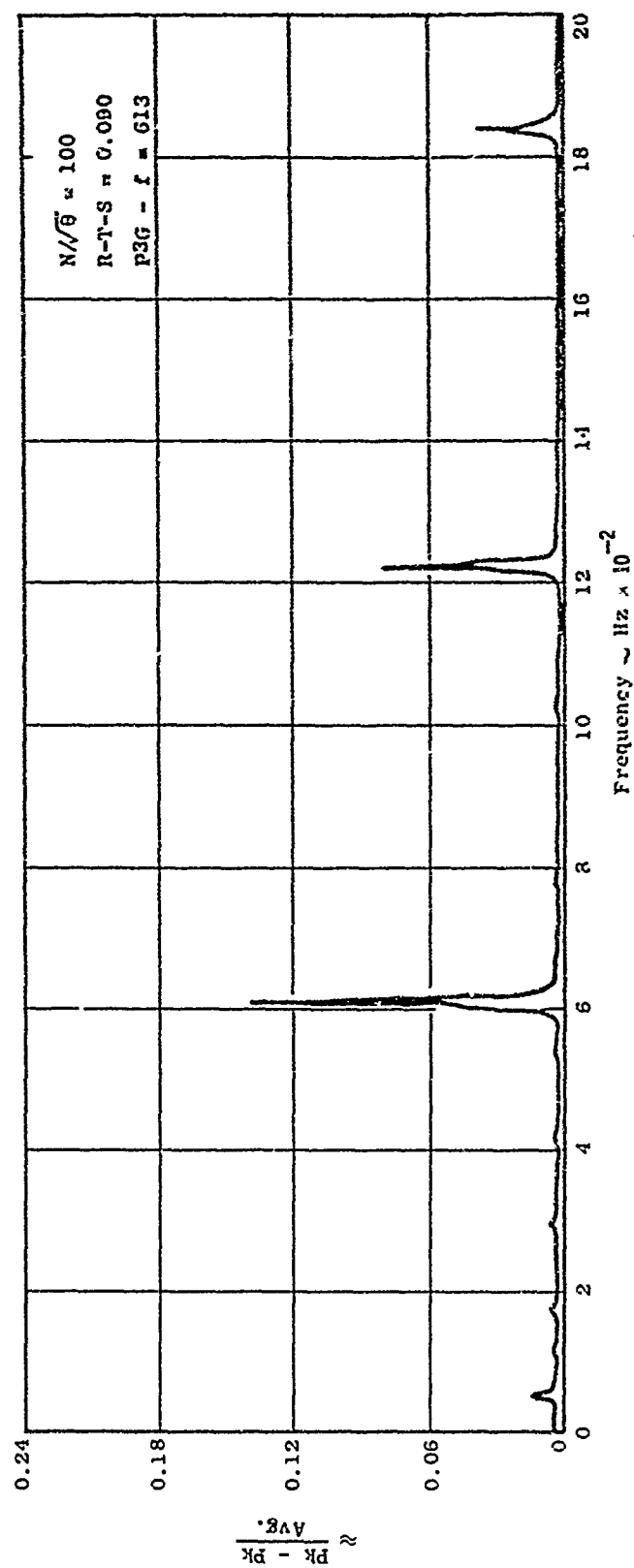


Figure 21. Reading 86 - Spectrum Analysis - P_T IGV D at 226° .

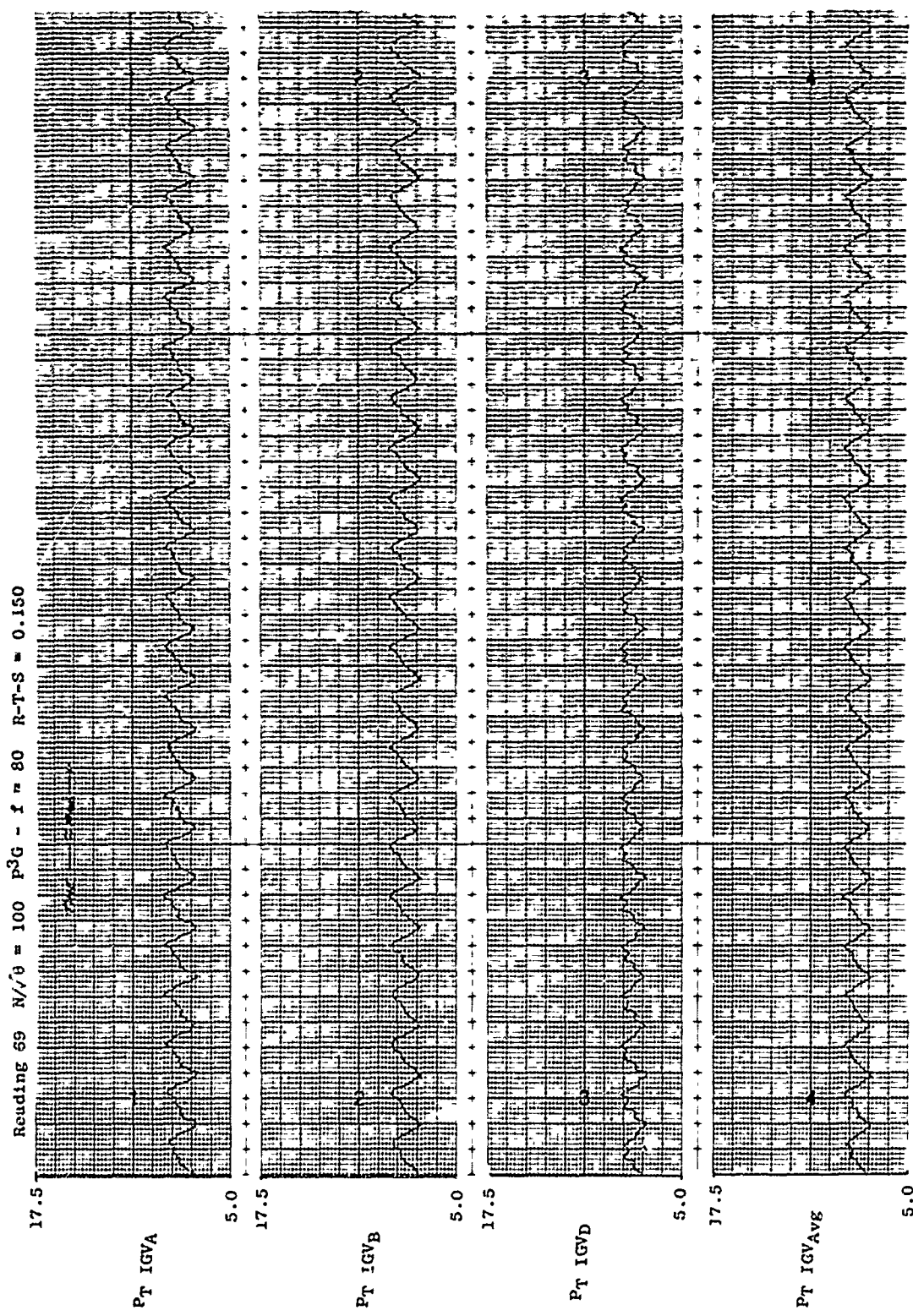


Figure 22. Fan/ P^3G Dynamic Data - Radial Planarity Waveforms - Reading 69.

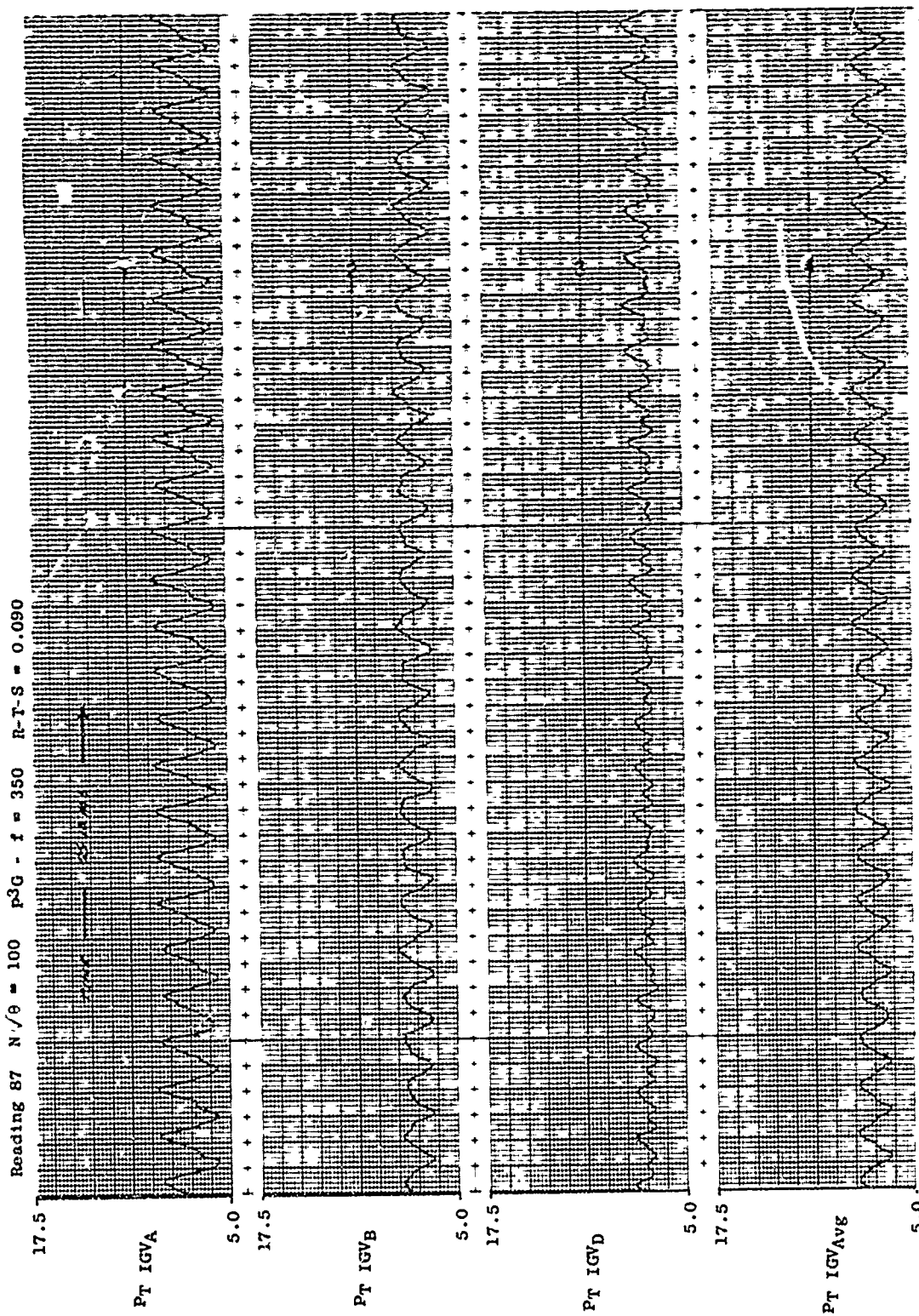


Figure 23. Fan/P³G Dynamic Data - Radial Planarity Waveforms - Reading 87.

Reading 86 $N/h = 100$ $p^3G - f = 613$ $R-T-S = 0.090$

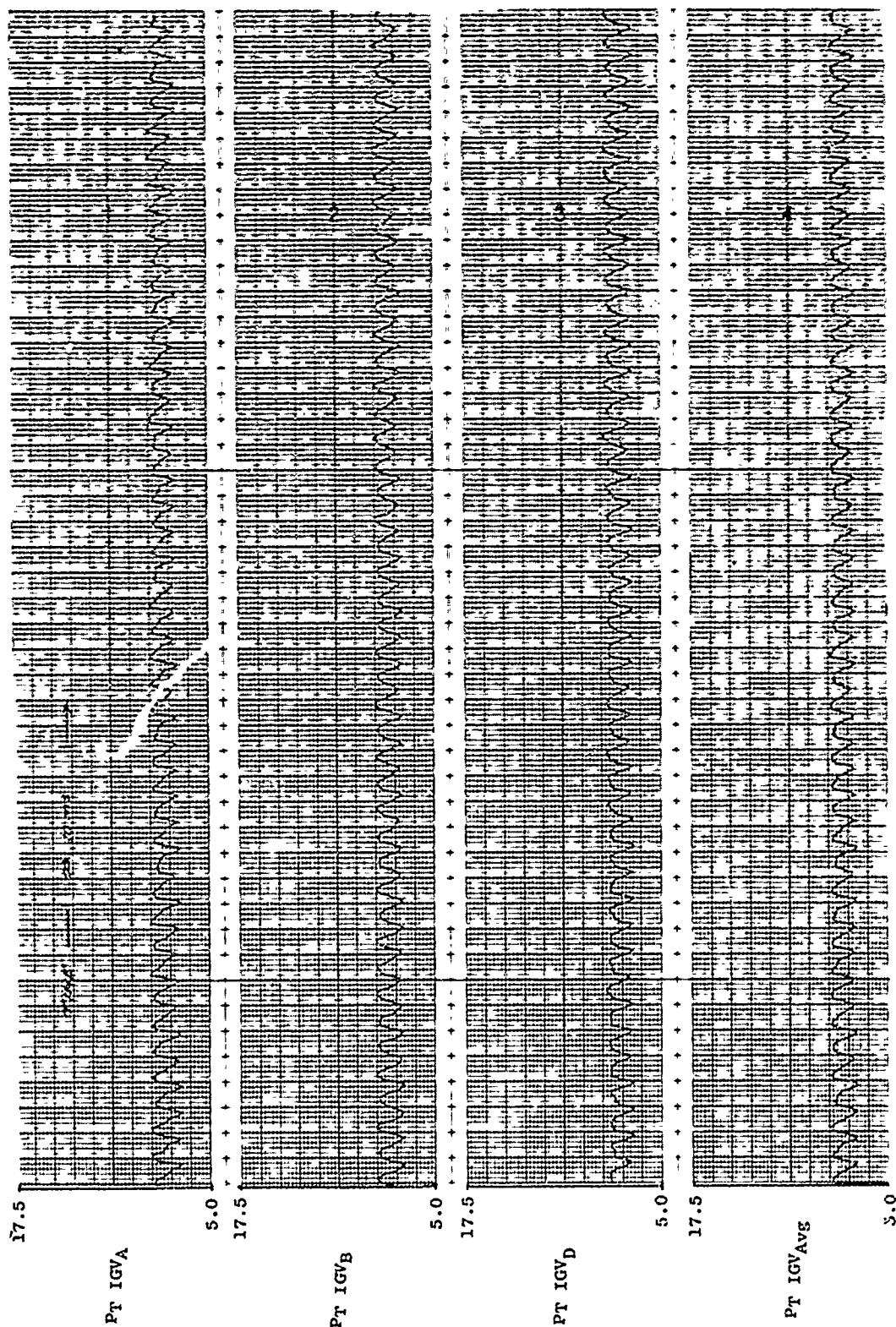


Figure 24.. Fan/ p^3G Dynamic Data - Radial Planarity Waveforms - Reading 86.

Reading 74 N/0 = 80 p3G - f = 75 R-T-S = 0.150

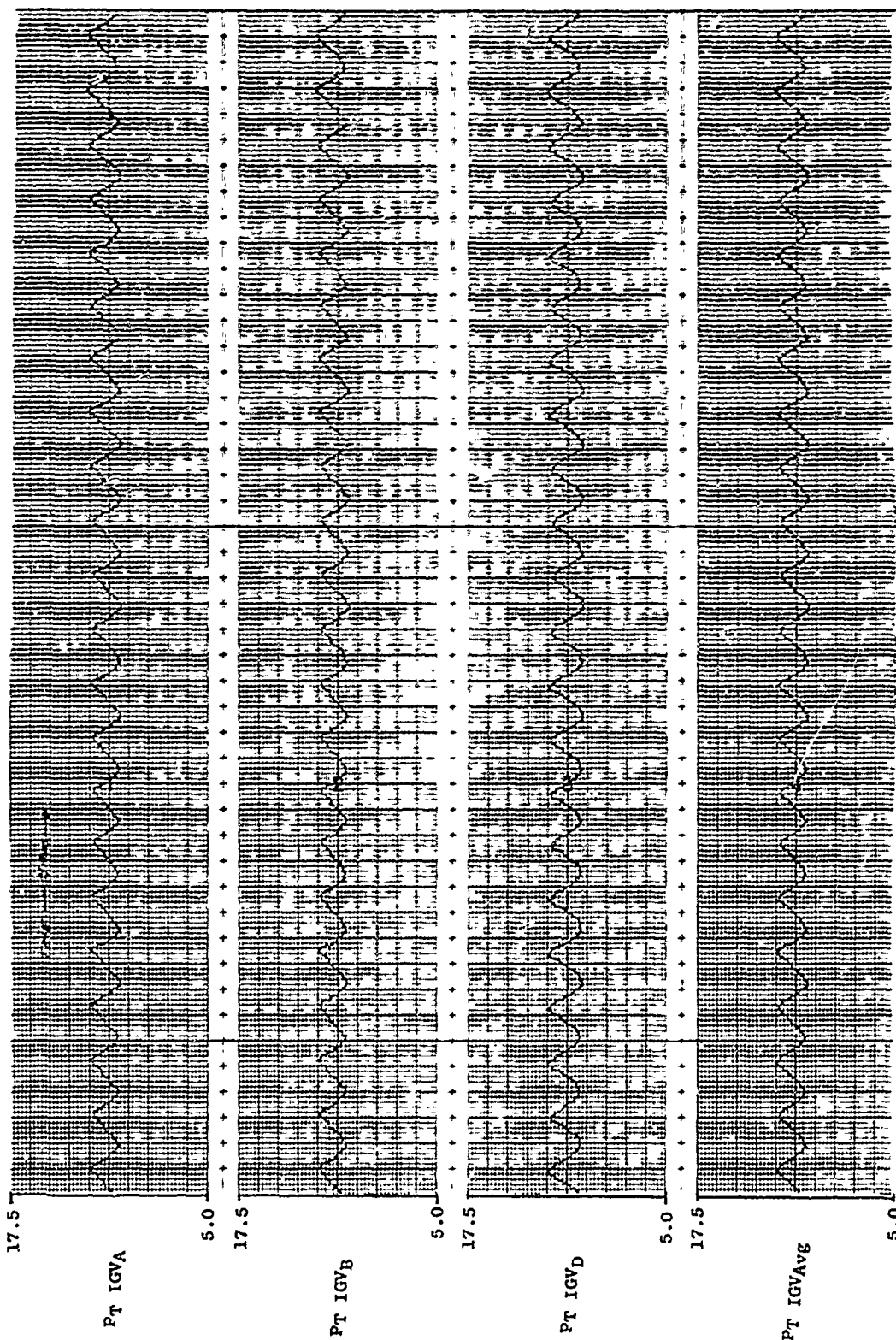


Figure 25. Fan/P³G Dynamic Data - Radial Planarity Waveforms - Reading 74.

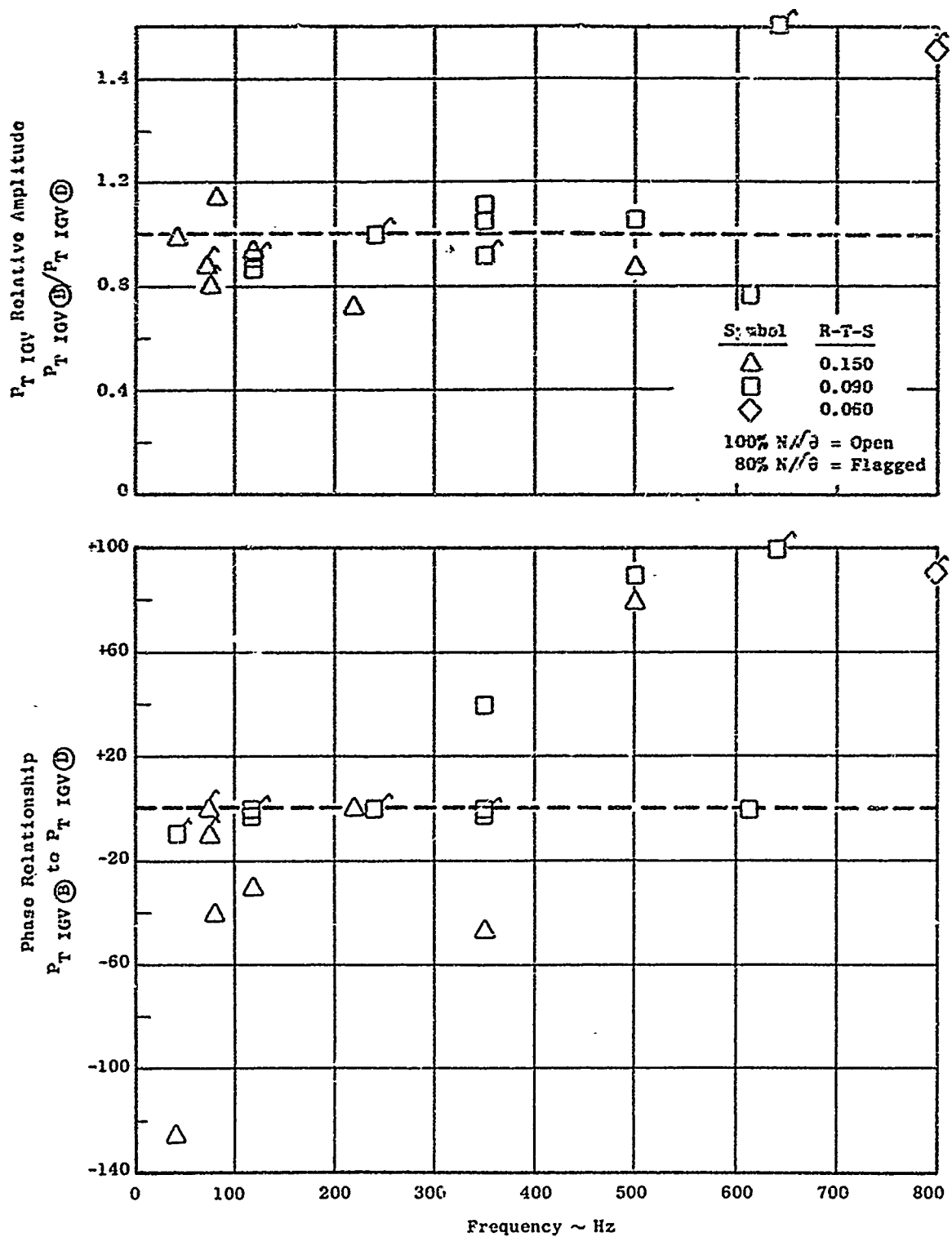


Figure 26. Wave Planarity Summary - Radial Mode.

Pressure Drop. The steady-state total pressure losses across the P³G were of concern, since the fan has a low (≈ 2.6) pressure ratio, and the discharged throttling valves had to remain partially closed for surge-clearing capability. The full-scale P³G losses came fairly close to the pretest predictions as seen in Figure 27.

Table III documents the P³G Aerodynamic Performance.

5.3 FAN AERODYNAMIC PERFORMANCE

5.3.1 General

The steady-state surge and speed lines for the 80% and 100% N/ $\sqrt{\theta}$ conditions are shown in Figures 28 and 29 in terms of fan duct pressure ratio. The fan duct pressure ratio is defined by the ratio of station 14 exit total pressures to the outer 3 rings of the Prigby measurement. Conditions represented by the fan duct pressure ratio and flow may be analyzed to determine the stability characteristics of the fan. Therefore, sensitivity to unsteady flow is discussed primarily in terms of the outer annulus flow conditions. Since distortion transfer to the core compressor is of major importance to an engine system, the unsteady flow at the hub was analyzed for this property.

Figure 30 shows the speed line to surge of the posttest steady-state surge condition versus the clean inlet pretest performance. Posttest surge airflow was approximately 1-1/2% lower than pretest surge airflow (338 pps versus 343 pps), and surge pressure ratio was decreased by approximately 0.008 Δ PRS. This agreement between the surge pressure ratio and flow for pretest and posttest measurements is considered good when all conditions of inlet distortion and data accuracy are taken into account, thus verifying the consistency of the clean inlet pretest performance and surge margin throughout the test.

5.3.2 Mean Performance

Since the entire inlet flow field oscillates at a given discrete frequency and amplitude, steady state performance levels cannot be discussed in the normal manner. However, for conditions up to where surge occurs, a stable "limit cycle" of fan operation is established and there exists some time-averaged, mean level of performance, measured by the steady-state instrumentation. Frequency and amplitude effects of the unsteady flow on mean performance may then be inferred from the steady-state measurements and related circumstances.

Figure 31 shows a plot of frequency versus corrected airflow for all near-surge points at 80% and 100% N/ $\sqrt{\theta}$. For the 100% speed condition, a sharp drop in surge airflow is observed in the frequency range of 40 to 100 Hz (≈ 10 pps) and then only slight frequency effects on flow are seen above the 100 Hz level. Increasing pulse amplitude produces increased losses in flow at all frequencies as shown by the two R-T-S settings in the figure. The 80% N/ $\sqrt{\theta}$ data show a similar flow effect in the low frequency area but continue to demonstrate a more pronounced flow degradation as frequency is increased (down 40 pps from the nominal 222 pps at 80 Hz). The different appearance of flow at 100% and 80% N/ $\sqrt{\theta}$ versus frequency is probably the result of the shape differences of the two speed lines, since the 80% speed line is naturally flatter resulting in a larger change in flow for a given pressure ratio change.

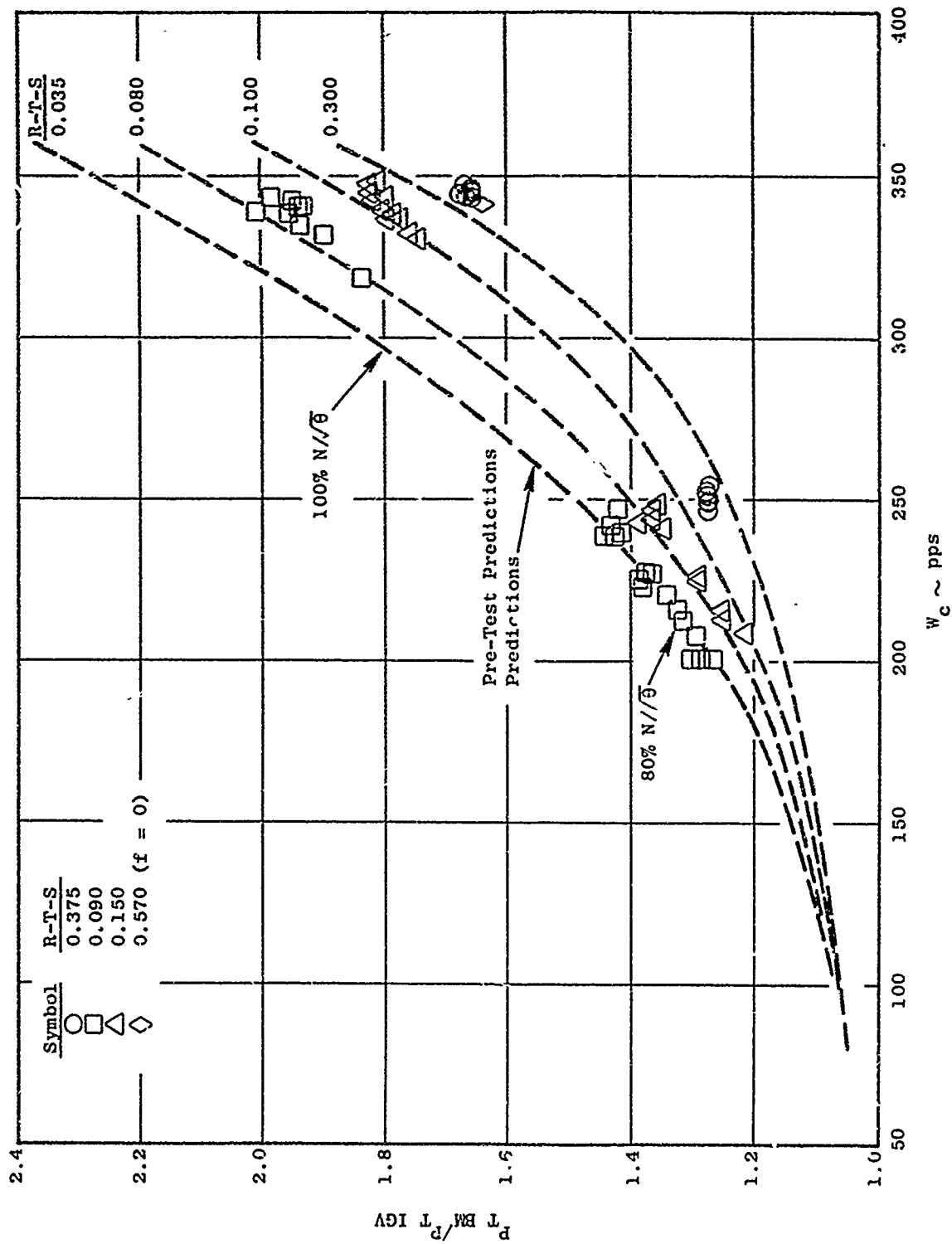


Figure 27. P^3G Mean Rotational Pressure Loss.

Table III. P³G Aerodynamic Performance.

Stall	Near Stall Rdg.	N/√6 %	f Hz	RTS In.	P _T IGV (B) to (D) Phase Deg.	P _T IGV (B) AMP %	P _T IGV (D) AMP %	ΔP _T IGV (B) / ΔP _T IGV (D)	P _T IGV Rake 46° to 226° Phase Deg.	T Rake 46° AMP %	T Rake 226° AMP %	ΔP _T 46° / ΔP _T 226°
1	38	100	80	0.150	DATA NOT AVAILABLE (N/A)	12.12	16.87	0.72	---	---	---	---
2	41	↓	220	0.150	0	20.96	N/A	---	---	---	---	---
3	43	↓	350	0.150	-47	14.53	16.47	0.88	---	---	---	---
4	45	↓	500	0.150	+80	26.67	25.17	1.06	---	---	---	---
5	47	↓	500	0.090	+90	29.03	27.27	1.06	---	---	---	---
6	49	↓	350	0.090	0	17.58	18.75	0.94	---	---	---	---
12	64	↓	118	0.150	-30	24.00	28.00	0.86	---	---	---	---
13	65/66	↓	118	0.090	0	21.34	18.52	1.15	0	20.25	21.59	0.929
14	69	↓	80	0.150	-40	21.34	18.52	1.15	---	---	---	---
15	69	↓	80	0.150	-40	13.75	13.89	0.99	---	---	---	---
16	71	↓	42	0.150	-125	19.23	16.70	0.77	0 to 30	21.90	25.59	0.856
20	86	↓	613	0.090	0	30.00	26.70	1.12	0	23.79	23.79	1.0
21	87	↓	350	0.090	+40	---	---	---	---	---	---	---
7	53/54	80	350	0.090	0	15.02	16.16	0.92	---	---	---	---
8	53/54	↓	350	0.090	0	15.02	16.16	0.92	---	---	---	---
9	57	↓	240	0.090	0	19.11	19.06	1.0	---	---	---	---
10	57	↓	240	0.090	0	19.11	19.06	1.0	---	---	---	---
11	61	↓	118	0.090	0	10.22	11.11	0.92	---	---	---	---
17	74	↓	75	0.150	-10	14.17	17.39	0.81	0	15.28	14.19	1.077
18	78	↓	75	0.150	0	14.58	16.67	0.87	---	---	---	---
19	82	↓	42	0.100	-10	---	---	---	---	---	---	---
22	91	↓	641	0.090	+100	21.06	11.61	1.81	---	---	---	---
23	92	↓	800	0.60	+90	21.03	12.26	1.71	---	---	---	---

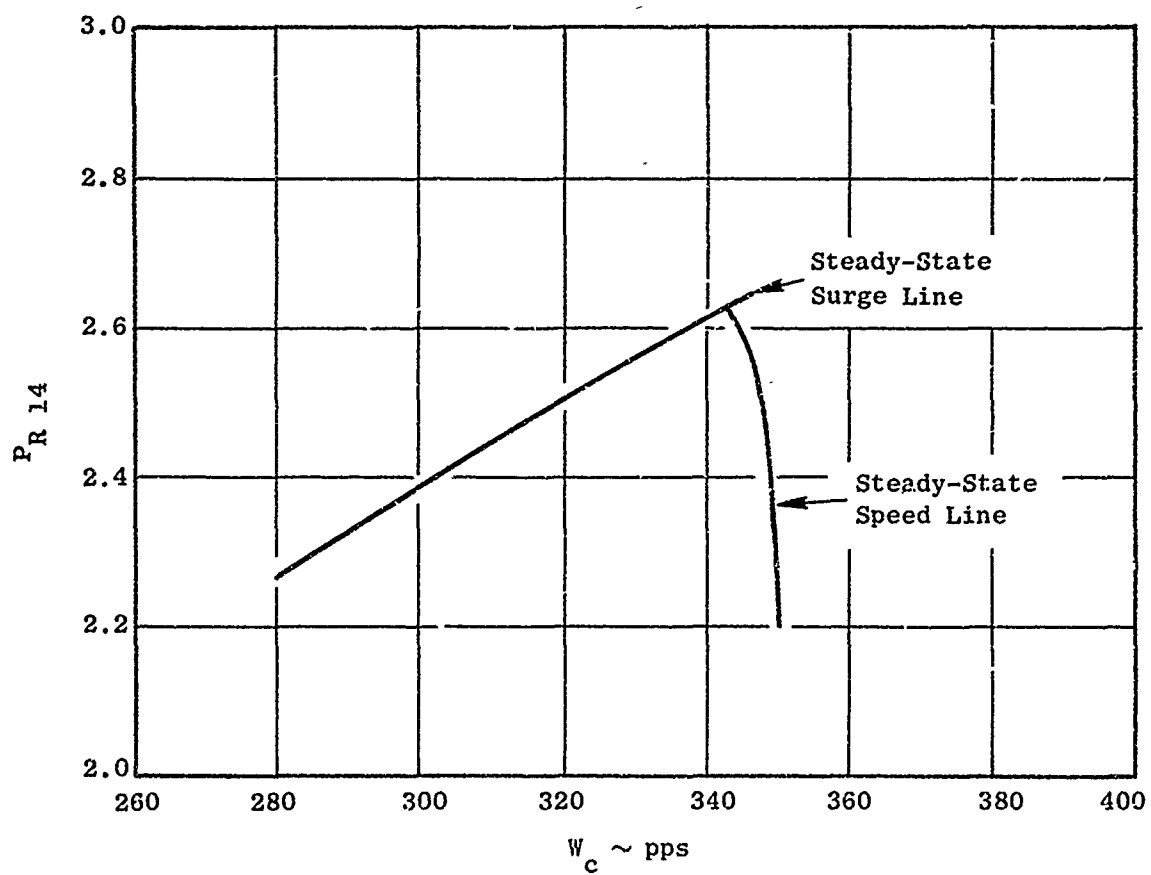


Figure 28. Fan Performance Map at $N/\sqrt{\theta} = 100\%$.

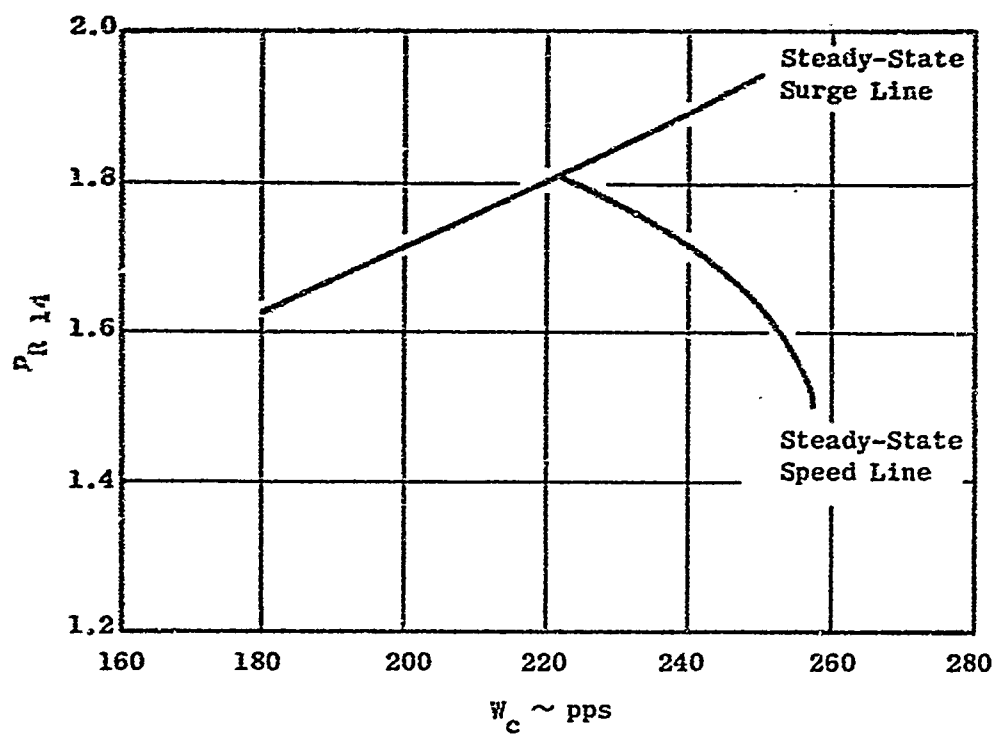


Figure 29. Fan Performance Map at $N/\sqrt{\theta} = 80\%$.

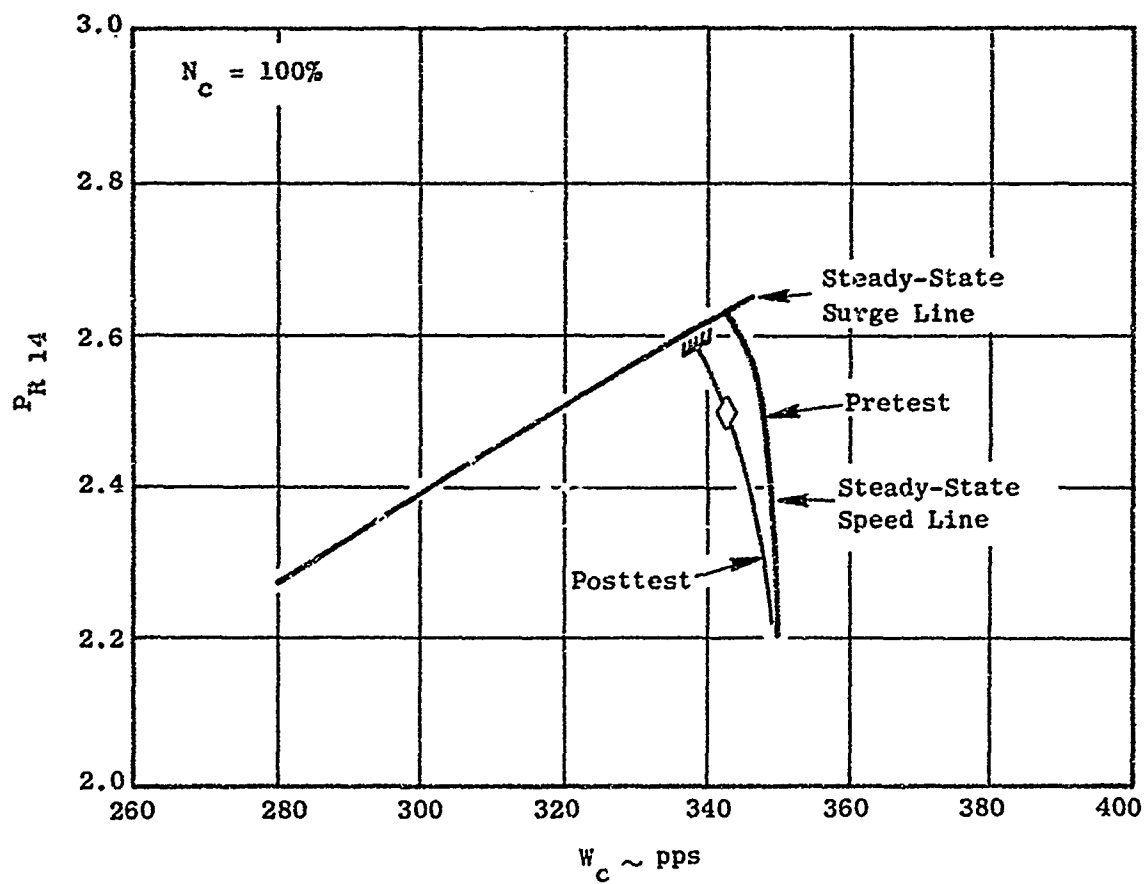


Figure 30. Posttest Steady-State Surge Margin Check.

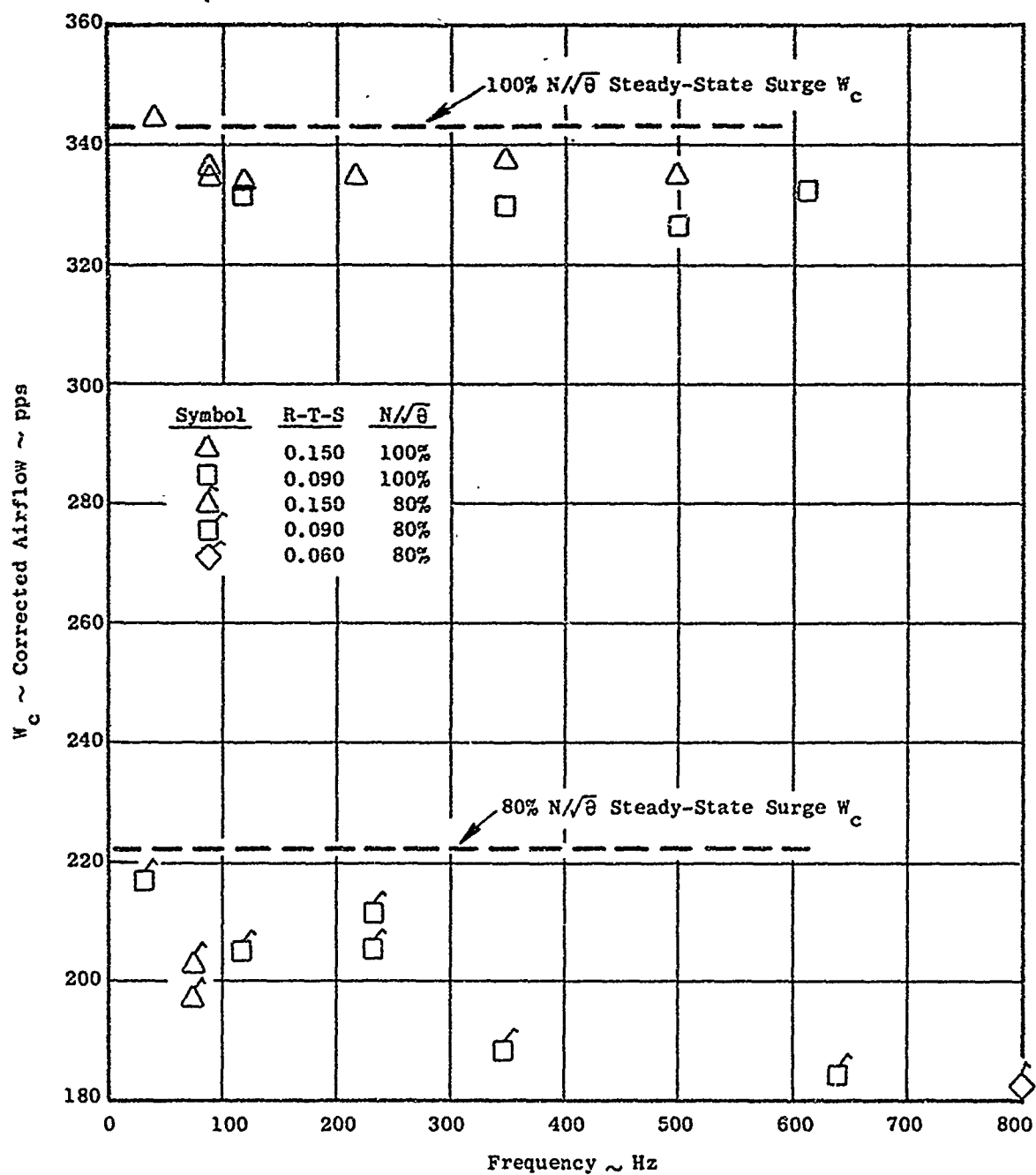


Figure 31. Frequency Effect on Corrected Airflow.

Overall fan efficiency for the near-surge points was less than nominal for all frequencies and followed the same general trend as the corrected airflow as shown in Figure 32. Hub-to-tip fan efficiency results were not generally well behaved, probably as a result of the bypass ratio variation since overall efficiency demonstrated an ordered pattern.

5.3.3 Dynamic Performance

Distortion Sensitivity. The definition of compressor sensitivity to flow distortions may be approached in many ways. In order to attack the special area of unsteady flow (time-variant distortion) and to simultaneously relate to previous work, the General Electric "Method D" (Reference 2) for steady-state distortion analysis will be used as a basis for nomenclature and parameter formalization.

Dynamic distortion sensitivity (named here - K_δ) is defined as the Δ PRS at surge divided by the total-pressure half amplitude at the fan inlet (IGV). Δ PRS is defined in Figure 33 as:

$$\left[\frac{(P_R)_{\text{Undistorted}} - (P_R)_{\text{Distorted}}}{(P_R)_{\text{Undistorted}}} \right] w_c = C$$

or simply the % loss in stall pressure ratio due to distortion, at a constant corrected airflow. The IGV total-pressure half amplitude is used to relate the dynamic distortion (since the flow oscillations were approximately sinusoidal) and considers that the low pressure (low velocity) regions are most detrimental to the stability of a compressor blade. As previously discussed, outer duct flow conditions are considered in stability determinations for this fan; it is necessary to use the dynamic pressure amplitudes in this region.

The dynamic distortion sensitivity (K_δ , constructed in the above fashion) is shown as a function of frequency for the 100% speed condition in Figure 34. A well-defined relationship between sensitivity and frequency is shown to exist. From the 42 Hz test point to approximately 150 Hz, sensitivity decreases from 0.77 to 0. Beyond 150 Hz, K_δ is zero or nearly zero. Fluctuation in K_δ above 150 Hz may be hidden by data scatter; but, regardless of the characteristic, it has a nearly negligible effect on the overall distortion sensitivity. Sensitivity increases as frequency decreases below 150 Hz; however, behavior near the steady-state region (0 Hz) cannot be necessarily inferred by the extrapolation of the curve, since the "effective" K_δ (near zero) is probably controlled by the internal and external geometry of the fan and fan installation. Increased pulse amplitude (lower R-T-S) as shown in the figure causes only marginal increases in the dynamic distortion sensitivity.

Figure 35 shows the K_δ function versus frequency for the 80% N/ $\sqrt{\theta}$ condition. The frequency where K_δ goes approximately to zero is shifted from 150 Hz at 100% N/ $\sqrt{\theta}$ to approximately 70 Hz at 80% N/ $\sqrt{\theta}$. As with the 100% speed data, a "cutoff" frequency is suggested where fluctuations above a given frequency do not affect (or only marginally affect) fan stability.

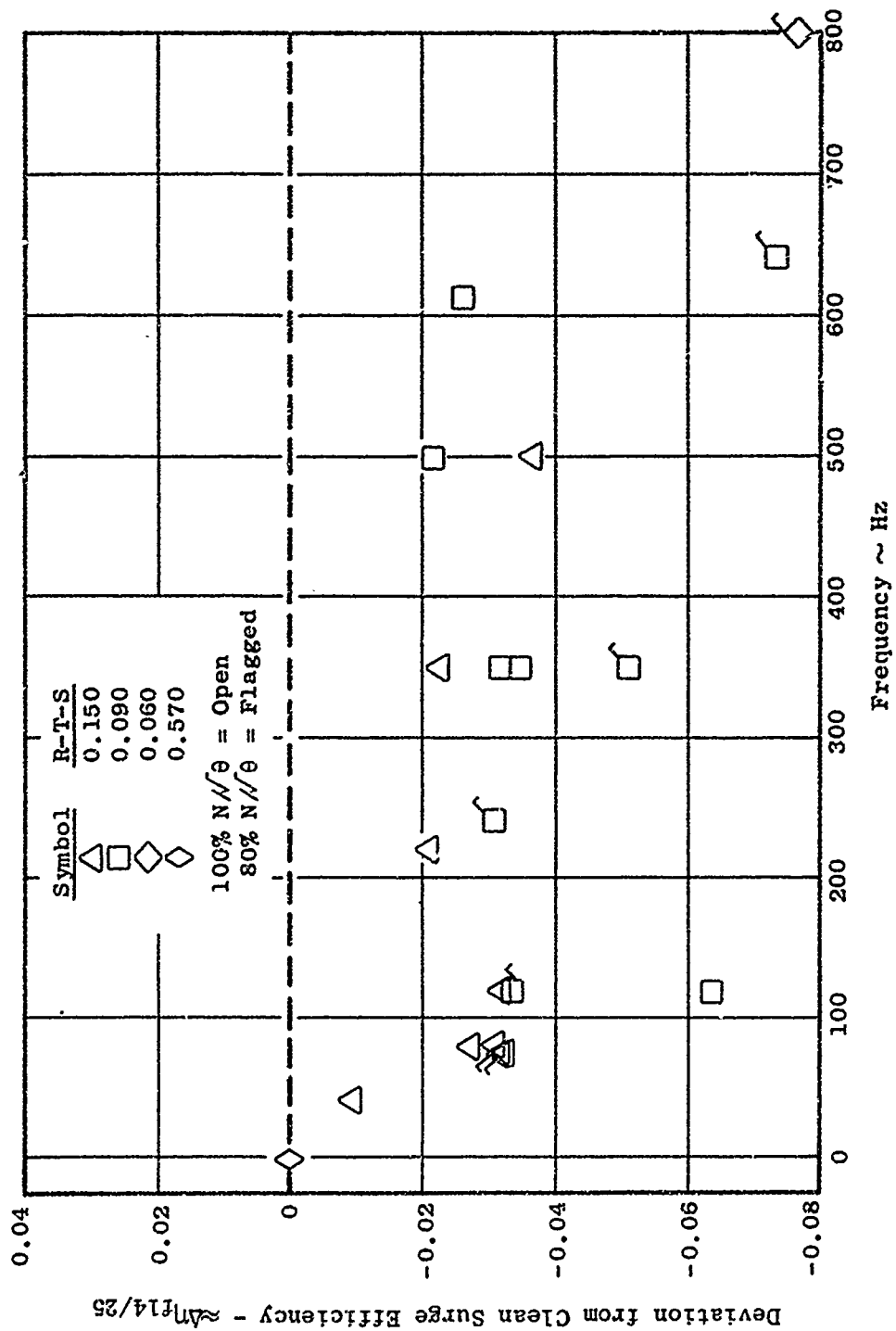


Figure 32. Frequency Effect on Overall Efficiency.

$$\Delta PRS = \left[\frac{(P_r)_{\text{Surge Undistorted}} - (P_r)_{\text{Surge Distorted}}}{(P_r)_{\text{Surge Undistorted}}} \right] W_c = \text{Constant}$$

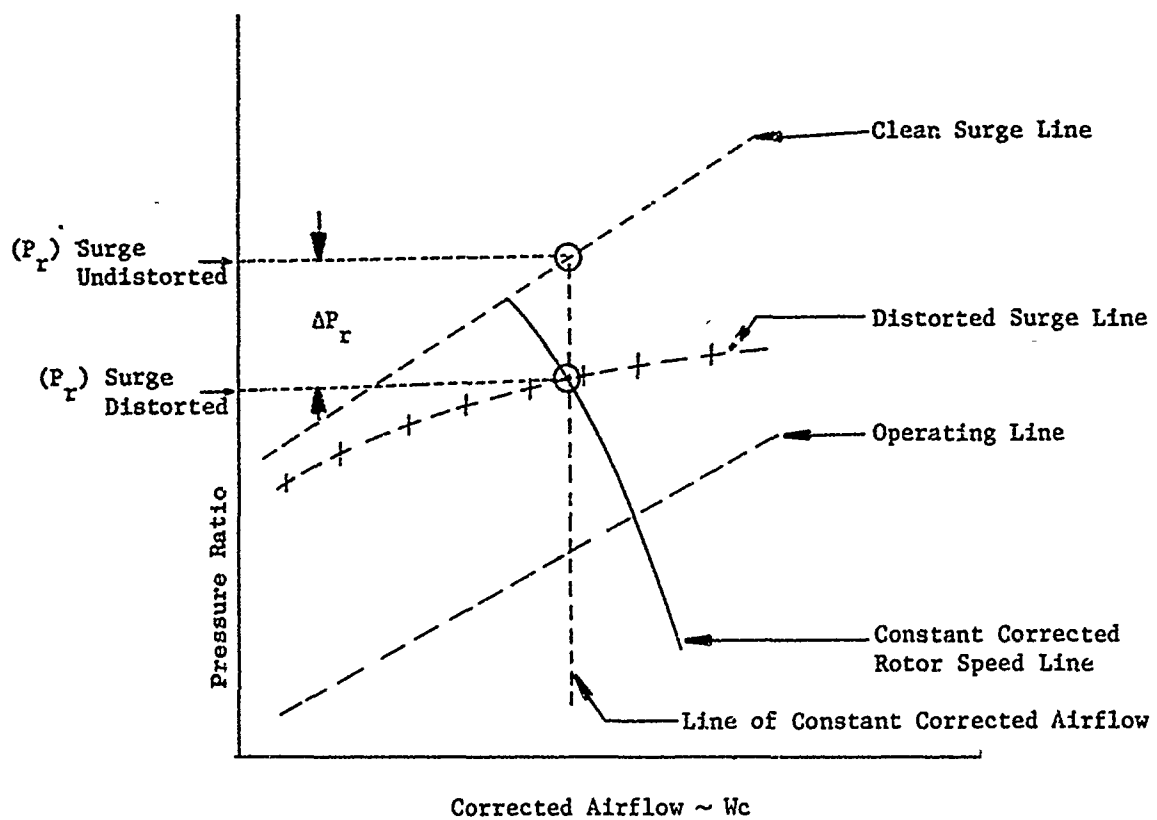


Figure 33. ΔPRS Definition.

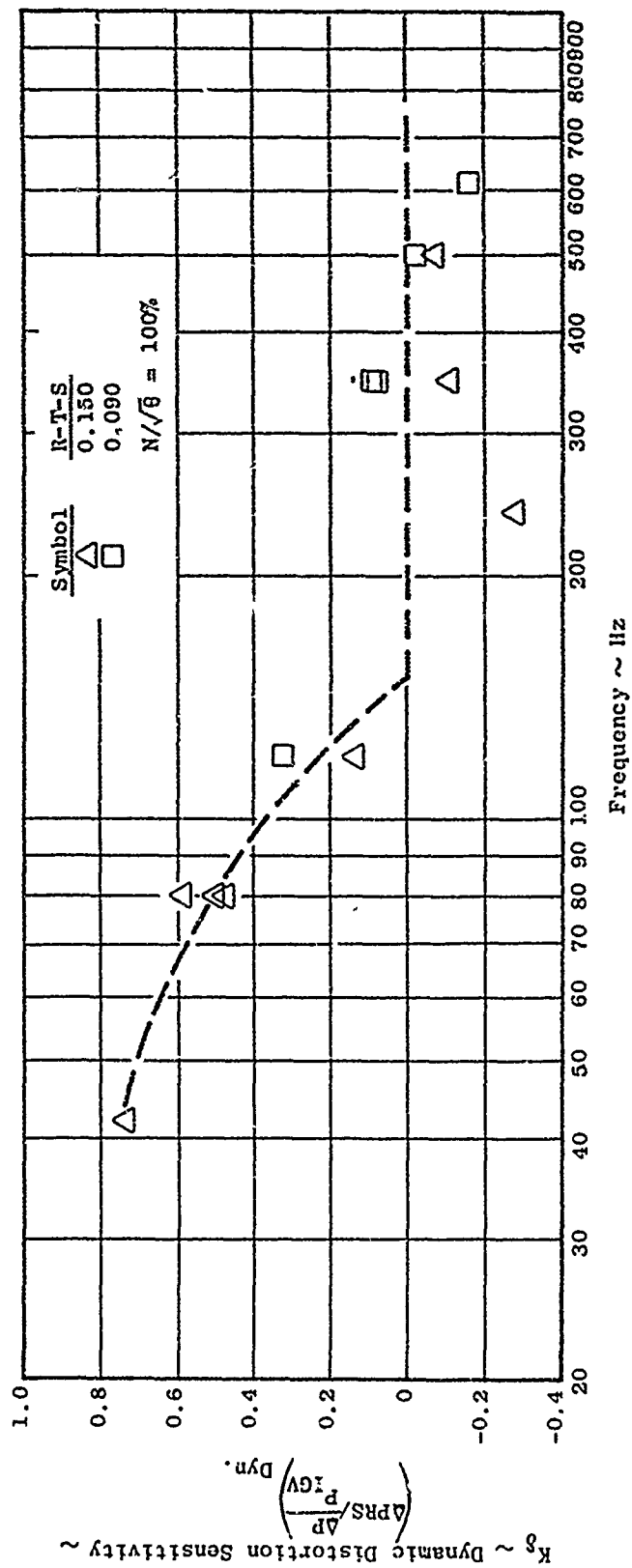


Figure 34. Dynamic Distortion Sensitivity Versus Frequency - $N/\theta = 100\%$.

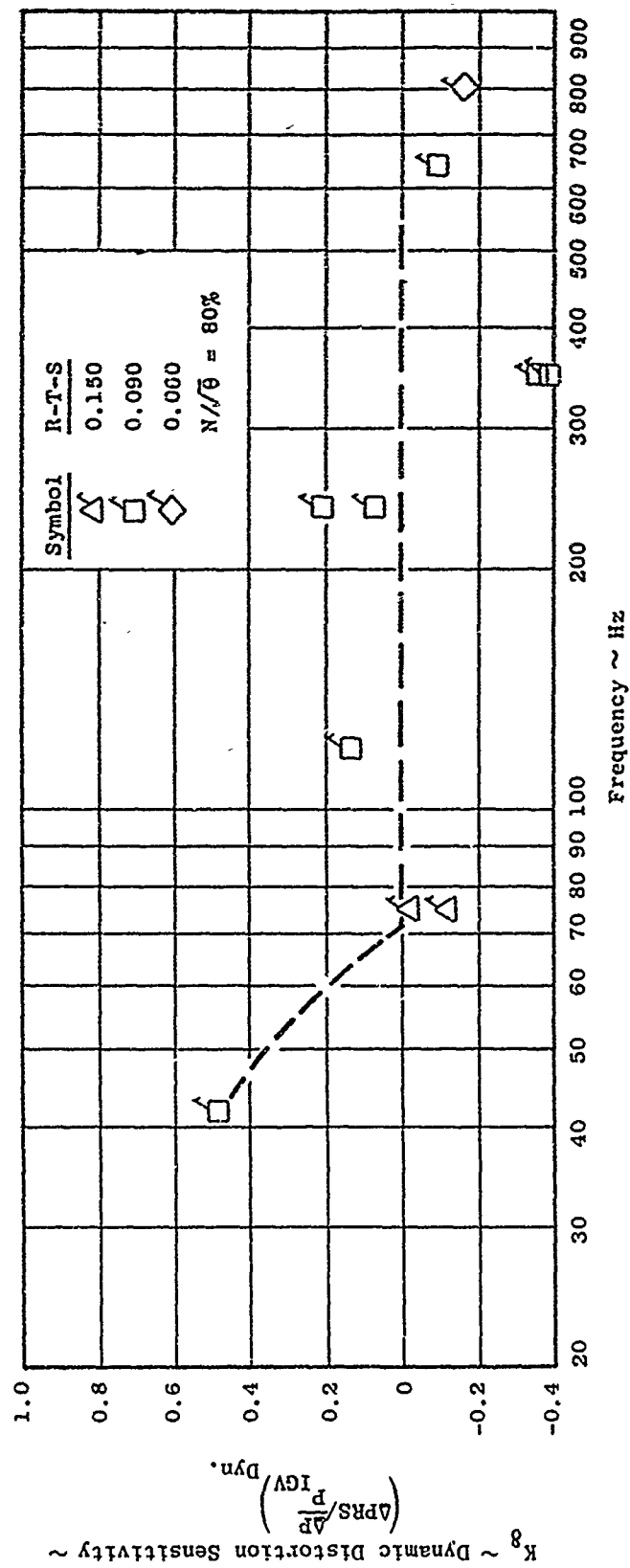


Figure 35. Dynamic Distortion Sensitivity Versus Frequency - $N/\bar{\theta} = 80\%$.

An attempt to correlate the 100% and 80% speed data by a simple ratio of speeds and frequency is shown in Figure 36. In this plot the 100% speed is the base and is shown as before, while the 80% $N/\sqrt{\theta}$ values of frequency are increased by the ratio of speeds (100/80). This approach does not collapse the data in any unique manner. Another approach was tried involving Mach number and frequency. In order to construct an equivalent frequency relationship between the two speeds using Mach number, the Mach number at the IGV for undistorted 100% speed surge was chosen as the base value. The frequency of oscillation was modified by ratio of base Mach number to test Mach number for all near-surge points,

$$f_{MN} = f * \frac{M_N @ 100\% \text{ clean surge}}{M_N @ \text{test condition}}$$

A plot of the sensitivity versus this effective frequency is shown in Figure 37. The good agreement shown suggests that dynamic sensitivity is a strong function of inlet Mach number. The region beyond 150 Hz, where data scatter had previously obscured the results, shows a trend of low level positive and negative sensitivity variation as viewed by this type of correlation.

The value of the dynamic distortion characteristics as presented in the aforementioned figures lies primarily in its definition of a cutoff frequency above which planar unsteady pressures have little or no effect. The characteristic between 150 and 40 Hz is established with very little steady-state distortion superimposed. The combination of random dynamic distortion occurring over a section of the annulus and in conjunction with a high base level of steady-state distortion is a much more complex phenomenon.

Dynamic Distortion Transfer Coefficient. Distortion transfer in steady-state terms can be defined as the distortion level at the compressor exit divided by the distortion level at the inlet for the portions of annulus seeing the same flow streamlines. In the case of dynamic distortion in this report, the magnitude of the unsteady pressure oscillation normalized by the mean level is computed at the entrance and exit, and the ratio of these two is defined as the Dynamic Distortion Transfer Coefficient (DDTC). This procedure is complicated when considering unsteady flow, since duct resonances and harmonic frequencies enter into the determination, driven by the fundamental flow oscillation and influenced by geometry and acoustic boundary conditions, as discussed and illustrated in the section on P³G wave quality. These interactions combine with the basic accuracy problem of dividing a small percentage by another small percentage to yield a large number and produce a fair degree of data scatter in the results. However, several clear trends may be observed from an overall look at the data.

The dynamic distortion transfer from the fan hub to the downstream compressor face (station 25) is of primary concern, since it affects the behavior of the core compressor system. Figure 38 shows the DDTC versus frequency for the 100% speed near-stall points to be of the order of only 20% of the incoming distortion amplitude for all frequencies but 80 Hz, and the 80 Hz level reaches only 36%. A similar result is seen for the 80% speed. The 80% $N/\sqrt{\theta}$ data indicate a slight rise in DDTC to a limit of about 50% except for the 118 Hz

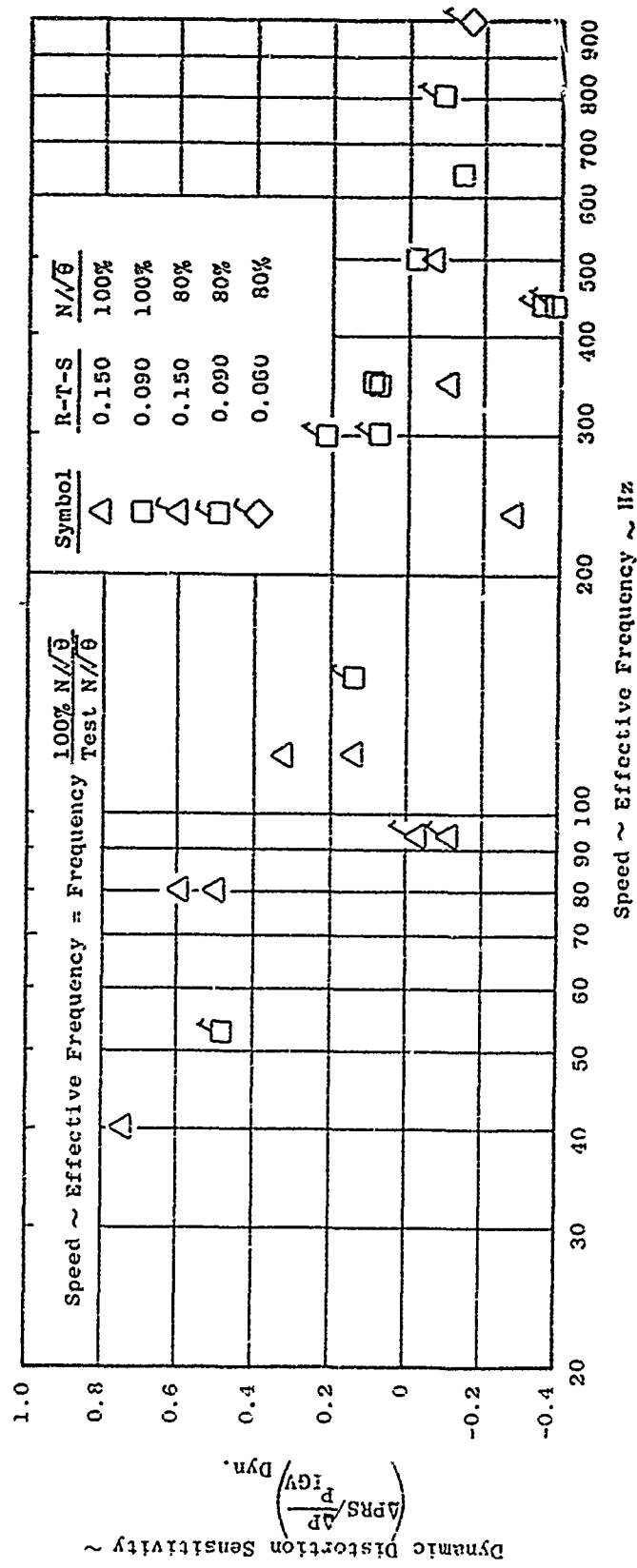


Figure 36. Dynamic Distortion Sensitivity Versus Effective Frequency - N/θ .

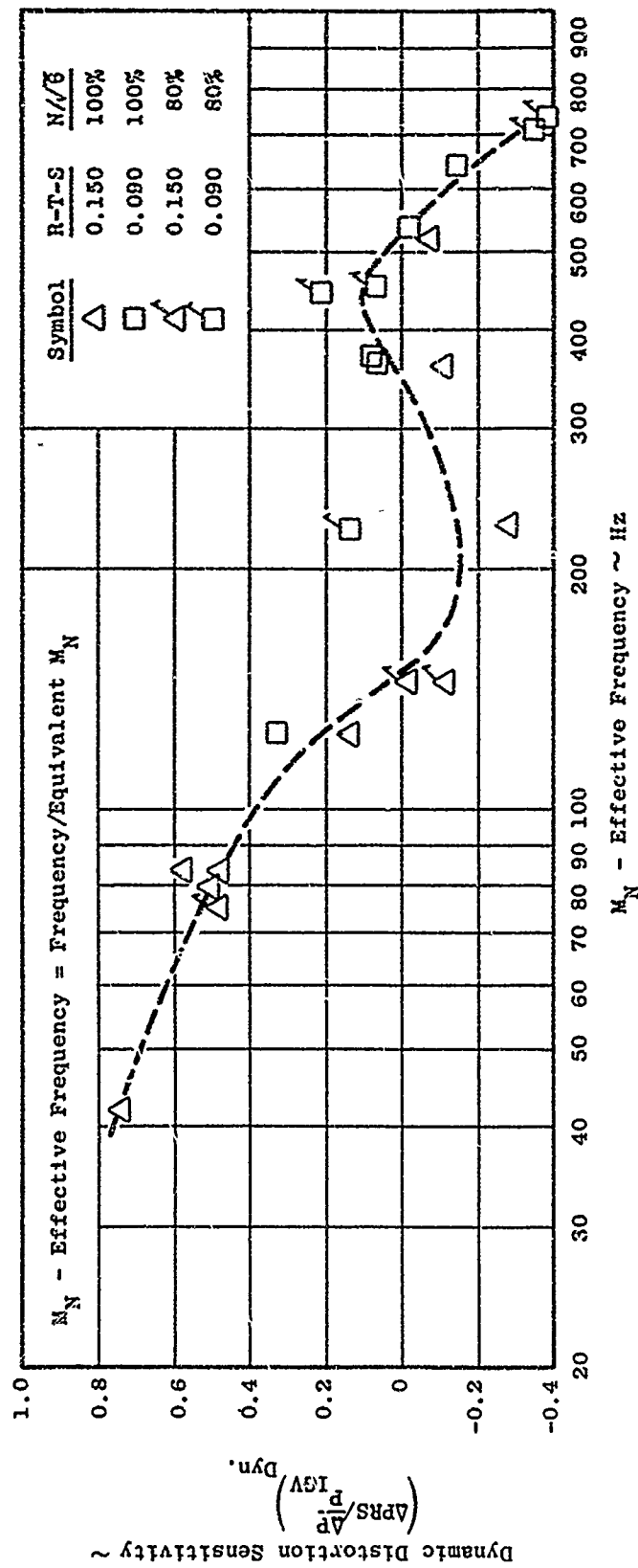


Figure 37. Dynamic Distortion Sensitivity Versus Effective Frequency - M_N .

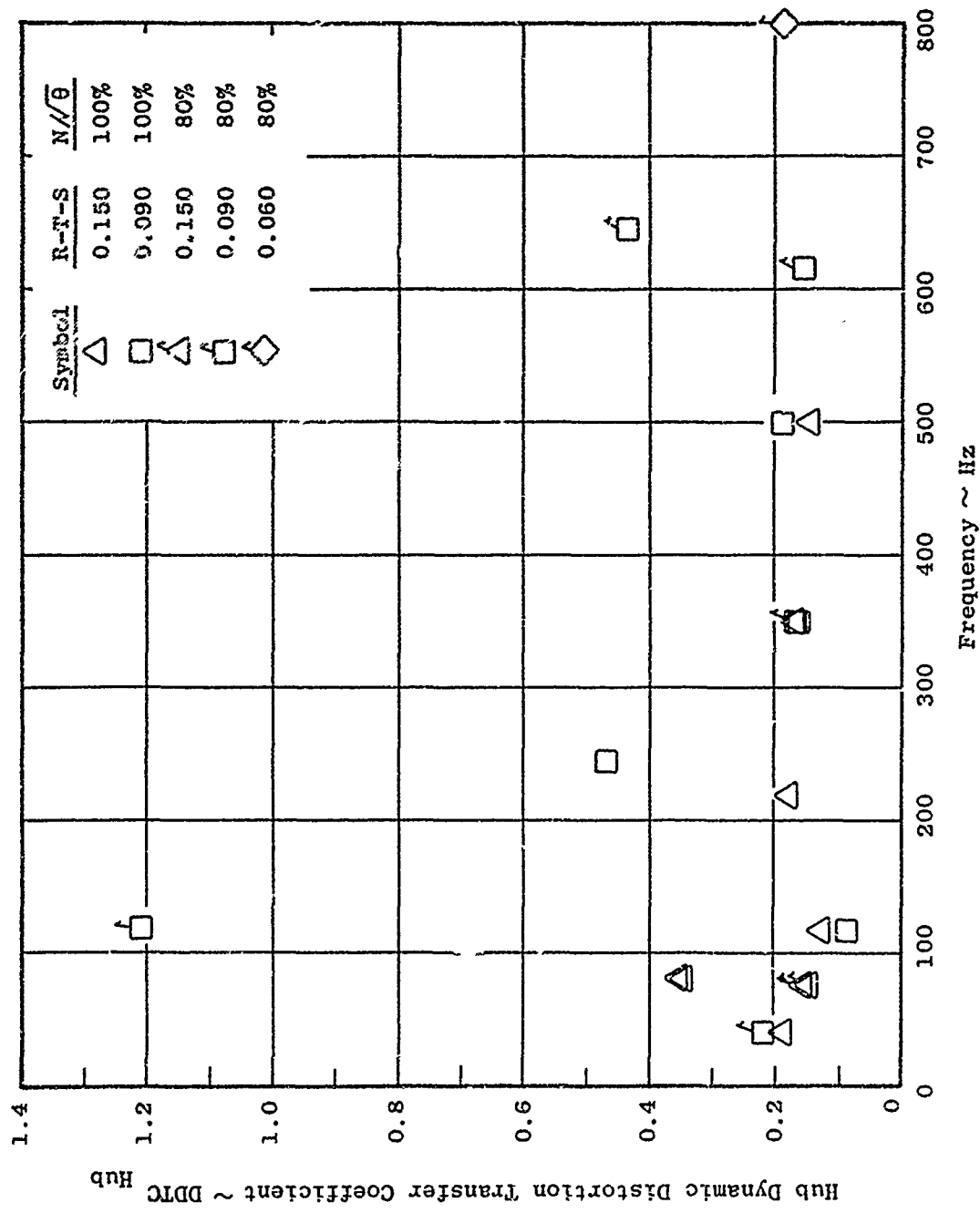


Figure 38. Hub Dynamic Distortion Transfer Coefficient vs Frequency.

case, where transfer jumps to 121%. The distortion transfer to the core, therefore, is considerably reduced for all but a few discrete frequencies for both speeds and all amplitudes. The spikes in DDTC at given discrete frequencies may be due to acoustic resonance characteristics, although an error in the data cannot be entirely ruled out despite double checking of the data handling procedures.

Although distortion transfer in the fan duct region is usually of lesser interest, in this particular case an additional insight into dynamic transfer is gained by using the same techniques as applied to the hub flow region. Figure 39 shows the fan duct DDTC to be a pronounced function of frequency for both fan speeds. In general, an increase of transfer is seen from 40 to 100 Hz up to approximately 100%, and then a gradual roll-off occurs at ≈ 150 Hz for the 100% speed and above 350 Hz for the 80% speed data. A spike in the 80% speed data at 118 Hz is also seen and is the same unique data point previously discussed with respect to hub DDTC. Waveforms reflecting these general results are shown in the Appendix.

It is apparent that there is considerably less dynamic activity going through the fan at the hub than at the tip. A proven concept to explain this phenomenon has not yet been defined. Table IV lists all the calculated results for Dynamic Distortion Sensitivity and Dynamic Distortion Transfer.

5.3.4 Bypass Ratio Effect

Surges 17 and 18 were completed for 80% speeds and 75 Hz P^3G frequency for bypass ratios of 1.34 and 2.11, respectively. The stability effects of this b BPR change were negligible. The speed lines to surge for the two conditions are shown to be nearly identical in Figure 40. The sensitivity (K_s) for the two conditions was -0.02 and -0.12; $DDTC_{HUB} + 0.16$ and 0.15 and, the $DDTC_{TIP} = 0.95$ and 0.92 for surges 17 and 18, respectively.

5.3.5 Repeatability

Two surges were duplicated using identical operational and test conditions to determine the repeatability of the results. Within the limits of normal data accuracy and mechanical tolerances for establishing test conditions, the system showed good agreement between the repeated points. Table V compares the results and imposed conditions for surges 1 and 14 (which were at 80 Hz, $R-T-S = 0.090$ and 100% $N/\sqrt{\theta}$) and surges 6 and 21 (which were at 350 Hz, $R-T-S = 0.090$ and 100% $N/\sqrt{\theta}$). Calculated distortion sensitivity and distortion transfer at the hub and tip showed excellent agreement for both surges. Total-pressure pulse amplitude at the IGV face showed agreement within the limits of the data accuracy.

5.3.6 Fan Dynamic versus Steady-State Operation

Definition of fan operation is normally represented in terms of the pressure ratio across the machine and the corrected airflow at the inlet for a given corrected rotor speed. Steady-state and dynamic instrumentation are positioned to define these parameters in the normal steady-state test setup. Since this

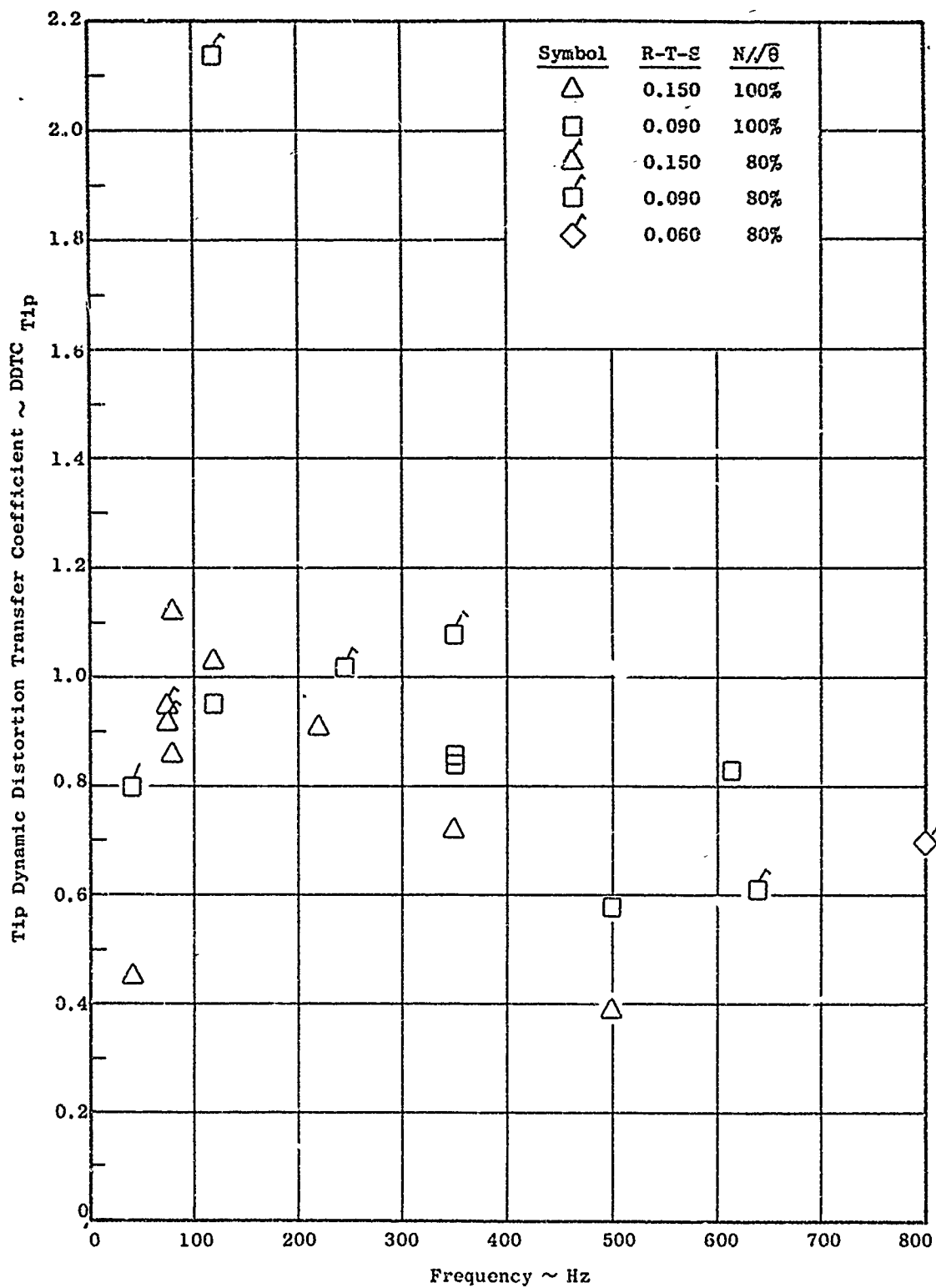


Figure 39. Tip Dynamic Distortion Transfer Versus Frequency.

Table IV. Calculated Fan/P3G Test Results.

Stall No.	Near Stall Rdg. No.	$N/\sqrt{\sigma}$ %	(P ³ G) f Hz	Pulse Half Amplitude @		Dynamic Distortion Sensitivity K_d TIP (APRS/1/2 AMP)	Dynamic Distortion Transfer Coefficient	
				IGV TIP %	IGV HUB %		DDTC TIP %/%	DDTC HUB %/%
1	38	100	80	8.40	8.40	+0.50	0.86	0.35
2	41	100	220	6.06	7.00	-0.28	0.91	0.18
3	43	100	350	10.48	9.20	-0.11	0.72	0.17
4	45	100	500	7.27	7.40	-0.07	0.39	0.15
5	47	100	500	13.34	11.50	-0.02	0.58	0.12
6	49	100	350	14.57	12.80	+0.08	0.84	0.17
12	64	100	118	8.79	9.30	+0.14	1.03	0.13
13	65/66	100	118	15.39	15.20	+0.33	0.95	0.09
14	69	100	80	10.67	8.30	+0.59	1.12	0.36
15	69	100	80	10.67	8.30	+0.48	1.12	0.36
16	71	100	42	6.88	4.50	+0.74	0.45	0.19
20	86	100	613	9.62	6.70	-0.15	0.83	0.16
21	84	100	350	15.00	13.00	+0.09	0.86	0.19
24	93	100	0	STEADY-STATE-STALL CHECK				
7	53/54	80	350	6.41	6.73	-0.395	1.08	0.17
8	53/54	80	350	6.41	6.73	-0.35	1.08	0.17
9	57	80	240	9.66	10.00	+0.07	1.02	0.47
10	57	80	240	9.66	10.00	+0.21	1.02	0.47
11	61	80	118	5.11	5.30	+0.14	2.14	1.21
17	74	80	75	7.09	6.50	-0.02	0.95	0.16
18	78	80	75	7.29	5.20	-0.12	0.92	0.15
19	82	80	42	5.84	5.25	+0.48	0.80	0.22
22	91	80	641	10.53	5.60	-0.09	0.61	0.44
23	92	80	800	10.52	5.20	-0.16	0.70	0.19

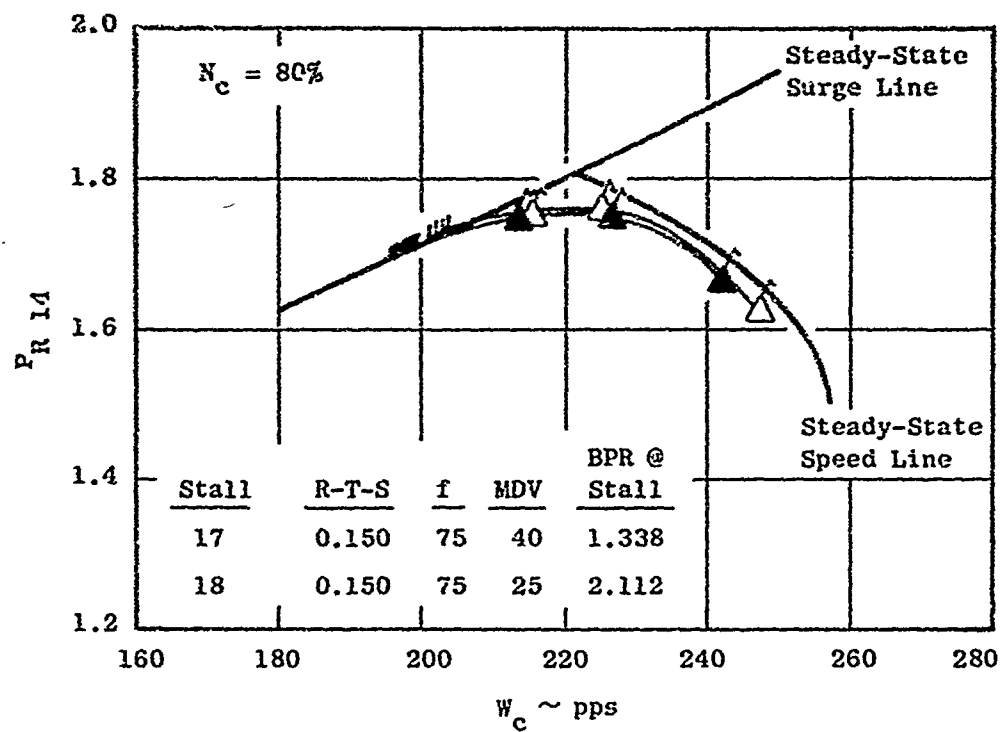


Figure 40. Bypass Ratio Effect on Stability.

Table V. Repeatability Results.

f, Hz	RTS, Inch	N/ $\sqrt{\theta}$, %	Stall	P _R	W _C , pps	K ₀	DDTC _T	DDTC _H	P _T IGV PULSE AMPLITUDE	
									HUB %	TIP %
80	150	100	1	2.485	336.5	+0.5	0.86	0.35	8.4	8.4
			14	2.42	334.0	+0.59	1.12	0.36	10.67	8.3
350	0.090	100	6	2.53	330	+0.08	0.84	0.17	14.57	12.60
			21	2.54	333	+0.09	0.86	0.19	15.0	13.0

form of presentation is well established, it is informative to at least initially observe the transient behavior of the fan relative to steady-state performance and stability in this manner. The dynamic pressure ratio and flow relationships for the 2-stage fan are only indirectly related to the individual stage loading characteristics. This may hinder a more quantitative analysis of the data when presented in this conventional format, but does not inhibit the graphical benefit of mapping the instantaneous operating point and observing its path relative to steady-state conditions.

Figures 41 through 44 illustrate this approach for 3 frequencies at 100% $N/\sqrt{\theta}$ and one similar frequency at 80% $N/\sqrt{\theta}$. The illustrations shown are a composite calculation of near-surge excursion loop measured amplitudes and phase placed at the surge mean pressure ratio and flow. In other words, the transient path shown is the one which would be expected to surge the fan. The plot beneath each map shows the term $(P_{R14})/(W_c)$ against time. This parameter may be approximately compared to the surge line by considering the surge line in the vicinity of the particular corrected speed to be the slope of a line defined by the P_R over W_c at surge and the point at $(P_R, W_c) = (0, 0)$. Therefore, any instantaneous value of (P_R/W_c) exceeding the steady-state surge line slope is considered to be potentially in an unstable region. Any value below steady-state $(P_R/W_c)_{\text{surge}}$ is considered to be in a potentially stable region. The functional relationship between compressor operation and time above steady-state surge is constructed in this manner and presented along with the instantaneous mapping function for the same cycle at surge conditions.

Figure 41 shows the pressure ratio and flow excursion for a 100% speed, 80 Hz test condition. The pressure ratio and flow conditions presented in this form are controlled by two factors: (1) the unsteady flow effect on compressor performance and (2) the phase lag between measurements at the IGV plane and plane 14, approximately 25" downstream. Since the pulse entering the fan is propagated at some mean velocity, the entering and exit stations do not see the same part of the wave at the same instant in time. This difference produces pressure ratios of incorrect magnitudes as the frequency of the pulse becomes large. However, at 80 Hz the pulse period is larger than the travel time between measurement stations, and this condition approximates the actual cyclic performance of the machine. A "dwell time" of 3 ms may be observed for this cycle. As P^3G frequency is increased, it becomes more difficult to functionally correlate P_{T14} and P_{TIGV} into a meaningful pressure ratio. Figure 42 shows the surge conditions at 100% $N/\sqrt{\theta}$ and 350 Hz. Conditions here are such that the appearance of the transient path still provides a "feel" for the kind of dynamic operation taking place. Figure 43 shows the surge conditions at 100% $N/\sqrt{\theta}$ and 613 Hz frequency for the P^3G . Phase considerations, and possibly an airflow measurement problem due to a probe resonant condition, prevent any detailed assessment of this point on the basis of the transient operating path. Figure 44 shows the 80% $N/\sqrt{\theta}$ surge condition at 75 Hz. The shape of the transient speed line coincides with the steady-state mean level data points which showed a marked roll-back in flow due to the unsteady environment. The large dwell time suggested by this plot (9 ms) is probably distorted by the combination of data accuracy and the proximity of the total cycle to the steady-state surge line.

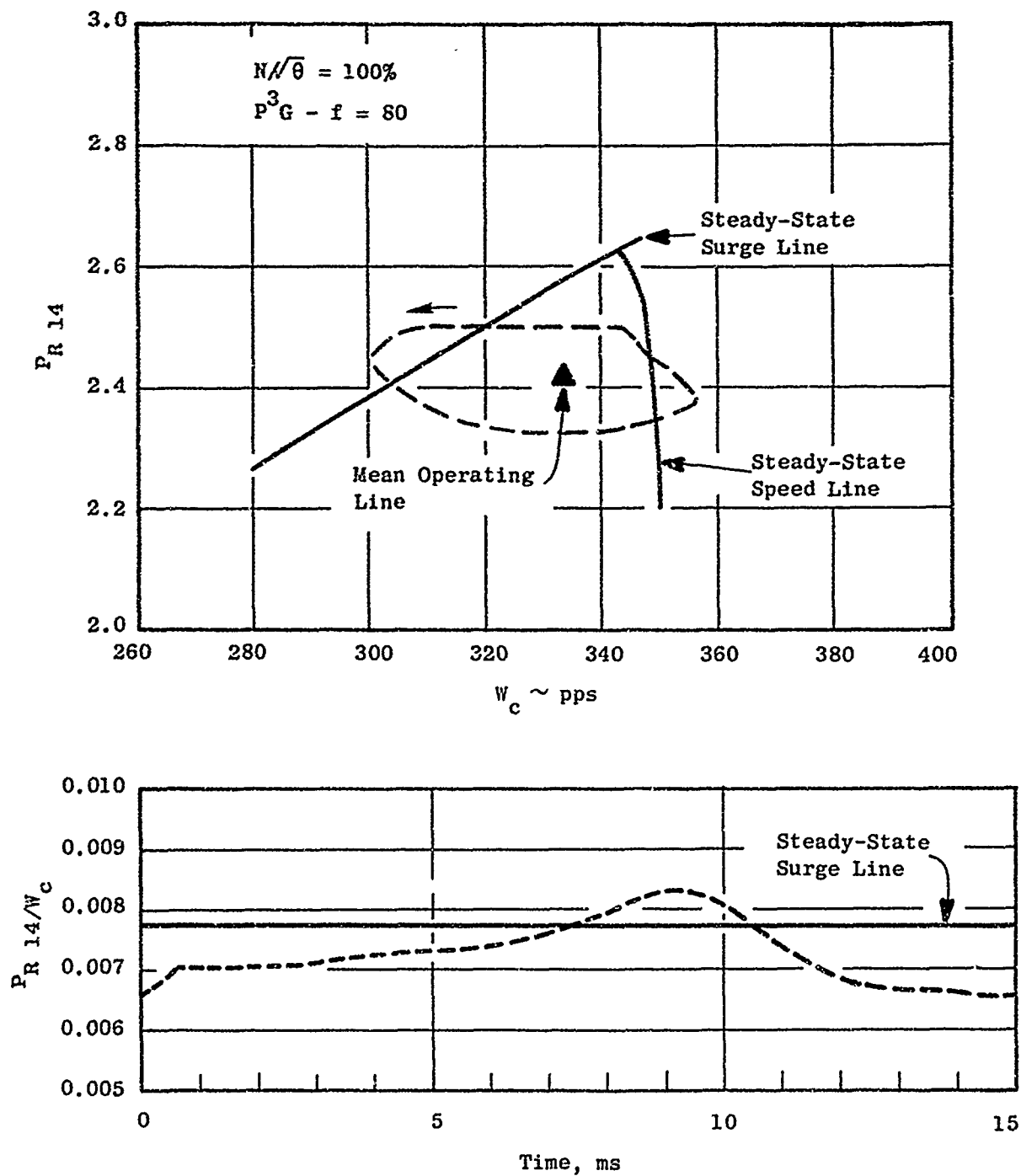


Figure 41. Pulsed Fan Operating Point Excursion Versus Steady-State Reading 69.

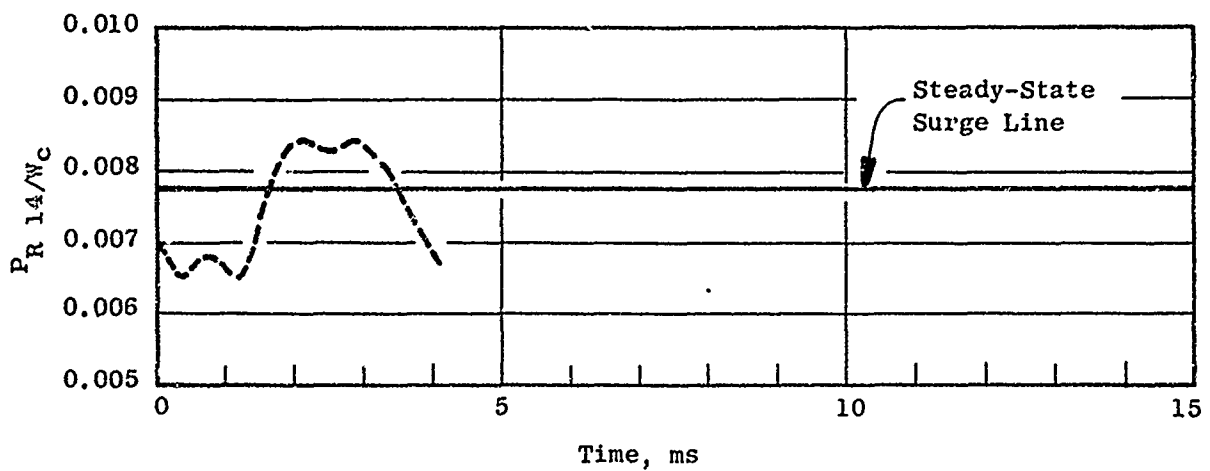
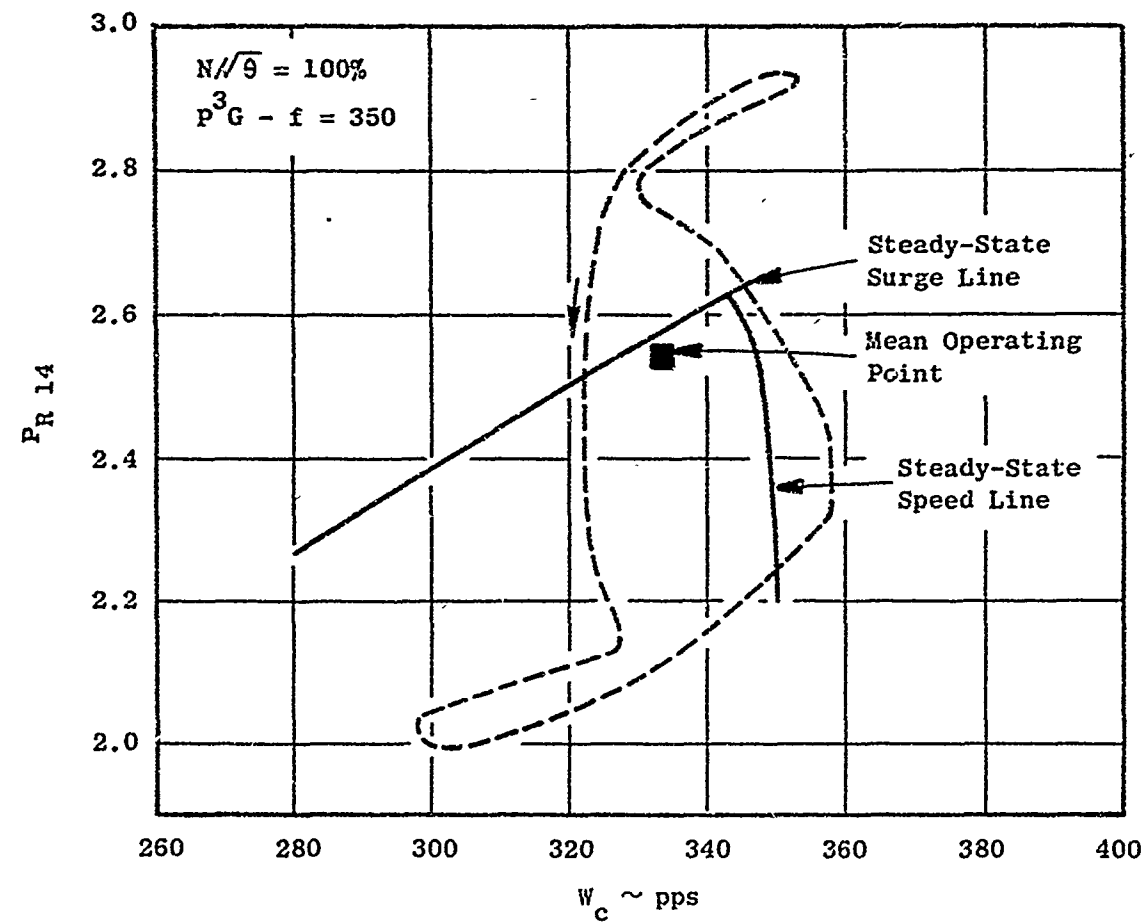


Figure 42. Pulsed Fan Operating Point Excursion Versus Steady-State Reading 87.

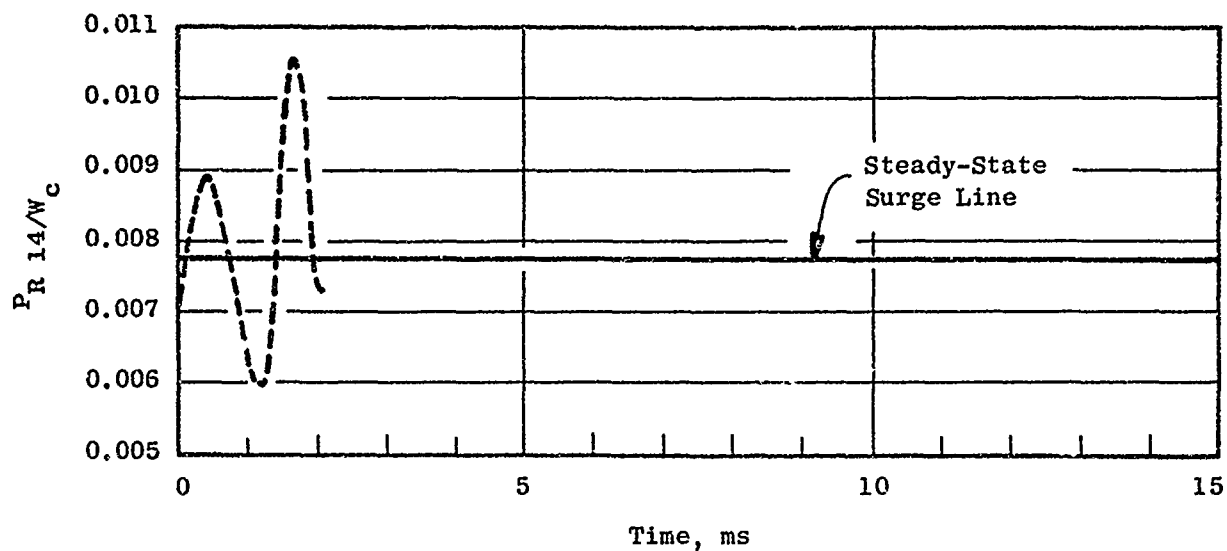
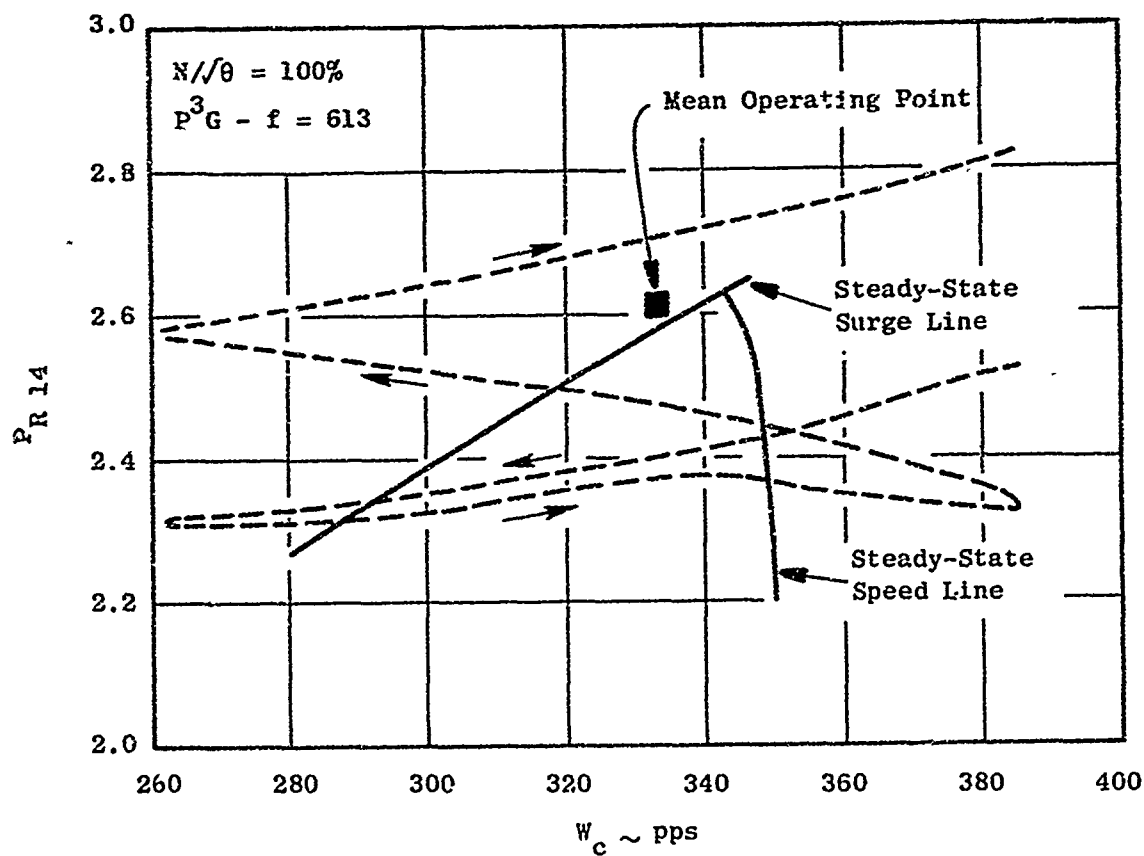


Figure 43. Pulsed Fan Operating Point Excursion Versus Steady-State Reading 86.

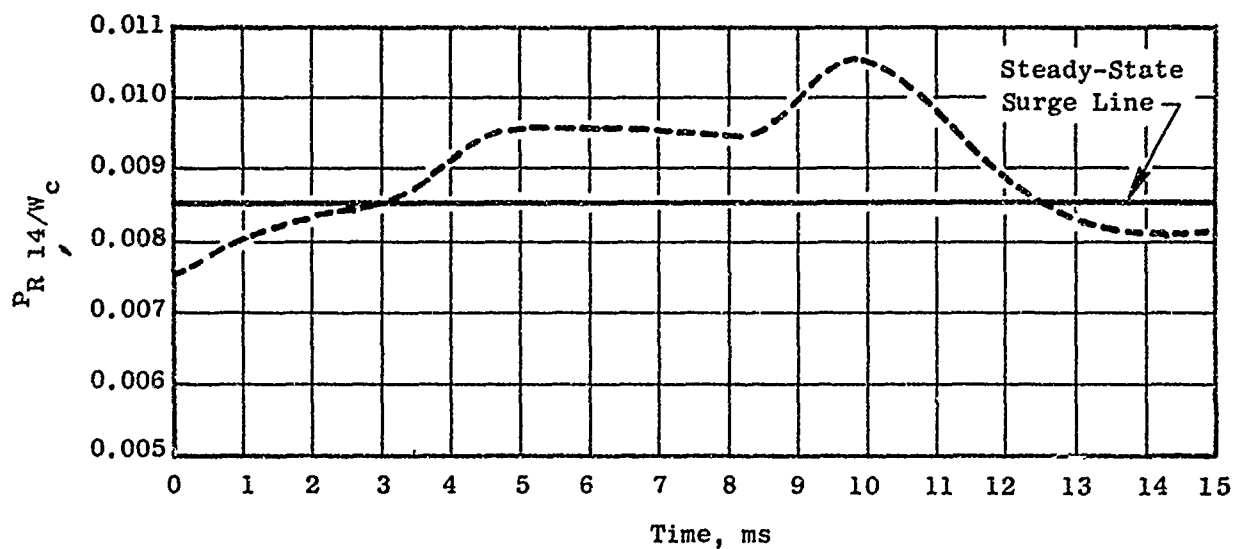
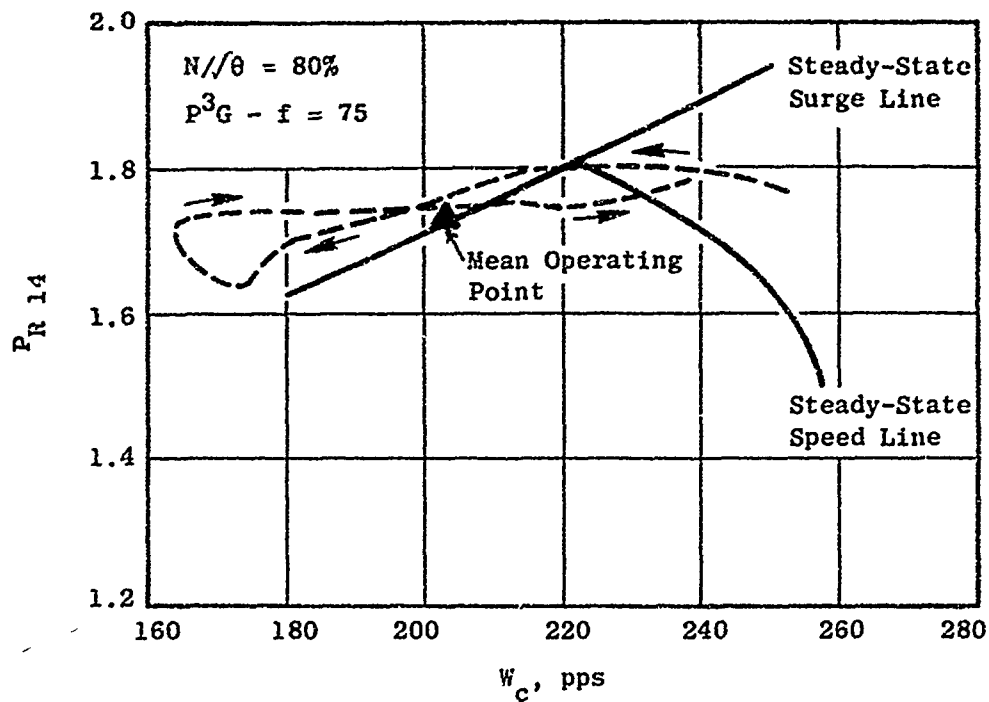


Figure 44. Pulsed Fan Operating Point Excursion Versus Steady-State Reading 74.

5.3.7 Planar Pulse Dwell Time

A value for the time a planar pulse must exist to produce surge may be inferred from the information presented on dynamic distortion sensitivity and illustrated in Figure 45. The plot of K_δ in terms of M_N equivalent frequency (f_{M_N}) shows that K_δ is zero at $f_{M_N} = 150$ Hz. Therefore, at this intersection the fan will surge on its clean surge line, and a pulse of essentially any magnitude will presumably not produce stall because its dwell time is not sufficiently long. The period for a sinusoidal pulse is inferred to be $P = 1/150 = 6.7$ ms. However, only 50% of the period is actually spent with the fan in the surge region, since the mean value of the pressure ratio is nominally on the surge line and spends 50% of the time above surge and 50% below the surge line. Therefore, the actual dwell time above the surge line required to produce surge is $P = 1/2f = 1/300 = 3.33$ ms. This concept is illustrated in Figure 45 which shows how the pressure ratio may exceed the steady-state surge value for identical periods of time independent of frequency. For frequencies less than 150 Hz, the mean P_R is below the steady-state surge level at the time of surge and yields a positive sensitivity to the unsteady flow. At $f = 150$ Hz, the mean P_R at surge rises above the steady-state surge line to satisfy the dwell time criterion as verified by the majority of negative sensitivities computed in this region.

A secondary effect of pulse amplitude on time above surge may also be inferred from Figure 37. A definite qualitative effect may be observed as the large pulse amplitudes (small R-T-S) show increase sensitivity to dynamic distortion in every case. The magnitude of the variation does not appear to suggest a strong dependency but does reflect upon the accuracy of the basic assumption of the above dwell time analysis that placed emphasis on the time above stall rather than the degree of penetration into the stall region.

This analysis uses the test results as measured and does not attempt an analytical interpretation based on fundamental characteristics which control fan dynamic behavior. Therefore, care must be exercised in the generalization of these results beyond this particular test setup, vehicle, and environment.

5.4 SYSTEM INTERACTION AND BOUNDARY CONDITIONS

Unsteady pressure fluctuation levels were measured at locations along the duct. The computed levels are tabulated for each near-surge point in Table VI for future reference and analysis. The pressure amplitudes along with the physical airflow (ρV) amplitude are plotted versus frequency in Figures 46 through 49. Several fundamental determinations regarding pulse character may be observed from the frequency plots.

The bellmouth inlet total-pressure probe was operational for only a short period of time despite considerable attention given to this installation. However, the amplitudes shown in Figure 46 for the available points clearly indicate that the bellmouth inlet does not act like a plenum with nearly constant total pressure as was originally speculated prior to test. The static pressure fluctuation level at the P^3G inlet face, also shown by Figure 46 (P^3GPS), attained amplitudes as high as 30%.

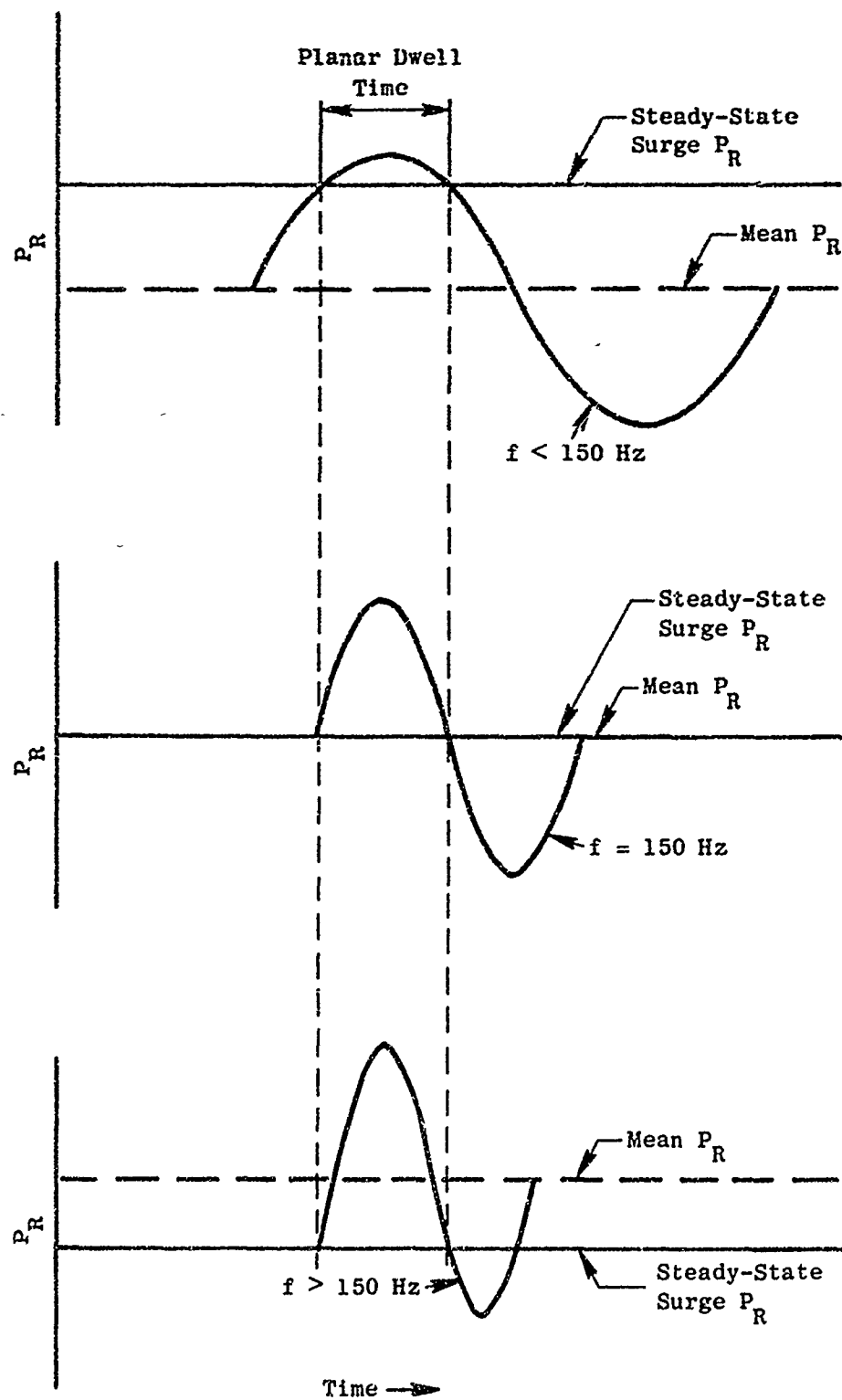


Figure 45. Planar Pulse Dwell Time Analysis.

Table VI. P³G/Fan Dynamic Performance Data.

Reading Number	Stall No.	N/o. %	L, lbs	R-T-S, Inch	Amplitude = (Max-Min)/Avg										P ₁₄ D	P ₁₅ C	P ₁₆ D
					P _{10V} FAIR	P _{10V} B	P _{10V} D	V ₀	P ₁₄	P ₁₅	EMPT	P ₁₇ C/S	A ₁₇ B	A ₁₇ C			
26	---	100	80	.375	1.65	---	---	2.01	4.23	---	---	---	---	---	---	---	---
27	Not Recorded on Tape	100	80	.150	16.85	---	---	19.26	14.46	6.00	---	---	---	---	Not Recorded on Tape	16.85	6.79
28	---	100	220	.150	12.50	---	---	17.25	11.04	---	---	---	---	---	---	---	---
29	---	100	220	.150	14.02	---	---	25.21	11.04	---	---	---	---	---	---	---	---
30	---	100	220	.150	18.61	---	---	25.21	13.77	---	---	---	---	---	---	---	---
31	---	100	350	.150	18.29	---	---	27.11	13.12	---	---	---	---	---	---	---	---
32	---	100	350	.150	13.41	---	---	27.20	5.73	---	---	---	---	---	---	---	---
33	---	100	500	.090	17.92	---	---	27.20	14.86	---	---	---	---	---	---	---	---
34	---	100	500	.090	23.03	---	---	24.96	18.06	---	---	---	---	---	---	---	---
35	---	100	500	.090	26.32	---	---	25.42	25.42	---	---	---	---	---	---	---	---
36	---	100	500	.090	25.64	---	---	43.61	24.36	---	---	---	---	---	---	---	---
37	---	100	350	.090	14.29	---	---	---	14.49	---	---	---	---	---	---	---	---
38	---	100	350	.090	14.08	---	---	---	14.55	---	---	---	---	---	---	---	---
39	---	100	350	.090	13.02	---	---	---	14.55	---	---	---	---	---	---	---	---
40	---	100	350	.090	14.78	---	---	---	16.25	---	---	---	---	---	---	---	---
41	---	100	350	.090	13.25	---	---	---	17.28	---	---	---	---	---	---	---	---
42	---	100	220	.150	12.38	---	---	---	7.10	---	---	---	---	---	---	---	---
43	---	100	220	.150	17.57	---	---	---	16.55	---	---	---	---	---	---	---	---
44	---	100	240	.090	20.00	---	---	---	19.43	---	---	---	---	---	---	---	---
45	---	100	240	.090	---	---	---	---	---	---	---	---	---	---	---	---	---
46	---	100	240	.090	---	---	---	---	---	---	---	---	---	---	---	---	---
47	---	100	240	.090	---	---	---	---	---	---	---	---	---	---	---	---	---
48	---	100	118	.090	20.00	---	---	---	17.44	---	---	---	---	---	---	---	---
49	---	100	118	.090	15.96	---	---	---	19.44	---	---	---	---	---	---	---	---
50	---	100	118	.090	13.64	---	---	---	20.80	---	---	---	---	---	---	---	---
51	---	100	118	.090	10.63	---	---	---	21.30	---	---	---	---	---	---	---	---
52	---	100	118	.150	15.00	---	---	---	12.62	---	---	---	---	---	---	---	---
53	---	100	118	.150	15.00	---	---	---	14.63	---	---	---	---	---	---	---	---
54	---	100	118	.150	15.52	---	---	---	16.07	---	---	---	---	---	---	---	---
55	---	100	118	.090	22.73	---	---	---	22.89	---	---	---	---	---	---	---	---
56	---	100	118	.090	20.38	---	---	---	33.31	---	---	---	---	---	---	---	---
57	---	100	80	.375	2.94	---	---	4.33	4.85	---	---	---	---	---	---	---	---
58	---	100	80	.150	19.20	---	---	17.41	24.86	---	---	---	---	---	---	---	---
59	---	100	80	.150	18.30	---	---	19.26	23.04	---	---	---	---	---	---	---	---
60	---	100	42	.150	10.40	---	---	---	6.46	---	---	---	---	---	---	---	---
61	---	100	42	.150	9.03	---	---	19.70	6.19	---	---	---	---	---	---	---	---
62	---	100	75	.150	10.53	---	---	23.03	17.86	---	---	---	---	---	---	---	---
63	---	100	75	.150	8.67	---	---	35.48	15.54	---	---	---	---	---	---	---	---
64	---	100	75	.150	13.04	---	---	37.04	13.50	---	---	---	---	---	---	---	---
65	---	100	75	.150	11.43	---	---	16.32	16.00	---	---	---	---	---	---	---	---
66	---	100	75	.150	11.26	---	---	39.75	13.85	---	---	---	---	---	---	---	---
67	---	100	75	.150	11.20	---	---	42.17	14.40	---	---	---	---	---	---	---	---
68	---	100	75	.150	10.42	---	---	46.82	13.48	---	---	---	---	---	---	---	---
69	---	100	75	.120	13.50	---	---	39.06	22.55	---	---	---	---	---	---	---	---
70	---	100	42	.100	10.10	---	---	---	9.67	---	---	---	---	---	---	---	---
71	---	100	42	.100	10.28	---	---	36.15	13.37	---	---	---	---	---	---	---	---
72	---	100	118	.375	3.49	---	---	5.80	5.43	---	---	---	---	---	---	---	---
73	---	100	613	.375	7.14	---	---	15.86	9.46	---	---	---	---	---	---	---	---
74	---	100	613	.090	12.62	---	---	46.47	12.72	---	---	---	---	---	---	---	---
75	---	100	613	.090	16.70	---	---	50.67	16.00	---	---	---	---	---	---	---	---
76	---	100	350	.090	20.00	---	---	41.40	25.71	---	---	---	---	---	---	---	---
77	---	100	641	.090	15.21	---	---	48.12	21.02	---	---	---	---	---	---	---	---
78	---	100	641	.090	14.56	---	---	55.31	13.74	---	---	---	---	---	---	---	---
79	---	100	641	.090	11.11	---	---	52.11	12.82	---	---	---	---	---	---	---	---
80	---	100	300	.090	10.38	---	---	26.83	14.71	---	---	---	---	---	---	---	---
81	---	100	0	.570	2.50	---	---	6.10	3.75	---	---	---	---	---	---	---	---
82	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
83	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
84	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
85	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
86	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
87	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
88	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
89	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
90	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
91	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
92	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---
93	---	100	0	.570	---	---	---	---	---	---	---	---	---	---	---	---	---

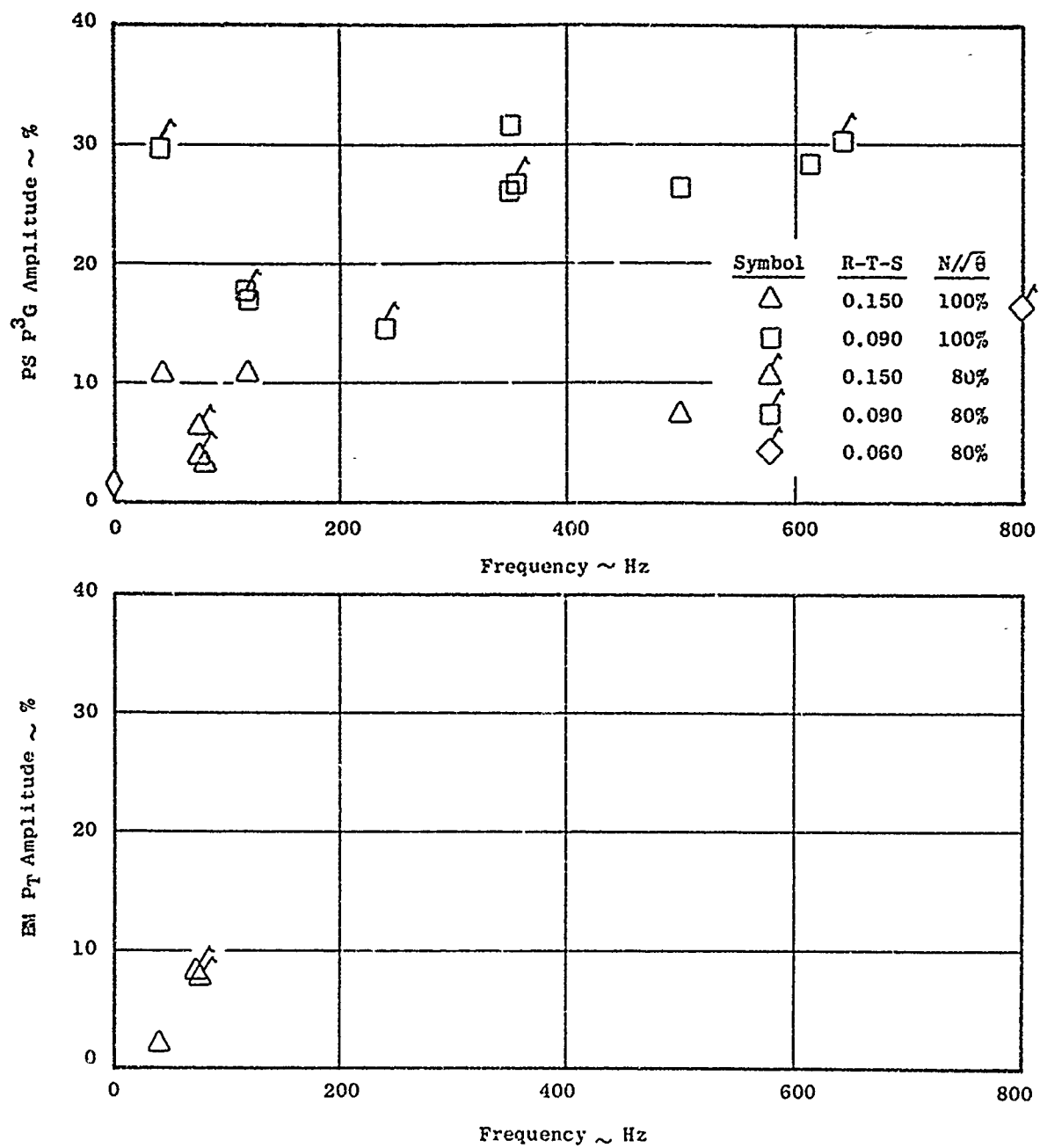


Figure 46. System Response Upstream of P³G.

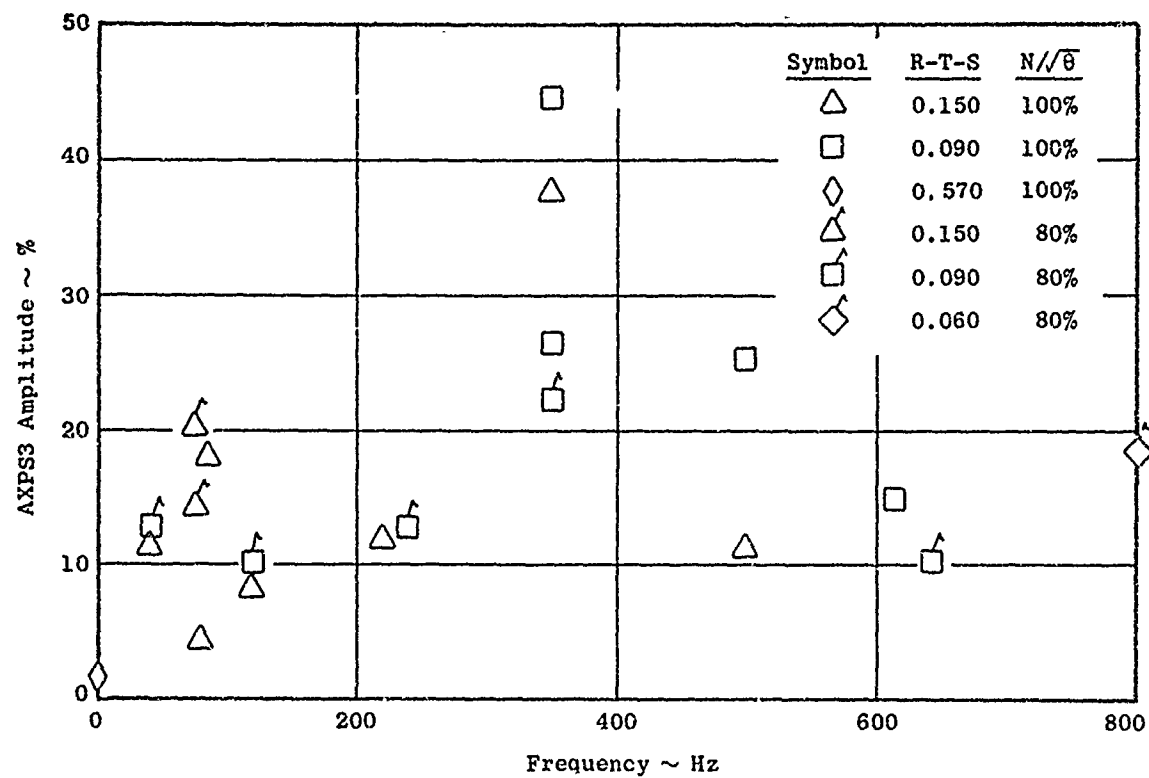
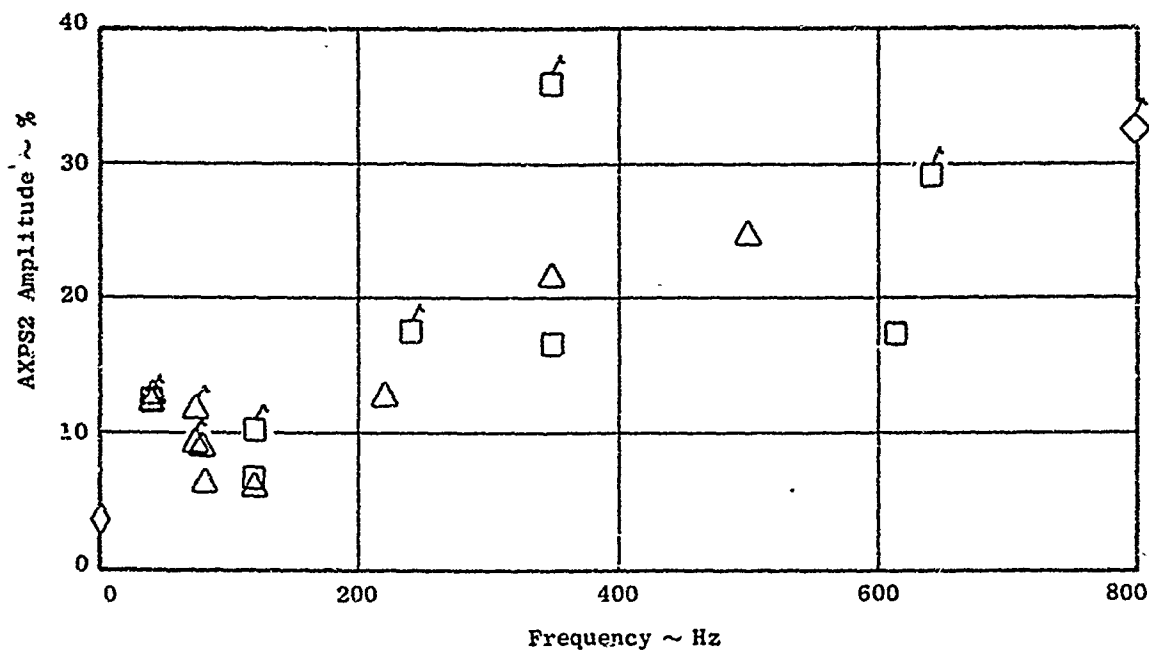


Figure 47. System Response Between the P³G and Fan.

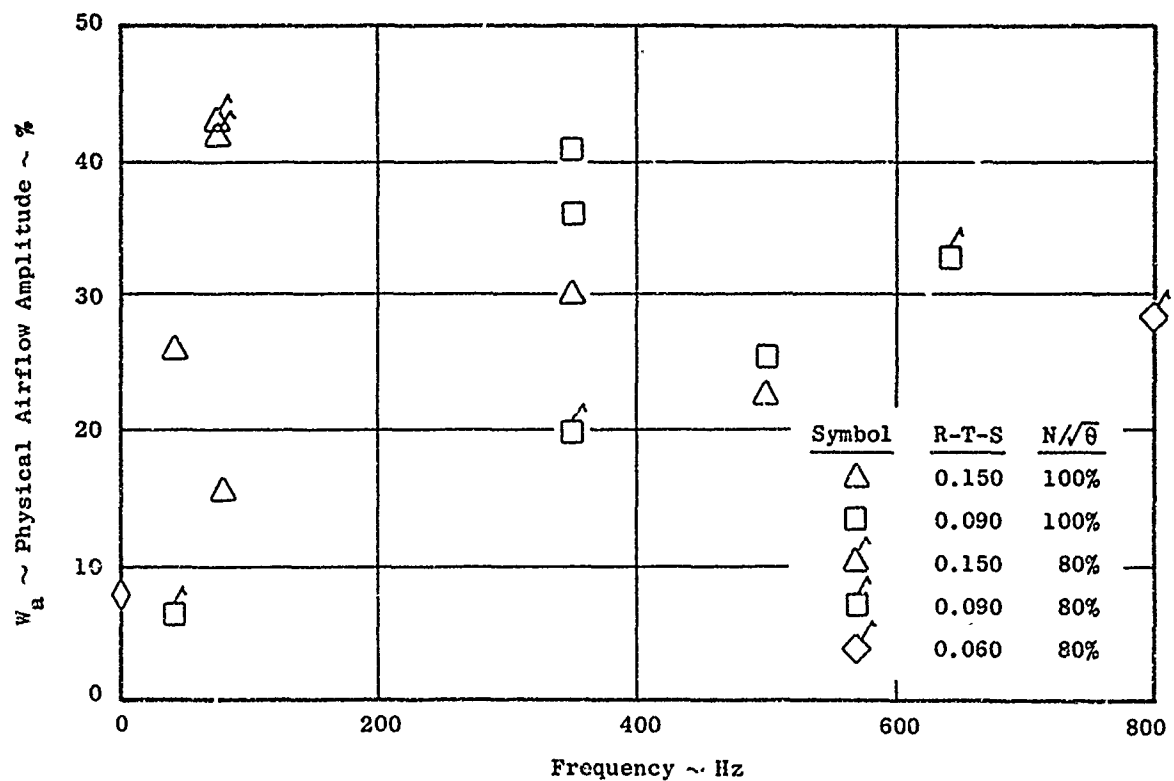
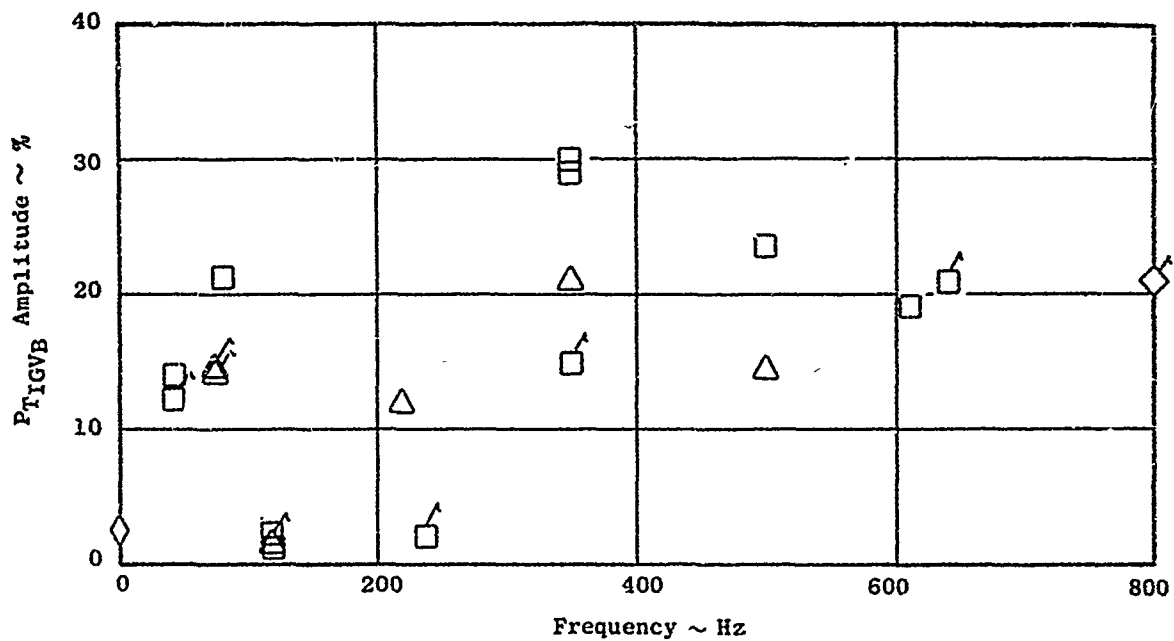


Figure 48. Physical Airflow and Total Pressure Amplitude at IGV Versus Frequency.

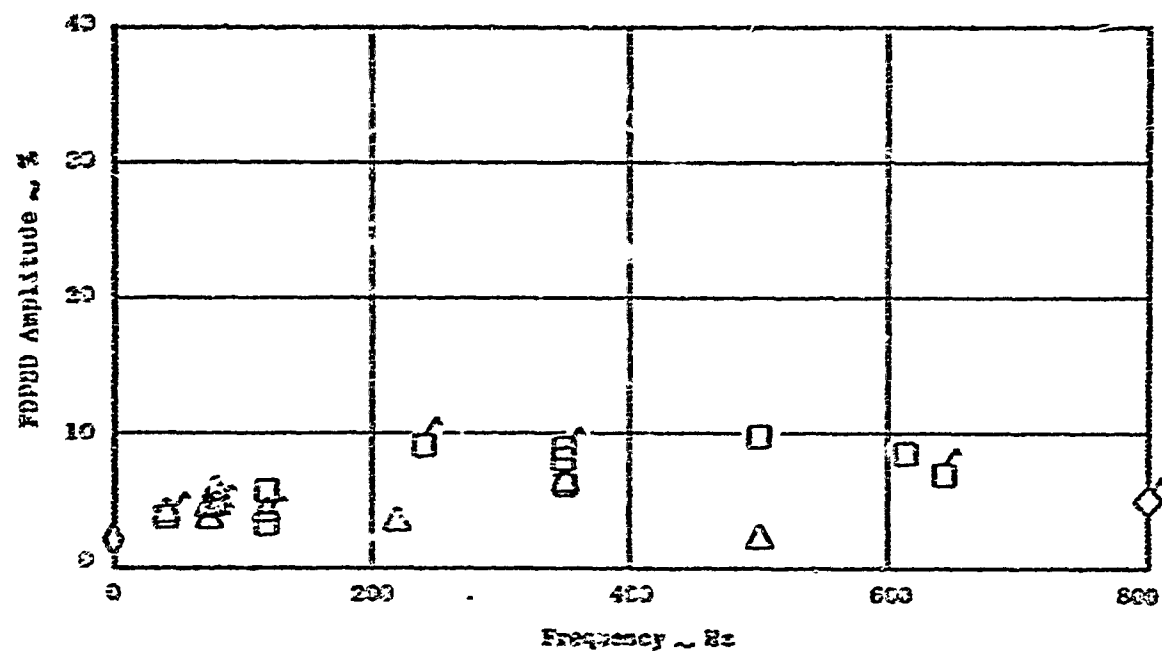
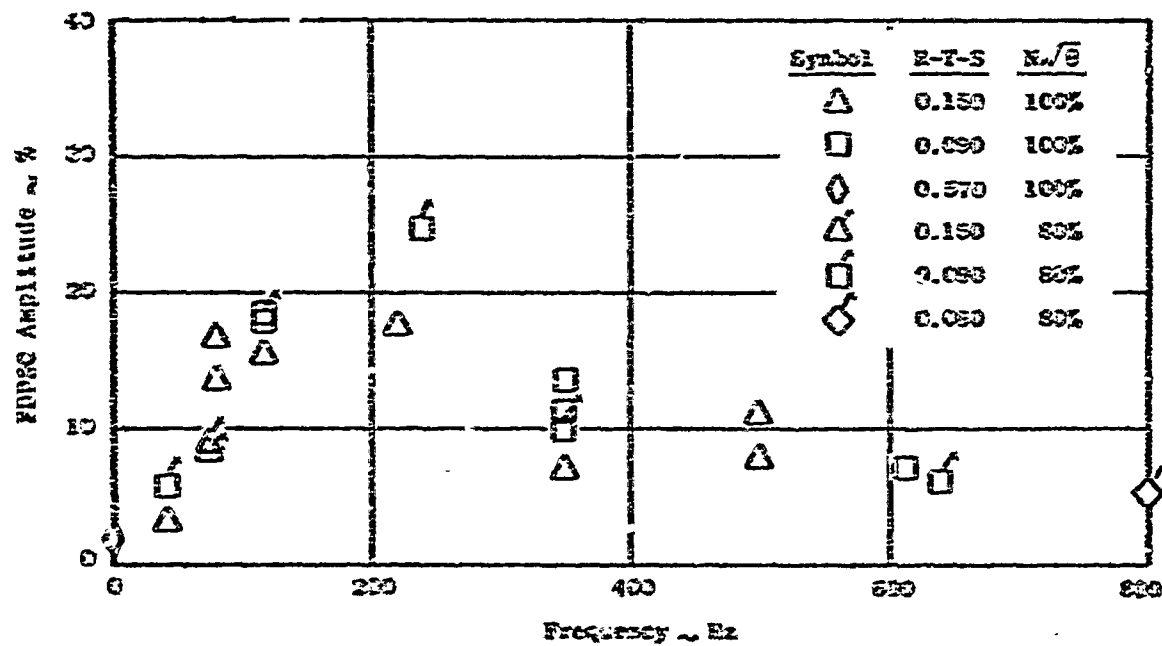


Figure 48 shows the P_T amplitude of the B-element ring and the results of the hot film probe in terms of physical airflow amplitude. The two parameters generally show the same order of magnitude of oscillation.

Static pressure oscillation behind the fan is shown in Figure 49 for two different axial positions. As expected, amplitudes are higher closest to the fan exit and diminish as the measurement plane moves downstream and exit areas become larger. The static pressure, FDPSC, is located 18 inches downstream of the PS14B measurement but still shows considerable unsteady effects. FDPSC is located 55" downstream of FDPSC in a large area ($\approx 6 \times$ area at FDPSC) and appears to be in a generally calm environment showing no more than 10% maximum amplitude and nominally only 4% to 8% maximum amplitude.

5.5 DATA REDUCTION

5.5.1 General

The data reduction of 28 dynamic measurements for 53 data points of the type of data taken during this testing is a program of major proportions. The data included for analysis in this report encompass all data acquired during testing on February 6 and 8, 1973, which were data points 36 through 93. In general, all near-stall data points were reduced for all meaningful parameters, and the remaining data points were processed for a select group of key parameters. Some gaps in this procedure occurred due to data handling problems and the erratic behavior of some instrumentation. The key dynamic parameters for which all possible data points were reduced include $(P_{TGV})_{AVG}$, P_{T14} , P_{R14} , W_C , and P_{R14}/W_C . The five parameters are displayed for each available data point in the Appendix. Tabulation of available parametric dynamic amplitudes and all steady-state parameters are shown in Tables VI and VII, respectively. Tabular analysis results are included with the particular topic under discussion and are referenced in the body of the report. All possible fundamental data in a graphical or digital form are included in the report in order to provide a substantial data bank for future investigation and investigators.

5.5.2 Procedure and Accuracy

Data reduction procedures may be broken into two sections, steady-state and dynamic. Steady-state data reduction has been developed over the years to the point where minimal effort is required to obtain finished results once the test setup is complete. Reduction and analysis of long records of dynamic data present an entirely different problem. Data processing techniques used and accuracy of the results are discussed below.

The dynamic data were recorded on FM multiplex tape using the previously discussed reference pressure system and the "Kulite" transducers. Retrieval of these data amounts to a reversal of this process, i.e., demodulation of the signals and recombination of the AC and DC portions of the total signal. The individual signals are then combined via an analog computer to yield the desired parameters and calculations. The results are displayed on an 8-channel Brush recorder. The analog output must then be hand digitized to achieve the final numerical results. This procedure was performed for 27 pressure transducers and

Table VII. NO_x and Steady-State Performance Data.[illegible]

Table VII. P³G/Fan Steady-State Performance[illegible]

VII. P³G/Fan Steady-State Performance Data.

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the single hot film airflow probe at the selected data points. Figure 50 shows a portion of the Stability Measurements Analysis Laboratory. The following instrumentation was used in the actual calculation of test results: nine total-pressure transducers at the IGV plane, four at plane 14, seven at plane 25, and all other individual operational measurements were reduced as required.

The accuracy of the final results is difficult to quantify. Estimates of individual dynamic pressure measurement accuracy, however, indicate that the results are probably within $\pm 3\%$ of the true value. This estimate includes allowances for electronic processing error and hand digitization of the strip chart output.

The accuracy of the hot film probe determination of airflow is dependent on several factors in addition to those affecting the pressure measurements. The fundamental accuracy of the probe has not been documented by extensive environmental testing and comparison against other measurement standards. Conceptually, the approach is well established and the electronics are highly developed.

The calculation of corrected flow combines the measurement of physical airflow and the instantaneous total pressure, and assumes that the total-temperature fluctuation is negligible. Analytical models of the system indicate that temperature variation may be of the order of $\pm 30^\circ$, and this type of variation would produce an approximate fluctuation in corrected airflow of $2\frac{1}{2}\%$. A clear definition of the corrected airflow calculation accuracy cannot be quantified, but trends and general levels are felt to be reasonable in most cases.

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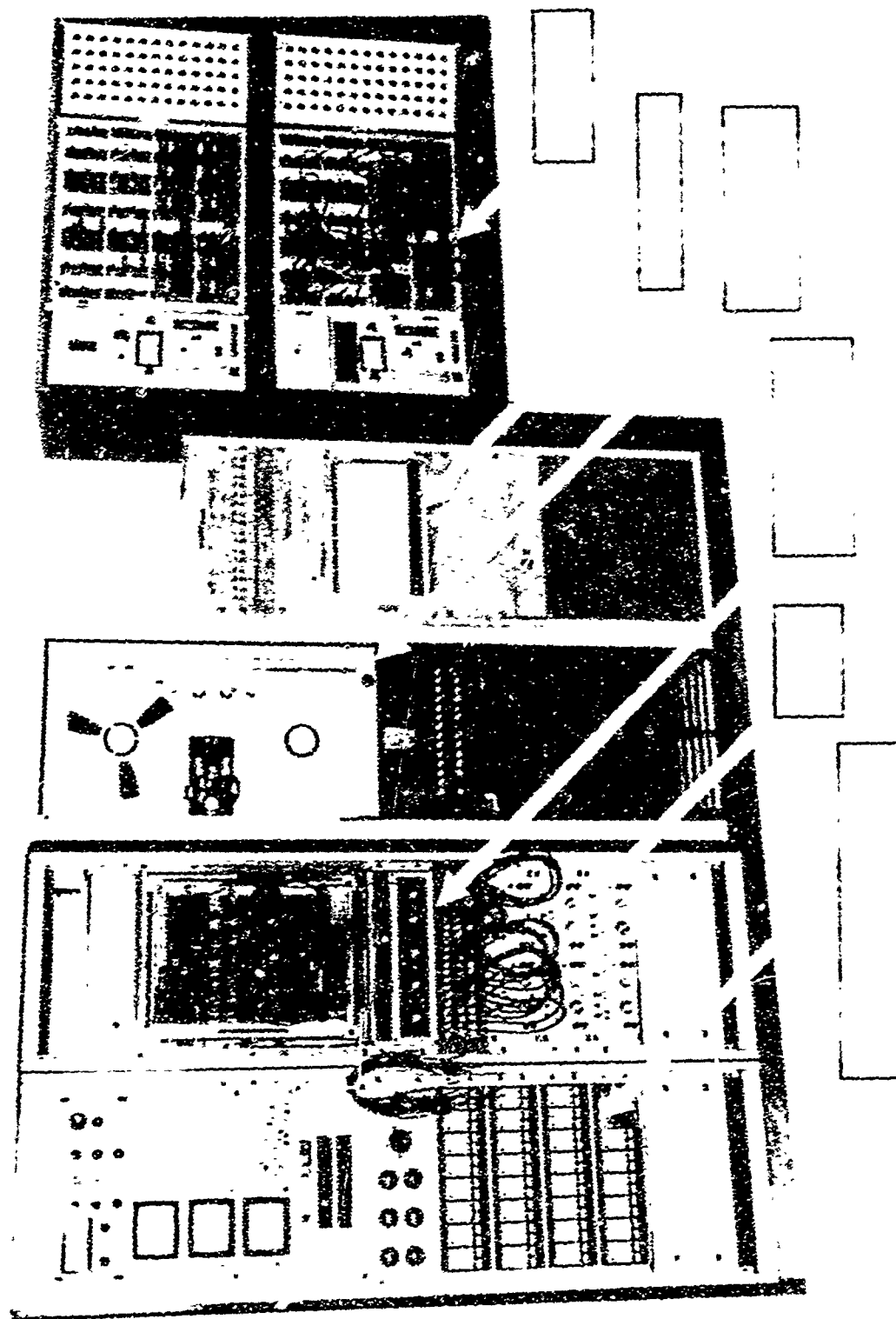


Figure 50. Stability Measurements Analysis Laboratory.

6.0 CONCLUSIONS

The major conclusions developed from this program cover a wide range of basic topics and, therefore, are categorized into the general areas as presented below.

6.1 OVERALL PROGRAM

- The basic objective of the program "to obtain fundamental information concerning the behavior of a fan compressor unit when subjected to planar pulses" was achieved.
- The P^3G proved to be a useful device for generating essentially planar pulses of sufficient amplitude to produce fan surge, and with frequency capability both below and above that for which the fan surge margin was significantly affected by these pulses.

6.2 FAN PERFORMANCE/STABILITY

- Dynamic measurements of pressure ratio and flow documented stable transient operation of the fan above the steady-state surge line over the frequency range of 42 to 800 Hz.
- Fan response to the planar pulse indicates that there is negligible loss in stall pressure ratio (no response) at frequencies above approximately the fan per rev frequency.
- The pulse amplitude, in general, is attenuated through the fan, and the attenuation increases with increasing frequency. Amplification was seen at very few conditions.
- Fan performance deteriorated sharply in the frequency range of 40 to 80 Hz and then showed limited but continued degradation as pulse frequency was increased. Flow decreases at 80% corrected fan speed were considerably larger than at 100% speed.
- Bypass ratio had no measurable effect on dynamic stability characteristics for the 2 points investigated.
- A final health check stall point showed that the fan suffered no measurable loss in clean surge margin during the testing.

6.3 P^3G PERFORMANCE

- Pulse amplitudes from approximately 9% to 30% were obtained over a range of frequencies extending from 40 to 800 Hz.

- The distortion/planarity characteristics of the pressure wave were very good circumferentially and showed some hub radial distortion with maximum peak values of 4% to 6% in the range of fan response (<300 Hz).
- The pulse waveforms were nearly sinusoidal in most cases, with second and third harmonics generally less than 20% and 15% fundamental amplitude, respectively, in the pitch rings. The hub ring showed harmonic content on the order of twice the pitch rings.
- The circumferential phase relationship between total pressures at the IGV was excellent, and little circumferential distortion was seen.
- Radial phase shift of hub pressures, relative to pressures in the tip region, were observed across the frequency spectrum. The majority of the data was within $\pm 20^\circ$; however, larger values were found at both ends of the frequency range.
- Pulse amplitude was essentially constant over the entire annulus. The average difference in amplitude from ring to ring was less than 2%.
- P³G mechanical operation presented no major obstruction to the achievement of overall program goals.

6.4 SYSTEM PERFORMANCE

- The bellmouth inlet total pressure indicated amplitude fluctuations of 10% or less.
- Static pressure fluctuations downstream of the fan were diminished to a maximum of 10% at a location with a flow area approximately 8 times larger than the fan discharge area.

7.0 RECOMMENDATIONS

- Tests (such as the one reported here), designed to isolate dynamic distortion effects on compressor and engine system stability, should be conducted in the future. Such data are considered to be prerequisite to understanding the effects of dynamic distortion on compressor stability, as required to ultimately learn how to design to minimize such destabilizing effects.
- More comprehensive analysis of this type data should be based on an accurate analytical math model in order to permit generalization of such test results beyond the specific test environment and installation.
- As a further expansion step toward better understanding of combined spatial/temporal distortion, design modifications to be P³G should be identified that would permit generation of classical time-variant per rev and radial distortion patterns.

APPENDIX

DYNAMIC DATA WAVEFORMS

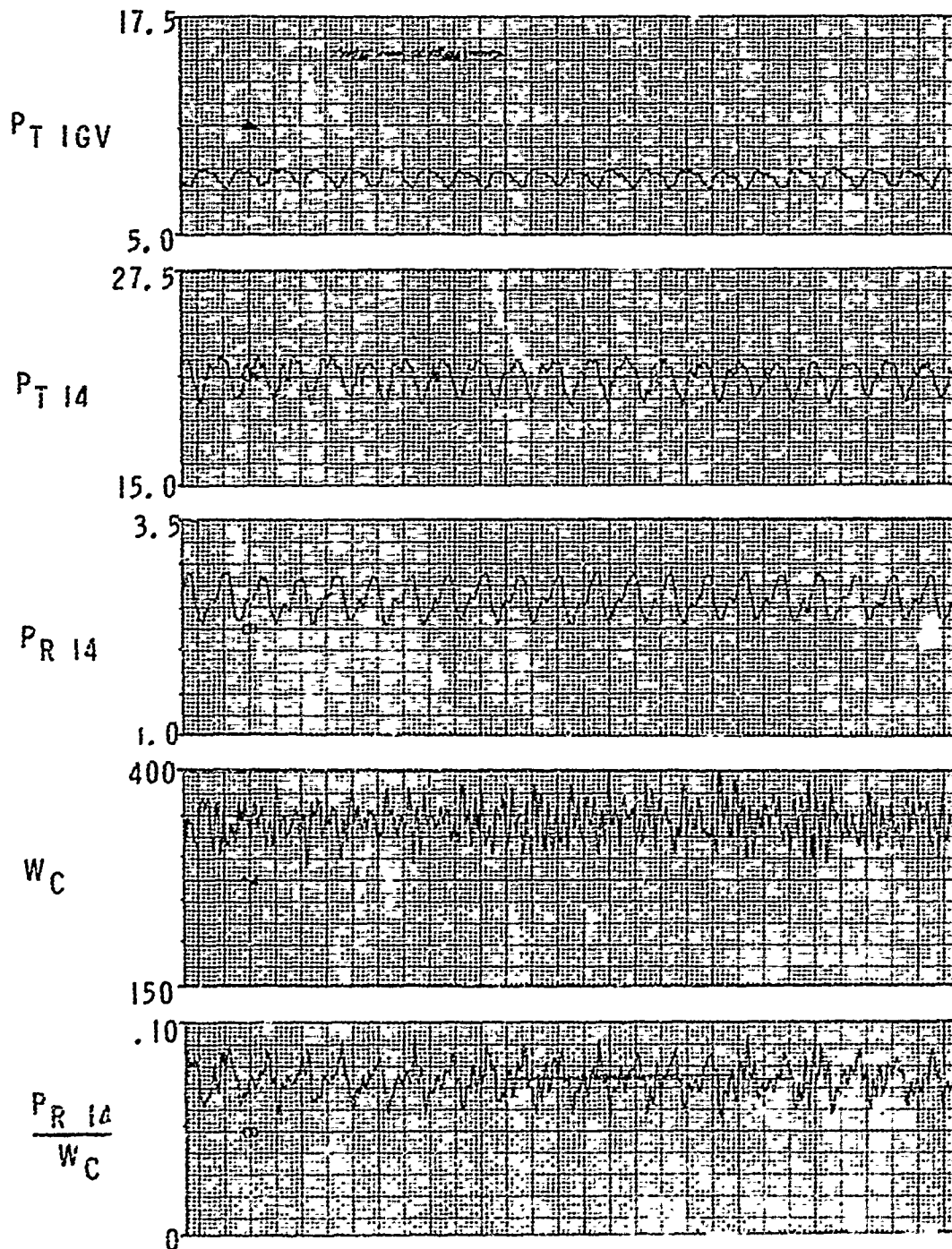
FAN / P³G DYNAMIC DATA

RDG 41

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$$P^3G - f = 220$$

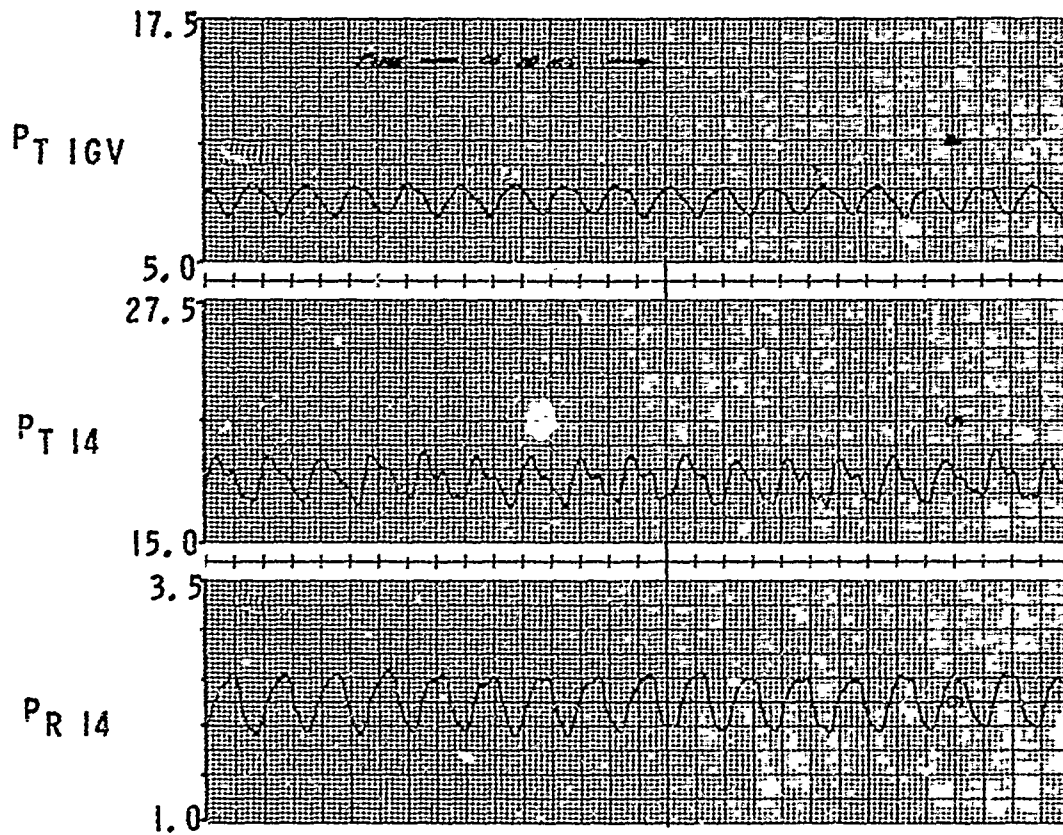
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FAN / P³G DYNAMIC DATA

RDG 42

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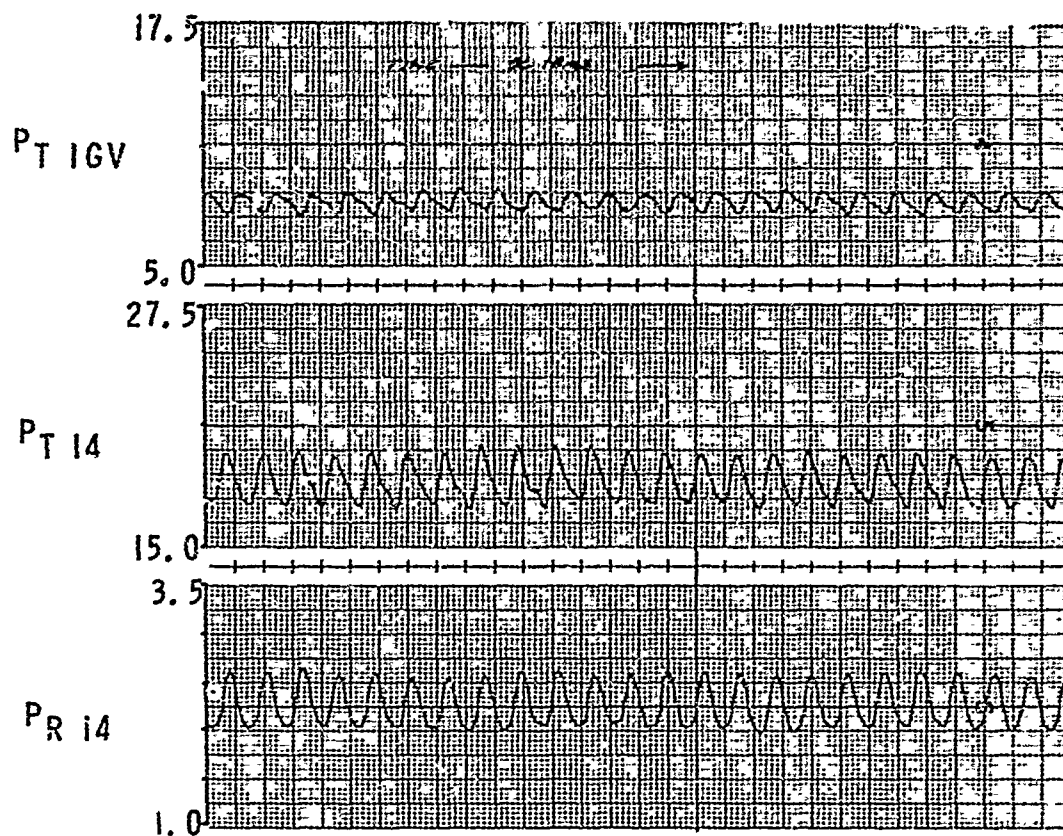
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RDG 44

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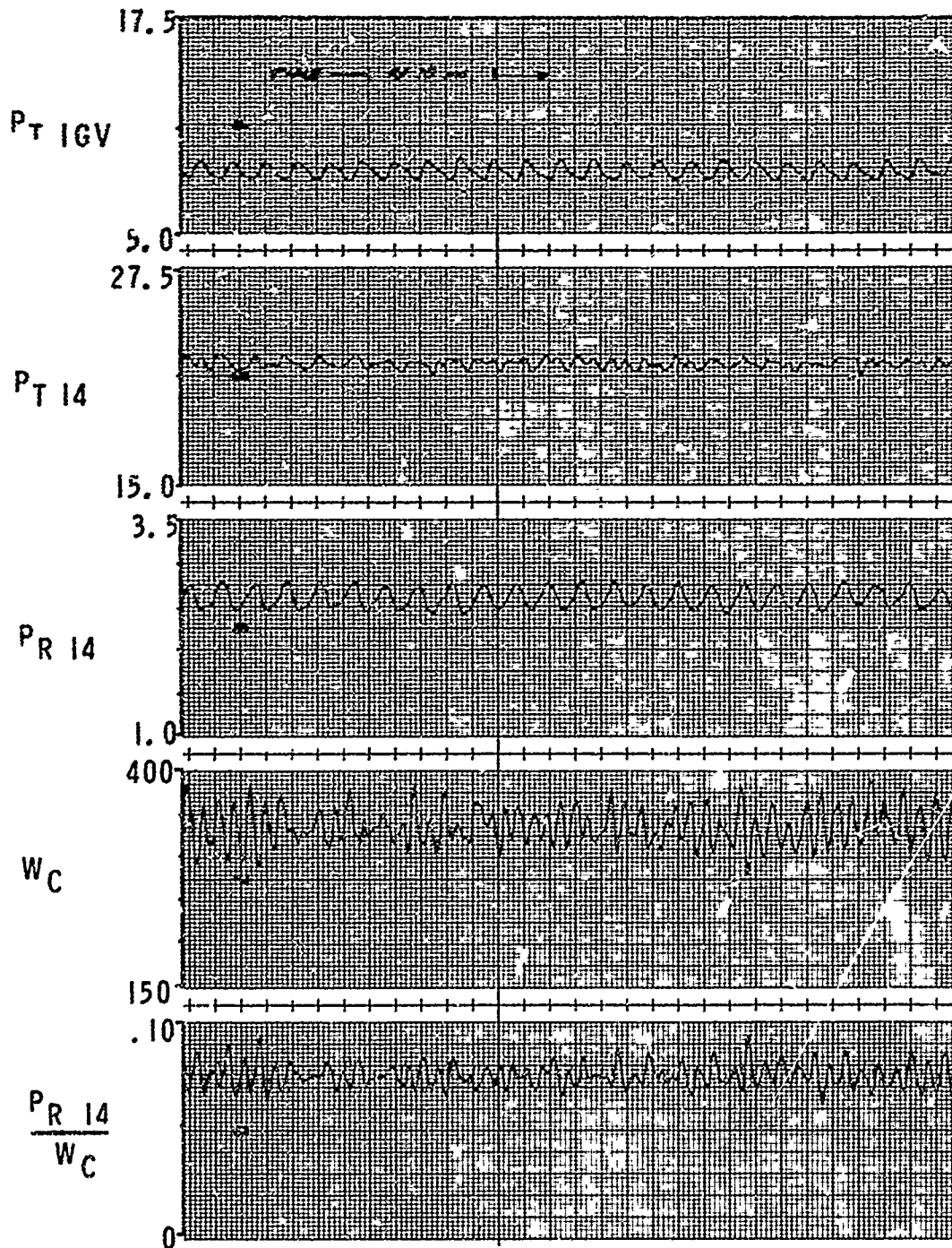
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FAN / P³G DYNAMIC DATA

RDG 45

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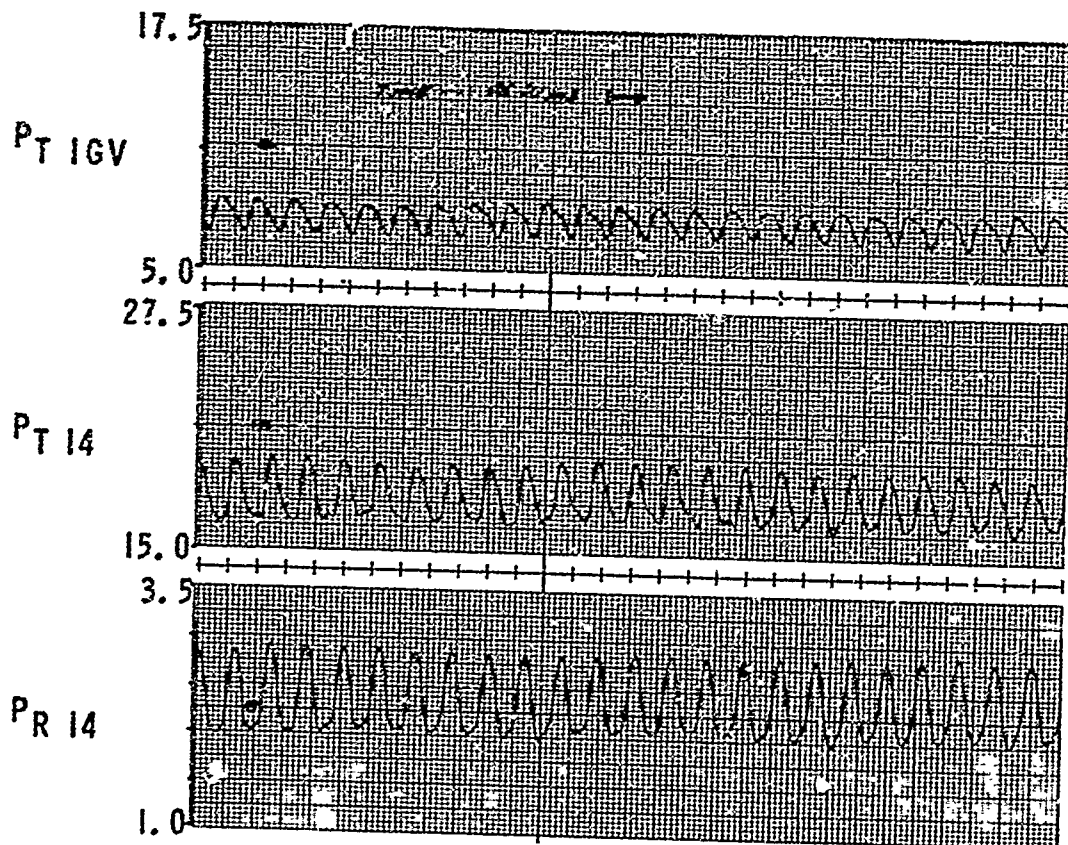
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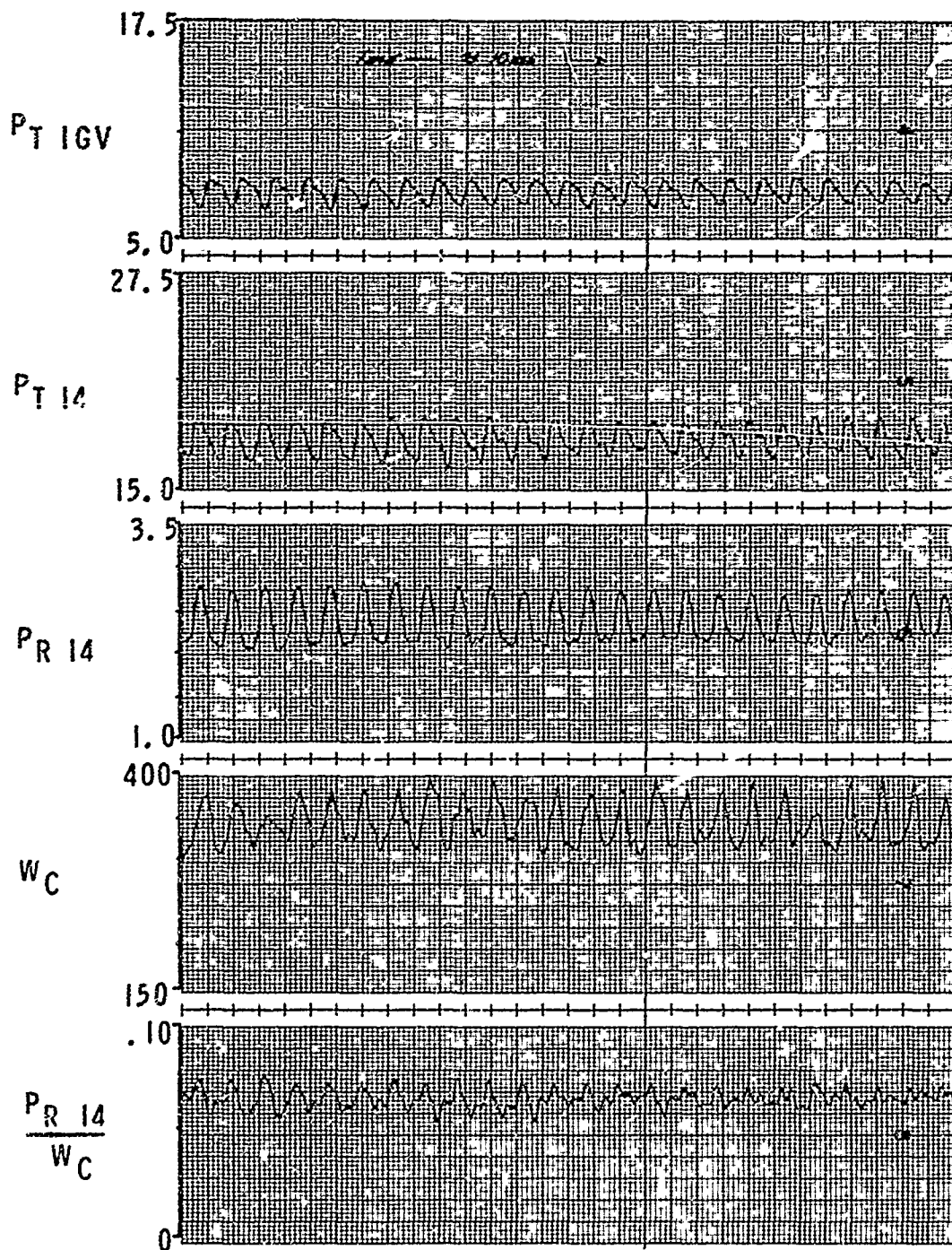
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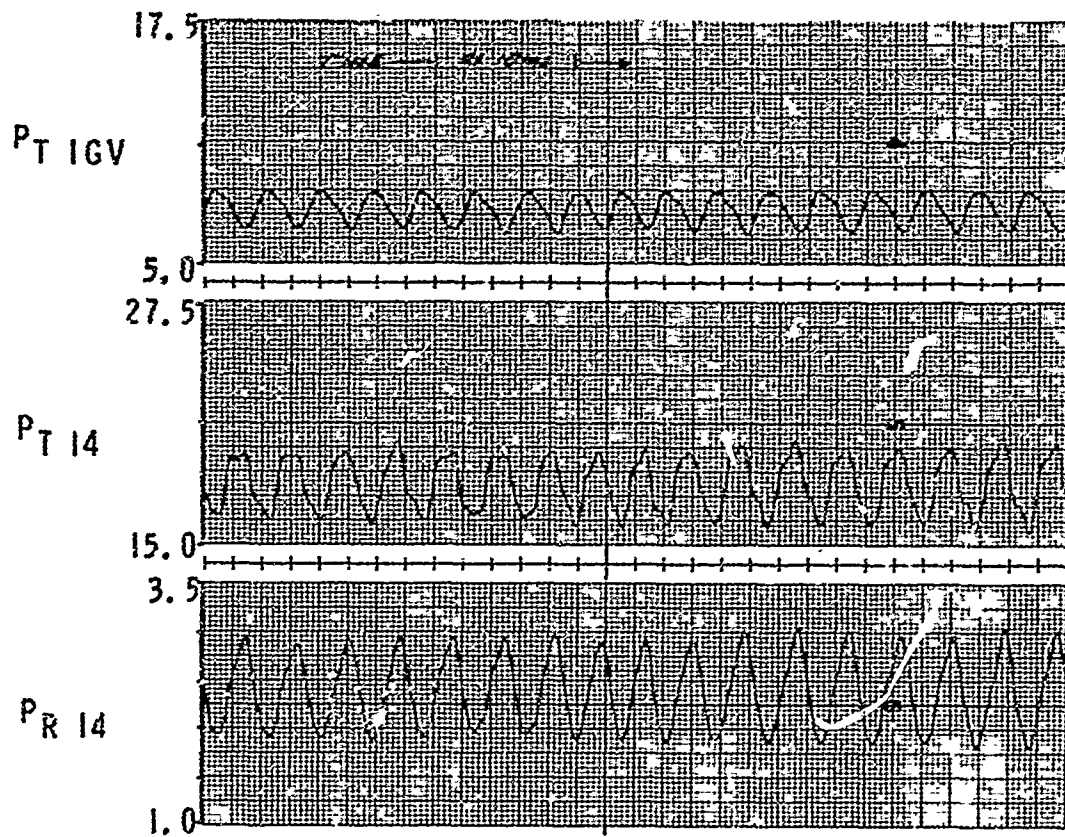
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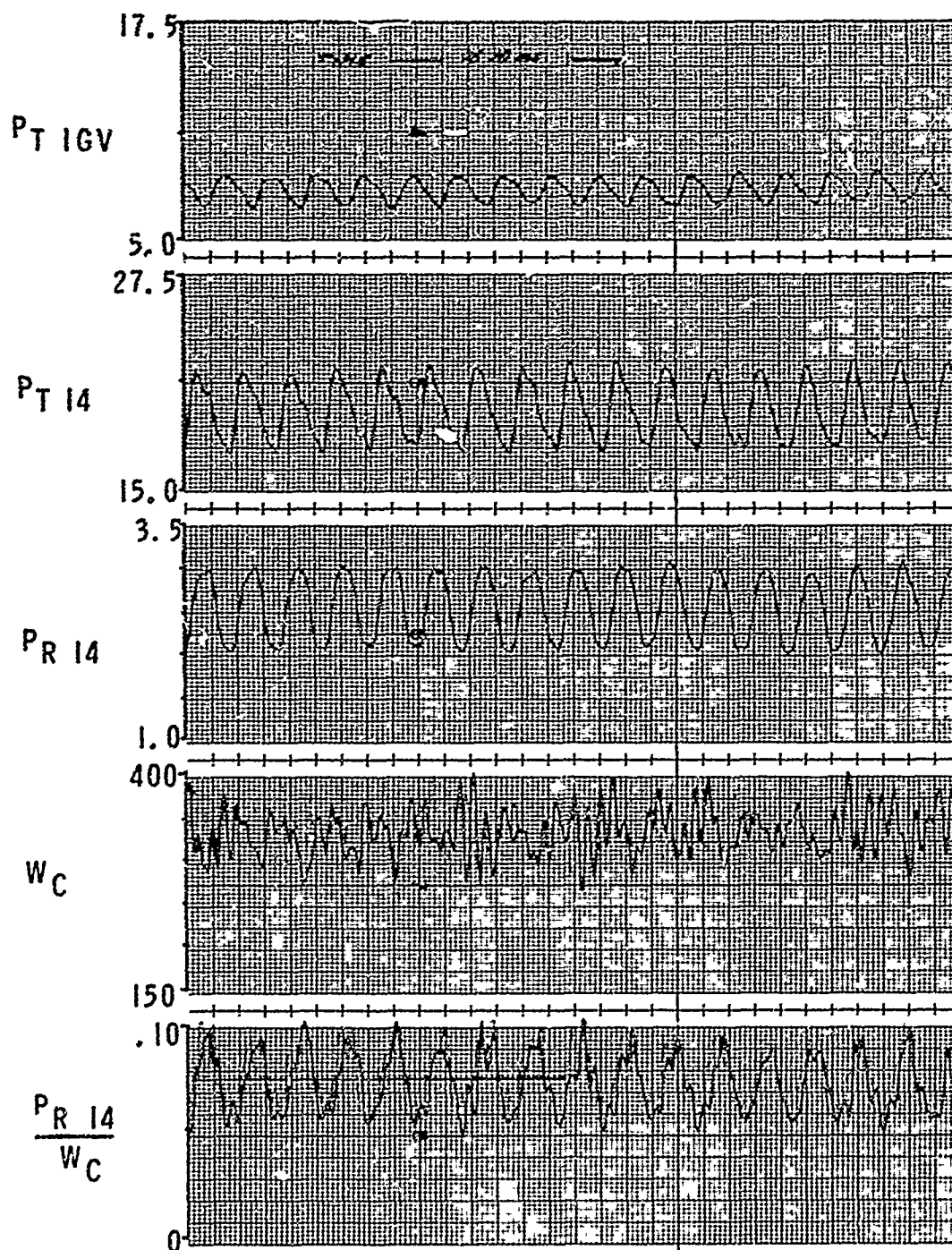
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FAN / P³G DYNAMIC DATA

RDG 49

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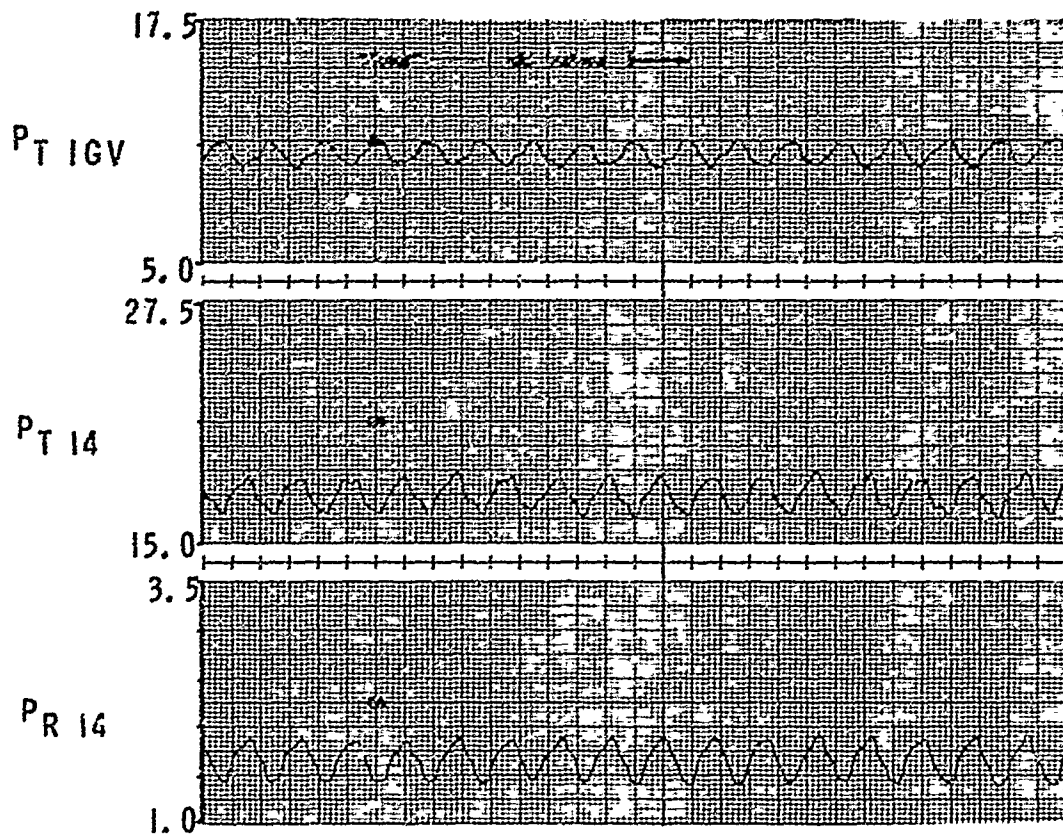
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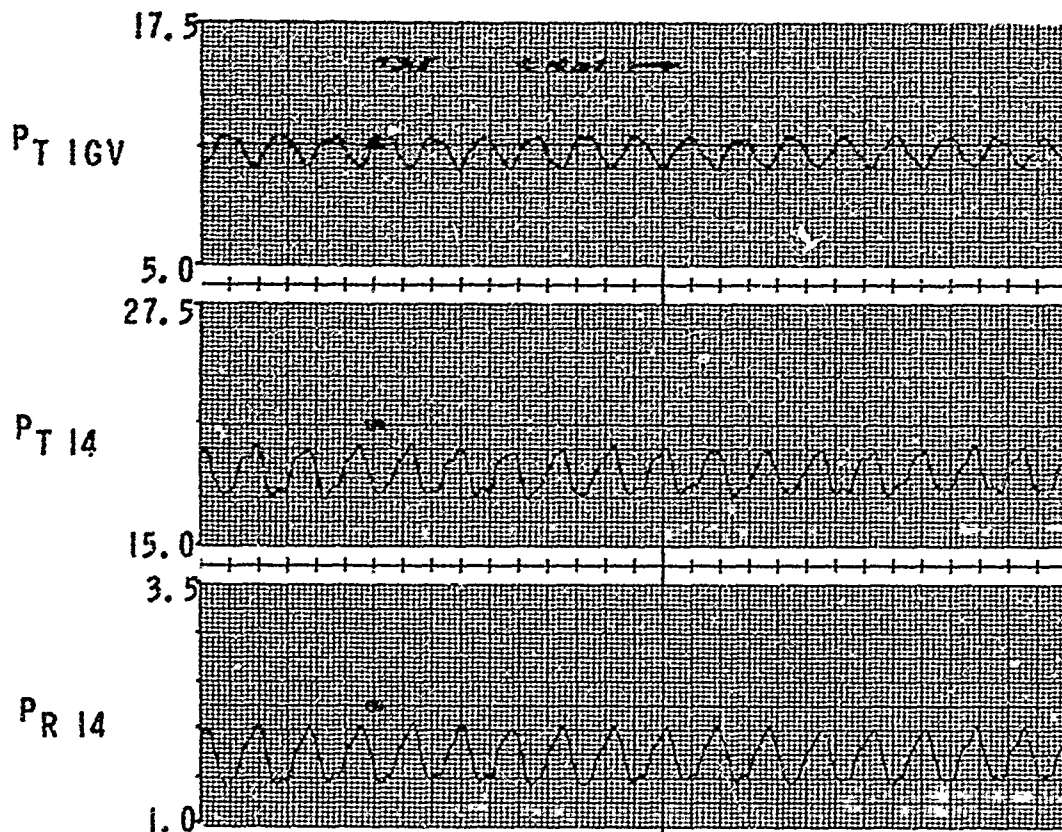
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RDS 51

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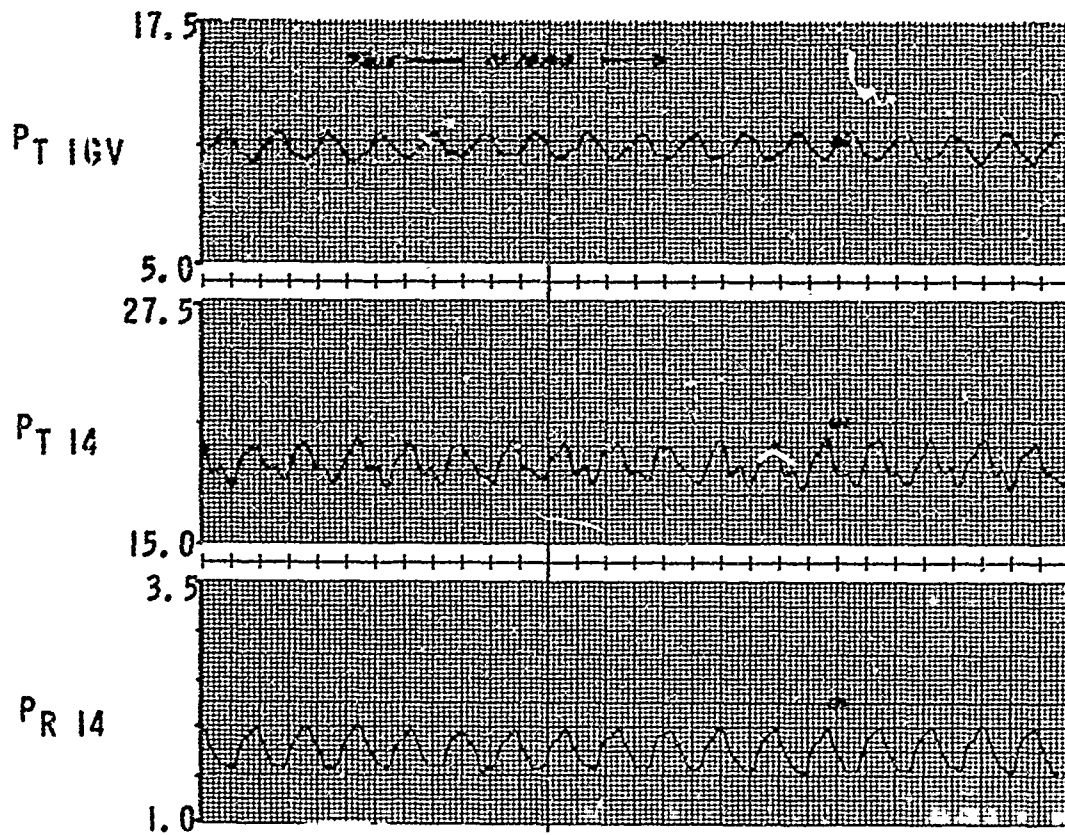
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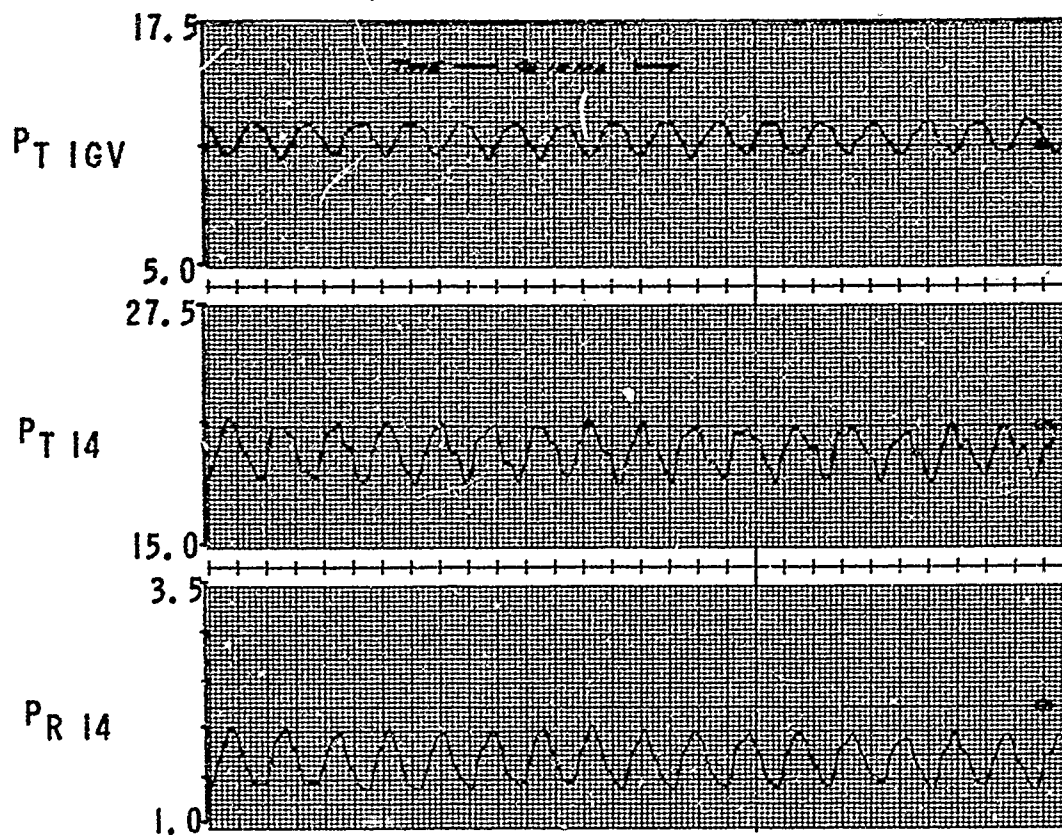
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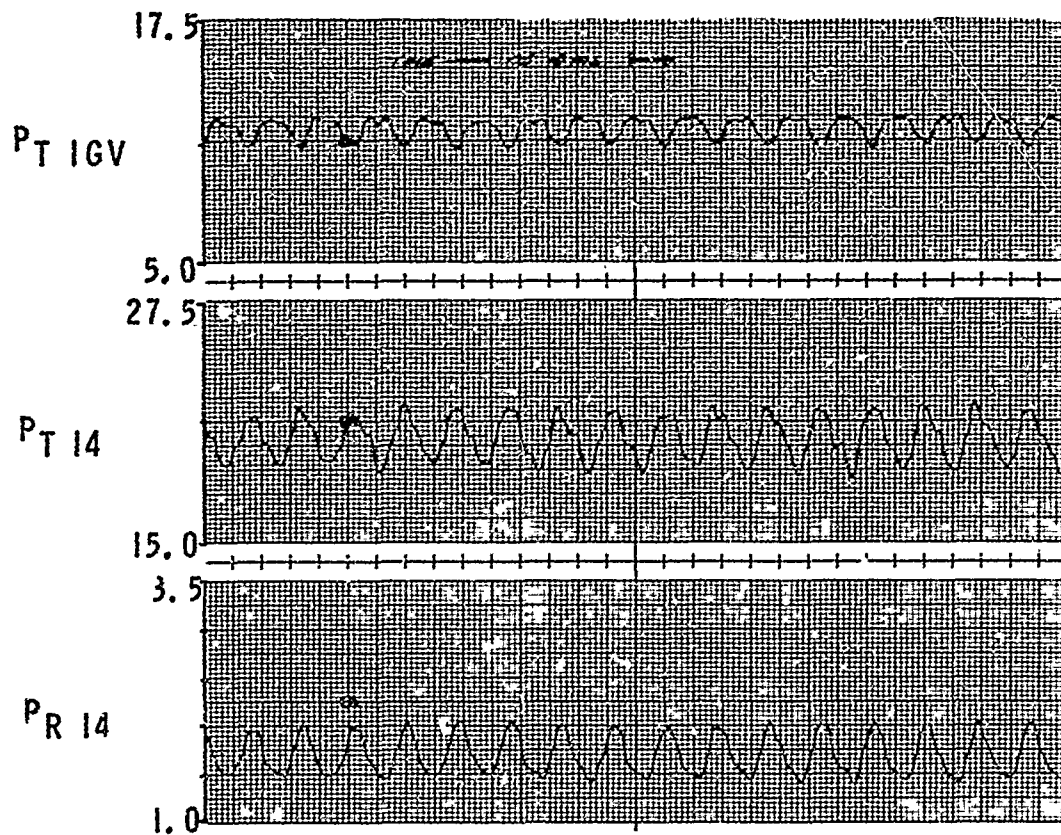
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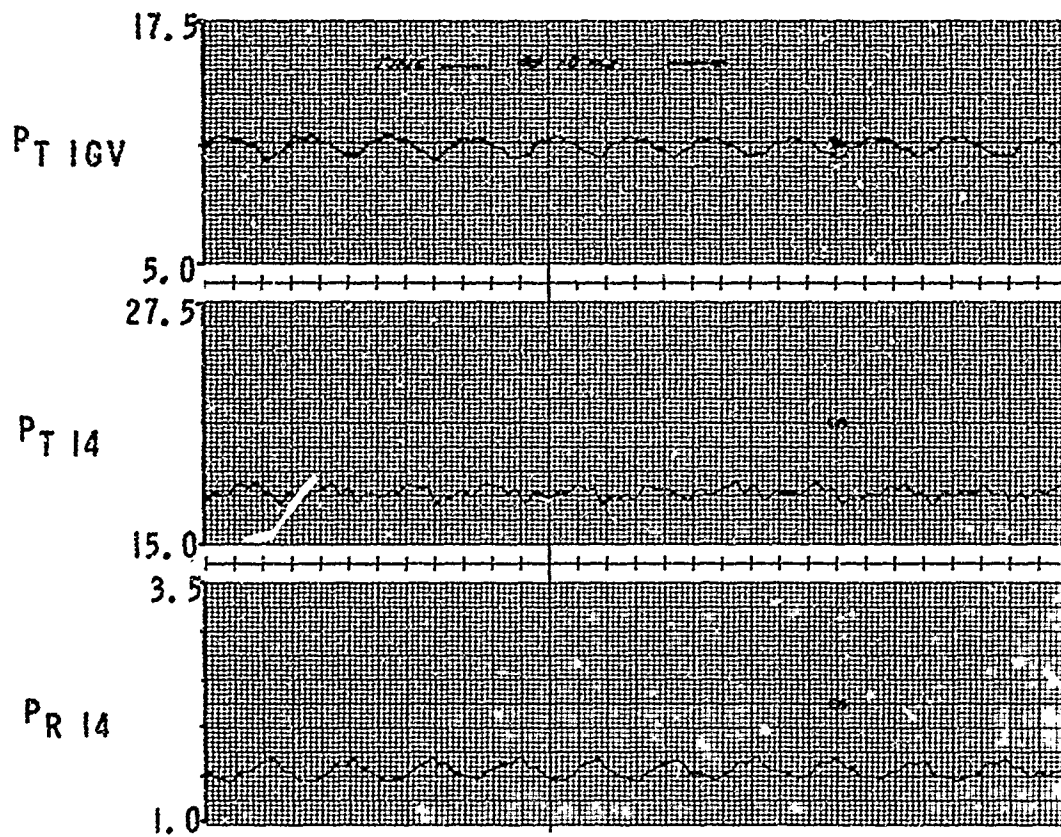
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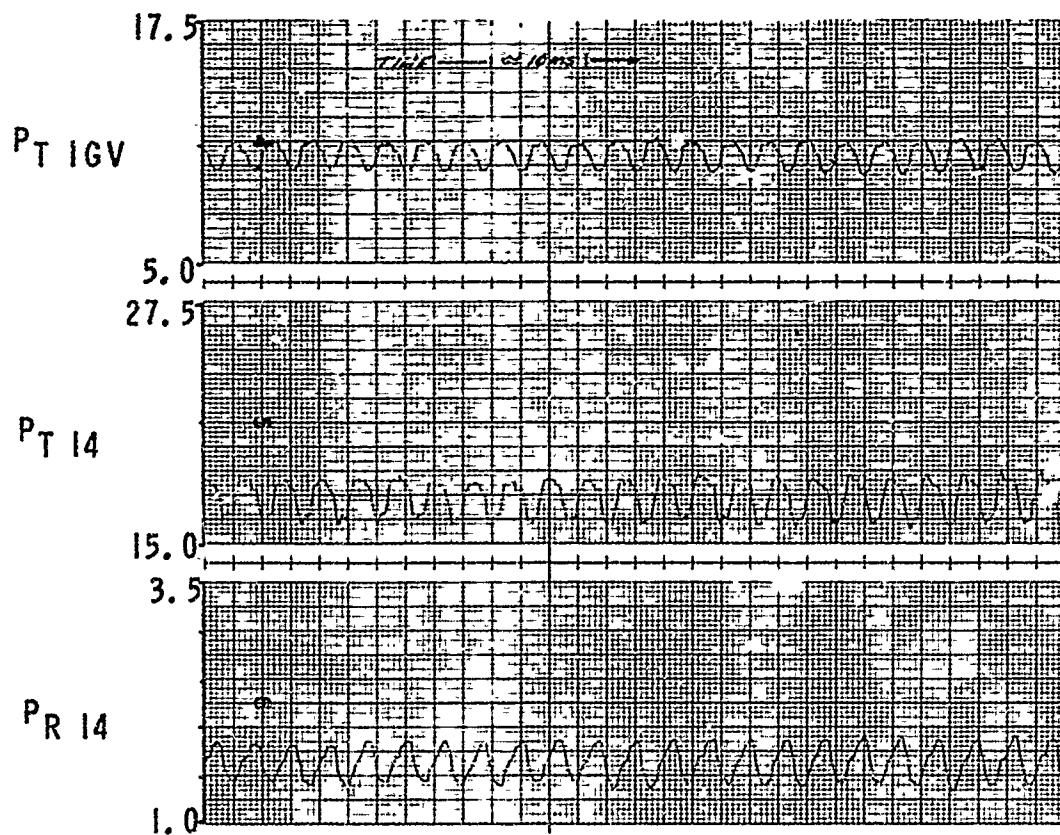
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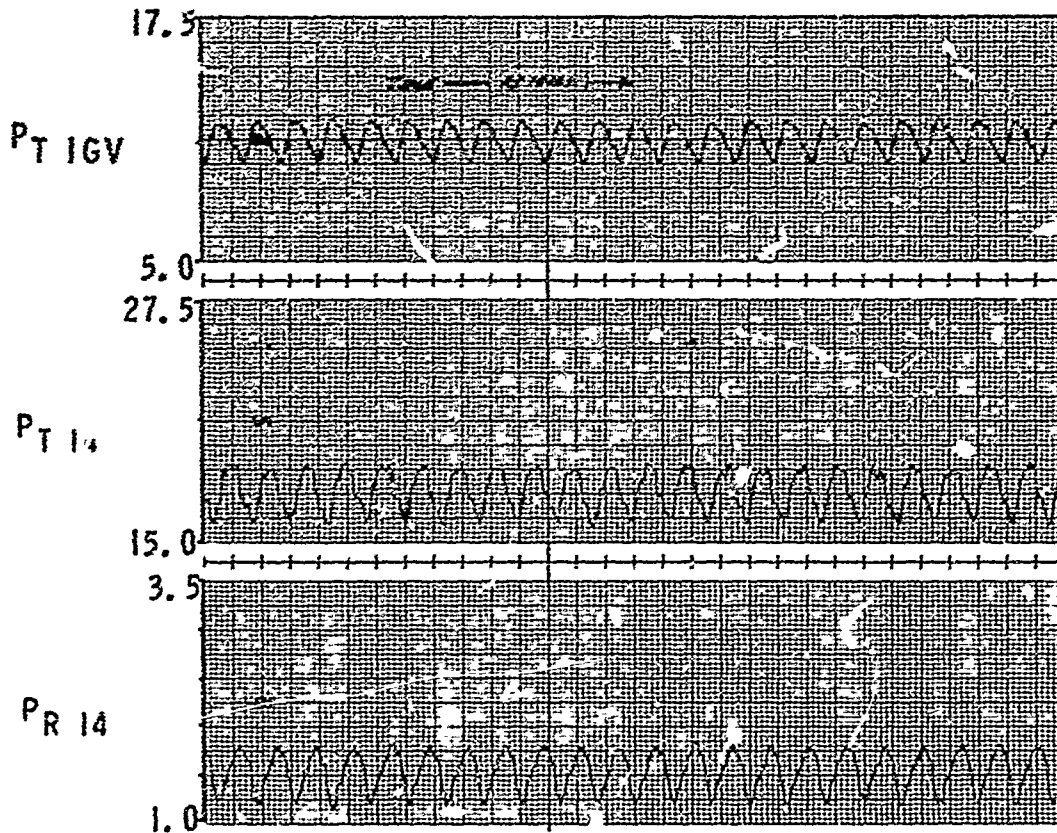
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FAN / P³G DYNAMIC DATA

RDG 57

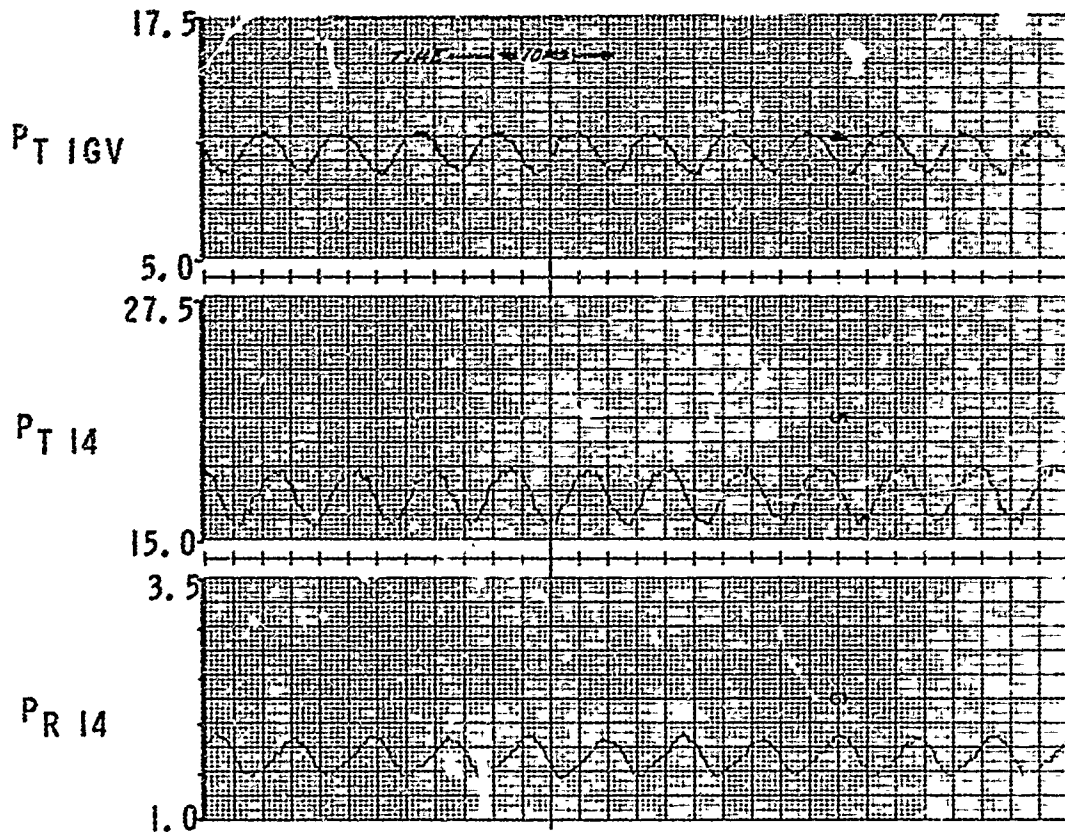
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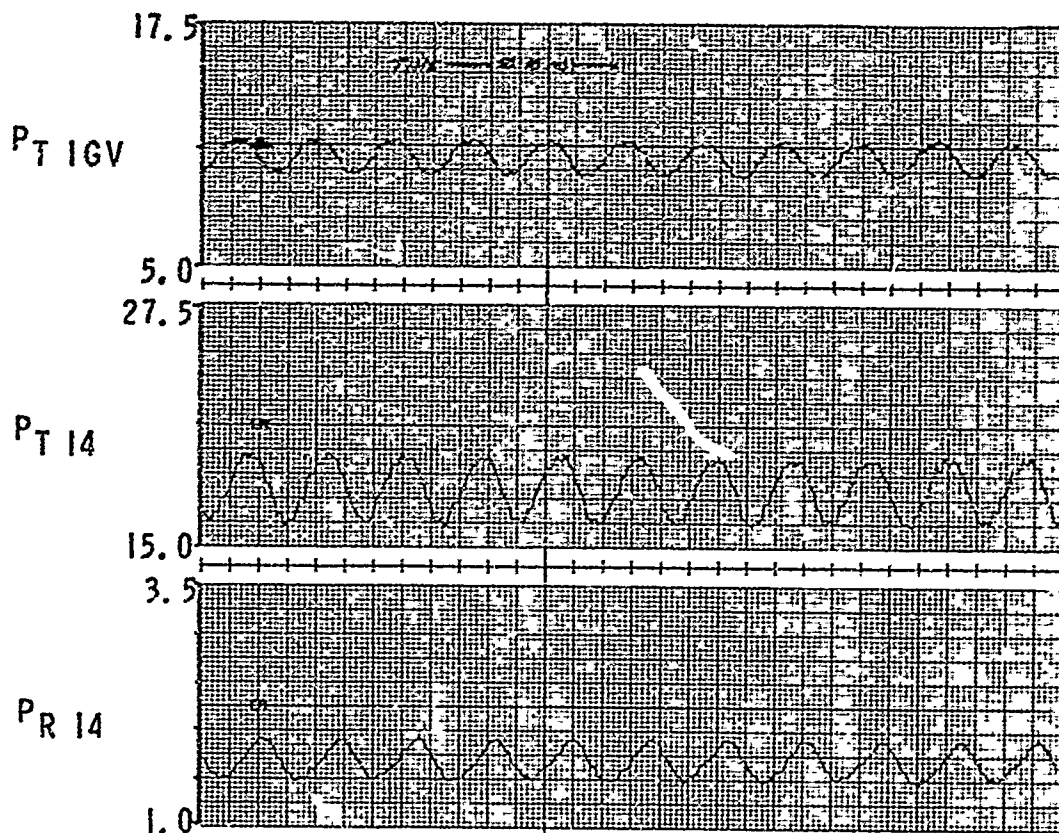
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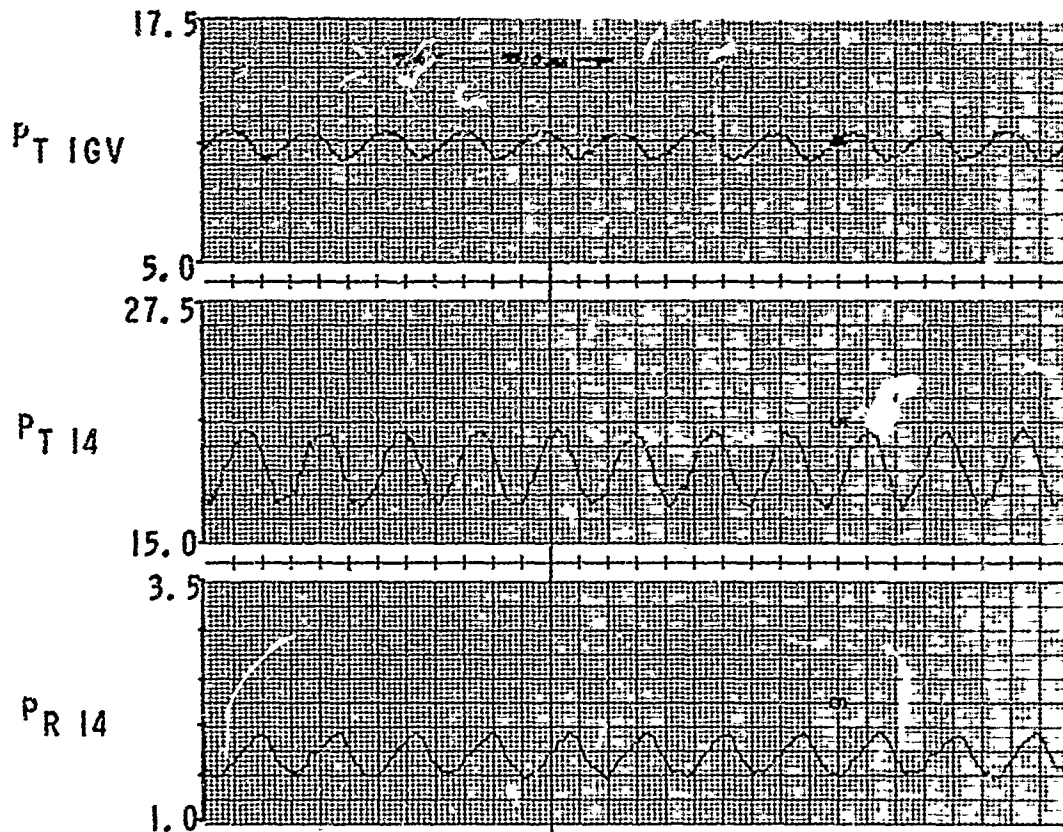
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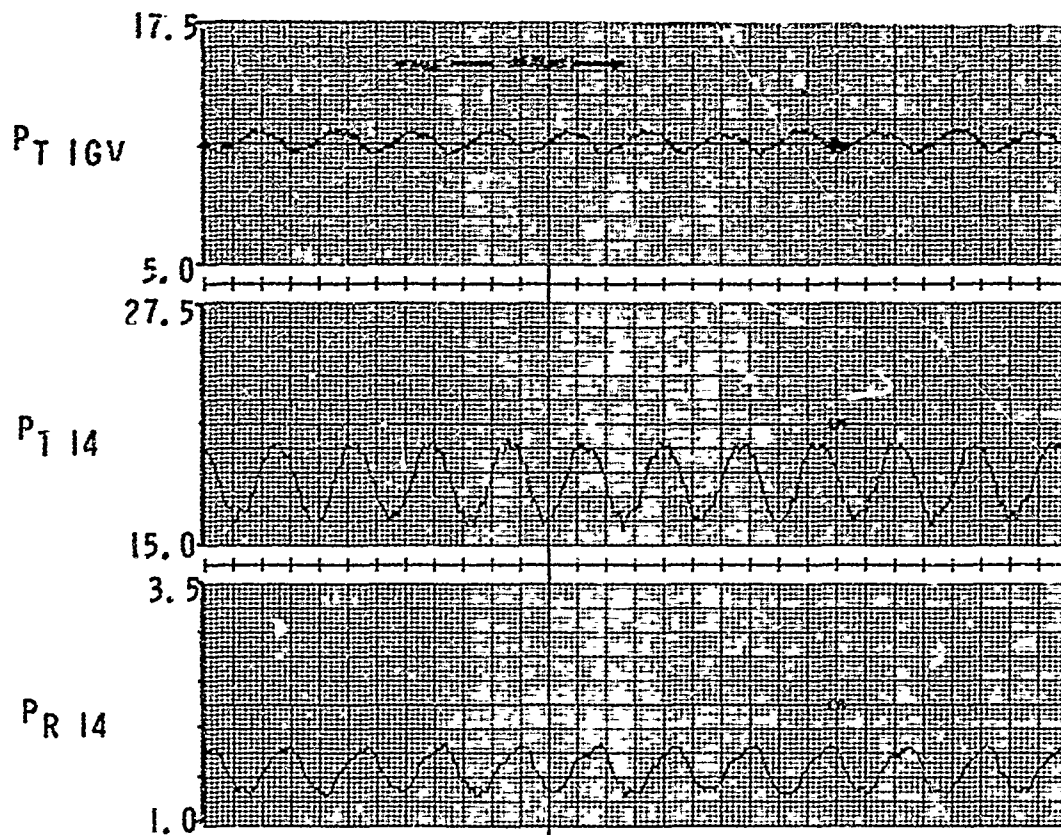
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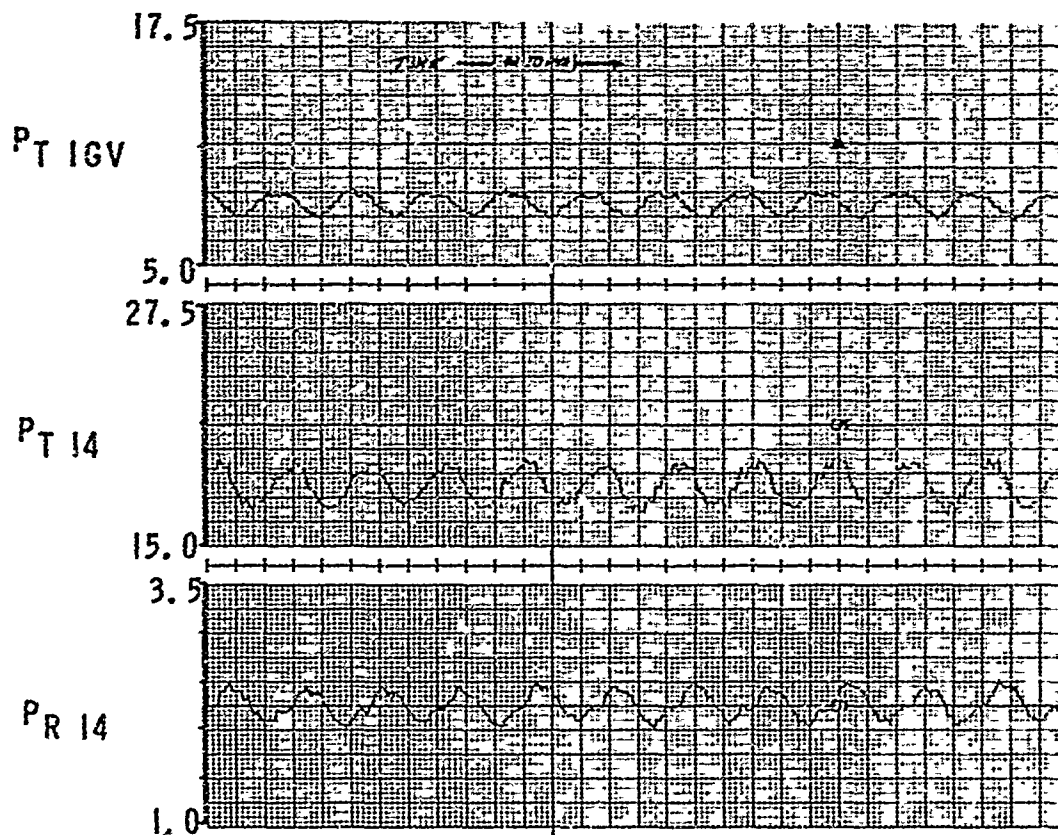
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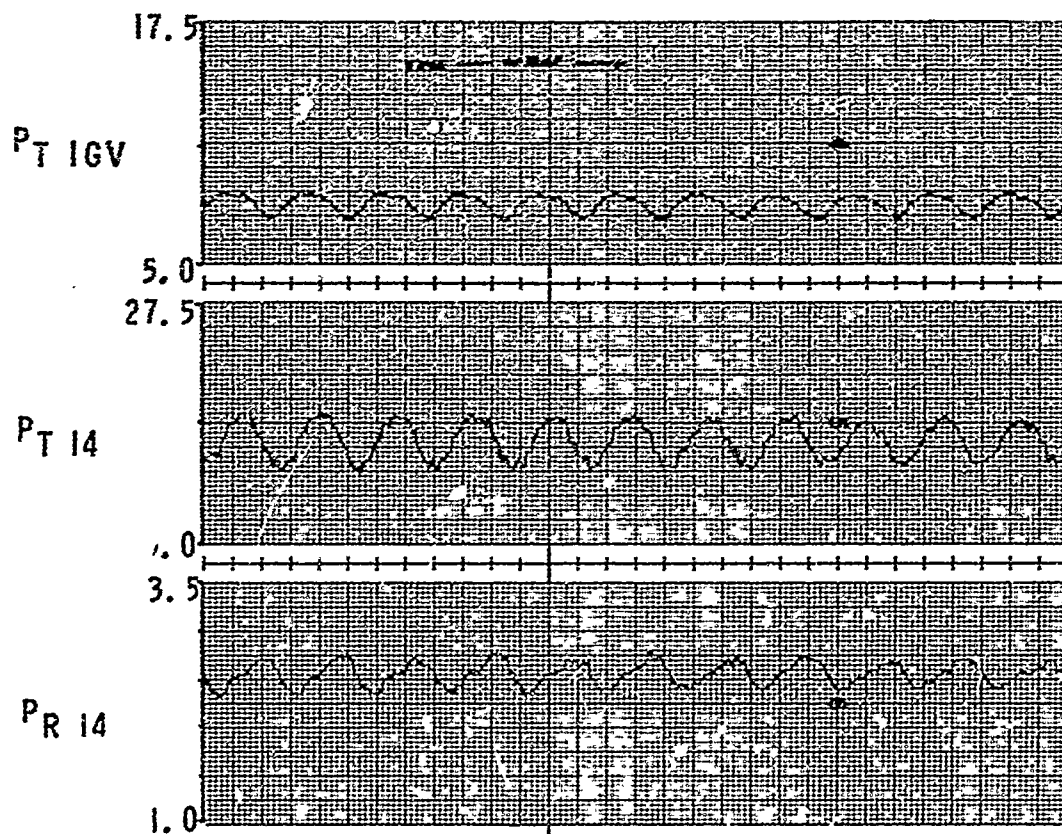
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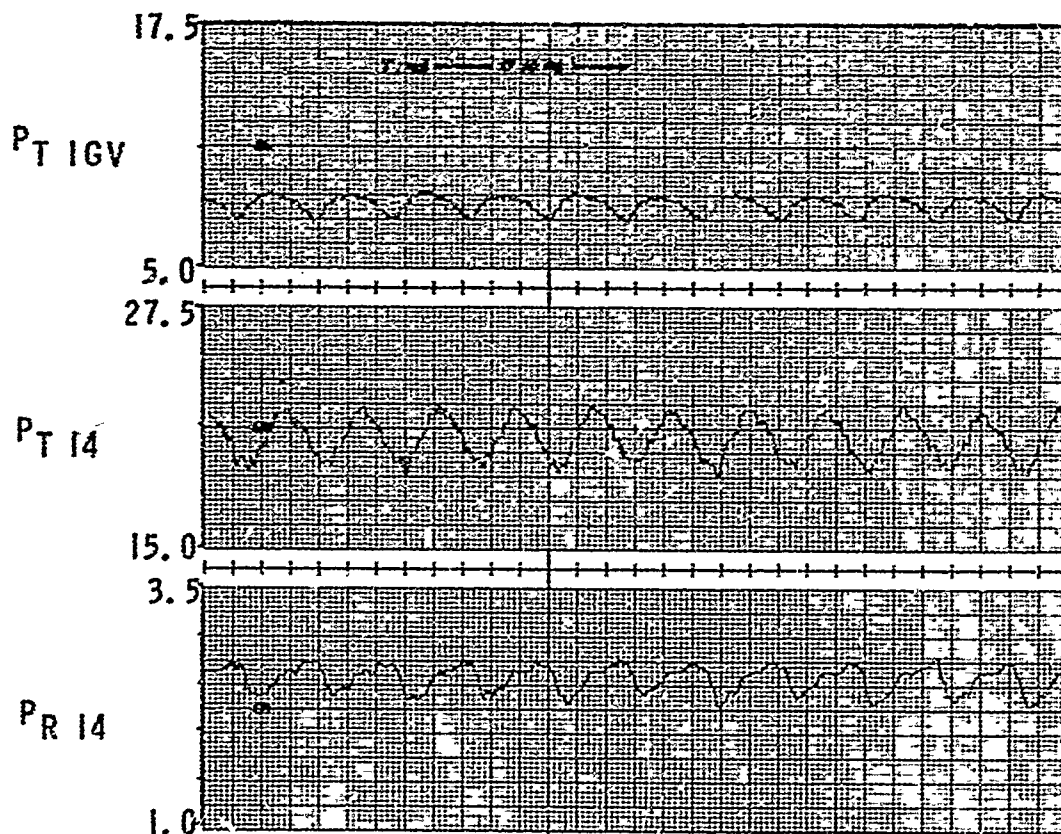
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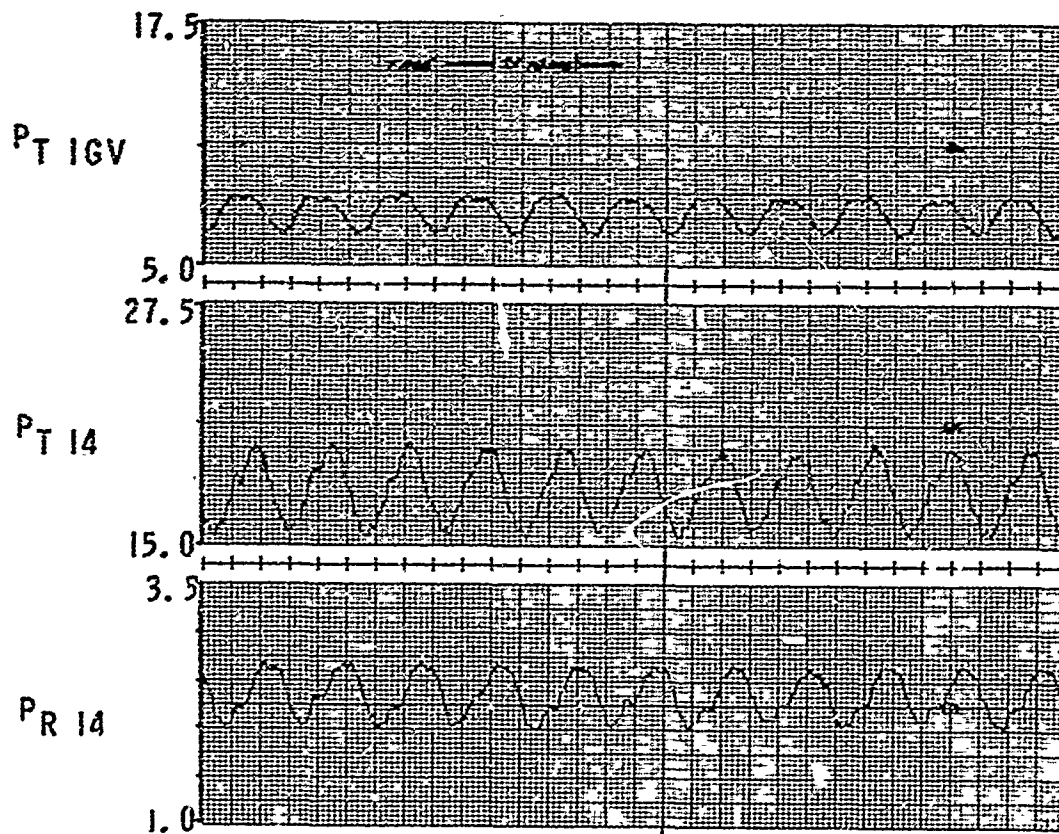
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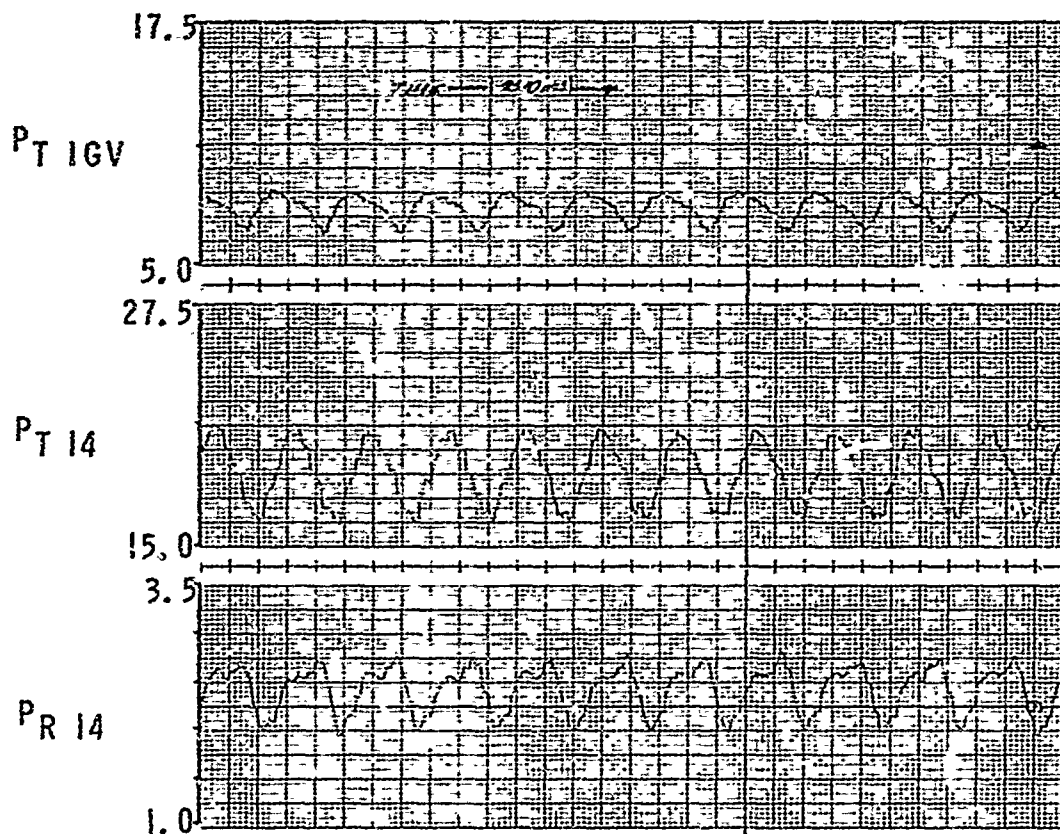
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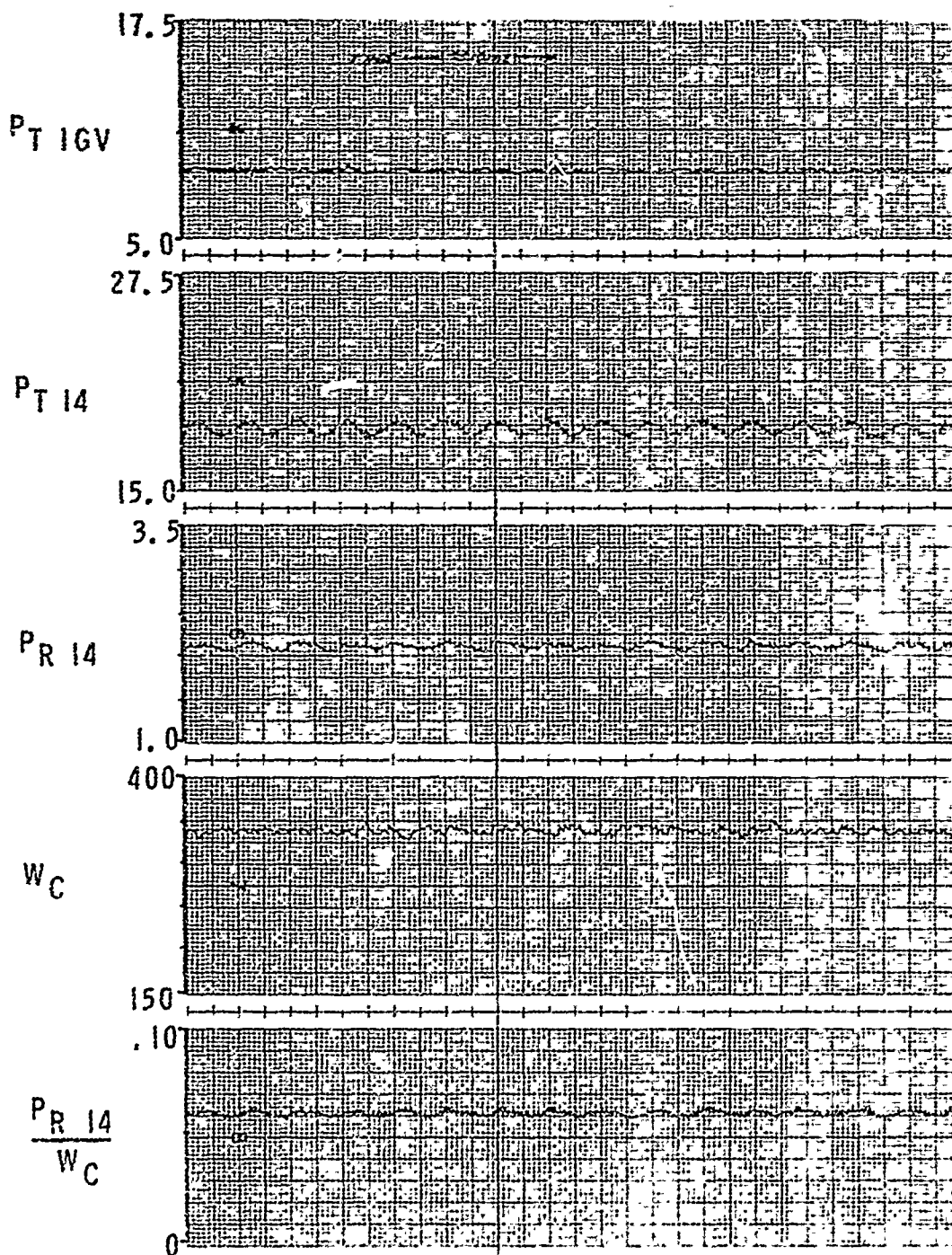
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$$P^3G - f = 80$$

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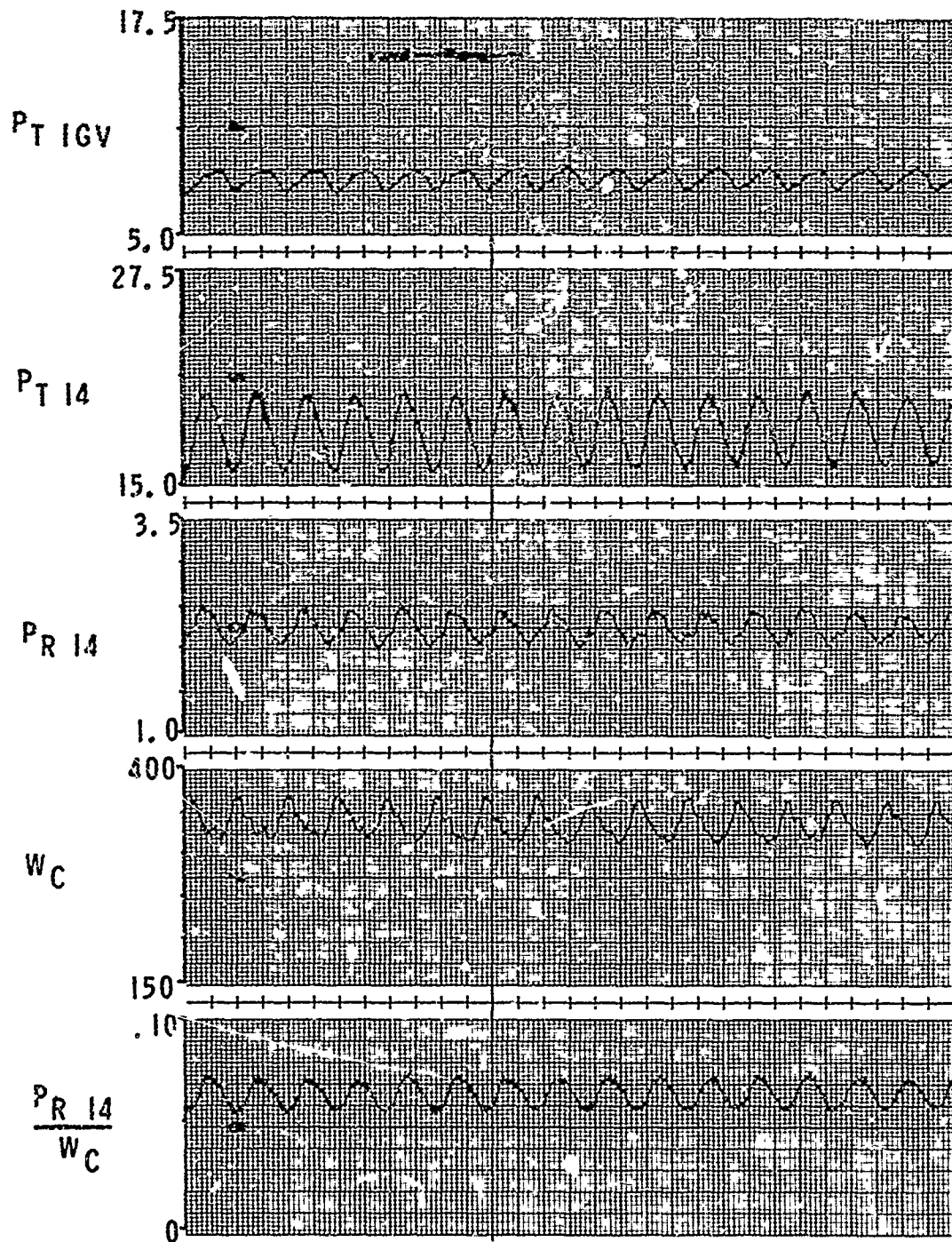
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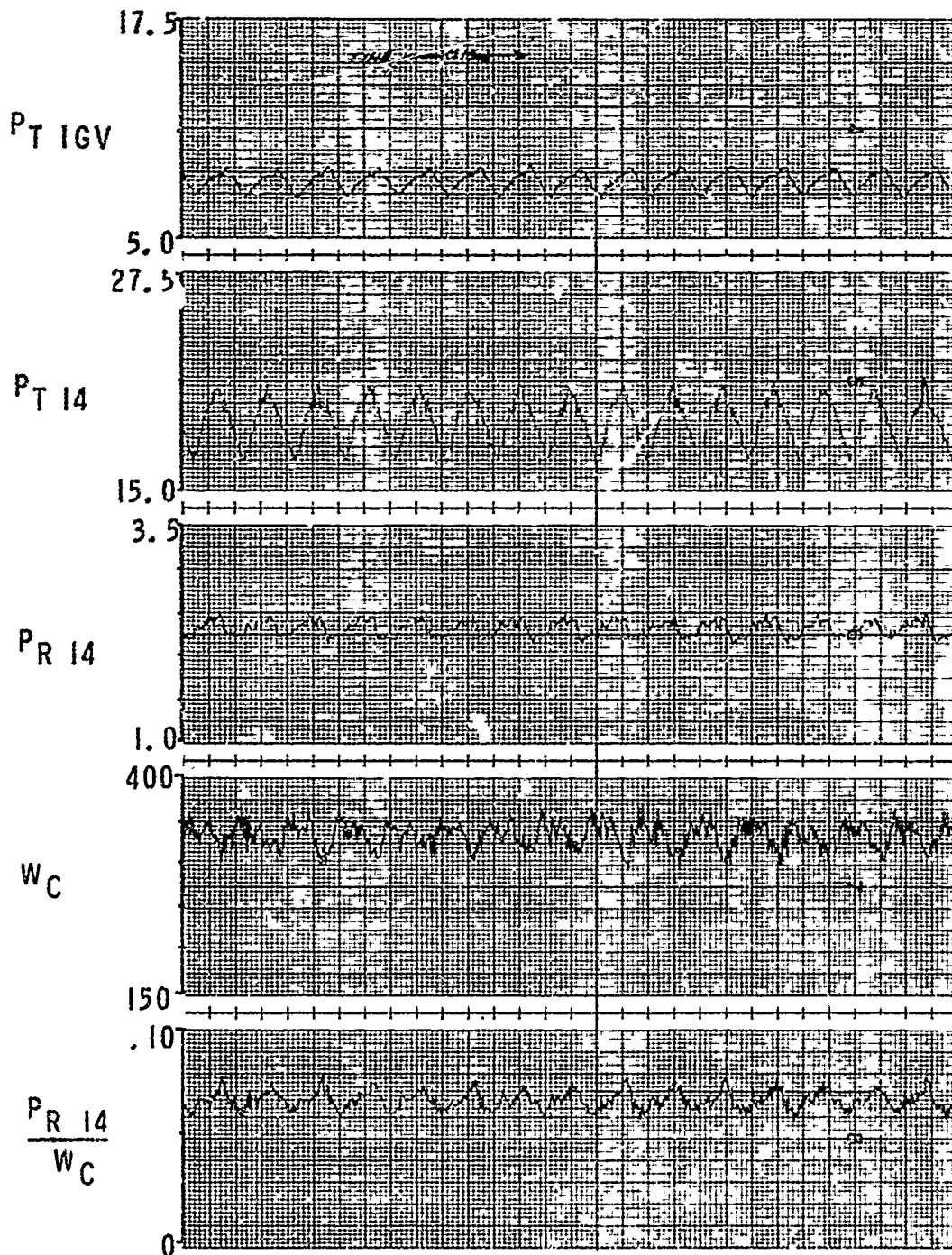
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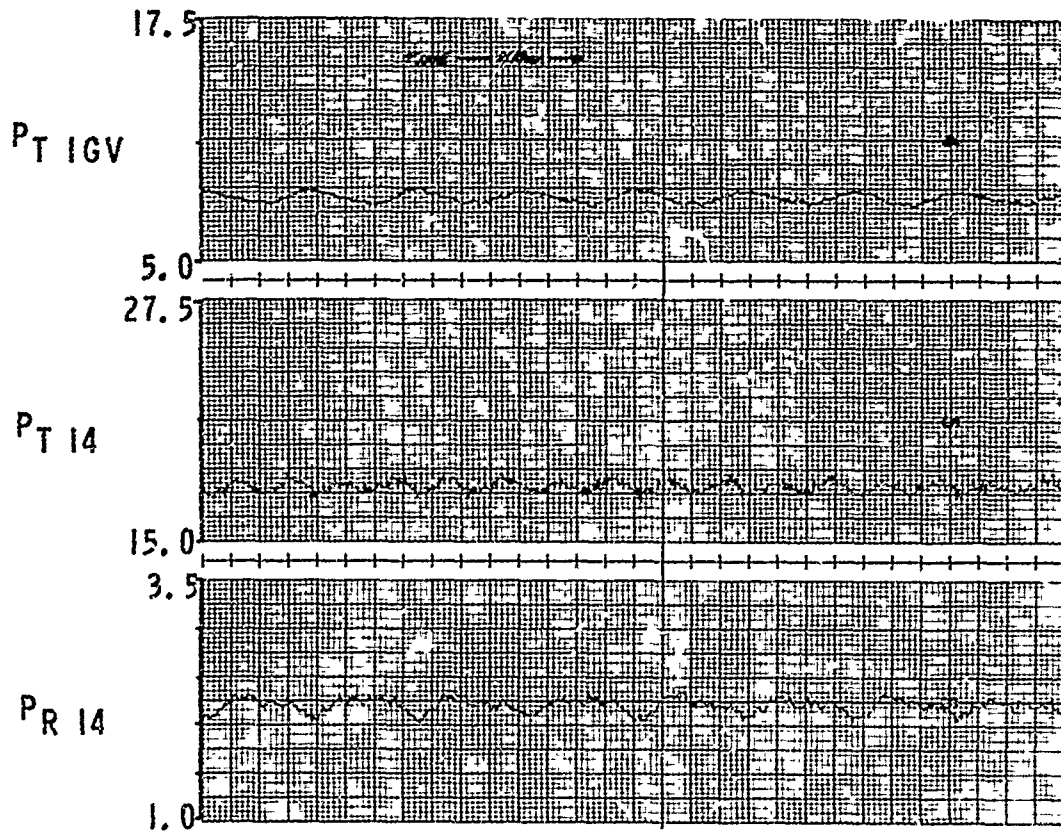
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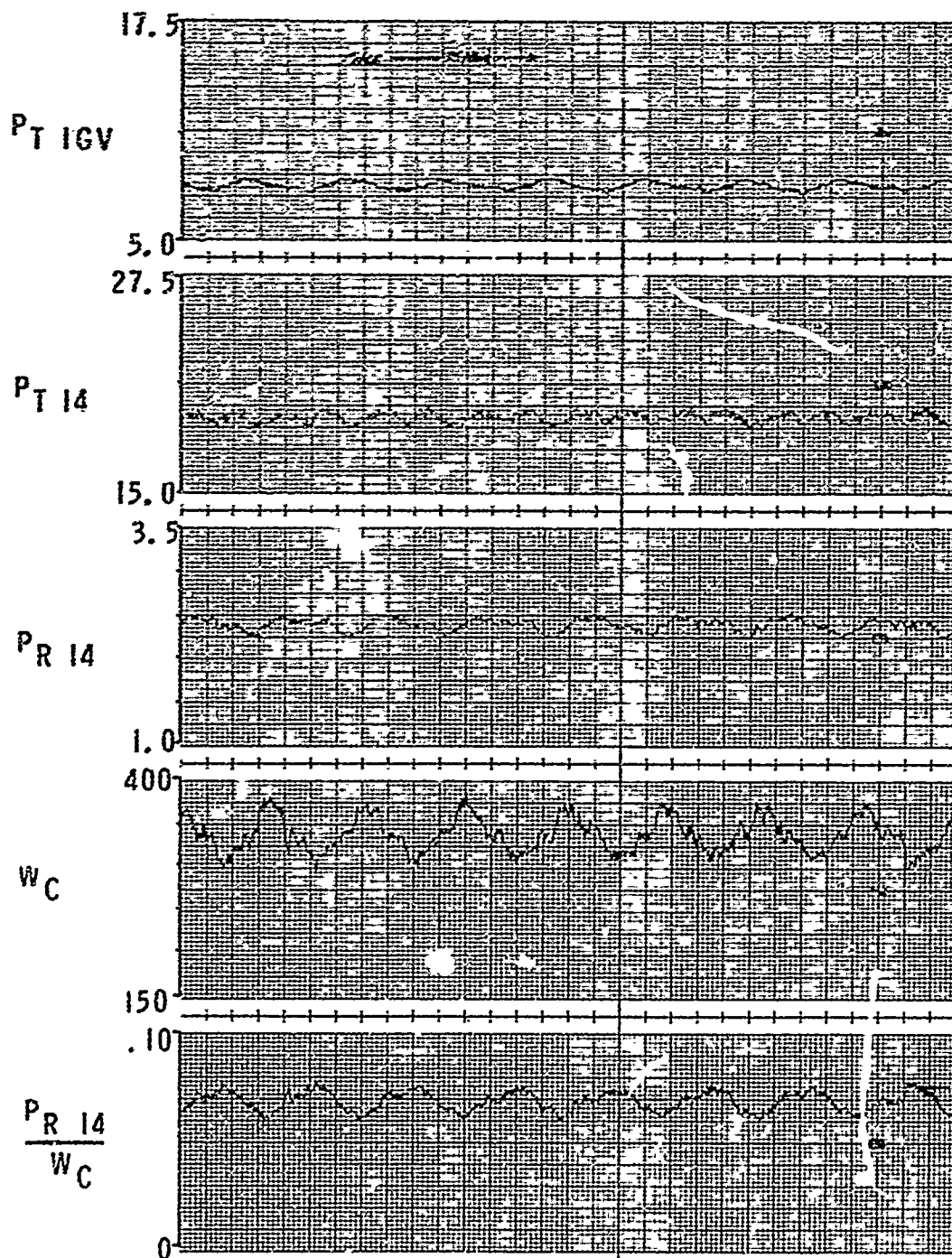
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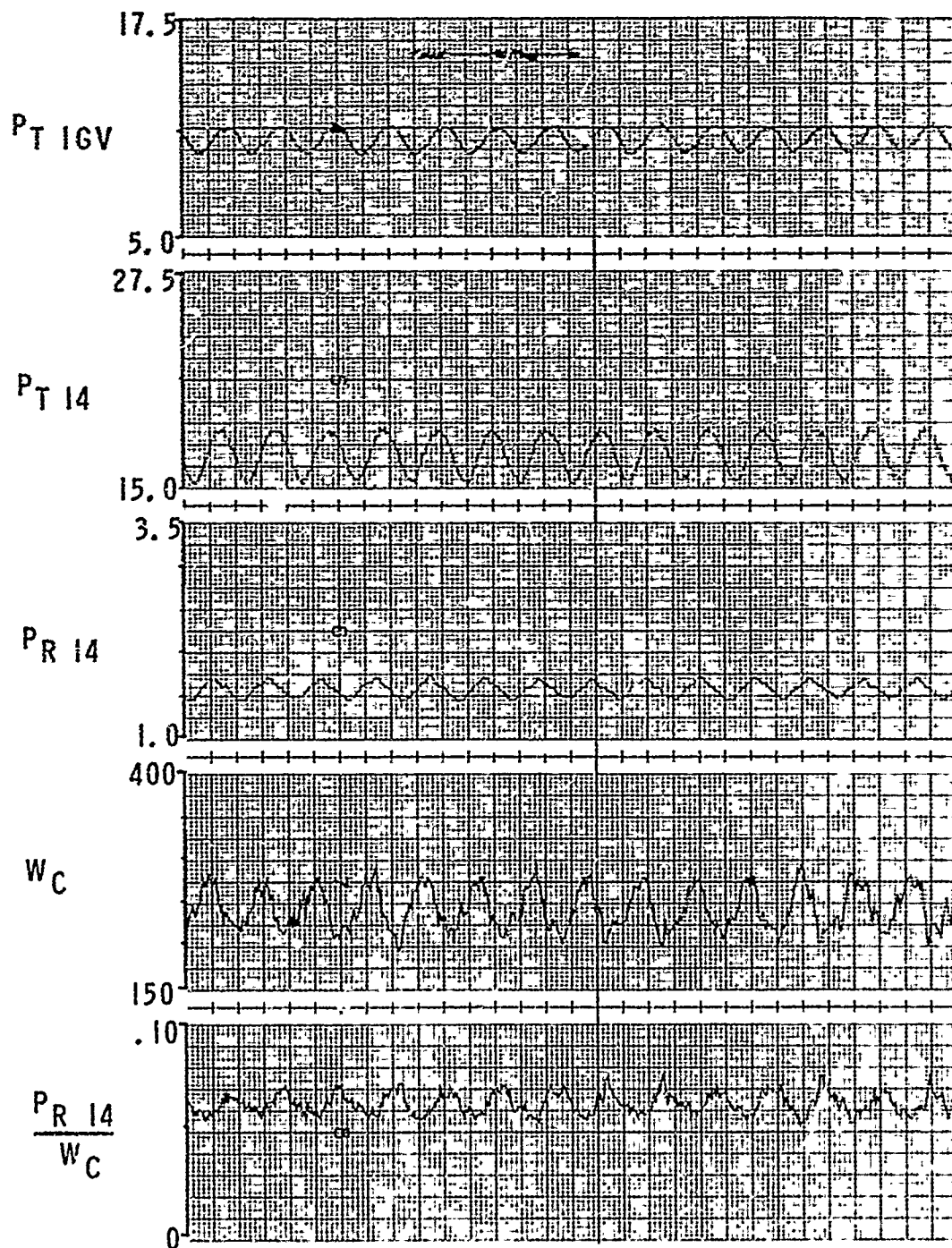
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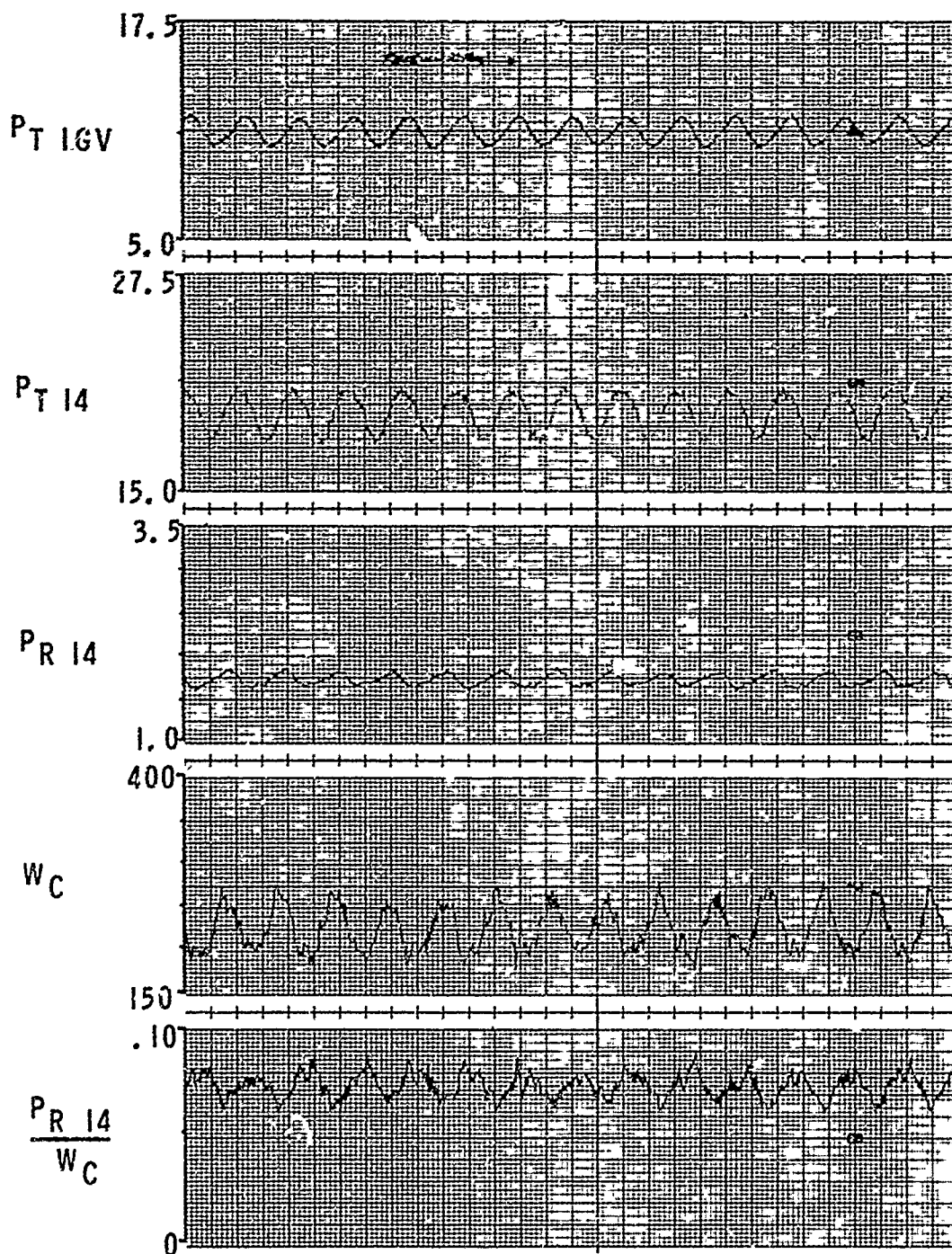
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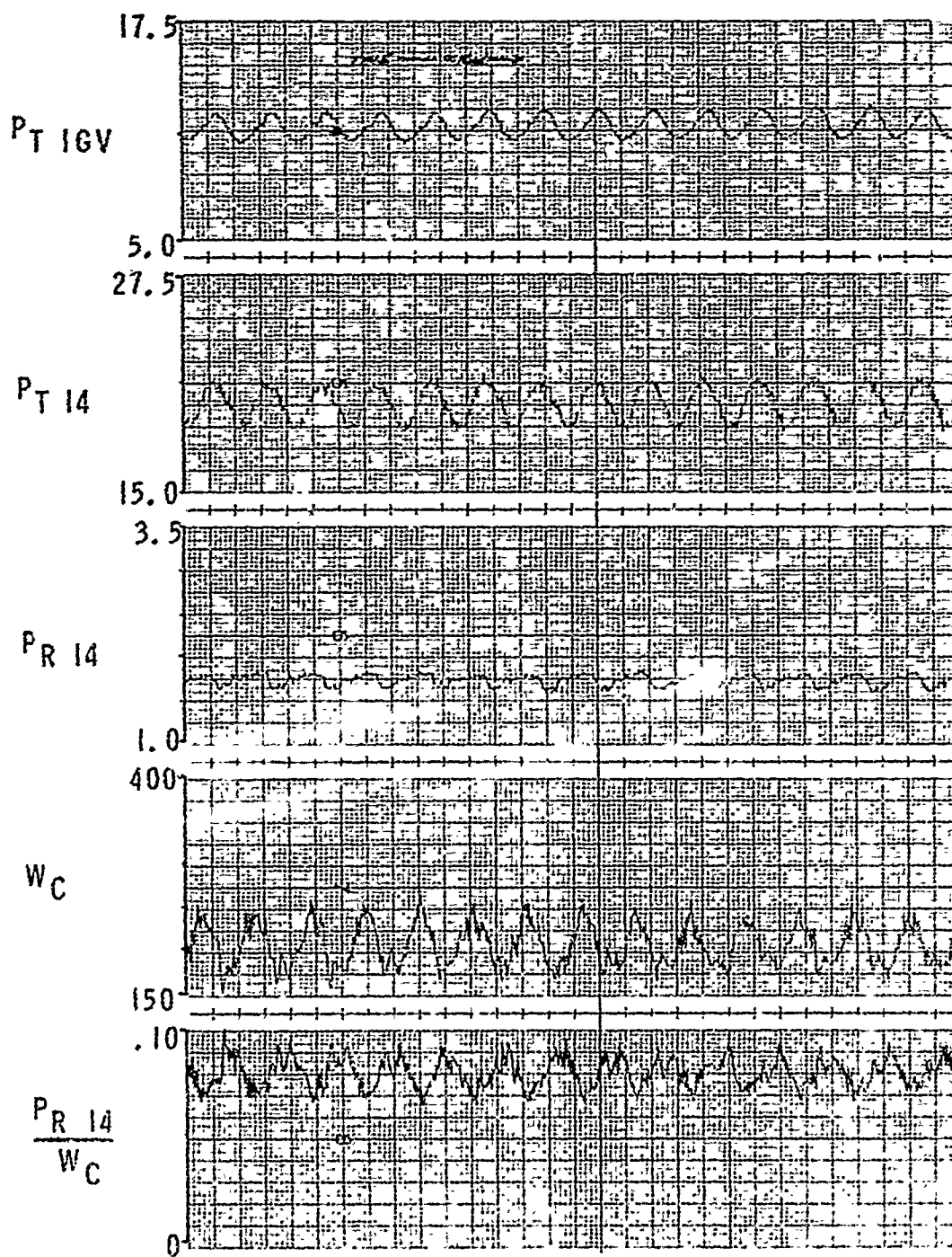
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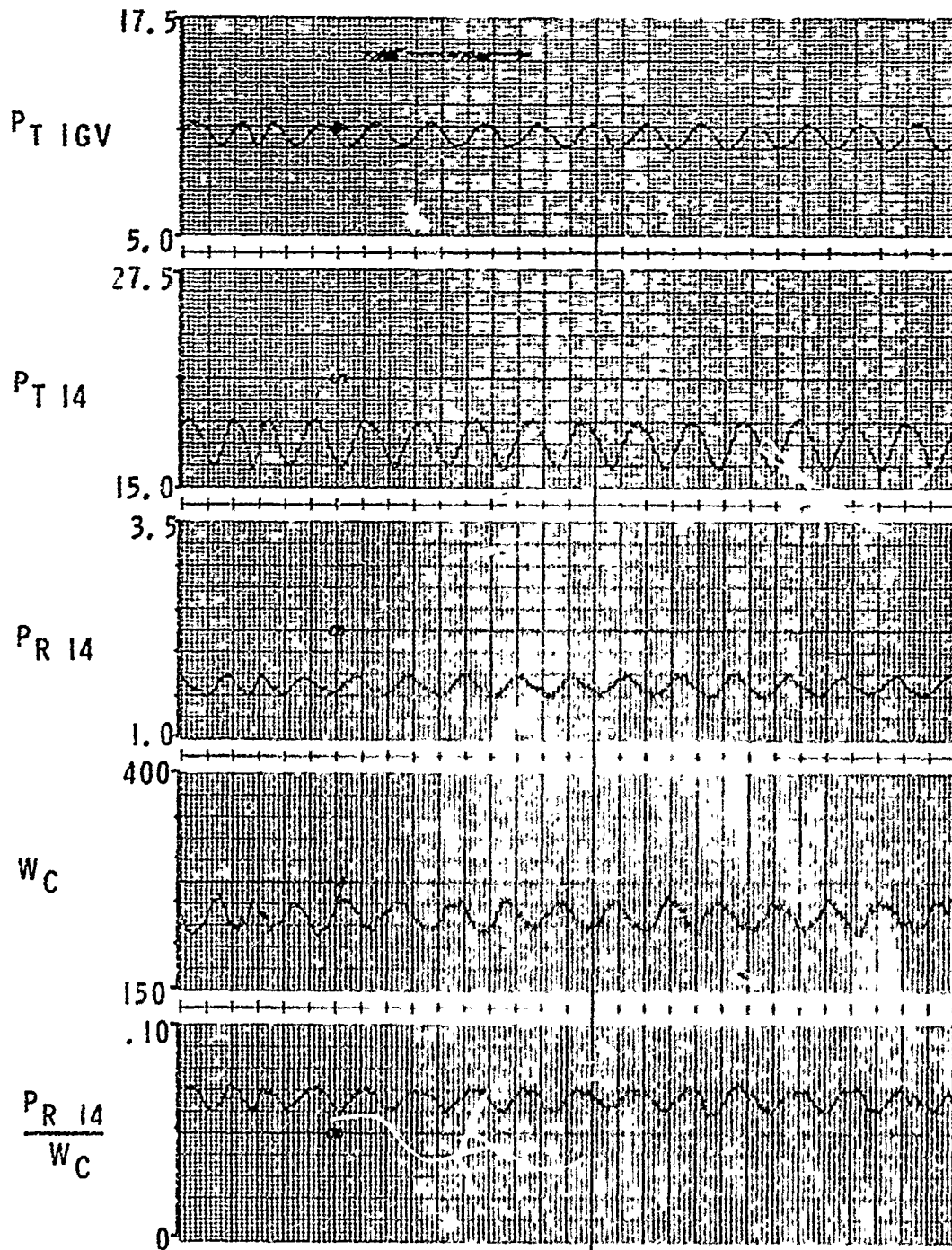
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FAN / P³G DYNAMIC DATA

RDG 75

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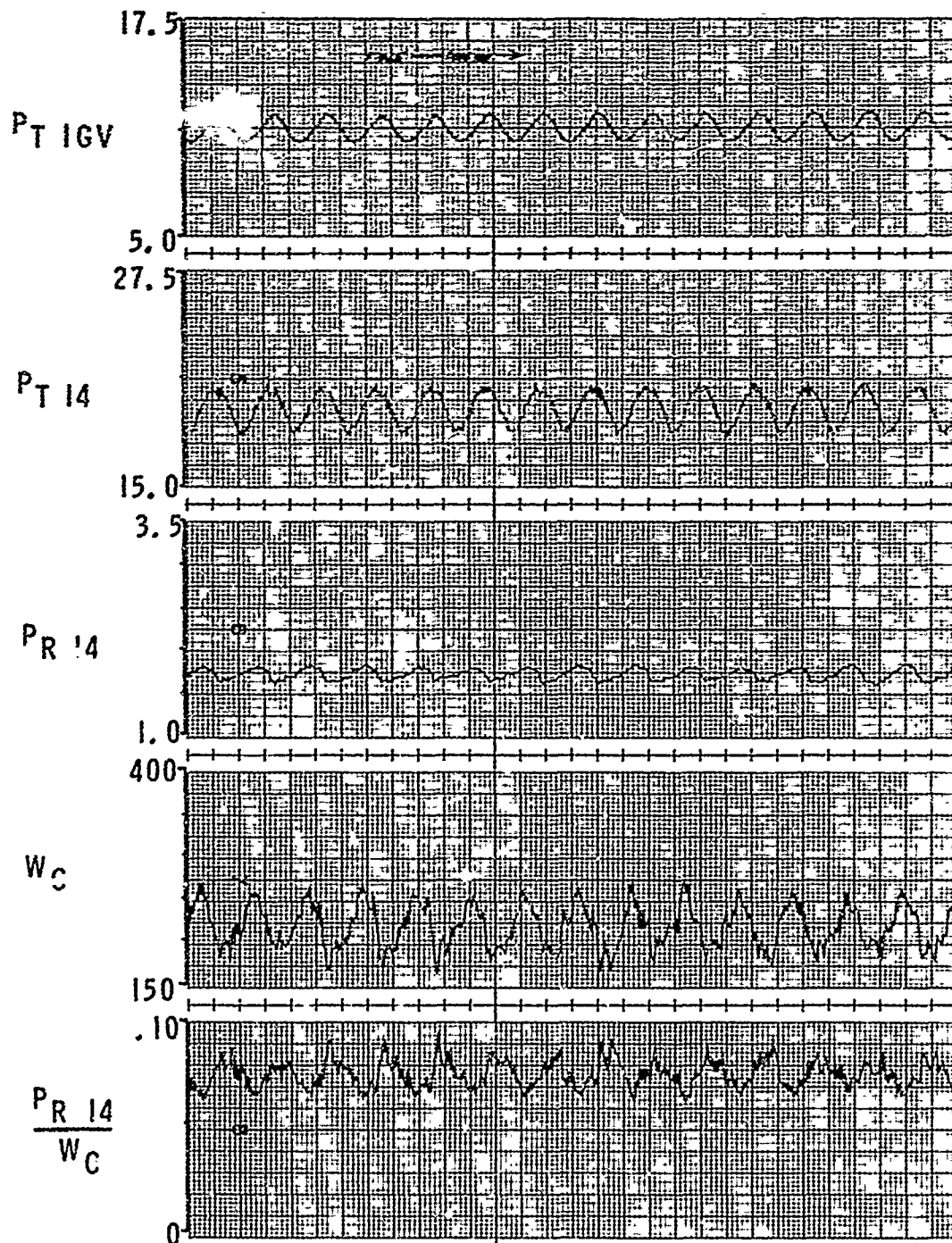
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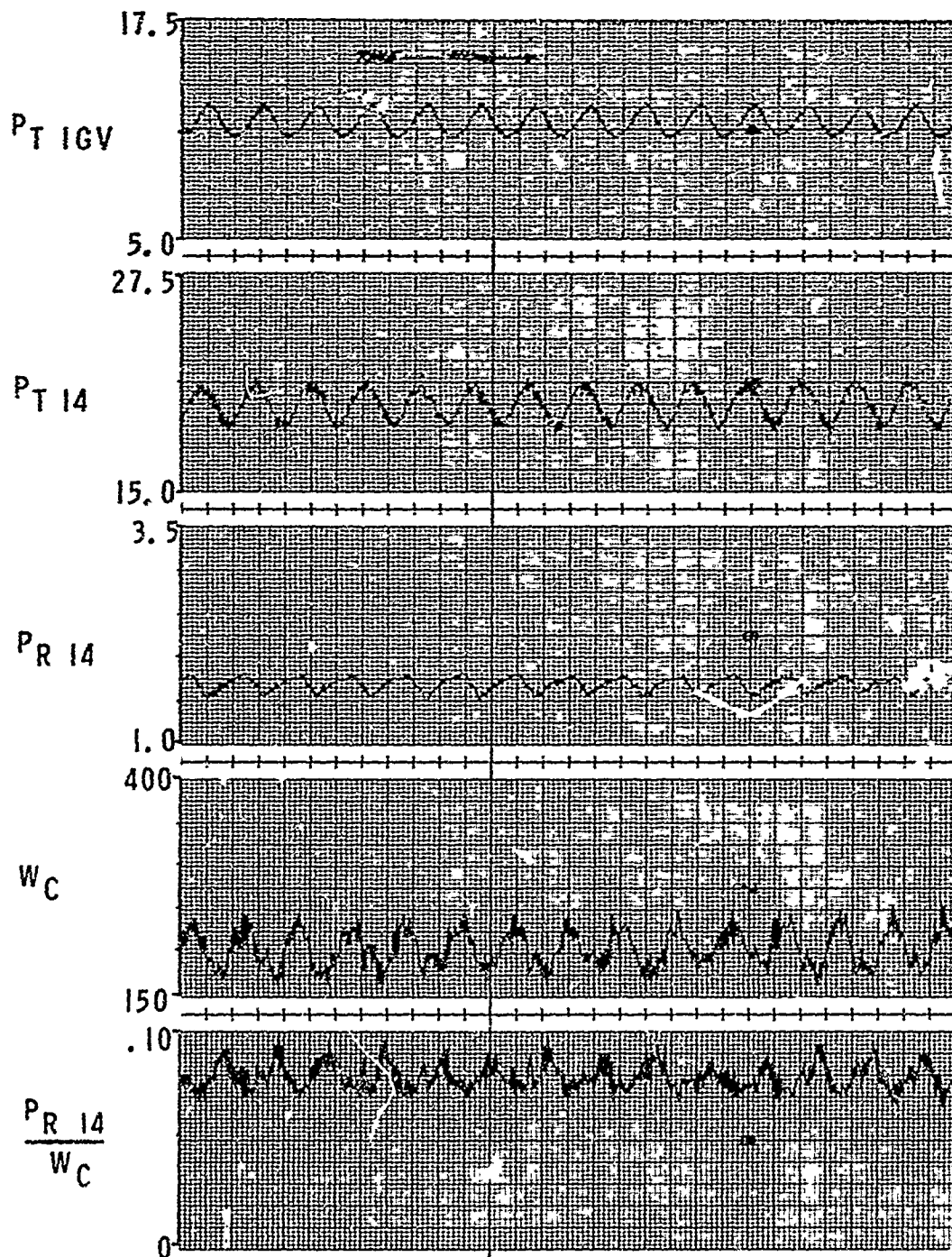
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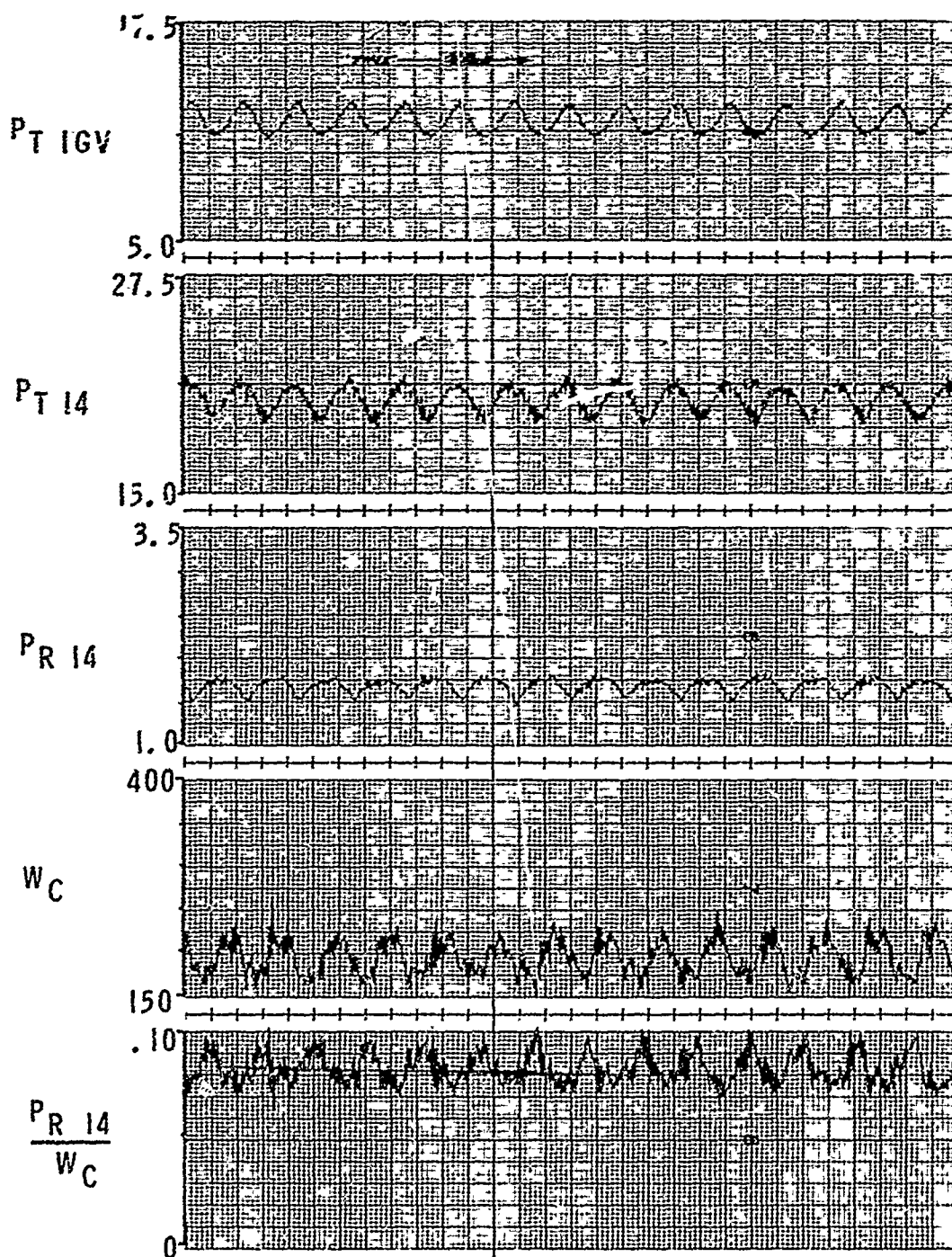
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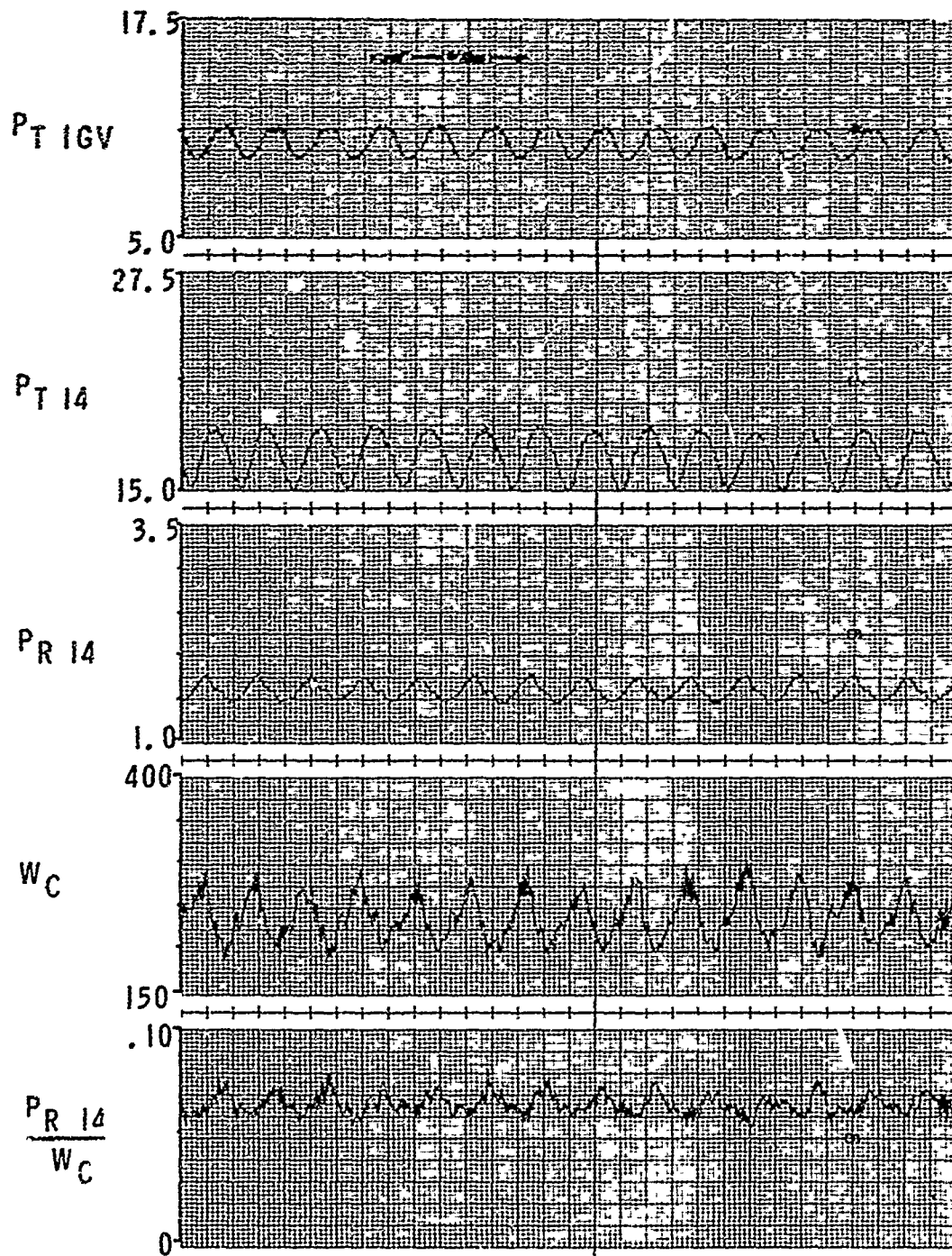
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RDG 79

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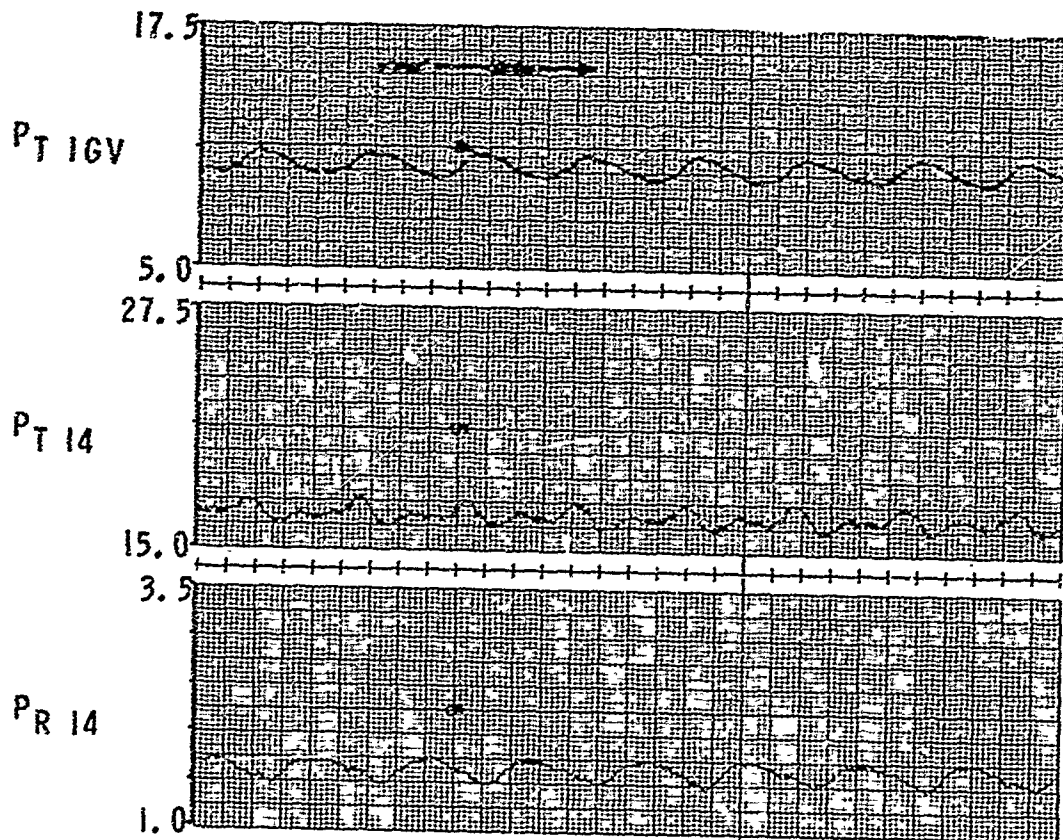
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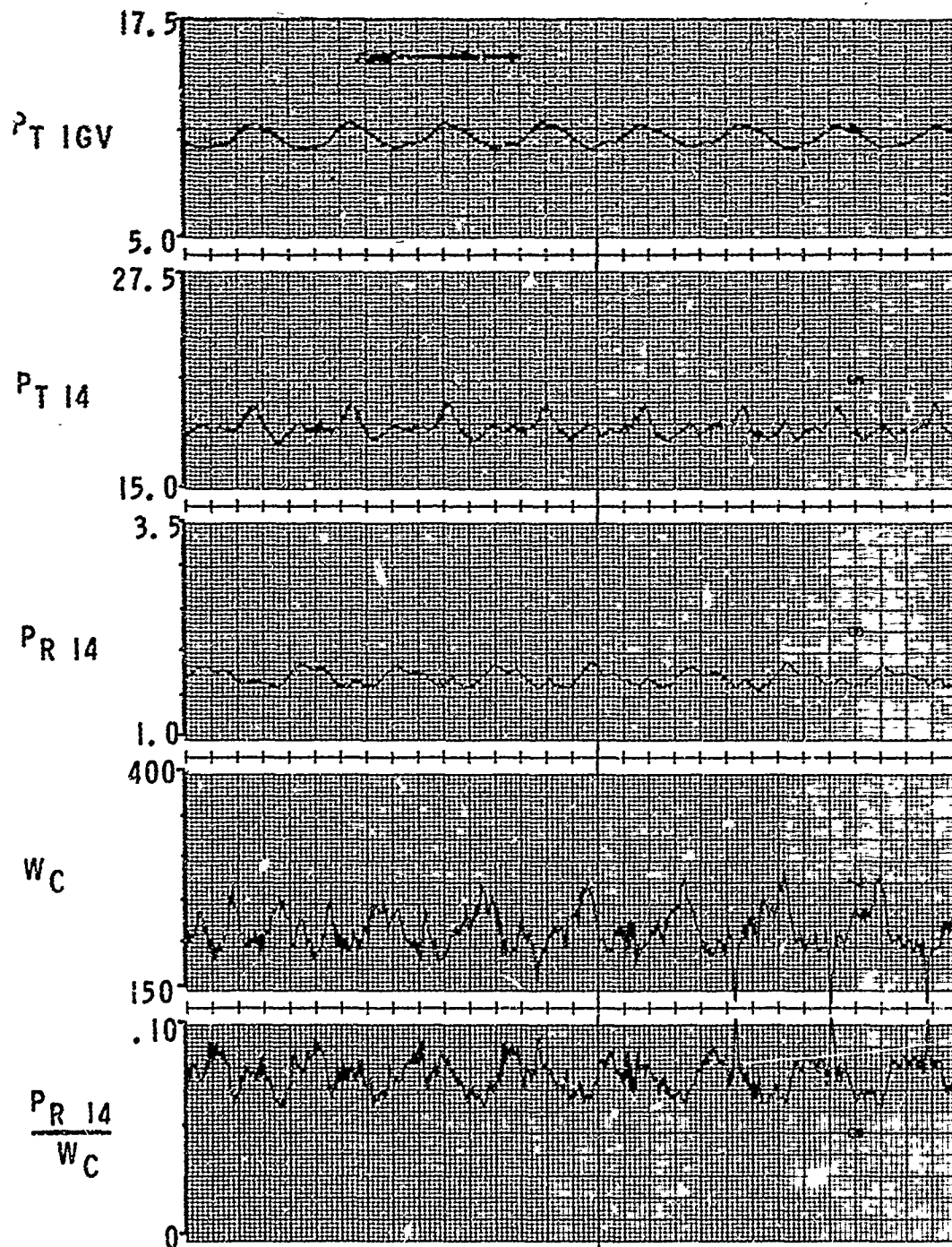
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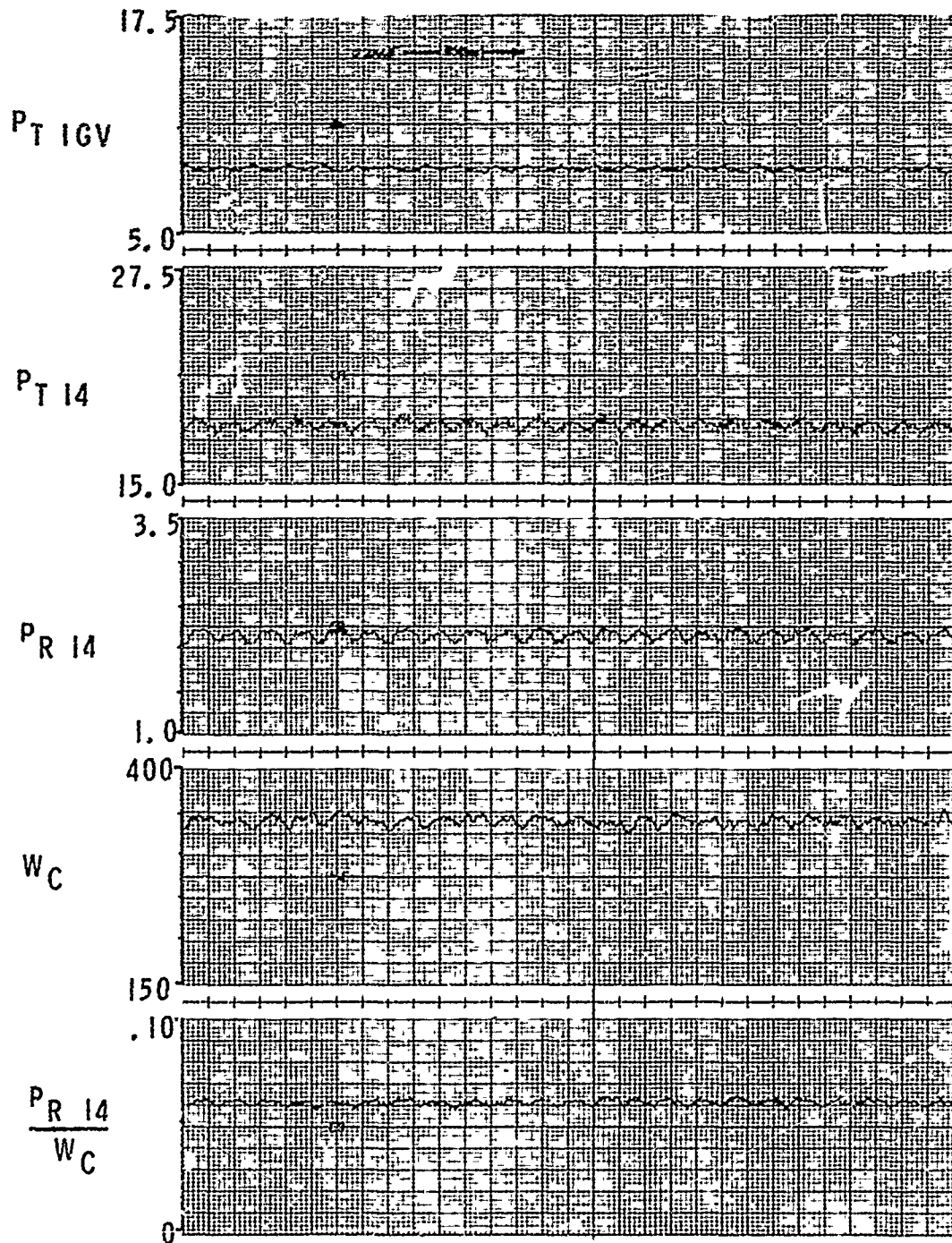
FAN / P³G DYNAMIC DATA

RDG 83

$$N/\sqrt{\theta} = 100$$

$$P^3G - i = 118$$

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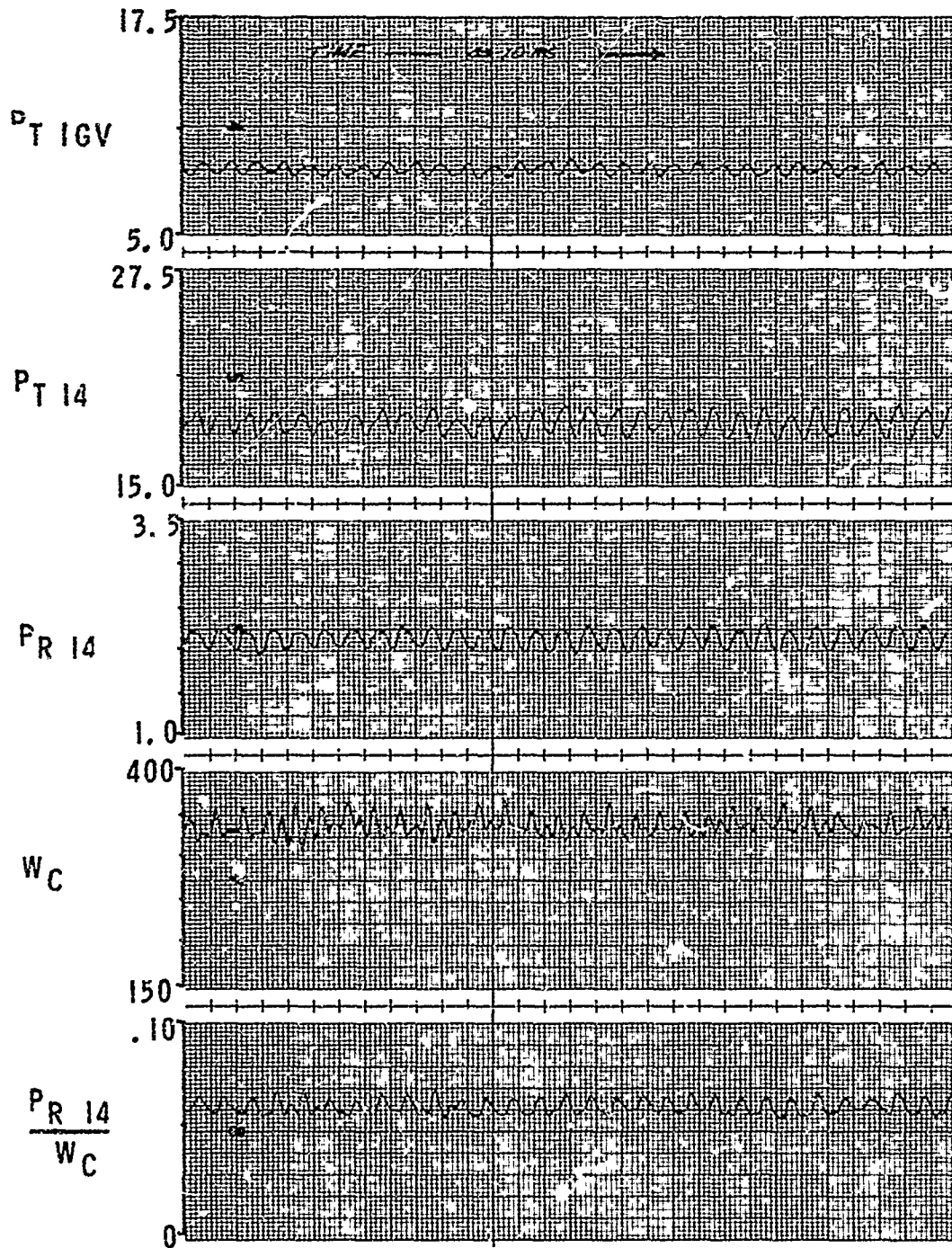
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$$P^3G - f = 613$$

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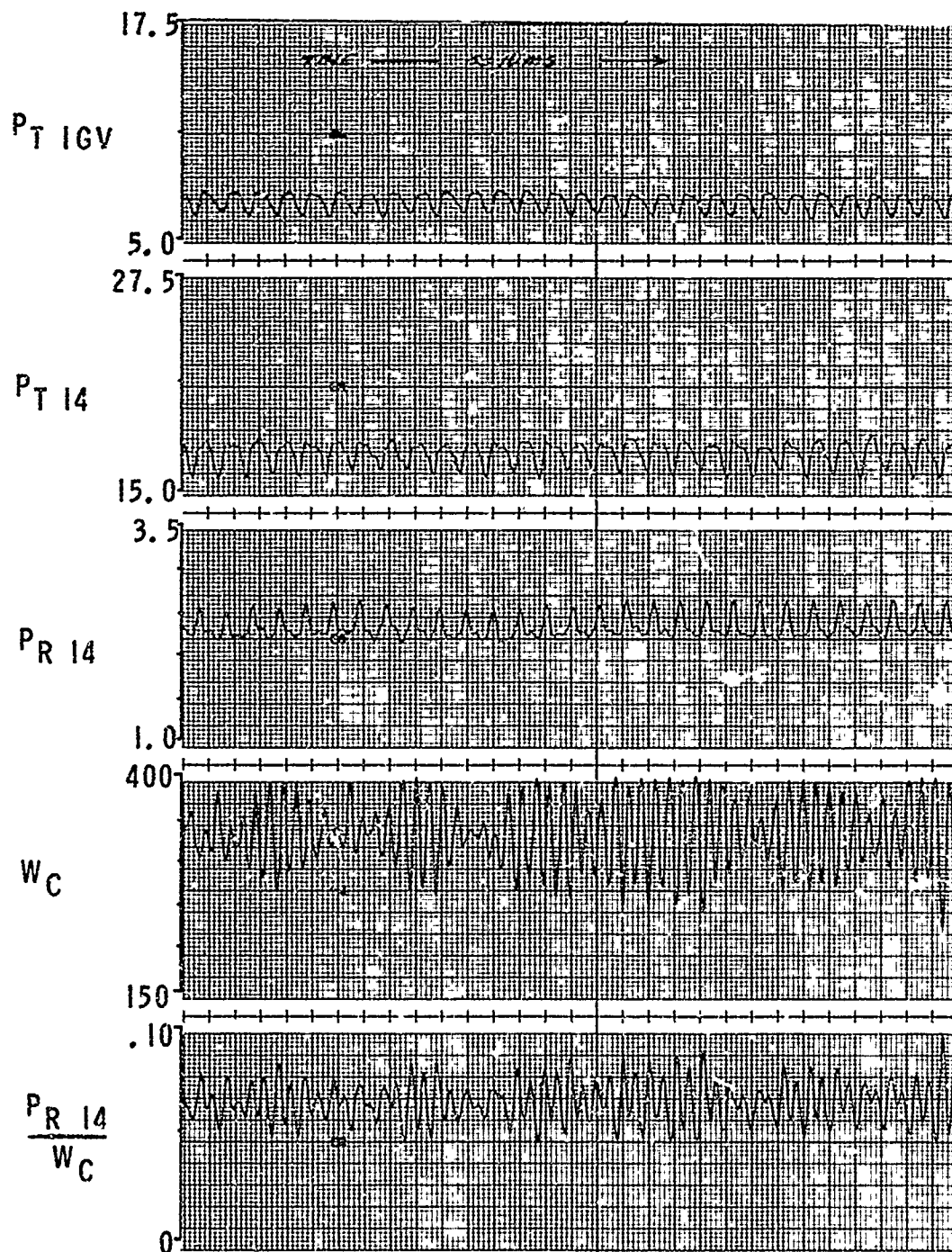
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RDG 85

$$N/\sqrt{R} = 100$$

$$P^3G - f = 613$$

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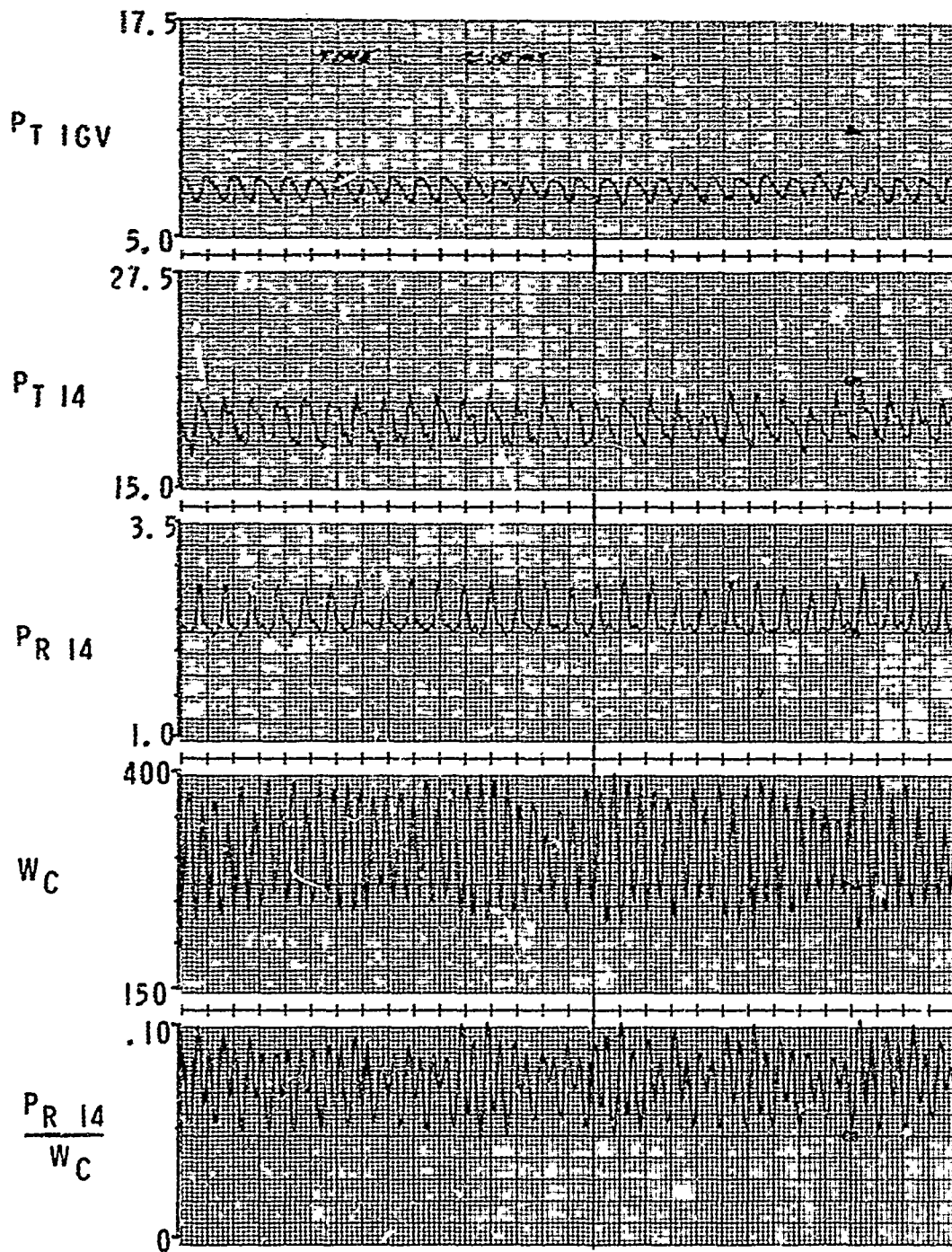
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$$P^3G - f = 613$$

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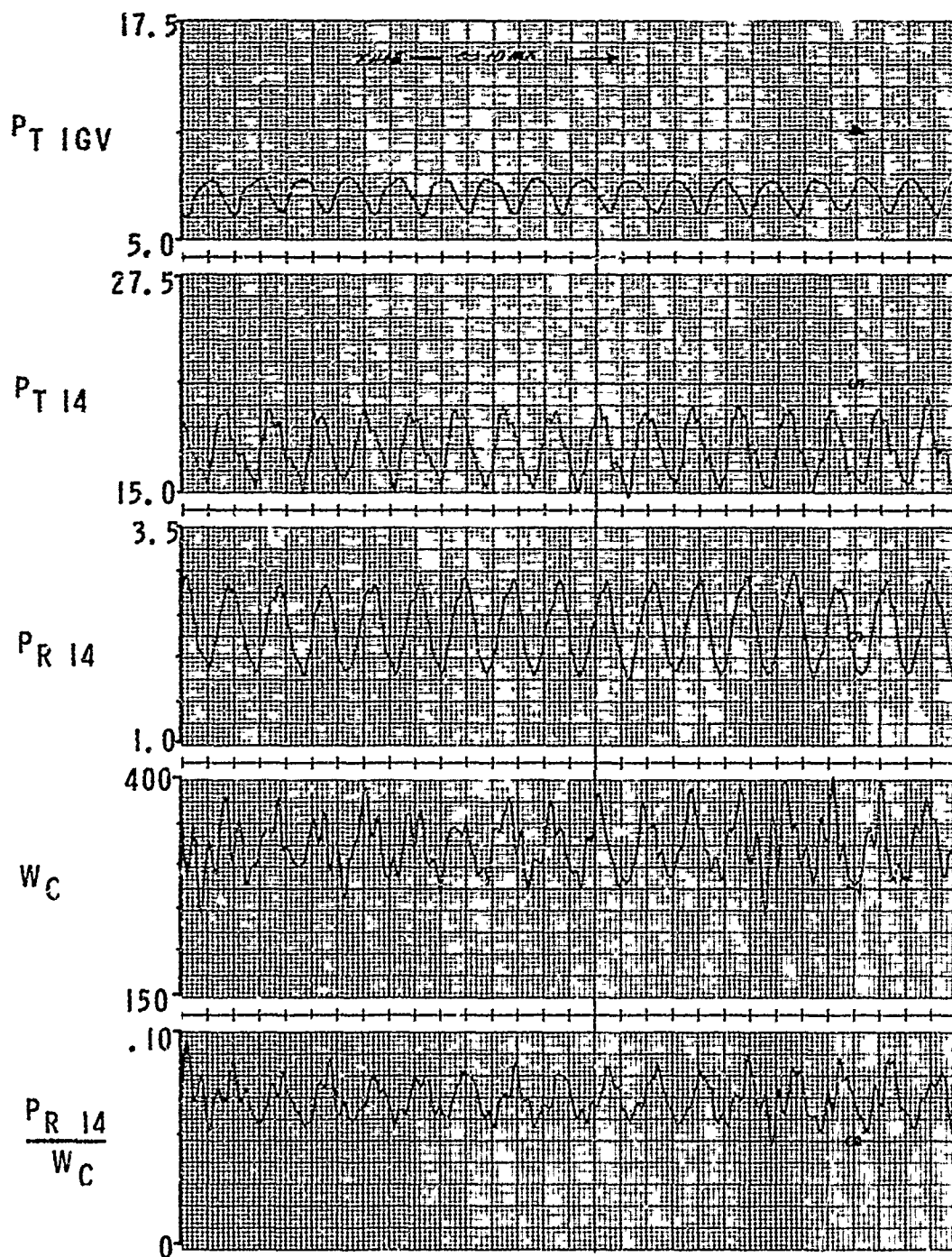
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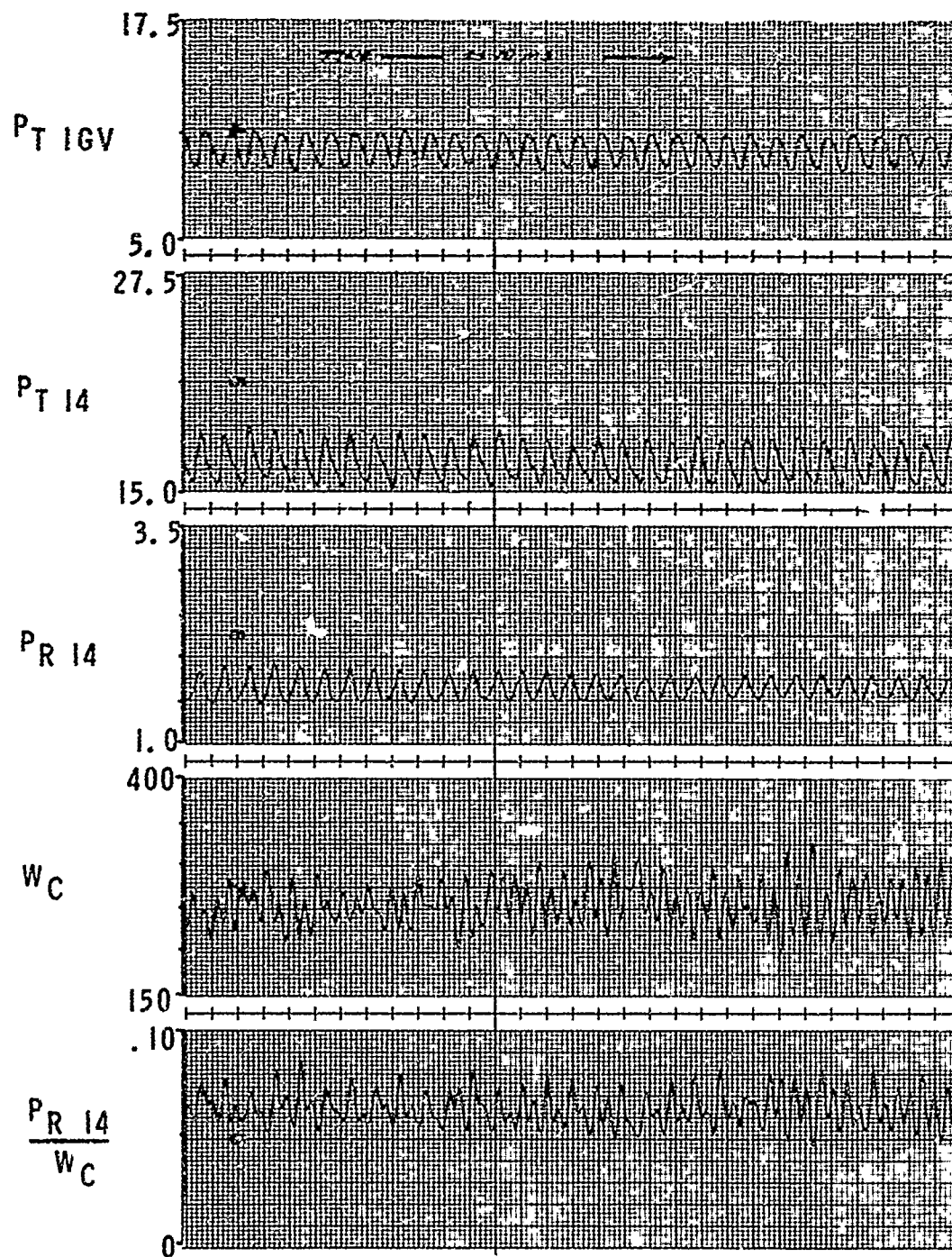
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FAN / P³G DYNAMIC DATA

RDG 89

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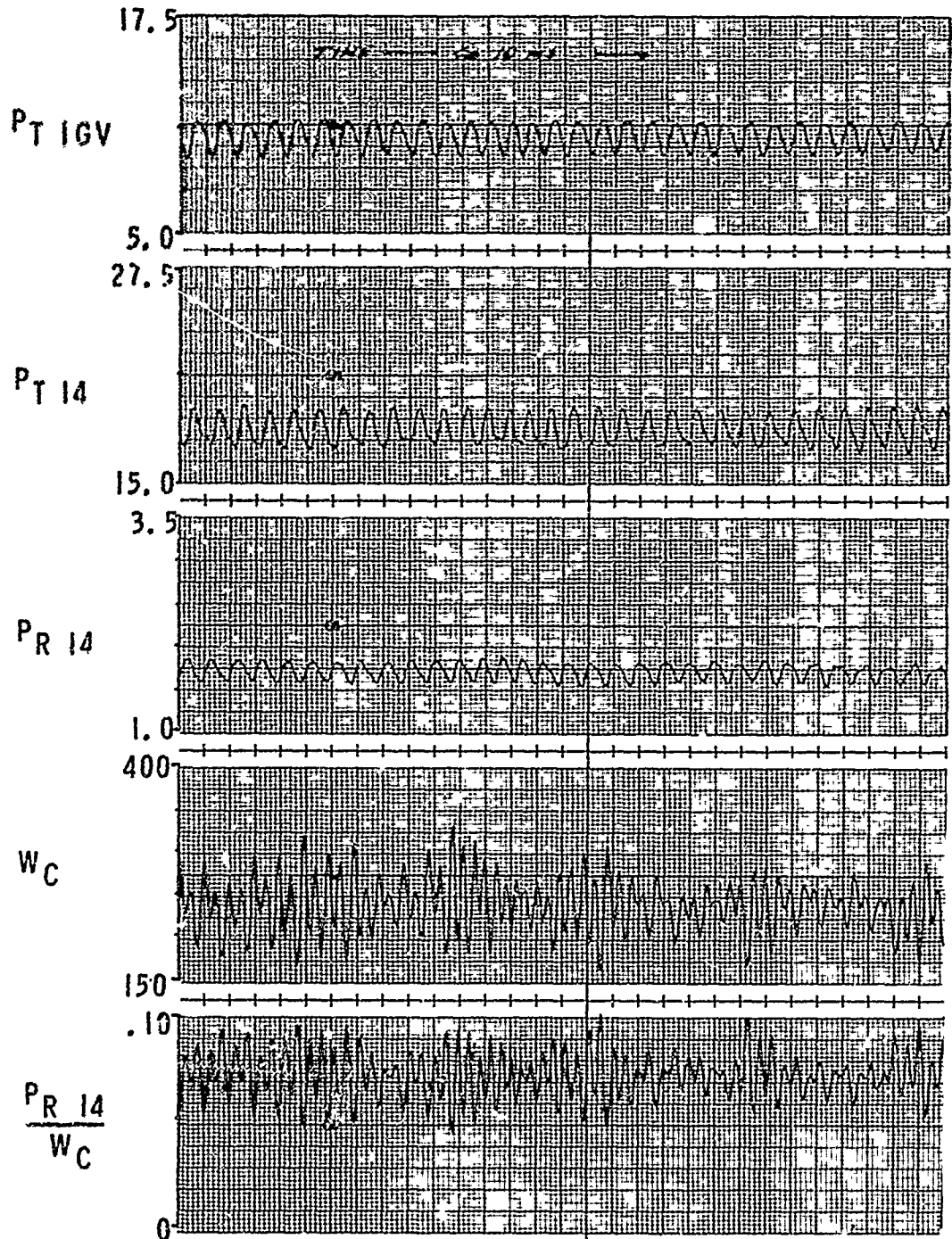
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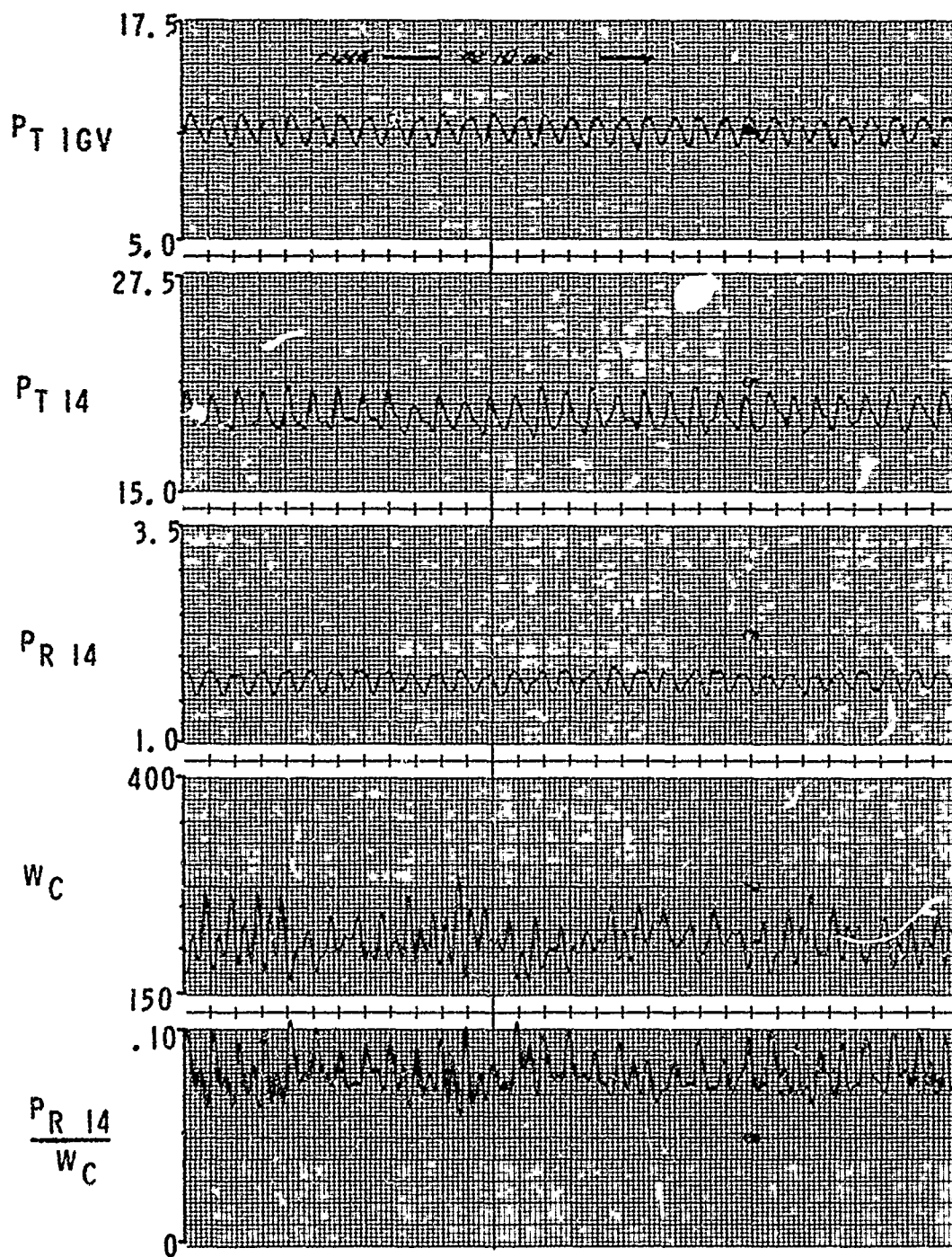
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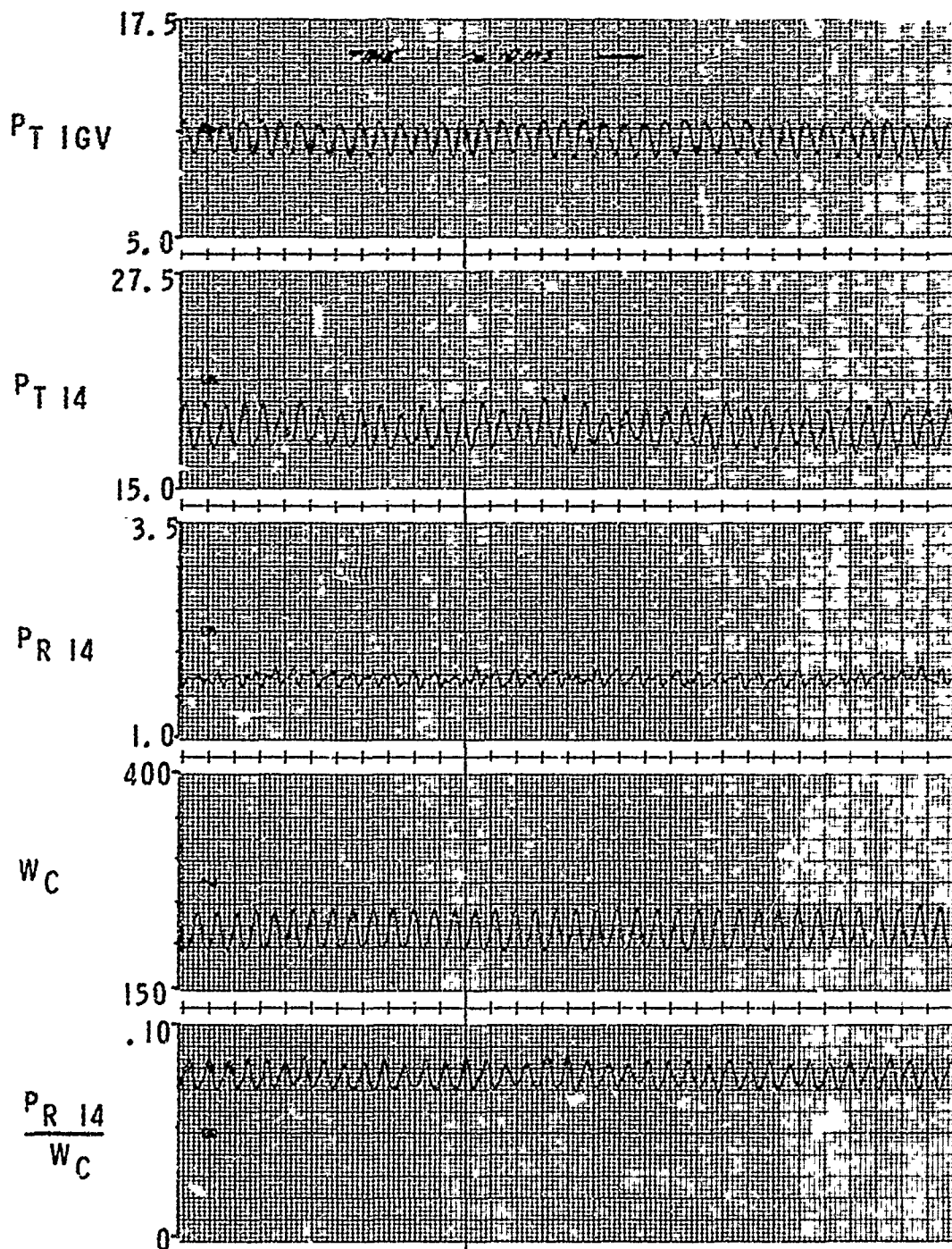
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$$P^3G - f = 800$$

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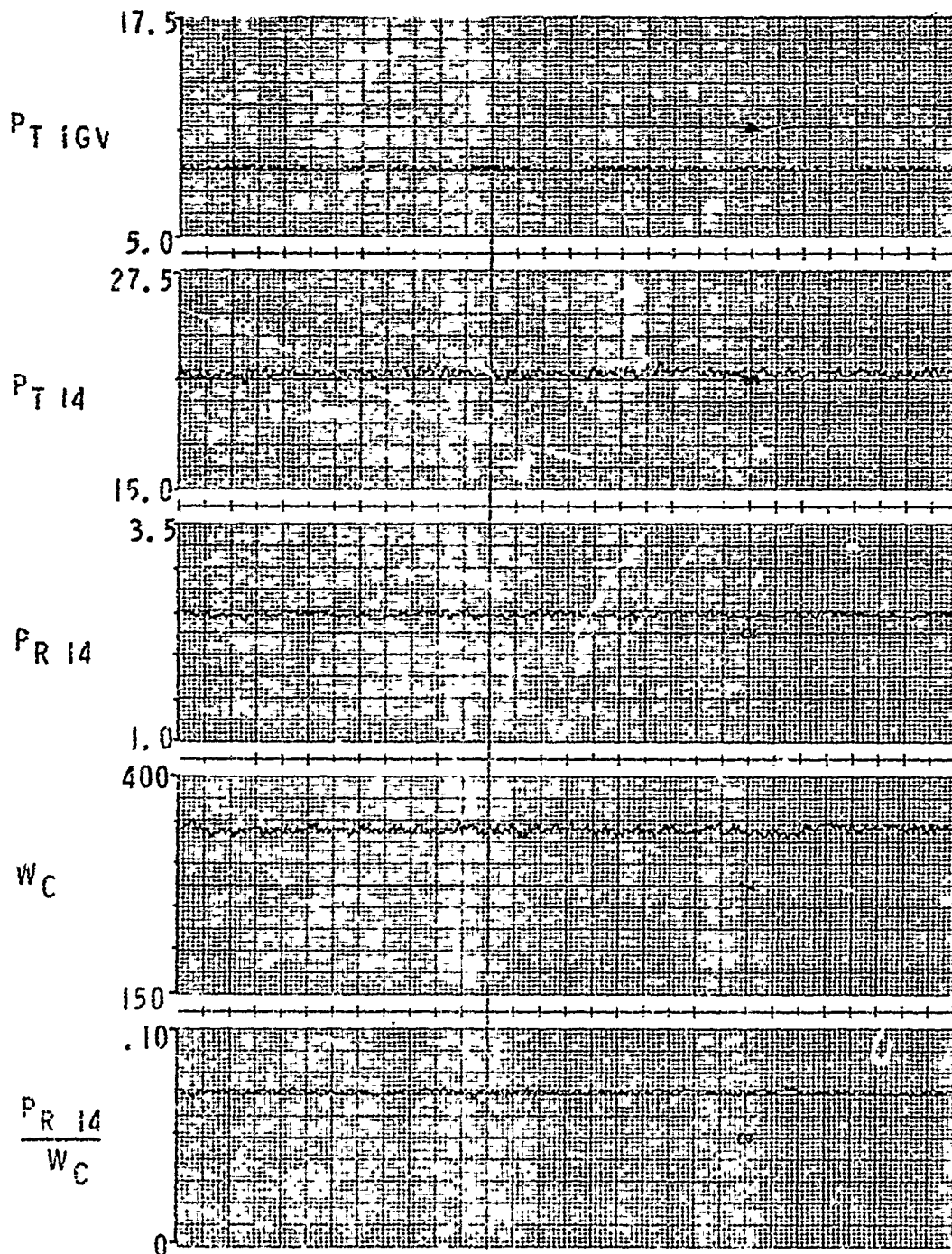
FAN / P³G DYNAMIC DATA

RDG 93

$$N/\sqrt{g} = 100$$

$$P^3G - f = 0$$

$$R-T-S = .570$$



REFERENCES

1. Kutschenreuter, P.H. and Younghans, J.L., "Near Term Distortion Methodology/Task Force Results," General Electric Report TIS R70AEG410, October, 1970.
2. Collins, T.P., Reynolds, G.G., and Vier, W.F., "Preliminary Pre-Test Report - Planar Pressure Pulse Generator P³G/F101 Fan," Internal General Electric Report ST72-3, November 21, 1972.