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VISUAL STUDY OF LOW GRAVITY
CRYOGENIC FLOW BOILING

A Thesis
Presented for the
Master of Science
Degree
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Jared Smith
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ABSTRACT

Flow visualization was used to view the boiling and other flow patterns of saturated liquid nitrogen upflow in a quartz tube test section. The experimental apparatus was subjected to low gravity conditions in aircraft parabolic flight experiments, and to normal gravity conditions during ground based tests. Data films from several days of tests were studied in detail. The various flow patterns seen during the ground tests were similar to those established by previous researchers. Differences between normal and low gravity boiling and other flow patterns were observed. Low gravity flow regimes for initial transition flows of dispersed droplets, wispy-annular flows ahead of the quench front, and the post quench liquid phase flows appeared to have characteristics different from those observed in previous ground based studies.

This thesis presents a discussion and catalogue of various 2 phase flow regimes encountered under transition to and from boiling processes. Further, the thesis presents a description of the differences in these regimes between the normal and low gravity environments, and makes recommendations for future experiments.

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I. INTRODUCTION

1.1 INTRODUCTION

Cryogenics are transferred in medical equipment, nuclear industry cooling systems, and spacecraft engines. The transfer of cryogenics through an initially warm pipe line generally results in rapid boiling, pressure surges, severe temperature gradients and two-phase flow patterns. Studies of the resulting flow patterns have been performed for decades as researchers attempted to create mathematical models of the processes and to predict cooldown process parameters such as cooldown time, driving pressure, and flow rate. Thus far, the majority of applications for such models have been in normal gravity environments, however with the advent of manned space stations and longer flight missions, any or all of the cryogen applications mentioned above may be required in a low gravity environment. Very little previous research has been performed on the actual two-phase flow patterns which occur during low-gravity. Because of the extreme cost of transport and the need to optimize piping system weight in low gravity applications, accurate engineering knowledge of the flow mechanisms and correlations between transient flow properties will be necessary in the design of these systems. Gaining an accurate picture of the flow mechanisms or fluid physics which occur during the cooldown process is an essential first step in this new aspect of the research.

The objective of this study was to compare flow patterns of saturated liquid nitrogen flow boiling both at low gravity and normal gravity conditions. Differences between low gravity and normal gravity flow behavior are identified, and requirements for future research projects are recommended.

A portable apparatus was designed by Dr. Basil Antar and Dr. Frank Collins [1] to be operable on board a NASA KC-135 aircraft or on the ground. High speed movies were made (by NASA personnel at Ellington Air Force Base) of transient two-phase flow patterns occurring in a quartz test section in both simulated low gravity and normal gravity environments. Very similar conditions (excepting gravitational conditions) and test procedures were established for the tests both on the ground and during low gravity flight simulations.

1.2 DISCUSSION OF PREVIOUS RESEARCH

The following introductory discussion of the results of previous researchers is included to clarify definitions used throughout this thesis. In addition, it provides a comparison of the differences and similarities between this experiment and the previous experiments conducted by other researchers.

1.2.1 FLOW REGIMES IN NORMAL GRAVITY

Many different flow regimes have been identified for cryogenic cooldown flows in vertical lines under normal gravity. The flow patterns change as the temperature differences between the fluid and the wall and the condition of the fluid are changed. Amestistov [2] illustrates in Figure I-1 some common two-phase flow patterns for nitrogen in vertical flows. When subcooled liquid enters a warm channel or tube, nucleate boiling on the surface can occur which generates a vapor film which gradually grows until the turbulent liquid flow is separated from the surface by the vapor film. Film boiling occurs after the liquid separates from the surface and a type of flow referred to as core flow results with an annular vapor surrounding a liquid core. This is referred to as core flow. The core flow (also called inverted annular flow in this study) usually has a short region just after the fluid separation from the wall of laminar vapor flow and liquid core flow which is less turbulent than the other flow regions. After additional evaporation of liquid and growth of the vapor boundary layer, vapor-liquid interfaces become turbulent and begin to interrupt the liquid flow pattern. The result is a core flow of string-like separated liquid segments (often referred to as filaments) which form a flow regime referred to as transition flow. Amestistov [2] states that in cooldown of warm passages

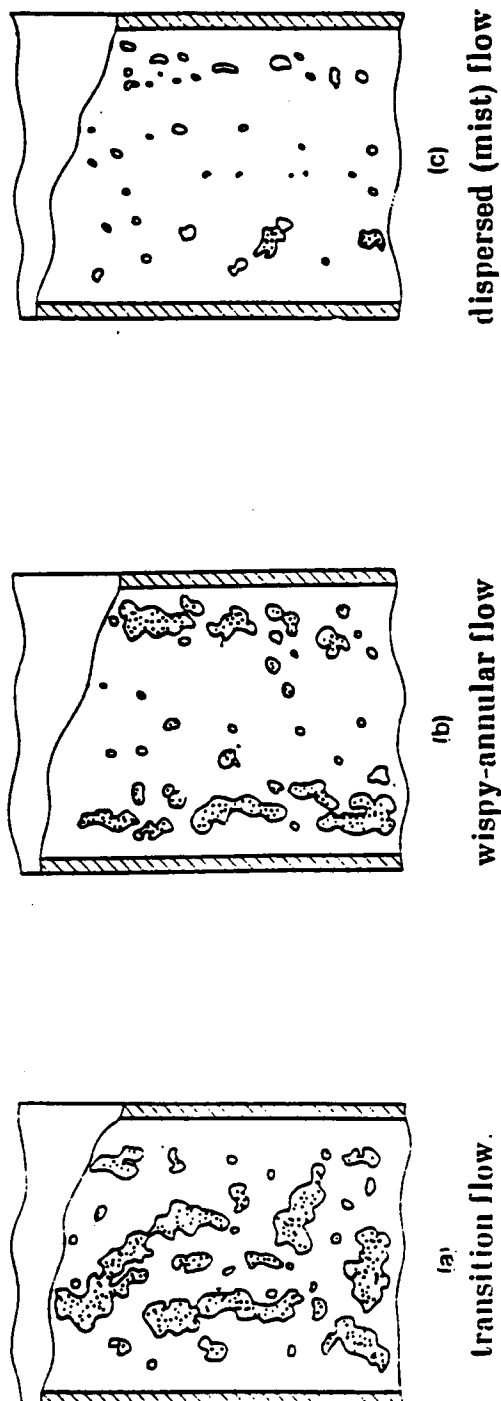
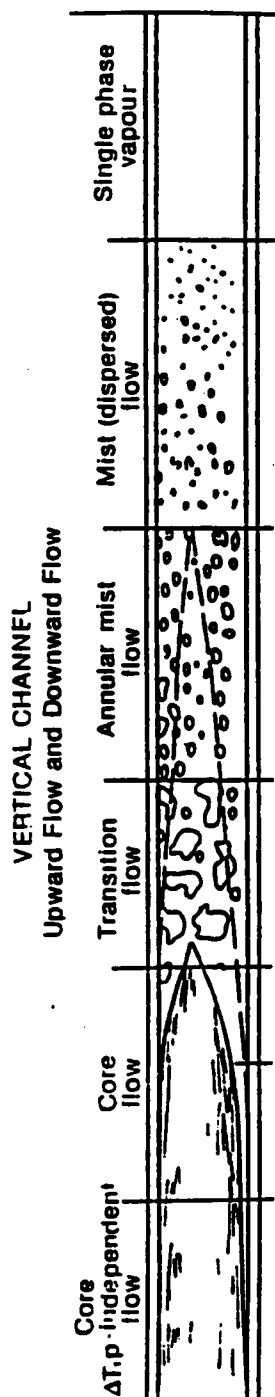


Figure I-1. Amestitov Flow Regimes for Film Boiling In a Vertical Channel

taken from Amestitov [2]

(causing sudden adverse pressure gradients due to rapid evaporation of liquid), or passages with geometry causing sudden deceleration of the liquid flow phase, inertia forces will cause liquid slugs to break off of the core flow and a different slug flow regime can occur. This phenomena is also described by Steward [3] in studies of transfer line pressure surges. Steward notes that the core flow's tendency to breakup into slugs increases with subcooling of the liquid in initial entry lengths which are partially cooled down such that liquid initially fills the line very quickly, then slows as vapor is generated with core liquid slugs being carried forward by initial momentum. In such cases the core flow regime can break down in an unpredictable manner. The transition flow changes character after additional travel through the passage and further evaporation. A regime described as wispy-annular occurs which has droplets dispersed in vapor flow. In the wispy-annular flow regime, the dispersed droplets are distributed such that larger droplets are concentrated in the vapor boundary layer at the passage perimeter. In this regime, vapor at the center of the flow is believed to move faster than vapor at the wall, where rapid evaporation forces vapor towards the center and causes a radial pressure gradient. Amestistov [2] notes that during the non-equilibrium cooldown process, superheated vapor at the flow centerline and saturated liquid nitrogen droplets can co-exist. The vapor in the center generally contains a high

degree of superheat. Large liquid particles in the center of the flow are either quickly disintegrated or forced away towards the wall by evaporative pressure. Reactive forces from evaporation and sharp pressure gradient at the wall as well as high vapor boundary layer velocities prevent liquid particles from contacting the wall. The resulting flow pattern causes larger liquid particles to be caught in a type of churn flow between the wall and the center of the flow where the velocity has been estimated to be about 15% slower than velocity of smaller liquid particles remaining in the core flow. Given flow conditions with a very high degree of superheat or very low mass flow rate it is possible that the wispy-annular regime will not occur. With additional evaporation, the flow will proceed from transition or wispy-annular regimes, to a new regime known as dispersed or mist flow. In the dispersed flow pattern, variations of droplet size and velocity are much smaller than in the previous flow patterns. Liquid particles are distributed evenly throughout the vapor flow, except for the thin vapor boundary layer at the wall where liquid does not occur.

Boiling flow regimes were also described in a study by Rohsenow [4]. Film boiling of saturated nitrogen flowing upward through a clear 1/2" O.D. tube was photographed for visual study in the experiment. The experimental apparatus consisted of a dewar pressurized by 15 PSIG helium gas. A

portion of the liquid nitrogen was bled off in a flash cooler prior to test section entry to ensure that saturated liquid entry conditions were achieved. A uniformly wound heating element surrounding the test section was regulated by a variable power transformer to ensure uniform heating of the tube. Exiting vapor and liquid were heated to pure vapor state in a post heater so that vapor mass flow rate could be determined with a rotameter. Pressure fluctuations in the test section were prevented by modulating a liquid nitrogen flow control valve to maintain constant pressure. The apparatus was capable of creating stable flow patterns which varied as a function of test section height or distance from the dewar. The test section was four foot tall and exhibited a good range of flow regimes. Figure I-2 contains sketches of flow patterns which were constructed from photographs and descriptions found in Rohsenow's [4] studies. Under steady heat flux conditions (a vapor boundary layer was being continuously generated at the test section wall by the heating element) a liquid core flow region (the inverted annular flow) was observed to occur in the lower region of the test section. Several inches higher and following additional evaporation, a transition flow region containing liquid filaments occurred. At a higher test section position this flow pattern was observed to change into another flow regime similar to the wispy-annular regime. Rohsenow [4] identified the annular distribution of larger droplets by photographing flow patterns

Rohsenow 2-Phase Flow Regimes in 1-g

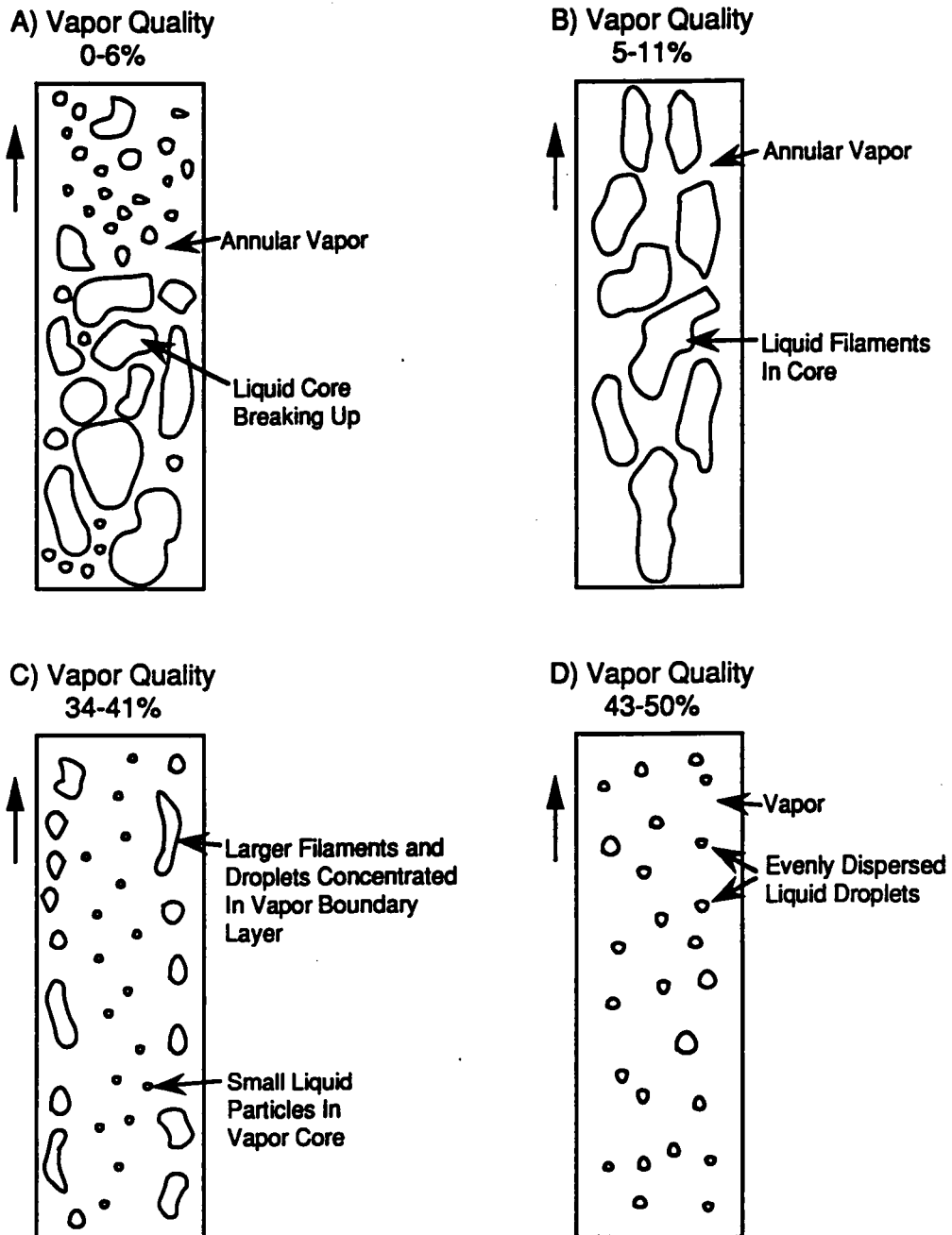
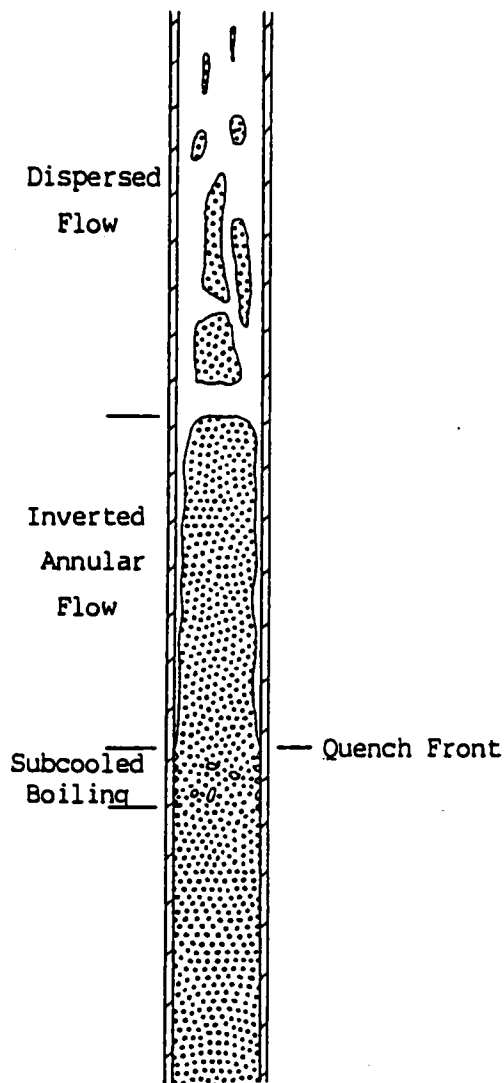


Figure I-2. Rohsenow 2-Phase Flow Regimes In Normal Gravity

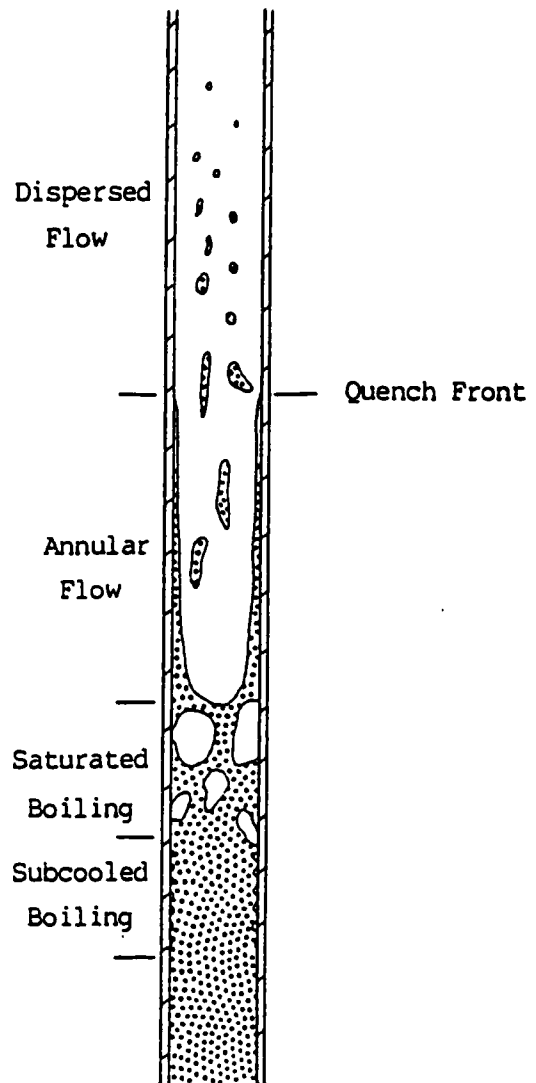
based on descriptions and photos taken from Rohsenow et al [4]

established as repeatable from run to run with different color (black vs. white) backgrounds behind the test section. This technique revealed different size droplets at the locations corresponding to wispy-annular flow. At higher positions in the test section, a dispersed flow region with more uniform droplet size and spatial distribution was observed to occur.

A similar type of study using steam instead of nitrogen was performed by Kawaji and Banerjee [5]. A 1.5 meter tall, 14.3 millimeter I.D. quartz tube with uniform external heat flux was studied under a variety of inlet flow conditions. Two general types of liquid flow patterns were observed during liquid quenching of the tube wall. The quench front illustrated in Figure I-3 is defined as the last position at which the liquid wets the surface of the tube wall. Figure I-3 illustrates two regimes referred to as inverted annular and annular. For inlet liquid conditions with high flow rates and/or significant subcooling of the liquid, the inverted annular or core flow pattern was observed to occur. For inlet flows of low mass flowrate or saturated liquid conditions the annular flow regime was found to occur. The experimental apparatus of Kawajee and Banerjee included the use of a gamma ray densitometer which was used to obtain estimates of void fraction. Void fraction is defined as the percent of the total mass flow which is in the vapor phase. Data from void fraction history, thermocouple heat transfer data from an



(a) Inverted Annular Flow
Regime near the Quench Front



(b) Annular Flow
Regime near the Quench Front

Figure I-3. Normal Gravity Flow Regimes
taken from Kawaji and Banerjee [5]

additional stainless steel tube, and visual studies were combined to produce the sketches of the two flow patterns. Kawajee and Banerjee [5] described flow regimes and trends in flow quality which are similar to the transition flow (filament region), and dispersed flow regimes. The annular quench front was studied in considerable detail under steady flow conditions, and unsteady conditions caused by a vibration type oscillator, that produced small pressure fluctuations. Under steady flow conditions, the annular quench front was observed to travel steadily upward with a thin annular liquid film (just separated from the wall) being ejected ahead of the quench front as detected from heat transfer data, gamma ray densitometer study and visual appearance. When given an oscillating excitation, the annular quench front was observed to travel in sudden jumps or accelerations with apparent burst or spluttering of liquid droplets from the liquid region into the vapor region. Wall heat transfer mechanisms varied by an order of magnitude depending on which mechanism was occurring. Large oscillations in void fraction and unsteady downstream conditions also accompanied the fluctuating type of annular quench front.

1.2.2 FLOW REGIMES IN LOW GRAVITY

Previous studies of two-phase flows in reduced gravity have been conducted for freons, steam, water-air mixtures and

saturated nitrogen. The studies of freons emphasize heat transfer characteristics with very little discussion of flow visualization. Very little work has been performed studying liquid nitrogen or other cryogen two-phase flows in low gravity. Some flow patterns observed in previous related experiments are summarized below.

Dukler et al. [6] conducted experiments with air-water mixtures at adiabatic conditions which included flow visualization. Various test conditions for the water and air flows were established in a 12.7 mm I.D. by 1.06 meter long plexiglass tube test section. The test section was instrumented for measuring temperatures and pressures. A high speed camera filmed the tests at 400 frames per second for flow visualization. One series of tests were conducted using the NASA Lewis Research Center (NASA LeRC) drop tower which produced low gravity conditions for approximately 2.2 seconds. Visualization results from these tests were not discussed in detail. A second series of tests were conducted with the apparatus on board a Learjet at the NASA LeRC facility. The Learjet flights enabled filming of the test section in a $+0.02$ g environment for periods of 12 to 22 seconds. Figure I-4 shows a series of flow patterns found for low liquid (water) flow rates with progressively increasing flow rates of air. Low flow rates of both water and air (reference run 15.1) resulted in long Taylor (full diameter bullet shaped) air

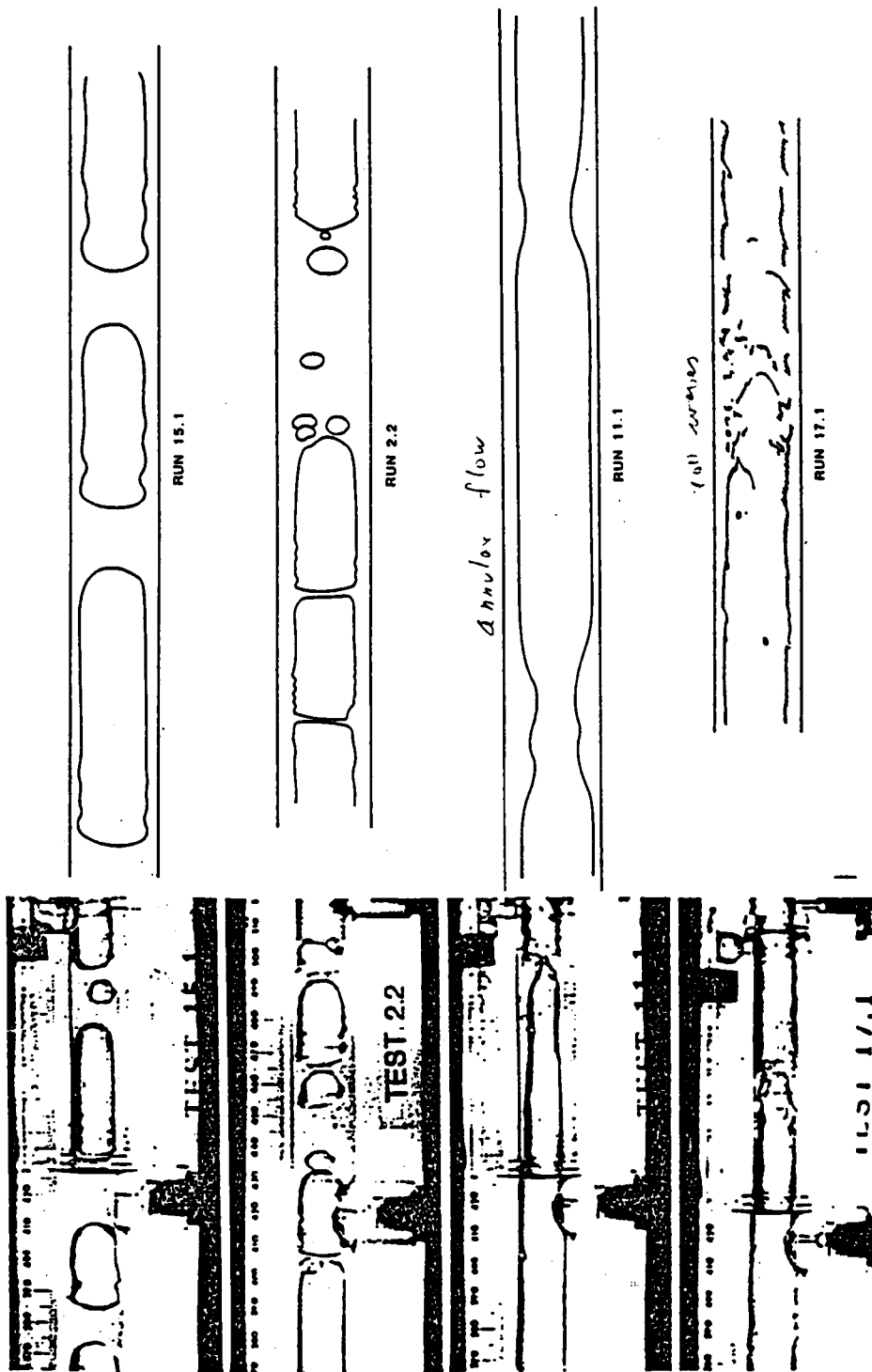
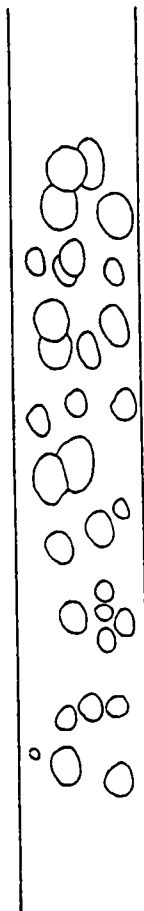


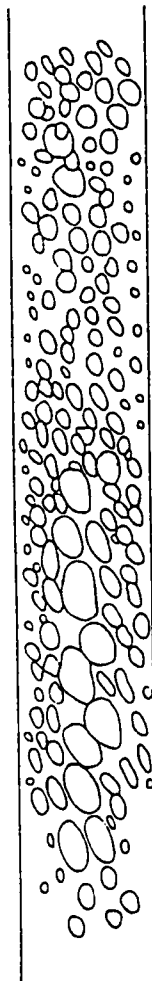
Figure I-4. Photos and Sketches for Low Liquid Flow Rate In Low G
taken from Dukler et al. [6]

bubbles with liquid bridging the test section separating the bubbles. This was termed slug flow. Increasing air flow rates tended to increase the length of the Taylor bubbles and decrease the size of the slugs. Further increases of the air flow resulted in an annular water flow surrounding a vapor core (reference run 11.1).

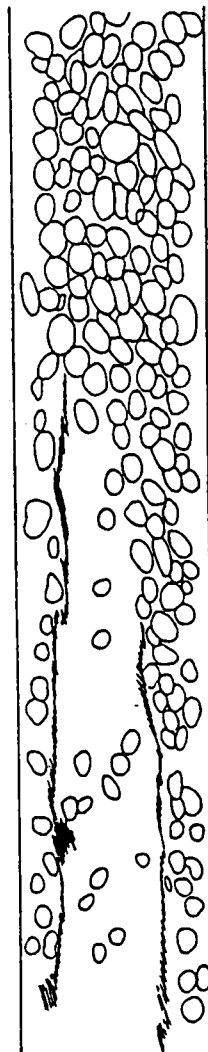
High air flow rates with low liquid flow rates caused the annular liquid film to exhibit roll waves and to move along the test section wall at a velocity comparable to the air flow velocity. Flow patterns for a high liquid flow rate with progressively increasing air flow rates are illustrated in Figure I-5. During high liquid flow rates, small air flow rates caused dispersed bubbles .2 to .5 mm in diameter to occur (reference run 15.21). Increasing the air flow rate caused more numerous smaller bubbles to occur. Simultaneous high flow rates of both water and air produced a complicated pattern of aerated liquid slugs intermingled with aerated liquid film flows (reference run 12.12). Figure I-6 shows a typical pattern found for intermediate flow rates of both air and water. Intermediate flow rates were found to produce large Taylor bubbles surrounded by clear annular liquid flow with regions of aerated liquid slugs separating the Taylor bubbles. Figure I-7 summarizes the flow visualization results of the flights. Dukler developed a flow pattern map correlates each flow regime to specific velocity ratios of air



RUN 15.21



RUN 14.1



RUN 12.12

Figure I-5. Photos and Sketches for High Liquid Flow Rate In Low G
taken from Dukler et al. [6]

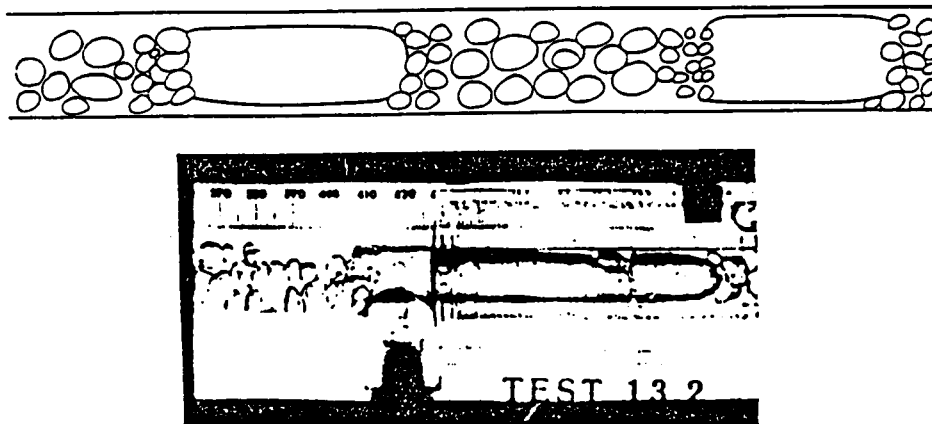


Figure I-6. Photograph and Sketch for Intermediate Liquid and Gas Flow Rates, taken from Dukler et al. [6].

RUN #	U_{GS} (m/s)	U_{LS} (m/s)	FLOW PATTERNS	Re_L	Re_G
2.1	25.32	0.080	ANNULAR : short roll waves	1016	23224
2.2	0.61	0.084	SLUG : long TB	1067	560
3.1	11.44	0.451	ANNULAR : roll waves	5728	10493
4.1	7.97	0.082	ANNULAR : roll waves	1041	7310
4.2	0.22	0.076	SLUG : 4D TB	965	202
5.1	2.22	0.079	ANNULAR : near transition annular-slug	1003	2036
5.2	0.64	0.080	SLUG : long TB	1016	587
7.1	2.99	0.438	ANNULAR : near transition annular-slug	5563	2742
8.1	1.09	0.460	SLUG : 3D TB ,bubbly slugs	5842	1000
9.1	0.09	0.478	BUBBLE	6071	83
10.1	23.00	0.418	ANNULAR : roll waves	5309	21096
11.1	1.80	0.079	TRANSITION : annular-slug	1003	1651
11.2	1.75	0.45	SLUG : long TB ,bubbly slugs	5715	1605
12.12	1.9	0.92	SLUG : 6D TB ,bubbly slugs	11684	1743
13.1	0.7	0.08	SLUG : long TB ,non bubbly slugs	1016	642
13.2	0.65	0.45	SLUG : 2D TB ,bubbly slugs	5715	596
14.1	0.65	0.94	BUBBLE	11938	596
15.1	0.16	0.079	SLUG : 2D 3D TB ,non bubbly slugs	1003	147
15.2	0.13	0.88	BUBBLE	11176	119
16.1	11.4	0.077	ANNULAR : roll waves	978	10456
16.2	0.134	0.46	BUBBLE	5842	123
17.1	10.1	0.08	ANNULAR : roll waves	1016	9264

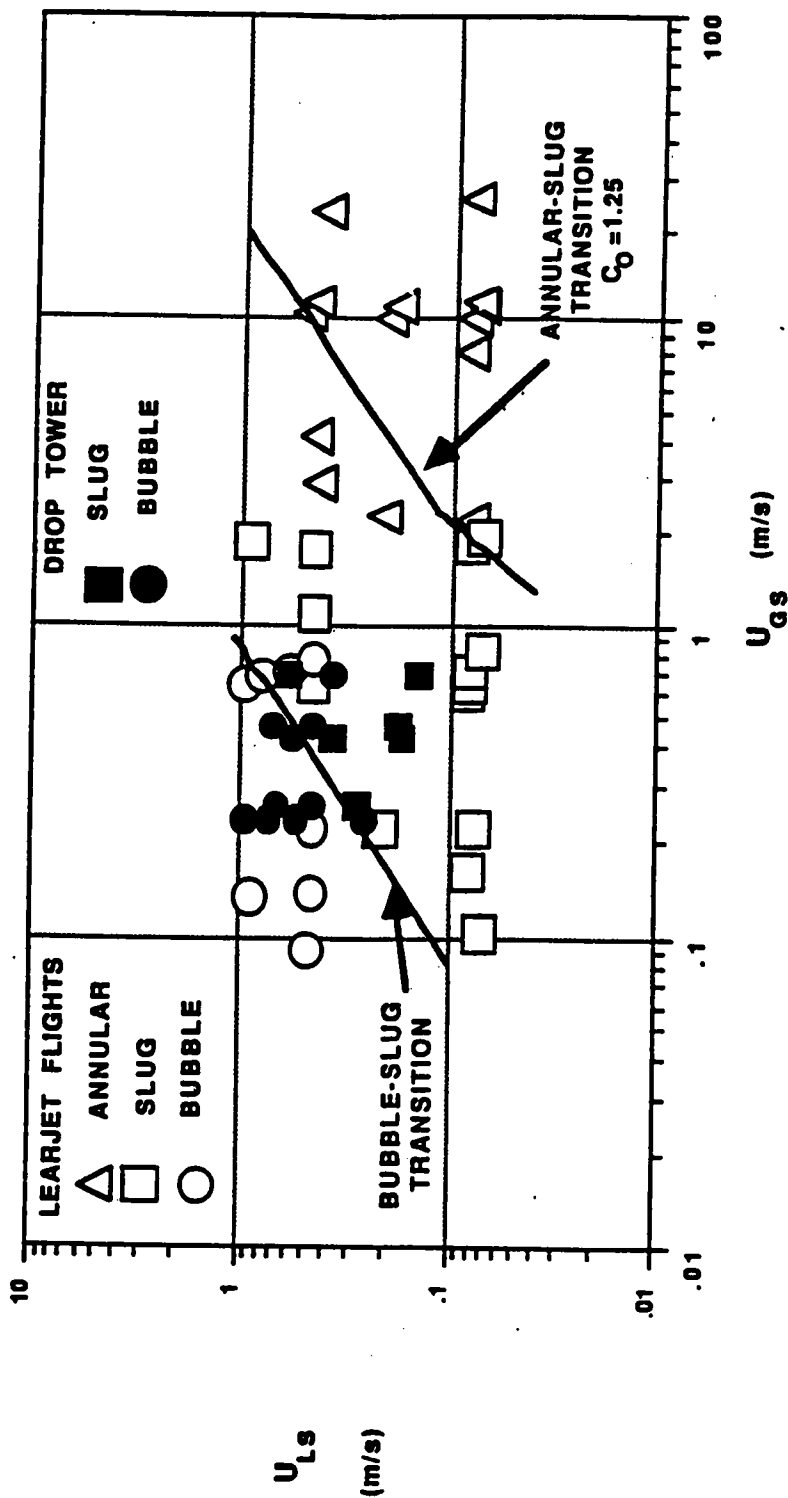
Figure I-7. Flow Summary from the Learjet Runs, taken from Dukler et al. [6].

and water for the Learjet and drop tower tests. This is shown in Figure I-8.

Dukler [6] mentions that the low gravity flow patterns exhibited dispersed bubbles traveling within the aerated slugs at the same speed as the slugs. In contrast, at normal gravity the bubbles typically traveled slower than the front of the slug. The mechanisms of pickup and shedding (transfer of vapor bubbles from the wall to the fluid) are believed to be different at low gravity than at normal gravity for this experiment. While the experiment yielded useful flow visualization descriptions, it had no temperature gradients, low rate of liquid vaporization, and property differences of the two fluids which do not adequately model all of the flow mechanisms needed to represent cryogenic cooldown.

A similar experiment was conducted by Hill and Downey of the Sundstrand Corporation reference [7]. Liquid nitrogen near saturated conditions was pumped through a swirl flow evaporator (a coiled tube with a heating element) and heated to produce liquid-vapor two phase flow. The evaporator heat flux was controlled to produce varying quality vapor content in the flow. The test section was a clear section of tubing installed in a return line to a condenser. The flow through the test section was observed under adiabatic conditions. Measurements of flow rates, temperatures, pressure drops and

0-g GAS-LIQUID FLOW



U_{Gs} = superficial velocity of the gas (calculated as if it flowed alone in the pipe)

U_{Ls} = superficial velocity of the liquid (calculated as if it flowed alone in the pipe)

Figure I-8. Dukler Flow Pattern Map

taken from Dukler [6].

visual observations were collected as a data base for predicting pressure drops for various line sizes in low gravity environments. An early series of test flights were conducted in October, 1987 on board the NASA KC-135 aircraft. Low gravity simulation flights were conducted for two days. Comparable normal gravity test runs were conducted on the ground as well. Films of the visual data in low gravity revealed four types of reduced gravity flow regimes similar to those defined by Dukler [6]. When vapor bubbles were longer than the tube diameter and were separated by liquid bridging the tube cross section the flow was termed slug flow. When bubbles were smaller than the tube diameter the flow was described as bubbly flow. Liquid slugs were observed to occur in bullet nosed Taylor bubble form with small vapor bubbles inside the liquid slug. Annular liquid flow along the tube wall was observed as well. An additional type of flow pattern documented was termed mist flow. In mist flow, high mass fluxes at high thermodynamic quality were observed as vapor flow with small liquid droplets dispersed evenly in the vapor flow. Figure I-9 illustrates the four regimes which were similar to the Dukler [6] patterns observed by Hill and Downey [7] in October, 1989. At very low quality, bubbly flow was observed to occur. At flow qualities of less than 10%, liquid slugs separated by Taylor vapor bubbles were observed. At flow qualities between 10% to 15% a type of transition flow regime was observed where the liquid slugs formed elongated

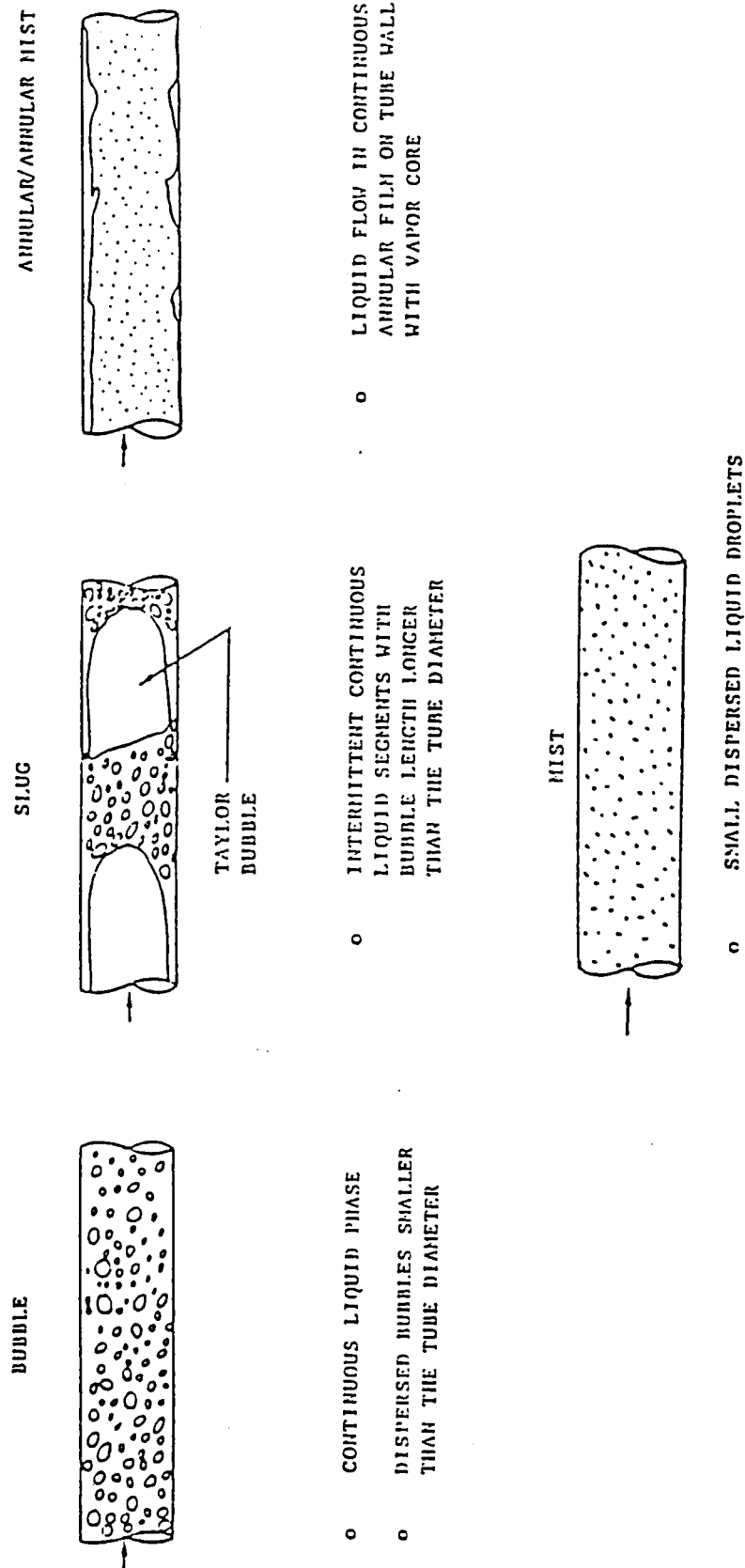
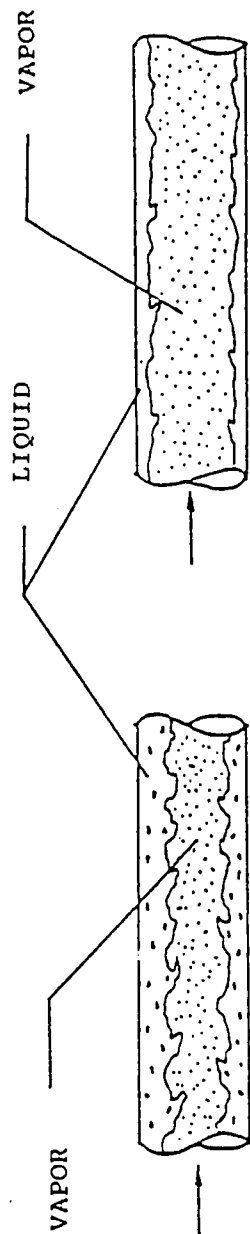


Figure I-9. Dukler Regimes for Reduced-Gravity 2-Phase Flows
taken from Hill and Downey [7].

strands intermingled with occasional regions of mist flow. This phase was compared with churn flow typically seen in vertical upflow at normal gravity. At flow qualities greater than 15%, annular liquid flow near the tube wall occurred. The annular liquid flow was observed to occur in an annular liquid film with dispersed mist in the vapor core at higher qualities. This combination of annular liquid and mist flow was termed annular-mist flow.

Further investigations of these high quality flow regimes by Hill and Downey [7] describe the possibility of additional flow patterns which could occur in low gravity. The low gravity annular liquid film flowing at the tube wall was observed to be roughly twice as thick as the annular film at corresponding flow conditions in normal gravity. This thick annular film was turbulent with roll waves that entrained vapor bubbles within the liquid film forming a frothy surface at the annular liquid-vapor core interface. The vapor core consisted of a mist flow having small droplets of liquid entrained in the vapor flow. This type of flow was termed frothy annular flow and is illustrated in Figure I-10. The low gravity frothy annular flow exhibited higher pressure drops than the normal gravity annular mist flow at similar flow rate conditions. Comparisons of flight data with the ground data are shown in Figure I-11.



REDUCED-GRAVITY FROTHY ANNULAR FLOW

- o LIQUID FLOW IN CONTINUOUS THICK ANNULAR FILM ON TUBE WALL WITH VAPOR CORE
- o LIQUID VELOCITY IS GREATER THAN IN ONE-GRAVITY ANNULAR FLOW
- o VOID FRACTION IS LESS THAN IN ONE-GRAVITY ANNULAR FLOW
- o SMALL DISPERSED BUBBLES IN THICK ANNULAR FILM

ONE-GRAVITY ANNULAR FLOW

- o LIQUID FLOW IN CONTINUOUS THIN ANNULAR FILM ON TUBE WALL WITH VAPOR CORE

Figure I-10. Reduced-Gravity "Frothy Annular Flow"

taken from Hill and Downey [7]

Quality	Observed Reduced Gravity Flow Pattern Description	Flow Regime	Observed Ground Test Flow Pattern Description	Flow Regime
0.05	Long Taylor bubbles followed by liquid slugs	Slug	no information provided	---
0.10	Short Taylor bubbles followed by liquid segments	Slug	no information provided	---
0.15	Annular flow separated by liquid segments	Slug/Annular	Stratified wavy/ occasional slug	Stratified Wavy/ Slug
0.20	Fully developed continuous annular flow with occasional droplet mist bridging	Annular	Stratified with less wave development	Stratified
0.30	Fully developed annular flow with thinner film with occasional droplet mist bridging	Annular	Stratified wavy/ thin annular film	Stratified/ Annular
0.40	More pronounced annular flow	Annular	Stratified wavy/ semiannular	Stratified/ Annular
0.50	Annular/mist	Annular	Thin stratified wavy/ semiannular	Stratified/ Annular
0.60	Annular/mist	Annular	Thin stratified wavy/ semiannular	Stratified/ Annular
0.80	Annular/mist (thinner annular film)	Annular	Semiannular	Annular

Figure I-11. Comparison of Reduced-Gravity and Ground Test Flow Regimes

taken from Hill and Downey [7]

Another experiment that has relevance to this study, was undertaken by Cuta and Krotiuk of Pacific Northwestern Laboratory [8] to obtain data on boiling and condensation in low gravity was performed . Their experiment provided visual flow patterns and data for comparison with predicted flow patterns obtained from the computer code Cobra/Trac, that had been developed based on ground-based studies. Their experiment was based on the study of flow mixtures of water with water vapor and water with nitrogen. An 8 mm I.D. quartz tube with a surrounding nichrome wire heating element served as the test section for the visual studies. The test section served as a boiler during the experiment while a condenser cooled the flows before ejection into the atmosphere. Data on pressure, heating power, flow rates, gamma ray densitometer measurements and films of the test were taken. The films were taken at speeds of 1000 and 2700 frames per second. The apparatus was tested on board the NASA KC-135 aircraft during two series of tests. The flows were studied at three levels of constant heat flux through the nichrome heating element surrounding the test section. A summary of results from testing water- nitrogen flows is shown in Figure I-12. Low vapor flows in a variety of liquid phase mass flow rates resulted in bubbly flows having small vapor bubbles inside of mostly clear liquid. Runs conducted with a reduced liquid phase flow rate and higher vapor content displayed two general types of flow regimes. High vapor flow rates caused the

Parabola No.	Flow (L/min.)	Power (W)	BOILER		CONDENSER	
			COBRA/TRAC Prediction	Experimentally Observed Near Exit*	COBRA/TRAC Prediction	Experimentally Observed**
10	Low (0.4)	Low (1049)	One phase with bubbly near exit	Bubbly	Bubbly	---
19	Low (0.3)	Low (2203)	Half one phase, half bubbly	---	Annular	---
23	Low (0.4)	Low (1902)	---	Annular/slug/dryout	---	---
14	Low (0.4)	Intermediate (2723)	---	---	---	Annular
15	Low (0.4)	Intermediate (3037)	---	Annular/froth/dryout	---	---
6	Intermediate (0.6)	Intermediate (3200)	---	Annular/long slug	---	---
17	Intermediate (0.5)	Intermediate (3323)	---	Annular/froth/dryout	---	Annular
21	Intermediate (0.5)	Intermediate (2530)	---	Annular/slug/some dryout	---	---
2	High (0.6)	Intermediate (3160)	Bubbly	---	Bubbly	---
3	High (0.7)	Intermediate (3037)	---	---	---	Bubbly
5	High (0.7)	Intermediate (3110)	Bubbly with annular near exit	---	Bubbly at start and annular at end of parabola	---
7	High (0.8)	High (5163)	---	---	---	Bubbly
9	High (0.8)	High (4671)	Bubbly with annular near exit	Annular	Annular	---

	Flow ($\text{kg/m}^2\text{-s}$)	Power (W)
Low:	< 150 (0.45 L/min.)	< 2300
Intermediate:	150 < $\dot{m}$ < 215	2300 < $\dot{q}$ < 3500
High:	> 215 (0.65 L/min.)	> 3500

* Observed at point about 80% of total boiler length.

** Observed at center of condenser length.

Figure I-12. Summary of Flow Regime Comparisons
taken from Cuta and Krotiuk [8]

liquid phase to form an intermittent pattern of frothy, aerated liquid slugs separated by regions of annular liquid flow. This annular liquid flow was observed to be a thick layer with roll waves. Increasing the vapor flow rate reduced the thickness of this annular liquid film. At the highest vapor flow rates, annular liquid flow was observed.

1.2.3 RELATION OF PREVIOUSLY DISCUSSED EXPERIMENTS TO THIS EXPERIMENT

The ground-based portion of this experiment should be expected to exhibit characteristics similar to those found by Amestistov [2] and Kawajee and Banerjee [5] for vertical flow of liquid nitrogen in a warm tube. Their experiments exhibited transient thermal conditions and working fluids similar to this experiment. The experiments conducted by Rohsenow [4], Dukler [6], Hill and Downey [6] and Cuta and Krotiuk [8] utilized steady heat flux or essentially adiabatic flow conditions which do not reflect all of the transient phenomena occurring in this experiment. The detailed study of 2 phase nitrogen flow patterns by Rohsenow does provide information relating normal gravity flow pattern lengths and thermodynamic quality for a test section of scale similar to this experiment. The significance of the low gravity Dukler experiments was the establishment of various flow regimes correlated with thermodynamic quality and velocity. Patterns

similar to those founded by Dukler were confirmed to occur in low gravity, adiabatic 2 phase nitrogen experiments by Hill and Downey. In addition, Dukler presented a hypothesis that the mechanism of pickup and shedding may be different in low gravity environments, which would significantly affect the transient boiling process studied in this experiment. The study by Cuta and Krotiuk probably has less applicability since the nitrogen-water mixture used would not behave the same as 2 phase nitrogen flows, however should be mentioned as the first effort to compare low gravity and normal gravity 2 phase flows.

In conclusion, one should expect the ground based tests for this experiment to exhibit flow patterns similar to those defined by Amestistov (with previously noted differences for saturated nitrogen) and by Kawajee and Banerjee. The flow patterns resulting from low gravity tests should exhibit differences in vapor content and boiling regions if Dukler's hypothesis regarding pickup and shedding mechanism differences in low gravity is correct. The actual flow patterns occurring in the low gravity tests of this experiment are expected to be different from those defined by Dukler and by Hill and Downey since the transient cooldown process results in entirely different thermodynamic conditions, however the flow patterns could be predicted to exhibit similar characteristics at times during the changing process.

II EXPERIMENTAL SETUP

2.1 APPARATUS

The test apparatus for conducting cryogenic flow research on flow boiling in initially uncooled tubes was designed and built at the University of Tennessee Space Institute (UTSI) Fluid Dynamics Laboratory. The system was designed to fit within a space 1.25 m. x 1.5 m. x 1.25 m. high on board a NASA KC-135 aircraft. The components were skid mounted on a baseplate and an angle iron frame structure. All components had to be rigidly secured. A very detailed account of the construction and components used is given by Sathasivam [9]. While Sathasivam provided some general description of the visual results from the experiment, his efforts were concentrated on the construction, trial flights, and subsequent revisions to the apparatus design. The present thesis concentrates on the critical review and quantitative analysis of the resultant data. The following summary descriptions of the apparatus and test procedures are provided to clarify applicability of this study to the problem of low gravity flow with boiling and phase change.

A process flow schematic for the apparatus is illustrated in Figure II-1. Saturated liquid nitrogen at 25 psia was transferred from a dewar to an accumulator. The accumulator

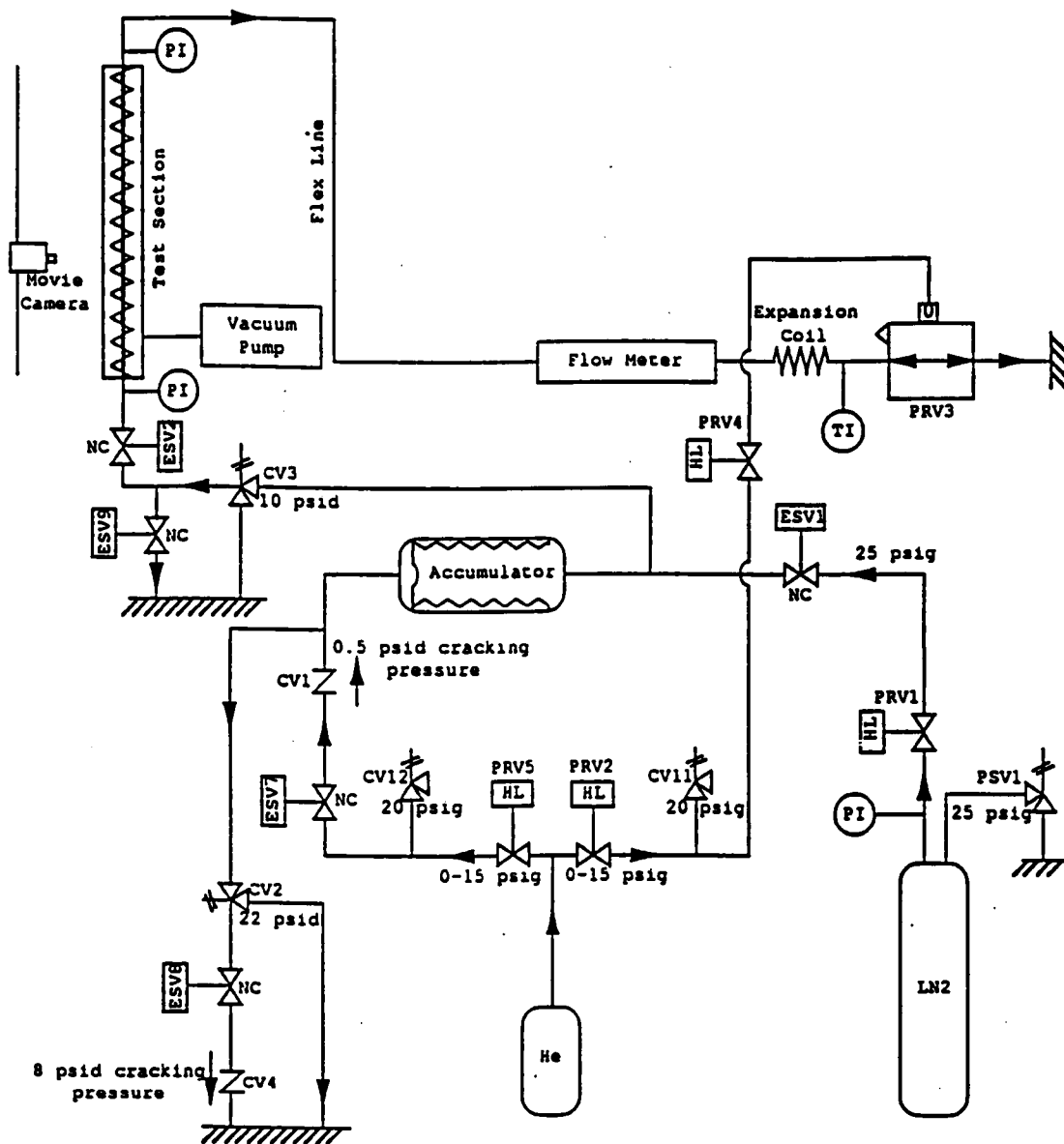


Figure II-1. Low-Gravity Liquid Nitrogen Flow System Diagram

taken from Sathasivam [9]

consisted of an inner bellows which held the liquid and an outer shell (a detailed schematic is shown in Sathasivam [9].) An annular discharge vent with an inner liquid line was located at the top so that vapor could exit during filling operations. Gaseous helium was forced into the cavity between the bellows and the outer shell to create liquid nitrogen supply pressure during the test. The liquid nitrogen was routed through prechilled insulated tubing to a vertical test section. The test section illustrated in Figure II-2 was oriented vertically with upward flow direction so that stratification and other ground based effects would not have to be considered when comparing low gravity data with normal gravity data. A 1/2 inch O.D. by 36 inch long quartz tube was used for the test section. A nicrome wire heating element was used to warm the test section and remove condensation between test runs. A 2 inch O.D. plexiglass tube was used as a vacuum jacket around the test section. The quartz tube test section was connected to the nitrogen supply line using Swagelock tubing fittings with teflon seals. The plexiglass jacket was glued to plexiglass flanges, and bolted to mating aluminum flanges with O-ring seals. The aluminum flanges were attached to the Swagelock tube connectors with threaded fittings. The annular space between the quartz tube and the plexiglass cylinder was partially evacuated using a vacuum pump. The occurrence of condensation on the quartz tube exterior proved that the affected seal and vacuum system did not work

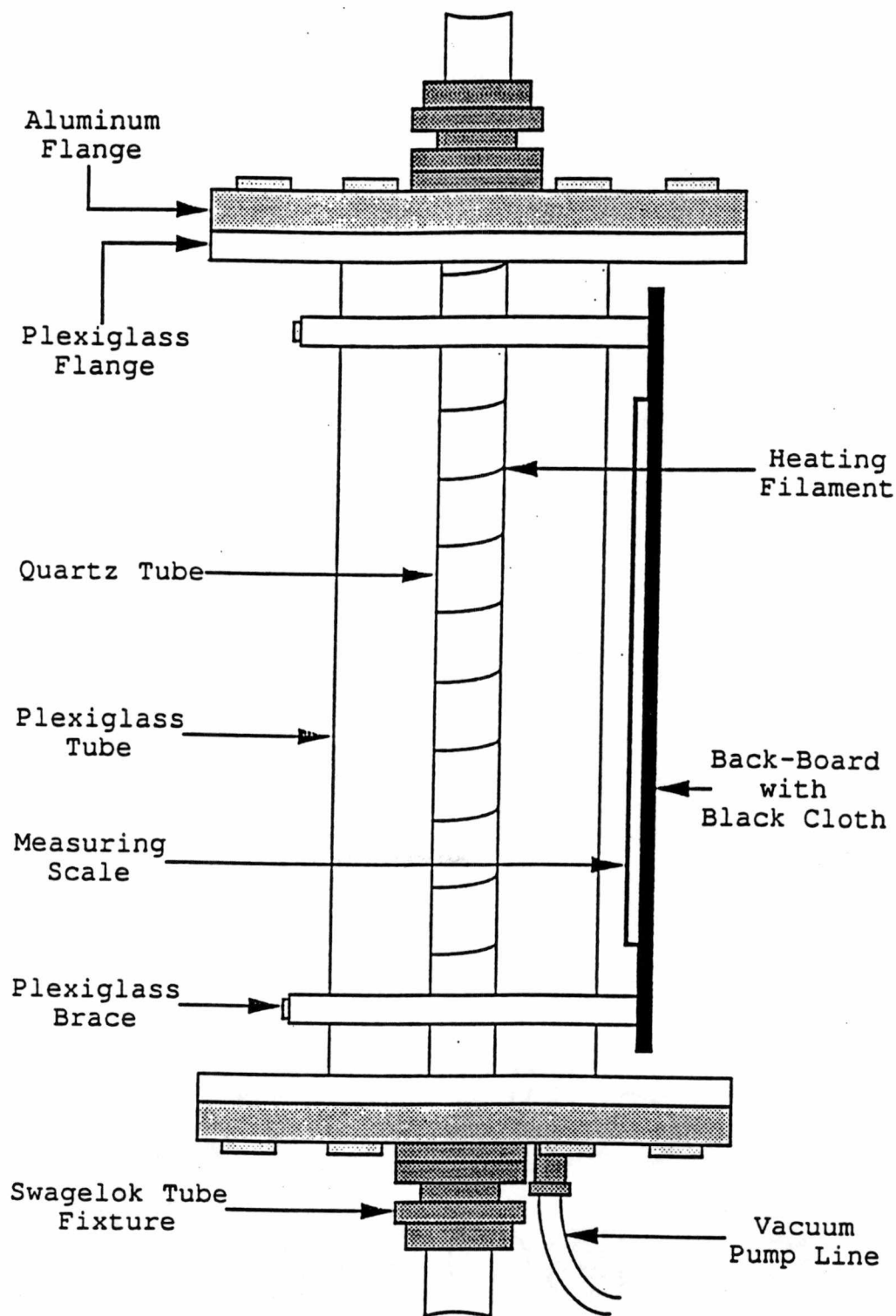


Figure II-2. Schematic Drawing of the Test Section
taken from Sathasivam [9]

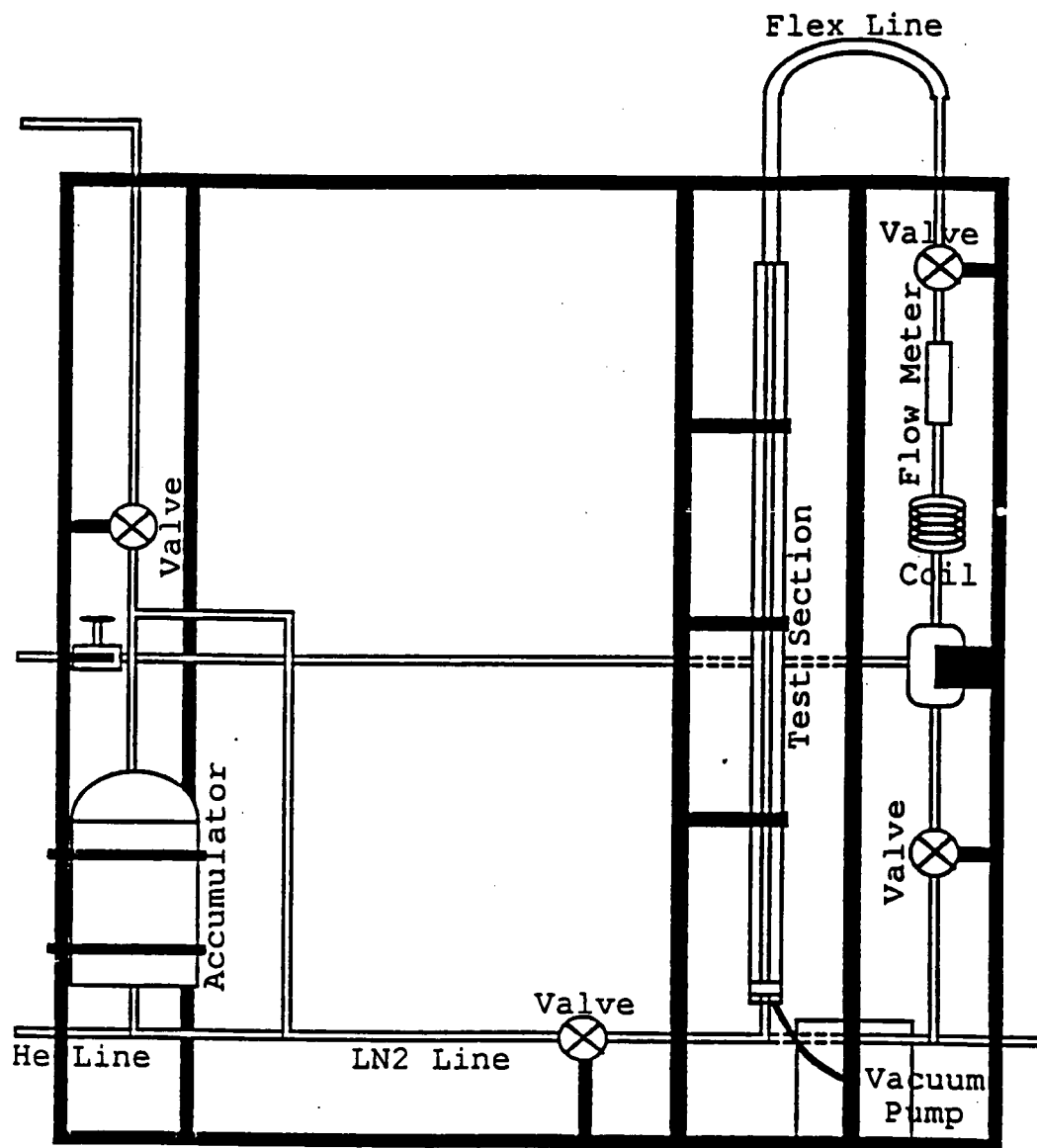


Figure II-3. Side View Schematic of the Experimental Apparatus

taken from Sathasivam [9]

perfectly; however it did allow adequate viewing throughout most of the data filming periods and greatly reduced ambient heat transfer to the test section. A teflon tubing line carried the flow exiting the test section to an ambient exit port. Efforts to measure and record the mass flow rate with a cryogenic rated vapor flow meter failed. Two different flow meters failed during liquid phase flows and so were not used for the experiment performed for this report. An exit flow pressure regulator was originally installed to try to maintain constant flow back pressure of one atmosphere during the KC-135 flight simulations. During trial runs, test section pressure surges well above one atmosphere occurred and decreased throughout test run time. The backpressure regulator was subsequently removed.

The apparatus instrumentation and controls were designed to automate data recording procedures and sequential valve operations so that test procedures would be easy to repeat. The test section had a fixed position yard stick with a black background mounted adjacent to it. A LED gauge on the background displayed the aircraft accelerometer readings during the flight. Pressure indicators were mounted at the test section inlet and outlet. The indicators were strain-gauges mounted on a thin quartz film. The indicators were rated for 50 psia and were calibrated for temperature compensation from 77.5 K to 310 K. A movie camera was

positioned in front of the test section and black background. The yardstick, accelerometer indicator, and test section were visible in the camera field of view. A temperature indicator was installed in the test section vent line. Although this was originally intended to calibrate a backpressure regulator, it later proved a useful indicator for establishing the exit flow phase. The pressure indicators, temperature indicator and accelerometer signal were connected to a PC.

The solenoid actuated flow control valves were activated by a control panel mounted on the viewing side of the apparatus skid. The control panel enabled the operator to select "FILL", "RUN" and "STOP" functions. The helium driving pressure was set and recorded manually using differential pressure gauges located downstream of a hand adjustable pressure regulator. The "FILL" function activated valves to vent helium driving pressure and permitted saturated liquid nitrogen at 25 psig to enter the accumulator. A vent valve just upstream of the test section was also opened by the "FILL" switch to precool the nitrogen supply line to the test section and permit vapors formed in the accumulator to escape. The "RUN" function was activated after flows exiting the accumulator vent and test section supply lines were observed to be liquid. Upon activation of the "RUN" mode, all valves used for venting during the fill process were closed. Valves which isolated the accumulator from the helium

driving pressure, and the test section from the liquid supply line were opened. Simultaneous with these valve changes, the PC based data recording program began recording the instrumented pressures and accelerometer readings to a file on the hard drive. The accumulator held enough liquid nitrogen to permit run times of up to 20 seconds with helium driving pressures of 15 psig. A test period was limited by the KC-135 dive time of roughly 15 seconds, after which the "STOP" function was activated. The "STOP" function closed the test section supply line valve and the helium driving pressure shutoff valve. Fill line vents were opened to prevent pressure buildup inbetween tests. A separate heater switch located on the control panel was used to activate the nicrome wire heater on the test section quartz tube. The heater was only used between tests to eliminate any condensate from the viewing area. Although the plexiglass jacket eliminated much ambient heat transfer and condensation problems, the quartz tube was observed to gain heat and warm to high enough temperatures between such that the heating element was only needed for short (approximately 1 minute) intervals before every test run. The KC-135 typically required 3 to 5 minutes to prepare for each new test flight and did not begin each flight at regular intervals. This resulted in some variation of initial temperature conditions for the test section.

2.2 TEST PROCEDURE

A general procedure was followed for the flight testing. Before each test during the flight simulations, the "FILL" switch was depressed to fill the accumulator and precool the test section supply tubing. The helium driving pressure was hand set and recorded. Upon flight simulation beginning, the "RUN" mode was activated as soon as the accelerometer gave an indication of $\pm .05$ g. The flight camera was turned on manually immediately after the "FILL" mode was activated.

During the first series of test flights in April of 1991, some trial and error adjustment of the camera height and driving pressure settings were required to obtain consistent results which captured the quenching of the test section on the data films. Although some quenches were captured, the apparatus settings required for consistent attainment of liquid quenching were not established until the end of the April 1991 flights.

2.3 METHOD OF OBSERVATION OF VISUAL DATA

During the experimental flights, visual data was recorded on 16 mm film using high speed cameras provided and operated by NASA personnel at Ellington Air Force Base. The original

cameras used film speeds of 250, 400 and 1000 frames per second. The negatives were later copied onto new 16 mm film, played at 24 frames per second during recording. The new (24 frame/sec) 16 mm films were also copied onto standard play speed VCR tapes. Films made at an original camera speed of 250 frames per second were difficult to study and make accurate flow velocity estimates from, even after speed reduction for viewing purposes at 24 frames per second. Flight camera speeds of 400 and 1000 frames per second provided much better recordings and were used for the August 1991 flights.

The VCR tapes were studied using a 19 inch monitor. Several commercial grade VCR machines were used to screen the films and select specific film segments for close examination and velocity measurements. A Sony Digital Picture Machine Model SLV-RSUC (VCR) was used for close study and velocity measurements. The digital picture machine enabled the tape to be played at 1/2 speed, 1/5 speed and 1/30 th second viewing time increments in forward or reverse directions. The experimental apparatus yard stick appeared in most of the films and gave a good reference for distance measurements. A maximum 4.5 vertical inches of the test section was visible on the viewing screen. While the 36" high test section may have exhibited several flow patterns during any instant in time, the closer field of view used for the films permitted viewing

of at least one flow pattern at a time, sometimes capturing transitions from one pattern to the next. A few close up views excluded the yardstick reference but were scaled based on known tube diameter. Estimates of elapsed flight time were based on a time scaling factor of 24 frames per second VCR recording time to flight camera speeds of 250, 400 and 1000 frames per second. Bulk fluid flow velocities were measured three times each. Deviations between measurements generally were less than 10% for velocities up to 200 inches per second. Some drift (relative motion between fluid elements in the flow) was noted and will be discussed qualitatively, but not quantitatively measured since the visual resolution of the film was not considered sufficiently accurate.

2.4 DATA SELECTION FOR COMPARISON AND STUDY OF TRENDS

As previously stated, many of the experimental flights conducted in April 1991 did not capture quenches because of trial and error selection of driving gas pressure and camera position. In addition, the heater element, which was left on for most of the intervals between tests, created test section surface temperatures too high to quench. However, with trial and error improvements, optimum procedures for the test were learned. A few cases of complete runs with quenches were obtained from the April flights. The majority of the flights with complete quenches occurred in August 1991

flights. For this reason, the present visual study emphasizes the films obtained from the August 1991 flights. In some instances, the experiment operators began filming too late (with quench fronts already in view) or performed the procedures in such a way that a complete film including initial flow through quenching was not obtained. For this reason, studies of trends and construction of histograms have been based on selected groups of films from each flight day which appear to have complete flight time and a quench on each film included in the groups.

III RESULTS AND DISCUSSION

3.1 INTERPRETATION OF VISUAL DATA

An inherent difficulty in interpreting the visual data is validating what appearance the liquid should have when viewed in a photograph. Initial droplets of liquid which were entrained in the vapor were easily distinguishable as shiny elliptical shapes in otherwise clear flow. Initial wet vapor had a "fog-like" appearance. Throughout each flight film a bright reflection occurred on one side of the quartz tube. Flow patterns such as quench front or liquid films consistently had an asymmetric appearance being more visible on the side of the quartz tube which appeared to have a lighting reflection. This may have been due to the camera crew's flood lighting or the flight trajectory of the aircraft. The right-hand tube side (opposite the yardstick) typically showed thin liquid films as a wavering of light noticeably thicker than the reflection seen on the tube wall with no flow. A few data cases were taken with the flight camera positioned on a close-up field of view which focused on 1" to 2" of the tube, but excluded the yardstick reference. These views provided adequate detail to confirm that thickening and wavering illumination of the region of the tube wall with the reflection was indeed a type of internal flow film. Both sides of the quartz tube showed discernable liquid

flows during quenches in the camera close-up data films. Most of the data films exhibited a type of dispersed droplet flow which appeared in surging cycles. The side viewing technique used to observe the quartz tube in this experiment did not provide any simple means of proving the existence of an annular droplet distribution, nor was the existence of such a flow pattern obviously discernable when viewing the films. A consistent appearance of elongated (1/4" wide by 1 to 2" high) voids which occurred at random intervals but only along the tube centerline was the main basis for assuming that annular flow distribution was occurring in aerated flows which were otherwise difficult to characterize. In theory, statistical distribution of droplets in an annular flow pattern should be detectable by use of a gamma ray densitometer, or simpler techniques such as light transmission variations from the center to the sides of the tube as seen in the films. Spatial constraints on board the KC-135 and budgetary limitations prohibited the use of a gamma ray densitometer during this experiment. Application of light transmission techniques was considered for estimating void fraction and crude droplet distributions from the movies, but had to be abandoned due to the relatively small size of the 16 mm movie frame negatives and difficulties with grainy appearance in the developed films .

Hand sketched illustrations representing the observations

will be used to analyze the data. The original flight camera films were taken with several different ASA film types. Although the first two days of April flights used a satisfactorily high ASA film, few cases of flights with liquid quenching were captured since the appropriate driving pressure and camera position needed to photograph quenching within the 15 second KC-135 dive time limit had not been determined. The more complete runs from the August flights used a lower ASA film which had poor photographic quality after developing. Attempts to photographically copy individual frames from the 16 mm movie films yielded copies with worsened grainy appearance. The 16 mm movie films also have inherent motion and blur which causes a still frame view of one movie frame to appear slightly blurred. Many of the finer details sought in the viewing observations were not distinguishable without the aid of flow pattern motion.

Ongoing efforts to digitize and enhance the movie films are being attempted. If successful, sharper images suitable for publication and more accurate estimates of velocities and flow profiles will be obtained and made available.

3.2 RESULTS OF VISUAL STUDIES OF LOW GRAVITY FLOW PATTERNS

The data films from the flights exhibited a consistent trend of flow patterns from the beginning to end of each

flight. Hand drawn sketches of the flow patterns as they appeared from beginning to end of each run are presented for this discussion. It should be understood that the quench phenomena is an inherently unstable phenomena involving rapid flashing of liquid to vapor with sudden pressure and flow variations. In general, the flow patterns tended to change character abruptly from the character illustrated in one sketch to another. In many cases, several oscillations took place with alternating flow patterns of varying durations prior to appearance of the quench front. Each flow pattern is discussed in order of chronological first appearance in the following descriptions.

Figure III-1 illustrates the initial flow. Mostly clear vapor flow with very fine sized droplets of entrained liquid or wet vapor condensate was seen at the beginning of each test. Although the exact size and density of the droplets is not known, the liquid quality is undoubtedly very low with large spacing between the small droplets (often of a barely visible size.) Estimates of the velocity of the entrained droplets was difficult to perform accurately since the speed was typically in excess of 200 inches/second (200 - 400 estimated), the initial speed decelerated very rapidly and the particles were of barely visible size. This character of flow is described as "thin mist" flow in the observation notes and summary sheets given in the Appendix. In general, the

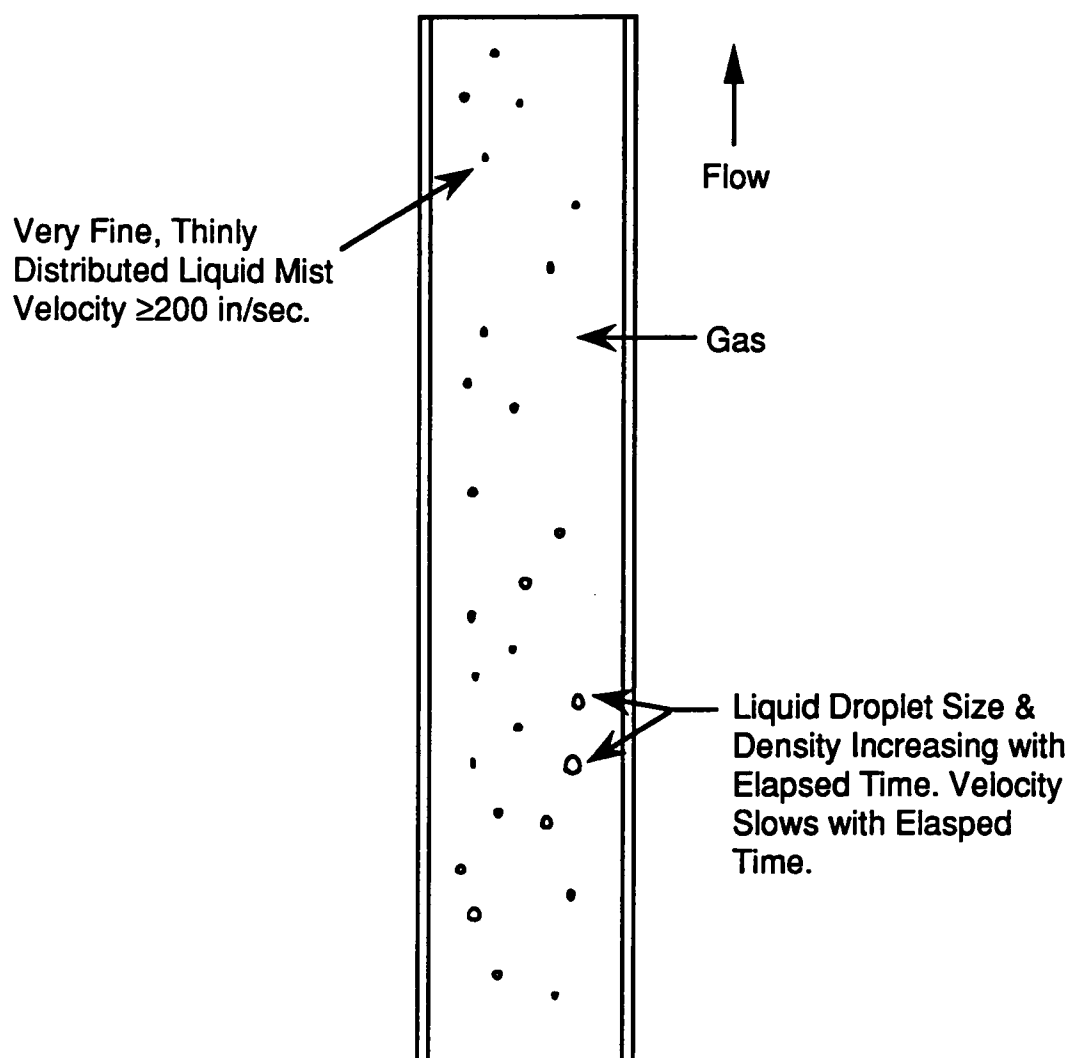


Figure III-1. Flow Description: Initial Mist Flow

initial appearance of this phase quickly slowed to a velocity of 200 inches/second with noticeably increased density of droplets, and slight increased droplet size. The duration of this phase of the flow pattern varied significantly (less than .1 seconds to several seconds of the initial flow) from flight to flight, but did appear to occur in most all cases where the camera was turned on initially (known by the brightening of flood lights and initial clear tube at the film beginning.) The duration of initial flow patterns recorded on the films also varied due to the manual procedure of starting the camera at random times after the valve opening. Two types of flow patterns followed this phase, in an apparently random order.

Figure III-2 shows a type of dispersed droplet flow which was often seen directly after the initial mist flow. A mixture of various sized droplets which appeared to be evenly dispersed (as viewed from the camera position at the test section side) was observed. Droplet sizes characteristic of this flow pattern were generally much smaller than 1/8th inch in diameter with occasional droplets of up to about 1/8th inch in diameter. Droplet shape was nearly spherical with slight elongation in the direction of flow. Larger droplets appeared to travel slightly (barely perceptible) slower than the smaller droplets. In general the speed of the entrained droplets ranged between 80 to 200 inches per second for most of the flights. The velocity of this flow phase was not

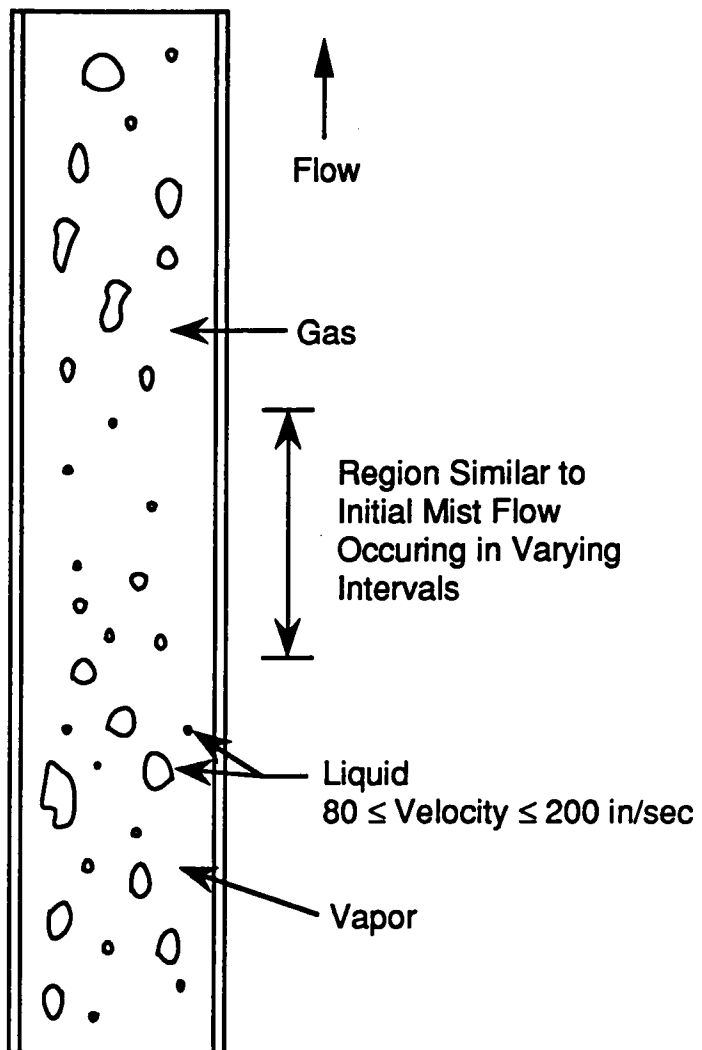


Figure III-2. Flow Description: Dispersed Droplet Flow

steady, but rather tended to accelerate and decelerate over time. Droplet size and density of distribution tended to oscillate with time as well. In some instances a trend to these variations was noticed. Flow would steadily decelerate with a corresponding increase of droplet size and/or droplet density. Then a steady acceleration with less dense droplet distribution and/or smaller size would follow. When exhibited, this trend gave a pulsating appearance to the flow with frequencies typically between 10 to 20 hertz. Although this flow pattern was not always fully established after the initial mist flow, a noticeable increase of droplet size in the initial mist flow usually took place before the next flow pattern appeared within 30% of elapsed movie film time prior to quench. Occasional brief surges of this flow pattern tended to reappear briefly (for a duration rarely exceeding .4 seconds) in a few of the films after this initial 30% of elapsed time. These elongated type droplets with meandering velocity are referred to as "filaments". Flow patterns of similar character have been observed in the work of other researchers and are generally believed to be pressure-dependent forms of transition flow or the result of liquid flow oscillating surges.

Figure III-3 illustrates an unusual flow pattern observed during the earlier portions of the flow in most of the test runs. Elongated chunks of liquid up to 1/8th inch in width

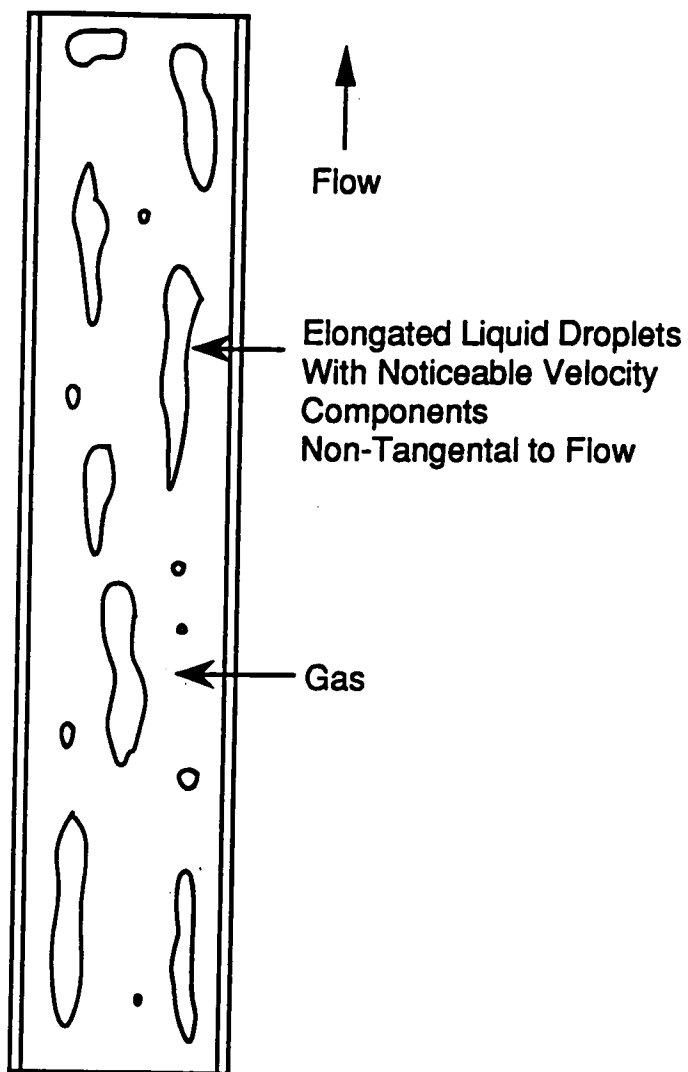


Figure III-3. Flow Description: Filamentary Flow

and of varying lengths (1/4" to 1") were observed to flow upward with random radial components of velocity. In some cases, collisions between neighboring strings took place causing a shattering of the liquid shapes into smaller droplets. The vertical velocity of this flow pattern ranged between 60 to 200 inches/second usually appearing with sudden acceleration, then gradually decelerating. Although this flow pattern did not always follow directly after the initial mist flow pattern, its appearance was concentrated in the first 10% to Prior to the appearance of the actual liquid quench front, a consistent pattern of the dispersed droplet flow pattern shown in Figure III-4A was noticed. The droplets were a liquid vapor mixture. Small vapor bubbles were observed passing from the liquid phase nucleate boiling sites through the quench region and into the liquid droplet flow downstream of the quench front. These small entrained gas bubbles gave the prequench region liquid its visibility. The liquid/vapor bubble mixture appeared as a frothy "milk shake" like mixture when high vapor generation rate existed or more like a carbonated beverage when lower vapor generation rate occurred. During the highly aerated frothy flow occurrences, elongated voids occurred in the tube center. Based on the appearance of these voids it is hypothesized that the flow pattern had an annular distribution similar to a "wispy-annular" flow type. Immediately preceding the quench, the dispersed flow velocity typically slowed to about 100 inches per second (actually

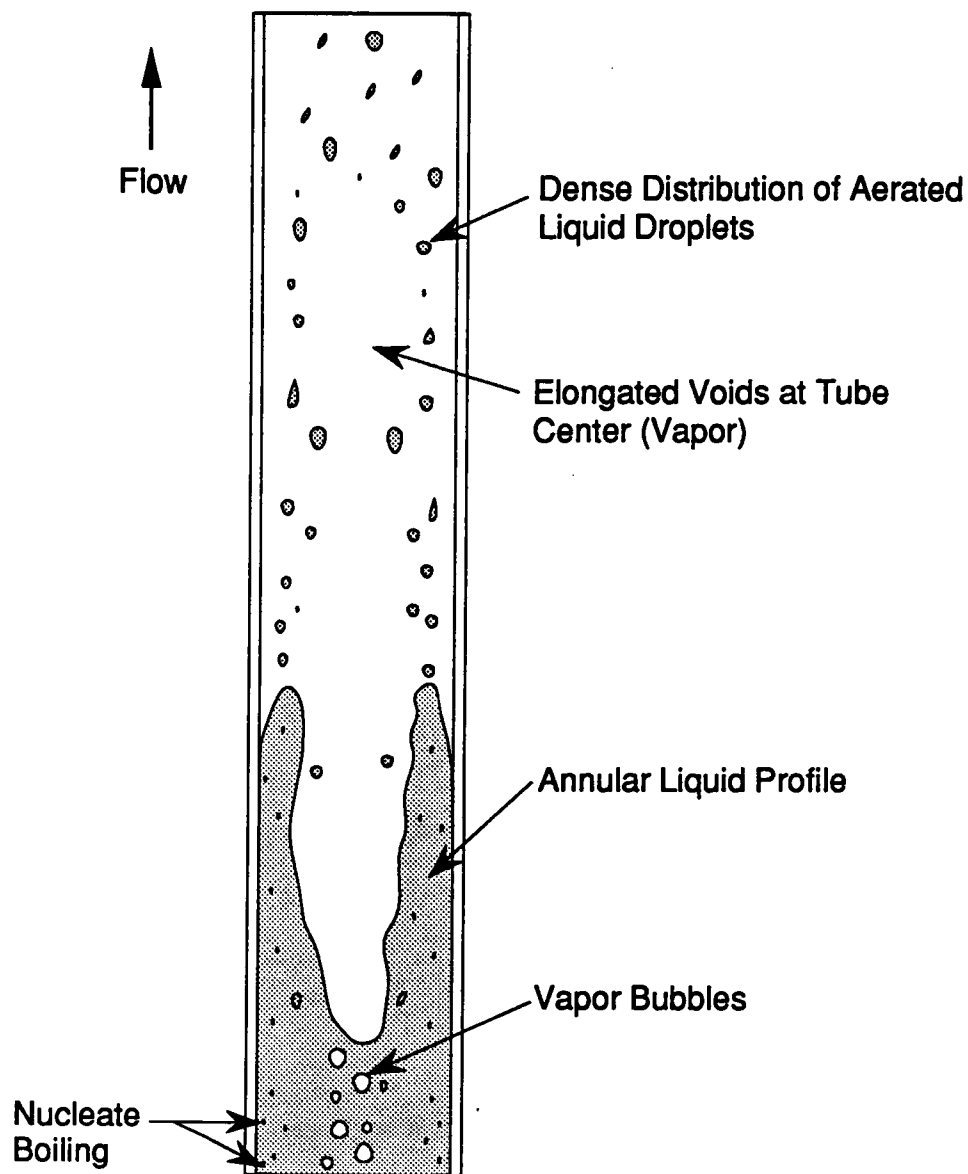


Figure III-4A. Flow Description: Quench Front With Steady Liquid Quality

observed between 75 and 150 inches/second during various tests) with a noticeable increase in density of distribution of aerated liquid droplets. The size and character of the droplets immediately ahead of the quench depended greatly on the liquid quality directly behind the quench front.

Figure III-4B illustrates a typical quench front advancing at a steady speed. This was observed to occur when vapor content in the liquid immediately behind the quench front was confined to a small region in the core of the liquid flow. Although the exact quality of the liquid flow behind the quench is not known, it could be guessed from the flow appearances that it would definitely be greater than 75% liquid mass flow. The quench front in these cases had an elongated annular profile with liquid "tongues" of about .25" to .5" for most of the tests, and as high as 2" in a few cases. The actual length of the liquid "tongue" was difficult to judge due to the high quality liquid's nearly transparent appearance. Quench front speeds ranged from .1 inch/second to about 1.5 inches/second for various flights and maintained fairly steady advance speeds while the liquid region had this high quality appearance. Flow just ahead of the quench front appeared to separate gradually from the wall as a dispersed mist and droplet flow. The appearance of a gradual wall separation, particularly in the camera close-up views supports the hypothesis that the dispersed droplet flow pattern may

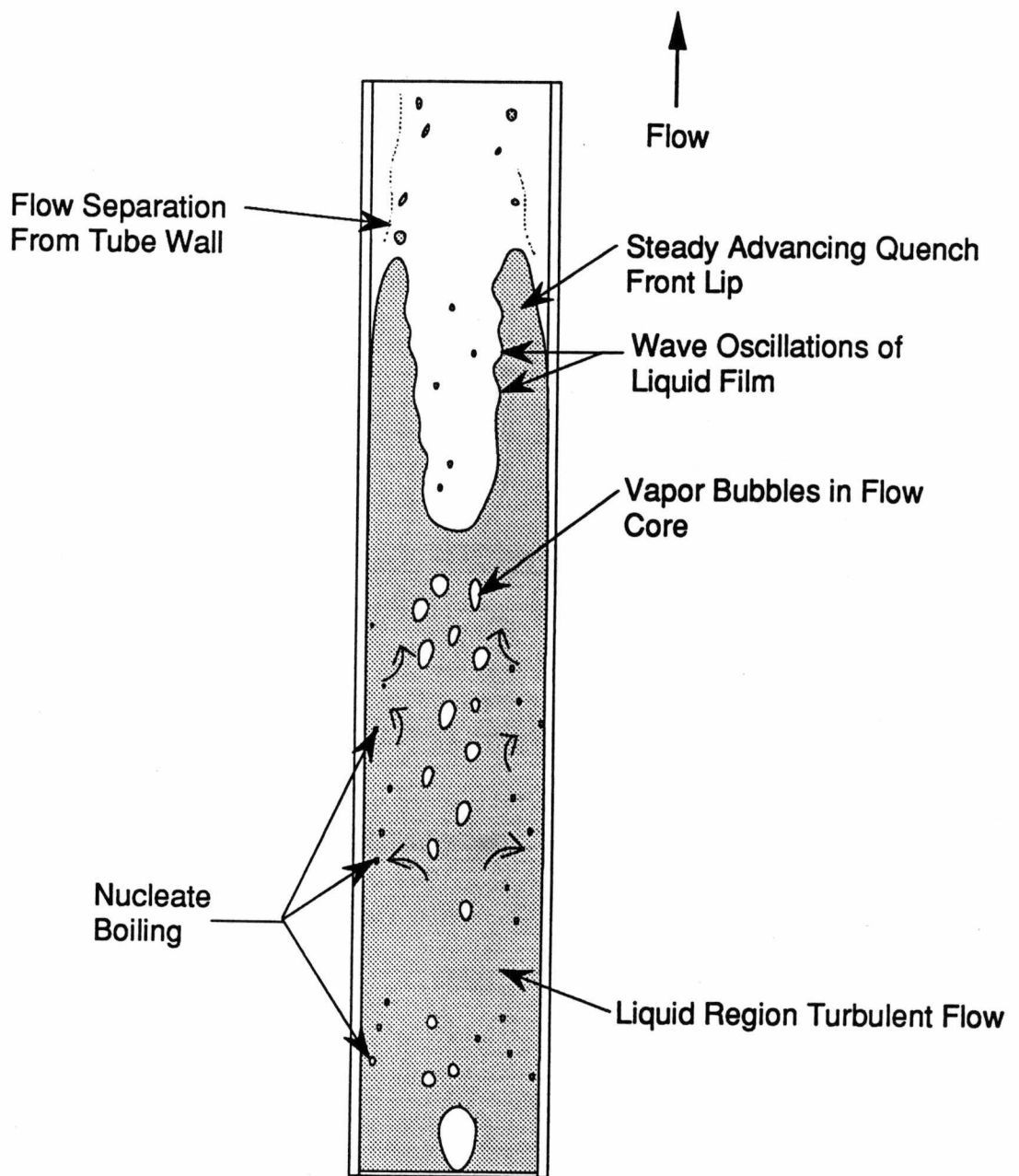


Figure III-4B. Flow Description: Post Quench Front With Steady Liquid Quality

actually have been an annular, dispersed droplet flow. Behind the quench front, the liquid region had visible nucleate boiling regions at the tube wall and turbulent liquid flow patterns as seen by the movement of small vapor bubbles leaving the boiling sites. All large gas bubbles were clearly concentrated in the core of the liquid flow region.

Figure III-5A illustrates a different type of quench front pattern seen in flight cases where the liquid flow immediately following the quench front was observed to have a very high vapor content as shown in Figure III-5B. The leading edge of this type of quench front pattern was barely perceptible as a small rounded liquid profile curving downward (parabolically) from the tube wall. Only 1/4 inch of leading edge of the liquid "tongue" was perceptible, with the rest of the liquid region appearing as a frothy foam, very high in vapor content. This type of quench front pattern was observed to eject droplets disbursing with random distribution. Ejected droplet sizes varied significantly from very dense fine mist to large chunks. It appeared that larger droplets were ejected coincident with large surges of vapor rising out of the core of the liquid immediately behind the quench in several of the films studied. This explosive phenomena generally resulted in a sudden acceleration of the quench front advance (momentary speed of 5 inches/second or faster) which gave the quench front an appearance of moving forward in

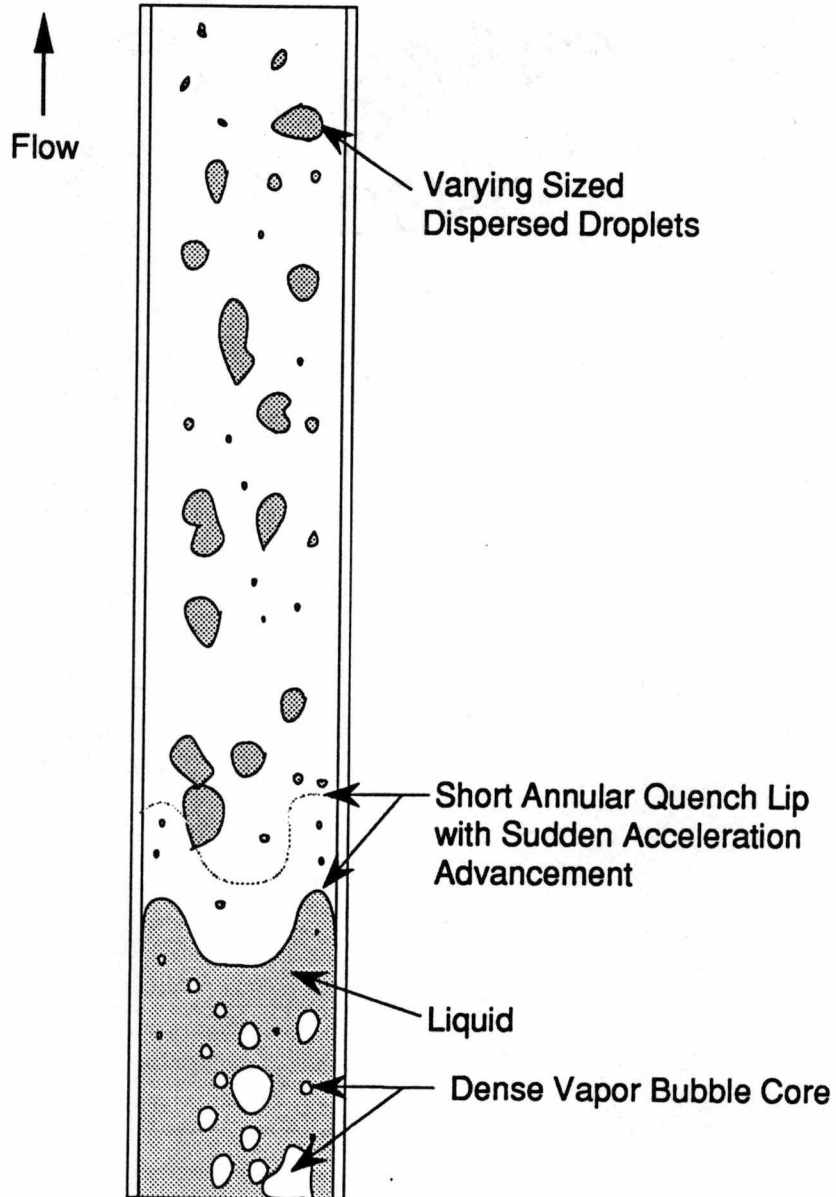


Figure III-5A. Flow Description: Quench Front With High Vapor Content In Liquid Region

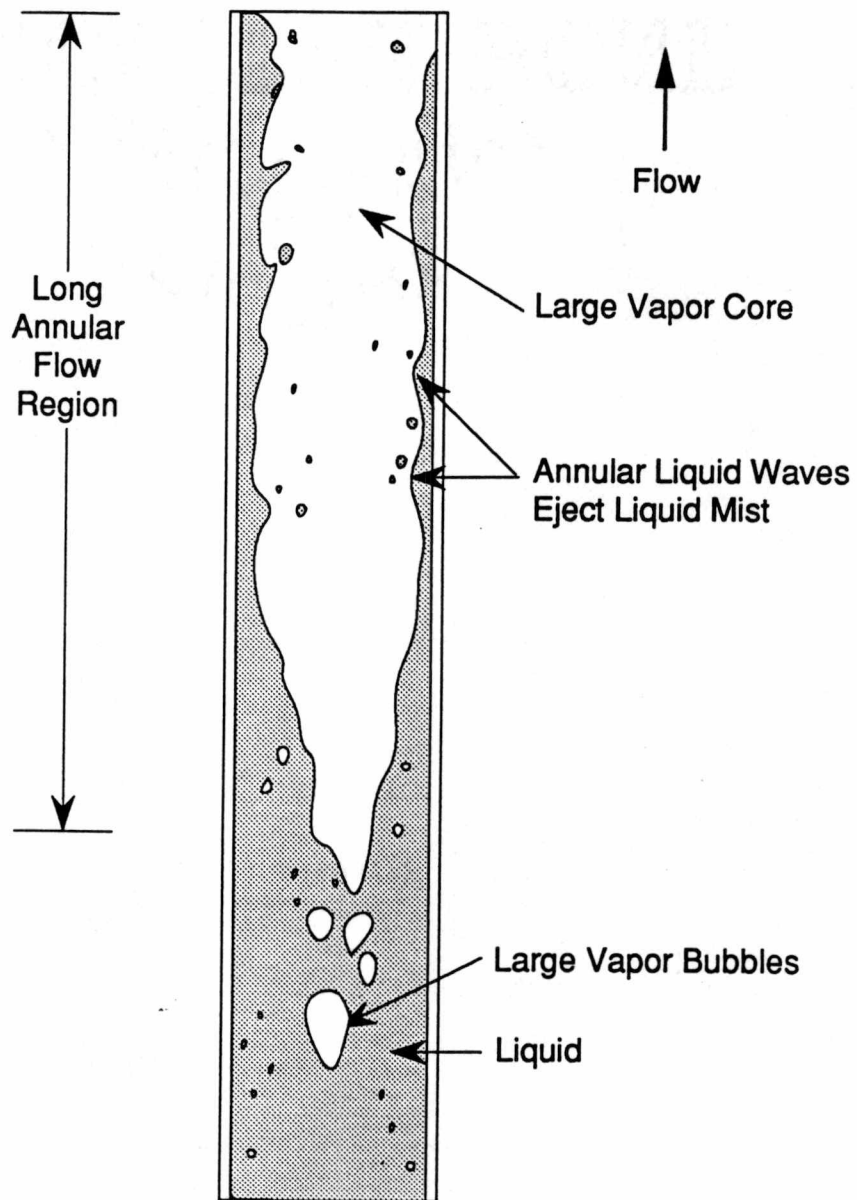


Figure III-5B. Flow Description: Post Quench Front
With High Vapor Content In Liquid Region

a step like fashion with surges of large liquid chunks being ejected in pulses with each step. The liquid region behind the quench front consisted of a thin (approximately 1/16 th inch. thick) annular liquid flow with a vapor core. In cases where adequate flight time permitted long enough filming of this flow pattern, it was seen that the annular liquid region lasted for several seconds, and was several inches long (stretching the entire field of view of the camera). The annular liquid film in this region had visible wave oscillations with very small liquid mist being ejected into the mostly gas core. After sufficient elapsed time this region was replaced with a mostly liquid flow region, which still had very large gas bubbles (1/8 th to 3/8 th inches in diameter) interrupting the liquid flow.

3.3 RESULTS OF VISUAL STUDIES OF GROUND BASED FLOW PATTERNS

Several films of the experimental apparatus were taken with the same test procedures used during the flights, for ground based data. The films obtained from the ground based runs appeared distinctly different from any of the flight films. A brief period of "thin mist" flow similar to the beginning of the flight tests occurred during the ground tests. Immediately following this, a lengthy period of annular-dispersed droplet flow occurred. Figure III-6 illustrates an overall flow pattern as would be seen over

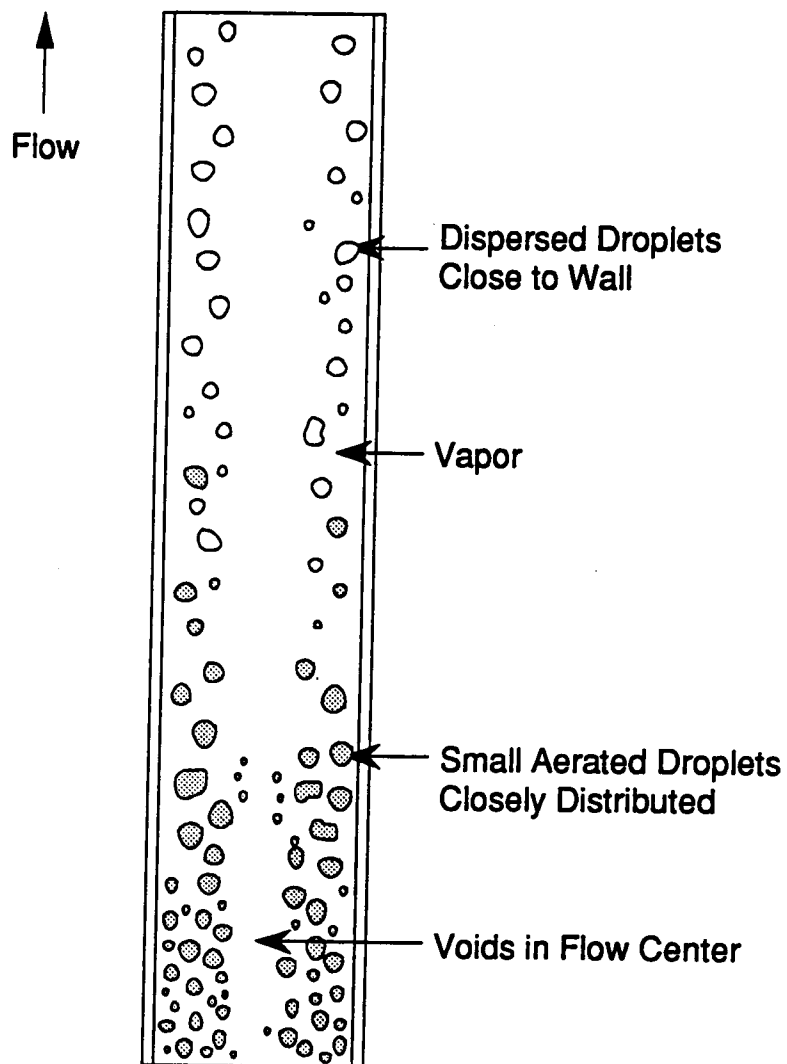


Figure III-6. Flow Description: Ground Test Initial Flow Pattern

several seconds during the early portion of a typical ground based test. Large droplets (1/16 inch diameter) were observed to flow very close to the wall with a rolling motion as if bouncing along against it. A constant void or less dense distribution of the droplets was constantly noticeable in the tube center. After several seconds this dispersed droplet flow transitioned into an aerated or frothy flow which also had noticeable voids in the tube center.

The quench front itself (illustrated in Figure III-7) was not easy to classify as annular or inverted annular since the profile was fairly transparent due to high liquid quality, and was fairly flat in appearance. Small strands of liquid issuing forth from the quench front were visible across the profile and appeared to be annular based on gradual separation from the wall for strands which happened to be located near the wall regions. Aerated liquid was seen to pass from the liquid flow region through the quench front into the prequench two phase flow region. The jagged quench front appeared to eject very long thin strings of aerated liquid which broke up gradually into shorter segments and mist sized small droplets. Velocity was typically steady throughout the film, with a slight slowing occurring gradually between initial mist flow and the flow just ahead of the quench. Abrupt velocity difference across the quench front was noticeable and steady, with a steadily advancing quench front as well. Post quench

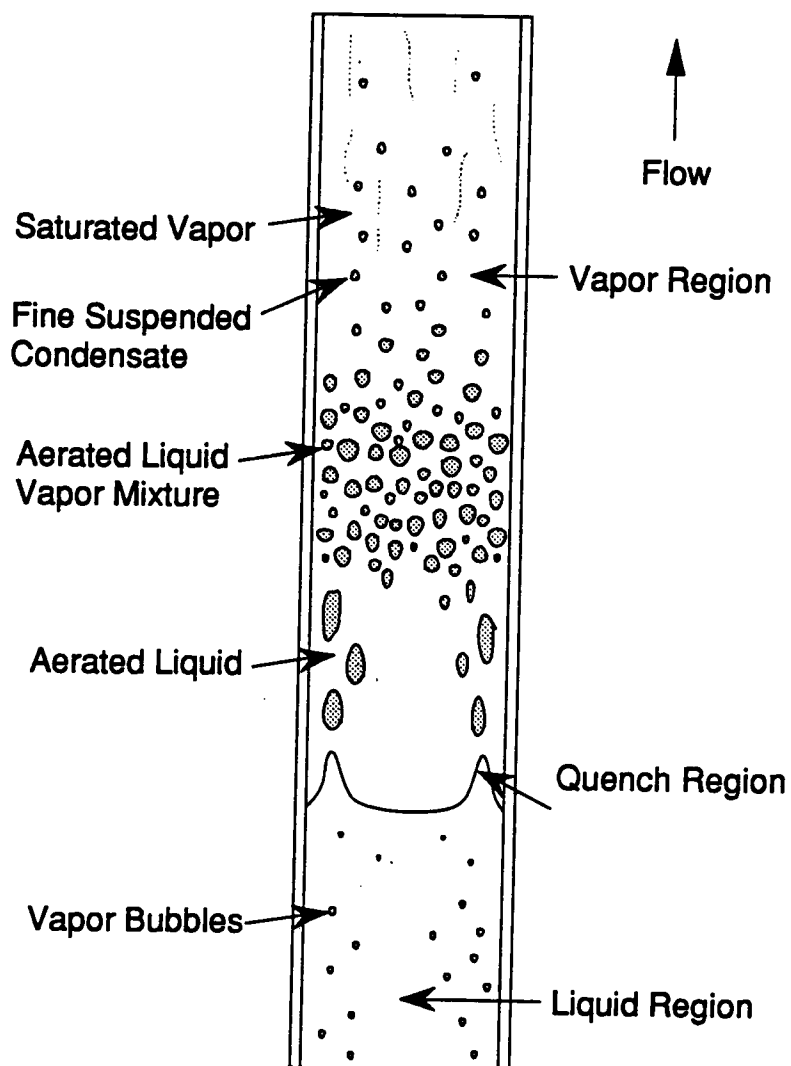


Figure III-7. Flow Description: Ground Test Quench Front Flow Pattern

liquid regions appeared mostly clear with small entrained vapor bubbles.

3.4 LOW GRAVITY PRESSURE RESPONSE DATA

Pressure response for a cooldown process is highly dependent on the length/diameter ratio for the apparatus. The magnitude of initial pressure surge increases with higher L/D values. Other parameters such as initial temperature (particularly pre-cooled entry lengths and sub-cooled liquid) contribute to high initial pressure surges. Pressure oscillations occur as slugs of liquid evaporate suddenly, producing vapor at a rate which is faster than the vapor can escape. During the peak magnitude of the pressure oscillation, ejection of liquid is thought to be retarded until the pressure can decay. Thus, the magnitude of initial pressure surge and periodic oscillations is often regarded as a measure of the cooldown process liquid propagation stability. For a more detailed analysis of the problem, refer to Steward [3].

A graph of a typical pressure response for the apparatus is shown in Figure III-8. During both low gravity simulation and ground based experiments, the apparatus exhibited initial test section inlet pressure surges of roughly 3 times the He

Figure III-8. Graph of Pressure versus Time

(For August 7, 91, Parabola #4)

The graph shows test section inlet pressure (P2), test section outlet pressure (P1) and the differential pressure drop across the test section ($P2 - P1$) as a function of test time. The pressure values were taken directly from the flight computer ASCII data file and plotted using a "Quattro Pro" spreadsheet graph program. Graphs of other test runs may be found in Appendix C.

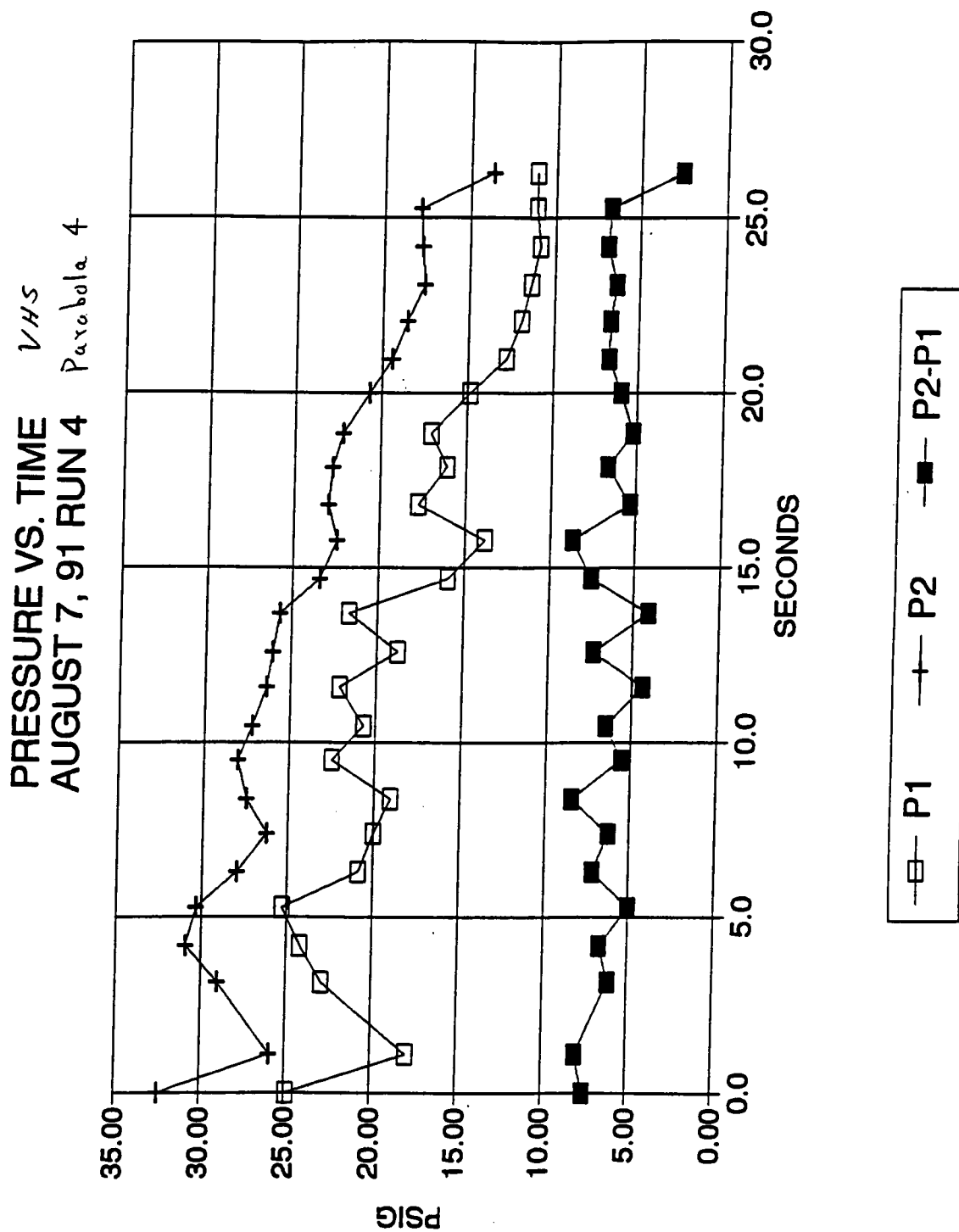


Figure III-8. Typical Test Section Pressure Response

driving pressure. This size of pressure surge is high for the L/D ratio of the test section (roughly 75) but is attributed to the effects caused by the additional exit flow tubing length and the initially pre-cooled liquid supply line. Based on the visual observation of liquid surges occurring at 10 to 20 Hz, pressure oscillations would be expected to occur more than once per second. The data recording system did not record pressure values this frequently, but given the relatively small range of pressure fluctuation compared to total magnitude oscillations can be assumed to have been on the order of +/- 0 to 3 PSI over small time periods smaller than 1 second. It is known from the visual observations that extreme flow rate instabilities such as flow direction reversal did not occur during the August flights. Also the observed velocity accelerations and decelerations observed generally stayed within an upward velocity value range of 70% to 100% of maximum velocity. Occasional exceptions where the flow appeared to come close to a complete stop occurred once or twice in a few of the tests. Having established the period of visual flow oscillations (10 to 20 Hz), it could be assumed that a data sampling system capable of recording pressure values at a rate of 50 to 200 Hz is needed to correlate the visual flow accelerations with pressure response.

From the standpoint of overall flow stability, the

pressure response is indicative of initial flow rate sudden deceleration, followed by small flow oscillations with a gradual trend toward inlet pressure equal to driving He pressure at quenched conditions.

Total cooldown times and average quench front speeds were expected to have a relationship to driving pressures in this experiment. Generally, cooldown time is known to decrease with increases in driving pressure (leading to higher flow rates). Average quench front speed should increase with higher driving pressures. These relationships are generally true for test section length/diameter ratios higher than in the range of this experiment such as $L/D > 460$ (reference Steward [3].) A typical ground based study often exhibits cooldown time versus driving pressure results as shown in Figure III-9. When comparatively short length/diameter ratios are used, the results are less predictable. With short L/D ratios, the duration of pressure surges is more significant compared to the total duration of cooldown time. In addition, entry length (particularly with saturated liquid coming from a pre-cooled length of fill line) and choking effects are often significant factors (reference Steward [3].) The data shown in Figure III-9 was obtained from ground based testing with a 12 foot tall test tube section .5 inches in diameter for vertical up-flow. The rate of travel for quench fronts is seen to decrease (as indicated by reduced slope) with

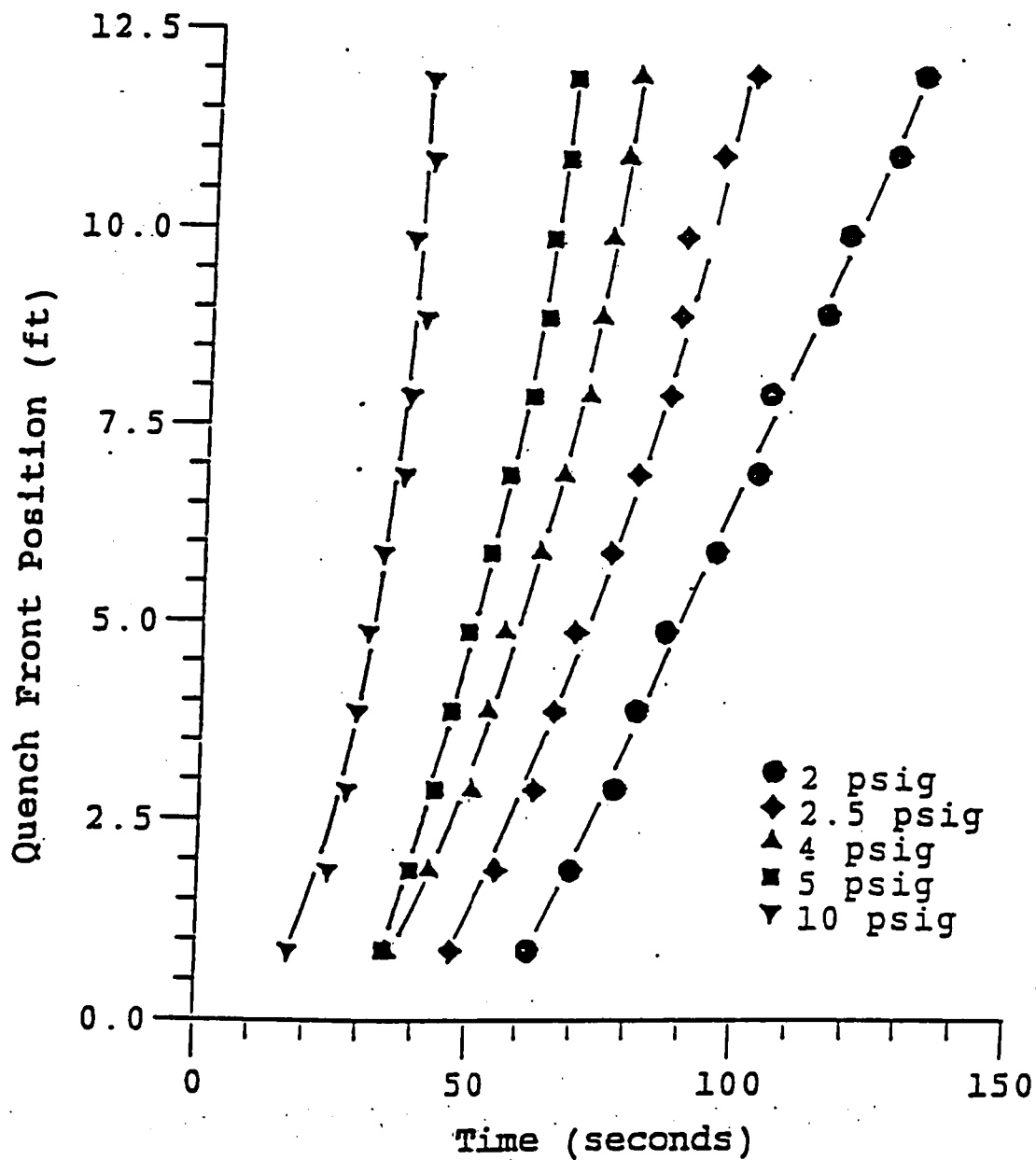


Figure III-9. Quench Front Position vs. Time For Varying Inlet Pressures (Typical of Previous Ground-Based Research)

taken from McGee [10]

decreases in driving pressure. At a given test section position, average quench front speed decreases with decreasing driving pressure. For this experiment, it was not possible to record the position of quench front over time due to the limited field of view. In addition, the procedure of starting the camera at random time intervals after the supply line valve was opened prevented accurate comparisons of position versus time for various driving pressures. Quench front speeds were not steady over short distances (.5") so average speeds as seen over the full field of view (about 5 inches) were studied for the low gravity tests. Figure III-10 shows the data obtained from the August 1991 flight tests which captured quench fronts in approximately the same field of view indicated by the apparatus yard stick markings between 12 and 17 inches. Average quench front speed did appear to increase with increased driving pressure as would be predicted from previous ground based research. This trend is not very strong, and one test at 8 PSIG driving pressure appears to conflict with the predicted response. However, considering the unsteady nature of the quench front speed and the limited number of data points, the amount of scatter in the data is not surprising. In conclusion, the correlation between driving pressure and quench front speed appeared to be the same for low gravity conditions as expected for normal gravity conditions.

Quench Speed VS Driving Press.

August 6th & 7th, 1991

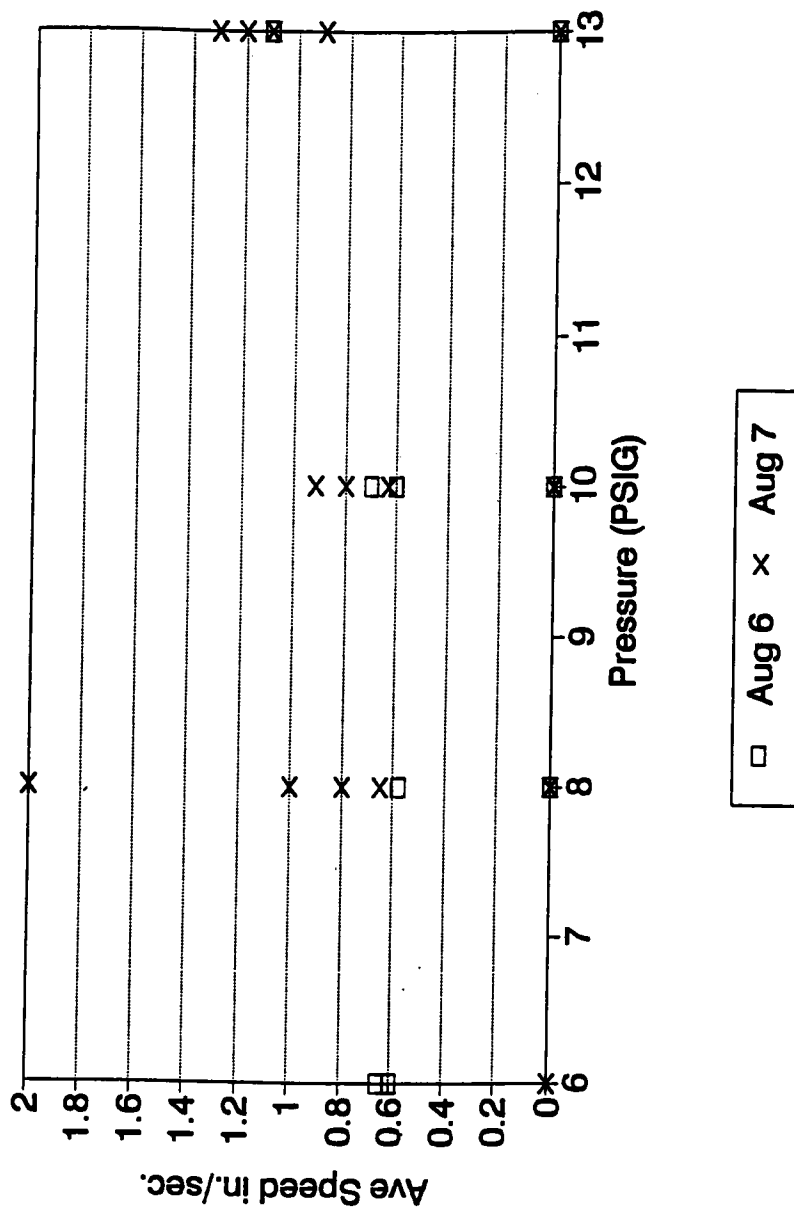


Figure III-10. Average Quench Front Speed vs. Driving Pressure
(August 1991 Flights)

3.5 DATA ON OCCURRENCE OF THE "FILAMENTARY" TYPE FLOW PATTERN

The occurrence of the filamentary type flow (see Figure III-3 on page 50) was observed only during the low gravity simulation tests. It was evident that this flow pattern occurred primarily during the early portion of each test run. Since the precise cause of this flow pattern is not known, a study was performed to determine statistically the time period over which this flow pattern was most likely to occur. If there is a significant statistical trend which locates where the flow pattern occurs during the cooldown process, other flow mechanisms known to be occurring at the same time may provide clues as to what caused the occurrence of this flow pattern. Since each test run had a unique elapsed time to quench, and varying amounts of post-quench film footage, a relative time scale based on percent of elapsed time up to the appearance of the quench front was used for the study. A type of filament occurrence histogram was constructed using timed measurements of filament appearance duration. The duration of filaments was recorded in absolute time (seconds) and as a percentage of a fixed time interval equal to 10% of the film footage length until quench. The histogram data and resulting charts are located in Appendix B. Each histogram is based on a complete flight day, and includes only tests which appeared to have a complete test (beginning at clear test section with brightening of camera flood lights and including appearance of

the quench front.) While the time scale contains the uncertainty introduced by the random starting procedure of the camera, the study is sufficient for an approximate illustration of the overall position of this flow pattern in relation to initial flow and the quench flow pattern.

Figure III-11 illustrates the average result for all complete August 1991 tests. The horizontal axis time scale represents the elapsed time between camera beginning and the citing of the quench front as a percentage from 0 to 100%. For each test case, the duration of filaments which occurred during each 10% elapsed time interval was measured and recorded as a percentage of the interval. For example, a test which had 10 seconds elapsed time between the camera start and the quench citing would be studied in 1 second intervals. A filamentary flow pattern which lasted .5 seconds would be recorded as lasting for 50% of the 1 second interval during which it occurred. The actual duration of individual filamentary flow patterns seen rarely lasted for 10% of the total elapsed time before quench time as captured on film (which would be shown as a bar 100% high in its time interval). In a few cases, this did occur, but was divided over two different time intervals. Each bar shown in the chart is an average of all of the tests. Separate charts constructed for each flight day are included in the Appendix and show a similar trend. It should be noted that individual

% Of Time Filaments occurred vs
% of Time from 0 To Quench
(AUGUST 91)

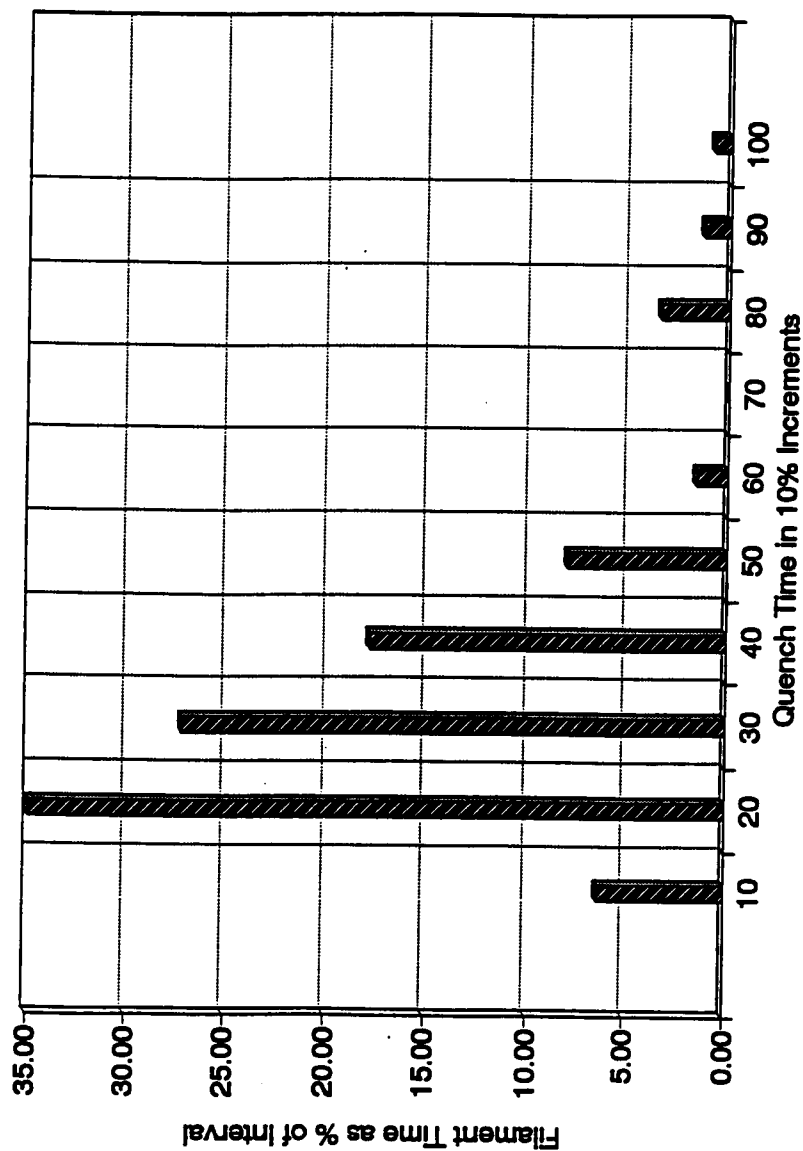


Figure III-11. Histogram of Filament Occurrence
(Average of August 1991 Flights)

tests often showed the filamentary flow pattern in just two or three of the 10% elapsed quench time intervals and occasionally at brief intervals just before the quench.

Statistically, the filamentary flow pattern was seen most frequently from 10% through 40% of the time elapsed between activation of the camera and the citing of the quench front. This roughly coincides with a time period during which several small peaks or dips in the test section pressures occurred as seen in Figure III-8 and other plots of pressure versus time given in the Appendix. It is not possible to correlate these two phenomena precisely due to the problem with synchronization of the camera. However, pressure surge would be expected to coincide with similar slug/transition flow patterns as established in previous ground based research. In contrast, similar pressure peaks occurred at the same time periods in the ground based tests, but no filamentary flows were seen. Only large droplet flows of much more regular duration were observed to occur during the ground tests. It is not likely that the low gravity filamentary flow pattern can be attributed to simple pressure fluctuation affects. At this time, the flow mechanism which causes the filamentary flow regime cannot be conclusively determined, but clues should be found if the flow mechanisms present at the statistical time of its occurrence are studied in more detail during future research efforts.

IV COMPARISON OF LOW GRAVITY OBSERVATIONS WITH NORMAL GRAVITY FLOW OBSERVATIONS

4.1 SUMMARY OF VISUAL DIFFERENCES BETWEEN LOW GRAVITY AND NORMAL GRAVITY TESTS

The following briefly summarizes the low gravity flow patterns observed:

A brief surge of "mist flow" occurred and was immediately followed by alternating "transition flow" and dispersed droplet flows. The "transition flow" took the form of large elongated liquid droplets described as filaments and appeared to occur primarily during flow surges in the first 30% of the time between test beginning and quench. The dispersed droplet flow also occurred early during the run but often continued to reappear until just before the appearance of the quench during flow velocity fluctuations. Elongated voids were not strongly noticeable in the droplet distribution at the flow center, meaning that there was no visible indication that the flow had an annular distribution similar to the "wispy annular" regime. Following this flow pattern, a "frothy flow" consisting of varying sized droplets containing both liquid and vapor bubbles occurred. The appearance of voids in the flow center were inferred to mean that this flow pattern did have a "wispy-annular" flow pattern. The quench front had a continuous (as opposed to jagged individual strands) annular

lip of varying length. The length of the quench lip and stability of advance speed was observed to increase with high liquid quality in the liquid region. Post quench regions often exhibited considerable turbulence and high vapor content, resulting in annular liquid flow in several of the data films.

Although the ground based films exhibited flows with the same initial "mist flow" as seen in the low gravity runs, the following pattern of rounded droplets in an obvious churn or "annular droplet flow" conformed to previous ground based trends (see Amestistov [2] - "wispy-annular", Rohsenow [4] - "wispy-annular"). There was a consistent absence of filamentary and apparently randomly dispersed droplet flows, which were seen in the low gravity flows. The gradual flow speed reduction and singular transition of the ground based flow pattern from "wispy-annular" to a "frothy" aerated flow was distinctly different from the abrupt oscillation of low gravity flow patterns showing fluctuating speed and alternating "frothy flow" and droplet flow patterns until the quench front appearance was very close. The quench front and post quench liquid region appearance was much more consistent in the ground based tests. High liquid quality and an apparently small "annular liquid" quench lip with jagged strands of liquid characterized the ground based quench front, while a continuous quench lip with liquid ejection patterns

and post quench liquid flow patterns dependent on fluctuating high vapor content in the liquid region characterized the low gravity quench region.

4.2 QUENCH FRONT COMPARISONS

A comparison could be made between the low gravity quench front during periods of high liquid quality, steady advance speed character and the ground based "annular flow" quench front pattern as observed by Kawaji and Banerjee [5]. This pattern was only observed to occur with sustained duration (grater than .1 seconds) in one April 11th test, four April 12 runs, two August 6th runs, and three August 7th runs (10 runs out of 32 runs with quench fronts captured on film). The rest of the low gravity movie data exhibited liquid regions with high vapor content and very turbulent liquid regions. Two April 11th, and five April 12th runs, 7 out of 13 April quenches, captured annular liquid, post quench flows at camera positions roughly 4 inches higher than the August camera position. Unfortunately this camera position was not used during the August tests since a lower percentage of successful quenches were obtainable at the higher test section location within the limited flight simulation time. It could be argued that similar effects occurred during the "unsteady annular quench" described by Kawajee and Banerjee [5], however the annular liquid flow, post quench region was not cited in their

publication. In addition, the complete absence of this high vapor quality / annular liquid, post quench region in the ground based movies made at similar apparatus settings contrasts sharply with the low gravity results. One possibility offered is the apparatus accumulator design. The accumulator was designed to vent excess vapors at the top. An annular fill/vent system included a liquid supply pipe protruding down into the accumulator while an annular sleeve permitted vapors at the top of the accumulator to escape through the annulus between the liquid line and the sleeve. Vapor generated within the accumulator may have remained at the top during normal gravity tests while mixing with the liquid during the low gravity tests. The preparatory cooldown and vent prior to each test was intended to minimize this effect as much as possible. Also, in many of the low gravity runs the vapor content in the post quench liquid region appeared to be very small bubbles similar in size to those being visibly generated at nucleate boiling sites, but in a very dense distribution. Occasional surges of large vapor bubble clusters seen during the runs may be attributed to the accumulator design, but it is likely that a higher rate of vapor generation and boiling occurred due to low gravity effects.

The liquid quench lip appeared to be much thicker and continuous in the low gravity movies, while the ground based

quench lip was observed only as thin jagged strands with very little curvature of the quench profile near the center. This difference could correlate directly with the type of downstream flow pattern differences (large filaments verses smaller annular droplet flows, frequent flow velocity and density fluctuations versus steady "wispy-annular flow", etc.) as the liquid ejected from these differing profiles would be likely to have differing distributions as well. This cannot be proven from the present data since the various flow patterns were observed at different points of elapsed time and may not have been present simultaneously.

4.3 TRANSITION FLOW AND PRESSURE OSCILLATION COMPARISONS

There is a high probability that the pre-quench flow patterns differences are due to gravitational effects. The filamentary flow pattern observed in the low gravity films showed large liquid chunks moving with random radial velocity components, while smaller sized droplets shown in the normal gravity tests appeared to flow along a straight axial path, excepting the wall region where the droplets apparently "bounced and rolled" in a narrow region near the tube wall. This churn flow mechanism was not nearly as pronounced, if it occurred at all in the low gravity droplet flows. There was the presence of continuous velocity surging in low gravity tests, where as normal gravity tests showed continuous gradual

velocity changes, which represents significant differences in behavior. It is possible that higher rates of liquid ejection from the low gravity quench front mechanism resulted in small pressure fluctuations and subsequent velocity changes. In Appendix C charts of the test section inlet and outlet pressure measurements show considerable fluctuation over time, although sampling was not performed at small enough intervals (10 to 20 hz velocity fluctuations observed versus 1 hz sampling) to correlate this from the data.

One experimental parameter was not controlled identically during low gravity and normal gravity test runs. During the flight profile taken by the aircraft to simulate low gravity atmospheric back pressures on the system varied from roughly 7 psia at 30,000 ft to roughly 12 psia at completion of the flight dive simulation. With initial inlet pressure surges measured at 25 psi gauge (relative to a cabin pressure maintained at about 12 psia) the differential pressure across the apparatus typically fell within a choked vapor flow driving pressure range throughout the entire flight run. However, similar pressure surges (25 psi gauge relative to 14.696 psia standard atmosphere) also occurred during the ground tests, and should also have caused similar choked vapor flow effects to occur during most of the ground tests.

V CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The movies obtained from the ground based tests of the apparatus appear to have two phase flow patterns consistent with those classified by previous researchers. The low gravity test films show several differences from the ground based results that are likely attributable to flow and boiling mechanism differences occurring in a low gravity environment. The primary flow pattern differences which occurred in the low gravity simulations are summarized below.

- 1) The low gravity boiling region contained much higher vapor content and more vigorous boiling. In several cases an annular liquid flow, similar to the "annular / annular mist" flow regime described by Hill and Downey [7], occurred in the post quench liquid region.
- 2) The low gravity quench front lip appeared to be noticeably thicker and to have a steeper meniscus at the test section wall than the normal gravity profile.
- 3) In low gravity, transition flows consisting of filaments and dispersed droplets occurred with random axial components of velocity. These velocity

characteristics were either absent or much less pronounced in the normal gravity test runs.

4) The filamentary transition flow regime occurred only in the low gravity tests, during the initial portion of the run. This contrasts sharply with the previously classified "wispy- annular" dispersed droplet regime which consistently occurred with a much longer duration during the normal gravity runs.

5) Velocity fluctuations and flow surges occurred within a consistent range of frequencies during the low gravity tests, where as the ground based runs had gradual consistent velocity decelerations.

It is the unproven opinion of this observer that the low gravity effects were most significant in two regions of the flow. The liquid's nucleate boiling region's much higher rate of vapor generation and inherently higher heat transfer, is assumed to be attributed to the low gravity environment. The apparent differences in vapor bubble pickup and shedding mechanisms as cited by Dukler [6] supports the notion that the nucleate boiling regions may generate vapor more rapidly in a low gravity environment. The other liquid region differences (high vapor content, and annular liquid flows) are byproducts of the vapor generation rate which have been induced in some

of the previously discussed experiments where liquid/vapor mixtures were controlled by injection of the separate phases.

The quench front region, with a profile of more gradual curvature away from the wall and thicker liquid lip thickness differs from the ground based tests in a manner which is predictable considering the greater effect of surface tension/adhesion effects in the reduced gravitational field. Although surface tension should approach zero for a saturated liquid, the cooldown process is known to create superheated vapor/liquid mixtures, high pressure surges and other non-thermal equilibrium conditions. The ejection of large elongated filaments would be a logical byproduct of the thick quench lip which was observed to have propagating wave fronts causing breakage during flow velocity decelerations in some of the April test flights.

Several hypothesis might be suggested to explain the above findings, both due to apparatus limitations and actual low gravity differences in two-phase flow mechanisms. However, the real purpose of this study was to identify as many potential flow differences as possible so that requirements for future testing and data gathering capability can be established for further experiments. The differences between the low gravity and normal gravity tests as outlined above provide an adequate basis for improving on the experiment.

5.2 RECOMMENDATIONS

Because of the limited space allowed with the present KC-135 flight simulations, many techniques employed in past ground based research are difficult to implement. Other effects such as initial entry length flow patterns versus fully developed flow are not likely to be addressed without the use of test sections or multiple camera stations which are larger than that which is currently manageable on board the KC-135 aircraft.

Several modifications to the apparatus and test section are currently being performed which should provide additional data. The quartz tube test section will be equipped with specially bonded thermocouples with a low thermal resistance bond. Synchronization of the movie film with the pressure and temperature data should also be attempted either with a visual readout display captured both on the film and the computer data, or by automated camera on/off release. A much higher rate of sampling (50 hz) is needed for the pressure measurements to explore correlatations between visual flow patterns of ejected liquid clusters and possible periodic effects. Obtaining temperature data which is synchronized with the visual flow data as well as visual data taken at camera positions just a few inches higher (as in the April 91 flights) should provide enough information to correlate the sequential occurrence of flow patterns occurring downstream of

the quench front at a single instant in time. The use of wide angle still photographs capturing the entire test section, and taken at regular time intervals should also provide a better means of describing how the overall flow pattern in the test section varied with time. Some analytical measurement of flow density and chordal distribution at varying locations should be performed in the future. While current gamma-ray densitometer equipment does not fit the spatial and safety constraints of the KC-135, optical properties of light intensity and frequency shift currently applied with laser based equipment provide another means of estimating flow density and distribution. This option may be attempted at later dates. At present, the first cases of data films which have been digitally enhanced are being viewed with noticeable improvements in details of distribution and particle sizes. However, an insufficient quantity of digitized footage is available for precise characterization of the tests since the digitization is both more costly and time consuming than affordable within the means of the present study. The digitization is a likely means of improving upon the results in the future however, and publication of more detailed actual photographs from the tests is anticipated.

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APPENDICES

APPENDIX A

LOW GRAVITY TEST VISUAL OBSERVATION SUMMARIES

FLIGHT DATE: APRIL 10, 1991

PARAB. NUMBER DELVAR PSI G's	FILM ROLL CAM SPD HI/MILLI QUENCH Y/N	FIELD OF VIEW INCHES HI/LO	PICTURE QUALITY	FILAMENT YES/NO DROPLET SIZE	TIME TO QUENCH TOTAL TIME QUENCH SPD INCHES/SEC	LIQUID QUALITY UPSTREAM OF QUENCH	LIQUID QUALITY DOWNST. OF QUENCH
10 13 PSI	1 MILLI N	6.5 10.75	AUE	Y SM/LRG	21.1		LARGE DROPLETS
11 6 PSI	1 MILLI N	6.5 10.75	AUE	Y MED	18		FINE TO MED DROPLETS
12 6 PSI	1 MILLI N	2.0 6.25	AUE	Y LARGE	13.9		LARGE DROPLETS
14 6 PSI	1 MILLI N	2.0 6.25	AUE	Y MED	15.9		MED SIZED DROPLETS
16 6 PSI	2 MILLI N	11.0 15.25	AUE	Y VARIES	13		OCCASIONAL DROPLETS
17 6 PSI	2 MILLI N	11.0 15.25	AUE	Y LARGE	17.3		LARGE QUANT. DROPLETS
18 6 PSI	2 MILLI N	11.0 15.25	AUE	Y MED/FINE	6.6		ALTERNATING MED/FINE DROPLETS
19 6 PSI	2 MILLI N	6.75 11.0	AUE	Y MED/FINE	20.6		FEW DROPS
20 6 PSI	2 MILLI N	6.75 11.0	AUE	Y SMALL	17.1		MOSTLY GAS
23 13 PSI	3 MILLI N	?	AUE	Y SMALL	24.2		MOSTLY GAS
25 13 PSI	3 MILLI N	?	AUE	Y MED/FINE	14.1		LOTS OF SMALL MED DROPS
28 13 PSI	3 MILLI N	?	POOR WASHED OUT	Y SMALL	23.2		FINE DROPS
31 13 PSI	3 MILLI N	?	POOR WASHED OUT	Y SMALL	12.12		LOTS OF FINE DROPS
33 13 PSI	4 MILLI N	12.0 16.25	AUE	Y MED	12		MED. DROPS
35 13 PSI	4 MILLI N	12.0 16.25	AUE	Y MED/FINE	21		ALT. MED/ FINE DROPS

FLIGHT DATE: APRIL 10, 1991

PARAB. NUMBER DOWN PSI S's	FILM ROLL CAM SPD M/MI QUENCH Y/N	FLOW DESCRIPTION UPSTREAM OF QUENCH	FLOW DESCRIPTION DOWNSTREAM OF QUENCH	OBSERVATIONS
10 13 PSI	1 MILLI N			EVENLY DISTRIBUTED DROPLET FLOW-SLOW OCCASIONAL FLUCTUATIONS FROM LARGE TO SMALL DROPS
11 6 PSI	1 MILLI N			EVEN DROPLET FLOW-FAST CONDENSATION PARTIALLY BLOCKS VIEW
12 6 PSI	1 MILLI N			LARGE DROP/SLUG FLOW WITH VARYING SPEED PARTIAL CONDENSATION BLOCKAGE
14 6 PSI	1 MILLI N			CLEAN INITIAL GAS FLOW, INCREASING DROPLET SIZE
16 6 PSI	2 MILLI N			VARYING SIZES OF DROPLET FLOW-SLOW COULD MEASURE DIST. FLOW STOPS NEAR RUN END
17 6 PSI	2 MILLI N			VARYING SIZES OF DROPLET FLOW COULD MEASURE DIST.
18 6 PSI	2 MILLI N			FAST DROPLET FLOW OF VARYING SIZES
19 6 PSI	2 MILLI N			FAST MED/FINE DROPLETS, MOSTLY GAS INITIALLY CHUNKS OR SLUGS BREAKING UP NEAR RUN END/ HIGH QUALITY
20 6 PSI	2 MILLI N			DROPLETS APPEAR AND INCREASE IN SIZE/QUALITY PARTIAL CONDENSATE BLOCKAGE
23 13 PSI	3 MILLI N			INITIAL FINE DROPLETS INCREASE IN SIZE AND QUALITY OCCASIONAL LARGE DROPLETS, QUALITY BECOMES HIGH NEAR RUN END
25 13 PSI	3 MILLI N			LOTS OF DROPLETS, QUALITY APPEARS TO BE HIGH
28 13 PSI	3 MILLI N			VERY LARGE CHUNKS/ SLUGS OCCUR AT TIMES DURING RUN
31 13 PSI	3 MILLI N			MED. AND SMALL DROPLET FLOW OF HIGH QUALITY FOLLOWED BY LARGE DROPLET FLOW
33 13 PSI	4 MILLI N			QUALITY AND DROP SIZE APPEAR TO INCREASE PARTIAL CONDENSATE BLOCKAGE
35 13 PSI	4 MILLI N			FLOW OSCILLATES BETWEEN MED/SMALL DROPLETS SMALL DROPLET FLOWS APPEAR TO BE FASTER

[illegible]

[illegible]

FLIGHT DATE: APRIL 11, 1991

PARAB. NUMBER DEBAR PSI 6's	FILM ROLL CAM SPD HI/MILI QUENCH Y/N	FIELD OF VIEW INCHES HI/LO	PICTURE QUALITY	FILAMENT YES/NO DROPLET SIZE	TIME TO QUENCH TOTAL TIME QUENCH SPD INCHES/SEC	LIQUID QUALITY UPSTREAM OF QUENCH	LIQUID QUALITY DOWNST. OF QUENCH
*****	*****	*****	*****	*****	*****	*****	*****
3	5	16.0	AUE	Y	4.6	ANNULAR LIQ.	ANNULAR WALL
13 PSI	MILLI	18.0		SMALL	5.67	ENTRAINED	SEPERATION
	Y				?	DROPLETS	OF MIST!
4	5	16.0	AUE	Y	?	POOR, LOTS	HIGH, MANY
13 PSI	MILLI	18.0		MED	23.6	OF GAS	DROPS
	Y				?	BUBBLES	
5	5	16.0	AUE	Y	4.42	ANNULAR	THIN MIST
13 PSI	MILLI	18.0		MED	5.45	WAVES	ANNULAR
	Y				4		
7	5	14.0	AUE	Y			
13 PSI	MILLI	15.0		FINE	10		
	N						
8	6	12.75		Y			
13 PSI	MILLI	17.0	GOOD	LARGE	25.3		
	N						
10	6	12.75		Y			
13 PSI	MILLI	17.0	AUE	MED/FINE	22.6		
	N						
12	6	13.0		Y			
13 PSI	MILLI	17.25	AUE	FINE	18.1		
	N						
13	7	12.75		Y	1	ANNULAR LIQ	VARYING MIST
13 PSI	MILLI	17.0	GOOD	MED &	18.4	LOTS OF GAS	DROPLETS
	Y			LARGE	?	AT CENTER	
16	7	9.75		Y			
13 PSI	MILLI	14.0	AUE	LARGE	18.8		
	N						
18	7	9.75		Y			LARGE DROPS
13 PSI	MILLI	14.0	AUE	FINE	15.6		OR CHUNKS
	N						
20	7	9.5		Y			
13 PSI	MILLI	13.75	AUE	CHUNKS	12.7		
	N			DROPS			
*****	*****	*****	*****	*****	*****	*****	*****

PARAM. NUMBER DEWAP PSI G's	FILM ROLL CAM SPD HI/MI/LLI QUENCH Y/N	FLOW DESCRIPTION UPSTREAM OF QUENCH	FLOW DESCRIPTION DOWNSTREAM OF QUENCH	OBSERVATIONS
3 13 PSI	5 MILLI Y	MED. LIQUID DROPLETS HIGH GAS FLOW WITH ANNULAR LIQUID	ANNULAR MIST	DROP SIZE AND QUALITY INCREASES, LIQUID WAVES SEEN ON WALL GOOD PROFILE OF QUENCH AND SEPERATION FROM WALL
4 13 PSI	5 MILLI Y	LARGE GAS BUBBLES	PULSING MED DROP FLOW	LOTS OF MED/LARGE DROPS SEEN. QUALITY HIGH DOWNSTREAM PARTIAL CONDENSATE BLOCKAGE
5 13 PSI	5 MILLI Y	SMOKEY APPEARANCE LARGE GAS BUBBLES VIS.	LIQUID TONGUES (LIKE FLAMES) AND MIST WALL SEPERATION	QUENCH PASSES QUICKLY ON THIS SCALE. GUESS HIGH SPEED. QUENCH PROFILE RESEMBLES FLAME SHAPE. DROPLETS AND MIST EJECTED. POOR LIQUID QUALITY.
7 13 PSI	5 MILLI N			INCREASING QUALITY AND DROP SIZE NOTED
8 13 PSI	6 MILLI N			CHUNKS OF LIQUID DISPERSING INTO DROPLETS SEEN SPEED VARIES. CAN BE MEASURED
10 13 PSI	6 MILLI N			ALTERNATING DROPLET/CHUNK FLOWS, SPEED INCREASES WITH SMALL DROP SIZES
12 13 PSI	6 MILLI N			INITIAL FINE MIST FLOW CONDENSATE BLOCKS 17.25 - 15.0
13 13 PSI	7 MILLI Y	ANNULAR LIQ. PULSING GAS BUBBLES AT CORE. LIQUID WAVES SEEN	LARGE DISPERSING DROPS	SUPER LONG ANNULAR REGION WITH LIQ. WAVES ON WALL QUENCH FRONT IS EARLY, APPEARANCE IS HARD TO DETECT VALLEY OF QUENCH PROFILE APPEARS VERY CLEARLY
16 13 PSI	7 MILLI N			SLIGHTLY ELONGATED LARGE DROPS OBSERVED
18 13 PSI	7 MILLI N			INITIAL CLEAR GAS QUICKLY CHANGES TO LARGE DROPS AND CHUNKS OF DISPERSING LIQUID
20 13 PSI	7 MILLI N			DROP SIZE AND QUALITY VARIES, RUN IS TOO SHORT

FLIGHT	DATE:	APRIL 12, 1991					
PARAB. NUMBER DEWAR PSI 6's	FILM ROLL CAM SPD HI/MILI QUENCH Y/N	FIELD OF VIEW INCHES HI/LO	PICTURE QUALITY	FILAMENT YES/NO DROPLET SIZE	TIME TO QUENCH TOTAL TIME QUENCH SPD INCHES/SEC	LIQUID QUALITY UPSTREAM OF QUENCH	LIQUID QUALITY DOWNST. OF QUENCH
*****	*****	*****	*****	*****	*****	*****	*****
2	8	7	GREAT	Y	22.7	ANNULAR	ANNULAR FILM
12 PSI	MILLI			LARGE	23.9	WAVES SEEN	LIQ. SPLASHIN
	Y				1.5		OCEAN LIKE
3	8	7	GOOD	Y			
12 PSI	MILLI			FINE	23		
	N						
5	9	10.0		N			
12 PSI	MILLI	14.25	AVE	CLEAN			
	N			GAS			
7	9	9.75		Y			
12 PSI	MILLI	14.25	AVE	MED/FINE	31.8		
	N						
9	9	13.5		Y	8.9	SIGNIFICANT	FROTHY
12 PSI	MILLI	17.75	GREAT	MED	10.76	GAS IN FLOW	
	Y				5.75	CORE	
10	10	13.25		Y	13.9	WISPY GAS	FROTHY
12 PSI	MILLI	17.5	GOOD	FINE	17.25	RINGS, BUBBLE	ANNULAR
	Y				2.6	OCCASIONAL	FILM
11	10	13.25		Y	9.1	TURBULENT	MED SIZED
6 PSI	MILLI	17.5	GOOD	MED/FINE	11.6	ANNULAR	DROPLET FLOW
	Y				5.5	LIQUID	SOME MIST
12	10	13.25		N			
6 PSI	MILLI	17.5	POOR	CLEAR	3.8		
	N		SHORT				
13	10	13.25		Y			
6 PSI	MILLI	17.5	AVE	LOTS OF	12.2		
	N			MED			
14	10	13.25		Y			
6 PSI	MILLI	17.5	POOR	MED/FINE	2.6		
	N		SHORT				
15	11	13.75		Y			
6 PSI	MILLI	18.0	AVE	MED/FINE	15.1		
	N						
21	11	13.5		Y	10.35	VERY	DROPS/
15 PSI	MILLI	17.75	GOOD	FINE	25.2	CLEAR	SLUGS
	Y				1.15		
23	11	13.5		Y			
15 PSI	MILLI	17.75	POOR	FROTH	5.2	LONG SLUGS	NOT SEEN
	N		SHORT				
24	12	8.75		Y	8.1	MOSTLY CLEAR	PULSING
15 PSI	MILLI	13.0	AVE	MED/FINE	8.5	SHORT ANNULAR	MIST
	Y				4	REGION	
31	12	8.75		Y	4.1	LOTS OF GAS	LOTS OF DROPS
15 PSI	MILLI	13.0	GREAT	MED/LARG	15.7	VERY LONG	DOWNSTREAM
	Y				3.9	ANNULAR	
*****	*****	*****	*****	*****	*****	*****	*****

FLIGHT	DATE:	APRIL 12, 1991		
PARAB. NUMBER	FILM ROLL	FLOW DESCRIPTION UPSTREAM OF QUENCH	FLOW DESCRIPTION DOWNSTREAM OF QUENCH	OBSERVATIONS
DOWNR PSI	CAN SPD			
6's	MILLI QUENCH Y/N			
2	8	NOT SEEN LONG, GUESSED	LONG ANNULAR WAVES	EXCELLENT QUENCH AND ABOVE. DROPLET FLOW WAS
12 PSI	MILLI	QUENCH SPEED	SPLASHING	WELL ROUNDED DROPLETS. LIQUID REGION NOT SEEN FOR MORE
	Y			THAN A SECOND
3	8	NOT SEEN		FLOW SLOWS AS DROP SIZE INCREASES, FLOW OSCILLATES
12 PSI	MILLI			BETWEEN FINE MIST AND LARGE CHUNK/DROPLETS
	N			CHUNKS APPEAR TO HUG TUBE WALL
5	9			NO FLOW SEEN
12 PSI	MILLI			
	N			
7	9			FAST FLOW, DROPLETS AND CHUNKS APPEAR CLOSE TO WALL
12 PSI	MILLI			SUSPECT ACCUMULATOR RAN OUT, FLOW LOOKED LIKE IT
	N			SHOULD HAVE QUENCHED, BUT STOPPED
9	9	LOTS OF LARGE BUBBLES	FROTHY FLOW	LOTS OF DROPLETS OF MED/FINE SIZE STEADY SPEED
12 PSI	MILLI	ANNULAR/ GAS CORE	WOULD GUESS ANNULAR	STEADY ANNULAR QUENCH. WOULD GUESS DRIVING FORCE WAS
	Y	CLEAR QUICKLY		STEADY AND THAT THIS WAS A GOOD MODEL CASE.
10	10	VAPOR FALLS OFF 2-3 IN	FILM OF SLUG/FROTH HUGS	FAST MED/FINE DROPLETS LOOK ALMOST ANNULAR FROM BEGINNING
12 PSI	MILLI	BEHIND QUENCH	TUBE WALL	ANNULAR REGION OF QUENCH LOOKS TO BE ABOUT 1 IN. LONG
	Y			QUENCH TAKES DISTINCT JUMPS FORWARD, AVE SPEED GIVEN
11	10	LARGE LIQ. SLUGS WITH GAS	MED DROP/CHUNK FLOW LOOKS	FLOW ALTERNATES SPEED/SIZE. CONDENSATE PARTIAL BLOCKAGE
6 PSI	MILLI	POCKETS	ANNULAR	QUENCH PROFILE OF VALLEY IS PRETTY GOOD
	Y			QUENCH SPEED IS STEADY
12	10			ONLY INITIAL FINE MIST SEEN
6 PSI	MILLI			
	N			
13	10			FAIRLY ROUND MEDIUM DROPLETS, QUANTITY & SPEED VARIES
6 PSI	MILLI			OCCASIONAL REGIONS OF CLEAR GAS FLOW
	N			
14	10			FAST FLOW IS CUT OFF SHORT
6 PSI	MILLI			
	N			
15	11			FLOW OSCILLATES BETWEEN FAST FROTH, SLOW MED DROPS
6 PSI	MILLI			FROTH FLOW TENDS TO PULSE, OCCASIONAL EXTRA LARGE CHUNK
	N			OR SLUG SEEN
21	11	OCCASIONAL GAS RINGS	DROPS/ OCCASIONAL CHUNKS	FAST INITIAL MIST THICKENS TO FROTH. QUENCH PROFILE
15 PSI	MILLI		BREAKING UP	LOOKS ABOUT .5 TO 1 INCH LONG AND IS NOT STEADY
	Y			
23	11	LONG SLUGS	NOT SEEN	LOOKS LIKE POST QUENCH FLOW, LONG LIQUID REGIONS WITH
15 PSI	MILLI			OCCASIONAL GAS POCKETS
	N			
24	12	OCCASIONAL HISSY RINGS	FINE MIST FLOW	VERY BRIEF INITIAL FILAMENT FLOW. GOOD DRIVING LIQUID
15 PSI	MILLI	MOSTLY CLEAR		
	Y			
31	12	TURBULENT LIQ. AND GAS	ANNULAR FLOW FORWARD, DRO	THE DRIVING LIQUID AFTER THE QUENCH SHOWED FLOW REVERSAL
15 PSI	MILLI	SOME ANNULAR LIQUID FLOW	FLOW SPLASHING DURING	AND CONSEQUENTLY FILAMENTS EJECTED IN BOTH PRE AND POST
	Y		REVERSAL	QUENCH REGIONS THROUGHOUT RUN. ANNULAR LIQ. SEEN TIL END
*****	*****	*****	*****	*****

[illegible]

[illegible]

FLIGHT	DATE:	AUG 6 1991		
PARAB. NUMBER DEMAN PSI G's	FILM ROLL CM/SPD HI/MILLI QUENCH Y/N	FLOW DESCRIPTION UPSTREAM OF QUENCH	FLOW DESCRIPTION DOWNSTREAM OF QUENCH	OBSERVATIONS
#####	#####	#####	#####	#####
#3 13 PSI	1 HI Y	THICK, EVEN MIST	THICK, EVEN MIST SURGES	INITIAL QUENCH ONLY SEEN ABOUT 1 INCH SEEN
#5 13 PSI	5 MILLI N			SCATTERED DROPS THROUGHOUT MOST OF FILM FROTHY TYPE FLOW ALSO OCCURS
#7 13 PSI	5 MILLI N			LARGE DROPS THROUGHOUT MOST OF FILM ELONGATED FILAMENTS/ANNULAR FILM TYPE FLOW
#9 13 PSI	5 MILLI N			SCATTERED OCCASIONAL DROPLETS, MIST FLOWS SOME MIXED FILAMENT MIST
#13 8 PSI	2 HI Y	MIST APPEARS TO BE DISPERSING EVENLY	THIN EVEN MIST ONE BURST OF FILAMENTS	CLARITY POOR AFTER QUENCH PASSED 16.5 INCHES MIST OBSCURES QUENCH PROFILE
#15 8 PSI	6 MILLI N			SCATTERED COMBINATIONS OF FILAMENTS/MIST LARGE DROPS THROUGHOUT MOST OF FILM AVERAGE DROPLET SIZE DECREASES AFTER 13 SECONDS
#17 8 PSI	6 MILLI N			CONDENSATE OBSCURES VIEW, DROPLETS SEEN AT VARIOUS TIMES THROUGH ENTIRE RUN
#19 8 PSI	6 MILLI N			SCATTERED DROPLETS AND FROTH FLOWS SEEN
#29 10 PSI	3 HI Y	MOSTLY CLEAR TO SWIRLING BUBBLES/VORTEXES	EVEN MIST/FROTH	GREAT INITIAL LIQ. DROPLET FLOW, PICTURE STUDY CASE QUENCH FRONT CENTER APPEARS TO HAVE FASTER CENTER ANNULAR TYPE PROFILE
#32 6 PSI	4 HI Y	THIN MIST, OCCASIONAL LARGE BUBBLE RISES FAST CLEARS BY END OF RUN	MIST THICKENS AND DISPERSES EVENLY/OR WITH BURSTING ACTION	ANNULAR PROFILE APPEARS TO DEEPEN AS QUENCH SPEED INCREASES, BECOMES SHALLOW AS QUENCH SLOWS
#34 10 PSI	7 MILLI Y	THICK MIST	FROTHY PULSING	CLEAR QUENCH UP TO 16.5 INCHES, PROFILE HARD TO SEE PHASE CHANGE EASY TO SEE, GOOD MECHANISM PICTURE
#37 10 PSI	7 MILLI Y			QUENCH JUST BEGINNING AS FILM ENDS
#38 6 PSI	7 MILLI Y	THIN MIST	SLUGS AND MIST DISPERSING	QUENCH PROFILE SEEMS PRETTY FLAT FLOW PATTERN NOT DISCERNABLE
#####	#####	#####	#####	#####

FLIGHT	DATE:	AUG 7	1991				
PARAB. NUMBER DEMAR PSI 6's	FILM ROLL CAM SPD HI/MILI QUENCH Y/N	FIELD OF VIEW INCHES HI/LO	PICTURE QUALITY	FILAMENTS YES/NO DROPLET SIZE	TIME TO QUENCH TOTAL TIME QUENCH SPD INCHES/SEC	LIQUID QUALITY UPSTREAM OF QUENCH	LIQUID QUALITY DOWNST. OF QUENCH
#####	#####	#####	#####	#####	#####	#####	#####
#3 13 PSI	8 HI Y	13 17.5	AVE	Y SLUGS/ DROPS	2.08 5.7 1.2	CLEAR, FINE BUBBLES	MISTY SURGING
#5 13 PSI	12 MILLI Y	12.0 17.25	AVE	N	5.6 17 1.3	LOTS OF MIST SUSP. POOR QUALITY	FINE MIST & FROTH
#7 13 PSI	12 MILLI Y	12 17.25	GOOD	Y OCCASION DROPS	6.1 13.5 0.9	MISTY O.K. QUALITY	FROTHY
#9 13 PSI	12 MILLI Y	12 17.25	AVE	N	0 14.1 1.1	VARIES CLEAR TO MISTY	SLUG/MIST
#13 10 PSI	9 HI Y	13 17.5	AVE	Y LARGE DROPS	1.26 6.39 0.8	SURGES OF FROTH	MIST & SURGIN DROPLETS
#15 10 PSI	13 MILLI Y	12.25 17.25	AVE	N	0 18.5 0.63	RINGS OF MIST	UNEVEN MIST/SLUGS
#17 10 PSI	13 MILLI Y	12.25 17.25	AVE CONDENS.	N	0 20.9 0.92	DENSE MIST RINGS	DENSE MIST RINGS
#24 8 PSI	10 HI Y	13 17.5	AVE	Y DROPLETS	2.75 6.4 1	VARIES FROM FROTH TO CLEAR	DROPS AND MIST SURGING
#27 8 PSI	14 MILLI Y	12.25 17.25	AVE BUT DIM	Y LARGE DROPS	1.5 5.8 2	FROTH BUT CLEARS UP	TURBULENT MIST/SLUGS
#28 8 PSI	14 MILLI Y	12.25 17.25	AVE BUT DIM	N FROTH	1.1 6.1 0.8	EVEN MIST	TURBULENT MIST/DEFINATE FILAMENTS
#29 8 PSI	14 MILLI Y	12.25 17.25	AVE BUT DIM	Y FINE DROPS	0.2 4.2 0.65	FROTH CLEARS	FROTH/ FILAMENTS
#34 6 PSI	11 HI N	13 17.5	AVE	N	20.5		
#####	#####	#####	#####	#####	#####	#####	#####

DATE:

AUG 7 1991

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APPENDIX B

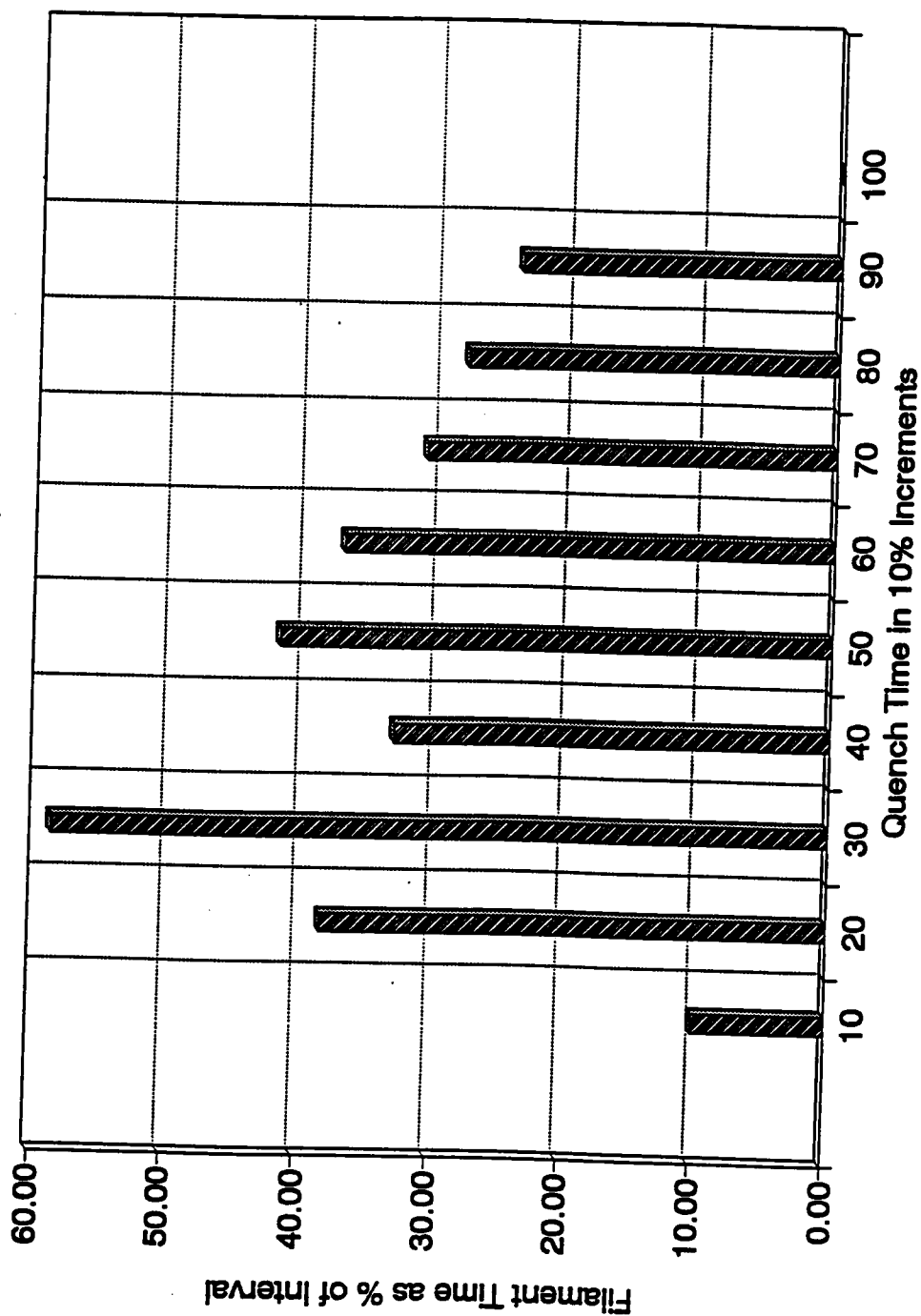
FILAMENT FLOW PATTERN HISTOGRAM DATA AND GRAPHS

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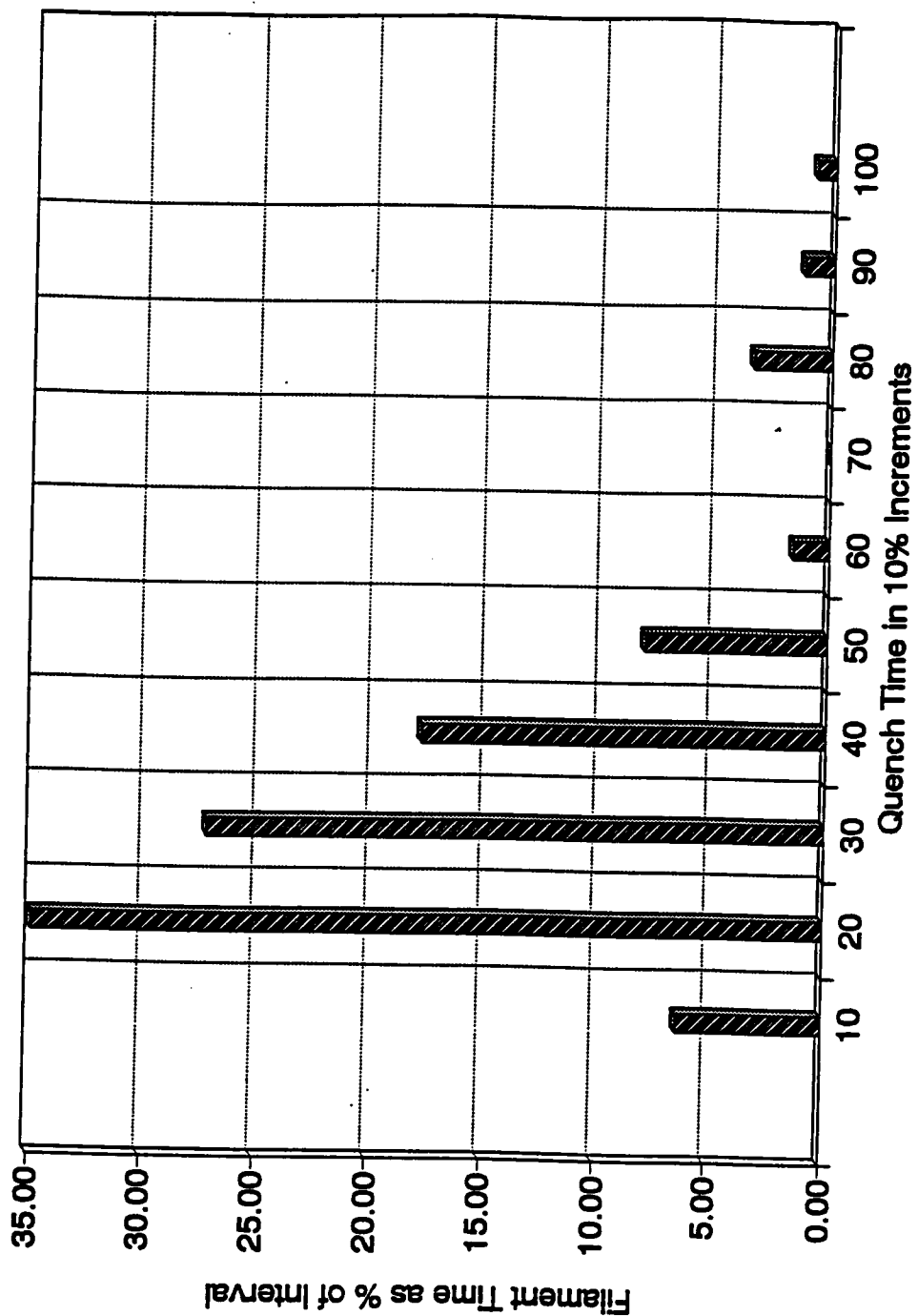
DATE	PARABOL QUENCH SEC	FILM				TIME				FILM ENT				TIME							
		0.1 10% DUR. SEC	10% 20% DUR. SEC	20% 30% DUR. SEC	30% 40% DUR. SEC	40% 50% DUR. SEC	50% 60% DUR. SEC	60% 70% DUR. SEC	70% 80% DUR. SEC	80% 90% DUR. SEC	90% 100% DUR. SEC	100% 110% DUR. SEC	110% 120% DUR. SEC	120% 130% DUR. SEC	130% 140% DUR. SEC	140% 150% DUR. SEC	150% 160% DUR. SEC	160% 170% DUR. SEC	170% 180% DUR. SEC	180% 190% DUR. SEC	190% 200% DUR. SEC
# 3	0	0	1.52	0.14	3.04	0.04	4.56	0	6.08	0	7.61	0	9.13	0	10.7	0	12.2	0	13.7	0	15.2
15.21	1.52		3.04	4.56			6.08		7.61		9.13		10.7		12.2		13.7		15.2		
9/6/91																					
# 13	0	0	1.32	0	2.63	0.29	3.95	0.27	5.27	0.1	6.59	0	7.91	0	9.22	0	10.5	0	11.9	0	13.2
13.17	1.32		2.63	3.95			5.27		6.59		7.91		9.22		10.5		11.9		13.2		
9/6/91																					
# 29	0	0.85	1.11	0.9	2.22	0.38	3.33	0	4.44	0	5.55	0	6.66	0	7.77	0	8.87	0	9.98	0	11.1
11.09	1.11		2.22	3.33			4.44		5.55		6.66		7.77		8.87		9.98		11.1		
9/6/91																					
# 32	0	0.07	0.79	0	1.57	0	2.36	0	3.14	0	3.93	0	4.72	0	5.5	0	6.29	0	7.07	0	7.86
7.86	0.79		1.57	2.36			3.14		3.93		4.72		5.5		6.29		7.07		7.86		
9/6/91																					
# 34	0	0.43	0.43	0.2	0.87	0.43	1.3	0.25	1.74	0	2.17	0	2.61	0	3.04	0	3.47	0	3.91	0	4.34
4.34	0.43		0.87	1.3			1.74		2.17		2.61		3.04		3.47		3.91		4.34		
9/6/91																					
# 37	0	0.05	0.55	0	1.11	0	1.66	0	2.22	0	2.77	0	3.33	0	3.88	0	4.43	0	4.99	0	5.54
5.54	0.55		1.11	1.66			2.22		2.77		3.33		3.88		4.43		4.99		5.54		
9/6/91																					
# 38	0	0	0.23	0	0.46	0	0.68	0	0.91	0	1.14	0	1.37	0	1.6	0	1.82	0	2.05	0	2.28
2.28	0.23		0.46	0.68			0.91		1.14		1.37		1.6		1.82		2.05		2.28		
9/7/91																					
# 3	0	0.09	0.21	0	0.42	0	0.62	0	0.83	0	1.04	0	1.25	0	1.46	0	1.66	0	1.87	0	2.08
2.08	0.21		0.42	0.62			0.83		1.04		1.25		1.46		1.66		1.87		2.08		
9/7/91																					
# 5	0	0	0.57	0	1.14	0	1.71	0	2.28	0	2.85	0	3.42	0	3.99	0	4.56	0	5.13	0	5.7
5.7	0.57		1.14	1.71			2.28		2.85		3.42		3.99		4.56		5.13		5.7		
9/7/91																					
# 7	0	0.61	0.61	0.61	1.22	0	1.83	0	2.44	0	3.05	0	3.66	0	4.27	0	4.88	0	5.49	0	6.1
6.1	0.61		1.22	1.83			2.44		3.05		3.66		4.27		4.88		5.49		6.1		
9/7/91																					
# 13	0	0.06	0.13	0	0.25	0.05	0.38	0	0.5	0	0.63	0	0.76	0	0.88	0	1.01	0	1.13	0	1.26
1.26	0.13		0.25	0.38			0.5		0.63		0.76		0.88		1.01		1.13		1.26		
9/7/91																					
# 24	0	0.1	0.28	0.05	0.55	0	0.83	0	1.1	0	1.38	0	1.65	0	1.93	0	2.2	0	2.48	0	2.8
2.8	0.1		0.28	0.55			0.83		1.1		1.38		1.65		1.93		2.2		2.48		

DATE	PARABOL QUENCH SEC	FILM		TIME		FILM		TIME		FILM		TIME		FILM		TIME		FILM		TIME		
		0.1 10%	DUR. 10%	10%	DUR. 20%	20%	DUR. 30%	30%	DUR. 40%	40%	DUR. 50%	50%	DUR. 60%	60%	DUR. 70%	70%	DUR. 80%	80%	DUR. 90%	90%	DUR. 100%	100%
2.75	0.28		0.55		0.83		1.1		1.38		1.65		1.93		2.2		2.48		2.75			
9/7/91																						
27	0	0	0.15	0	0.3	0	0.45	0	0.6	0	0.75	0	0.9	0	1.05	0	1.2	0	1.35	0	1.5	0
1.5	0.15		0.3		0.45		0.6		0.75		0.9		1.05		1.2		1.35		1.5			
9/7/91																						
28	0	0	0.11	0	0.22	0	0.33	0	0.44	0	0.55	0	0.66	0	0.77	0	0.88	0	0.99	0	1.1	0.05
1.1	0.11		0.22		0.33		0.44		0.55		0.66		0.77		0.88		0.99		1.1			

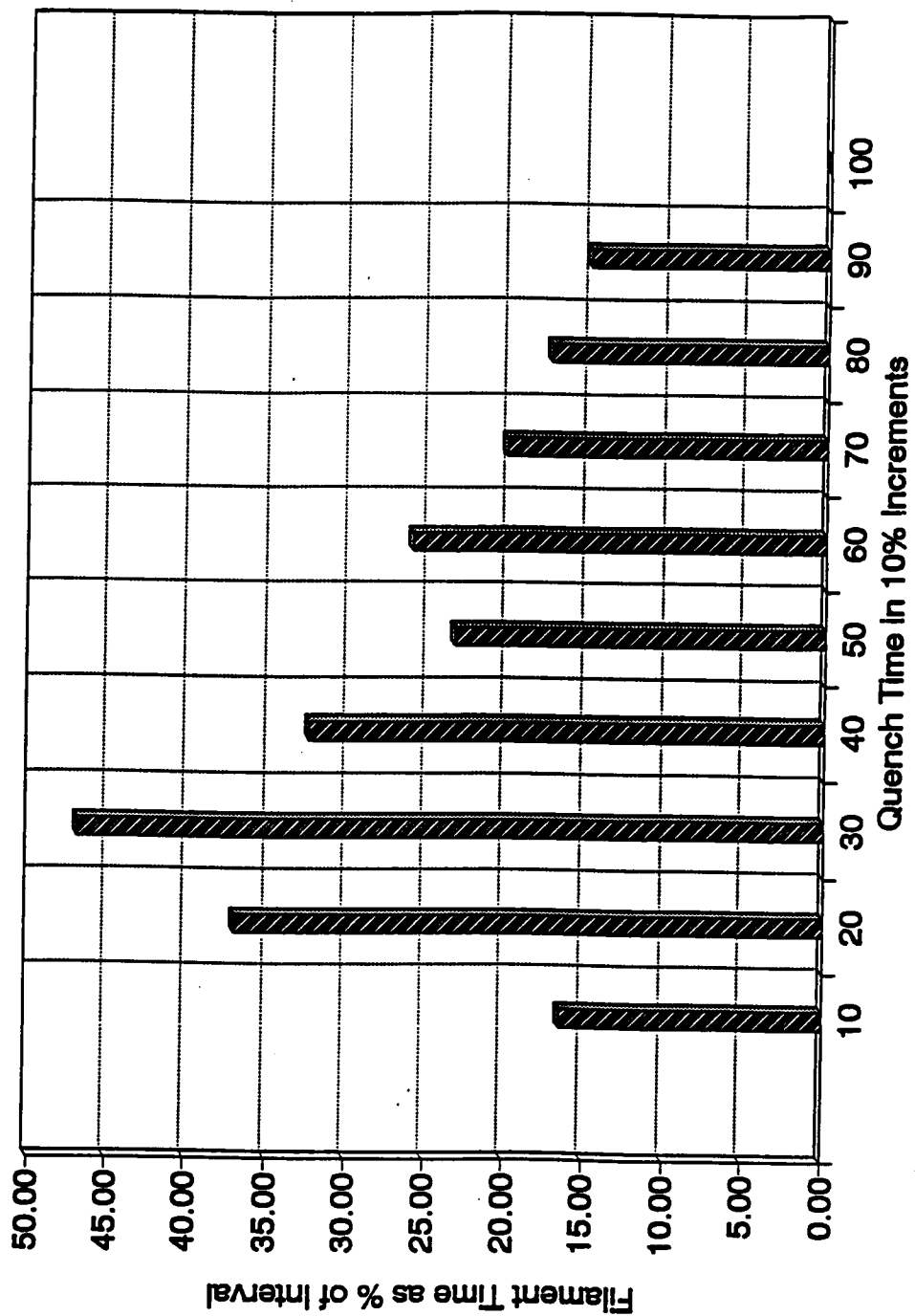
% Of Time Filaments occurred vs
% of Time from 0 To Quench
(APRILL 91)



% Of Time Filaments occurred vs
% of Time from 0 To Quench
(AUGUST 91)



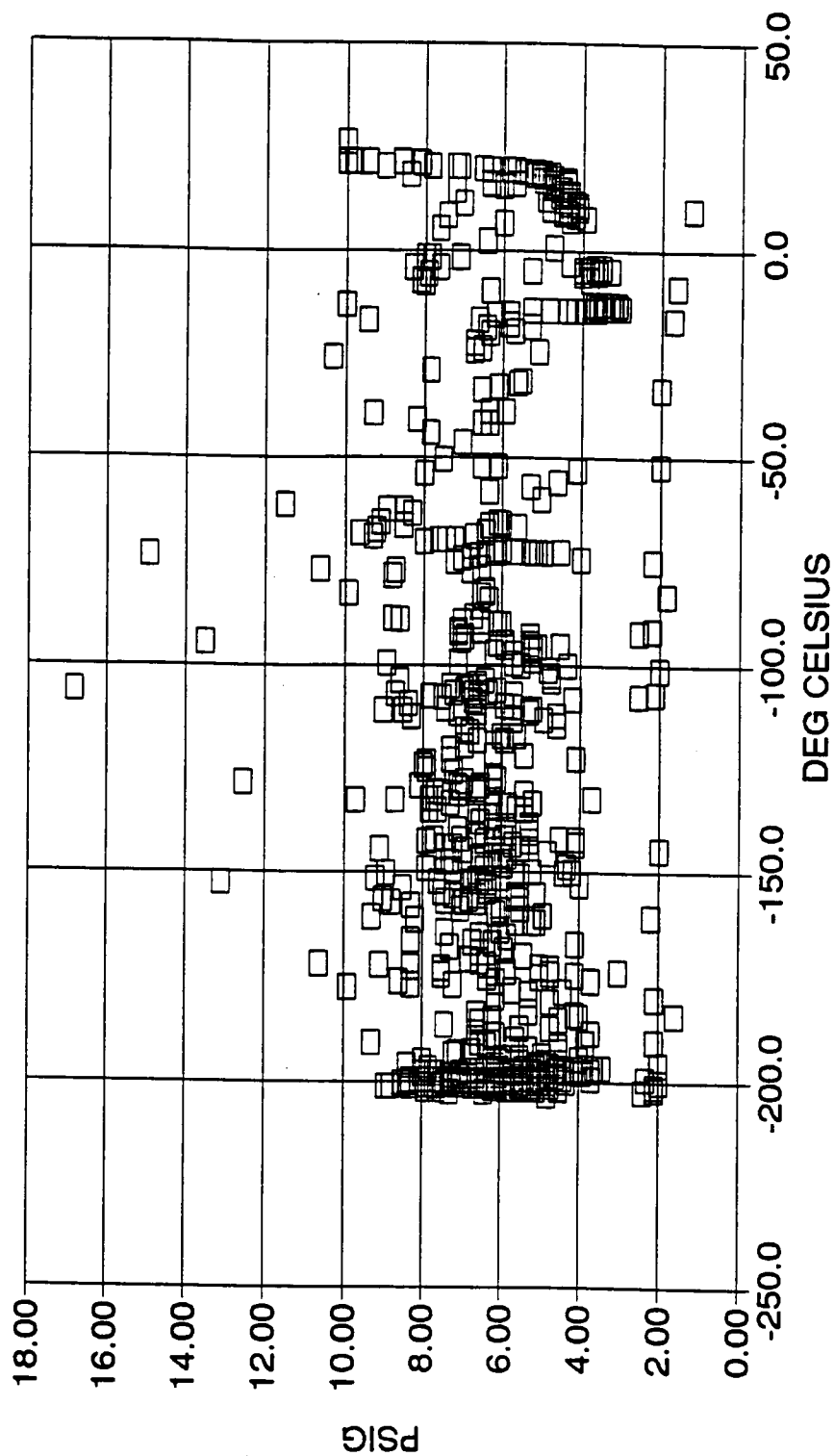
**% Of Time Filaments occurred vs
% of Time from 0 To Quench
(APRILL & AUGUST 91)**



APPENDIX C

EXPERIMENTAL PRESSURE DATA PLOTS

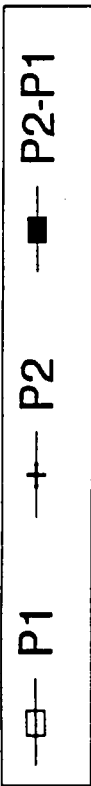
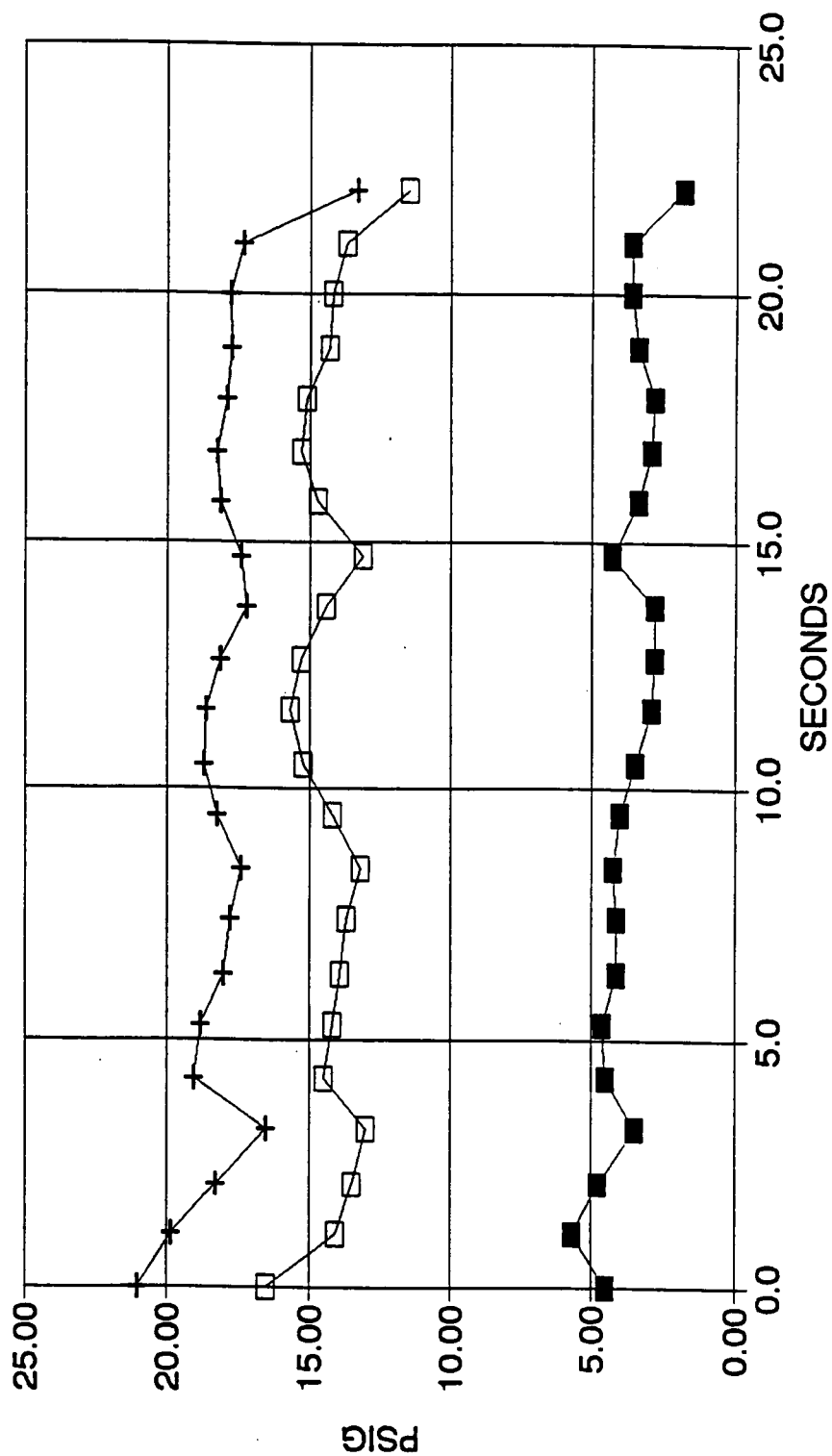
P2 - P1 VS TEMP 2
AUGUST 7, 91 RUN 1-25



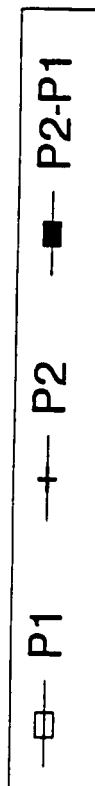
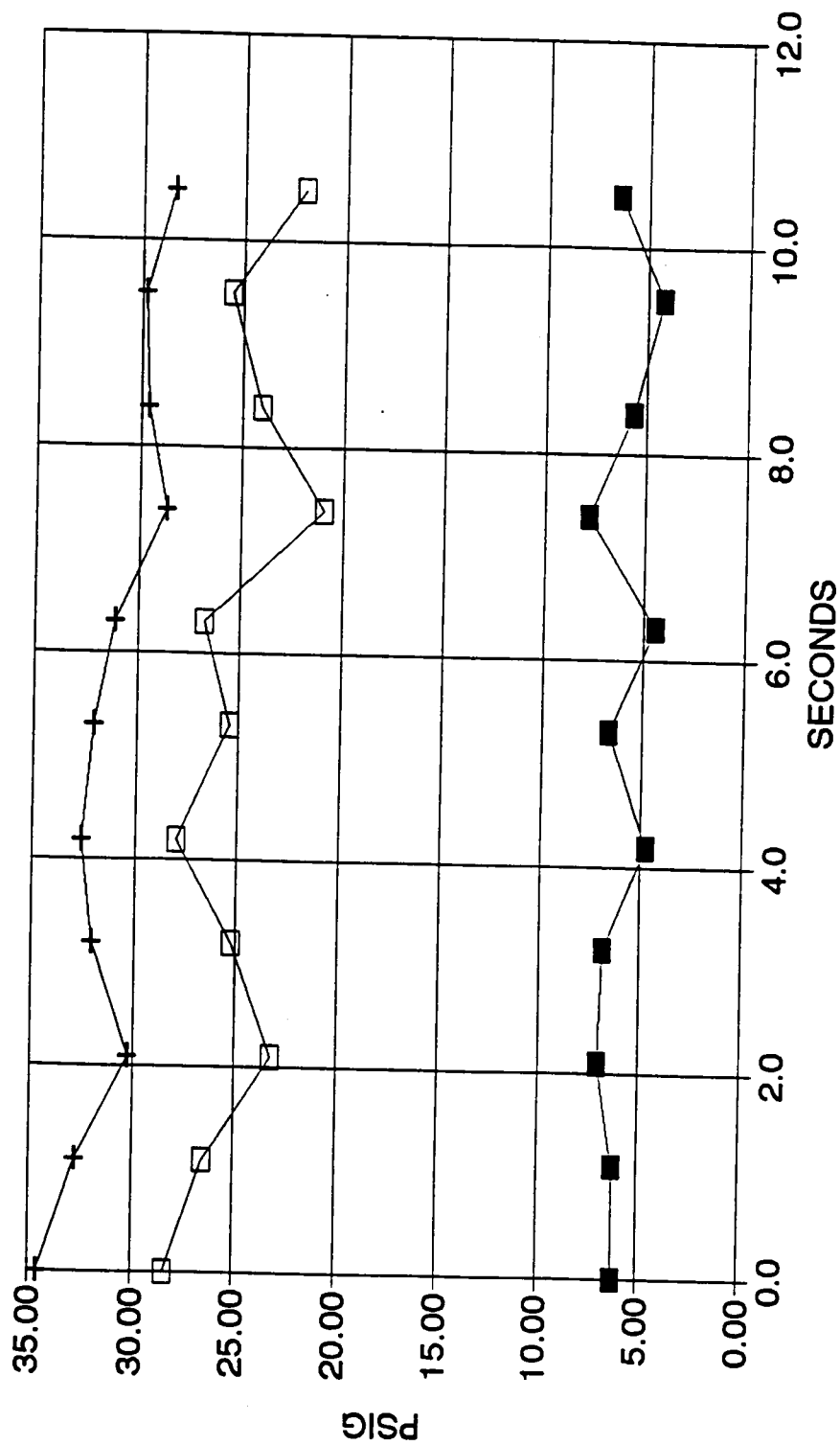
□ P2 - P1

PRESSURE VS. TIME AUGUST 6, 91 RUN 1

No. 100000
Parabola 11

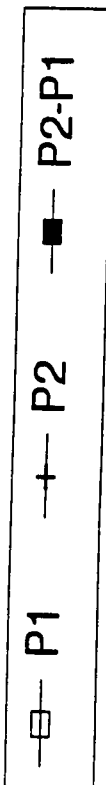
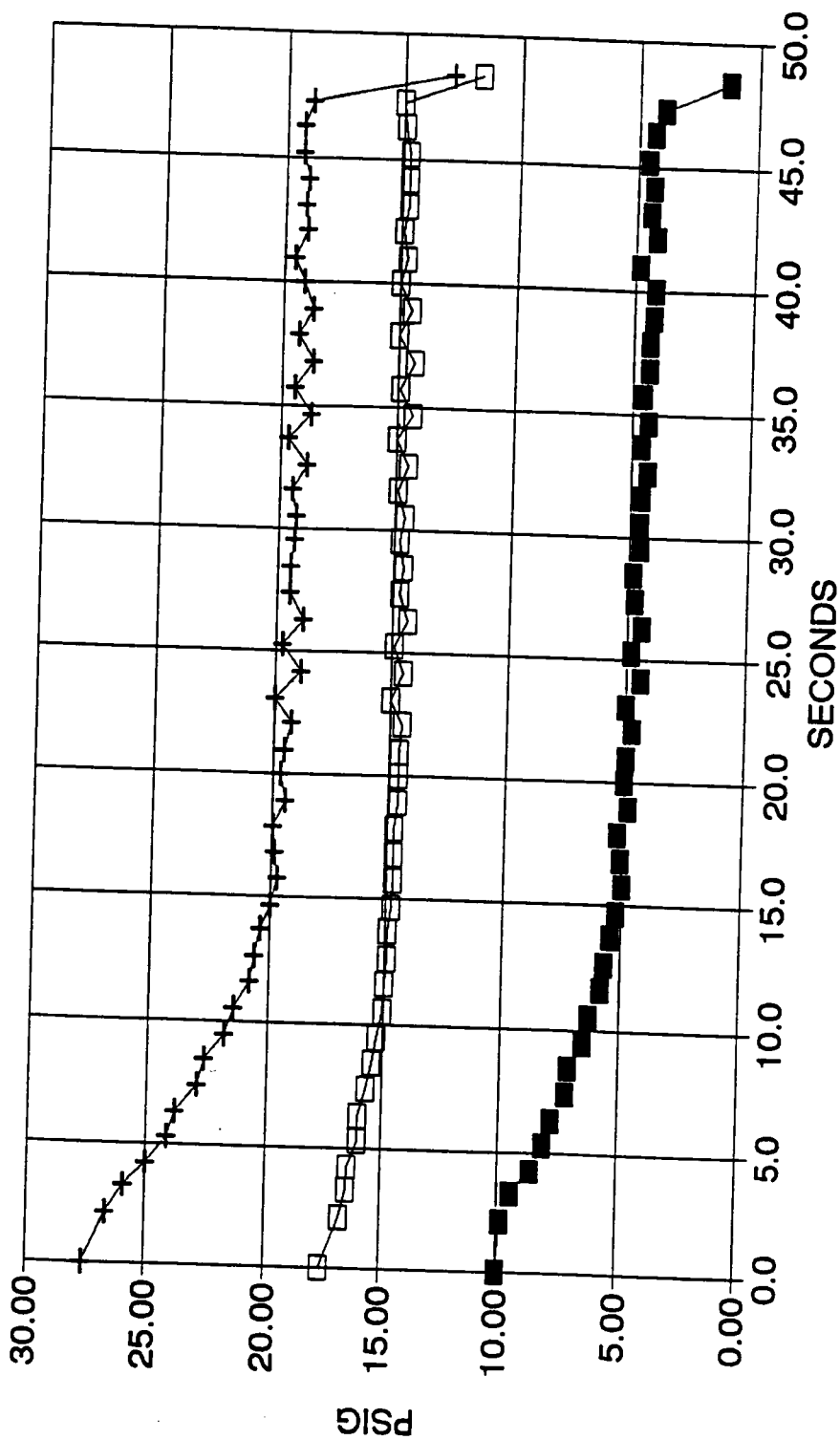


PRESSURE VS. TIME
 AUGUST 6, 91 RUN 2
No Cameral
Parabolic (20)

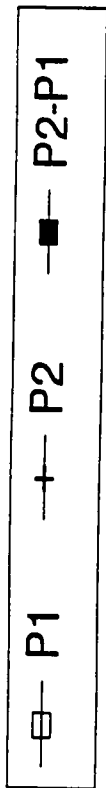
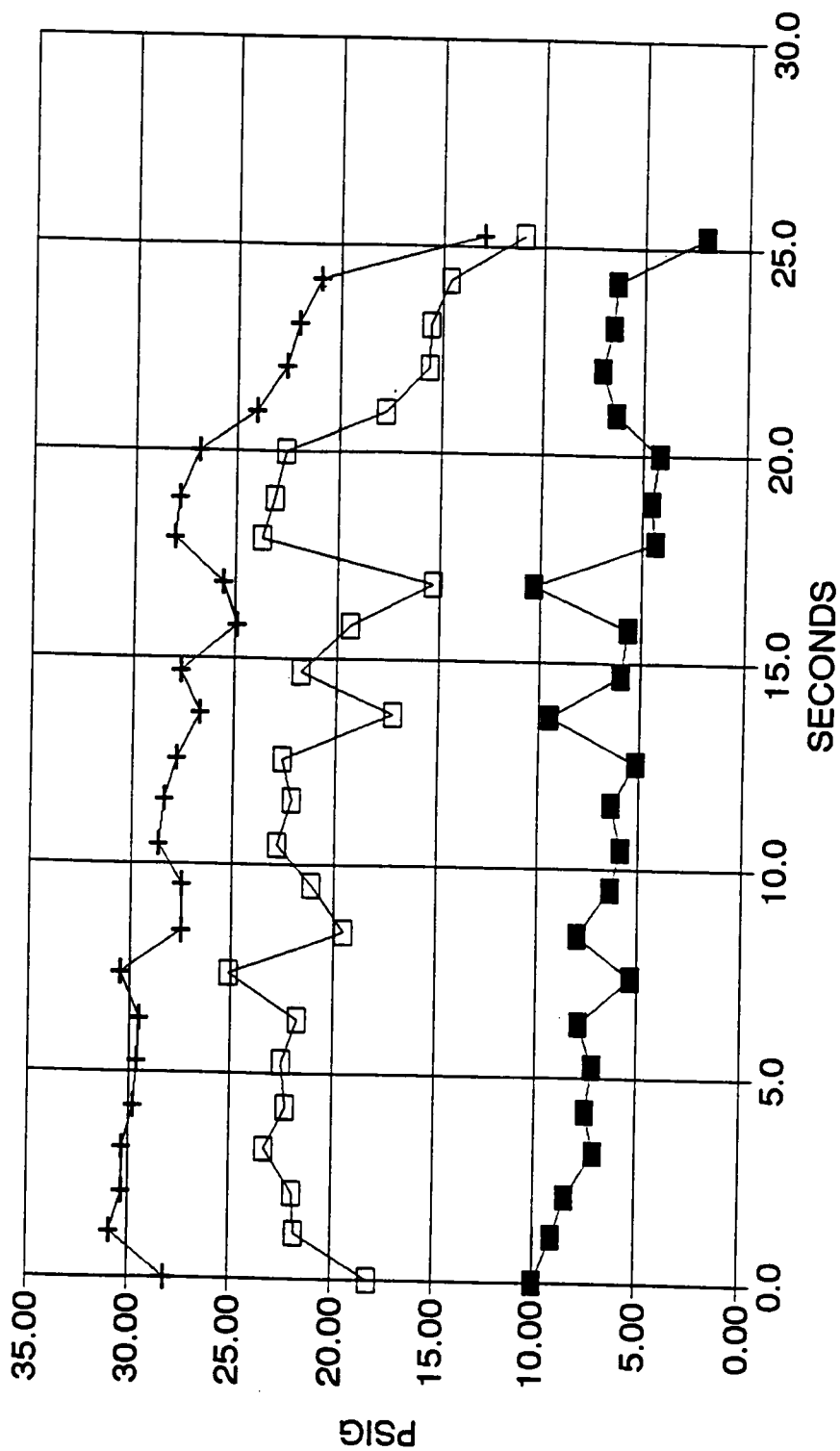


PRESSURE VS. TIME AUGUST 7, 91 RUN 1

1/2 inches
Parabola 1

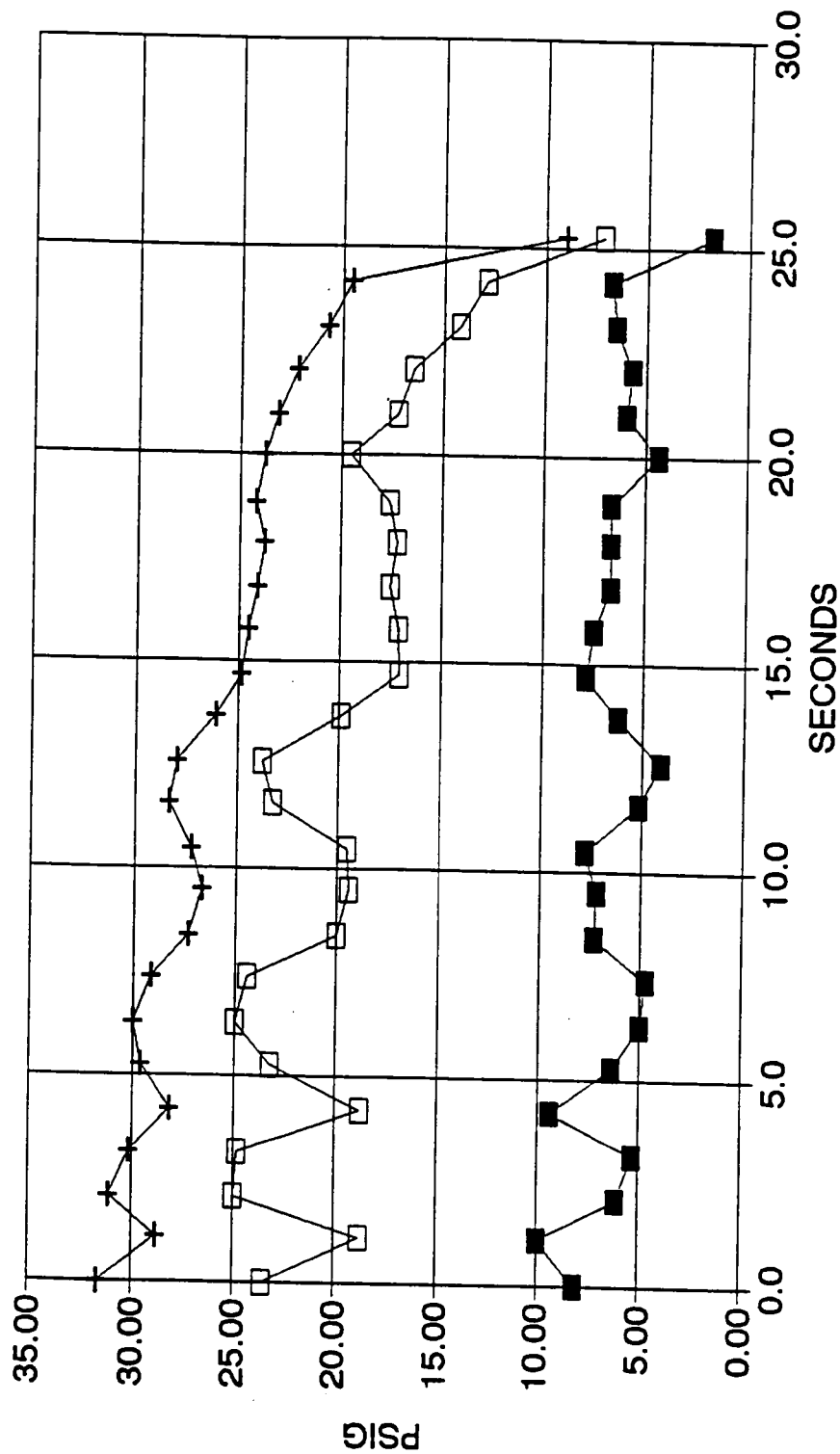


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 2
 No. Cannon
 Parabola 2



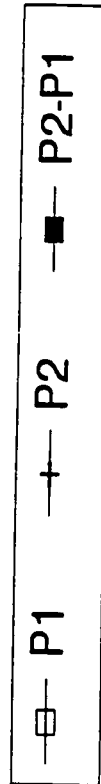
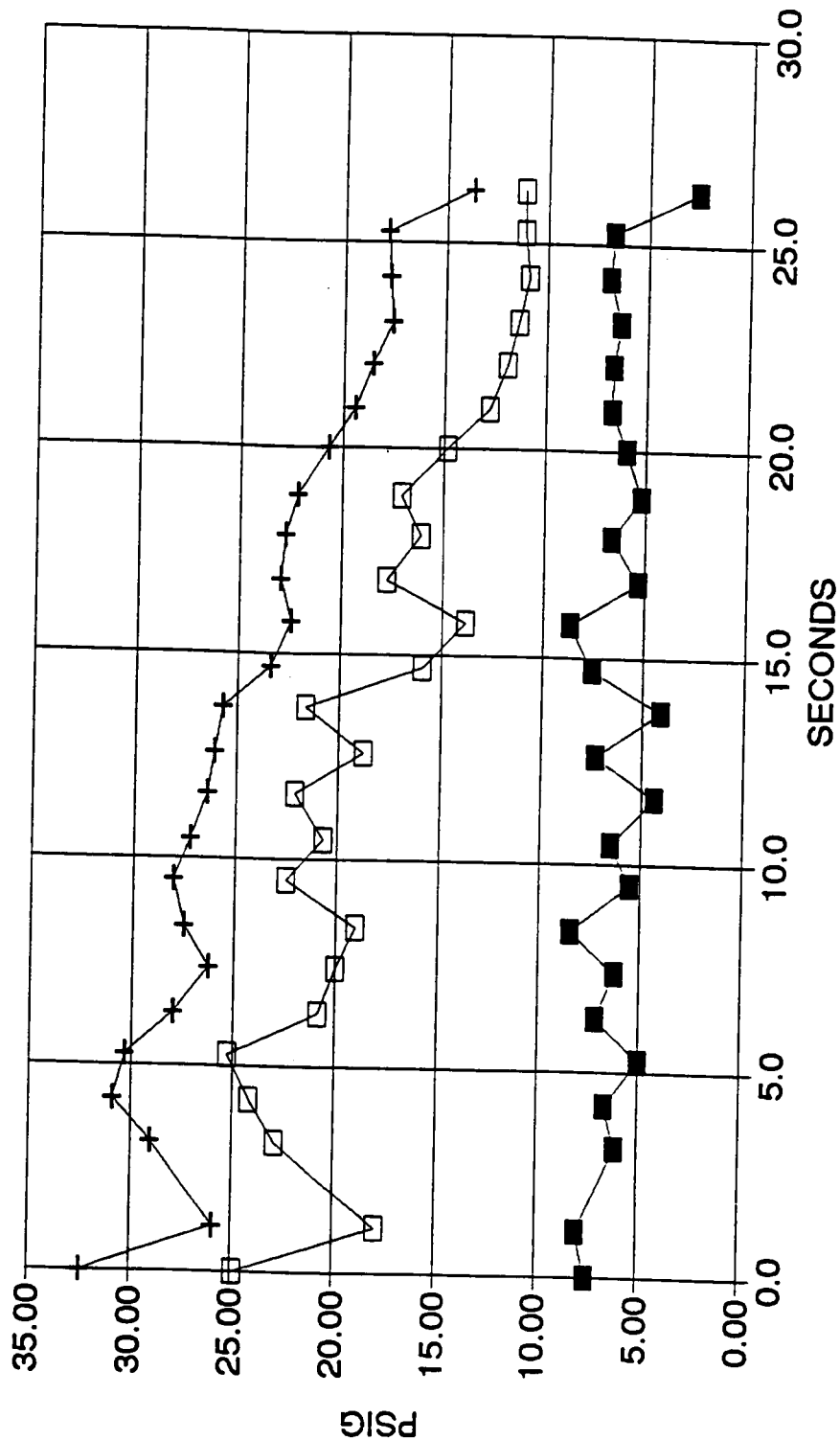
Green
H / VHS
Parolina 3

PRESSURE VS. TIME AUGUST 7, 91 RUN 3



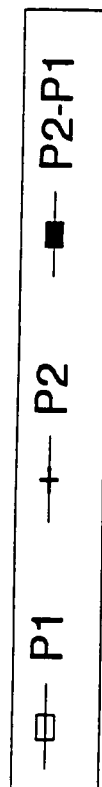
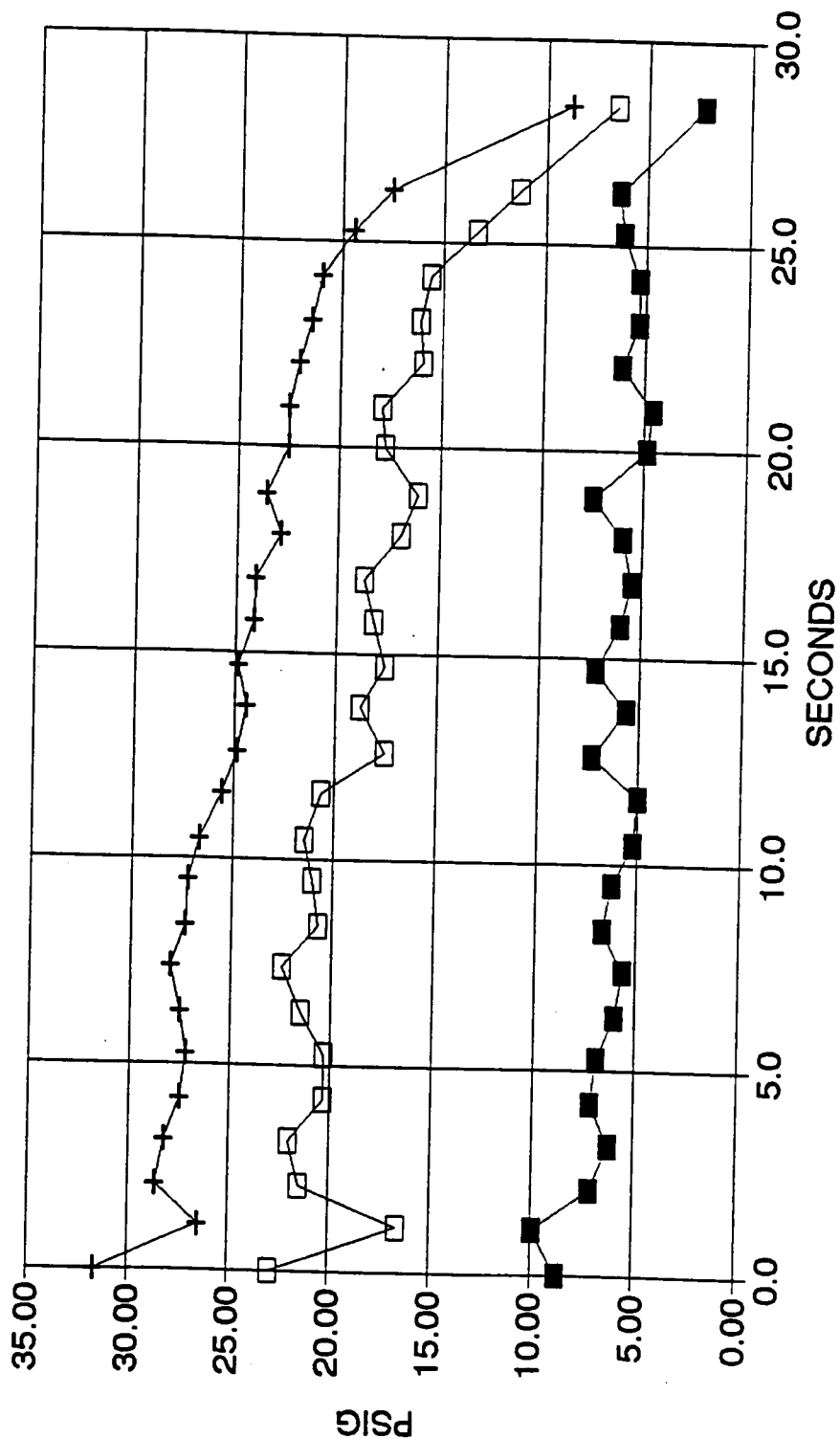
□ P1 + P2 ■ P2-P1

PRESSURE VS. TIME
 AUGUST 7, 91 RUN 4
 VHS Parabola 4



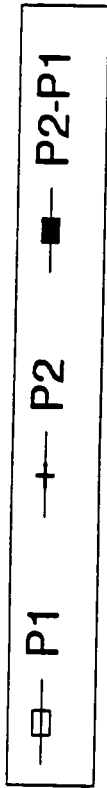
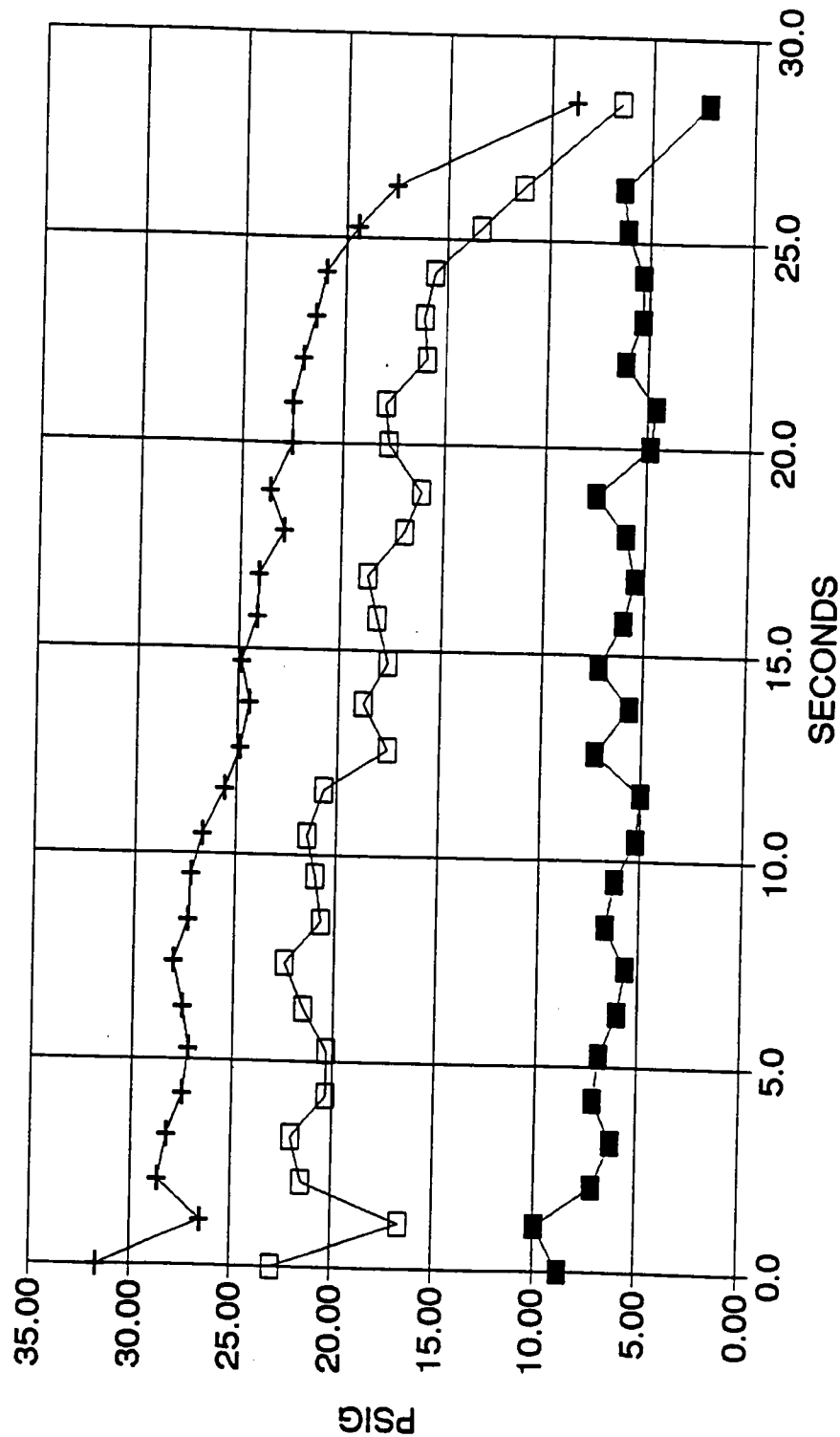
PRESSURE VS. TIME AUGUST 7, 91 RUN 5

Drenn
Mill / VHS
Parabola 5



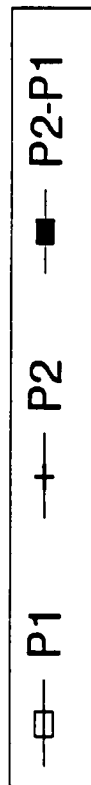
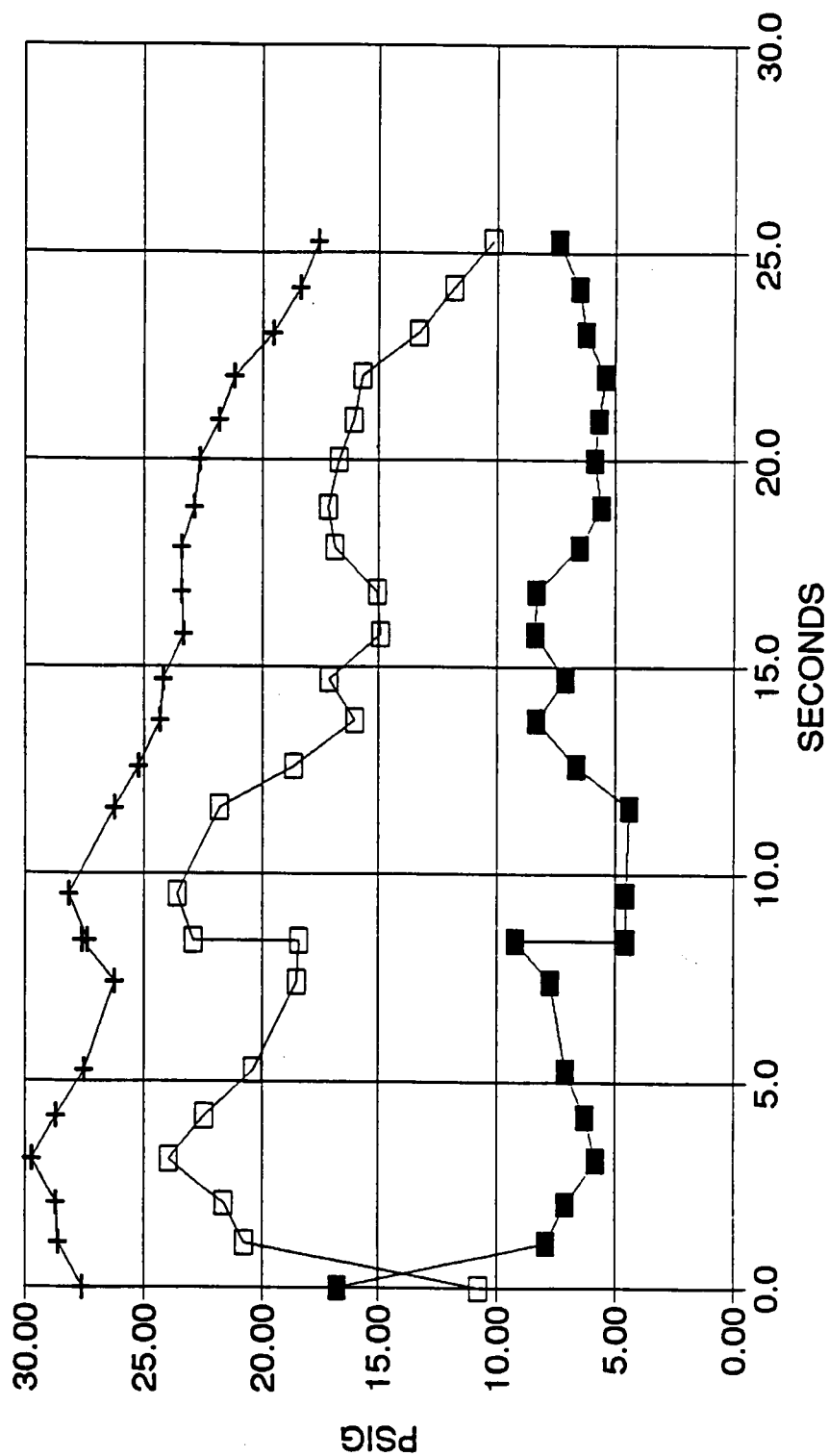
Drenn
Mill / VHS
Parabola 5

PRESSURE VS. TIME AUGUST 7, 91 RUN 5



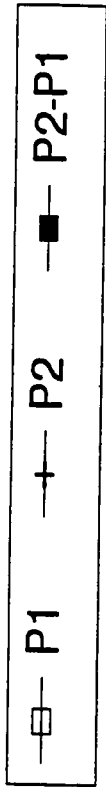
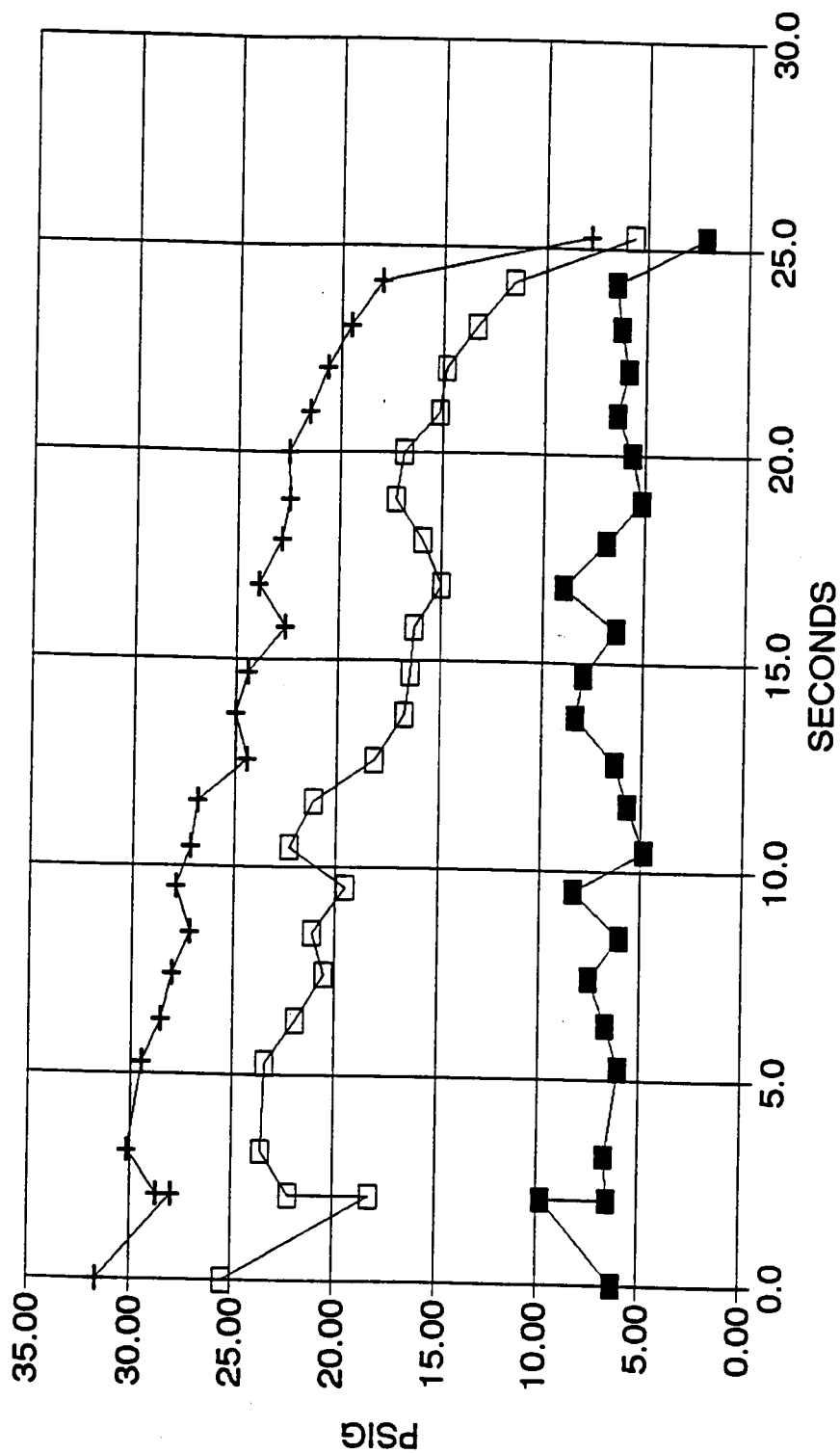
PRESSURE VS. TIME AUGUST 7, 91 RUN 6

VHS
 PAROBOLA CO

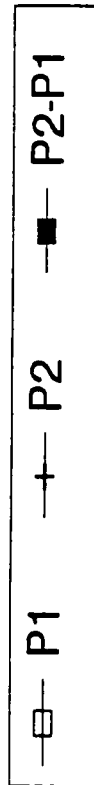
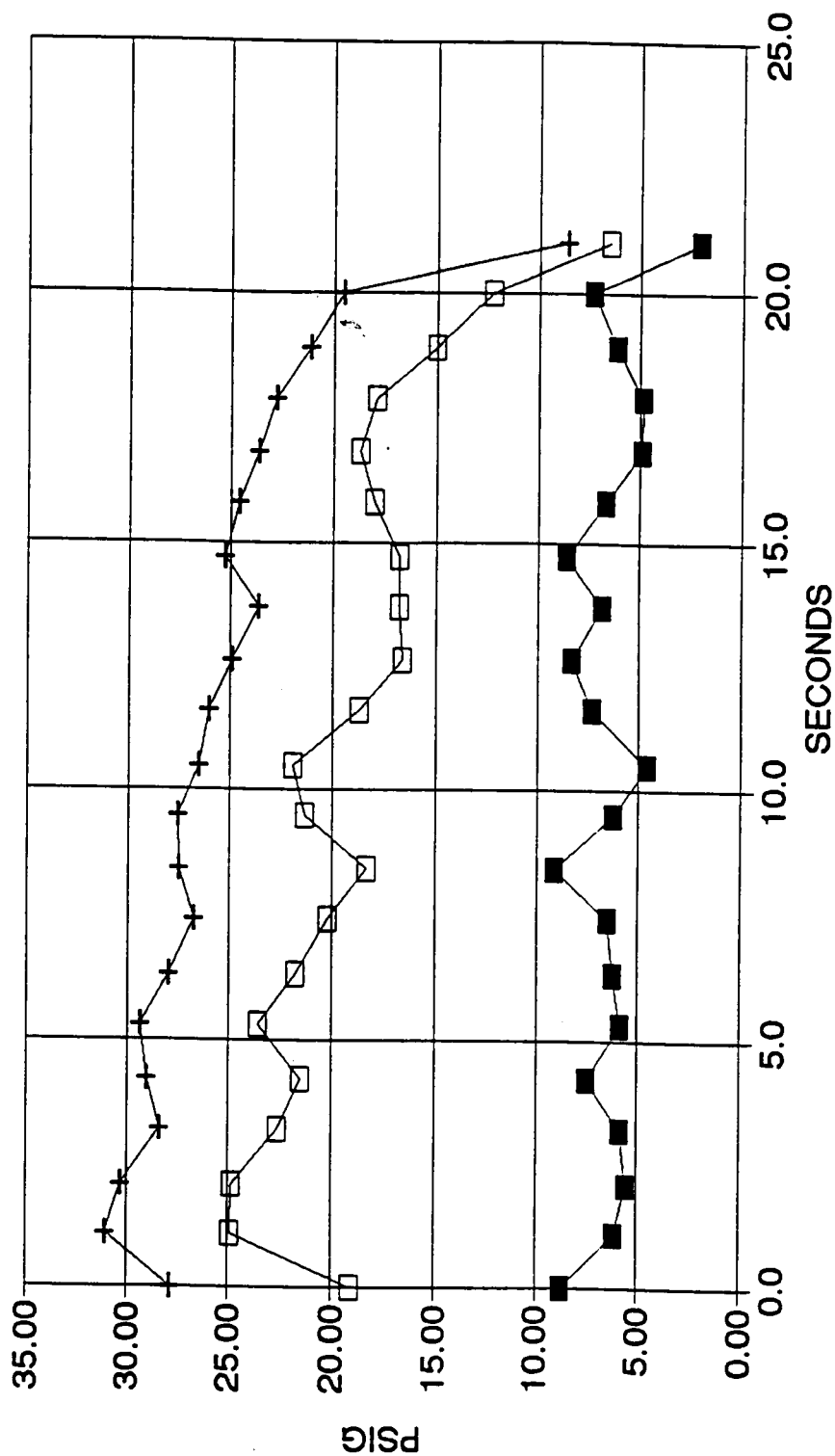


Glucos
Mill / VES
Parabola 7

PRESSURE VS. TIME
AUGUST 7, 91 RUN 7

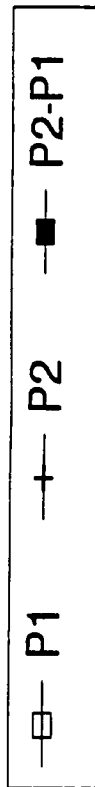
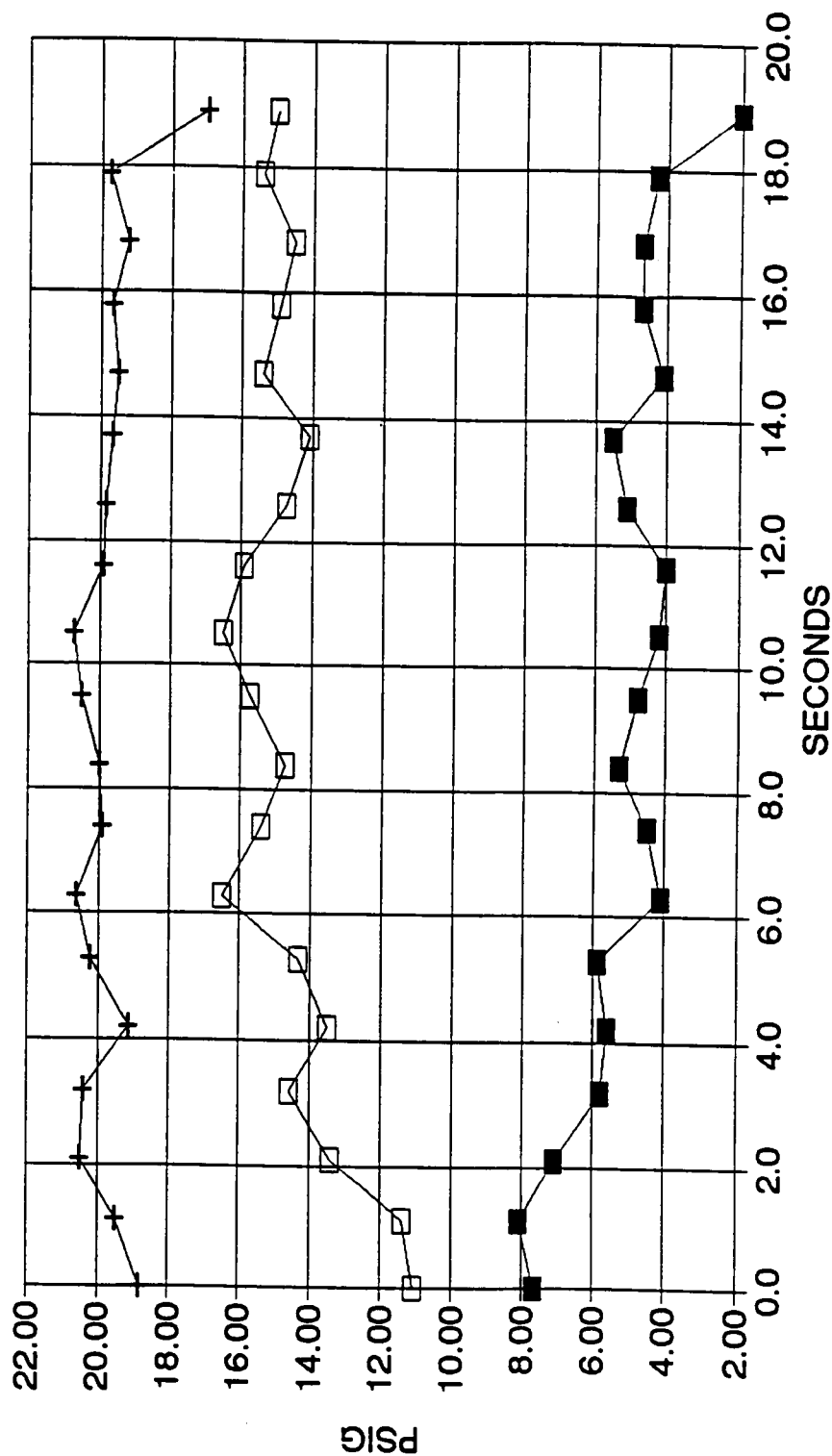


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 8
 VHS Parabola 8



French
M111/VAR
Parabola 9

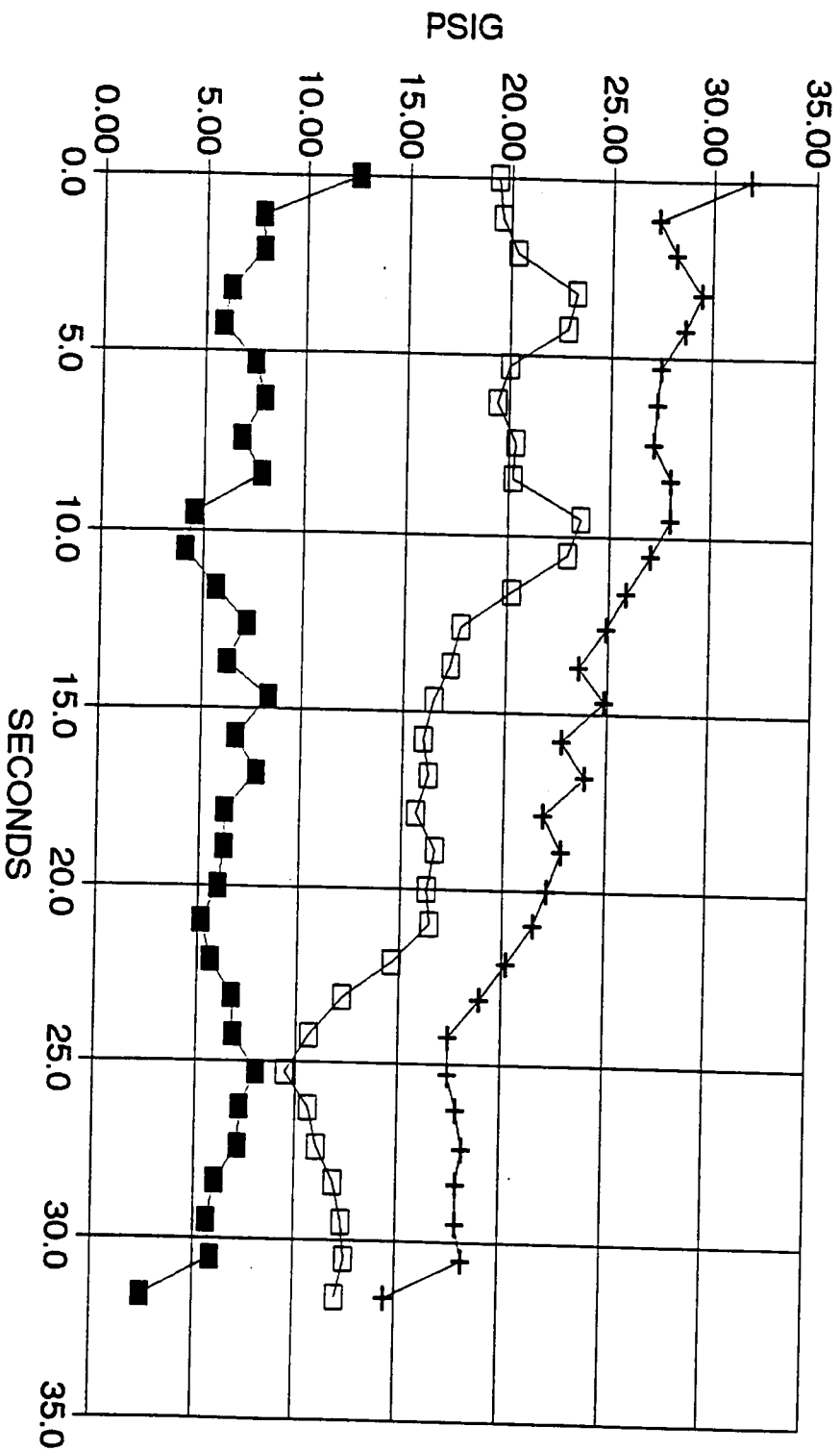
PRESSURE VS. TIME
AUGUST 7, 91 RUN 9



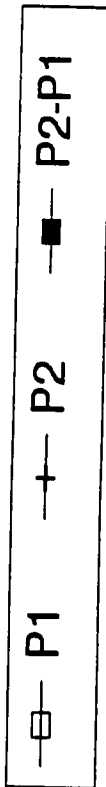
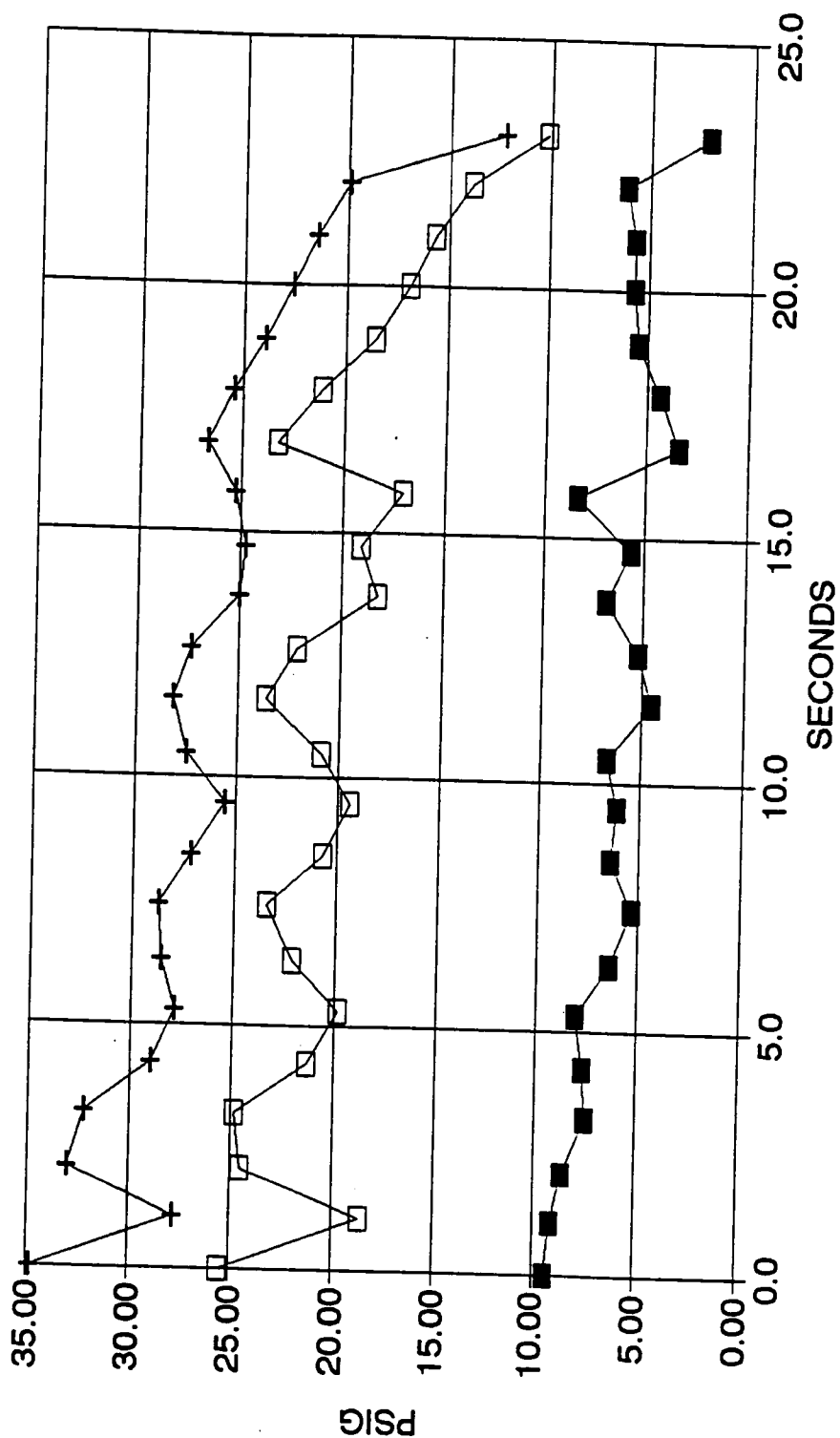
PRESSURE VS. TIME
 AUGUST 7, 91 RUN 10

VHS

Parabola 11

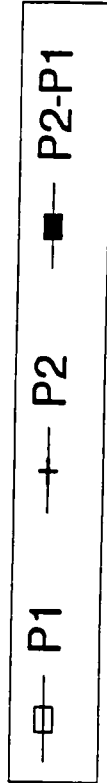
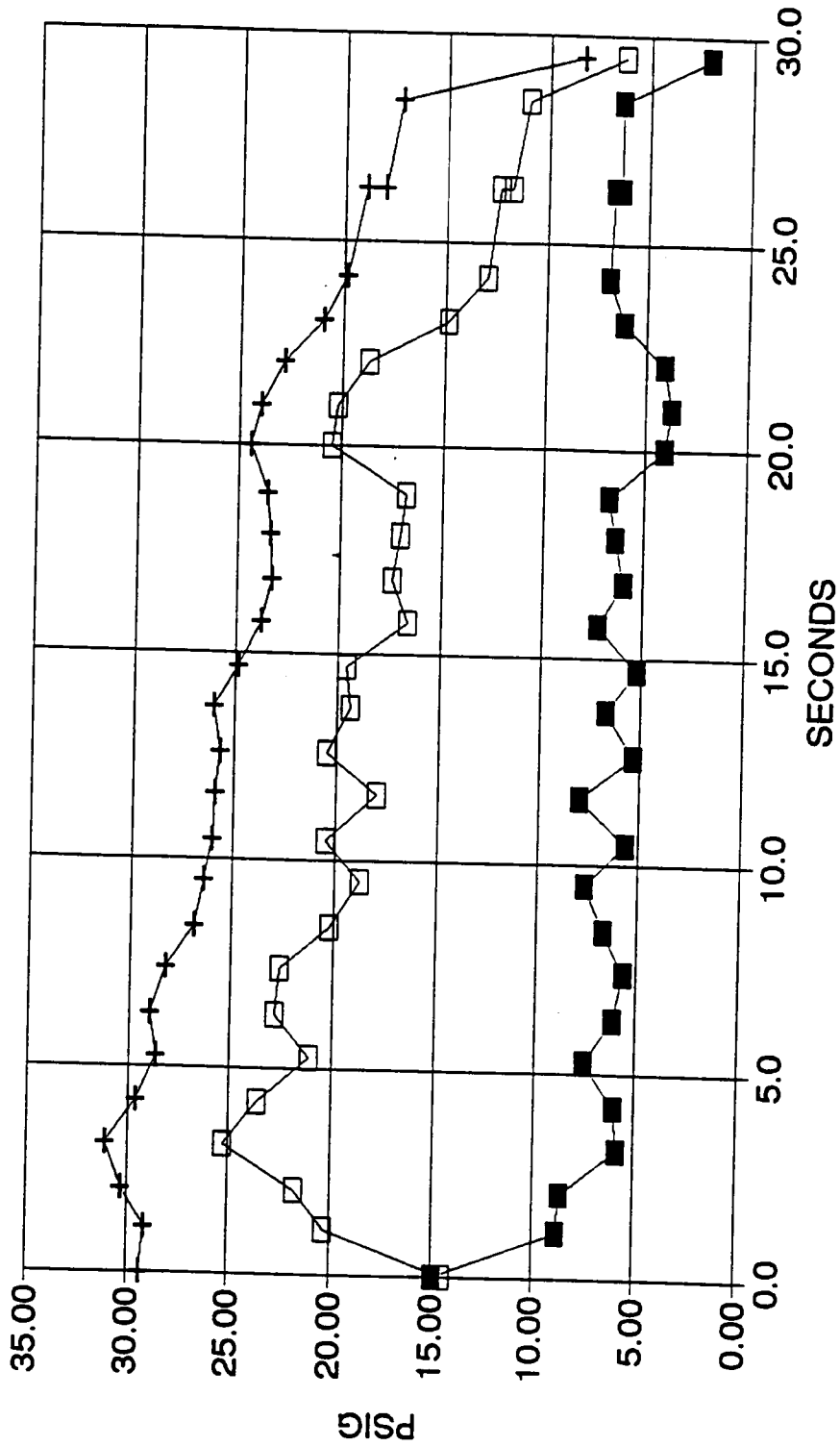


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 11
No Sensor
 Parabola 12

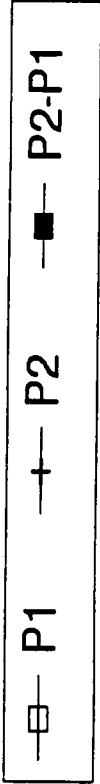
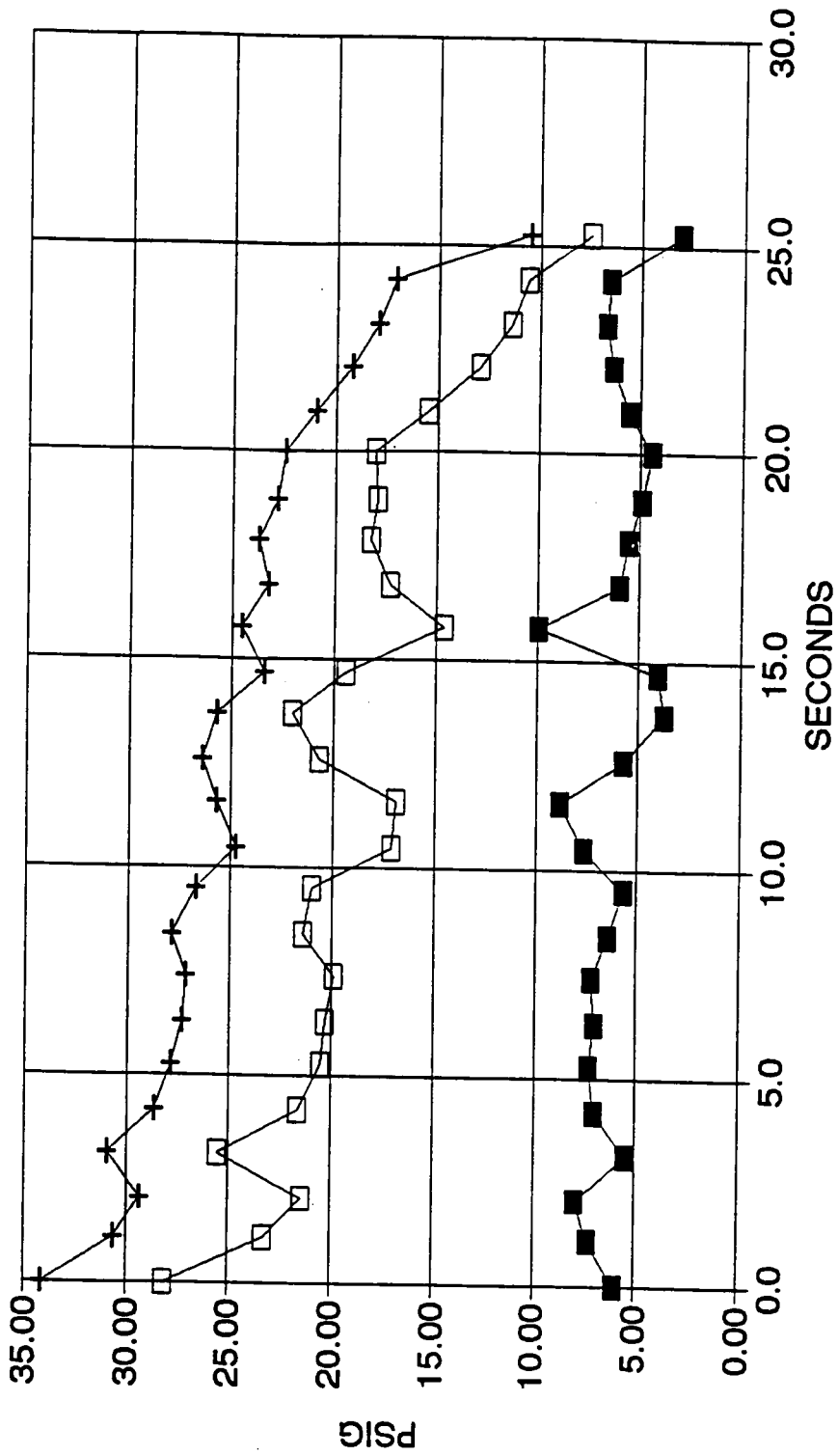


PRESSURE VS. TIME AUGUST 7, 91 RUN 12

Qvenci
 H1 / VHS
 Parabola 13

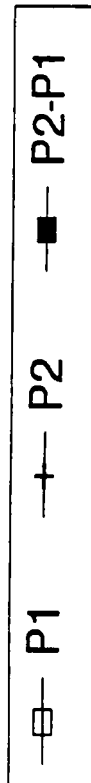
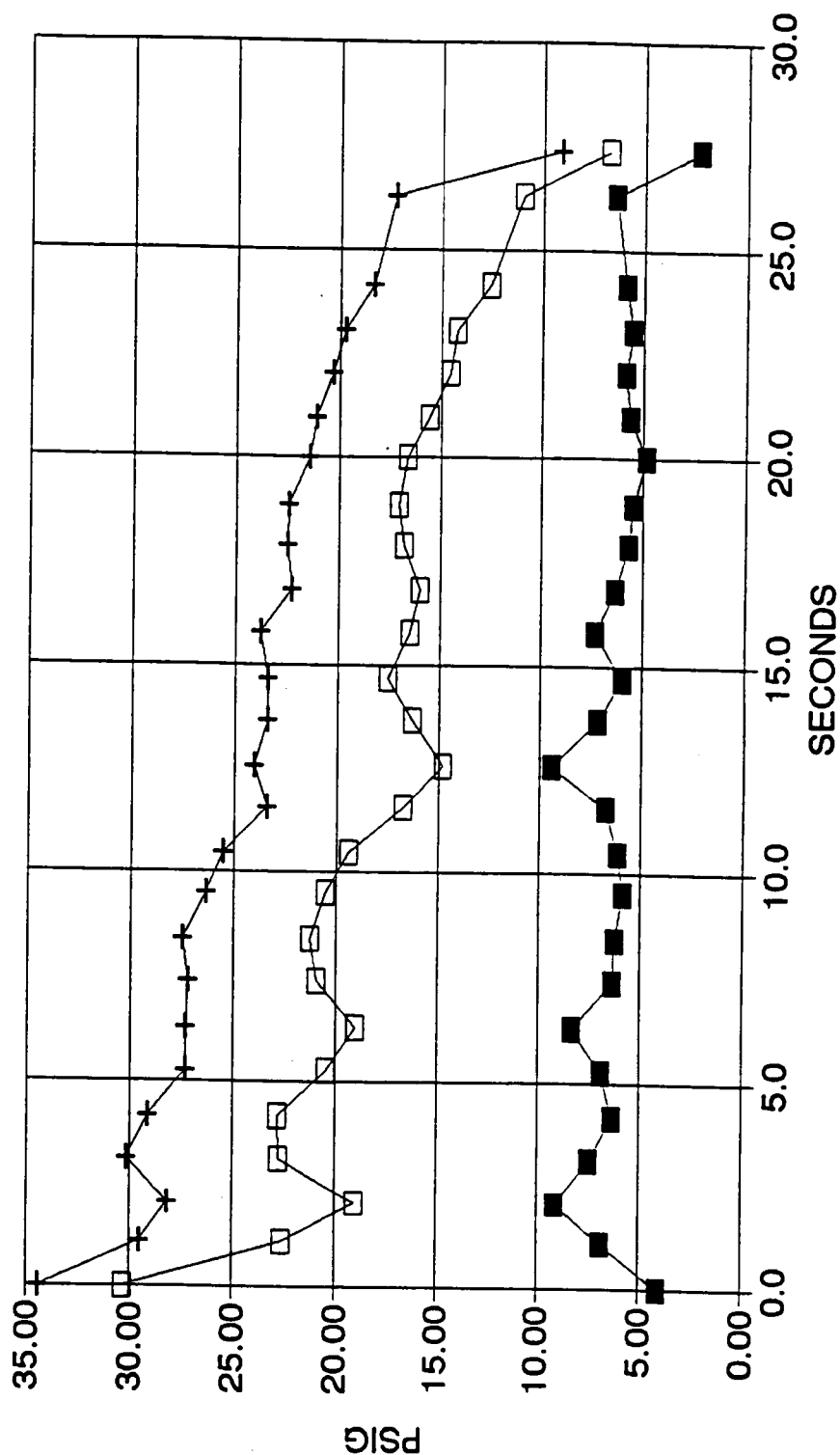


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 13
 VHS Parabola 14

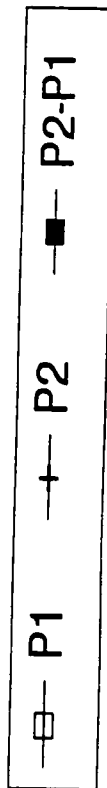
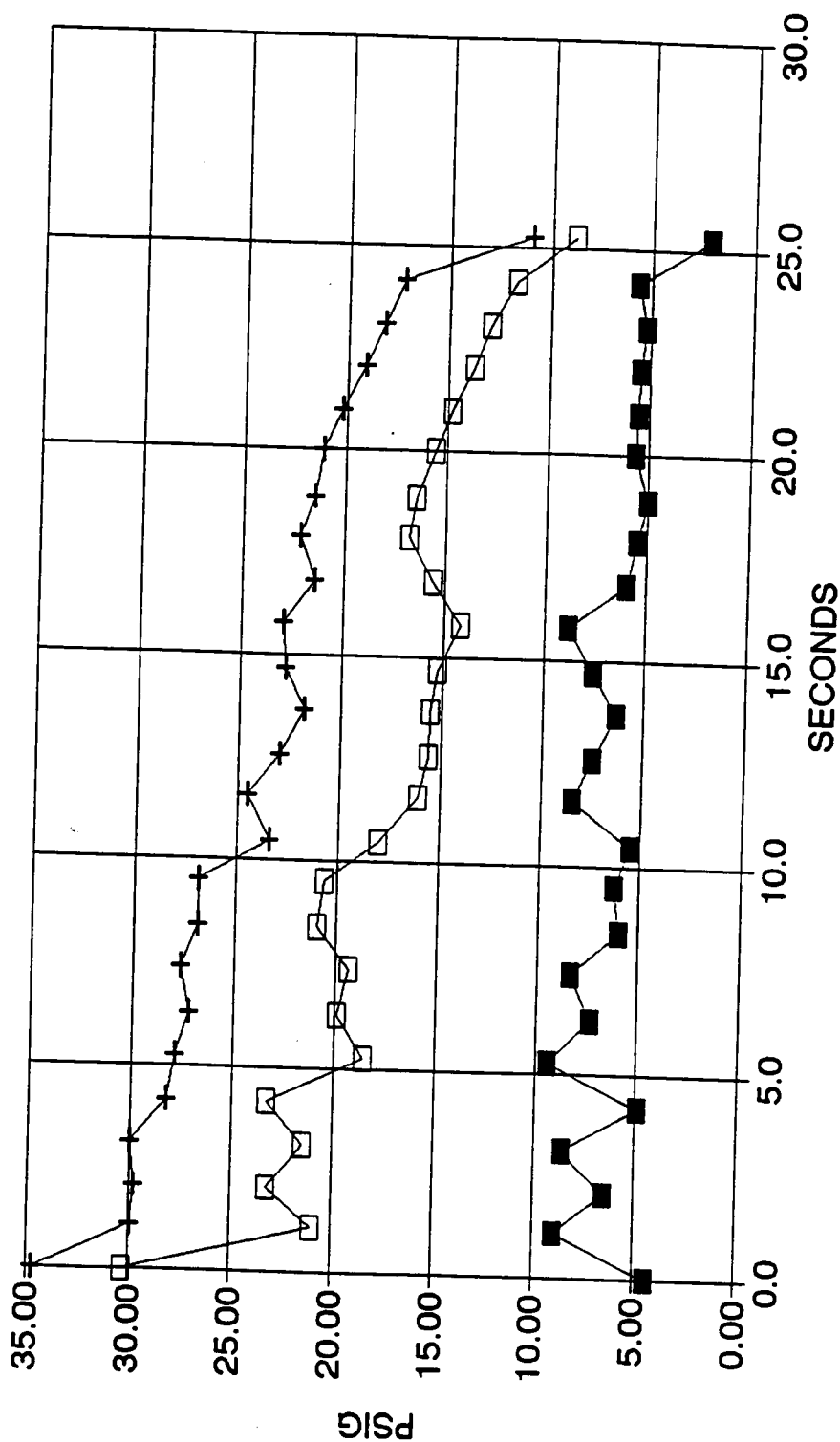


PRESSURE VS. TIME AUGUST 7, 91 RUN 14

French
M111 / VHS
Parabola 15

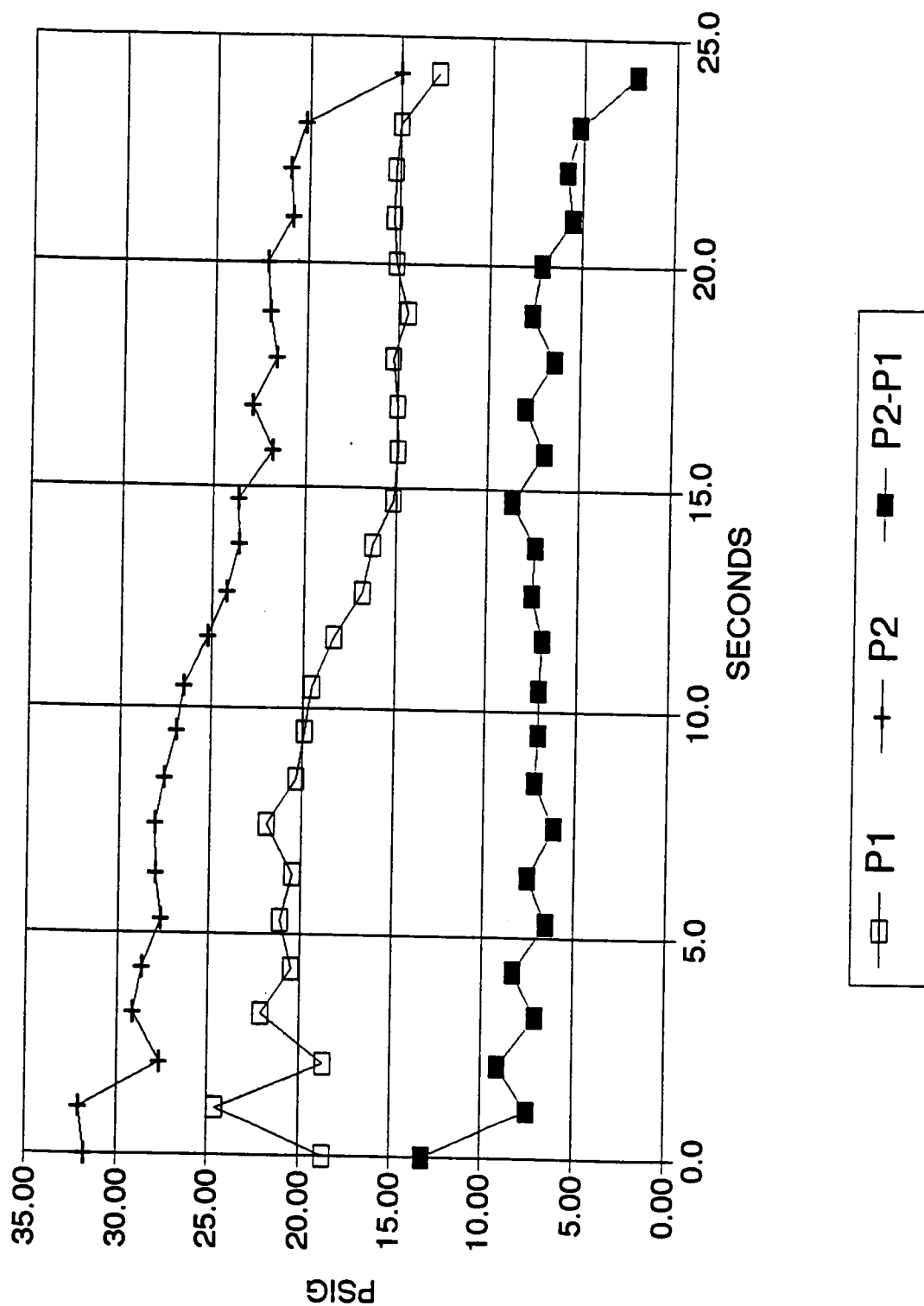


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 15
 VHS Parabola 16



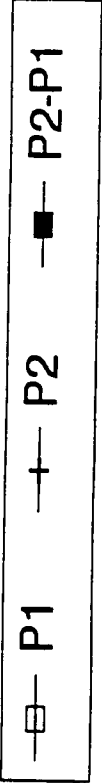
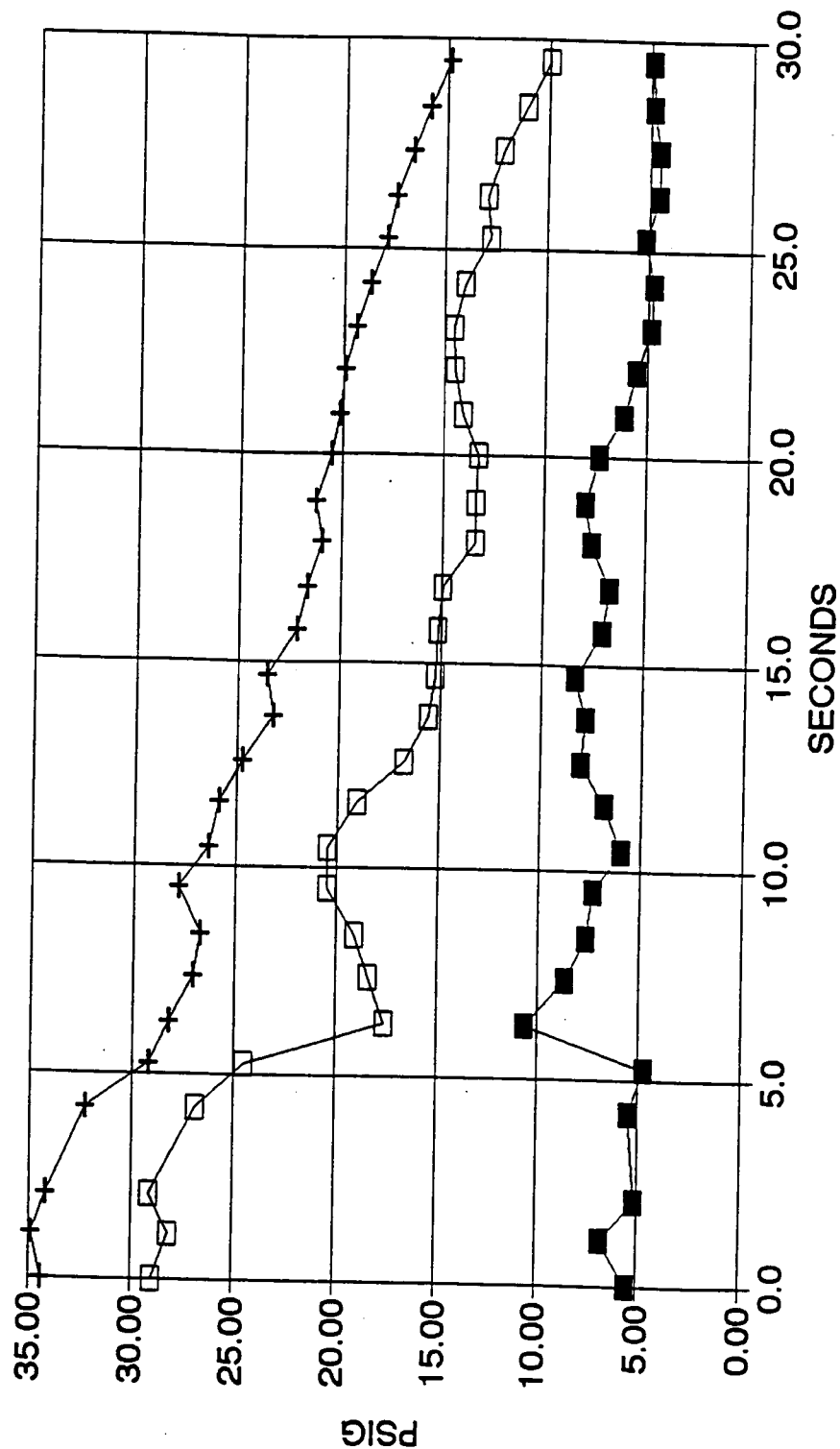
PRESSURE VS. TIME AUGUST 7, 91 RUN 16

Quench
 Mill: 1725
 Parabola 177

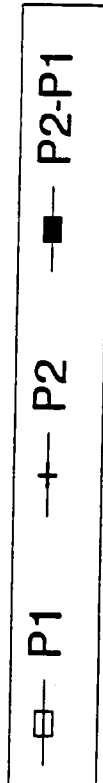
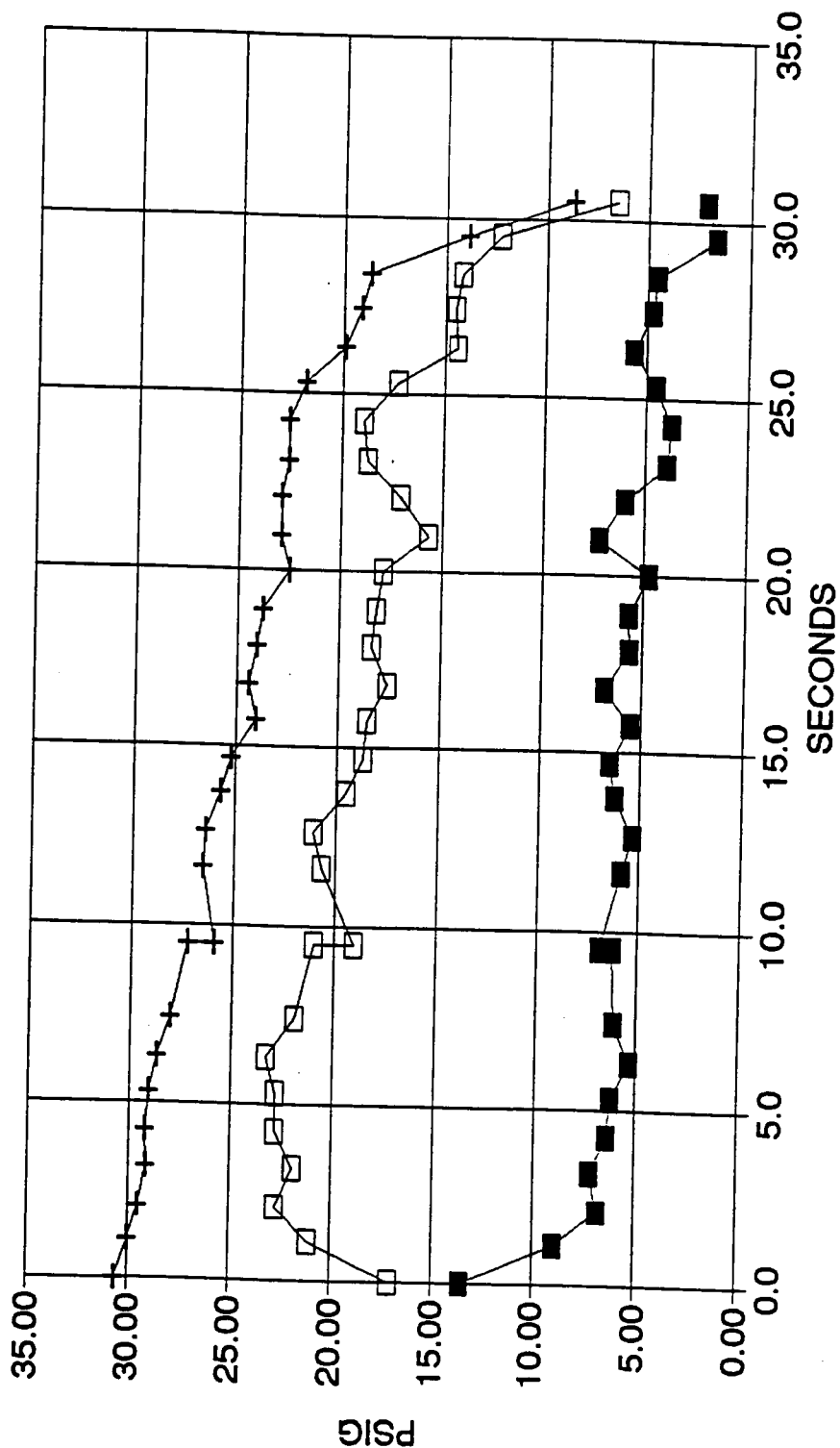


PRESSURE VS. TIME AUGUST 7, 91 RUN 17

M1111 / V445
 Parabola 19

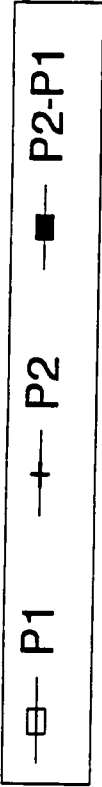
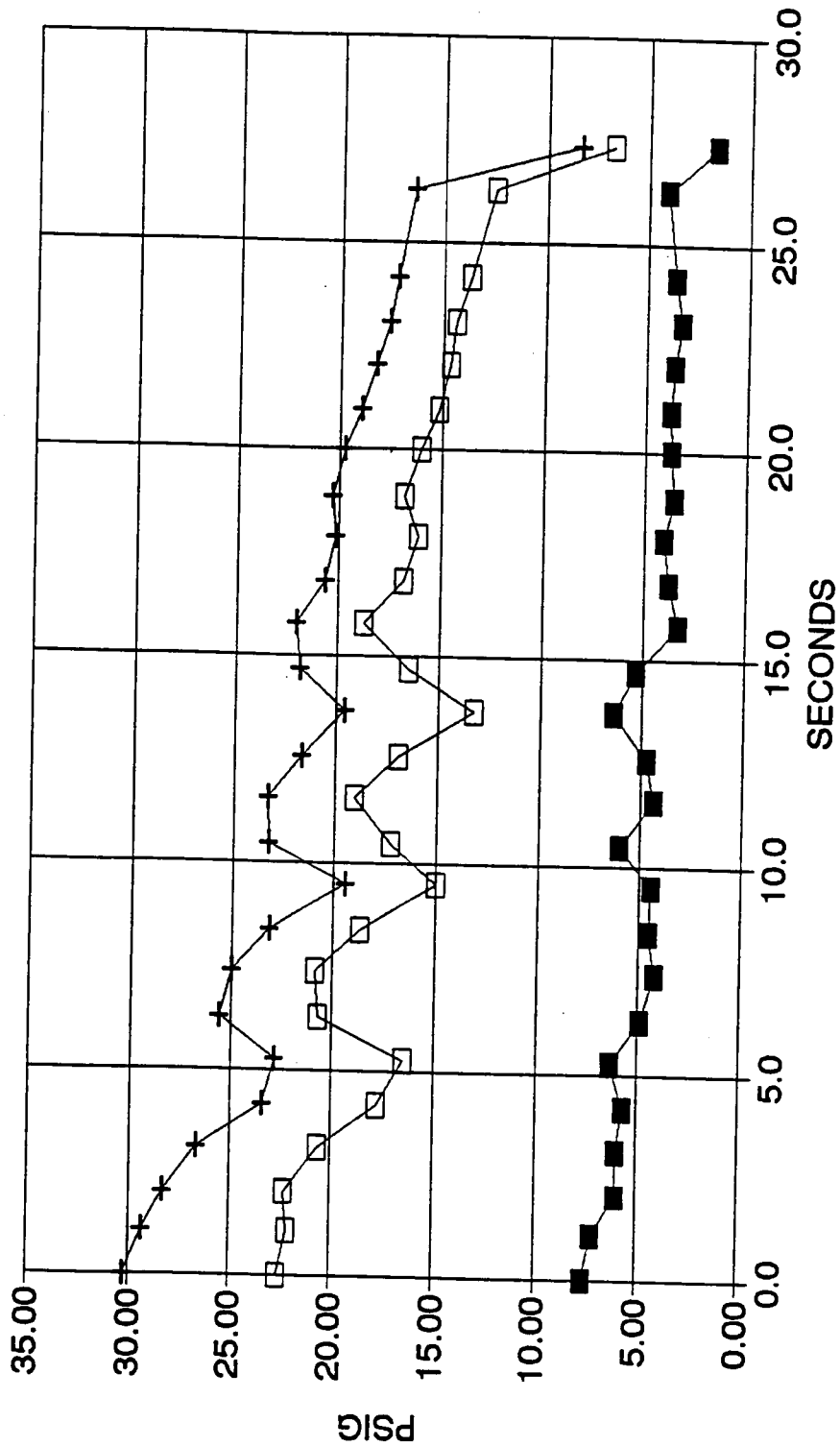


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 18
No Camera
Parabola 21

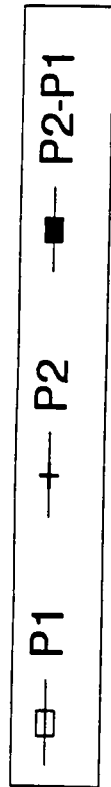
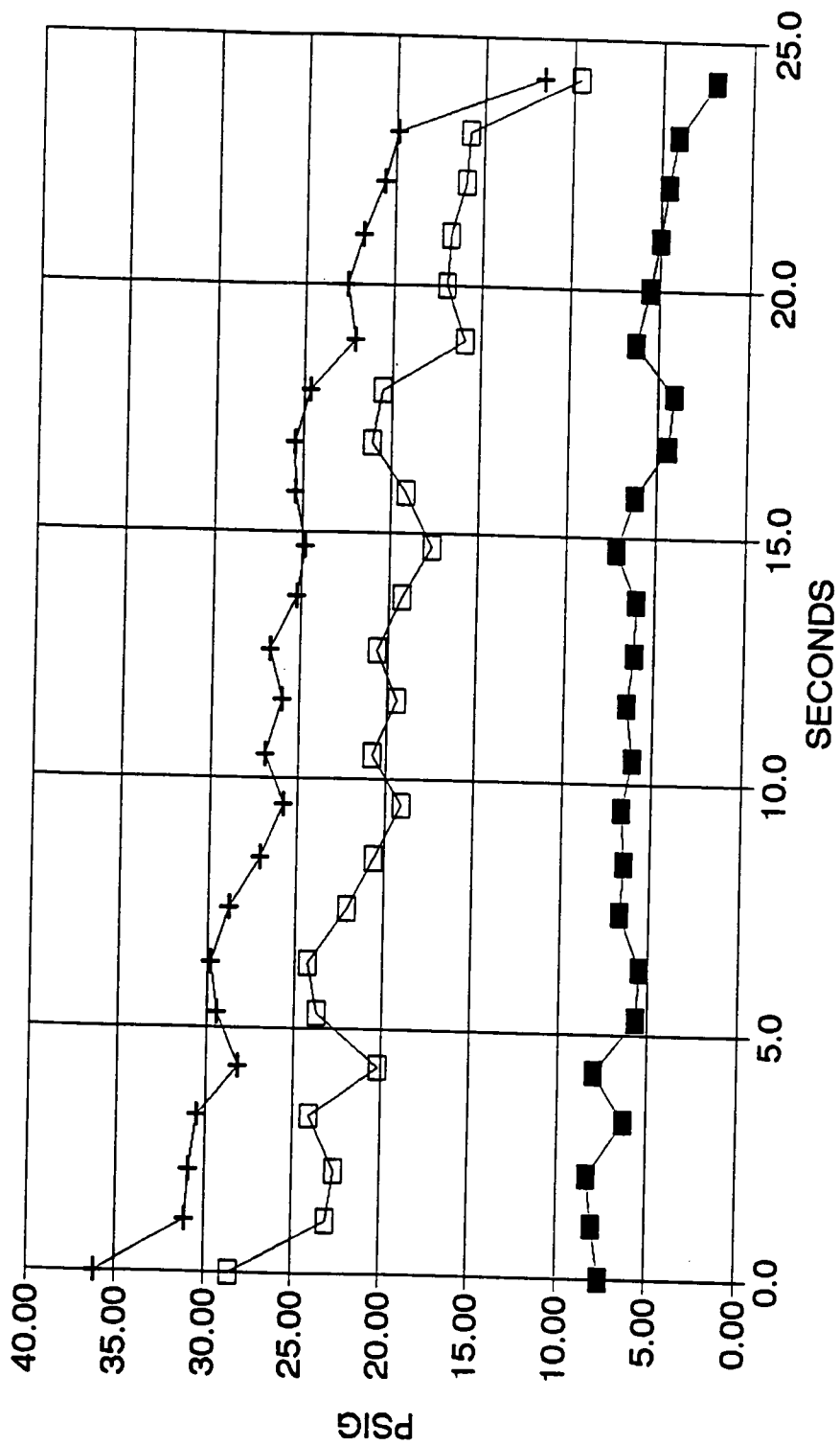


PRESSURE VS. TIME AUGUST 7, 91 RUN 19

VHS
Parabola 22



PRESSURE VS. TIME
 AUGUST 7, 91 RUN 20
 VHS Parabola 23

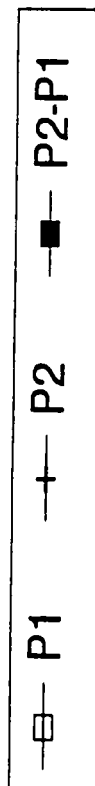
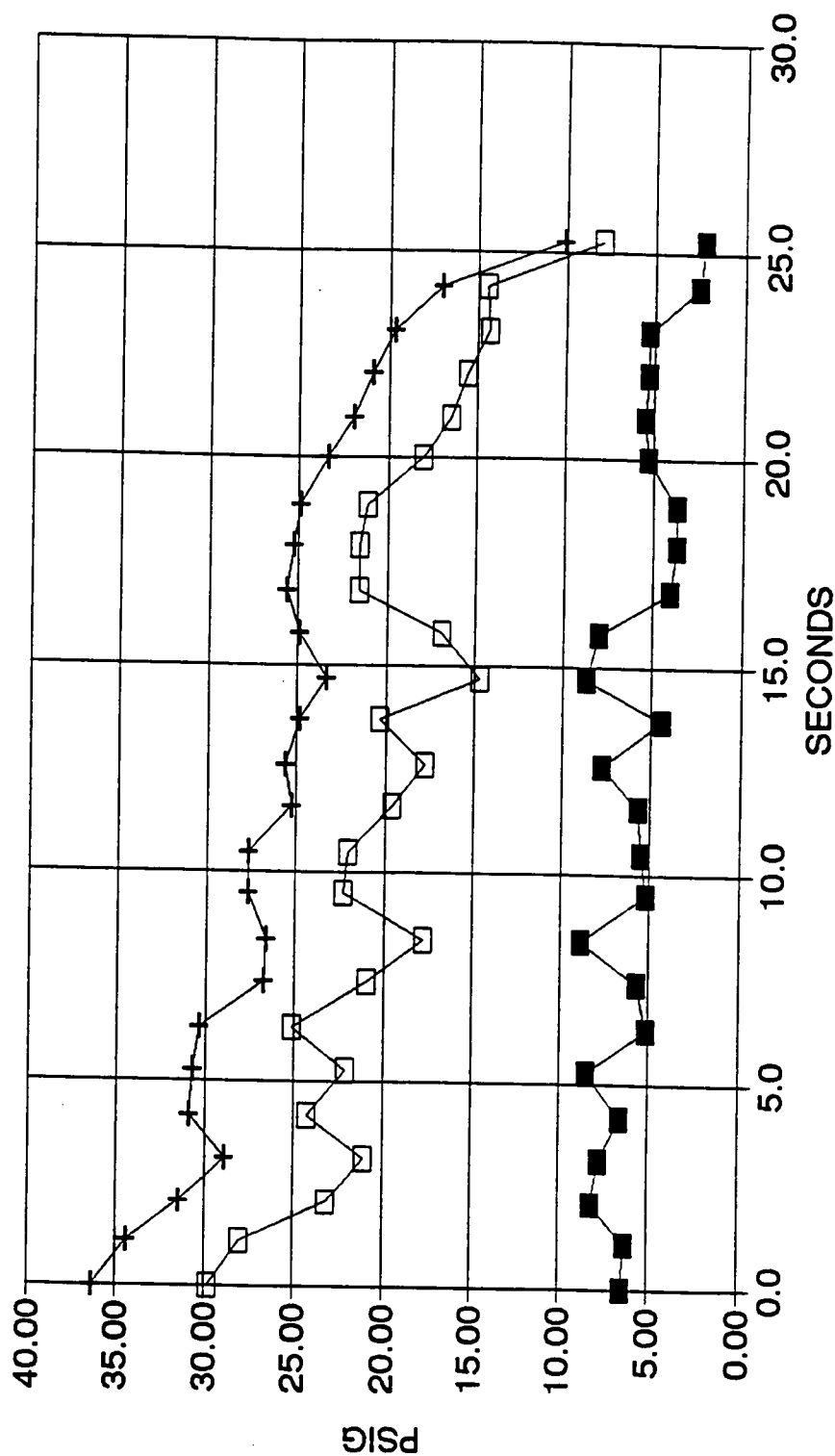


PRESSURE VS. TIME AUGUST 7, 91 RUN 21

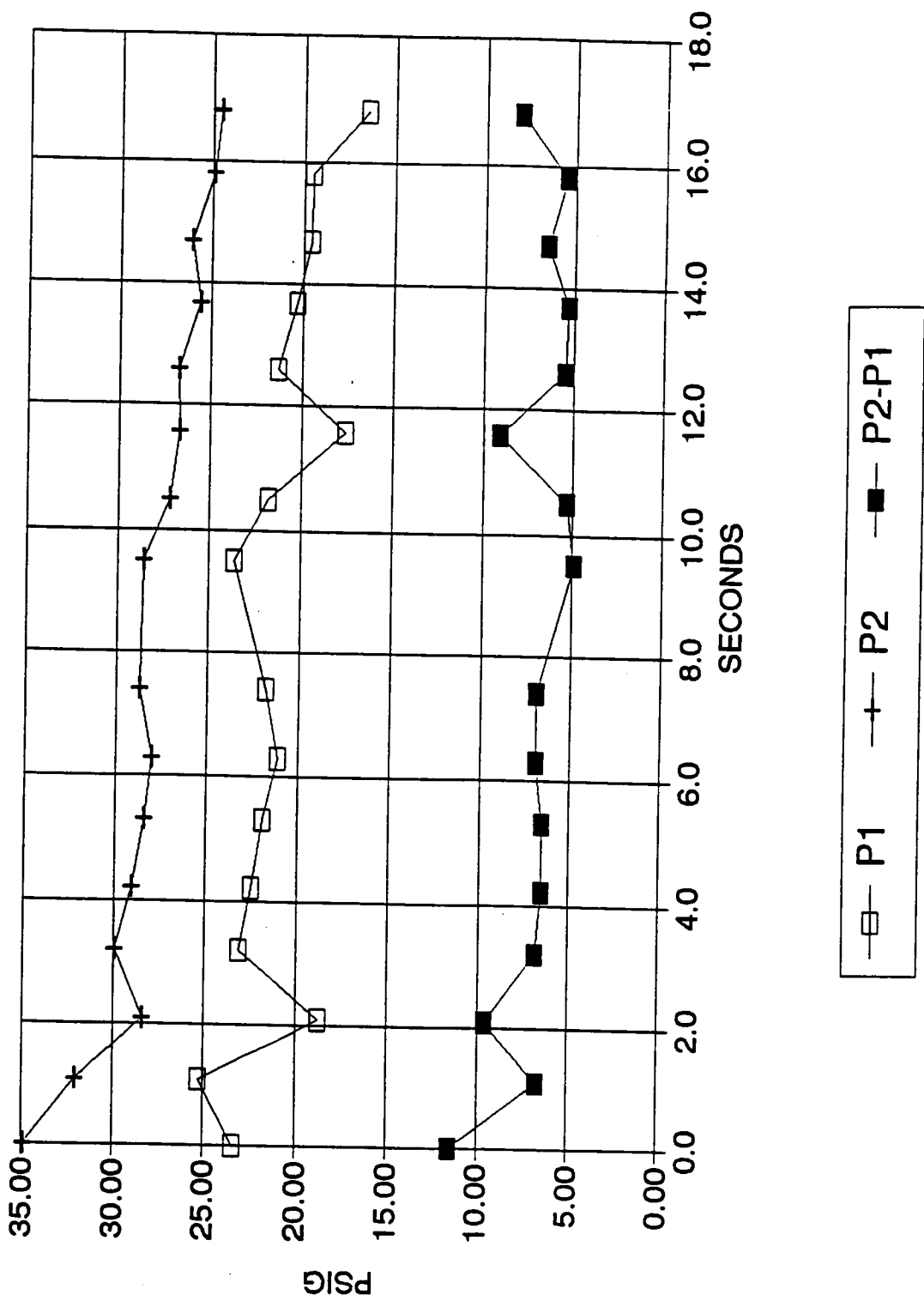
Overab

Hi / Vt's

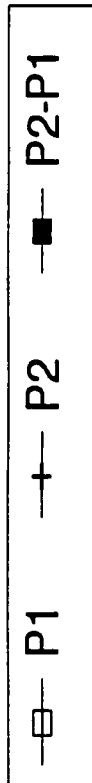
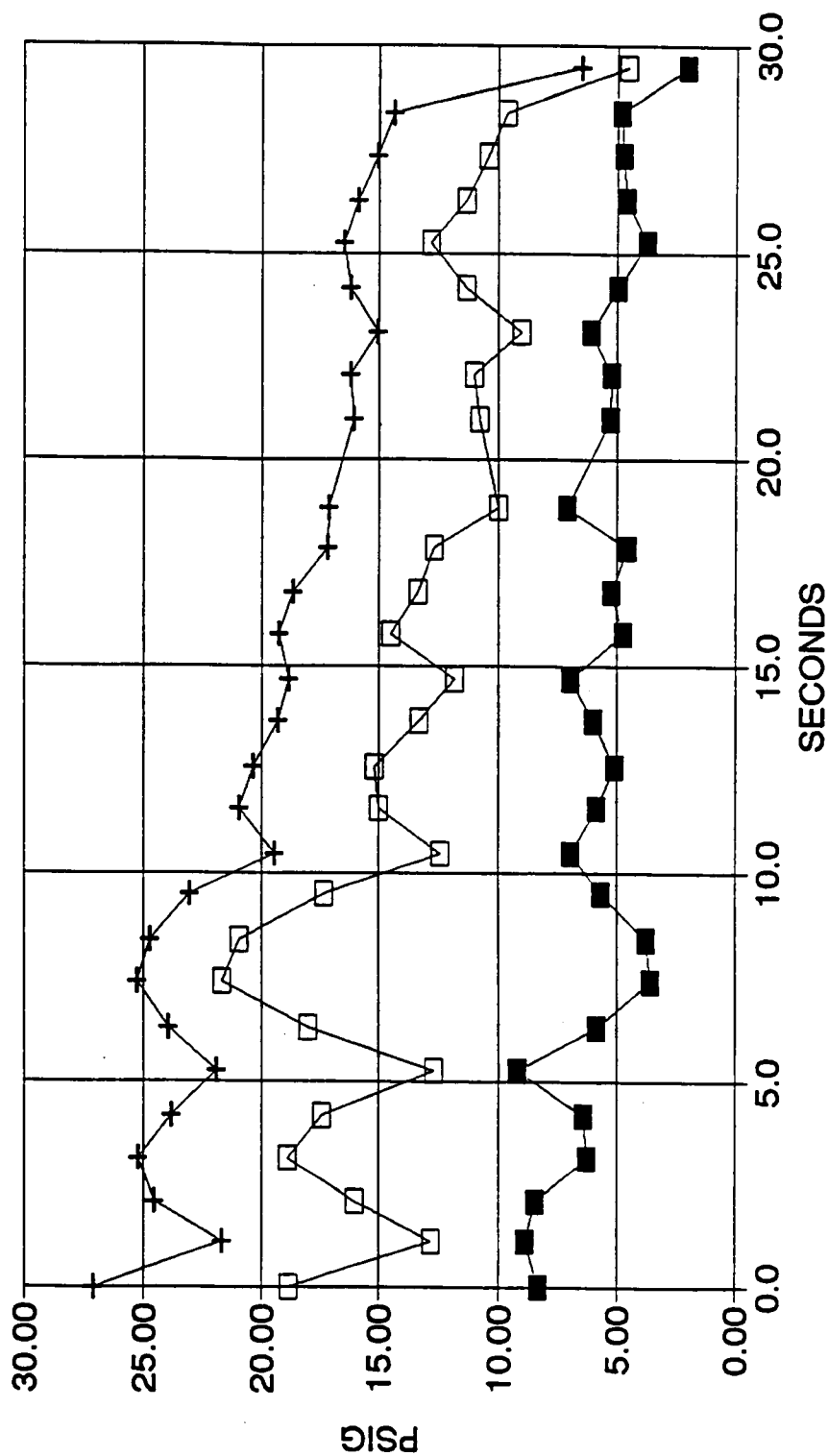
Parabola 24



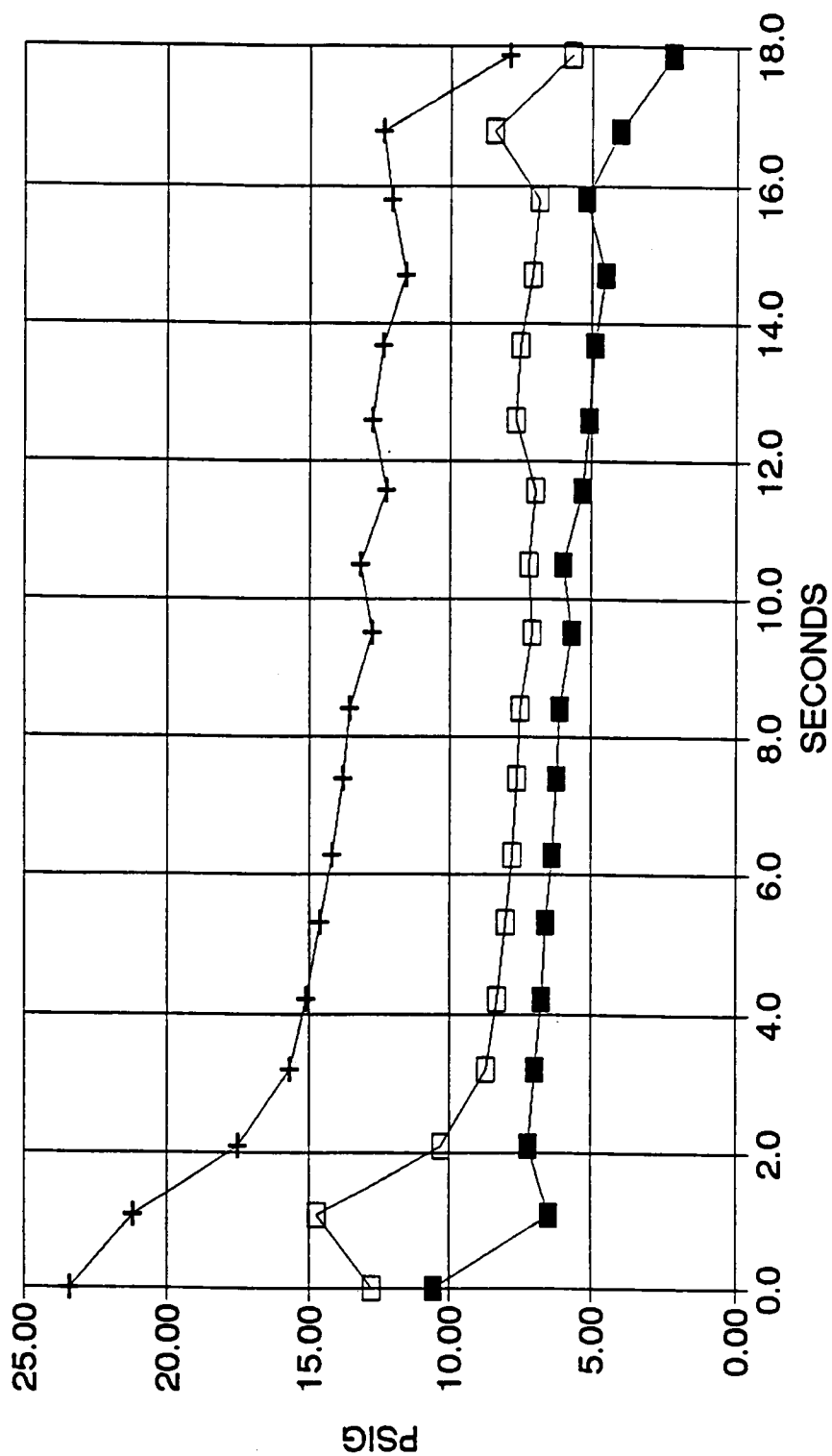
PRESSURE VS. TIME
 AUGUST 7, 91 RUN 22
No Canoe
 Parabola 31



PRESSURE VS. TIME
 AUGUST 7, 91 RUN 23
 VHS Parabola 33

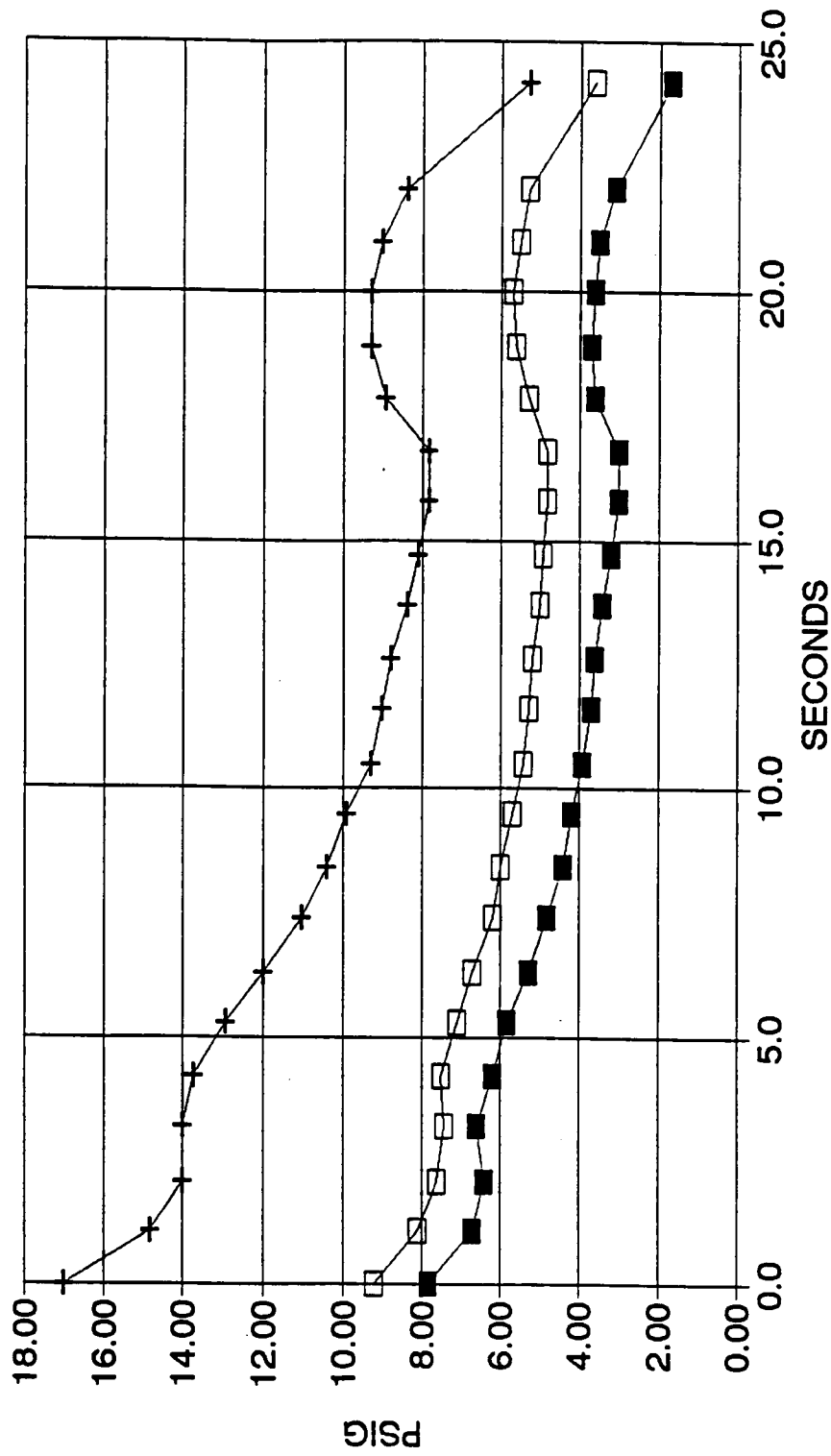


PRESSURE VS. TIME
 AUGUST 7, 91 RUN 24
 Hi / VHS
 Parabola 341



□ P1 + P2 ■ P2-P1

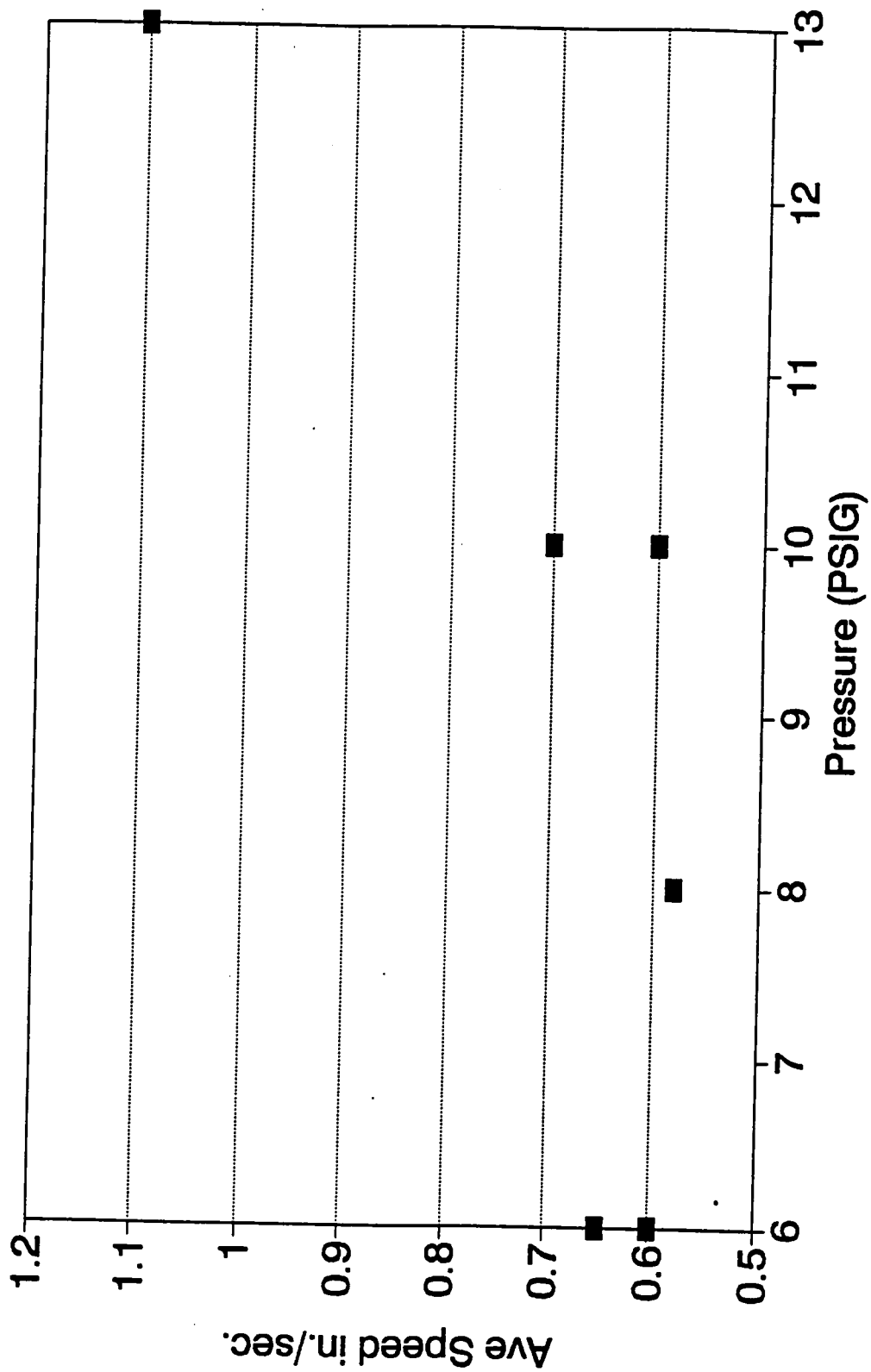
PRESSURE VS. TIME
 AUGUST 7, 91 RUN 25
No Camera
Parabola 36.7



□ P1 + P2 ■ P2-P1

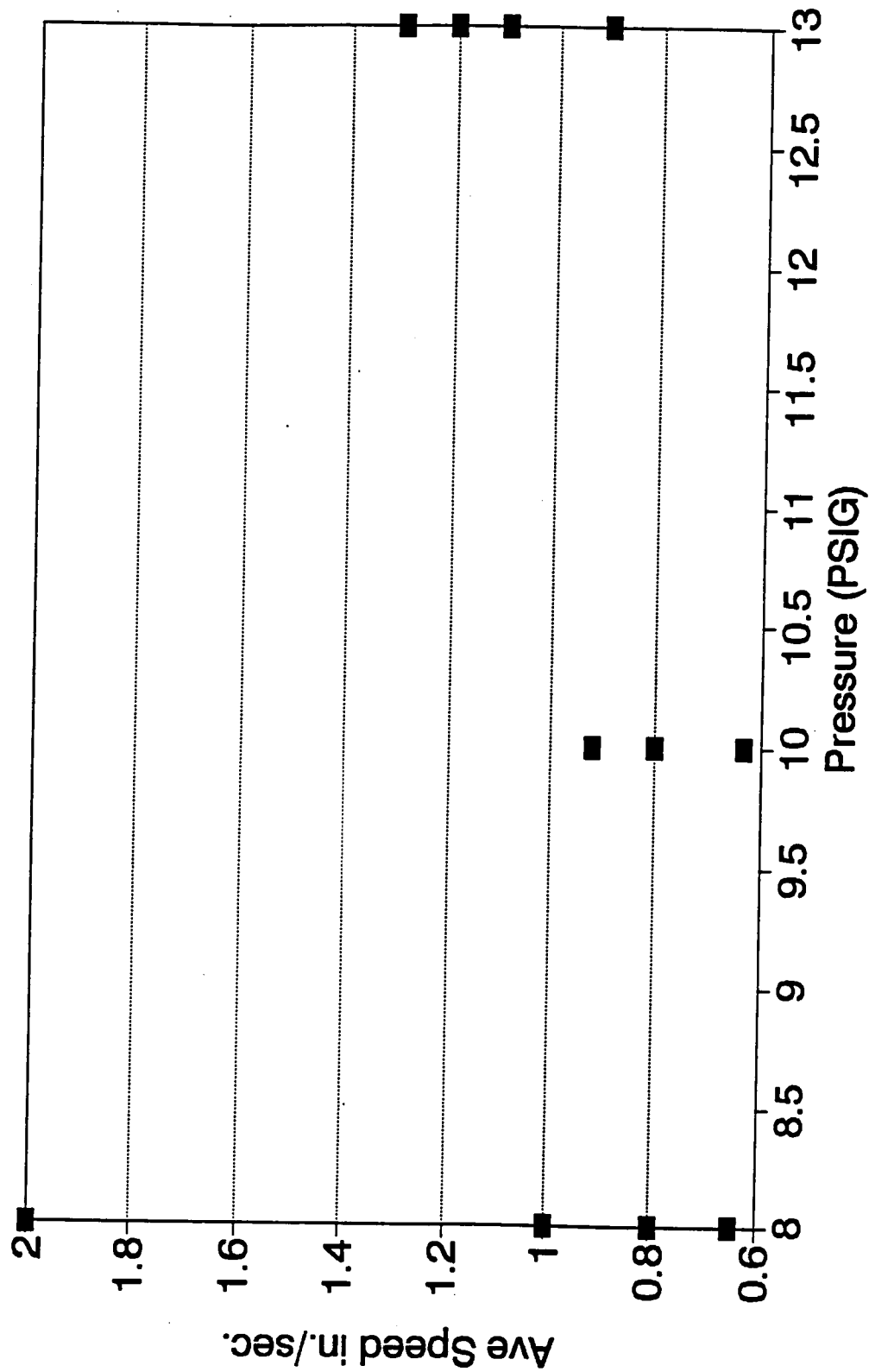
Quench Speed VS Driving Press.

August 6th, 1991



Quench Speed VS Driving Press.

August 7th, 1991



VITA

Jared P. Smith was born in Kirkwood, Missouri on November 6, 1963. He attended elementary schools in that area and graduated from Parkway South High School in June 1982. He recieved a Bachelors of Science degree in Mechanical Engineering at The University of Illinois at Champaign in December 1986. He has been practicing engineering full time in design of cryogenic fuel piping systems for aerospace industry applications, design of boundary layer capture systems for low speed through hypersonic wind tunnels, design of custom heat exchangers and engineering analysis of heat transfer and thermodynamic problems since 1987. He began working at a part time basis on graduate coursework through the University of Missouri Rolla in September 1988. Following a requested transfer, he continued to work part time in graduate studies at the University of Tennessee Space Institute beginning in May 1989. This degree was awarded in January 1993.

The author is a registered Professional Engineer in the state of Tennessee and is employed by Sverdrup Technology Inc. in Tullahoma, Tennessee.