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A-11 SEVEN CLUSTER MODEL:
PHASE V - FLOW INDUCED VIBRATION TESTS
(Title Unclassified)

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ABSTRACT

When a model is employed to obtain data for prediction of the pressure distribution in and the vibration characteristics of a full scale unit, a degree of uncertainty is always present regarding the usefulness of the model test data. In the A-11 Phase V test, experimental data were obtained from tests on a seven cluster reactor model which incorporated as many of KIWI B-4A design features as could reasonably be included in the NRX-A reactor envelope. The data obtained was compared with data from a pie sector full scale reactor test. From this comparison, it appears that the results obtained from the seven cluster model are reasonable, within the expected limitations, and insure confidence that stable operation of the NRX-A reactor can be expected, based on the NRX-A model tests (Tests A-11 Phases I, III and IV) performed earlier.

SUMMARY

An A-11 seven cluster prototype model was modified to include some of the pertinent design features of the KIWI B-4A configuration. The model was flow tested both in the upward and downward firing modes to investigate its stability characteristics. Experimental data was obtained with ambient temperature hydrogen over the range from 0.07 to 0.70 lb/sec with core pressure drops varying from 2 to 32 psi. Sustained oscillations from 9 to 28 cps were obtained at core pressure drops from 4 to 32 psi. The vibrations were verified by motion pictures taken at 250 frames per second together with oscillograph records of a position transducer mounted against one of the outer end support blocks. The film showing the vibrations is available in the Fluid Flow Laboratory.

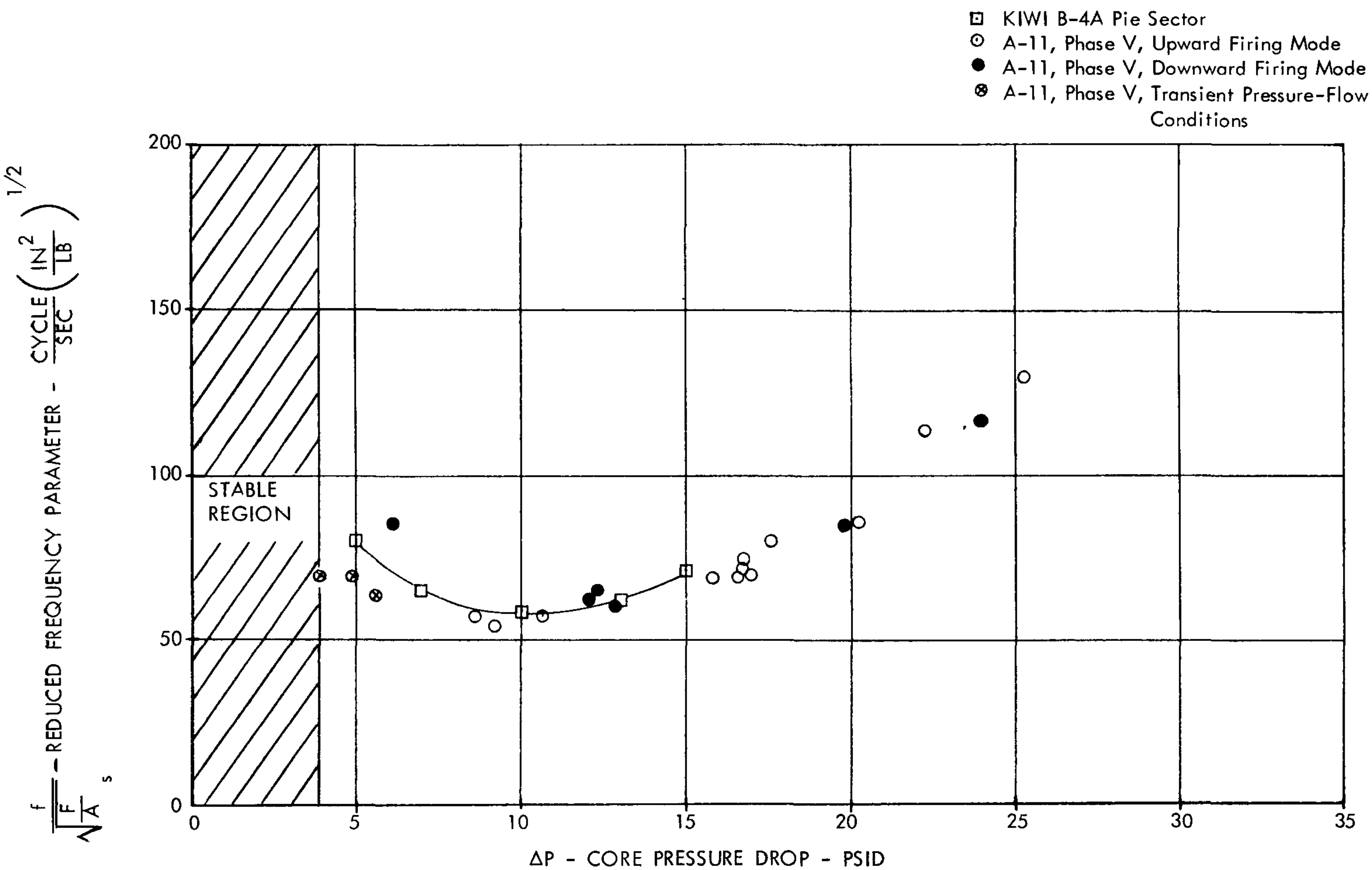
Good agreement was obtained between the Phase V model and the KIWI B-4A pie sector by normalizing the vibration data to a reduced frequency parameter.

Figure 1 shows the comparison of the reduced frequency parameters as a function of core pressure drop.

A-11, PHASE V AMBIENT HYDROGEN FLOW TESTS

NORMALIZED FREQUENCY CURVE

FIGURE 1



1.0 INTRODUCTION

This report summarizes the results of the fifth of a series of tests completed in the A-11 test program. These tests, comprising Phase V of the test program, consisted of modifying the NRX-A seven cluster prototype reactor model and flow testing it to obtain information concerning core behavior. The flow tests were carried out at the Westinghouse Astronuclear Hydrogen Experimental Facility (WANHEF) located at Waltz Mills. Test conditions were selected to determine the behavior of a core configuration having a dome end type seal and highly reduced bundling forces.

A total of twelve flow tests were completed utilizing ambient temperature hydrogen at flow rates extending from 0. 07 to 0. 70 lb/sec (4% to 38% design flow rates). The core inlet pressure varied from 17 to 79 psia and core pressure drops of 2 to 32 psid. Test duration was of the order of 1 minute for each test. The seven cluster core was monitored with pressure gages, a microphone, a triaxial accelerometer, four displacement sensors, and photographic equipment in order to evaluate audio and pressure data, and core movement or vibration.

The Phase V test core was assembled with available parts and incorporated modifications intended to simulate as many of the design features of the KIWI B-4A configuration to duplicating instability characteristics. This simulation was limited to: (1) the reduction of the spring bundling forces by reducing the number of seals (from the full complement of eighteen to three), (2) ventilation of all the seals to render them ineffective, (3) incorporation of a specially designed dome end type seal, and (4) elimination of the core banding feature.

Features in the Phase V core assembly which did not simulate the KIWI B-4A construction were: (1) the dome end seal of the model sealed against the inlet face of the filler strips rather than against the bottom of the seal groove, (2) the single section filler strip was supported between the first and second rows of seal segments rather than at the dome end, (3) three rows of seal segments were used to bundle the core instead of the spring slats, (4) the end support blocks used in the model features the NRX-A design which differs from the KIWI B-4A in that no alignment sleeves are used between the support block and individual fuel elements, and (5) the end support block of the model has an interlocking feature formed by the transition of the eighteen sided geometry of the fuel cluster periphery to the six sided geometry of the support block

A drawing showing the difference in design features of the model with the KIWI B-4A configuration is presented in Figure 2. Figure 3 shows a schematic showing the difference in support block geometry.

The results of the tests showed that. (1) below 4% of design flow rate the core components splayed (became out) without inducing sustained oscillations, and (2) from 4% to 38% of design flow rate sustained cluster vibrations occurred with the frequency of vibration varying with core differential pressure.

2.0 TEST RIG

A photograph of the A-11 test rig positioned in the downward firing mode is shown in Figure 4 with the general assembly drawing shown in Figure 5. Figure 6 shows a drawing of the Phase V test configuration. The basic configuration tested consisted of a prototype core fitted within a pressure vessel. Core components included a lightly loaded lateral support system, inner reflector, top support plate, support rings, and a seven cluster core. The following is a description of the test rig.

2.1 Core

The Phase V core consisted of a seven cluster assembly utilizing reactor grade hardware The fuel elements were Oak Ridge Y-12 uncoated, graphite elements and the bottom support blocks were of the uncoated, interlocking type without alignment sleeves. Brazed tie rods were used and the fuel element flow passages were orifices with 0.0255 inch diameter orifices.

Filler strips were specially designed for the seven cluster Phase V core and fabricated from grade HLM-85 (Great Lakes Carbon Company) graphite. There were no pyrotiles on the filler strips. The finished outside diameter of the assembled seven cluster was a nominal 6.75 inches.

2.2 Inner Reflector

Incorporated in the Phase V test configuration was the Number 2 inner reflector, 707 J 959 - C.

The inner reflector was initially designed to accommodate the small diameter core and lateral support and seal assembly. The reflector was fabricated from a single block of grade H4LM graphite and was not impregnated to reduce porosity. The inner surface of the reflector contains the lateral support system seal grooves while the outer surface has a series of openings for the lateral support system spring components and the instrumentation pressure taps and lines.

The inner reflector was supported by a special support stand on the core discharge end and spring loaded at the core inlet end. An "O" ring seal was located in the inner reflector support stand. Utilizing this configuration the outside of the reflector barrel should experience the static core inlet pressure during steady state runs.

2.3 Lateral Seal and Support System

The lateral seal and support system, utilized in the Phase V seven cluster model, have three rows (Numbers 1, 2 and 9) of segmented seal rings. This configuration employed flat back segment seals in conjunction with the flat face plunger cylinders. The pilot diameter of the plunger cylinders were decreased from $.3745 \begin{smallmatrix} +.0000 \\ -.0004 \end{smallmatrix}$ to $3.71 \pm .001$ inches to increase radial clearances to reduce frictional pin forces.

The flat back segment seals were used to reduce the frictional force between the bottom surface of the seal rings and the bottom surface of the seal groove in the inner reflector. Increased radial clearance between the plunger and graphite pilot holes allowed radial movement to occur more freely.

In the Phase V seven cluster test model, as in all A-11 models, the NRX-A lateral support leaf springs were replaced with coil springs. The coil springs were used because of the space limitations on the periphery of the inner reflector graphite cylinder. In the coil spring design, the plenum behind the seal segment communicates with the spring chamber by way of the plunger pin, however, the spring chamber is sealed from the outside surface of the inner reflector with a threaded aluminum plug fitted with an "O" ring. This precludes any gas leakage across the inner reflector, i. e., plunger pin leakage.

As a result of incorporating three rows of seal rings, only 36 of the original 216 plunger spring-cylinder assembly were used. The remainder of the spring chambers were sealed from the outside surface of the inner reflector only with the plunger plug fitted with an "O" ring.

Each seal ring in the lateral support system had six seal segments and each segment was spring loaded by two coil spring-plunger pin assemblies. The coil springs used in the Phase V tests had a spring rate of 1 - 2 lbs/in and were designed to exert a 0.625 - 1.250 pound nominal pre-load force per pin. This resulted in a pre-load core bundling pressure of approximately .02 - .04 psi based on total peripheral core area.

The flow slots on the inner surfaces of the seal segments were grooved over 66.5% of the core circumference. There were a total of 36 flow channels per seal ring, equivalent to one flow channel per filler strip. The flow channels had a uniform width and were distributed such that each channel spans a filler strip gap.

The depth of the flow slots were selected to provide ineffective seals. A description of the segment used for each seal ring follows.

2.3.1 No. 1 and 2 Seal Rings

Seal rings at Station 1 and 2 utilized the interlocking type flat back seal segments with 0.100 inch deep inner vertical flow slots and 0.100 inch deep flow slots on the bottom and top surfaces of the seal segment. The interlocking type segment seal ring on each side of the filler strip projection was preferred over the butt joint type to provide better radial support when rotating the test vessel. Typical seal segments are shown in Figures 7 and 8.

2.3.2 No. 9 Seal Ring

Seal ring at Station 9 utilized the butt joint type flat back seal segments with 0.100 inch deep inner vertical flow slots and 0.100 inch deep flow slots on the bottom and top surfaces of the seal segments.

2.3.3 Dome End Seal

A seal ring specifically designed for the Phase V tests incorporates an "O" ring between the top surface of the filler strips and the seal ring. A sketch of the seal ring assembly is shown in Figure 9.

2.4 Filler Strips (576 F 378 and 576 F 379)

Single section filler strips 53.800 inches long spanned the cluster assembly. These filler strips were specifically designed for Phase V and incorporated a projection at the core inlet end which is trapped between seal ring 1 and 2.

2.5 Core Band

The inlet of the core assembly was not banded in order to simulate the unrestrained condition characteristic of the KIWI B-4A configuration.

2.6 Core Support Plate

The core support plate as used in all A-11 test models was an aluminum plate containing coolant holes and openings to accept the tie rod nuts and locking devices.

The circumferential spring seals normally incorporated in the assembly were not used for the Phase V tests.

Axial support for the core support plate was provided by the outer support ring. The outer support ring is a stainless steel ring fitted with a flange supported by the pressure vessel flange. An inner support ring was retained by the core support plate and a spring load was applied between it and the inner reflector. All loads imposed on the core support plate were transmitted to the pressure vessel.

2.7 Pressure Vessel

The pressure vessel consists of two body sections; the short section containing the inlet diffuser and the long section containing the core proper. The body sections and closures are attached to one another by circumferential bolted flanges. The completed vessel is provided with a support trunnion so that the vessel can be rotated to relocate the inlet and discharge ends. The vessel was designed for vertical mounting in the downward firing mode but can also be used in an upward firing mode. The vessel was fabricated of type 304 stainless steel and was designed for a pressure of 1125 psia.

3.0 INSTRUMENTATION

The instrumentation used for the Phase V tests was limited to selected audio and pressure measurements, displacement and acceleration measurements, and a photographic record of the core. The instrumentation schematic showing the location of the measuring stations is shown in Figures 10 thru 12. Figure 13 shows the location of the interstitial pressure taps. The following is a description of the instrumentation.

3.1 Sound Pressure Transducer

A Glennite Model MA-299501 (P-420M-6) microphone, located at the core outlet was used to measure the intensity of the sound pressures. The sound pressure signal generated from the microphone was sent through a dual channel pre-amplifier (EICO, HF-80 Stereo Pre-Amp) where the signal was conditioned. The output signal of the pre-amp was transmitted through triaxial cables and the conditioned signal recorded on a Westinghouse Model 22RS Stereo Tape Recorder. The output signal of the downstream microphone was connected to a speaker in parallel with the tape recorder in order to monitor the sound during tests.

3.2 Pressure Gages

Calibrated Heise gages, 0 - 400 psig were used to measure the core inlet and the core discharge pressures on the upstream side of the restricting flow nozzle. Both gages incorporated dial followers to indicate peak pressures. Differential pressures in the lateral seal system were measured using Barton Model 200 differential pressure indicators.

All of the pressure gages were mounted on a panel board and a 70 mm automatic camera was used to record pressure data. The camera photographed the gage panel at approximately two second intervals. A clock with a sweep second hand was located on the panel for a time reference.

3.3 Core Photography

A Milliken Model DBM5BE, 16 mm high speed motion picture camera was used to photograph the bottom of the core during the flow tests. Camera speed was 250 fps. A Sylvania Sun Gun Photolight was used to illuminate the core during the test.

3.4 Temperature

A bare wire copper-constantan thermocouple was used to measure the gas temperature downstream of the core. The thermocouple was used in conjunction with a 150° reference junction and the resultant signal output recorded on a Visicorder oscillograph using the data acquisition system's signal conditioning equipment.

3.5 Pressure Transducers

CEC Type 4-326-0001 pressure transducers were used to measure core inlet, core outlet, outside reflector annulus, lateral support and seal annulus, and four interstitial pressures.

3.6 Position Transducer

Four Crescent Engineering Company linear variable differential transformers (LVDT) were used to monitor core displacement during the tests. Two transducers were mounted at the dome end and two at the nozzle end. A sketch showing the location of the position transducers is presented in Figure 14.

3.7 Vibration Transducer

An Endevco microminiature triaxial accelerometer, Model 2228B, mounted to the tie rod supporting one of the end support blocks was used to monitor acceleration levels during the test.

Table I summarizes the instrumentation used for the Phase V tests.

4.0 TEST PROCEDURE

The operating procedure used for the A-11 Phase V tests, A-11-V-GH_2-1 through 6, is outlined in the standard operating procedure included in Appendix A of the Phase I report, WANL-TME-605. The tests were conducted at the Waltz Mill Test Facility. A schematic of the experimental flow system is shown in Figure 15. High pressure hydrogen gas, supplied from tube trailers, flowed through a pressure control valve, and entered the test vessel at a specific pressure. The gas then flowed through the reflector-core assembly, passed through a shutoff valve, flowed through a critical flow nozzle, and discharged through the exhaust system to the flare stack where the hydrogen gas was burned. The duration of the tests were 21 to 45 seconds. Test data were recorded during the transient start-up period as well as during the steady-state conditions.

5.0 PHASE V TESTS

Two series of tests were conducted with the A-11 Phase V model consisting of twelve hydrogen tests. Ten of these tests, A-11-V-GH_2-1 through 10, were conducted with the core model positioned in the upward firing mode and two, A-11-V-GH_2-11 and 12, with the model positioned in the downward firing mode.

The purpose of the first series of tests, A-11-V-GH_2-1 through 6, was to determine if the core configuration was susceptible to flow induced vibration. The second series of tests, A-11-V-GH_2-7 through 12 were conducted: (1) to determine the pressure-flow conditions at which flow induced vibration starts, (2) to investigate the vibration characteristics at higher pressure-flow conditions, and (3) to provide experimental data at the intermediate pressure flow conditions, with the model positioned both in the upward and downward firing mode.

5.1 Exploratory Tests

In the first series of tests hydrogen gas was supplied to the system from a single tube trailer having a capacity of 63,000 SCF. The first two tests, A-11-V-GH_2-1 and A-11-V-GH_2-2 were conducted at low inlet pressures and mass flow rates with the pressure controlled by the upstream pressure control valve, PCV-2. Pressure control valve PCV-2 is a 1/4 inch Annin valve used to control at low pressure and flow rates. The Phase V core configuration was initially subjected to low pressure-low mass flow rates to determine the conditions at which flow induced vibration begins and to prevent damage to the model in event vibrations are induced. After completing the two flow tests at flow rates of 0.08 and 0.12 lb/sec, respectively, it was determined from the motion pictures and oscillograph traces that the core components moved radially outwards (broomed) but maintained a dynamically stable condition. This brooming effect indicated the possibility that flow induced vibration could exist at a higher flow rate and pressure drop.

In order to determine the core behavior at higher flow rates, additional tests were completed. These were conducted using pressure control valve, PCV-1, and installing a larger flow nozzle. Three hydrogen flow tests, A-11-V-GH_2-3 through 5 were conducted. A fourth test, A-11-V-GH_2-6 was conducted without a flow nozzle installed in the exhaust system to reduce the discharge back pressure. Flow induced vibrations were obtained at the higher flow rates and pressure drops.

From the motion pictures taken during the A-11-V-GH_2-1 through 6 tests, it was noted that the end support blocks returned to their original pre-start position after each test with the exception of test A-11-V-GH_2-6. At the end of test A-11-V-GH_2-6 it was noted that some of the support blocks separated from each other and remained in the open position. An inspection of the core showed that the peripheral elements of the cluster assemblies had separated and moved outward from the center element and remained displaced.

Before the second series of tests, A-11-V-GH_2-7 through 12, the cluster assemblies were rearranged to again form a compatible core.

5.2 Vibration Tests

The second series of tests were conducted with hydrogen gas being supplied to the system from two 63,000 SCF tube trailers connected in parallel using the newly installed flow loop which permitted remote manual or automatic control of the core inlet operating pressure.

Three different core inlet pressures were set during each test using a ramp method of operation. This method of operation included a 5 to 10 second transient pressure-flow ramp with a minimum steady state test duration of 10 seconds at a specific pressure level. After each of the tests a visual inspection of the discharge end of the core was made.

At the higher pressure-flow runs, i.e., A-11-V-GH_2-9 and 10, the post-test inspections showed that the peripheral elements in each of the cluster assemblies separated and moved outward from the center element where they remained displaced. The peripheral flow passage holes of some of the elements were visible between the gaps formed by the separated end support blocks. No attempt was made to rearrange the cluster assemblies between runs 9 and 10.

At the end of run A-11-V-GH_2-10 the pressure vessel was rotated and the cluster assemblies rearranged before testing the model in the downward firing mode.

6.0 DISCUSSION OF RESULTS

A summary of the Phase V flow test results including core pressures, core differential pressures, mass flow rates, and vibration frequency is shown in Table I. Mass flow rates varied from 0.07 to 0.70 lb/sec with core inlet pressures from 17 to 79 psia. Corresponding core pressure drops varied from 2.4 to 32.3 psi. The first two tests, A-11-V-GH_2-1 and 2, were conducted at low pressure-flow conditions with a 0.743 inch diameter flow nozzle incorporated downstream of the test rig. From the results of the oscillograph trace obtained from an end support block mounted position transducer together with the motion pictures taken of the nozzle end of the core, it was determined that the internal components splayed without any sustained oscillations. A trace of the position transducer signal reproduced from the oscillograph record taken during test A-11-V-GH_2-2 is shown in Figure 16.

Test runs, A-11-V-GH_2-3 through 5 were conducted with a 1.4982 inch diameter flow nozzle to obtain higher pressure-flow conditions. Traces of the position transducer signals were reproduced from the oscillograph records obtained during these tests and are shown in Figures 17 through 20. The motion pictures taken during these tests, in conjunction with the oscillograph record, show that sustained lateral cluster vibrations were obtained at these higher pressure-flow conditions.

Test run, A-11-V-GH_2-6, was conducted with reduced back pressure. This condition was achieved by eliminating the downstream restriction, i.e., flow nozzle, and discharging the hydrogen gas directly to the atmosphere. Figures 19 and 20 show a reproduction of the position transducer signal obtained during this test.

Test runs, A-11-V-GH_2-7 through 12, were conducted with a 1.8004 inch diameter flow nozzle incorporated in the system with the core inlet pressure controled manually from the control room. A trace reproduced from a section of a typical oscillograph record obtained during these tests is shown in Figure 21. The output signals obtained from the end support block mounted position transducer were reproduced from the oscillograph records taken during tests A-11-V-GH_2-7 through 12 and are shown in Figures 22 through 29, respectively. Included are low pressure-flow transient traces from tests A-11-V-GH_2-7 and 11 to show the transition from stable to unstable conditions. All of the tests with the exception of tests A-11-V-GH_2-11 and 12 were conducted with the model positioned in the upward firing mode.

The fundamental support block frequency of vibration obtained from a position transducer was found to range from 9 to 28 cps. Figure 30 shows the frequency of vibration obtained from all experimental Phase V data as a function of the core pressure drop compared with the KIWI Pie Sector data. The KIWI Pie Sector data presented here was conducted with gaseous ambient temperature helium, Reference 1 and 2.

The Phase V support block vibration frequency appeared to be independent of core firing position. The experimental Phase V curve in Figure 30 includes data obtained from both the upward and downward firing modes.

In general, the shape of the frequency-core pressure drop curves are similar. The frequency levels obtained from the Phase V tests, however, is lower than obtained in the KIWI Pie Sector tests.

One major difference which existed between the two configurations was that the lateral support pre-load bundling pressure of the Phase V configuration (.02 - .04 psi) was less than the KIWI Pie Sector (.13 psi).

In order to compare the results of the Phase V tests with the KIWI Pie Sector tests, a reduced frequency parameter was derived based on a normalized lateral support bundling force per total peripheral core surface area.

The reduced frequency parameter comparing the results of the Phase V tests with the KIWI Pie Sector tests was presented earlier in Figure 1 of the report and the derivation is shown in the Appendix.

Scatter of the experimental frequency-core pressure drop data is within the expected instrumentation accuracy with the exception of run A-11-V-GH_2-10. The indicated level of support block frequency of vibration of this test was not compatible with the data obrained from the majority of the Phase V tests. This frequency discrepancy may have been caused by the support blocks being in the displaced position prior to the start of test so the characteristics of the vibrating component changed.

From test observations and motion picture studies of the tests, it was concluded that the cluster assemblies, i.e., elements, support blocks, etc. vibrated as an integral part at the pressure-flow-conditions when there was no evidence of element displacement prior to the start of test. The frequency of vibrations obtained at these conditions is characteristic of the cluster assembly.

The flow pressure data obtained from the Phase V tests is shown in Figure 31 and 32 with the calculated core pressure drops shown in Figure 33. The experimental pressure data from these tests are tabulated in Table III and IV.

CONCLUSIONS AND RECOMMENDATIONS

The A-11, Phase V configuration, which basically simulated the pertinent design features of the KIWI B-4A configuration, i. e., top supported with a simulated dome end seal proved to be dynamically unstable under flow conditions ranging from 7 to 38% of design flow rate.

The frequency of vibration based on normalized vibration data of the Phase V model was in good agreement with the KIWI Pie Sector test data both in the limit of stability and frequency level when plotted as a function of core pressure drop.

The following recommendations are proposed based on the results of the A-11, Phase V tests.

1. Increase the lateral support bundling force of the A-11 model to simulate the bundling force of the KIWI B-4A configuration to verify that the frequency level can be duplicated.

2. Test the Phase V model or a simulated KIWI B-4A model with an adequate number of position and vibration transducers to investigate in datail the characteristics of this type of flow induced vibration.

APPENDIX

The reduced frequency parameter was determined on the basis of assuming the following conditions to be the same for both the Phase V model and the KIWI B-4A Pie Sector.

1. The forcing function which is proportional to the gas dynamic force of the fluid.
2. The restoring force due to the elasticity of the vibrating component.
3. The damping force of the vibrating component.
4. The inertia force per unit length of the vibrating component.

One major difference which existed between the two configurations was the restoring force due to the lateral support pre-load bundling force of the springs. Normalizing the total pre-load bundling force per total peripheral core surface area reduces the natural frequency to a common basis. In a simple self-excited system, the actual frequency of vibration approximates the natural frequency of the system, References 3 and 4.

The natural frequency of the system based on the total lateral support spring bundling force per total peripheral core surface area is approximated by the equation,

$$f = f_n = \frac{1}{2\pi}\sqrt{\frac{K}{m}} = \frac{1}{2\pi}\sqrt{\left(\frac{F}{A_s}\right)\left(\frac{A_e}{\Delta}\right)\left(\frac{1}{m}\right)}$$

Rearranging terms

$$f = \frac{1}{2\pi}\left(\frac{A_e}{\Delta \cdot m}\right)^{1/2}\sqrt{\frac{F}{A_s}}$$

which reduces to the frequency parameter,

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \text{constant}$$

assuming that the parameter $\left(\frac{A_e}{\Delta \cdot m}\right)^{1/2}$ is the same for each cluster for both configurations.
For the A-11 Phase V model the reduced frequency parameter

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \frac{f}{\sqrt{\frac{K_s \times D \times N}{A_s}}} = \frac{f}{\sqrt{\frac{(1.5)\,(0.625)\,(36)}{(\pi)\,(6.75)\,(52)}}}$$

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \frac{f}{0.175} = \text{constant}$$

For the KIWI B-4A Pie Sector:

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \frac{f}{\sqrt{\frac{L \times N}{A_s}}} \frac{f}{\sqrt{\frac{1.2 \times 612/6}{(\pi \times 35.88 \times 52) \div 6}}}$$

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \frac{f}{0.354} = \text{constant}$$

For the KIWI B-4A:

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \frac{f}{\sqrt{\frac{L \times N}{A_s}}} = \frac{f}{\sqrt{\frac{1.2 \times 612}{\pi \times 35.88 \times 52}}}$$

$$\frac{f}{\sqrt{\frac{F}{A_s}}} = \frac{f}{0.354} = \text{constant}$$

NOMENCLATURE

A_e = equivalent component area that the spring bundling force acts on - in^2

A_s = core peripheral surface area - in^2

DP = differential pressure gage

d = flow nozzle diameter - inches

D = nominal working distance of spring - inches

f = frequency - cps

f_n = natural frequency - cps

F = total spring bundling force - lb

G = vibration transducer (accelerometer)

K = spring constant due to the restoring force of the lateral support springs - lb/in

L = load per spring - lb

$\dot{m}$ = mass flow rate - lb/sec

m = mass of the vibrating component - $\frac{lb - sec^2}{in}$

M = microphone

N = number of springs

P = pressure (psia, psig)

t = time (seconds)

T = temperature (^oR, ^oF)

TDP = differential pressure transducer

TP = pressure transducer

r	=	radius - inches
x	=	core station - inches
δ	=	position transducer, displacement - inches
Δ	=	deflection - inch
ΔP	=	pressure drop - psid

SUBSCRIPTS

x	=	core station
r	=	radial station measured from model centerline

TEST NUMBER NOMENCLATURE

(A-11) - (V) - (GH_2) - (7a)

- 7a — Run Number
- GH_2 — Fluid: Gaseous Hydrogen
- V — Test Configuration: Phase V
- A-11 — Flow Induced Vibration Test

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TABLE I

A-11 PHASE V - HYDROGEN FLOW TESTS

Test Number	Core Inlet Pressure (PSIA)	Core Differential Pressure (PSID)	Mass Flow Rate (LB/SEC)	Frequency (CPS)
1	32.9	2.4	0.08	NONE
2	48.3	3.7	0.12	NONE
3	62.6	16.8	0.48	13
4	60.5	16.7	0.46	12.5
5	57.1	15.8	0.44	12
6	42.8	20.5	*0.42	15
7a	17.4	2.9	0.07	NONE
7b	25.4	8.6	0.15	10
7c	27.0	9.2	0.19	9.5
8a	38.9	16.6	0.34	12
8b	41.7	17.0	0.38	12
8c	63.2	25.3	0.57	23
9a	28.5	10.6	0.20	10
9b	41.4	17.6	0.37	14
9c	53.6	22.3	0.47	20
10a	29.8	11.9	0.20	18
10b	78.7	32.3	0.70	28
11a	22.2	6.1	0.14	15
11b	31.6	12.0	0.26	11
11c	32.5	12.3	0.29	11.5
12a	32.5	12.9	0.28	10.5
12b	53.0	19.8	0.51	15
12c	67.0	24.0	0.66	20.5

*Approximated

TABLE II

GENERAL PHASE V INSTRUMENTATION SUMMARY

Gage or Transducer No.	Manufacturer	Range Full Scale	Measurement
		Temperature	
T-1			Core Inlet
T-2			Core Outlet
		Pressure	
P-1	Heise	0-400 psig	Core Inlet
P-2	Heise	0-400 psig	Core Exit
DP-1	Barton	0-15 psid	Core Inlet Heise Gage and Core Inlet
DP-2	Midwest	0-100 psid	Core Inlet and Seal 1
DP-3	Barton	0-30 psid	Across Seal 2
DP-6	Barton	0-15 psid	Across Seal 9
TP-1	CEC	0-500 psia	Core Inlet
TP-1'	CEC	0-1000 psia	Between Seals 1 and 2
TP-2	CEC	0-500 psia	Core Outlet
TP-3	CEC	0-1000 psia	Barrel Pressure
TDP-9	CEC	0-50 psid	Across Seal 9
TP-17	CEC	0-1000 psia	Core Station 49.3 Inches
TP-28	CEC	0-1000 psia	Interstitial 28
TP-29	CEC	0-1000 psia	Interstitial 29
TP-30	CEC	0-10000 psia	Interstitial 30
TP-31	CEC	0-1000 psia	Interstitial 31
TP-35	CEC	0-900 psia	Flow Nozzle Inlet
		Displacement	
δ-1	Crescent		Dome End (Filler Strips Relative to Reflector)
δ-2	Crescent		Dome End (Filler Strips Relative to Reflector)
δ-3	Crescent		Nozzle End (Support Block Relative to Reflector)
δ-4	Crescent		Nozzle End (Filler Strips Relative to Reflector)

(Continued on next page)

TABLE II (CONTINUED)

Gage or Transducer No.	Manufacturer	Range Full Scale	Measurement
		Acceleration	
G-1-x	Endevco		120°Cluster (Perpendicular to Radius)
G-1-y	Endevco		120°Cluster (Radial)
G-1-z	Endevco		120°Cluster (Longitudinal)

TABLE III
A-11, PHASE V EXPERIMENTAL PRESSURE DATA

Test Number	Flow Nozzle Diameter d	Gas Temperature °R T-1	Gas Temperature °R T-2	Core Inlet Pressure TP-1	P_x - Station Pressure - PSIA, x - Core Station - Inches	TP-1'		TP-17	Pressure Drop Across Seal No. 9 TDP-9	Core Outlet Pressure TP-2	Outside Reflector Support Pressure TP-3	Flow Nozzle Inlet Pressure TP-35	Flow Nozzle Pressure Differential	Calculated Core Pressure Differential	Calculated Mass Flow Rate $\dot{m}$	Frequency f
	INCHES	INLET	EXIT	PSIA	0	4.3	26.8	49.3	PSID	PSIA	PSIA	PSIA	IN. °F H_2O	PSID	LB/SEC	(CPS)
UPWARD FIRING MODE																
A-11-V-GH$_2$-1	0.743	—	490	32.9	32.9	31.0	31.0	—	—	30.5	32.5	—	500	2.4	0.081	NONE
A-11-V-GH$_2$-2	0.743	—	490	48.3	48.3	46.8	46.8	—	—	44.6	44.3	—	749	3.7	0.118	NONE
A-11-V-GH$_2$-3	1.498	—	505	62.6	—	54.5	—	—	—	45.8	62.0	—	—	16.8	0.484	13
A-11-V-GH$_2$-4	1.498	—	505	60.5	—	51.9	—	—	—	43.8	59.1	—	—	16.7	0.463	12.5
A-11-V-GH$_2$-5	1.498	—	503	57.1	—	49.0	—	—	—	41.3	56.0	—	—	15.8	0.438	12
A-11-V-GH$_2$-6	NONE	—	500	42.8	—	33.0	—	—	—	22.3	43.3	—	—	20.5	*0.42	15
A-11-V-GH$_2$-7a	1.800	511	513	17.4	—	15.5	—	14.7	X	14.5	16.6	X	10	2.9	0.074	NONE
A-11-V-GH$_2$-7b	1.800	510	513	25.4	—	20.5	—	17.9	X	16.8	26.1	X	63	8.6	0.145	10
A-11-V-GH$_2$-7c	1.800	511	513	27.0	—	22.4	—	17.9	X	17.8	26.1	X	78	9.2	0.186	9.5
A-11-V-GH$_2$-7d ▷	1.800	510	513	19.0	—	16.7	—	15.8	X	15.1	22.1	X	20	3.9	—	12
A-11-V-GH$_2$-7e ▷	1.800	510	513	20.1	—	16.7	—	15.3	X	15.2	19.0	X	20	4.9	—	12
A-11-V-GH$_2$-8a	1.800	520	523	38.9	—	27.7	—	22.6	X	22.3	37.2	X	220	16.6	0.336	12
A-11-V-GH$_2$-8b	1.800	521	524	41.7	—	31.0	—	25.5	X	24.7	40.5	X	292	17.0	0.383	12
A-11-V-GH$_2$-8c	1.800	523	523	63.2	—	46.6	—	37.1	X	37.9	60.1	X	668	25.3	0.57	23
A-11-V-GH$_2$-9a	1.800	521	523	28.5	—	22.1	—	18.2	4.9	17.9	26.9	X	77	10.6	0.202	10
A-11-V-GH$_2$-9b	1.800	521	524	41.4	—	30.4	—	24.5	8.4	23.8	38.8	X	270	17.6	0.370	14
A-11-V-GH$_2$-9c	1.800	523	524	53.6	—	39.9	—	32.2	X	31.3	51.4	X	516	22.3	0.470	20
A-11-V-GH$_2$-10a	1.800	520	523	29.8	—	23.8	—	17.7	5.9	17.9	29.1	X	X	11.9	0.202	18
A-11-V-GH$_2$-10b	1.800	522	521	78.7	—	59.9	—	46.8	X	46.4	73.8	X	X	32.3	0.696	28
DOWNWARD FIRING MODE																
A-11-V-GH$_2$-11a	1.800	508	509	22.2	—	17.8	—	16.3	4.1	16.1	22.4	X	33	6.1	0.136	15
A-11-V-GH$_2$-11b	1.800	508	509	31.6	—	25.3	—	20.2	7.0	19.6	31.5	X	123	12.0	0.257	11
A-11-V-GH$_2$-11c	1.800	509	509	32.5	—	27.0	—	21.2	7.6	20.2	32.1	X	150	12.3	0.285	11.5
A-11-V-GH$_2$-11d ▷	1.800	X	509	21.7	—	17.8	—	16.8	4.0	16.1	20.8	X	30	5.6	—	11
A-11-V-GH$_2$-12a	1.800	509	509	32.5	—	26.5	—	20.7	7.0	19.6	31.5	X	140	12.9	0.276	10.5
A-11-V-GH$_2$-12b	1.800	511	509	53.0	—	43.8	—	32.9	10.7	33.2	53.0	X	578	19.8	0.507	15
A-11-V-GH$_2$-12c	1.800	512	509	67.0	—	55.3	—	42.2	12.6	43.0	67.0	X	750	24.0	0.656	20.5

* Approximate.

▷ Transient: Pressure-Flow Conditions Recorded At Start of Indicated Cluster Oscillation During Start-Up Ramps.

— No Instrumentation.

X Instrumentation Inoperative.

TABLE IV

A-11 PHASE V AMBIENT HYDROGEN FLOW TESTS
INTERSTITIAL PRESSURE MEASUREMENT AT CORE STATION X = 48 INCHES

Test Number	P_r - Interstitial Pressure - PSIA			
	r - Radius - Inches			
	0.38	0.93	1.66	2.99
A-11-V-GH_2-1	31.4	29.5	31.1	31.8
A-11-V-GH_2-2	43.1	41.2	43.7	41.8
A-11-V-GH_2-3	47.3	47.3	48.1	47.8
A-11-V-GH_2-4	45.0	45.8	45.8	45.8
A-11-V-GH_2-5	43.3	43.3	43.3	43.3
A-11-V-GH_2-6	24.5	25.5	24.8	25.0
A-11-V-GH_2-7a		14.2	14.8	14.2
A-11-V-GH_2-7b		17.7	18.7	18.4
A-11-V-GH_2-7c		18.4	19.9	20.1
A-11-V-GH_2-8a		24.7	23.6	25.0
A-11-V-GH_2-8b		26.0	26.2	28.0
A-11-V-GH_2-8c		40.2	41.3	42.2
A-11-V-GH_2-9a		18.2	19.5	19.6
A-11-V-GH_2-9b		24.7	25.7	26.2
A-11-V-GH_2-9c		29.9	35.0	35.7
A-11-V-GH_2-10a		19.5	19.0	20.2
A-11-V-GH_2-10b		50.6	51.6	51.6
A-11-V-GH_2-11a		16.3	15.3	16.1
A-11-V-GH_2-11b		20.8	20.5	21.3
A-11-V-GH_2-11c		20.8	20.5	21.8
A-11-V-GH_2-12a		20.8	21.0	21.3
A-11-V-GH_2-12b		34.9	35.8	36.5
A-11-V-GH_2-12c		45.2	46.0	46.1

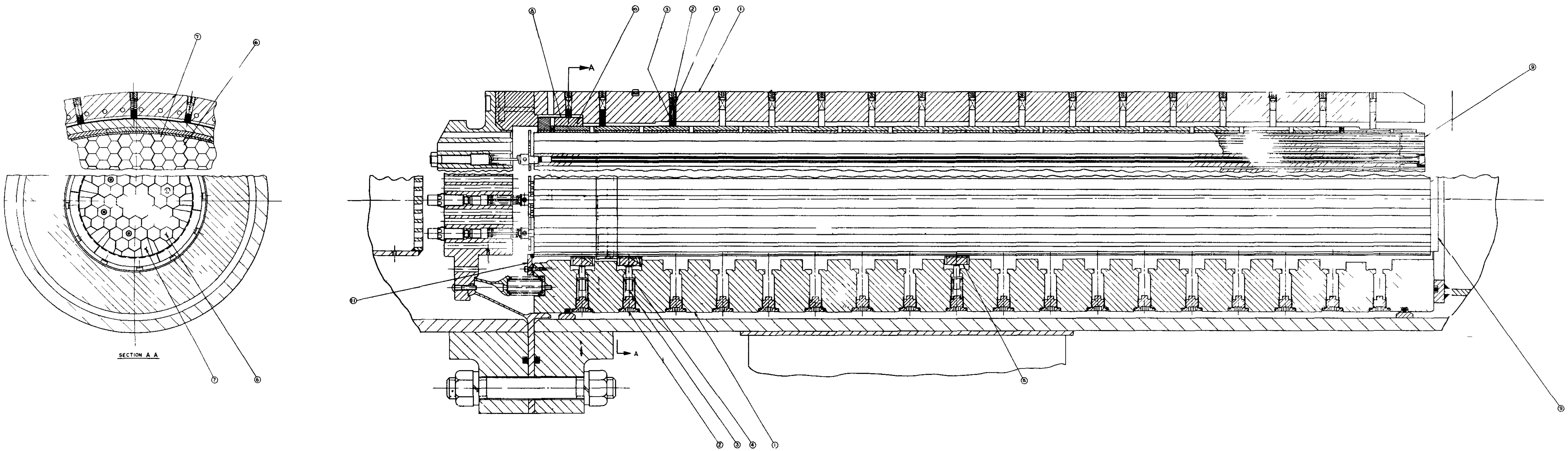


FIGURE 2 - A-11 AND KIWI B-4A CORE CROSS SECTION

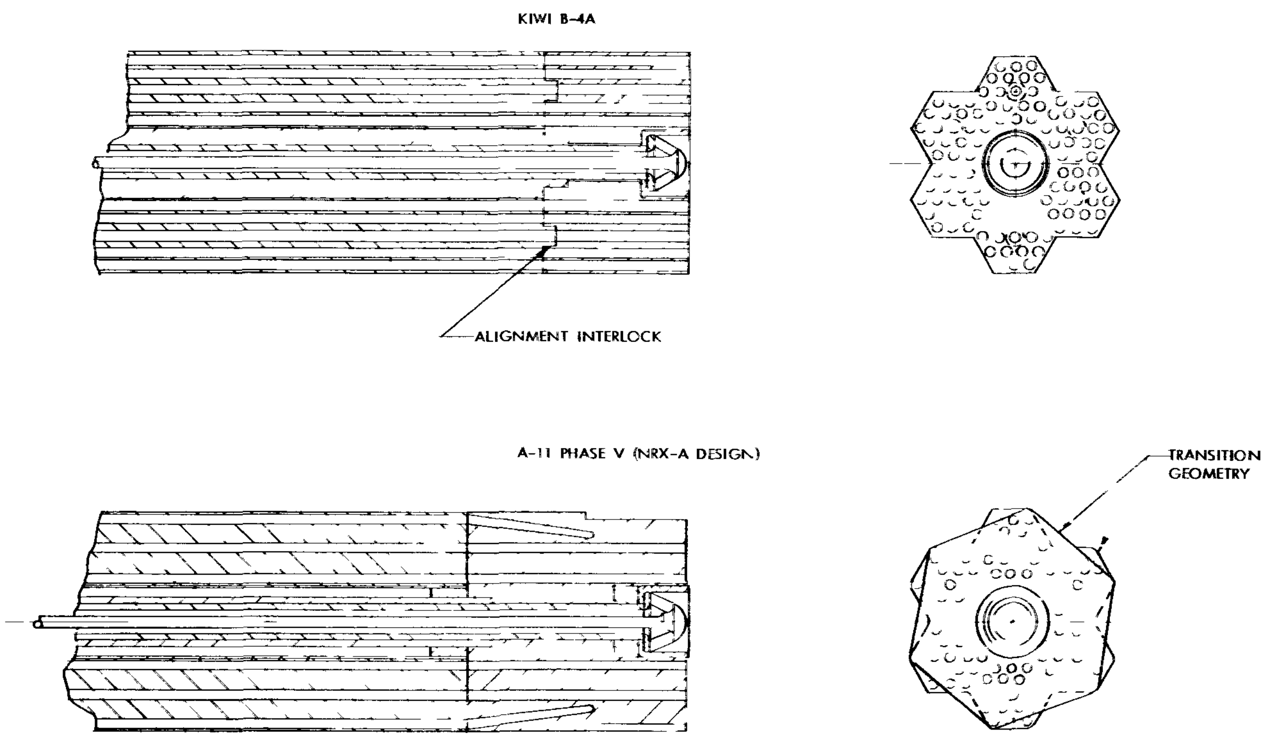

KIWI B-4A
ALIGNMENT INTERLOCK
A-11 PHASE V (NRX-A DESIGN)
TRANSITION GEOMETRY

FIGURE 3

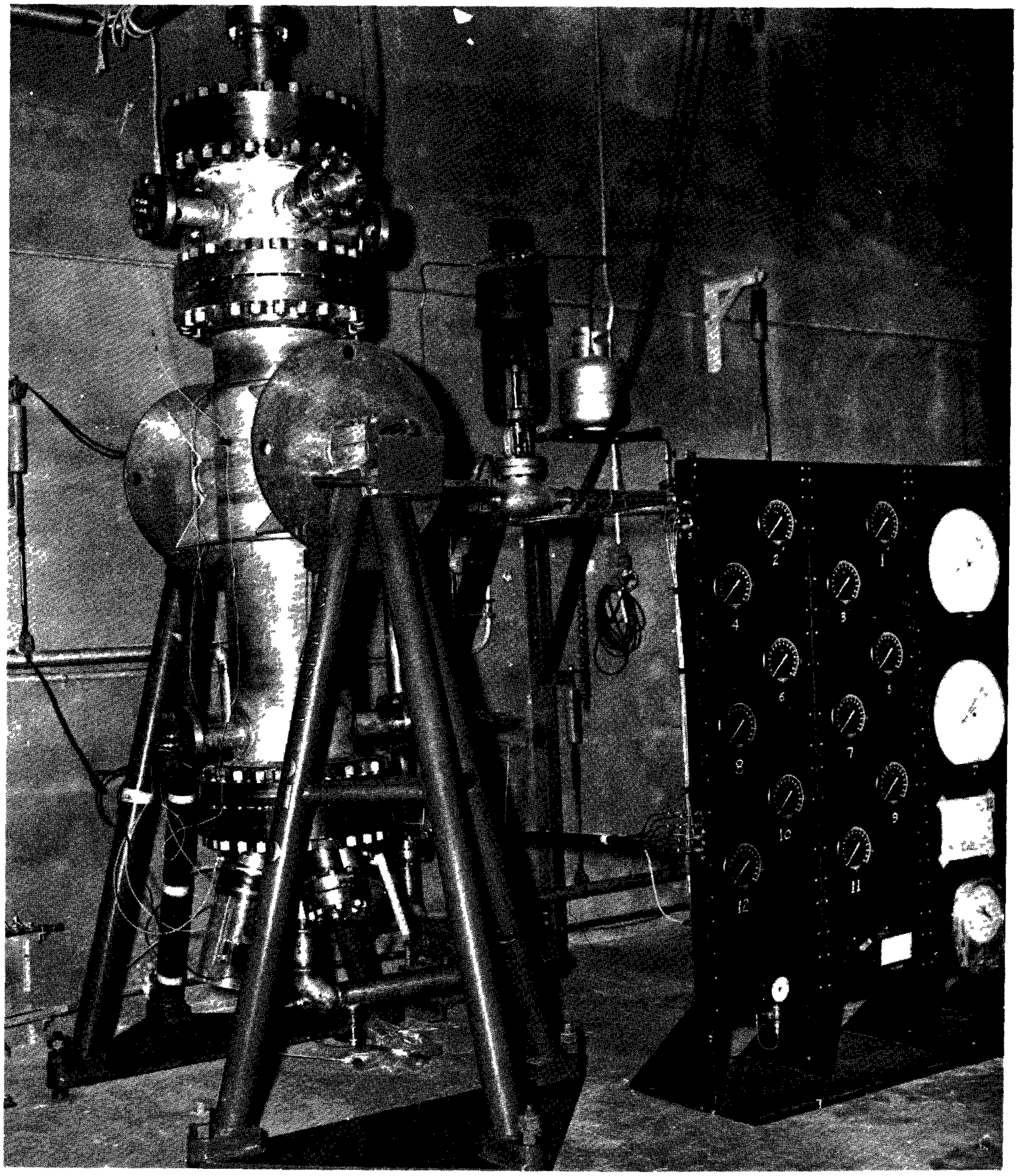


FIGURE 4 - A-11 FLOW INDUCED VIBRATION TEST RIG

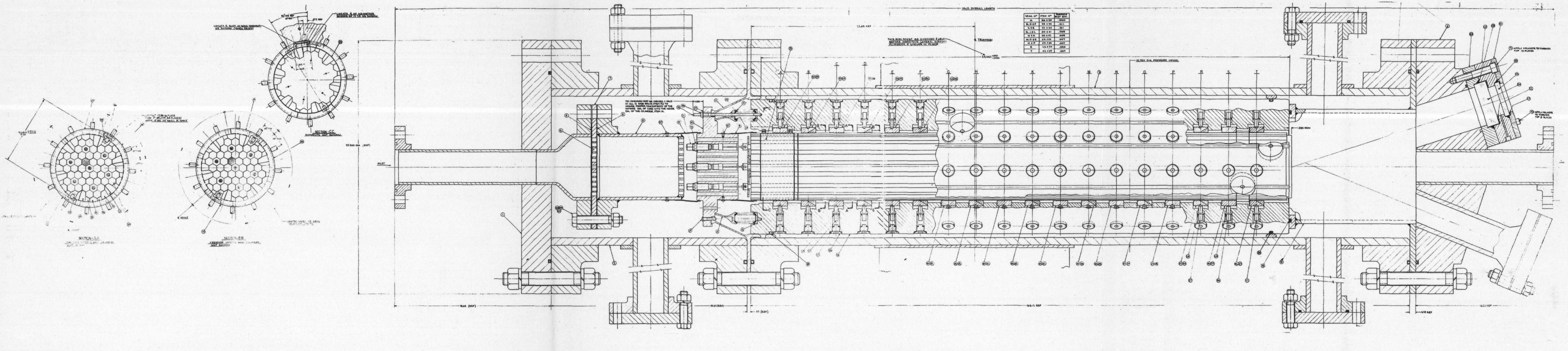


FIGURE 5 - A-11 FLOW AND VIBRATION TEST GENERAL ASSEMBLY

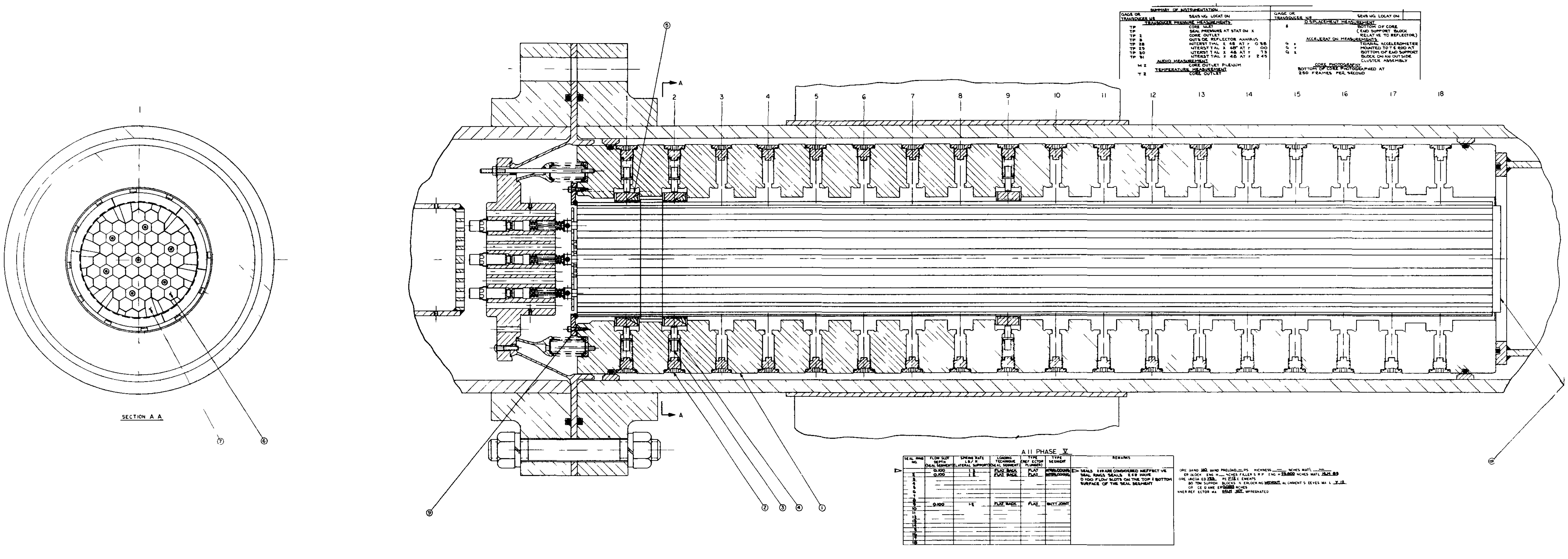
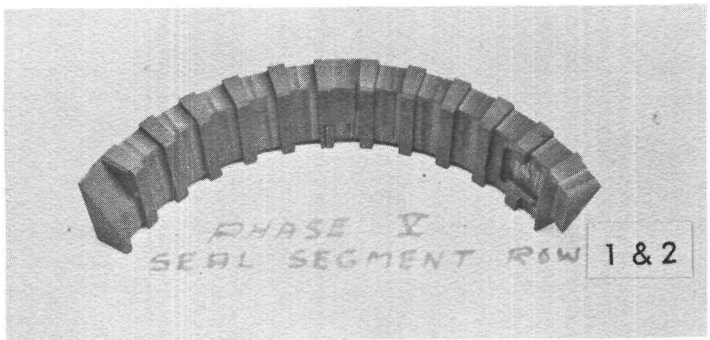
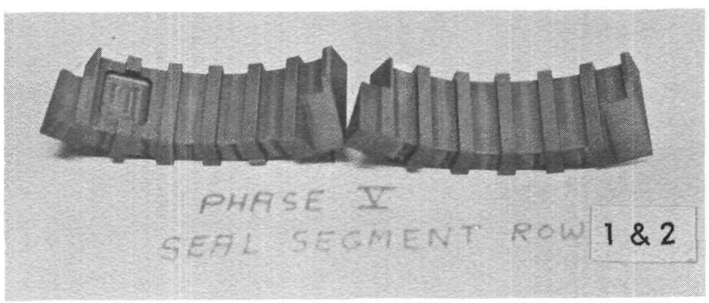


FIGURE 6 - A-11 PHASE V FLOW INDUCED VIBRATION TEST RIG





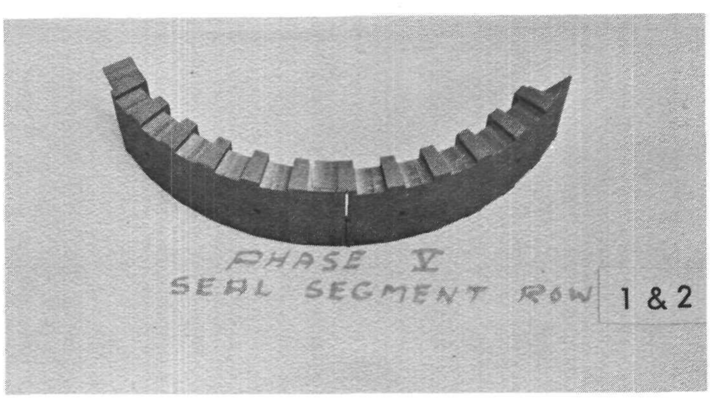


FIGURE 7 - A-11 PHASE V TYPICAL SEAL SEGMENTS
FROM SEAL RING NUMBER 1 AND 2

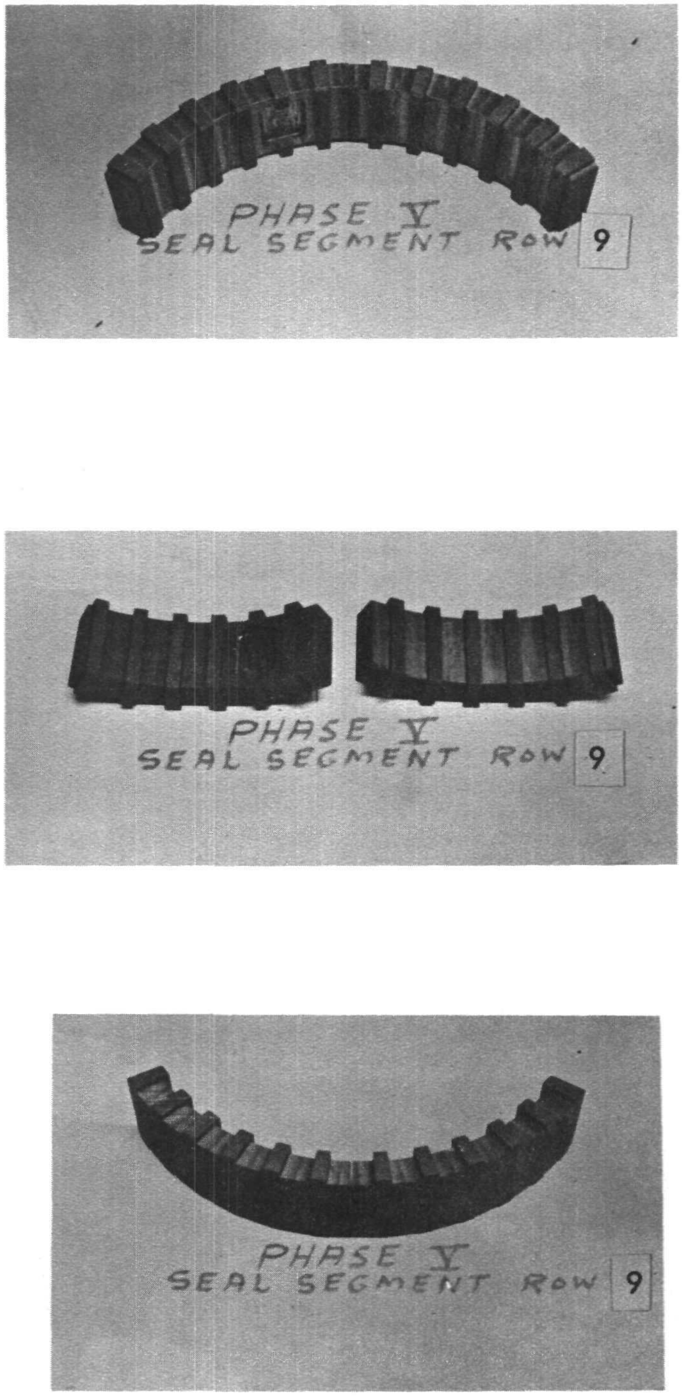


FIGURE 8 - A-11 PHASE V TYPICAL SEAL SEGMENTS FROM SEAL RING NUMBER 9

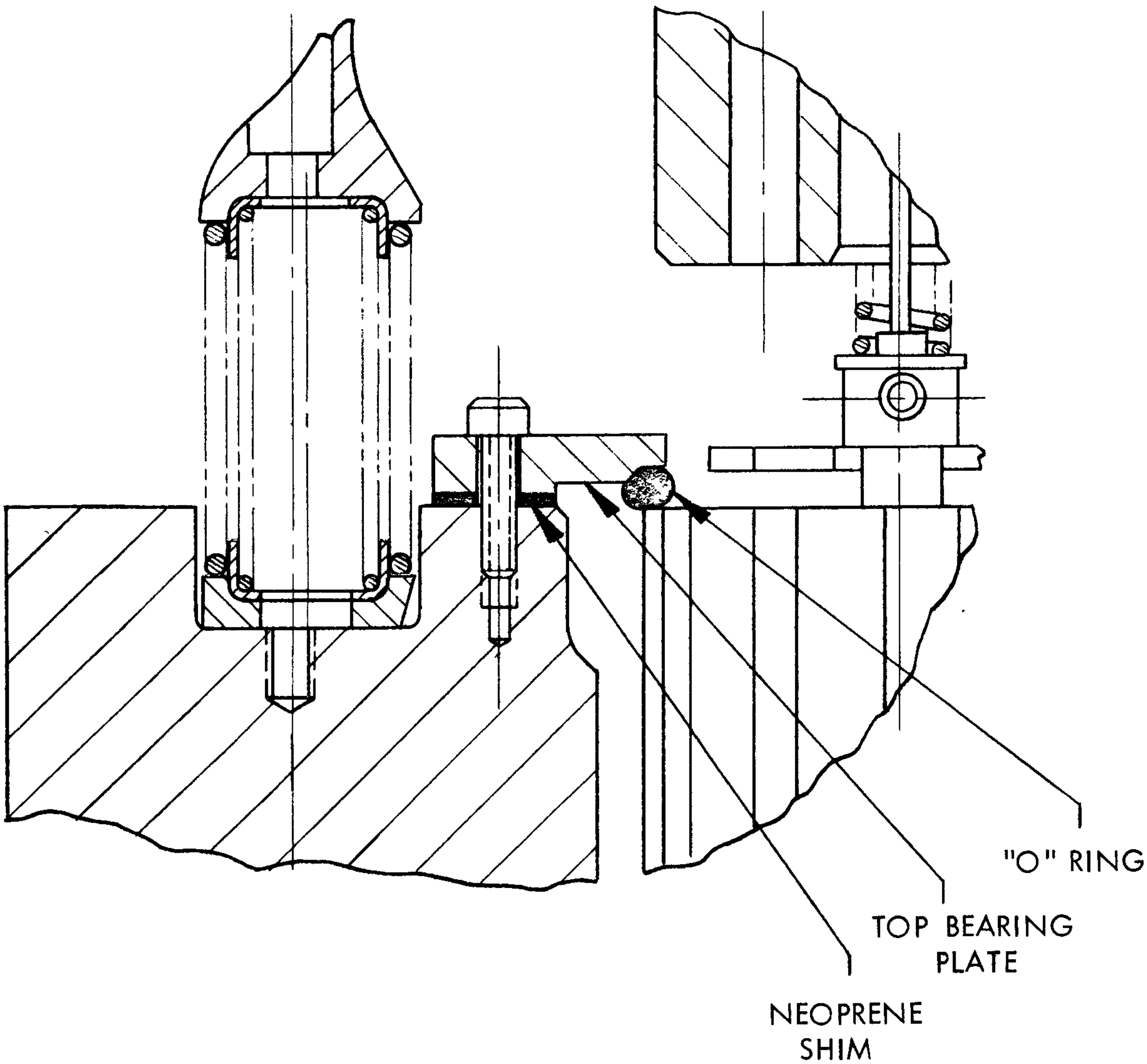


FIGURE 9 - A-11 PHASE V DOME END SEAL RING ASSEMBLY

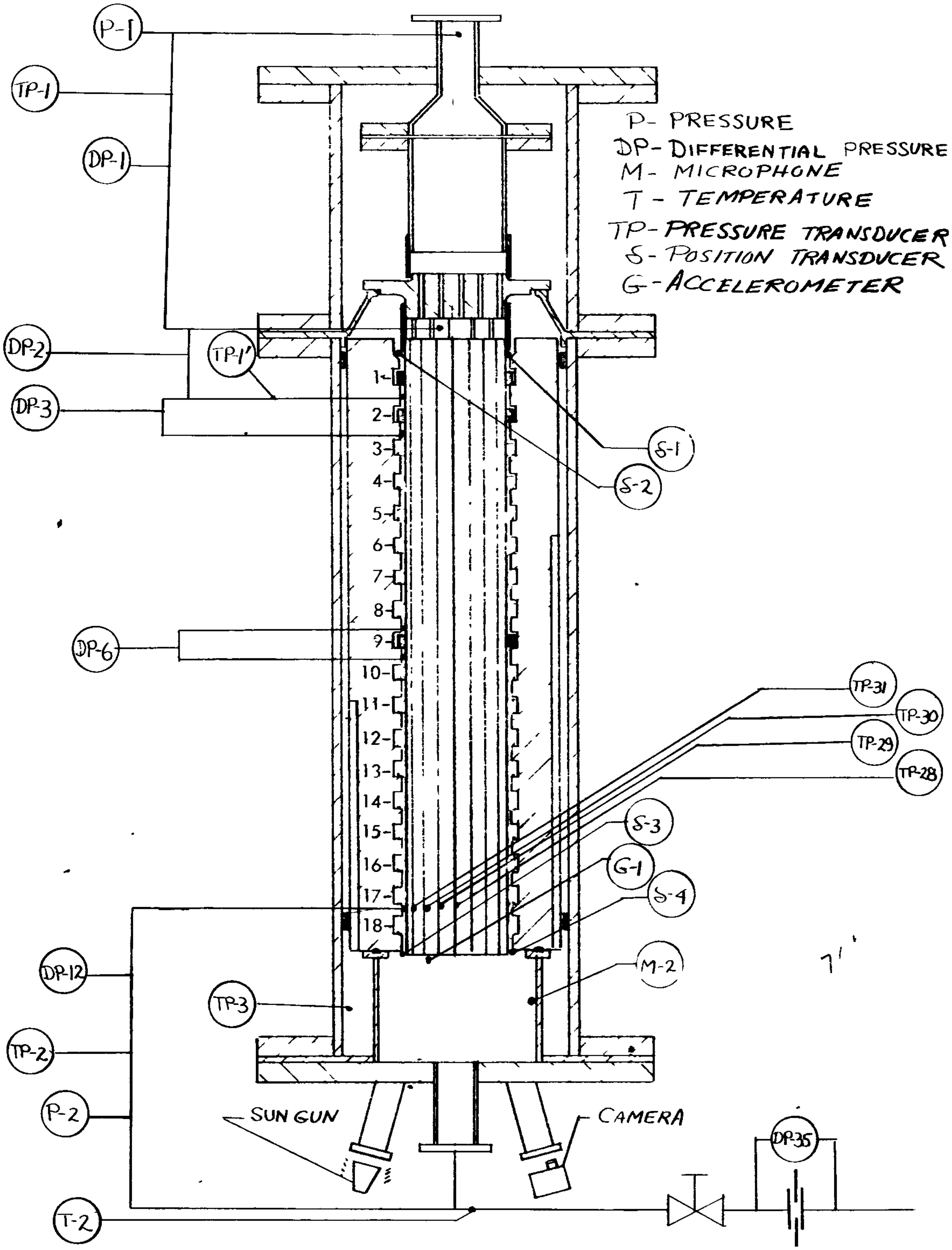


FIGURE 10 - TEST RIG SCHEMATIC

A-11-V-GH_2-1 and 2

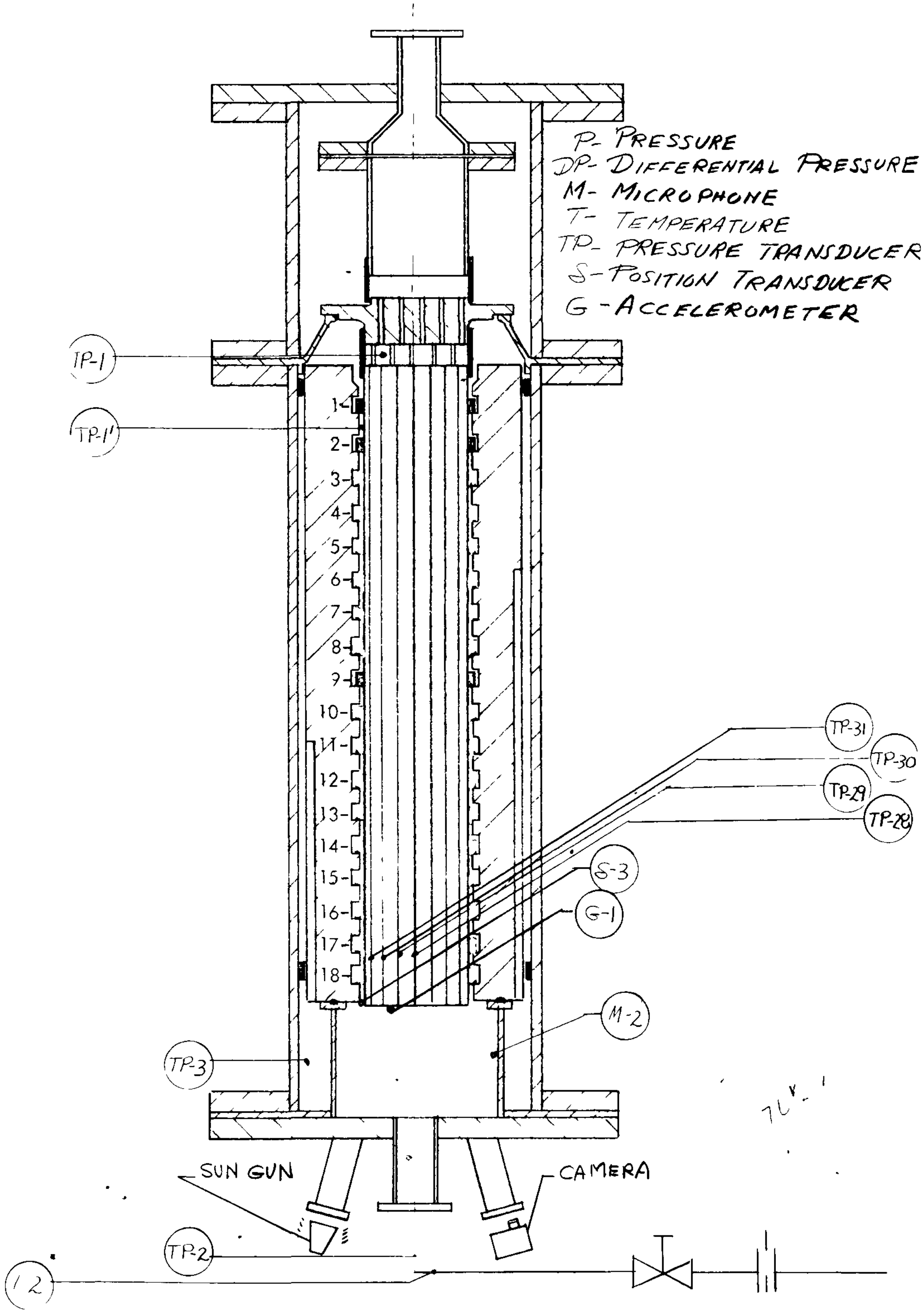


FIGURE 11 - TEST RIG SCHEMATIC
A-11-V-GH_2-3 THRU 6

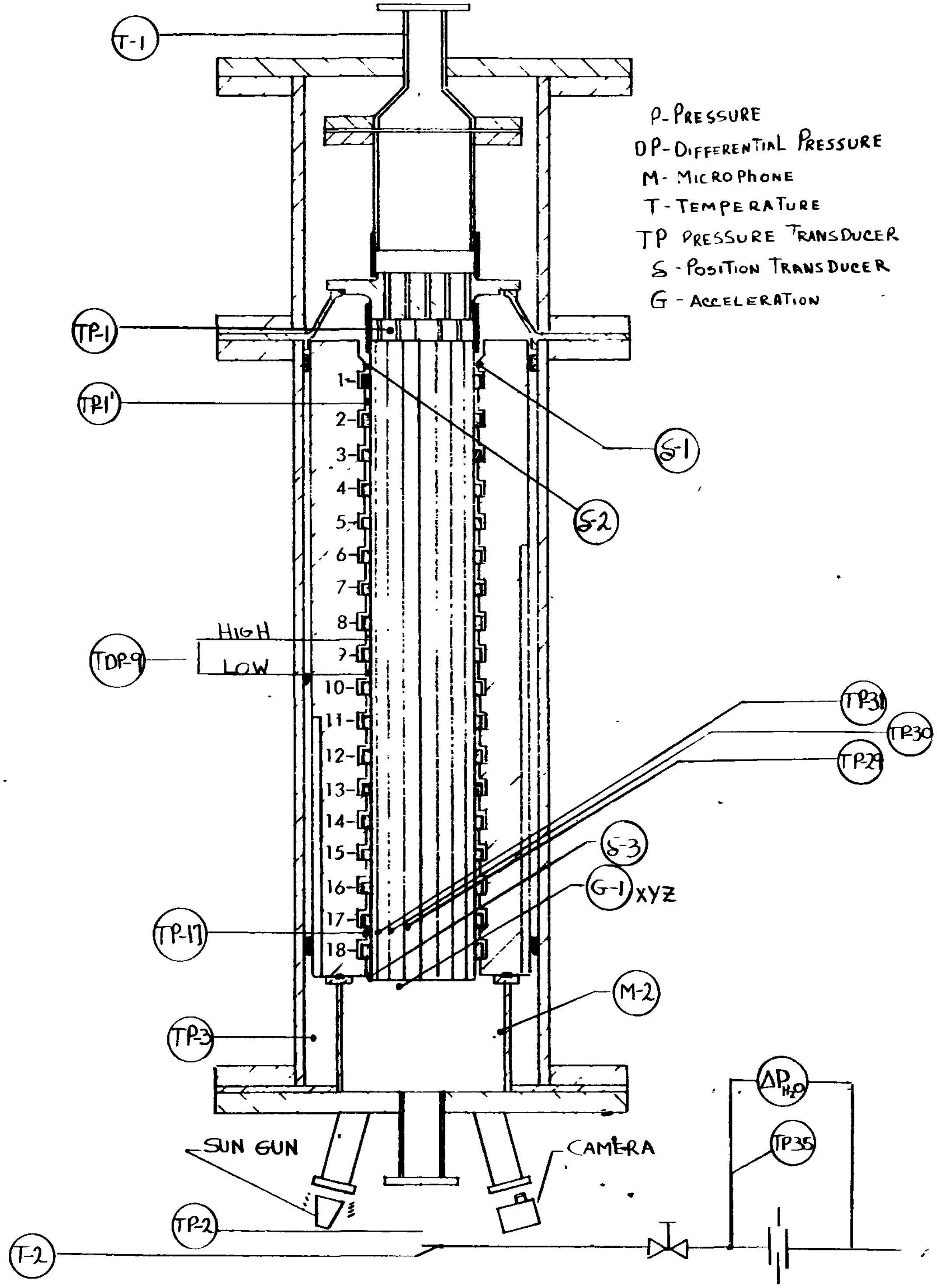
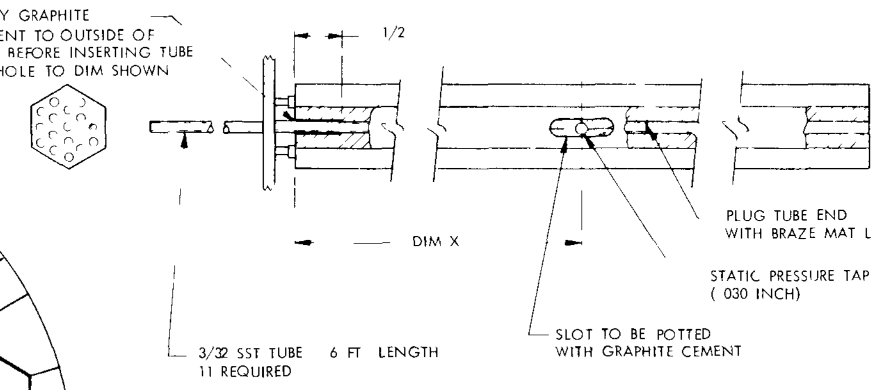


FIGURE 12 - TEST RIG SCHEMATIC
A-11-V-GH_2-7 THRU 12



ELEMENT NO	DIM X
21 THRU 24	10 IN
25 THRU 27	30 - IN
28 THRU 31	48 - IN

TUBES TO BE TAGGED ON ASSEMBLY FOR IDENTIFICATION

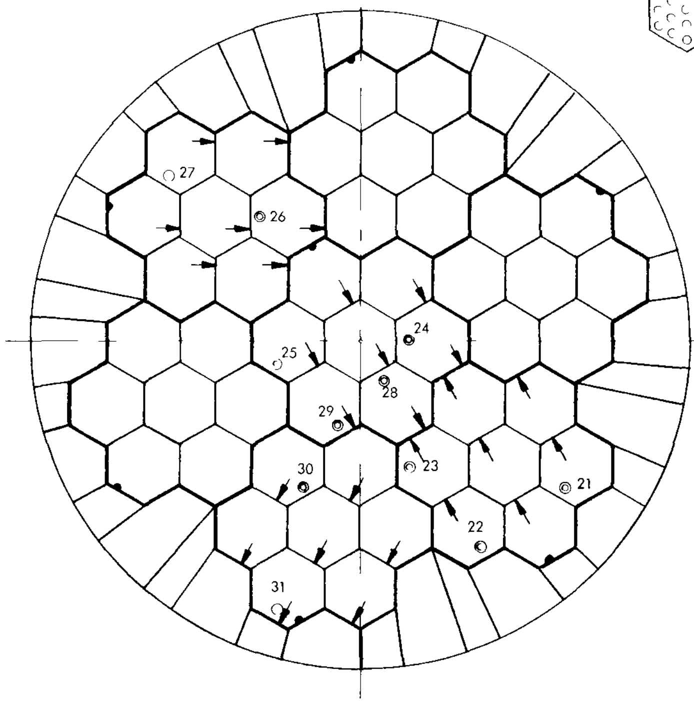


FIGURE 13 - A-11, PHASE V INTERSTITIAL STATIC PRESSURE TAP LOCATION

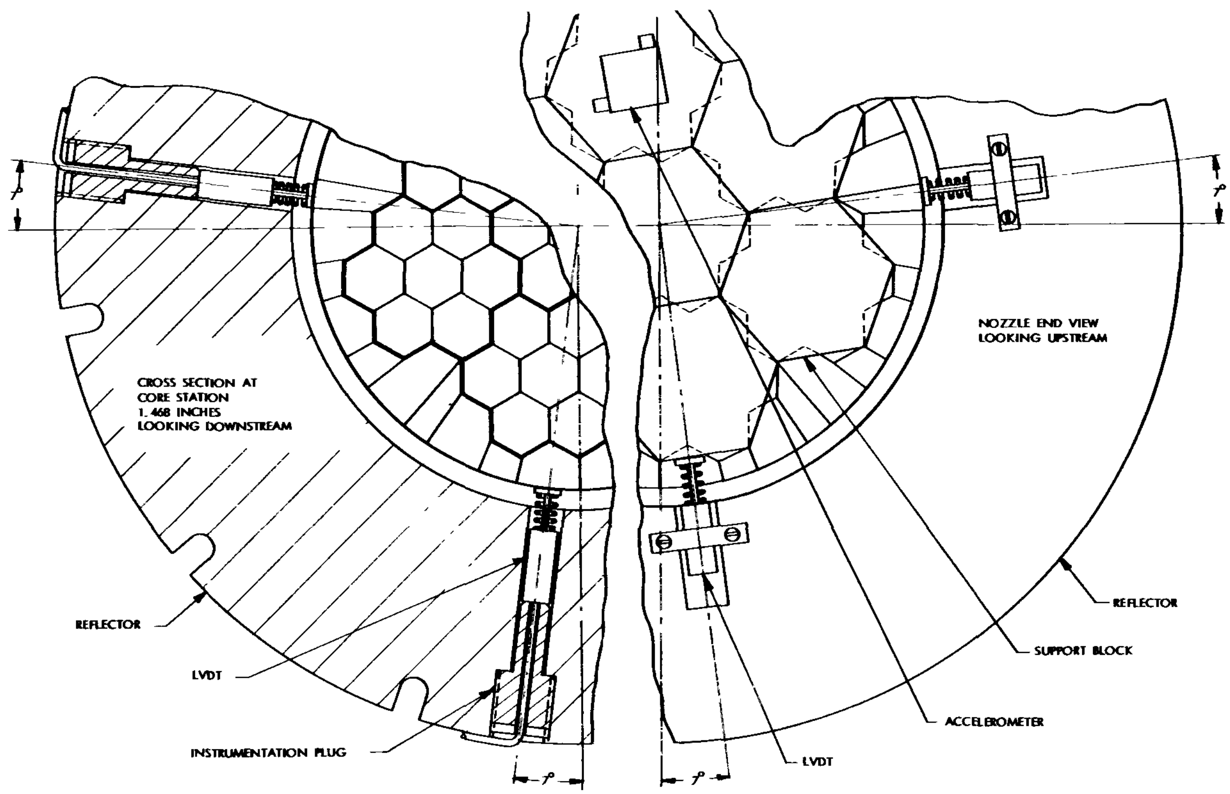


FIGURE 14 - A-11, PHASE V INSTRUMENTATION SCHEMATIC

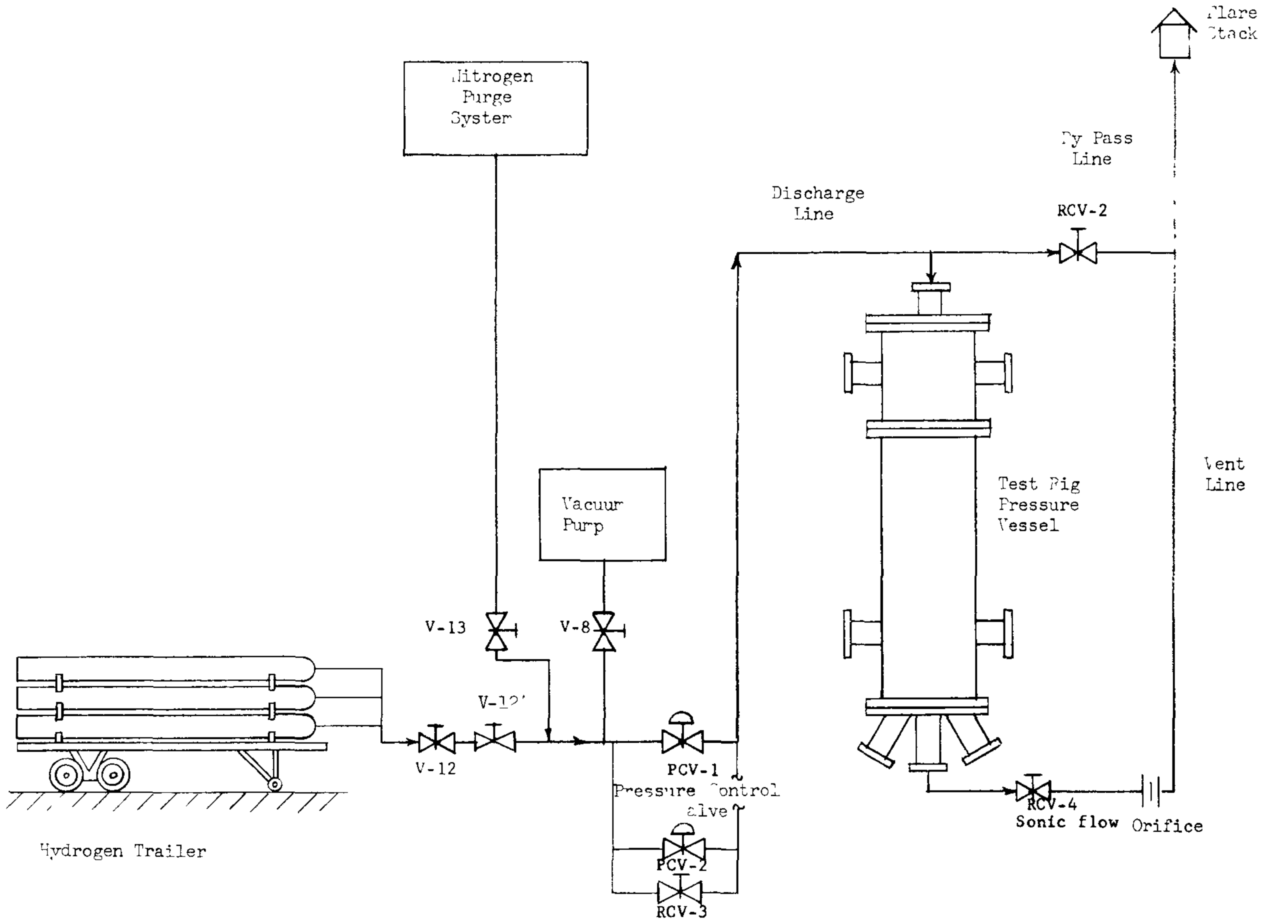


FIGURE 15 - FLOW INDUCED VIBRATION TEST SCHEMATIC

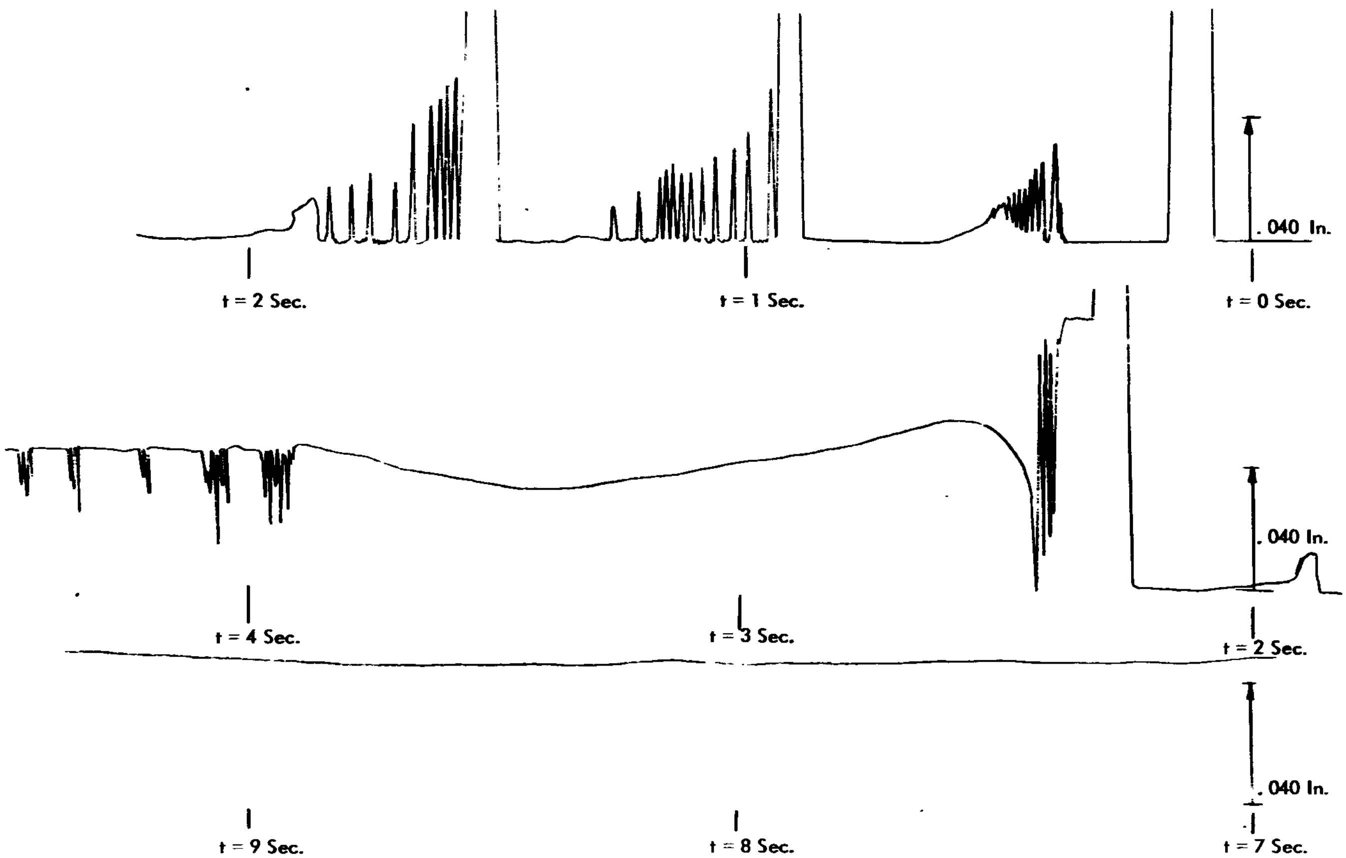


FIGURE 16 - A-11-V-GH_2-2 OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

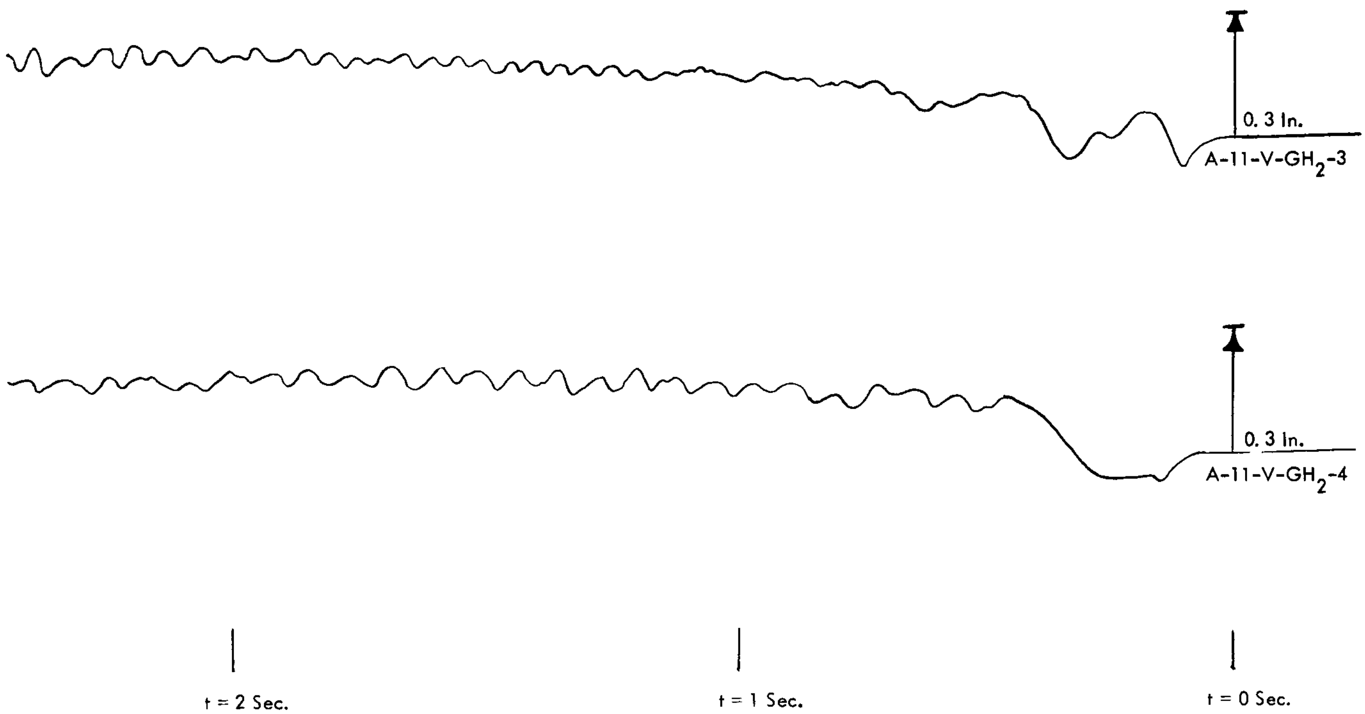


FIGURE 17 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ -3

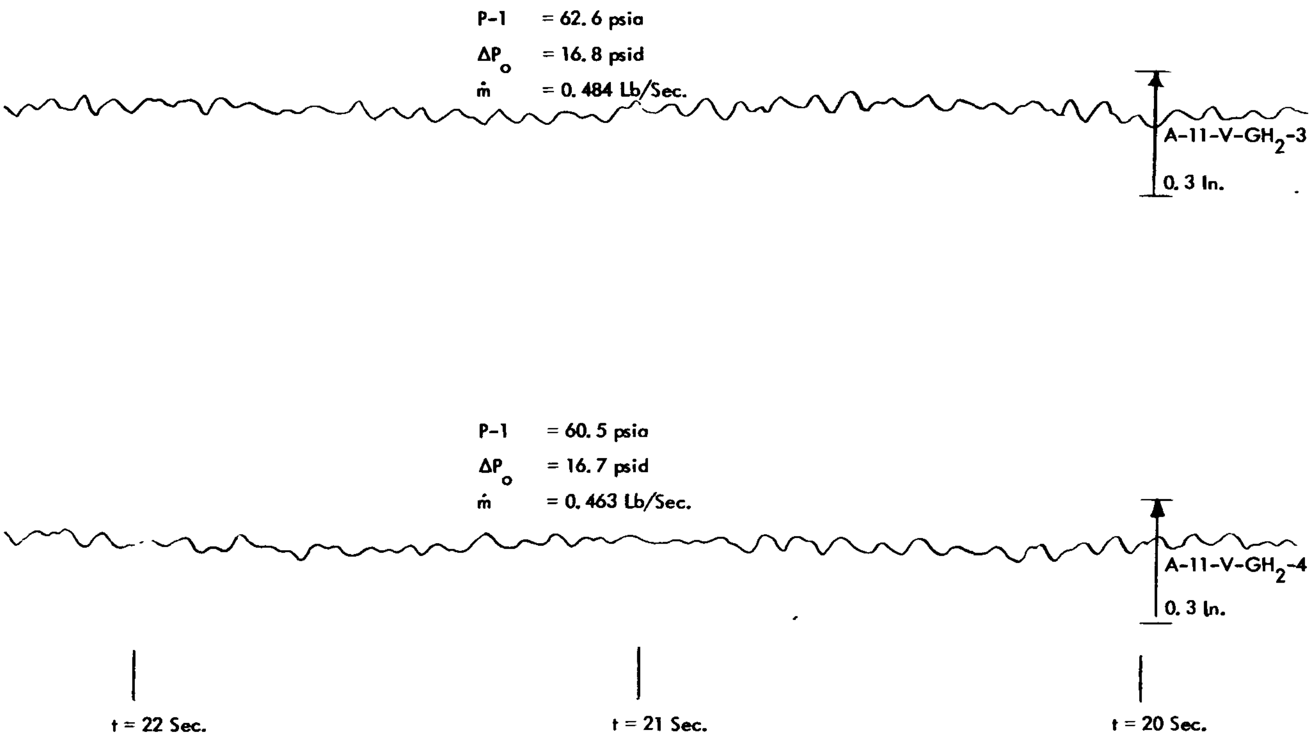


FIGURE 18 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

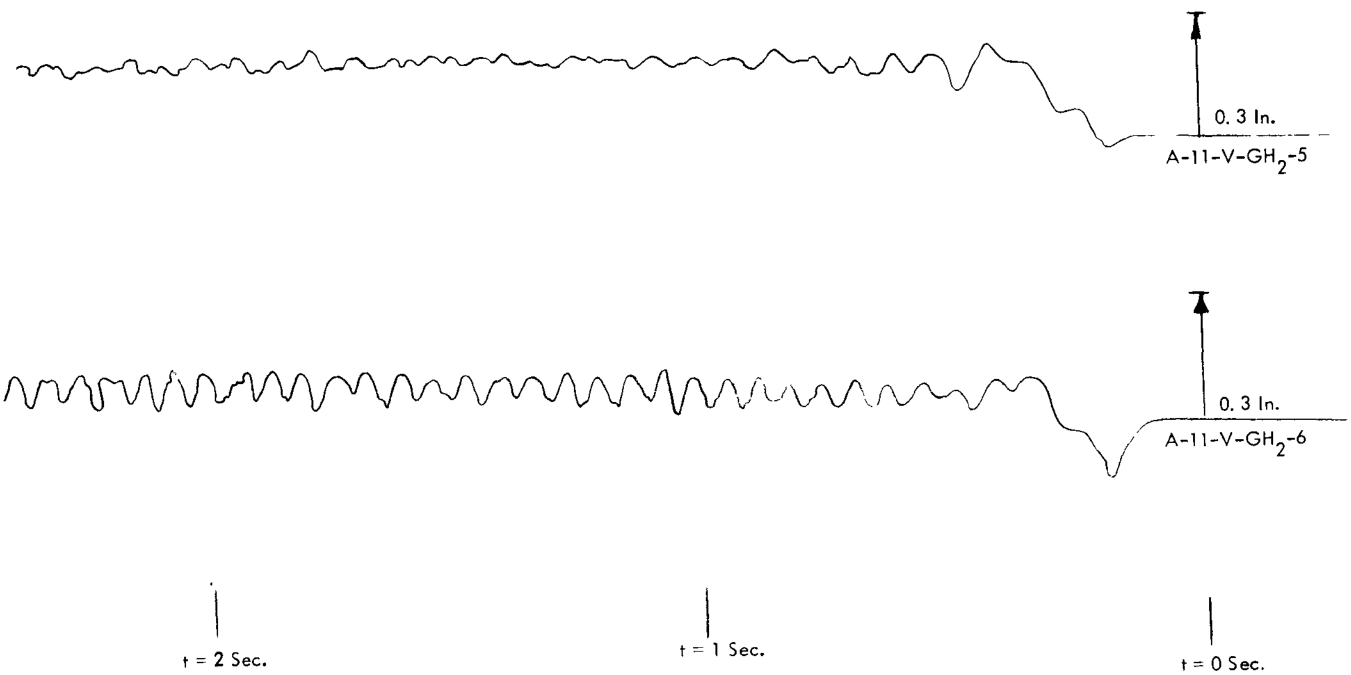


FIGURE 19 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

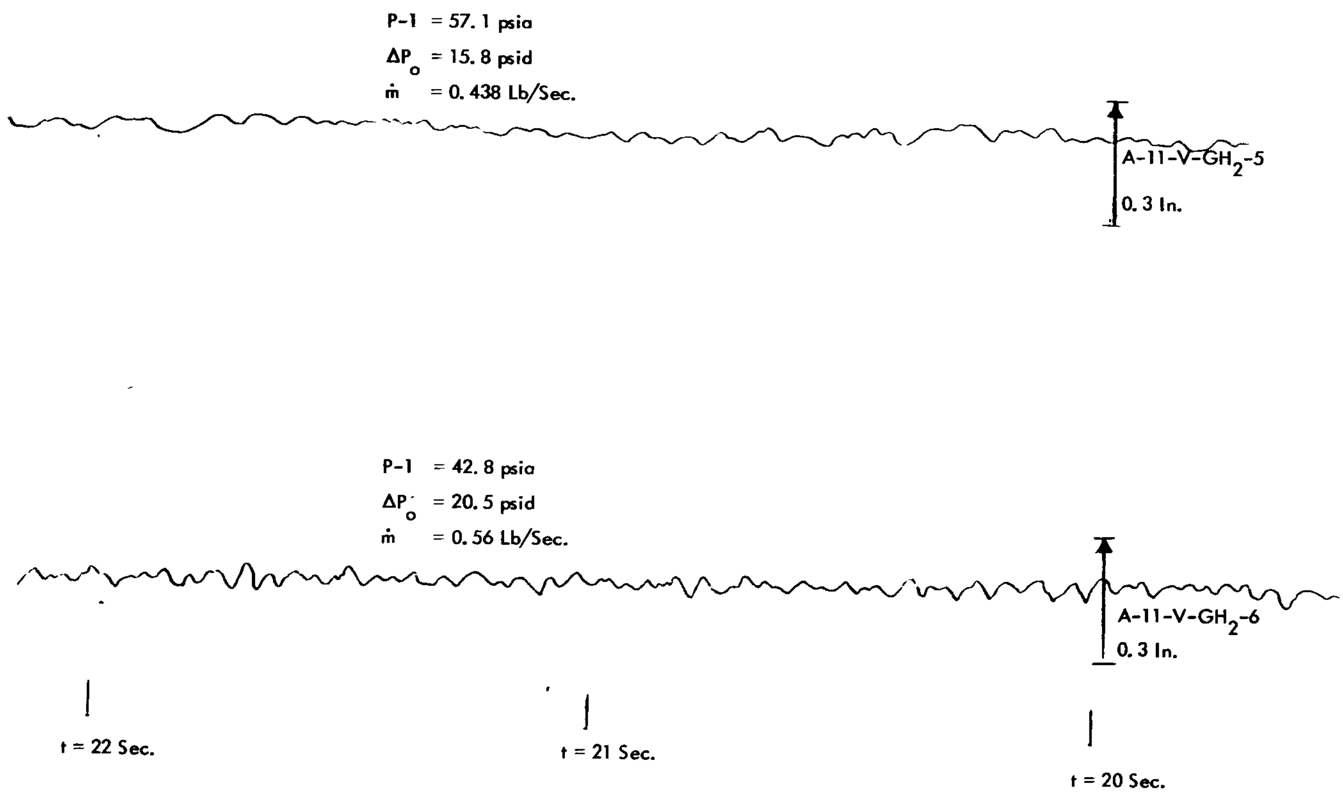


FIGURE 20 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ -3

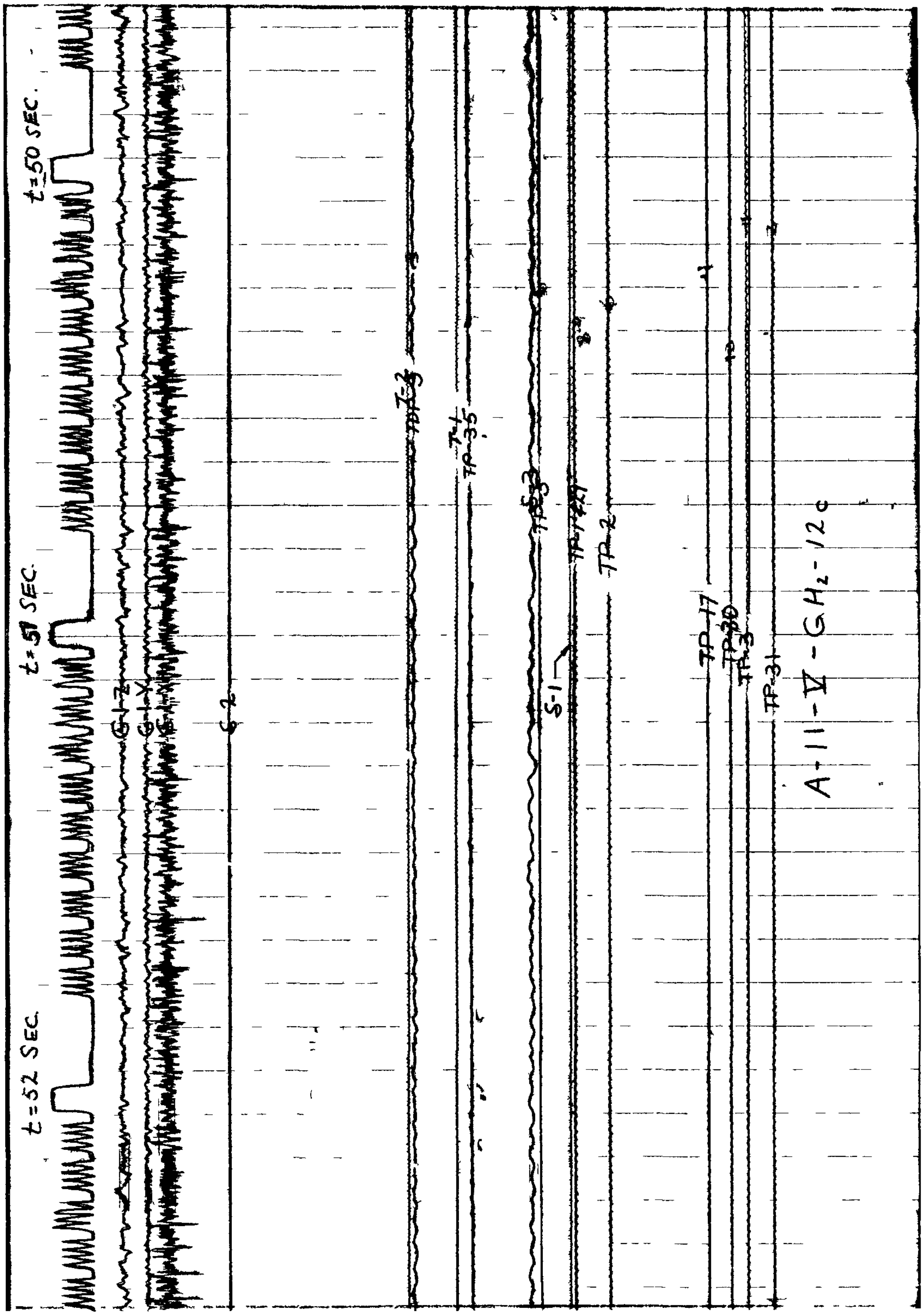


FIGURE 21 - TYPICAL OSCILLOGRAPH RECORD

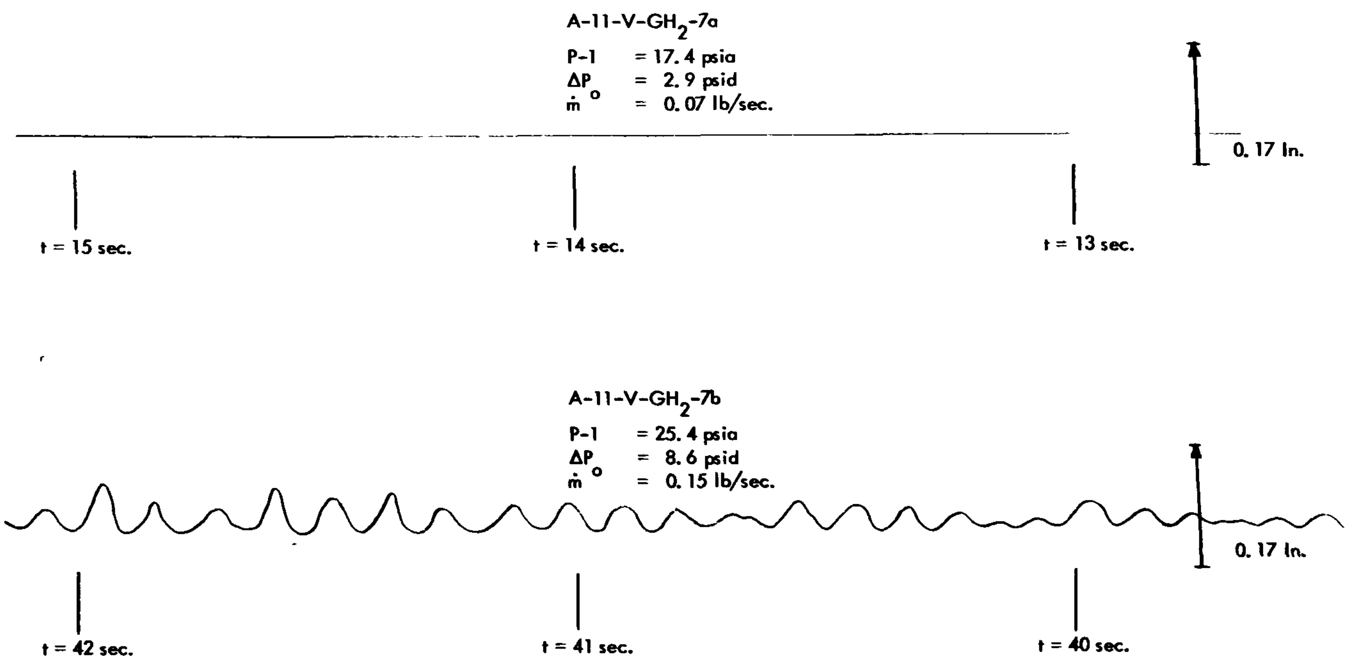
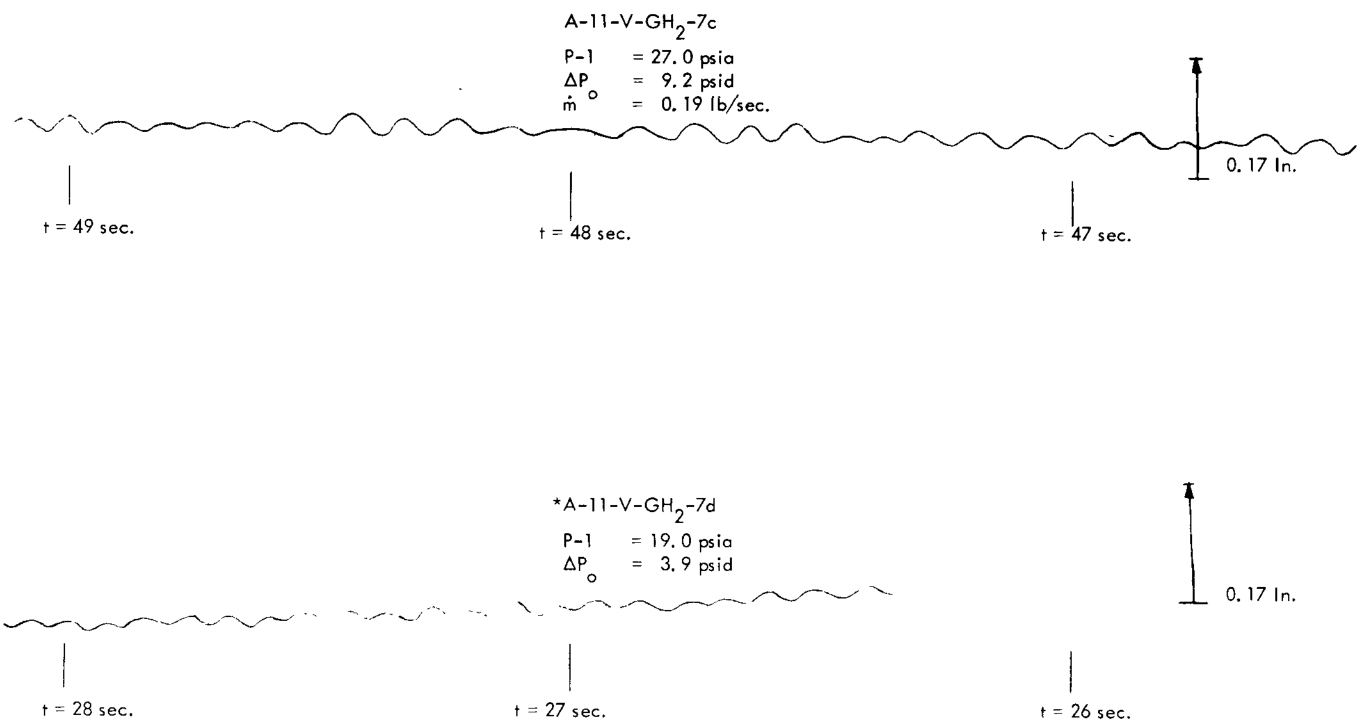


FIGURE 22 - A-11, PHASE V OSCILLOGRAPH RECORD
OF POSITION TRANSDUCER, δ-3



* Transient

FIGURE 23 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

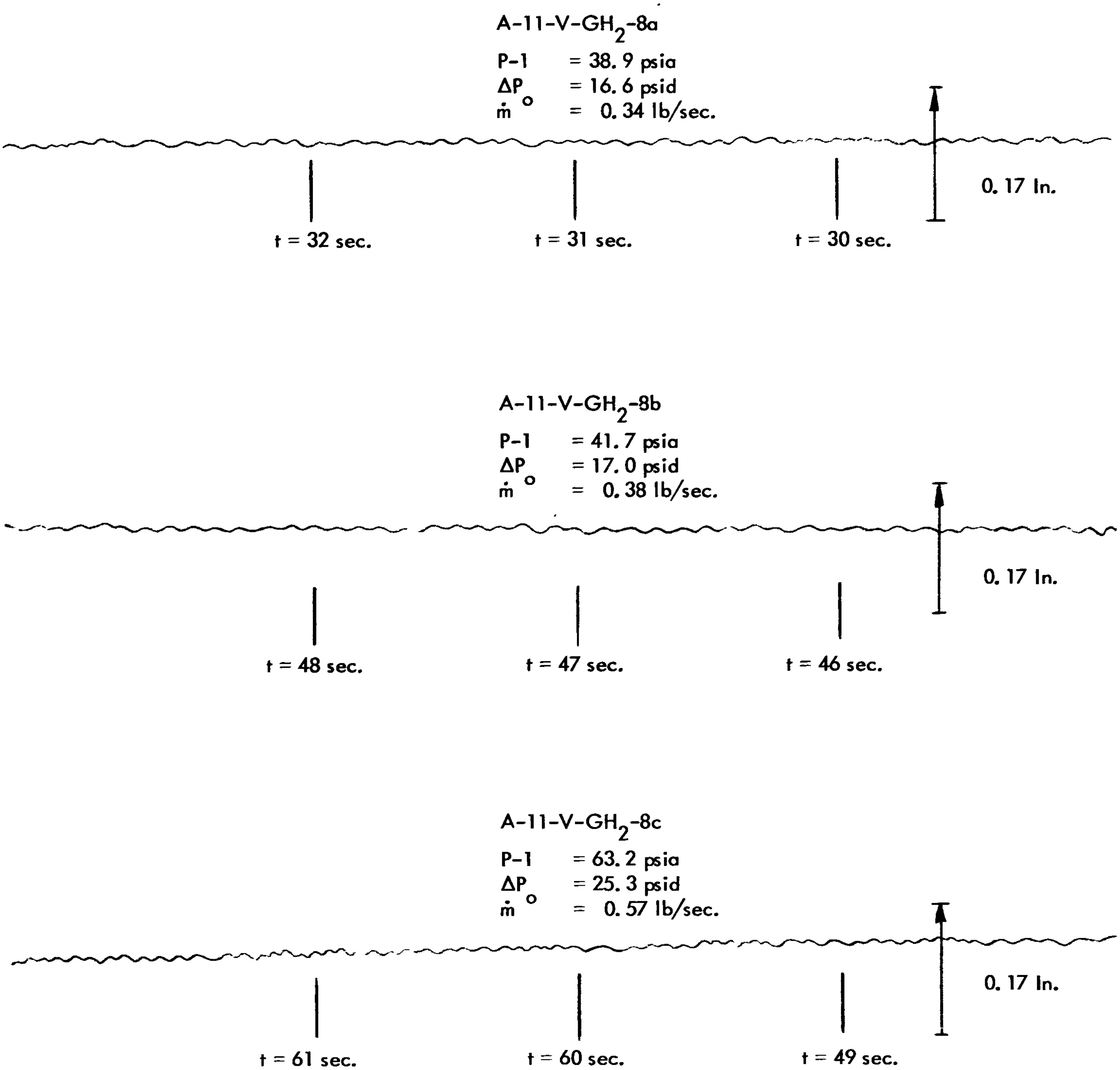


FIGURE 24 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ -3

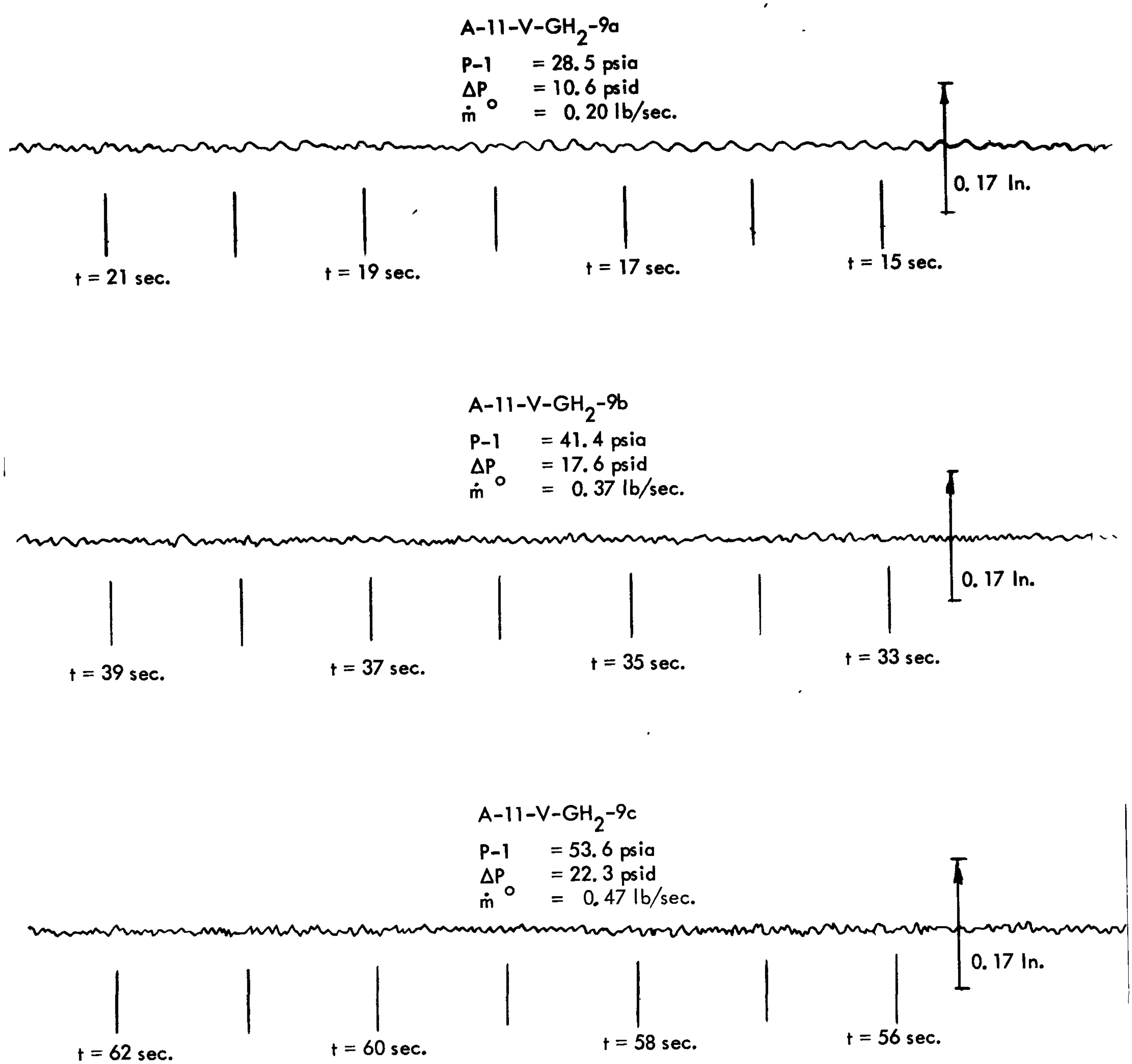
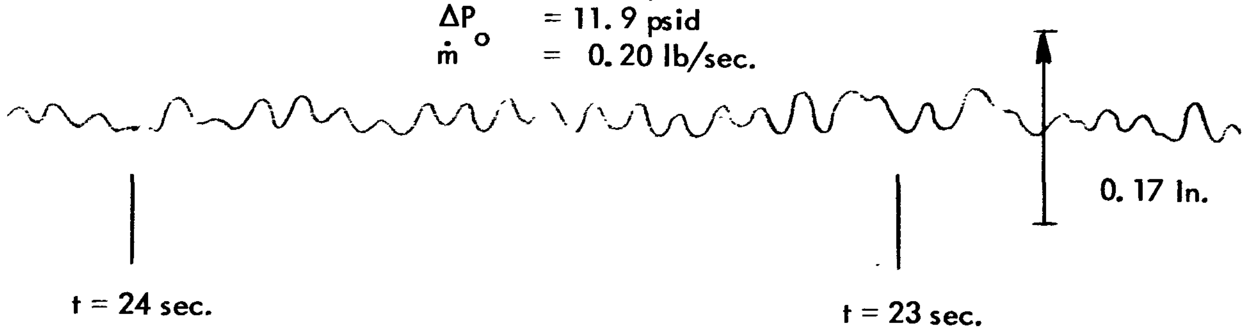


FIGURE 25 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, $\mathcal{J}$ -3

A-11-V-GH_2-10a

P-1 = 29.8 psia
ΔP_o = 11.9 psid
$\dot{m}$ = 0.20 lb/sec.



A-11-V-GH_2-10b

P-1 = 78.7 psia
ΔP_o = 32.3 psid
$\dot{m}$ = 0.70 lb/sec.

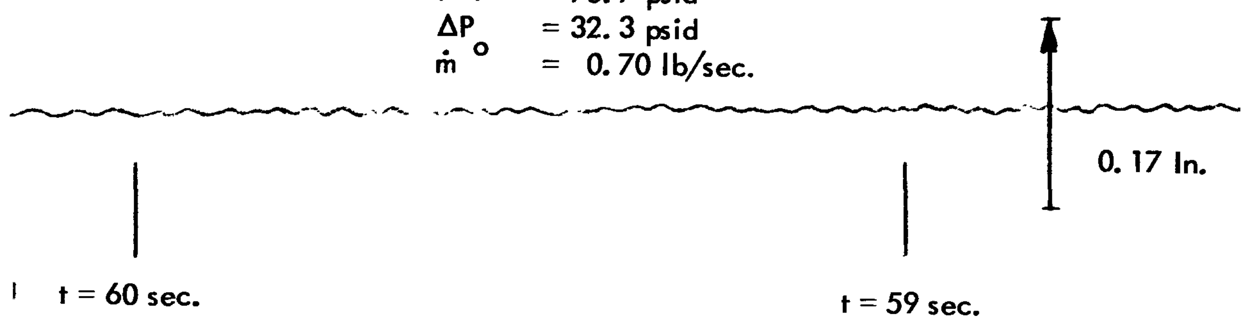


FIGURE 26 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

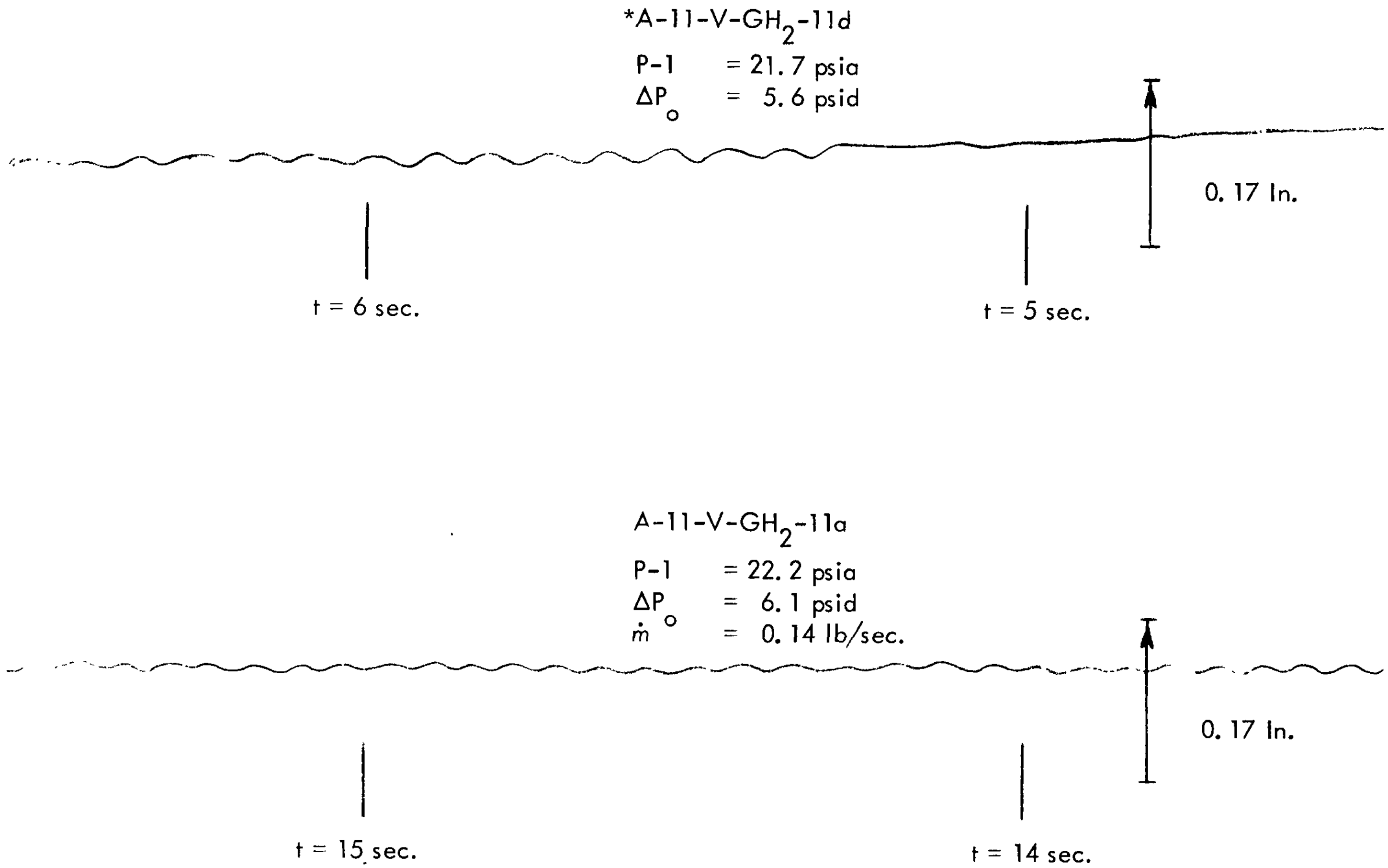


FIGURE 27 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

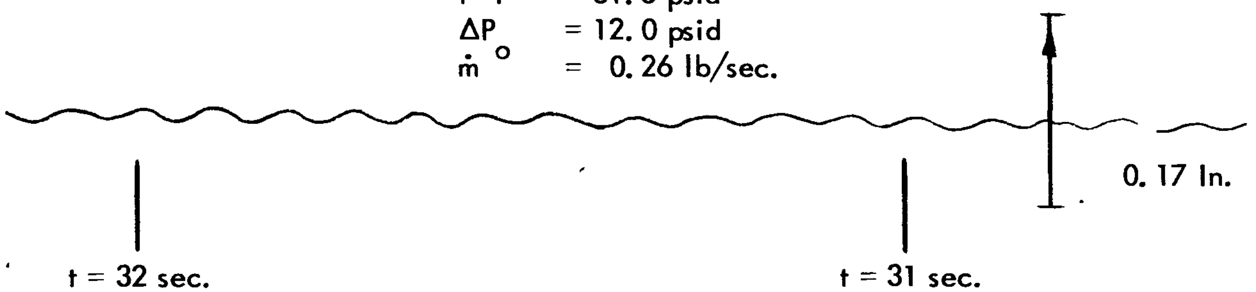
* Transient

A-11-V-GH_2-11b

P-1 = 31.6 psia

ΔP_o = 12.0 psid

$\dot{m}$ = 0.26 lb/sec.



A-11-V-GH_2-11c

P-1 = 32.5 psia

ΔP_o = 12.3 psid

$\dot{m}$ = 0.29 lb/sec.

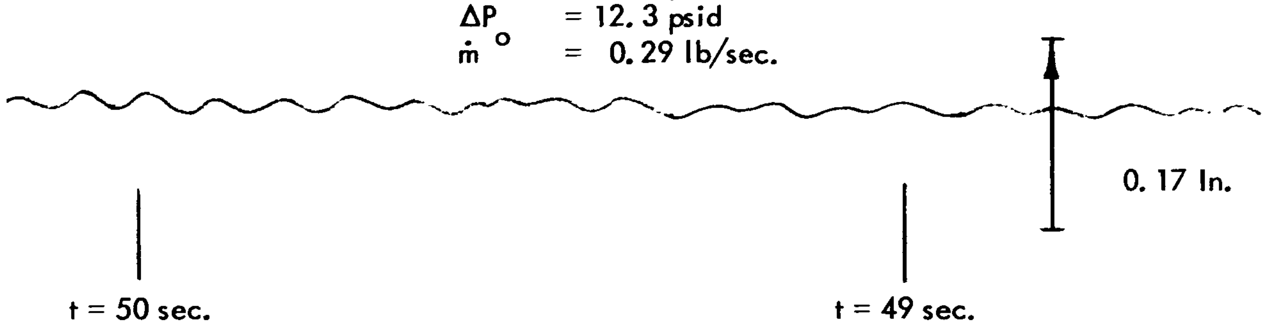


FIGURE 28 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, $\mathcal{S}$-3

[redacted]

[redacted]

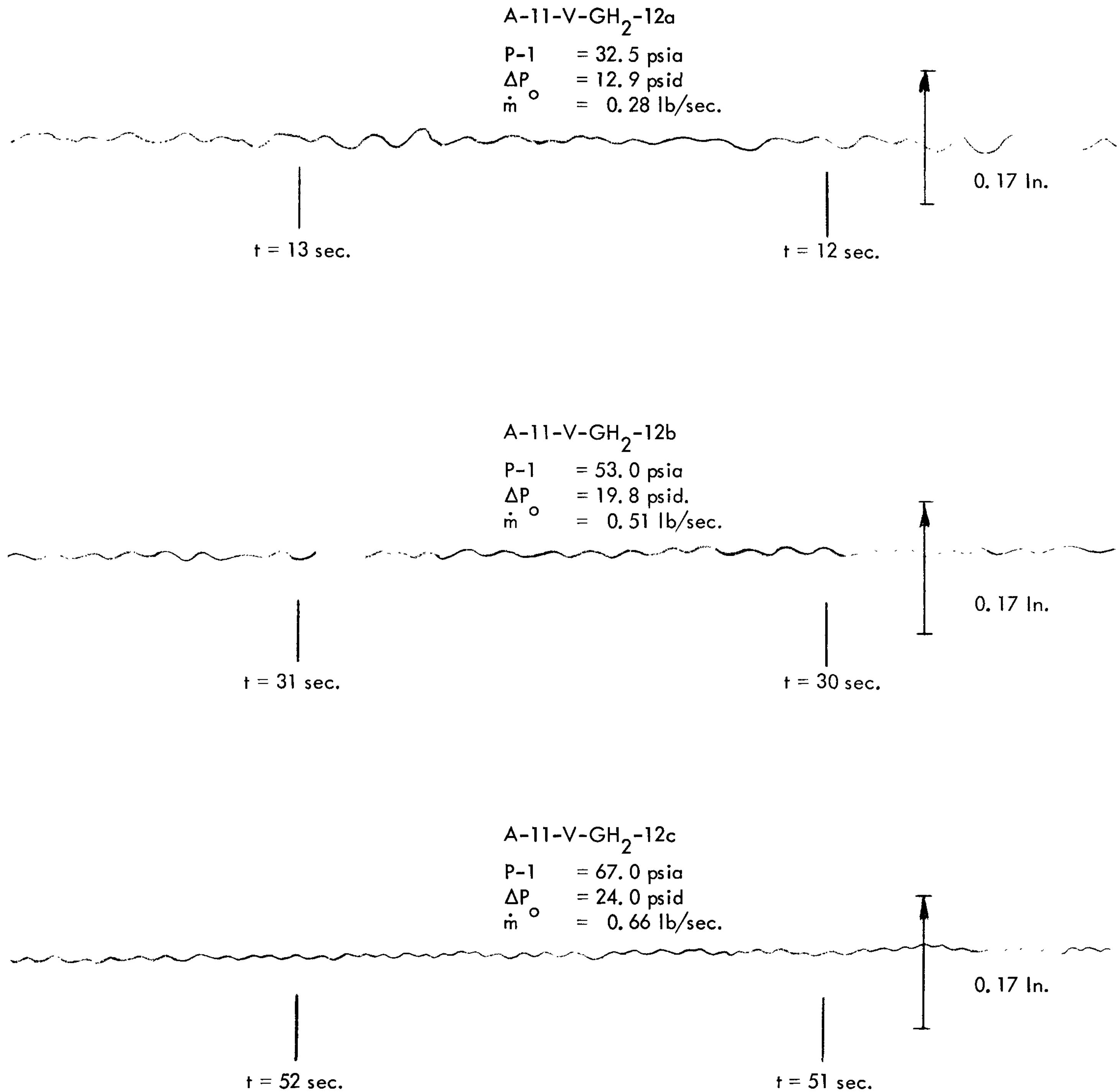


FIGURE 29 - A-11, PHASE V OSCILLOGRAPH RECORD OF POSITION TRANSDUCER, δ-3

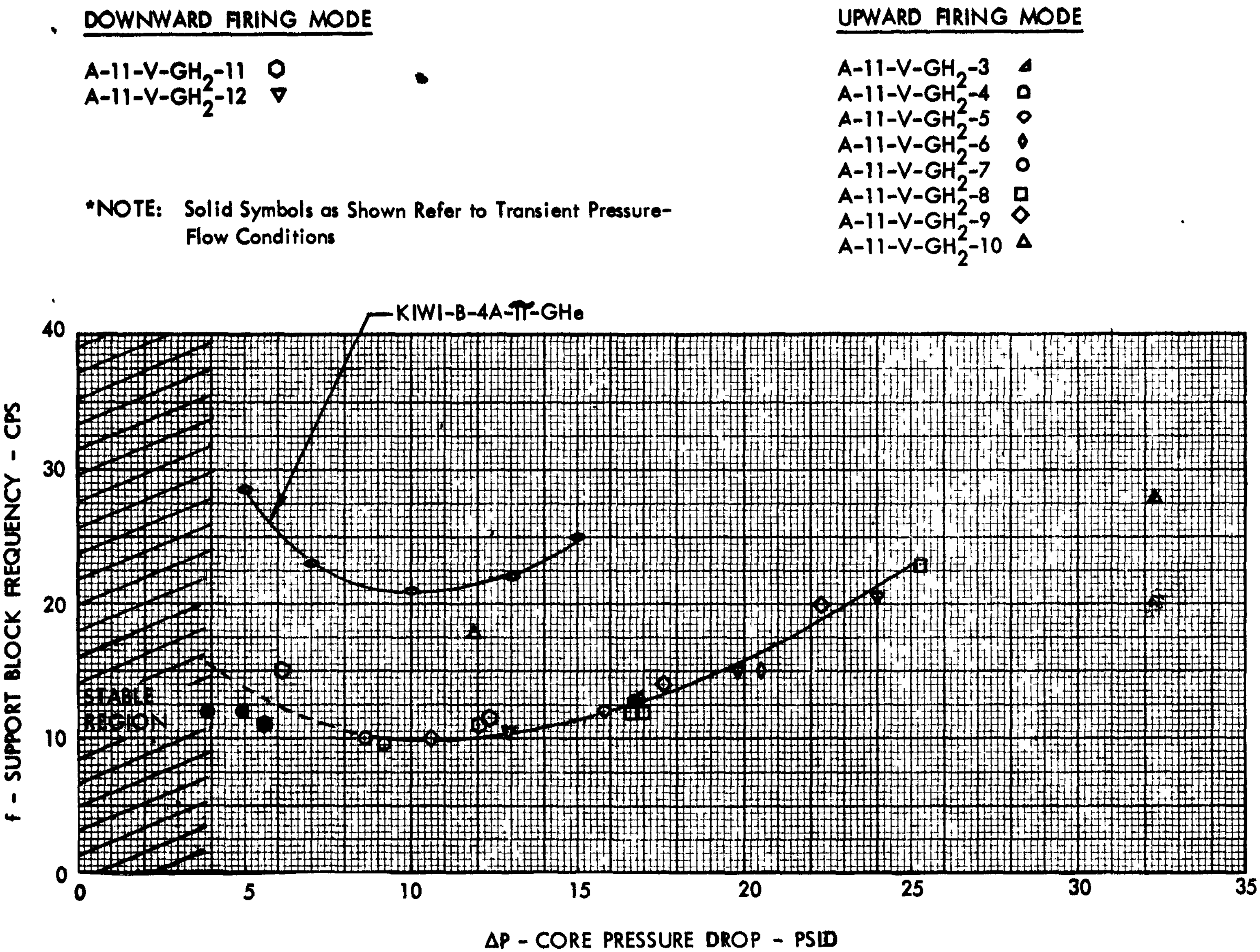


FIGURE 30 - A-11, PHASE V CLUSTER FREQUENCY

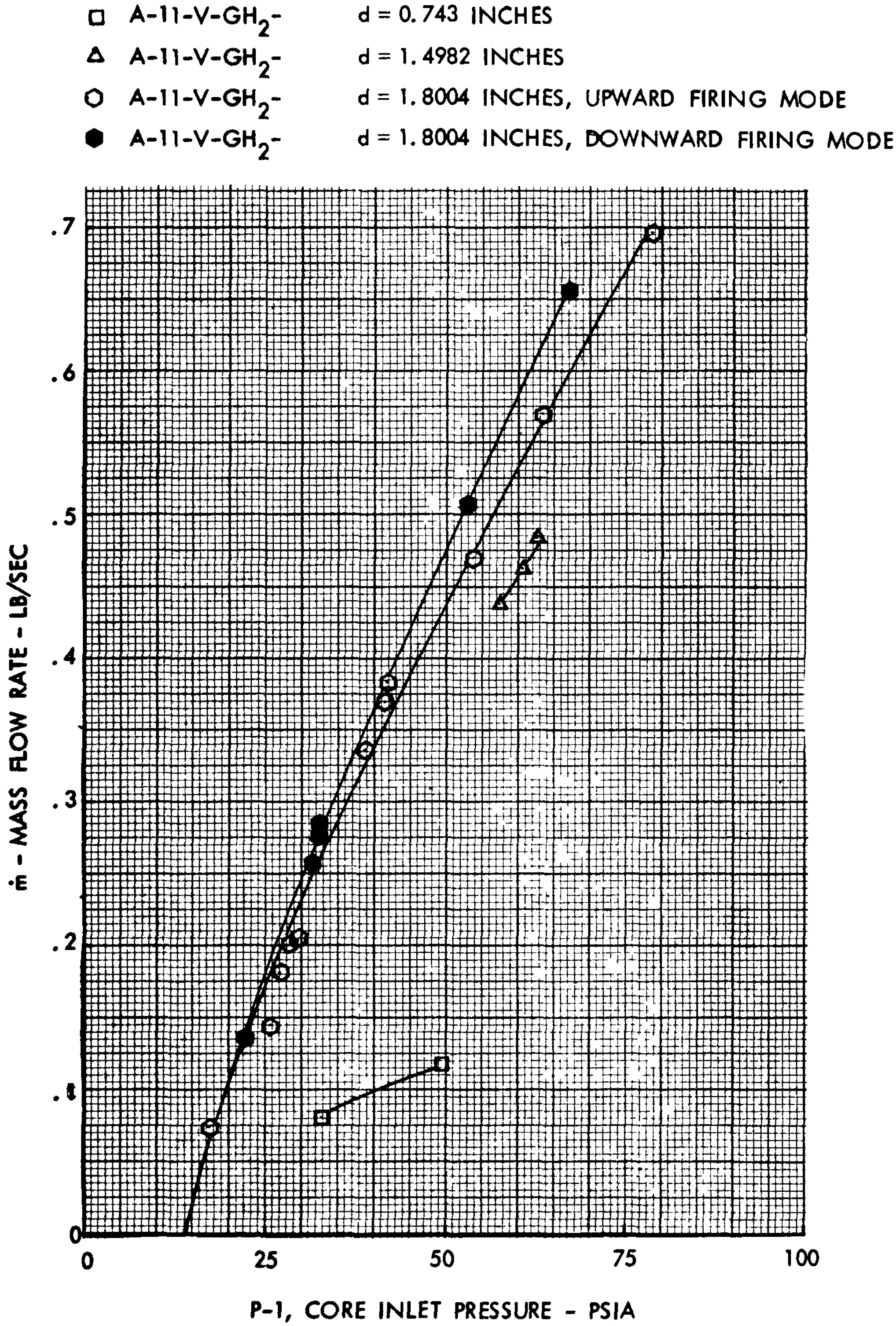


FIGURE 31 - A-11, PHASE V EXPERIMENTAL FLOW-PRESSURE DATA

[redacted]

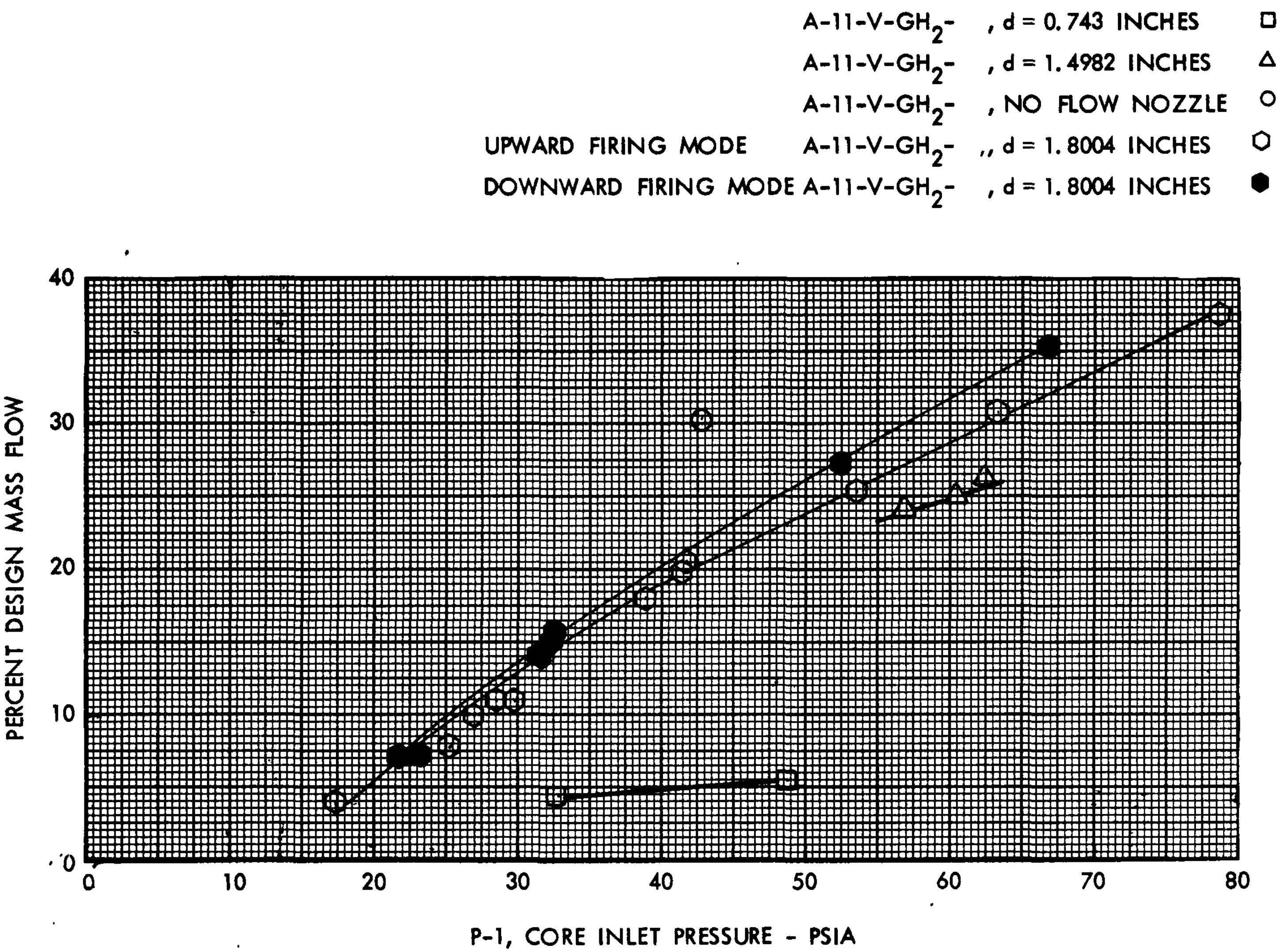


FIGURE 32 - EXPERIMENTAL FLOW-PRESSURE DATA

[redacted]

[redacted]

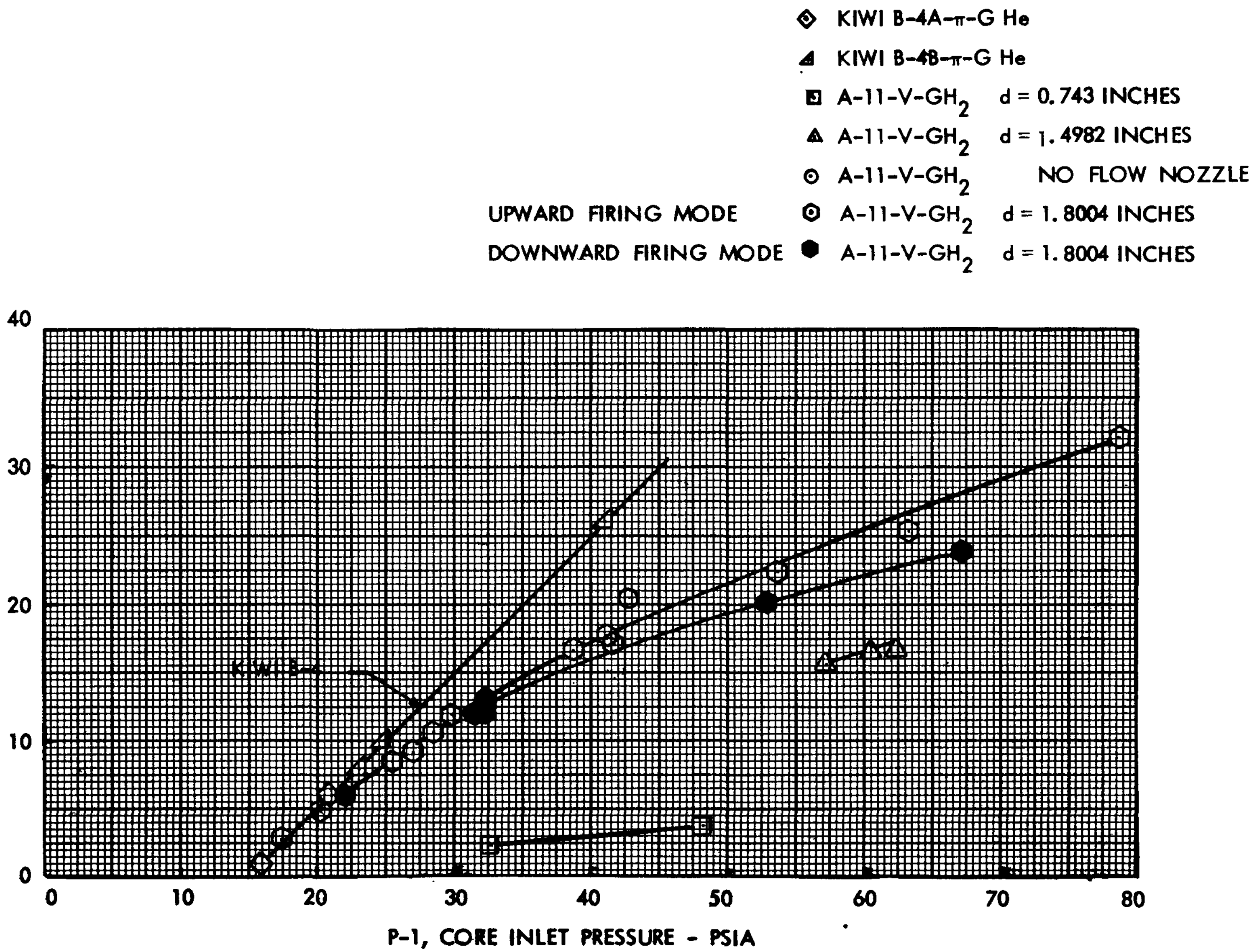


FIGURE 33 - A-11, PHASE V CORE PRESSURE DROP

[redacted]