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PROJECT TECHNICAL REPORT

CHARACTERIZATION EVALUATION OF THE ATTITUDE CONTROL PROPULSION SYSTEM

INTERIM REPORT

MSC/TRW TASK 705-1

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CONTENTS

		Page No.
1.0	PURPOSE AND CONCLUSIONS	1
2.0	INTRODUCTION	2
3.0	CHARACTERIZATION EVALUATION	5
	3.1 Literature/Computer Simulation Search	5
	3.2 Comparison Review	8
	3.3 Technique Evaluation	21
	3.4 Recommended Techniques	32
	3.4.1 Transient Combustor Model	34
	3.4.2 Steady-State Combustor	46
	3.4.3 Supply Lines Transients	48
	3.4.4 Supply Lines Steady State	68
	3.4.5 Turbomachinery Transients	71
	3.4.6 Turbomachinery Steady-State	71
	3.4.7 Heat Exchanger Transients	76
	3.4.8 Heat Exchanger Steady-State	78
	3.4.9 Accumulator & Pressure Vessels Transients	80
	3.4.10 Accumulator & Pressure Vessels Steady-State	81
	3.4.11 Manifolds and Injectors Transients	85
	3.4.12 Manifolds and Injectors Steady-State	87
	3.4.13 Orifices, Pipebends, & Valves Transients	88
	3.4.14 Orifices, Pipebends, & Valves Steady-State	88
	3.4.15 Gas Generator Transients	89
	3.4.16 Gas Generator Steady-State	[illegible]
	3.4.17 Valves	[illegible]

TABLES

		Page No.
1.	COMPUTER PROGRAM CAPABILITY REQUIREMENTS	4
2.	TYPICAL ACPS COMPONENTS/SUBASSEMBLIES	7
3.	NUMERICAL CODE FOR ACPS FILE	9
4.	ACPS RELATED LITERATURE	10
5.	ACPS RELATED COMPUTER PROGRAMS	18
6.	ACPS (TASK 705-1) CHARACTERIZATION EVALUATION FORMS	22
7.	PHASE III TECHNIQUE EVALUATION SYNOPSIS FOR ACPS RELATED LITERATURE	23

ILLUSTRATIONS

1.	FLOW DIAGRAM OF ACPS CHARACTERIZATION EVALUATION	6
2.	ACPS TURBO PUMP CYCLE	27
3.	LOW PRESSURE ACTIVE BIPROPELLANT SYSTEM	28
4.	COMBUSTOR CHAMBER MODEL EULER'S INTEGRATION SCHEME	38
5.	COMBUSTOR CHAMBER MODEL RUNGE-KUTTA INTEGRATION SCHEME	39
6.	COMBUSTOR MODEL SCHEMATIC	40
7a.	PRESSURE AT THE VALVE	60
7b.	FLOW RATE AT UPSTREAM END	61
8a.	PRESSURE AT THE VALVE	62
8b.	FLOW RATE AT UPSTREAM END	63
9a.	PRESSURE AT THE VALVE	64
9b.	FLOW RATE AT UPSTREAM END	65
10a.	PRESSURE AT THE VALVE	66
10b.	FLOW RATE AT UPSTREAM END	67
11.	[illegible]	68
12.	[illegible]	[illegible]

Page No.

13. TYPICAL PUMP PERFORMANCE MAP ---------- 72

14. TYPICAL PRELIMINARY PUMP PERFORMANCE (HYDROGEN PUMP) ------ 73

15. TYPICAL PUMP PERFORMANCE MAP ---------- 74

16. TYPICAL TURBINE PERFORMANCE MAP ---------- 75

17. HEAT EXCHANGER BLOCK DIAGRAM ---------- 76

18. ACCUMULATOR ---------- 80

19. GAS ACCUMULATOR ---------- 81

20. GAS/LIQUID PRESSURE VESSEL ---------- 81

21. MANIFOLD DIAGRAM ---------- 85

22. SIMPLIFIED MANIFOLD/ORIFICE ---------- 87

APPENDICES

1. REQUEST FOR LITERATURE SEARCH ---------- 99

2. LITERATURE SEARCH ON MATHEMATICAL MODELING FOR STABILITY OF HYDROGEN AND OXYGEN ROCKET PROPULSION ENGINES RESPONSE ------- 101

3. PROGRAMS FOR POTENTIAL USE ---------- 109

4. UNAVAILABILITY OF PROGRAM DOCUMENTATION REQUESTED FROM THE ADP PROGRAM SHARING LIBRARY ---------- 112

5. APS TRANSIENT COMPUTER PROGRAM LISTING ---------- 113

1.0 PURPOSE AND CONCLUSIONS

1.1 Purpose

The purposes of this document are fourfold. They are: (1) to present the results from a literature/computer simulation survey of methods and programs currently used by industry, NASA centers and other government agencies which may be used to simulate the steady-state and dynamic behavior of attitude control propulsion systems (ACPS); (2) to present a comparison of the various simulation techniques which were obtained from the survey; (3) to present an evaluation of the applicable techniques which resulted from the survey; and (4) to recommend to NASA/MSC the techniques which should be used to develop flexible steady-state and dynamic simulations of attitude control propulsion systems. The recommended techniques will result in computer programs which, upon approval of the MSC Task Monitor, will form the basis for the program development effort which will be carried out under Subtask II of this effort.

NOT REPRODUCIBLE

1.2 Conclusions

The literature search provided extensive information that has been used directly to formulate ACPS component modeling approaches. The applicable documents are referenced specifically throughout section 3.4 of this report. Unfortunately, no computer programs were found that could be directly applied in an efficient and economical manner to the program development objectives of Task 705-1. However, in many cases, techniques used in these programs were adopted. Every attempt was made to choose methods that were proven, that provide a high degree of accuracy, that are computationally efficient, [illegible]

2.0 INTRODUCTION

The design and development of attitude control propulsion systems (ACPS) for future mission applications will require extensive analyses to establish optimum system concepts. These analyses will consist of parametrically generating sufficient component and subsystem data to permit evaluation of ACPS concepts which meet a variety of mission objectives for a wide range of operating conditions. Since emphasis will be placed upon reusability, lightweight, high performance, safety, reliability and low cost for all components of future spacecraft, it is imperative that the analytical tools available for performing these analyses provide the capability to parametrically integrate system components into a variety of ACPS configurations to define optimum subsystem configurations. These analysis programs must also be capable of evaluating point designs of potential systems, determining the effects of component operation on overall system performance, determining system performance under both design and off-design conditions and characterizing final ACPS design configurations. Since the ACPS must be integrated with other vehicle subsystems to achieve optimum overall vehicle performance, the analysis programs must provide the additional capability of determining the effects on ACPS performance of subsystems integration and interaction.

MSC/TRW Task 705-1, "Characterization of Auxiliary Propulsion Systems," was initiated because of these requirements. The objectives of this task are to develop transient and steady-state analysis computer programs in a modular structure with generalized simulation capability suitable for:

1. Determining ACPS [illegible] criteria and operational constraints;

[illegible]

4. Determining ACPS performance due to vehicle subsystem integration and interaction;

5. Characterizing final design configuration operation.

Under this task all ACPS components will be modeled in sufficient detail to fully characterize the thermodynamic and fluid mechanics performance of each component and its effect on overall system performance. The resulting models will provide the capability for determining fluid pressure and temperature profiles required to operate the ACPS during a mission duty cycle and for determining methods of control and system operation compatible with a given mission duty cycle. In addition, the models will provide the ability to determine ACPS performance while simulating critical system component modes of operation.

The objectives of this Task will be achieved by performing the following three subtasks:

Subtask I — Evaluation of various analytical techniques used to characterize the dynamic behavior and performance of propulsion systems and a definition of the recommended approach.

Subtask II — Application of the techniques selected in Subtask I to the development of general purpose computer programs to satisfy the requirements listed in Table I.

Subtask III — Demonstration and operation of the program by selecting a typical ACPS design and operating the program over a range of conditions on the MSC computer facilities.

This report presents the accomplishments of Subtask I and delineates the analytical techniques and recommended characterization approaches for the ACPS computer program development activity to be carried out under Subtask II.

TABLE 1

COMPUTER PROGRAM CAPABILITY REQUIREMENTS

Transient Analysis Program

1. Component Sequencing
2. Subsystem energy requirements
3. Transient total impulse
4. Supply system dynamics
5. Supply system stability feedback:

   "line, valve and injector pressure surge, engine and feedline pressure overshoot"
6. Effects of geometry changes on start and shutdown
7. Effect of initial conditions
8. Component malfunction
9. Component performance
10. Varied component design and location
11. Varied engine configuration

Steady-State Program

1. Supply system balance requirements
2. Component performance
3. Varied component design and location
4. Effects of initial conditions
5. Component malfunctions
6. Statistical sampling capability

3.0 CHARACTERIZATION AND EVALUATION

Analytical techniques available for characterizing the dynamic behavior and performance of ACPS components (shown in Table 2) have been evaluated on the basis of: state-of-the-art; efficiency; adaptability to solution by digital computer; previous usage; accuracy; availability of characterization parameters and adaptability to modular computer program construction. Basically, this subtask was divided into four phases, (see Figure 1):

Phase I	Literature/Computer Simulation Search
Phase II	Comparison Review
Phase III	Technique Evaluation
Phase IV	Recommended Techniques

The initial part of this subtask consisted of a survey of methods and programs currently used by industry and other NASA centers and governmental agencies including those at Lewis Research Center (LeRC), Marshall Spaceflight Center (MSFC), Jet Propulsion Laboratory (JPL), Arnold Engineering Development Center (AEDC), and Air Force Rocket Propulsion Laboratory (AFRPL). Contacts were established with companies performing ACPS simulation work on the Shuttle Vehicle, and the computer programs applicable to this task which are being formulated by these companies are being reviewed as they become available.

3.1 LITERATURE/COMPUTER SIMULATION SEARCH (PHASE I)

Several literature search requests covering the entire scope of information deemed pertinent to the modeling of the Shuttle ACPS were submitted to the TRW Technical Information Center. These literature search requests were issued using general descriptions with detailed key word identifiers. Typical examples of these literature search requests are shown in Appendix A. The action taken on these literature search requests was and all available information [illegible]

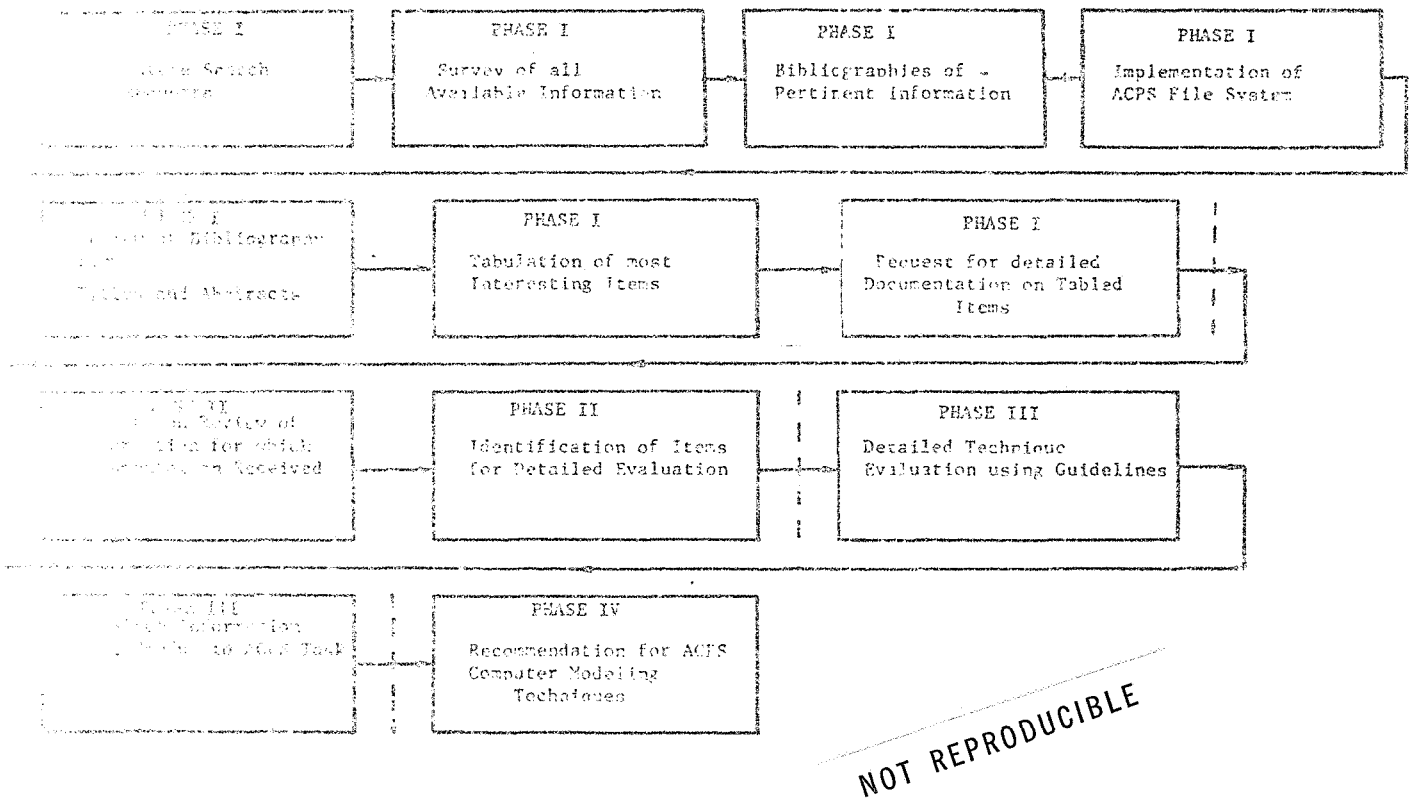

FIGURE 1

FLOW DIAGRAM OF ACPS CHARACTERIZATION EVALUATION

TABLE 2 - TYPICAL ACPS COMPONENTS/SUBASSEMBLIES

- Combustors
- Injectors
- Manifolds
- Turbopumps
  - Pumps and Compressors
  - Inducers
  - Turbines
  - Electric Motors
- Heat Exchangers
- Fluid Supply
  - Accumulators
  - Supply lines
  - Pressure vessels
  - Gas lines
  - Liquid lines
  - Orifices, bends/restrictions
- Regulators
- Control Valves
- Valve Actuators
  - Pneumatic/Hydraulic
  - [illegible]
  - [illegible]

1 - Manually performed survey of all engineering and scientific publications including advanced degree theses.

2 - Manually performed review of indexes containing lists of computer programs shared by all NASA facilities and contractors. Among those indexes which contained the most pertinent information were COSMIC (Computer Software Management and Information Center) and the NASA ADP Resource Sharing System Computer Programs.

3 - Computerized search of all information available to NASA facilities and the Defense Documentation Center (DDC)

The bibliography results of Action 1 above are shown in Appendix 2. Action 2 results are shown in Appendix 3. Action 3 resulted in voluminous computer printouts of titles and abstracts of pertinent ACPS information; these printouts are too massive for inclusion in this report. They are being retained by TRW in the ACPS Literature Search file, and are available upon request.

With the receipt of these bibliographies, the next item accomplished was a review of all titles and abstracts (if available) in order to select information for further examination in the Phase II comparison review. Also at this time, the ACPS Literature Search File was implemented in order to systematically control the receipt and filing of the ACPS information obtained. Table 3 shows the numerical index code used to file and retrieve all ACPS information.

3.2 COMPARISON REVIEW (PHASE II)

After a review of the above mentioned bibliographies, those items indicating strong applicability for the ACPS were chosen for the PHASE II Comparison Review. Table 4 shows, specifically, the selected literature related to the ACPS while Table 5 shows those computer programs pertinent to the task. A preliminary review was made of the literature and computer programs to determine which would be most suitable for comparison, and detailed documentation was ordered. For a detailed review, several of the computer [illegible]

[illegible]

TABLE 3

NUMERICAL INDEX CODE FOR

ACPS FILE

INDEX	DESCRIPTOR
0.0	ACPS LITERATURE SEARCH RESPONSES
0.1	ACPS LITERATURE SEARCH REQUESTS TO LIBRARY
1.0	TANKS
1.1	LIQUID TANKS
1.2	GAS TANKS
2.0	COMPRESSORS
2.1	LIQUID COMPRESSORS
2.2	GAS COMPRESSORS
3.0	REGULATORS
3.1	LIQUID REGULATORS
3.2	GAS REGULATORS
4.0	VALVES
4.1	LIQUID VALVES
4.2	GAS VALVES
5.0	HEAT EXCHANGERS
6.0	LINES
6.1	LIQUID LINES
6.2	GAS LINES
7.0	ENGINES
7.1	LIQUID ENGINES
7.1.1	LIQUID ENGINES: STEADY STATE
7.1.2	LIQUID ENGINES: TRANSIENTS
7.2	GAS ENGINES
8.0	TURBINE
8.1	HYDRAULIC TURBINE
8.2	GAS TURBINE
[illegible]	[illegible]
10.0	[illegible]

TABLE 4
ACPS RELATED LITERATURE

	TASK REF.	STAR I.D. NO.	TITLE	COPY **
	1.0	N68-25107	Post Test Analysis of Generart Tank	MF
		AD-646681	The Combined Laboratory and KC-135 Aircraft Zero-g Test Program	MF
		AD-817057	Tank Mounted Insulation Program	MF
	1.1	AD-863275L	Launch System Branch Destratification of Cryo Propellants	
		AD-863843L	Thermodynamic Studies of Cryogenic Propellant Management	
		AD-844181	Liquid Hydrogen Pressure Loss Phase	MF
		AD-843476	Sundstrand Model 876 APU Part I: (Cryogenic Liquids)	
		AD-693361	Forced Convection Heat Transfer to Supercritical Cryogenic Hydrogen, Part I, Lit. Survey	MF
		AD-677074	The Prediction of the Wetting of Solids by Liquid Hydrogen and Liquid Oxygen	HC
		AD-614039	Consistent Vibrations Model of Internal Dynamics of Liquid Hydrogen	MF
		AD-888035	Zero-g Report Liquid/Liquid Models	MF
		AD-820052	Feasibility of Using Liquids Other Than Hydrogen for Liquid Behavior Tests of Zero-g Test Program	MF
	1.2			
*	2.0	AD-851905	Development of Turbocompressor Performance Rotating Stall Prediction Model	MF
		AD-851902	Analytical Model for Predicting Turbocompressor Performance with Combined Circumferential and Radial Inlet Distortion	MF
	2.1	N65-18703	Design, Technology, and Performance of High Pressure Turbopumps for Large Thrust LH2 and LOX Rocket Engines.	
		N69-33219	Analytical Model for Use in Design of Pump Inlet Accumulators for Prevention of Liquid Rocket Longitudinal Oscillation	HC
		N69-32759	An Analysis of Two-Phase Flow in LH2 Pumps for O_2/H_2 Rocket Engines	HC *
		AD-432042	Study Design, and Test of Experimental Liquid Hydrogen Pump for use in Flight Vehicle System	HC *
	2.2		* Indicates Literature which was reviewed for Phase III - Technique Evaluation	
			** HC,MF - Indicates hard copy or microfiche copy received and reviewed for Phase II - Comparison	

TABLE 4 (Contd.)
ACPS RELATED LITERATURE

[illegible]	[illegible]	STAR I.D. NO.	TITLE	COPY
[illegible]	3.0			
[illegible]	3.1			
[illegible]	3.2			
[illegible]	4.0			
[illegible]	4.1	AD-854595	Wide Range Flow Control Program	MF
		AD-462537	Valve, Regulator Relief, Recirculation, System	HC
		AD-467090	Dev. of Cavitating Venturi Valves for Deep Throttling of Cryogenic Liquids	MF
[illegible]	4.2			
[illegible]	5.0	N69-31489	Computer Analyzed Hydrogen Reliquefier Cycles for Selection of Optimal Cycle, Rates, and Heat Exchangers	MF
		N69-23231	Analytical Model of Thermal Flow Oscillations in Heat Exchangers for Super Critical Fluids	MF
[illegible]	6.0			
[illegible]	6.1	Am.Soc.C.E. Pro., My '62	Computer Model for a LOX Manifold System	
		N66-32330	Digital Distributed Parameter Model for Computing Dynamic Response of Rocket Propellant Feed Systems to Pressure and Flow Disturbances	HC *
		N67-23795	Effect of Propellant Feed System Coupling and Hydraulic Parameters on Analysis of Chugging	HC *
[illegible]	6.2	[illegible]-8361226	Two GH2 Manifold Assemblies. Two GOX Manifold Assemblies	
[illegible]	7.0	A63-15610	Rocket Combustion Chamber Ignition Studied By Mass, Spectroscopy of Chemical Species	
		[illegible]-26561	Mathematical Model for Combustion at Zero Gravity in Spacecraft Environments	MF
		[illegible]-20070	Small Rocket Engine Research	
		[illegible]-27545	Current Design Technology of Attitude Control Systems for Large Launch Vehicle	
		[illegible]-[illegible]	Survey of the Relationship Between Theory and Experiment for Convective Heat Transfer from Rocket Combustion Cases.	

TABLE 4 (Contd)
ACTS RELATED LITERATURE

[illegible]	[illegible]	TITLE	COPY
[illegible]	[illegible]	The Effect of Nozzle Flow Striations on Engine Performance	MF
	[illegible]	Effect of Chamber Pressure on Performance of Small Reverse Flow Rocket Engine	MT
	[illegible]	Space Prop. Dev. System Specification (RL10A-3 Engine)	
	[illegible]	Compressible Laminar Boundary Layer with Fluid Injection	HC
	[illegible]	Transpiration Cooling in Porous Metal Walls	HC
	[illegible]	Temperature of a Transpiration Coolant Plate	HC
	[illegible]	Mathematical Model of Cylindrical Electric Gas Dynamic Generator	MF
[illegible]	[illegible]	Improvement of High Performance Liquid Fuel Rocket Engine by Opt. of Liq. H2 and Liq. O2 Propulsion	
	[illegible]	Interagency Chemical Rocket Propulsion Group Method of Treating Measurement Error for Liquid Rocket Engine Performance Parameters Using Uncertainty Model	
	[illegible]	Mathematical Model for Calculating Radiative Heat Transfer From Turbulent Diffusion Buoyant Flame and Predicting Liquid Fuel Burning Rate	MF
	[illegible]	The Design and Manufacture of a Liquid Hydrogen/Oxygen Thrust Chamber	MT
	[illegible]	Stabilizing Effects of Several Injector Face Baffle Configurations on Screech in a 20,000 lbs. Thrust Rocket-Thrust Hydrogen/Oxygen Rocket	
	[illegible]	Quantitative Analysis of Liquid Oxygen Hydrogen Combustion Products	
	[illegible]	Thermodynamic Calculation of a High-Rate Cylindrical Combustion Chamber of a Liquid Fuel Rocket Engine	
	[illegible]	Rocket Engines - Liquid Propellant, Vol. I - Small Engine	
	[illegible]	Design Parameters for Large Liquid-Propellant Rocket Engines	HC
	[illegible]	Quantitative Analysis of Liquid Oxygen - Liquid Hydrogen Combustion Products	HC
	[illegible]	Study of Catalytic Reactors For H2/O2 Ignition	MF
[illegible]	[illegible]	General Equations for Constructing Mathematical Model on Steady State Liquid Propellant Rocket Engine Performance, and Algorithms of Solution	[illegible]
	[illegible]	Development and State-of-Art in Analytical Steady-State Liquid Propellant Rocket Combustion Models	L
	[illegible]	Kinetics and Thermodynamics in High Temperature Gases	H

TABLE 4 (CONT'D)
ACPS RELATED LITERATURE

[illegible]	[illegible]	STAR I.D. NO.	TITLE	COPY
[illegible]	[illegible]	N68-20014	Experimental Investigation of High Frequency Longitudinal Combustion Instability in Gaseous Propellant Rocket Motors	
		ARS Jour-June '59	Rocket Thrust Termination Transients	HC*
		See Table 7	TRW Proposal Report, "Generalized Bipropellant Propulsion System Transient Computer Simulation." 12 June 1969.	HC*
		Review of MOD Physics April 1969	Theory of Transport Coefficients for Moderately Dense Cases	HC
		Phy. of Fluids Jan.'69	Variational Calculation of Transport Coefficients in a Binary Mixture	HC
		Soviet Physics Mar.'69	Transport Phenomena in Reacting Gas Mixtures	HC
		A65-22461	Combustion Process Influence on Stability	HC
		NASA-TM-1112	The Effect of Turbulence on the Flame Velocity in Gas Mixtures	HC
		Jet Prop. #26 1956	Low Frequency Comb. Instability	HC
		Jet Propulsion 1955	Structure and Propogation Mechanism of Turbulent Frames in High Speed Flow	HC
		J. Spacecraft. 64, 1964	Mixing in Turbulent Axially Symm. Free Jets	HC
		AIAA Jour. 52, 1964	A Shock Wave Model of Unstable Rocket Combustors	HC
		A69-38743	Rocket Comb. Instability	HC

TABLE 4 (Contd)
ACPS RELATED LITERATURE

[illegible]	[illegible] CODE	SCAP I.D.	TITLE	COPY
[illegible]	[illegible]	[illegible]69-17098	Mathematical Model for Solving 3-dimensional Combustion Instability in Liquid Propellant Rocket Engines	HC,MF
		[illegible]65-22572	Nonlinear Model for Calculating Combustion Stability in Liquid Propellant Rocket Engines	MF
		[illegible]66-10130	Mathematical Model to Determine Longitudinal Instabilities in Liquid Propellants Rocket Vehicle	MF
		[illegible]70-18071	Boundary Value Problems and Cauchy Problems Considered for Mathematical Model of Turbulent Motion in Liquid or Gas	
		[illegible]AIAA Sc.'66	Theory for Ignition and Deflagration of Fuel Drops	HC
		[illegible]68-20743	Rocket Combustion Instability Studied Experimentally Using Theoretical Model Characterizing Combustion by Time Lag and Interaction Index	
		[illegible]A69-18100	Nonsteady Combustion Models for Gases, Liquid Fuels, and Solid Propellants, Reviewing Errors in Physics and Mathematics	
		[illegible]70-12007	Nonlinear Combustion Instabilities in Liquid Propellant Rockets, Considering Various Combustion Models and Experimental Techniques	
		[illegible]A70-12011	Three Dimensional Linear Combustion Instability in Liquid Propellant Rocket Motors Using Concentrated Combustion Mode, Presenting Mathematical Analysis as Boundary Value Problem	HC
		[illegible]0-842 959	Analytical Model Development to Study Liquid Rocket Engine Combustion Instability at High Chamber Pressures	HC
		[illegible]67-37086	Analytical Model for Describing Combustion Chamber Disturbances During Start Transient and Steady-State Operations of Hypergolic Liquid	MF
		[illegible]68-25302	Double Dead-Time Model for Combustion Stability Analysis in Liquid Bipropellant Rocket Engines	MF
		[illegible]-60185	Linearized Mathematical Models of Feed System Coupled Combustion Instability of Liquid Propellant Rocket Engines	HC
		[illegible]	Theoretical Propellant Combustion Model for Rapid Depressurization Effects	MF
		[illegible]-20349	Mathematical Development of Sensitive Time Lag Theory of Liquid Rocket Engine Combustion Instability	MF
		[illegible]-18034	Mathematical Model of Ignition Transient for Hypergolic Rocket Propellants	[illegible]
		[illegible]-18473	Combustion Stability Model of Advanced Injector for Use on High Pressure Hydrogen Oxygen Engines	

TABLE 4 (CONTD)
ACPS RELATED LITERATURE

[illegible]	[illegible]	TITLE	COPY
[illegible]	AIAA Paper #69-[illegible]	Errors in non-Steady Comb. Theory in the Past Decade	HC
	[illegible] Report No.	Research on Combustion Instability in Liquid Propellant Rockets	HC
	AIAA Journal [illegible], [illegible]	Stability of Hi-Frequency Press. Oscill. in Rocket Comb. Chambers	HC
	[illegible]-20[illegible]5	Theory of Acoustic Instability in Solid Propellant Rockets	MF
	Acrg Lab. Princeton, #380 [illegible]	Transverse Wave & Entropy Wave Combustion Instability in Liq. Prop. Rockets	MF
	AD [illegible] 8[illegible]	The Sensitivity Time Lag Theory and Its Application to Liq. Rocket Comb. Instab. Vol. I	HC
	AD 842 950	Comb. Instab. Analysis at High Chamber Pressure	HC
	AD [illegible] 8[illegible]	5th ICSPG Combustion Conference	HC
	[illegible]-1287-1956	Spark Ignition of Flowing Gases	HC

TABLE 4 (Contd)
ACPS RELATED LITERATURE

[illegible]	FILE CODE	STAR I.D. NO.	TITLE	COPY
[illegible]	7.2	N67-27227	Test Firings and Analytical Model Used to Evaluate Chugging Instability in Subscale Experiments with LOX Gaseous Hydrogen Combustors	MF,HC
		N67-32360	Spacecraft Attitude Control Gas Systems Analysis Final Report	MF, HC
		1043	Effect of Combustor Parameters on the Stability of Gaseous Hydrogen-Liquid Oxygen Engine	
		AD-615798	Steady State Rocket Combustion of Gaseous Hydrogen and Liquid Oxygen	MF
		AD-465875	Heat Transfer and Performance Studies on Propellant Combination Gaseous Hydrogen/ Gaseous Oxygen, Part 3	MF*
		AD-817981	Thrust Variation of a Gaseous Propellant Rocket Engine	MF*
		AD-652797	An Investigation of the Performance of Various Mixtures of Hydrogen and Methane	MF
		See Table 7	TRW Briefing Report on O2/H2 Thruster (Prop)	HC*
		See Table 7	TRW R.B.Proposal for High Pressure ACPS to MSFC	HC*
		See Table 7	TRW R.B. Proposal for Low Pressure ACPS to MSFC	HC*
		See Table 7	TRW Capabilities in O2/H2 Igniter and Injector Flow Characterization	HC*
		See Table 7	TRW Capabilities Relative to Development of a Generalized Shuttle Thruster Model	HC
		Aerolab Princeton 4539	An Experimental Investigation of Longitudinal Combustion Instability in a Rocket Motor Using Pre-Mixed Gaseous Propellants	HC
		See Table 7	NASA Memo on O2/H2 Perf. Curve Plots, Feb. 1970.	HC*
			TRW Memo "Space Shuttle APS Dynamic Analysis"	HC*
		N63-22409	Summary of Experimental Investigation of Combustion Pressure Oscillations in Gaseous Propellant Rocket Motors	MF
		Aerolab Princeton 45.7	Analysis of High Freq. Comb. Instab. in a Gas Fueled Rocket Motor	MF
[illegible]	8.0	N68-12231	Digital Computer Programs, Mathematical Models and Propulsive System Disturbance Functions for Integrating Engine and Inlet Dynamic Controls in Turbine Engine Design	MF

TABLE 4 (Contd)
ACPS RELATED LITERATURE

[illegible]	[illegible]	FTAM I.D. No.	TITLE	COPY
[illegible]	[illegible]	N68-19420	Computer Models for Inducer System of Hydraulic Turbine Drive for Liquid Hydrogen	
	9.2	AD-832454	An investigation of the Effects of Secondary Stream Turbulation on the Thrust Augmentation of an Ejector-Afterburner	MF
		British Inst. M.E. 56: 1954	Convective Heat Transfer to Gas Turbine Blade Surfaces	HC
[illegible]	9.0	AD-802911	Propellant Perf. Handbook, Vol. V, Part B, Oxygen/Hydrogen	MF*
		NBS TN 120A	Tabulation of Thermo Prop. of Normal H2 From Low Temp. to 540°R and From 10 to 1500 psia. NBS Tech. Note	HC*
[illegible]	10.0			
[illegible]	11.1			
[illegible]	11.2	See Table 7	Space Shuttle Low Pressure Auxiliary Propulsion Subsystem Definition - MacDac	HC*
		See Table 7	Space Shuttle High Pressure Auxiliary Propulsion Subsystem Definition - Subtask A - Conceptual Design Study Review - TRW	HC*

Table 5

ACPS COMPUTER PROGRAMS

[illegible]	[illegible] NUMBER	[illegible] REPORT NO.	TITLE	COPY
	3.1	F MSC M080	Tank Pressurization Program	
		F MSC M095	Analysis of Propellant Tank Pressurization	
		F MSC 370170	Asymmetric Propellant Heating	
		F MSC M125	Ullage Pressure Variation with Temperature	
		F MSC 474069	Low-G Liquid-Vapor Interface	
		F MSC M231	Oxygen Cryogenic Program	
	3.2	F MSC 354639	Heat Transfer to a Spherical Container	
		F MSC 343429	Heat Transfer Sphere	
		F MSC F246	Nuclear Shuttle Hydrogen Program	
[illegible]	3.1	F MSC 566930	SIV Pump Cooling	
[illegible]	2.2	J MSC 3071	Fan, Blower, and Pump Design	HC
[illegible]		J MSC 3197	Optimization/Evaluation of Fans, Compressors, and Pumps	HC
[illegible]	3.1	MSF 1675	Orifice Sizing for Fluid Systems	
[illegible]	6.0	MSC 10133	Actuation Timing of a Linear Actuated Valve	
[illegible]	5.0	MSC 10140	Computer Programs for the Design & Performance Analysis of Compact Multi-Fluid Heat Exchanger	HC *
		MSF 2122	Heat Exchanger Program	HC
		MSC 10169	Transient and/or Steady State Thermal Analysis with Coupled Fluid Flow and Heat Conduction	HC
		F MSC 758	Generalized Explicit Two-Phase Flow Finite Difference Generalized Heat Exchanger	HC*
			HC - Indicates program documentation received and reviewed for Phase II - Comparison Review. *Indicates program which was reviewed for Phase III - Technique Evaluation	

Table 5 (Contd)
ACPS RELATED COMPUTER PROGRAMS

[illegible]	[illegible]	[illegible] NO.	TITLE	COPY
[illegible]	[illegible]	[illegible] 3057	Design and Performance Analysis of Compact Heat Exchangers	NA
		[illegible] 134070	Heat Exchanger	NA
		[illegible] 8094	Propellant Feedline Heat Exchanger	HC *
		[illegible] 8182	Spacecraft ECS Heat Exchanger Program	
		[illegible] 8230	Three-Fluid Cross Flow Heat Exchanger Program	HC
		[illegible]	Transient Start-Up	NA
		[illegible] No. [illegible]-26040	FORTRAN II Computer Program for Aerothermodynamic Behavior of Compact Heat Exchanger Component Models for Nuclear Ramjet and Rocket Engines Based on Real Gas Properties	MF
[illegible]	[illegible]	[illegible] 374210	Low-G Fluid Dynamics	
		[illegible] AP237	SPS Feed Lines	HC
		[illegible] 586	Computer Program for the Prediction of Flow Distribution in a Ring Injector	
	[illegible]	[illegible] 443	Solution of Compressible Flows in Piping Systems	HC *
		[illegible] 369250	Heat Transfer and Thermal Problems	
		[illegible] 369320	Duct Flow TL/D,Q, DA	NA
	[illegible]	[illegible] 370170	Axisymmetric Two-Phase Perfect Gas Program	
[illegible]	[illegible]	[illegible] 8120	Lunar Module Reaction Control System Engine Injector	
[illegible]	[illegible]	[illegible] AP[illegible]	RCS Steady State Analysis	HC
		[illegible] 359410	Gas Generator Combustion Program	HC
	[illegible]	[illegible] Rpt. [illegible] 7-[illegible] [illegible] 70	Computer Modeling of Rocket Engine Ignition Transients	HC

Table 5 (Contd)
ACPS RELATED COMPUTER PROGRAMS

[illegible]	[illegible]	APP SUPPORT NO.	TITLE	COPY
[illegible]	3.2	STAR No. N68-17537	FORTRAN Computer Program for Predicting Aerodynamic and Heat Transfer Characteristics of Annular and Rectangular Gas Turbine Combustors	MF
		N69-10241	Radial Turbine Synthehetic (sic) Mapping Program	
[illegible]	2.0	STAR No. N63-16290	Formulation and Digital Coding of Approximate Hydrogen Properties for Application to Heat Transfer and Fluid Flow Computation	
	10.0	B MSC B086	Fifth-Order Runge-Kutta Integration Subroutine	HC
		B MSC B120	Newman Real Root Approximation Subroutine	HC
		B MSC B132	Non-Linear Simultaneous Equations Solver	HC
	11.1	Brown Engr. NSVDP67TR003	General Propellant Pressurization Program	HC
	11.2	GaC Rpt. [illegible],'70	Low Pressure APS Computer Model - Grumman	HC *

had been received (HC-hard copy or MF-microfiche). Comparisons were made to determine similarities and differences between the analytical approaches as well as to ascertain their detailed applicability to the ACPS task. Unique solution techniques were evaluated to the extent necessary to assess the validity and accuracy of approach.

3.3 TECHNIQUE EVALUATION (PHASE III)

The candidates defined in Section 3.2 were further reviewed to determine the final, pertinent information of the ACPS characterization evaluation. This was accomplished by using the Table 6 form guidelines for each finally selected item of Section 3.2. Information which was selected in Phase III is considered the most useful to the ACPS task and is indicated in Tables 4 and 5 by asterisks. Table 4 information denoted by asterisks is more oriented toward descriptive analytical techniques and background information necessary for the ACPS computer modeling. Table 5 items denoted by asterisks are actual computer programs which may be utilized in the ACPS computer simulation. A synopsis of the PHASE III information items is presented in Table 7.

A cursory review was also performed of the Space Shuttle High and Low Pressure Auxiliary Control Propulsion Subsystem Definition studies (References 1, 2, 3, and 4). These studies are being performed by McDonnell-Douglas Corporation and TRW Systems Group, Redondo Beach. A typical high pressure turbopump cycle was obtained from Reference 3 and is shown in Figure 2. A typical low pressure system was obtained from Reference 4 and is shown in Figure 3. These figures represent configurations which are [illegible] for the Shuttle ACPS. Therefore, the modeling as [illegible] [illegible]

TABLE 6

ACPS CHARACTERIZATION EVALUATION FORM

TITLE & CLASSIFICATION:

STATE OF THE ART:

PREVIOUS USAGE:

ACCURACY RESULTS:

AVAILABILITY OF CHARACTERIZATION PARAMETERS:

ADAPTABILITY OF MODULAR COMPUTER PROGRAM CONSTRUCTION:

ANALYTICAL TECHNIQUES:

APPLICABLE TO ACPS MODELING:

TRANSIENT

STEADY STATE

TABLE 7

PHASE III - TECHNIQUE EVALUATION SYNOPSIS FOR ACPS RELATED LITERATURE

[illegible]	INDEX	REMARKS	STAR I.D. NO.
[illegible]	2.1	AIAA Paper. Advanced state-of-the-art. Highly detailed modeling of turbopump designed to pump two-phase flow and thus reduce tank pressurization (and weight) plus chilldown time. NASA Study Contract. Design data on blade configuration.	A 69-32759
[illegible]	2.1	Rocketdyne report of piston-pump configuration, etc. Report deals with detailed design aspects of two-phase pumping such as materials requirements, bearing lubrication. Probably too detailed for initial ACPS modeling, however, could be used for later analysis of two phase pumping if weight savings become of paramount importance.	AD-432042
[illegible]	6.1	Present state-of-the-art. Models pump, tank, line and couples to liquid engine. Uses wave plan method of characteristics. Can be utilized for transient analysis if modified for gas-gas system. Gives listing of computer program.	N69-32330
[illegible]	6.1	Very similar to above document. Used to analyze chugging instability in liquid engine. Must be modified for gas-gas system if used in ACPS. Provides good background for feed system coupled stability analysis.	N67-23795
[illegible]	7...1	Present state-of-the-art; description of steady-state analysis of combustion chamber, liquid pumps, liquid tanks, etc. Very oriented towards J-2 engine. Related to computer program TENSOR.	X67-14913

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TABLE 7 (CONTD)

	TOPICS	REMARKS	STAR I.D. NO.
[illegible]	7.1.2	Detailed thermo-chemical analysis of hypergolic combustion chamber and injector provides background for transient analysis but probably too detailed for direct ACPS application.	Final Rpt. Contract NAS7-467
[illegible]	7.1.2	ARS Journal Paper; Background information for liquid hypergolic engine transient model.	ARS JOURNAL June '69
[illegible]	7.1.2	Background information for hypergolic engine transient analysis. Describes TRW Redondo Beach capabilities in transient analysis.	In Response to Proposal No. RFPBG 721-6-9-3939
[illegible] Part 3	7.2	Part 3 is heat transfer by radiation - other parts (1 and 2) would have more interest. Technical Information Center is trying to locate these.	STAR No. A345587
[illegible]	7.2	Master's thesis concerning testing of a O_2/H_2 engine at different conditions. No analytical models presented; however, provides test data which may be of interest.	STAR No. AD-817891
[illegible]	7.2	Good ACPS background information related to hardware.	No. Report No. - Date probably June 1970
[illegible] ACPS	7.2	Background information.	Proposal No. 14572.000
[illegible]	7.2	Background information.	Proposal No. 14572.000

NOT REPRODUCIBLE

TABLE 7 (CONTD)

[illegible]	[illegible]	REMARKS	STAR I.D. NO.
[illegible]	7.2	Background Information	TRW IOC 70.4712.4-93 Aug. 1970
[illegible]	7.2	Background information on transient simulation capabilities with analog computer.	TRW IOC 70.4712.7-13 Feb. 1970
[illegible]	7.2	Plots of steady state performance characteristics such as C_p, C^*, Isp for O_2/H_2 engine. Generated from NASA Lewis Thermochemical Program.	NASA Memo from Donovan Hyatt to [illegible]
[illegible]	3.0	Very poor reproduction. Could be used in steady-state analysis of ACPS where thermodynamic properties of propellants are necessary.	STAR No. [illegible]
[illegible]	8.0	Tabulated data useful for steady state analysis of ACPS.	NBS-TN 1206
[illegible]	[illegible]	Good background information.	Contract No. NAS 9-11017
[illegible]	[illegible]	Good background information.	Contract No. NAS 9-11017
[illegible]	[illegible]	Parallel flow, counter flow, cross flow, plate-fin configuration. Multi-fluid heat transfer [illegible]. Program has possible ACPS application since it has several flow configurations.	ADP No. [illegible]

TABLE 7 (CONTD)

[illegible]	[illegible]	REMARKS	I. D. NO.
[illegible]	[illegible]	Applicable to Apollo fuel cells with two-phase flow. Parallel flow. Finite difference solution technique for steady-state or transient analysis. Radiation heat transfer included. Good analysis of two-phase flow considerations.	ADP No. F MSC 150
[illegible]	[illegible]	Liquid-gas heat exchanger for fixed helical coil configuration. No change of phase capabilities - could be modified to include this. Applicable to potential ACPS heat exchanger configuration.	ADP No. H MSC 4034
[illegible]	[illegible]	Steady state, compressible gas flow with or without heat transfer: multiple pipe configuration systems. Ideal for ACPS steady-state flow.	ADP No. MSF 443
[illegible]	[illegible]	Extensive steady- tate modeling of components with some transient simulations. Currently being revised by Grumman.	GAC Rpt. B 31-15[illegible] June 1970

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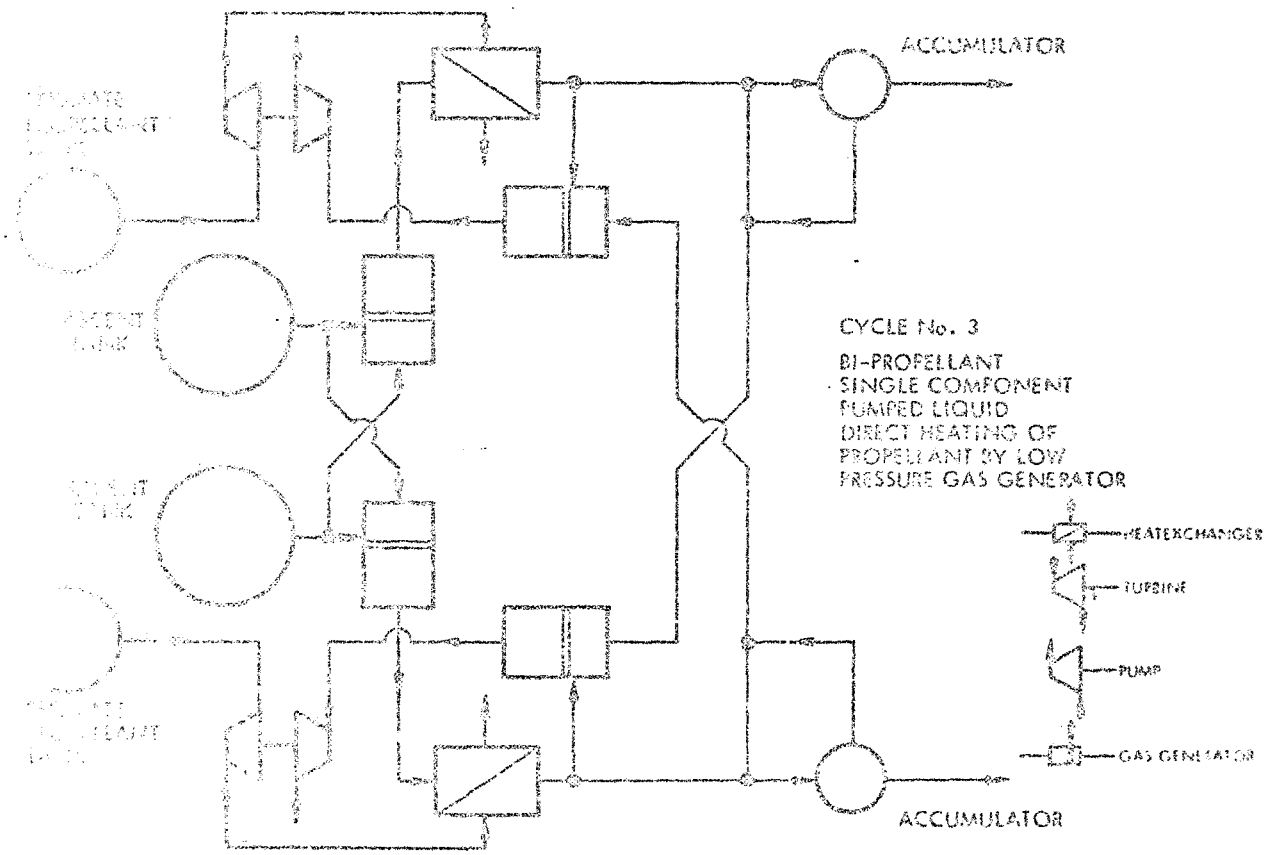

FIGURE 2

ACPS HIGH PRESSURE TURBOPUMP CYCLE

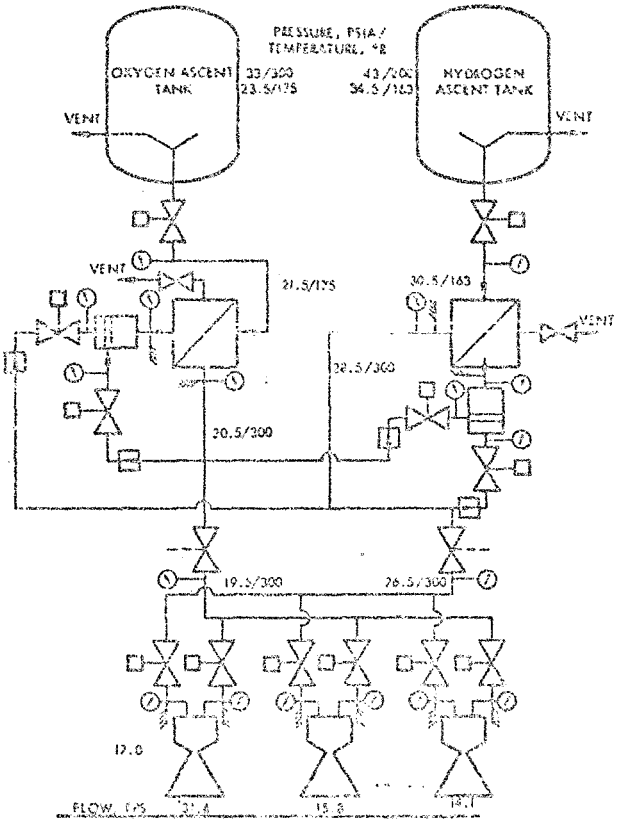

FIGURE 3

ESH PRESSURE ACCT

The technique evaluation was performed extensively on the supply line model, combustor model and general program organization. Running time, integration techniques, model adequacy (accuracy) and digital computer adaptability (Univac 1108) were evaluated.

The general program organization was evaluated by initially reviewing the Pipetran Computer Program, Reference 5, the Matrix Oriented Production Assembly System (MOPAS), Reference 6, the Propulsion Analysis Program (PAP), Reference 7, and a generalized method of characteristic water hammer program (DVP) by Dr. F. Young supplied to TRW from MSC Auxiliary Propulsion and Pyrotechnics Branch. The ideas and forms associated with the configuration selection, executive operation and modularized form of these programs were useful in setting up the general ACPS programs. The namelist data input was selected for program input due to ease of handling for the engineer. The executive program operation was fashioned after that of the Pipetran program with the configuration selection as input data and the executive driver handling the coupling of components and the solutions of simultaneous equations.

The line model was established as the main program link due to the coupling of line segments with the other ACPS modularized components. The liquid flow or low Mach number gas-line model was, therefore, extensively evaluated. Four programs were established as possible candidates. The method of characteristics solution for the equations governing the unsteady flow of liquids in closed systems (ORI), Reference 8, DVP Program as mentioned above, Pipetran, and a preliminary dynamics line model of the Space Shuttle Vehicle from the [illegible] on Project Design and Analysis [illegible]

[illegible] The Pipetran Computer [illegible]

the partial differential equations. The dynamics line model from TRW/Redondo Beach was eliminated because it is simplified and not generalized enough for this application. This left two programs which were closely related, the ORI and DYP programs. The DYP program is a generalized model and the ORI program is not. Both programs use the method of characteristics solution as presented in Reference 9 to solve the transient fluid flow equations (including friction terms). The method of characteristics solution technique transforms the partial differential transient fluid flow equations into ordinary differential equations which are then solved by the first order finite difference method. The other method of solution considered was to solve the partial differential equations directly using the finite difference solution. But since this solution may present stability problems, it was decided not to use this approach. Therefore, since both the DYP and ORI programs used the method of characteristics for their solution technique, it was decided to incorporate this technique in the ACPS dynamic line model (Reference Section 3.4.3). The ORI program has substantial documentation with several checkout cases, but the DYP program has been used by the Auxiliary Propulsion and Pyrotechnics Branch at MSC to evaluate Apollo transient data and Skylab propulsion test transient data. It has, therefore, demonstrated its adequacy utilizing actual test data. Therefore, the ACPS supply line model developed for this task will be verified by comparison with the DYP model. Since the solution technique was well understood and neither the ORI nor the DYP programs had [illegible] adequacy flexibility to be readily [illegible] this to the ACPS problem [illegible] [illegible]

approximation. In the ORI model, the Roberts extrapolation procedure (Reference 10) was used to increase the accuracy of the computations and the need for this approach will be evaluated, but at present it does not appear necessary. After evaluating the four programs, it was decided to:

1. Use the method of characteristics.
2. Construct the generalized model using the Streeter (Reference 11) technique as a baseline.
3. Check finite-difference integration for adequacy after model buildup and if necessary, incorporate a more elaborate integration scheme (Roberts, Runge-Kutta, Predictor Corrector, etc.)

The preliminary line model developed on this basis is described in Section 3.4.3.

In selecting a combustion chamber transient model, two TRW models were reviewed. The first was developed for solution on an analog computer and is the one adapted for use in this program. A Runge-Kutta integration scheme was incorporated to adapt it for use on a digital computer. This model is described in Section 3.4.1, as is the evaluation that led to the adoption of the integration scheme. The second model used the rather interesting approach of linearizing the equations over each time step and obtaining a semi-analytical solution. This approach has some merit, but in this particular formulation the treatment of sonic flow into the chamber and of the valve forcing function did not appear to be satisfactory. The claimed advantage of this second approach is that the computational time step sizes could be double that which can be used with the Runge-Kutta scheme. However, verification of this advantage would require that the two models be put on a [illegible] comparable basis, since they now differ in more than just their inte- [illegible] the effort [illegible] to make the comparison [illegible]

3.4 RECOMMENDED TECHNIQUES

The fourth phase of the characterization evaluation was to recommend to the NASA Task Monitor those techniques identified in PHASE III of this subtask as applicable to the characterization of ACPS components. The recommended techniques provide a high degree of accuracy and are amenable to computer solutions. The results of this subtask upon approval by the NASA Task Monitor will form the basis for the program development under Subtask II.

This section recommends transients and steady-state modeling techniques for the following components:

- Combustors and gas generators
- Manifolds and Injectors
- Turbomachinery
- Heat Exchangers
- Accumulators and Pressure Vessels
- Supply Lines
- Orifices, Pipebends and Valves

The steady-state program will consist of a main-driver program and subroutines representing the components. After initialization, the steady-state program will essentially consist of a set of non-linear simultaneous algebraic equations written in implicit form. The choice of which variables are known and which ones are to be solved for will be determined by input [illegible] by the user. For instance, in the [illegible] chamber, [illegible] chamber pressure are specific [illegible] as known and the throat area and [illegible]

[illegible]

program. The nature of the equations in the transient program will require that hardware dimensions and hardware characteristics, such as resistances, be input, and flow conditions, e.g., velocity, pressure, etc., will be calculated by the program as a function of time.

3.4.1 TRANSIENT COMBUSTOR MODEL

A preliminary dynamic model of an ACPS combustor has been developed on the time share terminal and implemented on the MSC 1108 computer. This basic model will be used as the combustor component of the total ACPS transient program. A study was performed utilizing this preliminary combustor model to determine its numerical stability and running time, and to investigate the advantages of various numerical integration techniques. This model will eventually be expanded to include curve fits of combustor performance data for a typical engine thruster.

Based on the study results, the following conclusions were made:

1 - Representation of the ACPS combustors with this type model appears satisfactory and a more detailed model will be constructed with this characterization as the foundation.

2 - Numerical integration of the model equations utilizing Euler's integration scheme is relatively unstable. After thrust build-up and during the period that the engine simulation is in steady-state, the simulated chamber pressure oscillates ±0.3 psia with a 0.01 millisecond (ms) computation interval and ±2 psia with a 0.25 ms computation interval. The solution never stabilizes.

3 - The Runge-Kutta integration scheme operates very well with the model equations. No oscillations were observed during any of the computation intervals. The solution stabilizes after 2.4 ms of calculations and only becomes unstable if a computation interval [illegible] is used.

model has been set up initially as a "stand alone" model which operates with a constant pressure boundary upstream of the chamber, thereby eliminating the effects of any feedline perturbations for this study only. This was done to simplify the stability, time step, and integration study.

During the checkout phase of the program development, the combustor model was exercised as a "stand alone" program for simulating a typical engine. For this checkout phase, a test case was employed with the combustor model to utilize gaseous oxygen and gaseous hydrogen as propellants with the following input data: characteristic exhaust velocity = 7500 ft/sec, nozzle throat area = 5.1 in^2, combustor gas temperature = 6000°R, and the specific heat ratio was fixed at 1.4. The propellant feedlines to the combustor were maintained as a constant pressure boundary of 360 psia and a temperature of 530°R. The propellant flow control valves were opened instantaneously and transient profiles of the propellant flow into the combustor and the chamber pressure were calculated.

The model was exercised at various integration step sizes using both the Euler and the Runge-Kutta numerical integration schemes. Arbitrary variations were used for the integration step sizes to evaluate the maximum integration interval which can be effectively utilized, the accuracy of the results and the model's stability. The integration step sizes examined were 0.01, 0.10, 0.25 and 0.4 ms. As noted on Figure 4 the simple Euler integration scheme has a transient response which is somewhat erratic [illegible] for the 0.01 ms time step. With a step size of 0.5 [illegible]

[illegible]

At a step size of 0.25 ms., the oscillations are ±2 psia while for a step size of 0.1 ms, the oscillations are approximately ±5 psia.

In an attempt to decrease the running time and increase the accuracy achieved with the Euler technique, the Runge-Kutta integration scheme was evaluated at calculation intervals of 0.01, 0.1, 0.25, and 0.4 ms. Stable solutions were obtained as noted in Figure 5. As the integration interval was increased to 0.5 ms., the transient pressure rise becomes less accurate during the period from 0.8 ms to 4.0 ms of elapsed time as noted from the slow pressure buildup shown in Figure 5. By 4 ms, all solutions reached a steady-state simulation of 310 psia chamber pressure. The integration step size was increased to 0.5 ms and the solution diverged extensively from the true physical system and went unstable because too much propellant was allowed into the chamber, thus driving the model into a reverse flow situation.

From this study it was concluded that a Runge-Kutta integration scheme will be satisfactory. A computational step size of approximately 0.25 ms, which is one-fourth the step size being utilized with the dynamic feedline model, appears to be ideal.

Implementation of more extensive combustor performance data, a manifold accumulation model, and a flow control valve characterization are still required for the combustor model. Performance for a typical thruster will be generated using the data from the ICRPG computer programs (References 12-16). This will consist of specific impulse as a function of mixture ratio, combustor inlet propellant temperatures, thrust, expansion ratio and possibly, chamber pressure. The vacuum thrust coefficient will be [illegible] and the characteristic exhaust velocity (C*) will be calculated as a function of

calculated from chamber pressure, vacuum thrust coefficient and combustor throat area. The combustion temperature will be calculated as a function of mixture ratio and possibly of chamber pressure. Implementation of the preceding will complete the dynamic combustor model development.

NO. 310R-M DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.
MADE IN U. S. A.

Figure 4 Combustor Chamber Model
Euler's Integration Scheme

NO. 340R-M DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.
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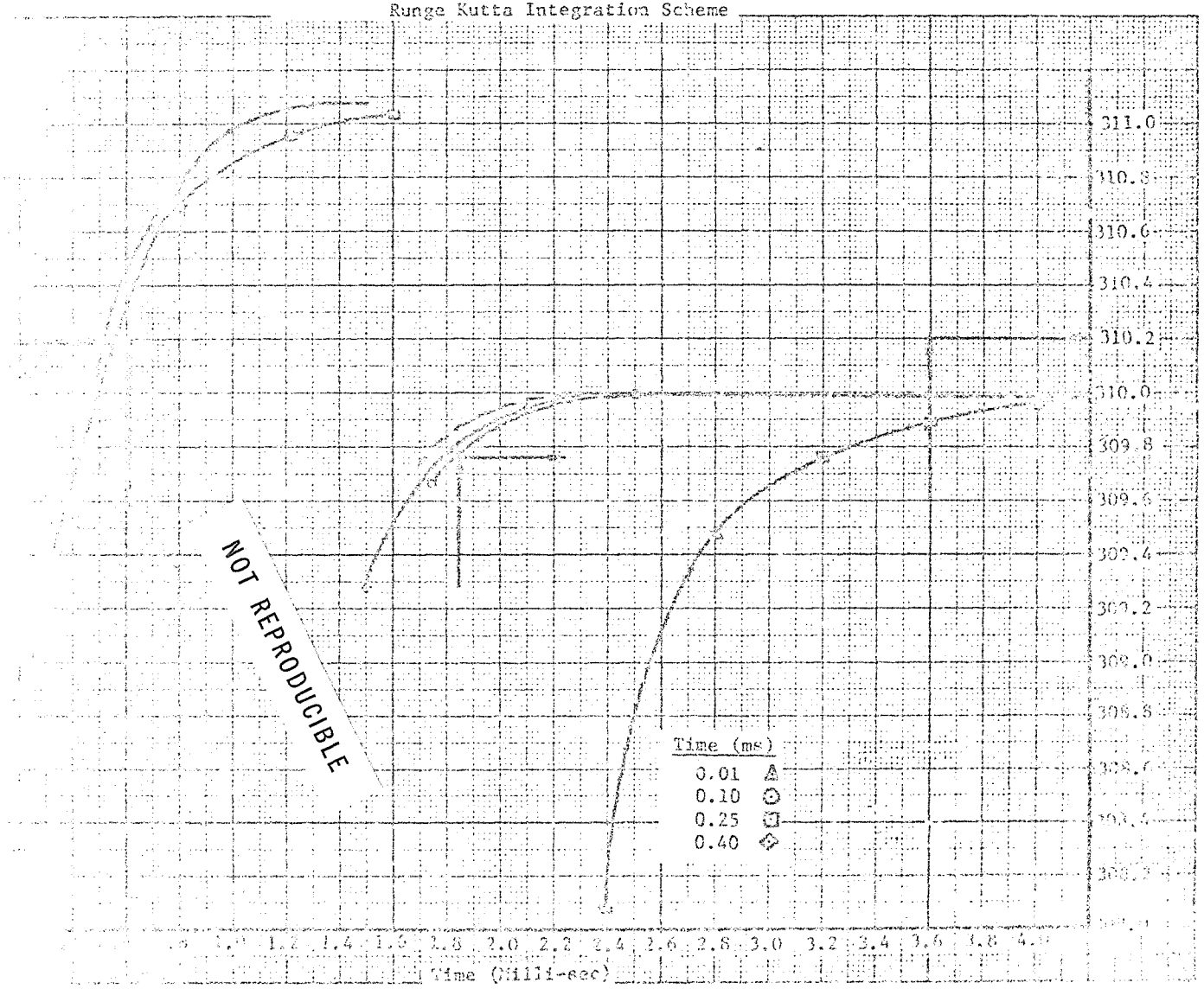
Figure 5 Combustor Chamber Model
Runge Kutta Integration Scheme



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COMBUSTOR DYNAMIC ACPS MODEL EQUATIONS

The combustor model is schematically shown in Figure 6. The combustor model to be utilized in the ACPS transient program interfaces with the feed line model and will utilize input from that model to solve a set of simulations equations for a variable number of thrusters and feed lines. The model will use a Newton-Raphson technique to solve the equations and will operate with the use of the Runge-Kutta integration scheme. The program nomenclature and units are described at the end of this discussion.

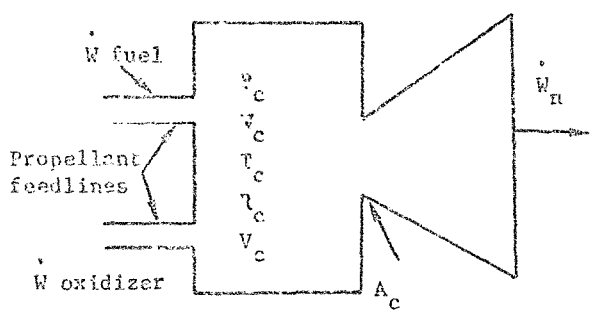


FIGURE 6 - Combustor Model Schematic

The initial entry into the combustor model establishes the following:

1) The number of combustors

2) The number lines connected to combustor I.

3) The number of the feedline hooked to combustor I and Line N.

4) The specific heat ratio of combustor gases

5) The volume of Ith combustor.

6) The gas constant of combustor I.

The model then performs a series of calculations for each combustor in the [illegible] order.

The combustor model utilizes the data form the last two nodal points to the inlet feedlines to calculate the (n+1) point of the junctions between the combustor and feedlines.

The parameters ($\dot{w}_R$, z_R, P_R) at point R, are calculated in the same fashion as in the line model (Section 3.4.3). See Section 3.4.3 for nomenclature for $\dot{w}_R$, z_R, and P_R.

$$\dot{w}_R = \frac{\dot{w}^n_{i,j} - \Theta_i a_i \left(\dot{w}^n_{i,j} - \dot{w}^n_{i,j-1}\right)}{1 + \Theta_i \left(\dot{w}^n_{i,j} - \dot{w}^n_{i,j-1}\right)/(\rho_i A_i)}$$

$$z_R = z_{i,j} - \Theta_i \left(\frac{\dot{w}_R}{\rho_i A_i} + a_i\right)\left(z_{i,j} - z_{i,j-1}\right)$$

$$P_R = P^n_{i,j} + \frac{g\,\rho_i\, z_{i,j}}{g_c\ 144} - \Theta_i \left(\frac{\dot{w}_R}{A_i \rho_i} + a_i\right)$$

$$\left(P^n_{i,j} + \frac{g\,\rho_i z_{i,j}}{g_c\ 144} - P^n_{i,j-1} - \frac{g\rho_i z_{i,j-1}}{g_c\ 144}\right) - \frac{g\rho_i z_R}{g_c\ 144}$$

The weight of gas in the combustor is calculated based on the flowrate in the feedlines minus the [illegible] flow.

$$W_{chamber} = \int_{t1}^{t2} \left(W_{lines} - W_{nozzle} \right) dt$$

This equation is calculated using Runge-Kutta integration.

The chamber pressure is calculated based on the perfect gas equation of state.

$$P_c = \frac{W_c \; R_c \; T_c}{V_c}$$

The nozzle flowrate is calculated from the characteristic exhaust velocity equation.

$$\dot{W}_n = \frac{P_c \; A_n \; g_c}{C^*}$$

If sonic flow exists in the injector orifices, the flowrate into the chamber for each line is

$$\dot{W}_c = A_i P_i C_v \sqrt{\frac{g_c}{RT} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \qquad (1)$$

and the pressure at the junction of the lines less the manifold pressure loss is equivalent to the pressure in the injector orifices; therefore,

$$P_{\text{into combustor}} = \Delta P_{\text{manifold}} - P_{\text{lines}} \qquad (2)$$

The flow from the line model (Section 3.4.3) into the chamber is as follows:

$$\dot{W} = C3 - P_1 \text{ (final node) (C1)} \qquad (3)$$

where:

$$C3 = -\dot{w}_R + \frac{A_i}{a_i}\left(g\rho_i z_{i,j} - 144\, g_c P_R - g\rho_i z_R\right) + \frac{g}{a_i}\, \dot{w}_R \,(\sin \alpha_i)\Delta t + \frac{f_i \dot{w}_R |\dot{w}_R| \Delta t}{2(D_i/12)\rho_i A_i}$$

(See Section 3.4.3 for nomenclature)

$$C1 = \frac{(\text{Area line})\,(144 g_c)}{(\text{Speed line})}$$

Equating the sonic flow from line 1 to the line 3 above and using the equality of $\dot{W}_1$ [illegible] 2 above gives the following:

$$\dot{W}_c = \sqrt{\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$$

NOT REPRODUCIBLE

Solving for the pressure in the manifold orifice one gets

$$P_1 = \frac{C3}{C1 + AC_v \sqrt{\frac{g}{RT} \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}}$$

If the flow through the injector is subsonic it is defined by the compressible gas flow relationship

$$\dot{W}_c = P_1 A C_v \sqrt{\frac{g_c}{RT} \left(\frac{2\gamma}{\gamma-1}\right) \left[\left(\frac{P_c}{P_1}\right)^{2/\gamma} - \left(\frac{P_c}{P_1}\right)^{(\gamma+1)/\gamma}\right]} = P_1 A C_v \phi \tag{4}$$

Equating Equation 4 to Equation 3 and setting that equal to zero a function C7 is defined

$$C7 = 0 = C3 - P_1 C1 - P_1 C_v A \phi \tag{5}$$

Calculating the derivative of Equation 5, one gets:

$$\frac{dC7}{dP} = -C1 - C_v A\phi - \frac{P_1}{2\phi} \left[\frac{2}{\gamma} \left(\frac{P_c}{P}\right)^{(2-\gamma)/\gamma} \left(-\frac{P_c}{(P)^2}\right) - \frac{\gamma+1}{\gamma} \left(\frac{P_c}{P}\right)^{1/2} \left(-\frac{P_c}{(P)^2}\right)\right]$$

Using Newton-Raphson method of solution:

$$P_1 = P_1 - \frac{C7}{dC7/dP}$$

and iterate until the following convergence criteria is obtained

$$\frac{dC7}{dP} < 0.001$$

NOMENCLATURE FOR COMBUSTOR MODEL COMPUTER SUBROUTINE CHAM (I)

NAME		UNITS
γ	Specific heat ratio	
NLC	Number lines connected to the Ith combustor	
ICHAM	The Ith combustor connected to the Nth line	
C	Constant portion of SP equation	
C1	Constant portion of WP equation	
$\dot{W}_n$	Nozzle flow of Ith combustor	lbm/sec
W_c	Weight of gas in the Ith combustor	lbm
P_c	Chamber pressure in Ith combustor	psia
R_c	Gas constant on combustor	ft/lb^{o}R
T_c	Temperature of gas in combustor	^{o}R
V_c	Volume of Ith Combustor	in^3
A_i	Area injector	in
A_n	Nozzle throat area Ith combustor	in^2
C6,8,9,10	Constants in derivative of pressure equation	
$\frac{dC7}{dP}$	Derivative of pressure equation variable	
C7	Pressure equation expression for subsonic flow	
$\dot{W}$	Temporary injector flow rate	lbm/sec
P_{cr}	Critical pressure ratio Ith line J node	
C_v	Flow coefficient	
$\dot{W}_c$	Weight flow rate into chamber	lbm/sec
P_1	Injector orifice entrance pressure	psia

[illegible]

[illegible]

S Value interpolated in the X-direction lying on a right running characteristic that passes through the grid point at which the flow variables are to be determined.

3.4.2 Steady-State Combustor

The steady-state model of an ACPS combustor will use curve fits of chamber performance data, calculated using the ICRFG programs, to describe the steady-state operation of combustion chamber parameters. Curves are presently available, but may require modifications to account for effects of chamber pressure variations. Evaluation of the curve fits are being performed by comparing them with data from TRW Redondo Beach's high and low pressure ACPS studies.

The model calculations will be performed as follows:

The specific impulse is given by:

$$ISP_v = f\ (MR,\ T_{O_2},\ T_{H_2},\ F,\ \varepsilon,\ P_c)$$

The thrust coefficient is given by:

$$C_f = \text{Constant}$$

The characteristic exhaust velocity if given by:

$$C^* = \frac{g_c ISP}{C_f}$$

The nozzle flowrate is given by:

$$\dot{W}_n = \frac{P_c\ A_t\ g_c}{C^*}$$

The combustion gas temperature is given by:

$$T_c = f\ (MR \text{ and possibly } P_c)$$

NOMENCLATURE

T_{O_2}	Inlet Temperature	°R
T_{H_2}	Inlet Temperature	°R
A_t	Area Combustor Throat	
F	Thrust	lbf
ε	Expansion Ratio	
P_c	Chamber Pressure	psia
ISP_v	Vacuum Specific Impulse	sec
T_c	Chamber Temperature	°R
C*	Characteristic Exhaust Velocity	ft/sec
$\dot{W}_{O_2}$	Oxidizer flowrate	lbm/sec
$\dot{W}_{H_2}$	Fuel flowrate	lbm/sec
$\dot{W}_n$	Nozzle flowrate	lbm/sec
MR	Mixture ratio	
g_c	Conversion constant	$32.2 \frac{\text{lbm-ft}}{\text{sec}^2\text{-lbf}}$

3.4.3 Supply Line Transients

In order to model the ACPS transients, analytical representations of the fluid lines must be available. A generalized line network model has been programmed on the Univac 1108 computer. The model is suitable for both gases at low Mach numbers and liquids. The program, which is in the preliminary stages of development and checkout, will be able to handle networks of considerable complexity. Presently, it can treat networks consisting of distributed lines, junctions, valves, pressure boundaries, and flow boundaries. Pressure boundaries are pipe ends at which the pressure as a function of time is specified. Flow boundaries are similar except that the flow rate as a function of time is specified. In the case of valves, the resistance versus time must be given. As components which are necessary for the computation of an ACPS transient are developed, they will be incorporated into the program. For instance, the combustor model described in Section 3.4.1 will be added shortly. In the paragraphs that follow, the equations used are described and some results are given.

The partial differential equations representing the one-dimensional flow of a liquid in a pipe are given in Reference 11 as

$$g \frac{\partial H}{\partial t} + a^2 \frac{\partial V}{\partial X} + gV \frac{\partial H}{\partial X} + gV \sin \alpha = 0 \qquad (1)$$

$$g \frac{\partial H}{\partial X} + V \frac{\partial V}{\partial X} + \frac{\partial V}{\partial t} + \frac{fV|V|}{2D} = 0 \qquad (2)$$

H is the head, a is the speed of sound, g is the local acceleration, V is the velocity of the fluid, X is the distance along the pipe, f is the pipe friction factor, D is the pipe diameter, t is time, and α is the [illegible] of the [illegible] [illegible]

[illegible]

or nearly zero, the above two equations are not satisfactory. This is because the product of g times H as g approaches zero becomes the indeterminate form of 0/0. The equations can be readily put into a form suitable for use at both zero and non-zero g' by making the substitution:

$$H = 144 \frac{g_c}{g} \frac{P}{\rho} + Z \tag{3}$$

P is the static pressure, ρ is the fluid density, Z is the elevation, and g_c is a conversion factor.

Equations 1 and 2 which are hyperbolic in form can be solved by substituting directly a finite-difference approximation for each term or by converting them into four equivalent ordinary differential equations by the method of characteristics and then substituting finite-difference approximations into them (see References 17, 18, and 19). The former approach has some advantages (see References 18 and 19), but there appear to be no cases reported in the literature of equations having exactly the form of Equations 1 and 2 being solved in this manner, although there are examples for somewhat similar sets (References 17 and 20). In Reference 11, the method of characteristics was used and in this reference are presented several comparisons of the computational results with experimental data. The agreement was excellent. Thus, for the sake of expediting the task, the method of characteristics was chosen to solve (1) and (2). It would be interesting, however, to make a comparison between the two approaches and this will be done if time allows. The equations used in the transient fluid flow program are presented at the end of this section. They may easily be derived from the equations given in Reference 11, substituting Equation 3 where required.

[illegible]

the density is constant, Equations 1 and 2 become, respectively,

$$\frac{144\ g_c}{\rho}\ \frac{\partial P}{\partial t} + a^2\ \frac{\partial V}{\partial X} + 144\ g_c\ \frac{V}{\rho}\ \frac{\partial P}{\partial X} = 0 \tag{5}$$

$$\frac{144\ g_c}{\rho}\ \frac{\partial P}{\partial X} + V\ \frac{\partial V}{\partial x} + \frac{\partial V}{\partial t} + \frac{fV|V|}{2D} = 0 \tag{6}$$

The continuity equation and equation of motion suitable for the one-dimensional flow of a gas are from Reference 21, p. 972,

$$\frac{\partial \rho}{\partial t} + \rho\ \frac{\partial V}{\partial X} + V\ \frac{\partial \rho}{\partial X} = 0 \tag{7}$$

$$\frac{144\ g_c}{\rho}\ \frac{\partial P}{\partial X} + V\ \frac{\partial V}{\partial X} + \frac{\partial V}{\partial t} + \frac{fV|V|}{2D} = 0 \tag{8}$$

Equation 8 is identical to Equation 6

Multiplying both sides of Equation 7 by $\frac{\partial P}{\partial \rho}$ and a conversion factor gives

$$144\ \frac{\partial P}{\partial \rho}\ \frac{\partial \rho}{\partial t} + 144\ \rho\ \frac{\partial P}{\partial \rho}\ \frac{\partial V}{\partial x} + 144\ V\ \frac{\partial P}{\partial \rho}\ \frac{\partial \rho}{\partial x} = 0 \tag{9}$$

Using the fact that for an isentropic process

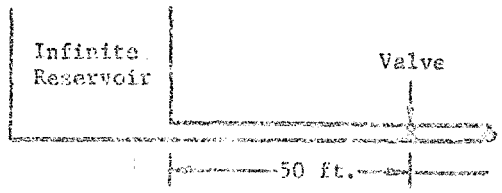
$$\frac{144\ \partial P}{\partial \rho} = \frac{a^2}{g_c} \tag{10}$$

Equation 9 becomes identical to Equation 5.

The equations in Appendix A are based on the speed of sound remaining constant in the pipe and the density being independent of the velocity. In a gas, these assumptions hold fairly well for Mach numbers less than about 0.2. For higher Mach numbers, the energy equation and the equation of state must be solved along with Equations 7 and 8.

To check the transient model, the flow rates and pressures at points in a 50-foot horizontal, frictionless steel pipe were calculated after the sudden closure of a valve (see the following illustration). Before the valve closure, the fluid which was water was flowing steadily. The calculations [illegible] intervals [illegible] stability [illegible] Equation [illegible] The stability [illegible]

in References 19 and 22. The plot of pressure at the valve as a function of time should be nearly a perfect square wave. Since this analytical model takes into account the fact that the wave velocity with respect to the pipe travels at the speed of sound plus or minus the velocity of the fluid, the wave shape will differ from a square wave. However, at the fluid velocity used in this example, about 1.64 ft/sec, the difference should be imperceptible. At very high fluid velocities the wave shape will differ considerably from a square wave.



Fluid velocity, 1.64 ft/sec
Speed of sound in pipe, 4067 ft/sec
Friction factor, 0
Pressure in pipe before valve closure, 100 psia

TEST CASE

Four different computer "runs" were made. The first was for a computational time increment of 1.0 ms and a value of S of 0.001. S is a value which determines the size of the length increment, ΔX, once the time increment, Δt has been selected. It is shown in References 19 and 22 that S must equal or exceed the ratio of the maximum velocity in the pipe to the speed of sound in the pipe. The pressure at the valve is shown in Figure 7a and the flow rate at the entrance to the pipe is shown in Figure 7b. The results show good [illegible] with those anticipated. The pressure amplitude [illegible]

but S was set to 0.2. Increasing S has the effect of introducing an artificial dampening which again is the result of the numerical approximations. Reducing the time increment, however, will eliminate the effect. This is shown in Figures 9a and 9b where S is equal to 0.2, but the time increment is 0.15 ms. The effect of violating the stability criterion is depicted in Figures 10a and 10b. In these, S is -0.2 and the time increment is 1.0 ms. In this case, the solution diverges wildly. The results given in Figures 7-10 indicate that for maximum accuracy for a given time increment, S should be as small as possible without violating the stability criterion.

EQUATIONS FOR TRANSIENT FLUID FLOW PROGRAM

Initial Calculations

$$a_i = \sqrt{\frac{144\ B_i\ g_c}{\rho_i\left(1 + \frac{B_i D_i}{E\ e_i} c\right)}} \quad \text{-- for liquid line} \tag{1a}$$

$$a_i = \sqrt{\gamma_i g_c R_i T_i} \quad \text{- for gas line} \tag{1b}$$

$$\text{Minimum } \Delta X_i = (1. + S)\ (\Delta t)\ a_i \tag{2}$$

$$N_i = \frac{L_i}{\text{Minimum } \Delta X_i} + 1 \quad (N_i \text{ is an integer} \leq \text{ to the R.H.S.}) \tag{3}$$

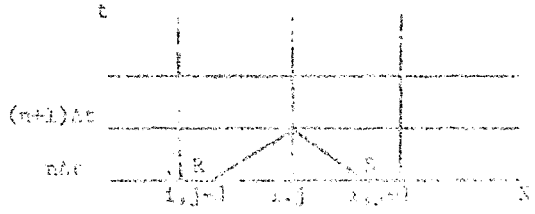
$$\Delta X_i = \frac{L_i}{N_i - 1} \tag{4}$$

$$A_i = \frac{\pi D_i^2}{4(144)} \tag{5}$$

$$\Theta_i = \Delta t / \Delta X_i \tag{6}$$

NOT REPRODUCIBLE

Interior Pipeline Points



Computational Grid

$$z_R = z_{i,j} - \theta_i\left(\frac{\dot{v}_R}{\rho_i A_i} + a_i\right)\left(z_{i,j} - z_{i,j-1}\right) \tag{9}$$

$$z_S = z_{i,j} + \theta_i\left(\frac{\dot{v}_S}{\rho_i A_i} - a_i\right)\left(z_{i,j} - z_{i,j+1}\right) \tag{10}$$

$$P_R = P^n_{i,j} + \frac{g\,\rho_i\,z_{i,j}}{g_c\,144} - \theta_i\left(\frac{\dot{v}_R}{A_i\rho_i} + a_i\right)\left(P^n_{i,j} + \frac{g\,\rho_i z_{i,j}}{g_c\,144} - P^n_{i,j-1} - \frac{g\rho_i z_{i,j-1}}{g_c\,144}\right) - \frac{g\rho_i z_R}{g_c\,144} \tag{11}$$

$$P_S = P^n_{i,j} + \frac{g\,\rho_i z_{i,j}}{g_c\,144} + \theta_i\left(\frac{\dot{v}_S}{A_i\rho_i} - a_i\right)\left(P^n_{i,j} + \frac{g\rho_i z_{i,j}}{g_c\,144} - P^n_{i,j+1} - \frac{g\rho_i z_{i,j+1}}{g_c\,144}\right) - \frac{g\rho_i z_S}{g_c\,144} \tag{12}$$

$$\dot{v}^{n+1}_{i,j} = 0.5\left[\dot{v}_R + \dot{v}_S + \frac{A_i}{a_i}\left(144\,g_c P_R + \rho_i g z_R - 144\,g_c P_S - \rho_i g z_S\right) - \frac{B_i}{a_i}\Delta t\,\sin(\theta_i)\,(\dot{v}_R - \dot{v}_S) - \frac{f_i \Delta t\,(\dot{v}_R|\dot{v}_R| + \dot{v}_S|\dot{v}_S|)}{2\,\rho_i A_i (D_i/12)}\right] \tag{13}$$

$$P^{n+1}_{i,j} = 0.5\left[P_R + \frac{g\rho_i z_R}{144\,g_c} + P_S + \frac{g\rho_i z_S}{144\,g_c} + \frac{a_i(\dot{v}_R - \dot{v}_S)}{144\,g_c A_i} - \frac{g\Delta t(\dot{v}_R + \dot{v}_S)\sin\theta_i}{g_c A_i\,144} - \frac{f_i\Delta t(\dot{v}_R|\dot{v}_R| + \dot{v}_S|\dot{v}_S|)}{2\rho_i A_i (D_i/12)}\right]$$

NOT REPRODUCIBLE

PRESSURE BOUNDARY

$P_b = f(t)$ is given.

a) Boundary is at upstream end of pipe. $j = 1$

Compute $\dot{w}_S$, z_S, and P_S using Equations 8, 10 and 12, respectively.

$$\dot{w}^{n+1}_{i,j} = \dot{w}_S + \frac{A_i}{a_i}\left(144\, g_c P_b + g\rho_i z_{i,j} - 144\, g_c P_S - g\rho_i z_S\right) + g\,\frac{\dot{w}_S}{a_i}\,(\sin\alpha_i)\,\Delta t - \frac{f_i \dot{w}_S |\dot{w}_S| \Delta t}{2\, A_i \rho_i (D_i/12)} \tag{15}$$

b) Boundary is at downstream end of pipe. $j = N_i$

Compute $\dot{w}_R$, z_R, P_R using Equations 7, 9, and 11, respectively.

$$\dot{w}^{n+1}_{i,j} = \dot{w}_R - \frac{A_i}{a_i}\left(144\, g_c P_b + g\rho_i z_{i,j} - 144\, g_c P_R - g\rho_i z_R\right) - \frac{g\dot{w}_R}{a_i}\,(\sin\alpha_i)\Delta t - \frac{f_i \dot{w}_R |\dot{w}_R| \Delta t}{2\, A_i \rho_i (D_i/12)} \tag{16}$$

VALVE

Set i to its value for the downstream pipe. $j = 1$

Compute $\dot{w}_S$, z_S, and P_S using Equations 8, 10 and 12, respectively.

$$C1 = -\dot{w}_S - \frac{A_i}{a_i}\left(g\rho_i z_{i,j} - 144\, g_c P_S - g\rho_i z_S\right) - \frac{g\,\dot{w}_S (\sin\alpha_i)\Delta t}{a_i} + \frac{f_i \dot{w}_S |\dot{w}_S| \Delta t}{2(D_i/12) A_i \rho_i} \tag{17}$$

$$C2 = -\frac{A_i}{a_i}\, g_c\, 144$$

[illegible]

$$C4 = \frac{A_i}{a_i} g_c \, 144 \tag{20}$$

$$C5 = 2K^2 g_c \rho (144) \left(\frac{1}{C4} - \frac{1}{C2} \right) \tag{21}$$

$$C6 = 2K^2 g_c \rho (144) \left(\frac{C3}{C4} - \frac{C1}{C2} \right) \tag{22}$$

$$\text{If } C6 < 0, \ \dot{v} = \frac{C5}{2} - \sqrt{\frac{C5^2 + 4C6}{2}} \tag{23}$$

$$\text{If } C6 > 0, \ \dot{w} = -\frac{C5}{2} + \sqrt{\frac{C5^2 - 4C6}{2}} \tag{24}$$

$$\dot{w}^{n+1}_{i,j} = \dot{v} \tag{25}$$

$$p^{n+1}_{i,j} = -\frac{\dot{w}^{n+1}_{i,j}}{C2} - \frac{C3}{C4} \tag{26}$$

Set i again to its value for the downstream pipe. j=1

$$\dot{w}^{n+1}_{i,j} = \dot{w} \tag{27}$$

$$p^{n+1}_{i,j} = -\frac{\dot{w}^{n+1}_{i,j}}{C2} - \frac{C1}{C2} \tag{28}$$

FLOW RATE BOUNDARY

$\dot{w}_b = f(t)$ is given

a) Boundary is at upstream end of pipe. $j = 1$

Compute $\dot{w}_s$, f_s, P_s

Compute C1 and C2 using Equations 37 and 38, respectively.

$$\dot{w}^{n+1}_{i,j} = \dot{w}_b \tag{29}$$

$$\frac{C1}{C2} - \frac{\dot{w}^{n+1}_{i,j}}{C2}$$

NOT REPRODUCIBLE

b) Boundary is at upstream end of pipe. $j = N_i$

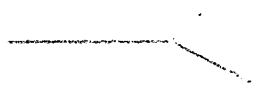
Compute $\dot{w}_R$, z_R, P_R

Compute C3 and C4 using Equations 19 and 20, respectively.

$$\dot{w}^{n+1}_{i,j} = \dot{w}_b \tag{31}$$

$$P^{n+1}_{i,j} = -\frac{C3}{C4} - \frac{\dot{w}^{n+1}_{i,j}}{C4} \tag{32}$$

N-PIPE JUNCTION



For each pipe downstream of the junction. $j = 1$

Compute $\dot{w}_S$, z_S, P_S

Compute $C1_i$ using Equation 17 and $C2_i$ using Equation 18.

For each pipe upstream of the junction. $j = N_i$

Compute $\dot{w}_R$, z_R, P_R

Compute $C1_i$ using Equation 19 and $C2_i$ using Equation 20.

$$P = -\frac{\sum C1_i}{\sum C2_i} \tag{33}$$

If pipe is upstream $j = N_i$, if downstream $j = 1$.

$$P^{n+1}_{i,j} = P \tag{34}$$

$$\dot{w}^{n+1}_{i,j} = -C1_i - C2_i P \tag{35}$$

NOMENCLATURE

A	Cross-sectional area of pipe	ft^2
a	Speed of sound	ft/sec
c	Correction for the effect of Poisson's ratio	
E	Young's modulus of pipe	psi
D	Pipe diameter	in
e	Pipe thickness	in
f	Friction factor	
g	Acceleration	ft/sec^2
g_c	32.174	$lbm\text{-}ft/(sec^2\text{-}lbf)$
B	Bulk modulus of elasticity of liquid	psi
L	Pipe Length	ft
N	Number of nodes in pipe	
P	Pressure	psi
$\dot{w}$	Flow rate	lbm/sec
z	Elevation	ft
t	Time	sec
X	Distance along pipe	ft
ΔT	Time increment	sec
ΔX	Length increment	ft
α	Angle pipe makes with horizontal	deg.
ρ	Density	lbm/ft^3
[illegible]	Valve conductance	ft^2
	Gas constant	[illegible]
	Temp	[illegible]
	Ratio of	

NOMENCLATURE (Continued)

Subscripts

i	Indicates ith pipe
j	Indicates jth node in pipe
R	Value interpolated in the X-direction lying on a left running characteristic that passes through the grid point at which the flow variables are to be determined.
S	Value interpolated in the X-direction lying on a right running characteristic that passes through the grid point at which the flow variables are to be determined.
b	Value specified at end of pipe

Superscripts

n	Indicates nth time interval

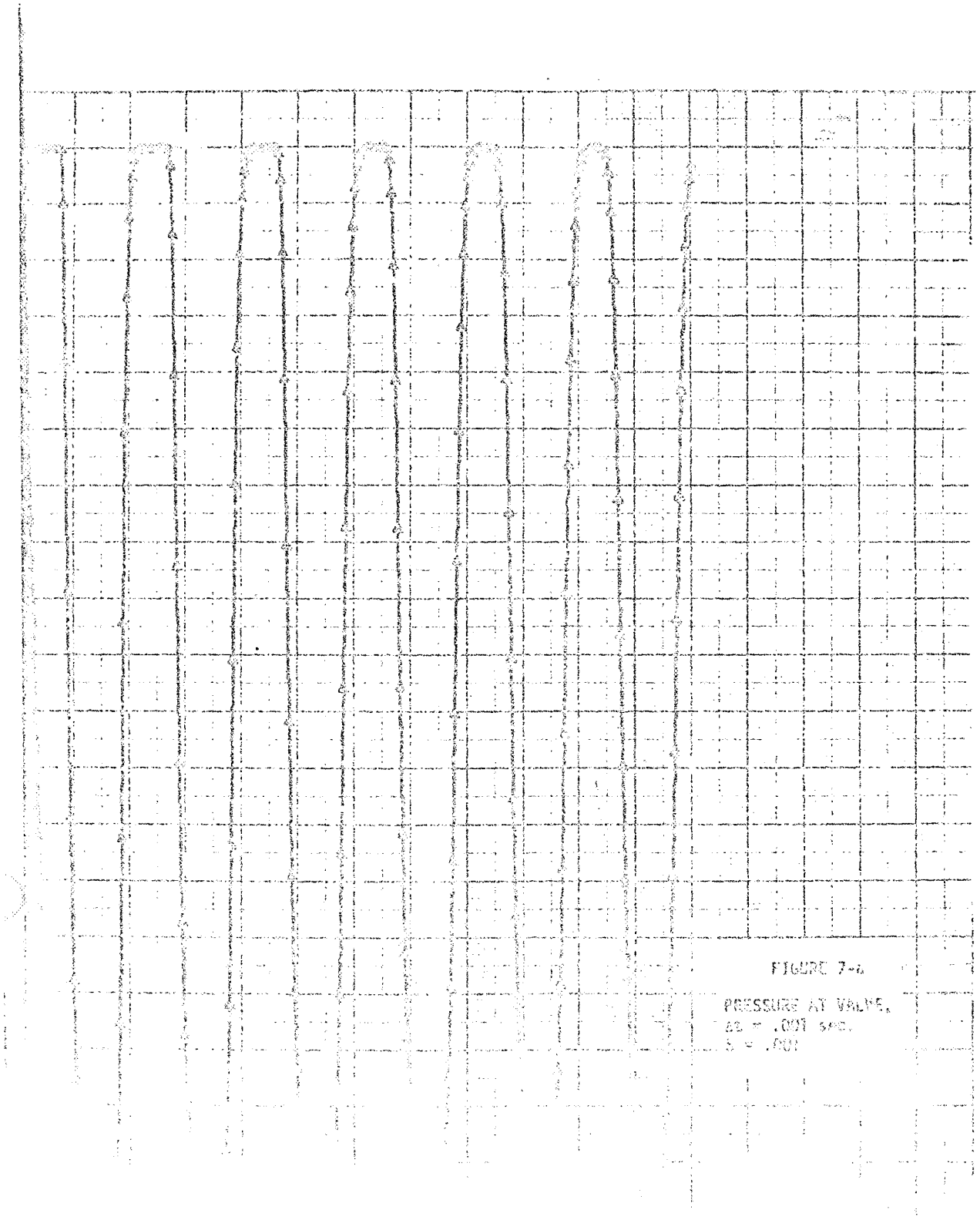
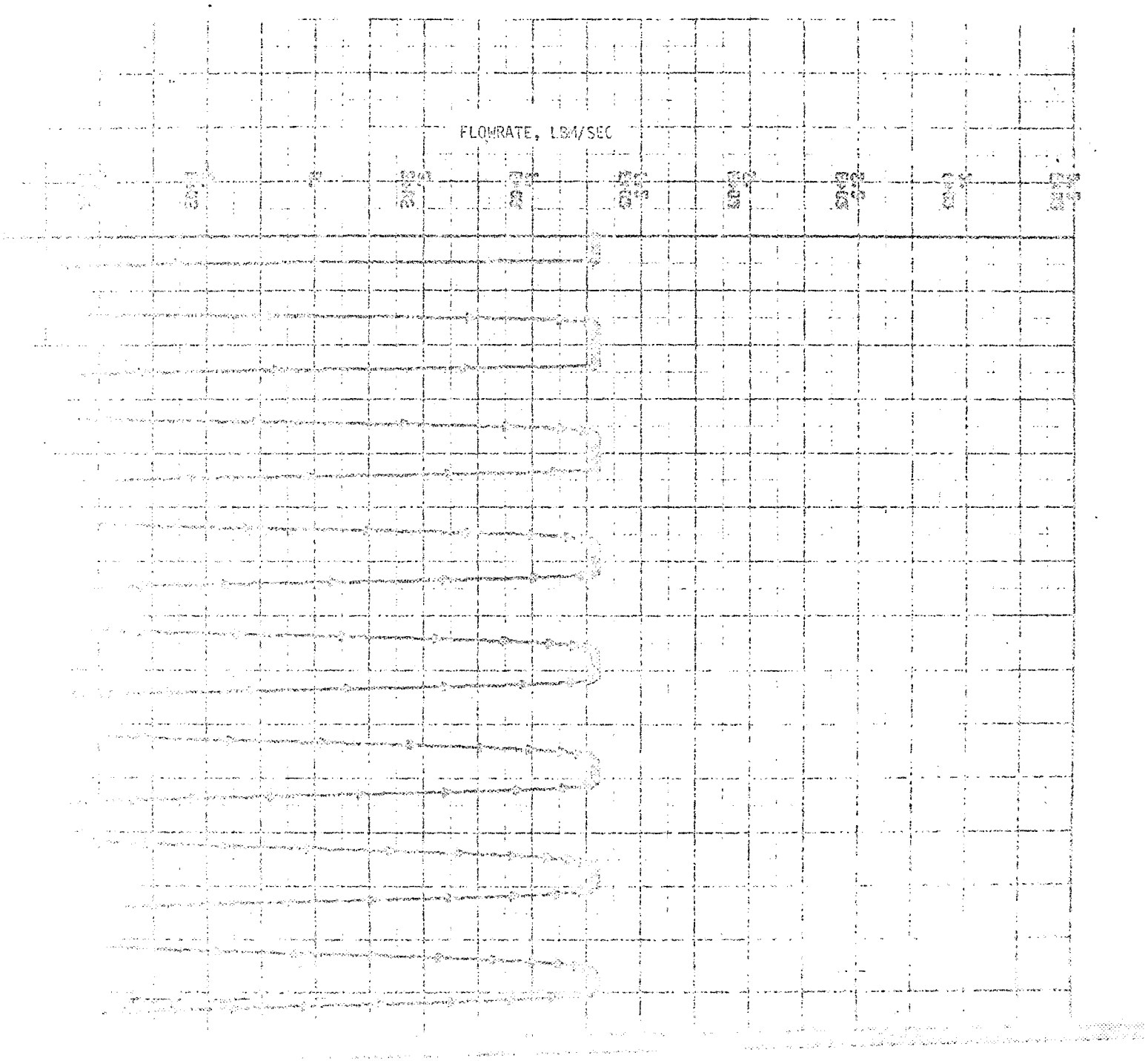


FIGURE 7-6

PRESSURE AT VALVE,
Δt = .001 sec.
ζ = .001


FLOWRATE, LBM/SEC

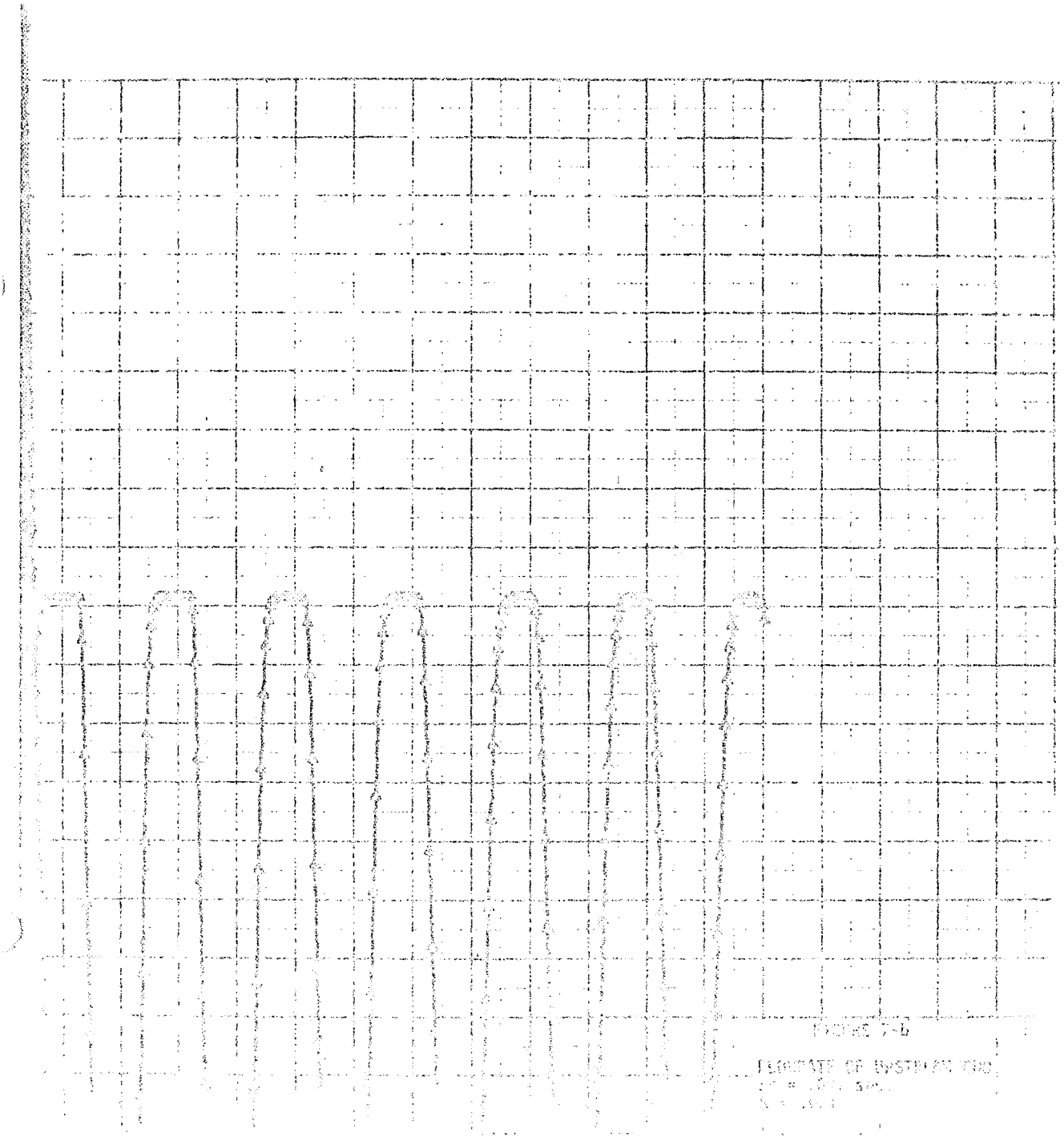
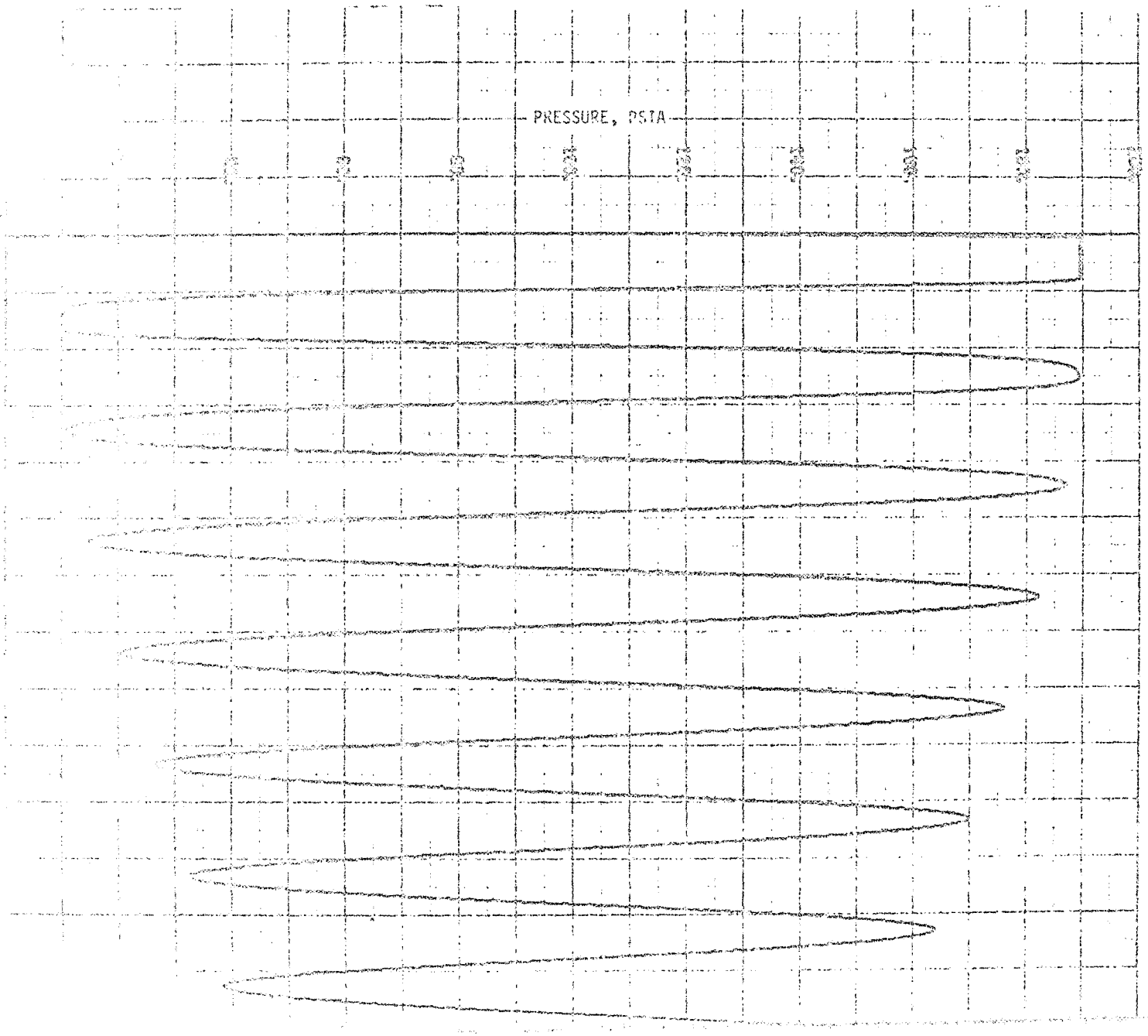


FIGURE 7-b

FEDERATE OF BYSTREAM END


PRESSURE, PSIA

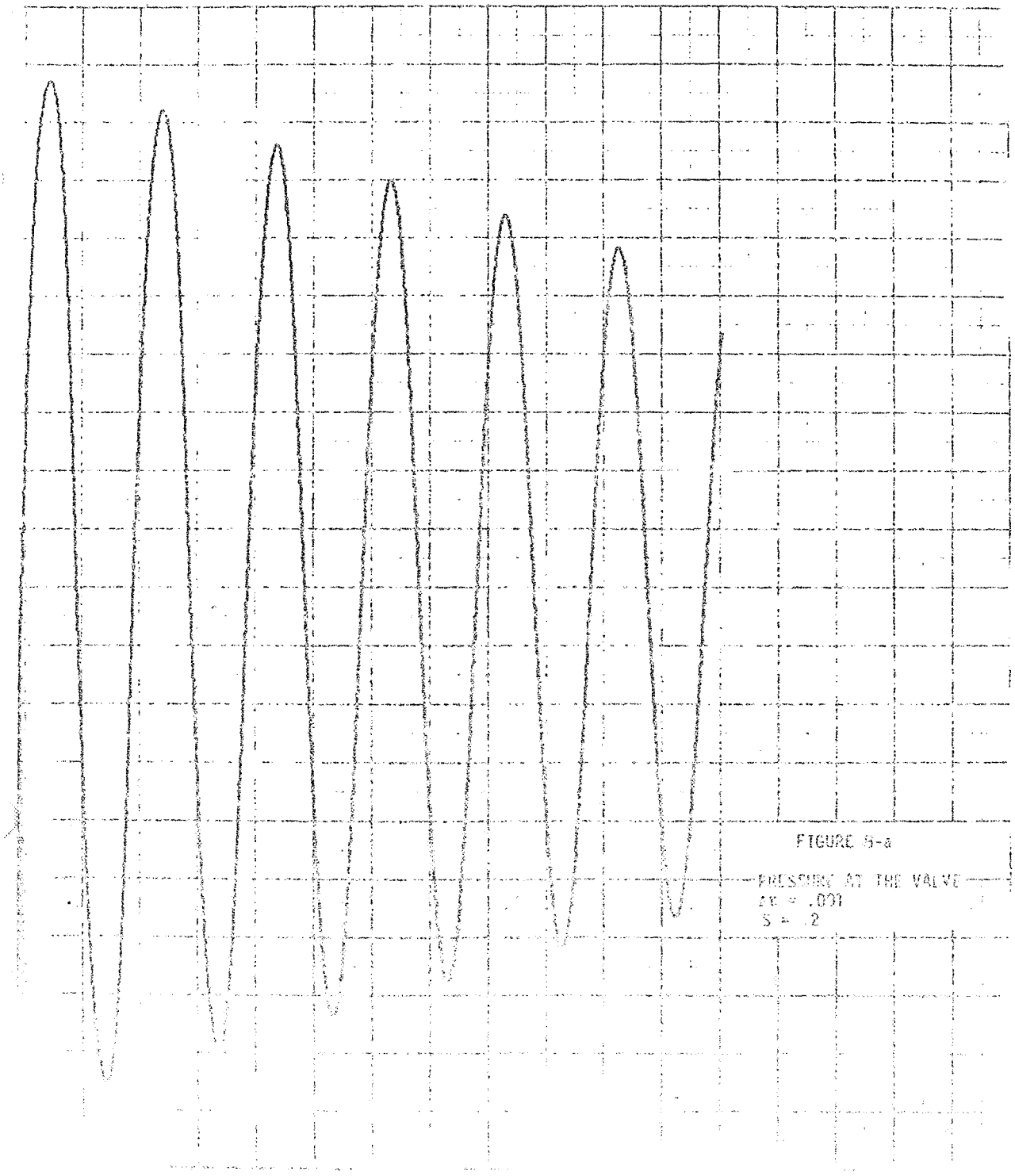
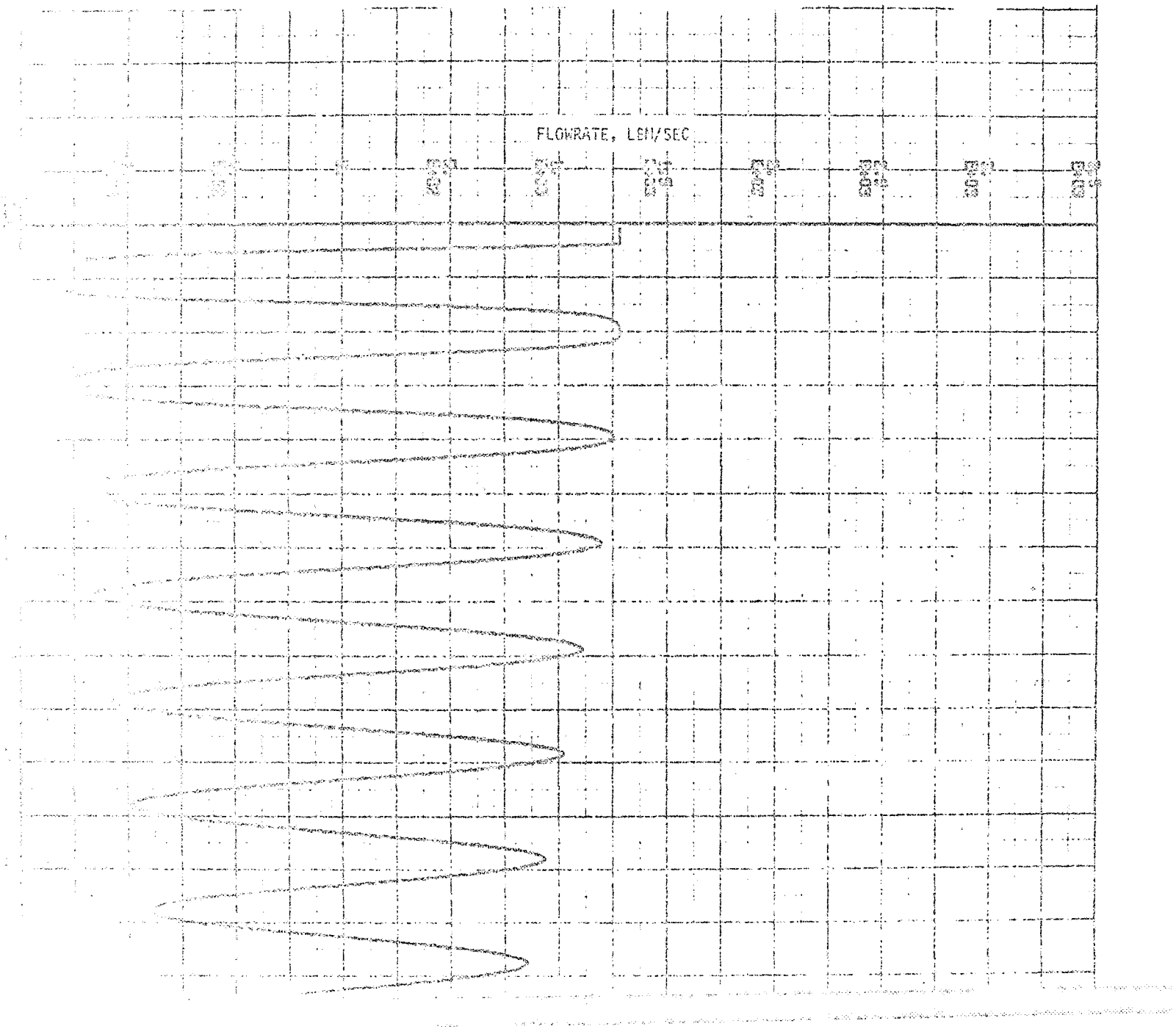


FIGURE 5-a

PRESSURE AT THE VALVE
$\Delta x = .001$
$S = .2$


FLOWRATE, LBM/SEC

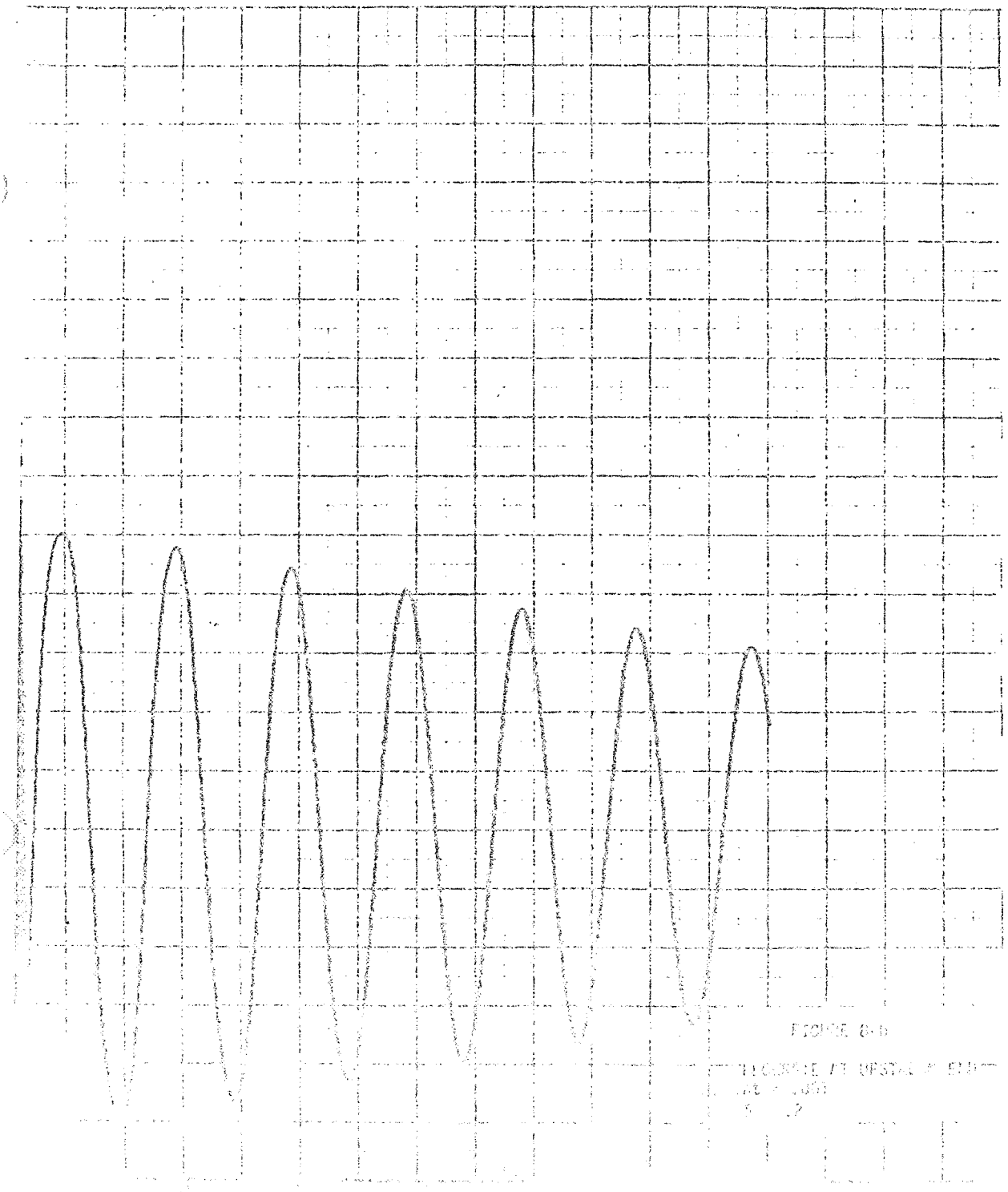
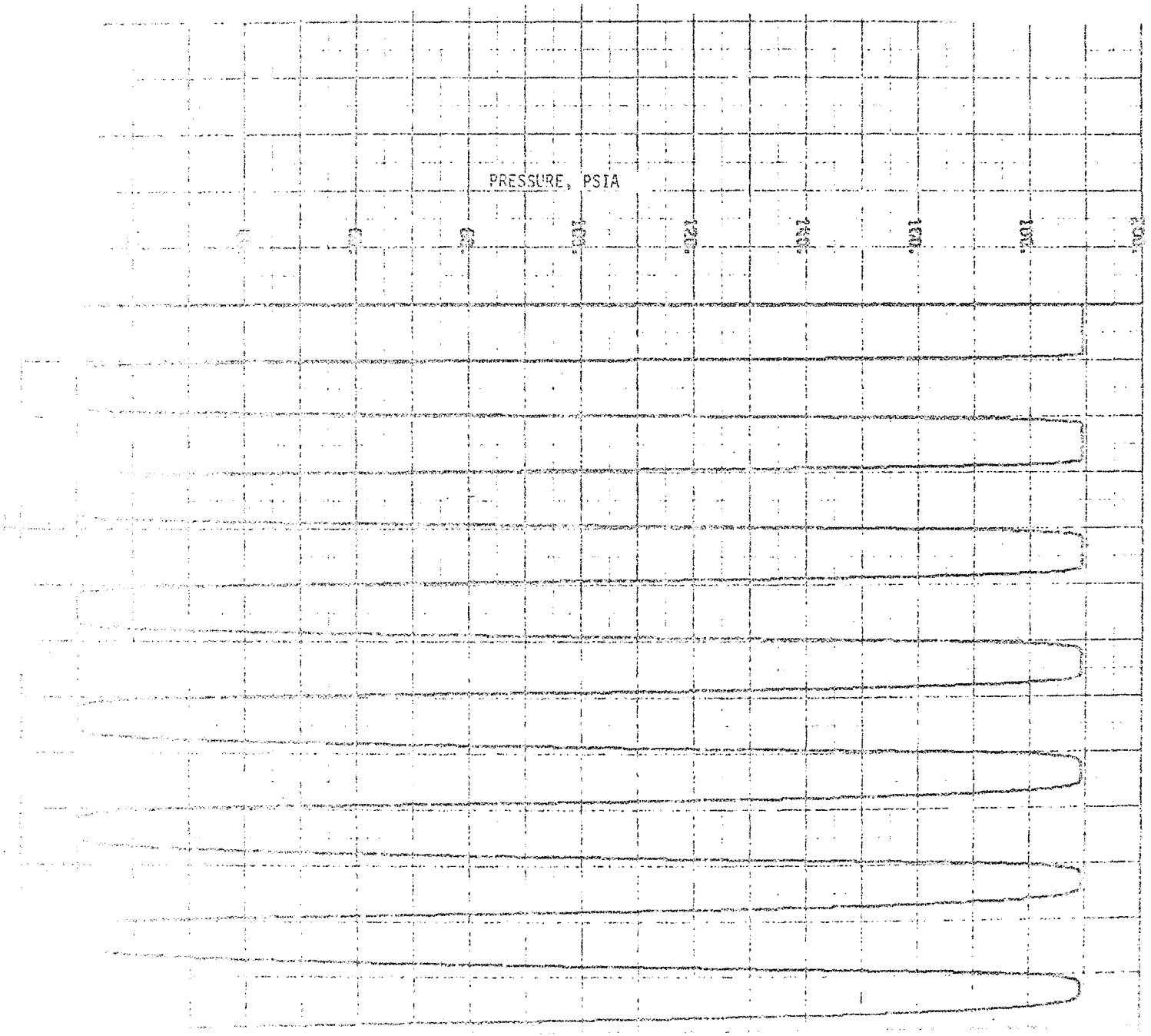


FIGURE 8-6


PRESSURE, PSIA
0.
20.
40.
60.
80.
100.
120.
140.
160.
180.
200.

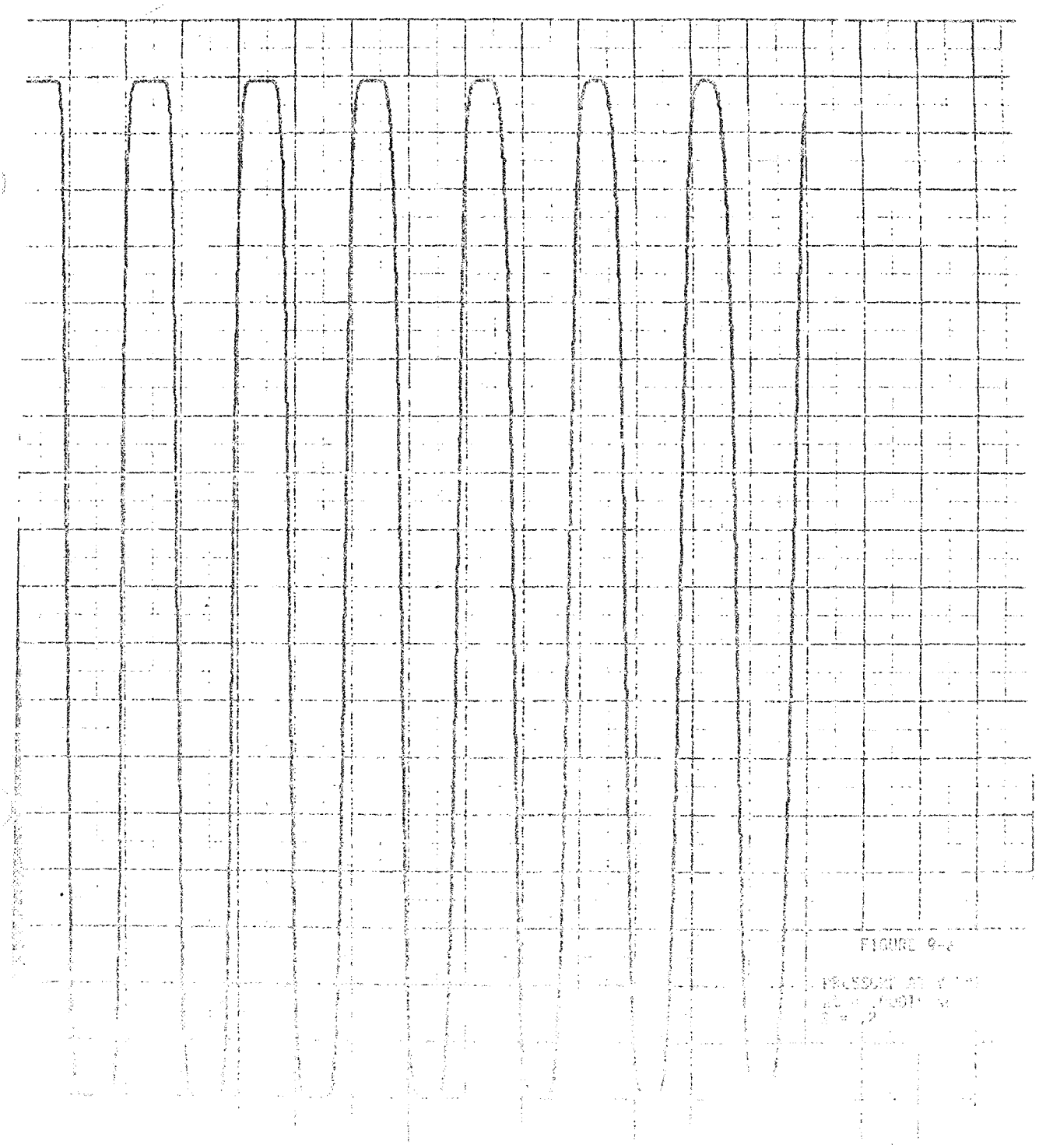
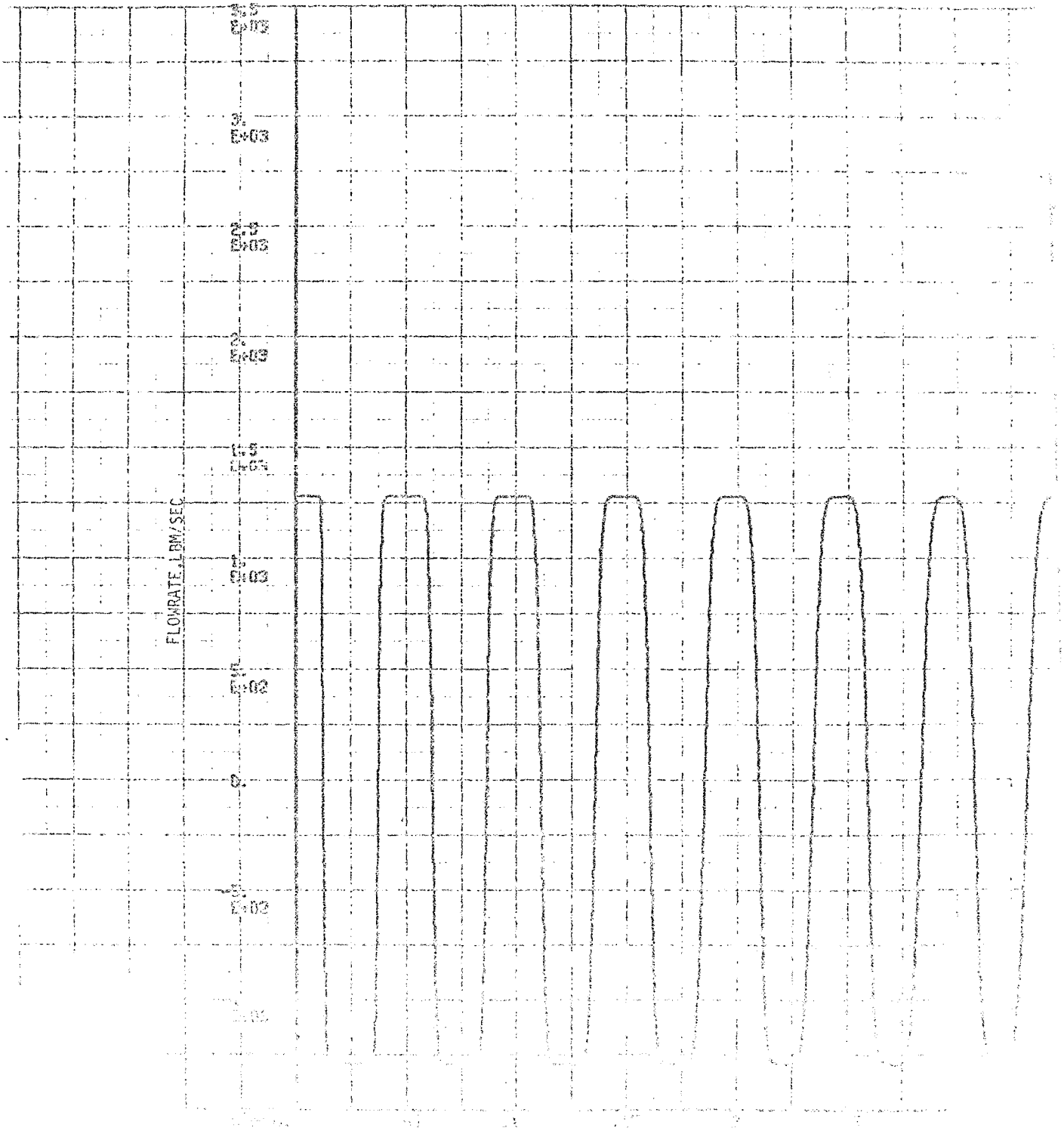
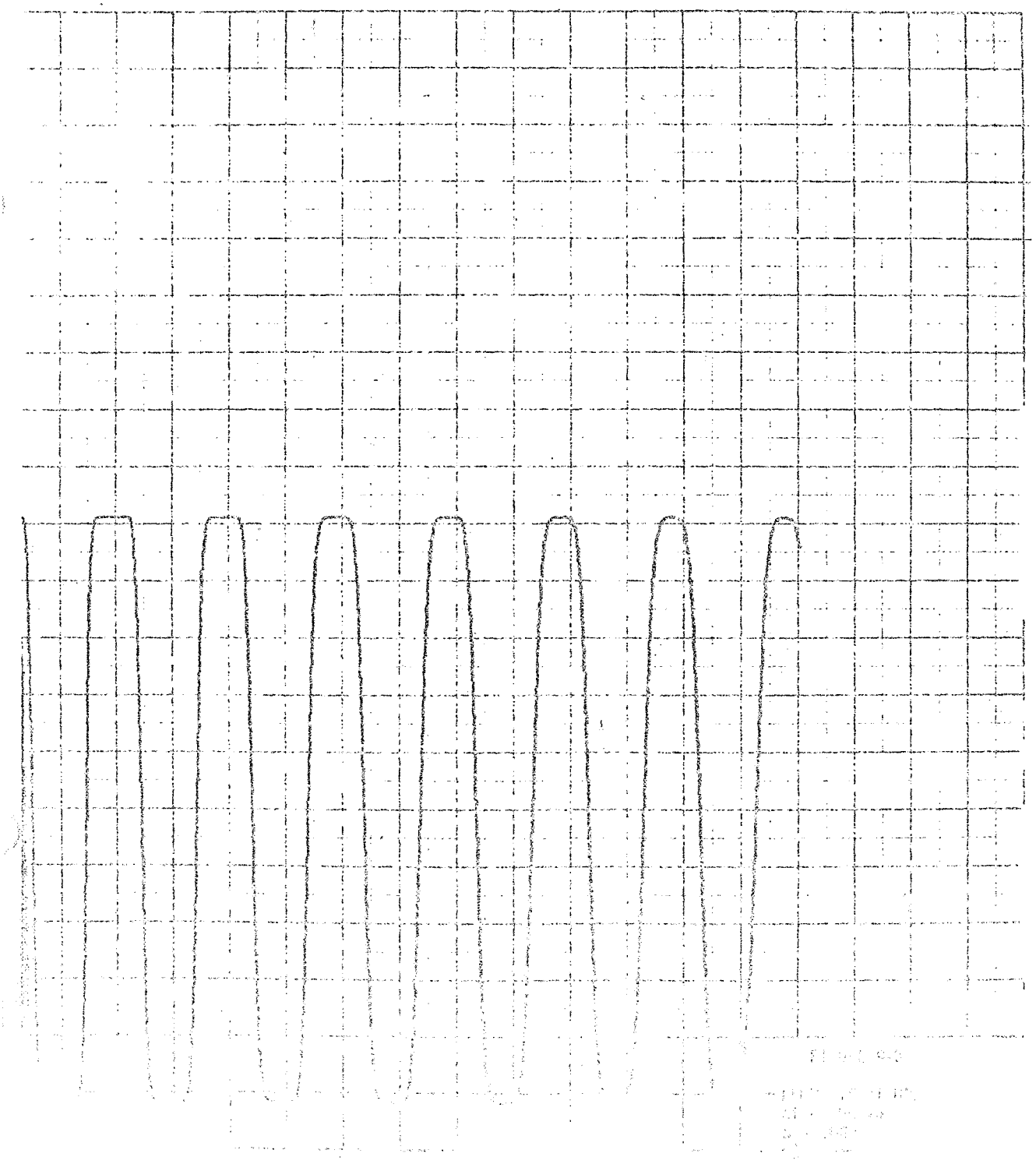
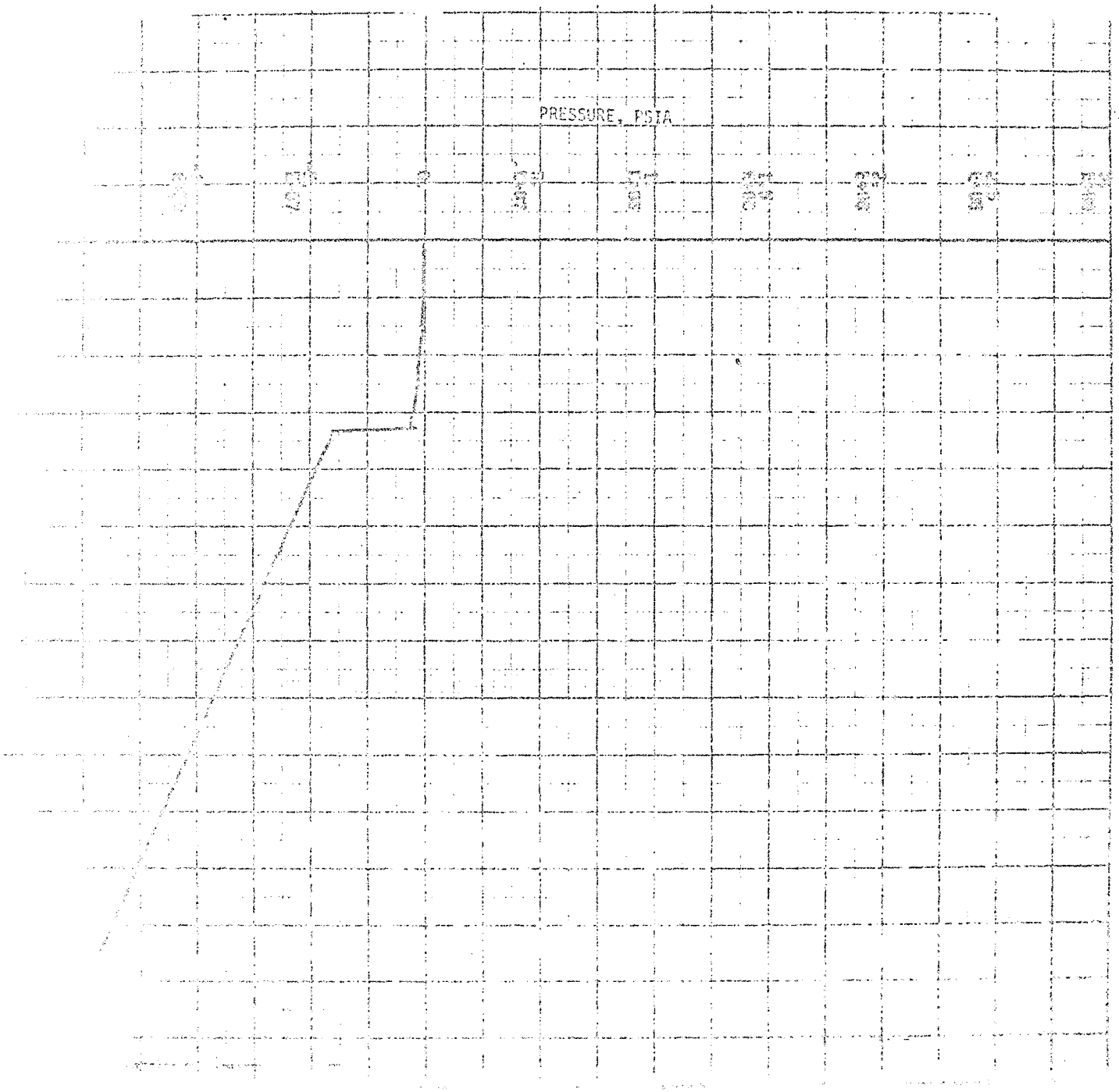


FIGURE 9-4


FLOWRATE,LBM/SEC
3.5
E+03
3.
E+03
2.5
E+03
2.
E+03
1.5
E+03
1.
E+03
0.5
E+03
0.
-0.5
E+03




PRESSURE, PSIA

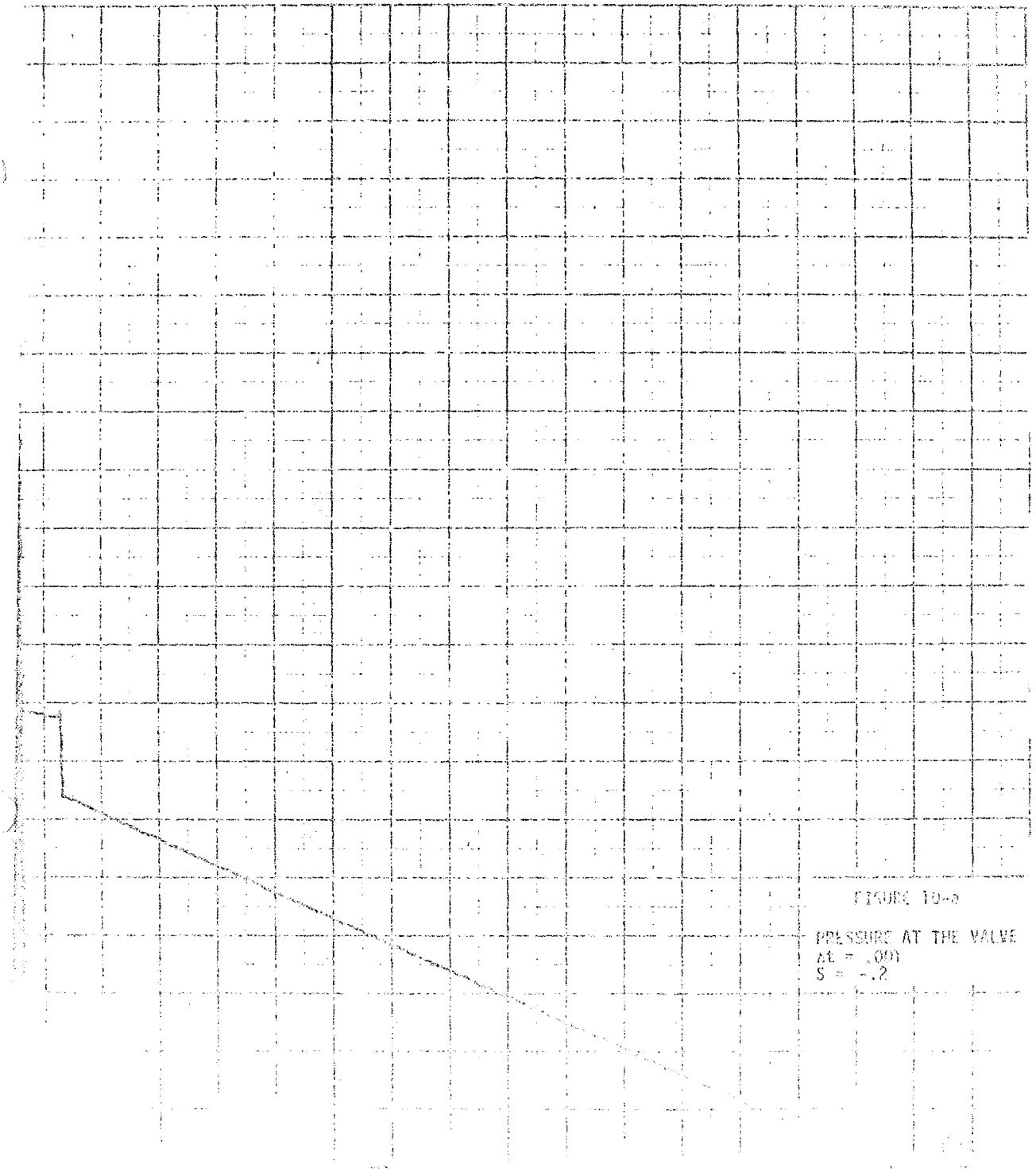
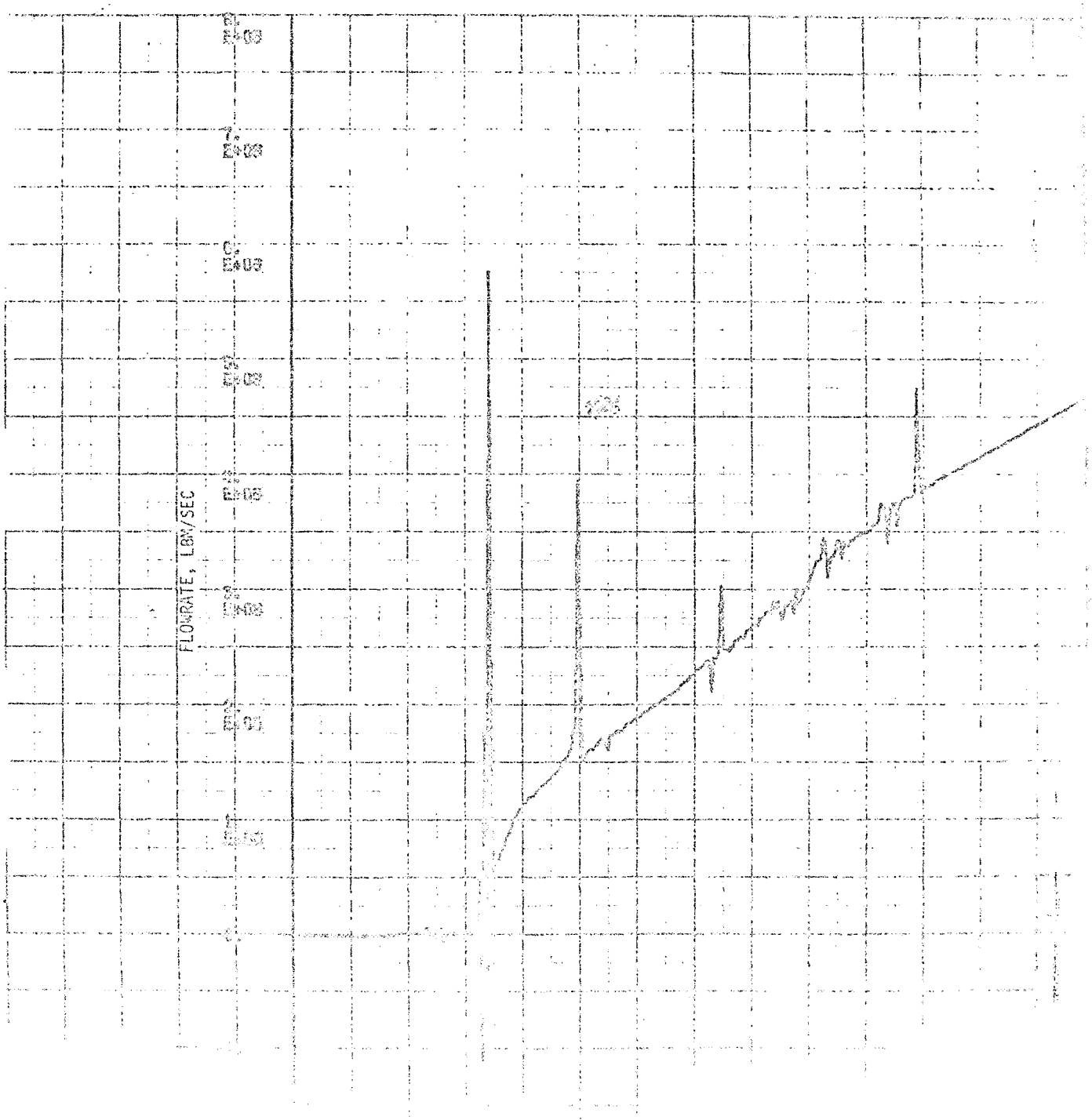


FIGURE 10-6

PRESSURE AT THE VALVE
$\Delta t = .001$
$S = -.2$


FLOWRATE, LBM/SEC

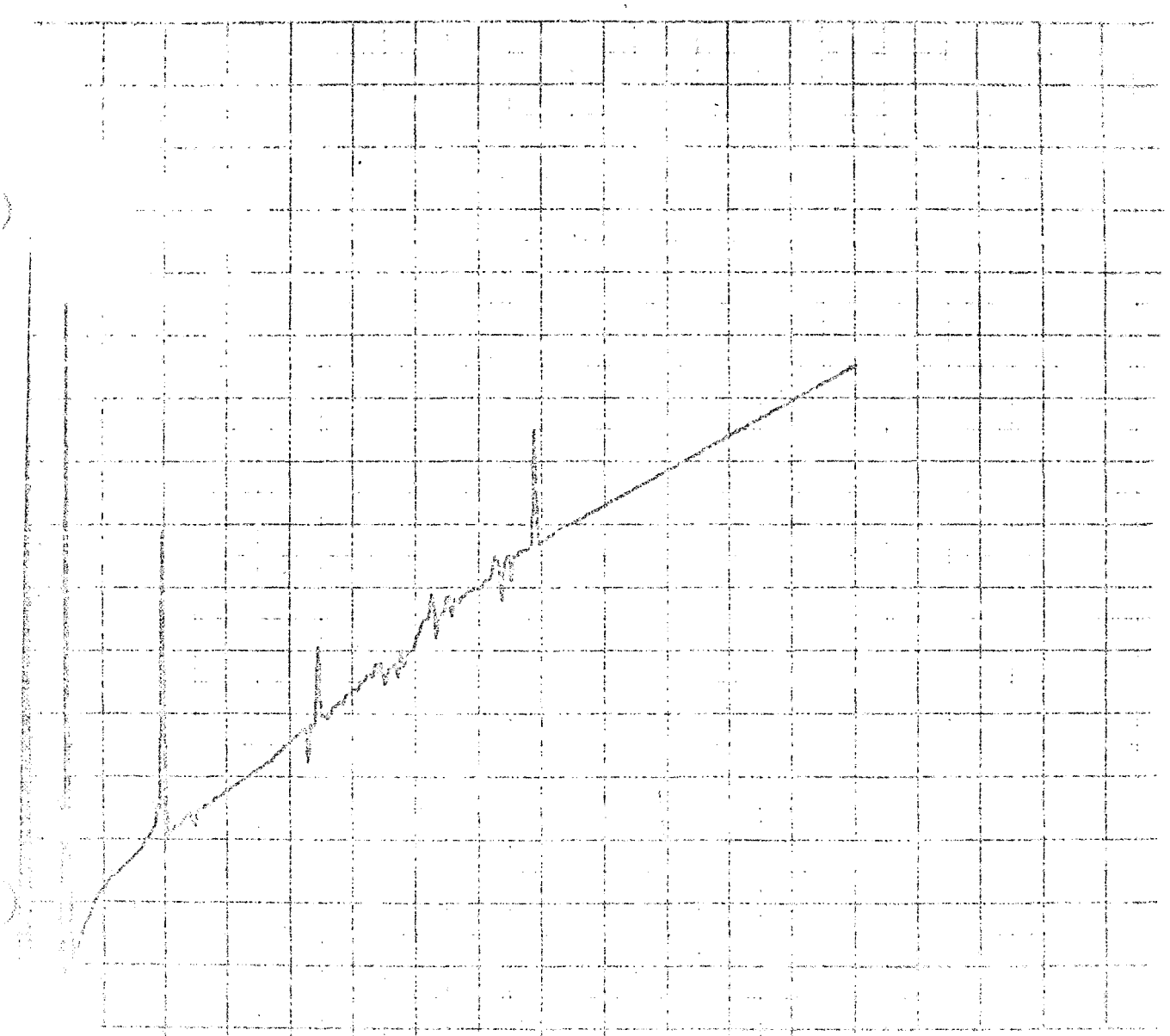


FIGURE 12-6

3.4.4 Supply Lines Steady-State

The supply lines for the steady-state model will be simulated assuming a constant heat flux into the lines (Figure 11). Therefore, the heat transfer coefficient, h, is a constant. Heat transfer into the fluid flowing in long gas lines will be treated by numerical integration with respect to distance. The supply line model will handle the case of combined friction and heat transfer. The nomenclature is included at the end of this section.

The general approach will utilize the energy equation expressed as a function of the heat transfer coefficient (page 243 of Reference 20).

$$\dot{W}\, dQ = \frac{\pi}{4} D^2 \rho V (C_p dT_o) = h \pi D\, dx\, (T_w - T_{aw}) \qquad (1)$$

where T_{aw} = Adiabatic wall temperature (Figure 12).

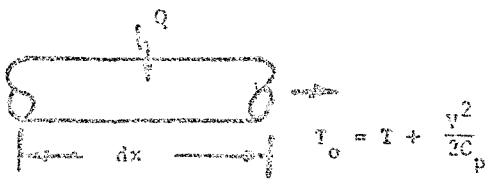


FIGURE 11 - CONSTANT HEAT FLUX INTO LINE ELEMENT

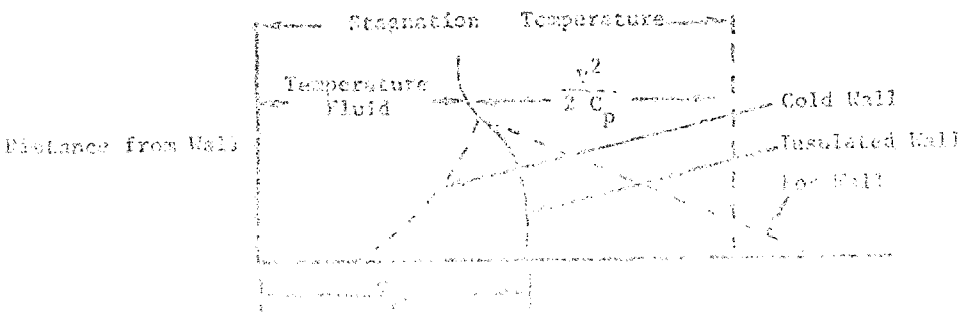


FIGURE 12

For subsonic flow the adiabatic wall temperature, T_{aw}, does not differ much from the stagnation temperature T_o. Therefore, $T_{aw} = T_o$ and Equation 1 becomes

$$\frac{dT_o}{T_w - T_o} = \frac{4\ h\ dx}{\rho\ V\ C_p\ D} \qquad (2)$$

using Reynolds Analogy between friction and heat transfer;

$$\frac{dT_o}{T_w - T_o} = \frac{2\ f\ dx}{D}$$

and integrating yields

$$\frac{T_{o_2} - T_{o_1}}{T_{w_1} - T_{o_1}} = 2f\left(\frac{X_2 - X_1}{D}\right)$$

Therefore, T_o can be calculated for any value of line length, X.

Now the Mach number can be obtained by the finite difference iterative integration

$$dM^2 = \left(F_{T_o} + \left[\frac{2T_o}{T_{w_1} - T_{o_1}}\right] F_f\right) \frac{dT_o}{T_o}$$

where the influence coefficients are as follows:

$$F_{T_o} = \frac{M^2(1+\gamma M^2)(1+\frac{\gamma-1}{2} M^2)}{1 - M^2}$$

$$F_f = \frac{\gamma M^4(1 + \frac{\gamma-1}{2} M^2)}{1 - M^2}$$

evaluating, the finite difference equation is written

$$M_2^2 - M_1^2 = \left[\frac{2 F_{T_o}}{\left(\frac{T_{o_2}}{T_{o_1}} + 1\right)} + \frac{2 F_f}{\left(\frac{T_{o_2}}{T_{o_1}} - 1\right)}\right]\left(\frac{T_{o_2}}{T_{o_1}} - 1\right)$$

[illegible]

If additional accuracy is required, the simplifications in this model can be eliminated. That is, the adiabatic wall temperature would not be assumed equal to the stagnation temperature and the Reynolds Analogy between friction and heat transfer would not be used. This would complicate the model extensively and at present, the minimal accuracy the improvement gains does not warrent this additional complication.

NOMENCLATURE

T_f To	Temperature Fluid or Temperature Stagnation Fluid	°R
V	Velocity fluid initial	ft/sec
P	Pressure	psia
$\dot{W}$	Flowrate	lbm/sec
D	Diameter line	in.
dx	Pipe segment	ft.
Q	Constant heat flux into pipe	BTU/sec
ρ	Density fluid	lbm/sec^3
μ	Viscosity fluid	Centipoise
f	Friction factor	
C_p	Specific heat constant pressure	BTU/°R
M	Mach number down pipe	
T_w	Temperature wall	°R
T_n	Temperature fluid down pipe	°R
h	Heat transfer coefficient	$\frac{BTU}{hr\ ft^2\ °F}$
	Specific heat ratio	

3.4.5 Turbomachinery Transients

Fluid flow through the turbomachinery may be adequately described by utilizing steady-state plots of turbomachinery characteristics. Typical examples of pump characteristics curves are shown in Figures 13 and 15, and examples of turbine characteristic curves are shown in Figure 16. The relationships represented by these curves along with the equality between the pump speed and turbine speed and the equality between turbine power output and pump power required are solved with the line flow equations to give the turbine and pump operating points at each instant of time. The hydrogen pump performance curve, Figure 14, was obtained from AiResearch through TRW/ Redondo Beach Product Design and Analysis Department. This performance curve was based on the ACPS studies being performed for the shuttle conceptual design activities. Justification for using steady-state flow relations is that the fluid capitance of the turbomachinery is usually far less than that of other components of the system. The acceleration of the turbomachinery rotors may be taken into account by a relationship of the form:

$$T = I\, dN/dt$$

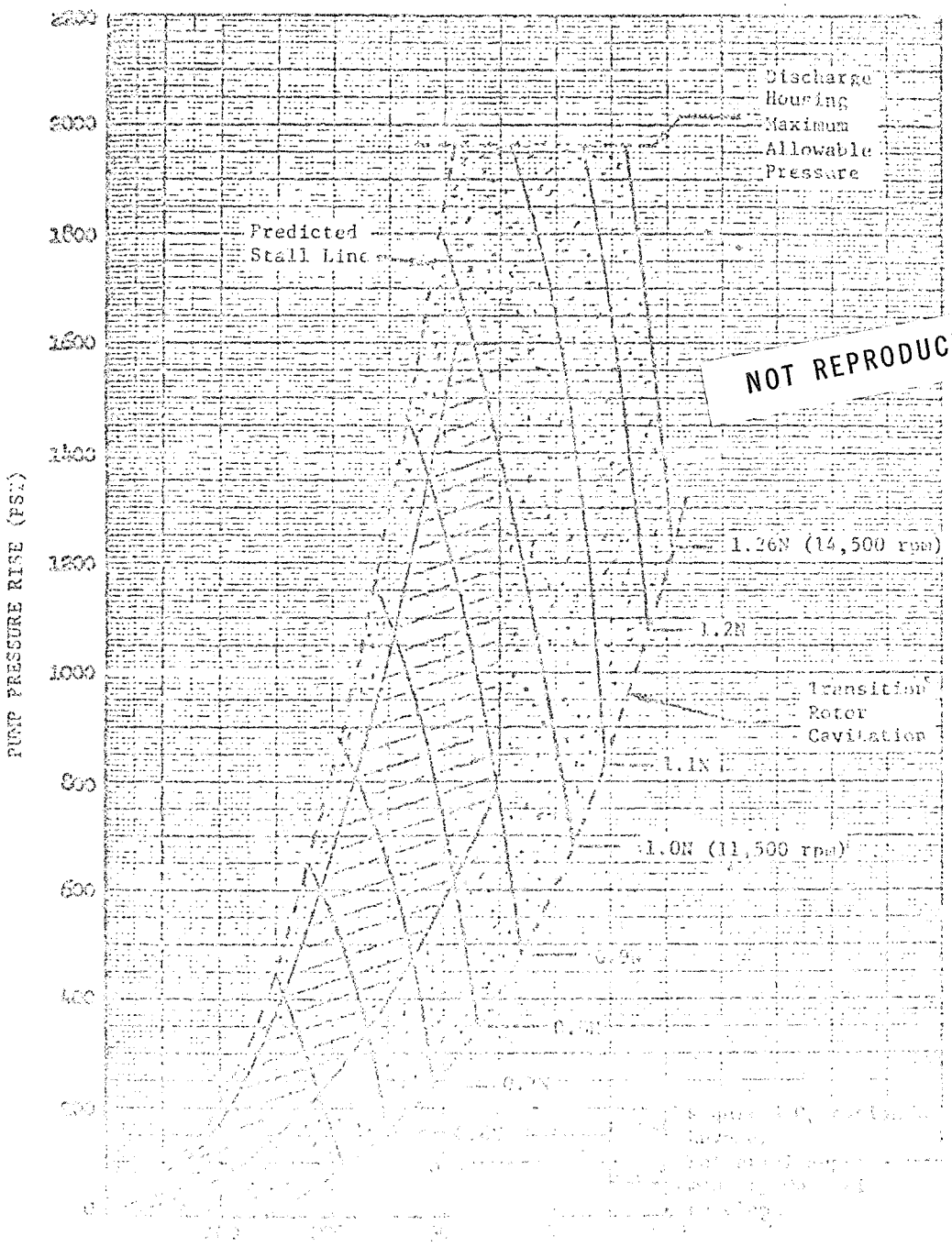
where:

T is the net torque supplied to the rotor, I is the moment of inertia of the rotor and the entrapped fluids and N is the rotor speed.

3.4.6 Turbomachinery Steady-State

Relationships of the type shown in Figures 13 through 16 are sufficient to represent the turbopump and turbine in a steady-state program when the turbine power and pump power equality constraints are satisfied simultaneously with the propellant continuity constraints as described in Section 3.4.3. [illegible]

REFERENCE: Aerojet General Corporation
Proposal No. LR-501-0
Fuel Turbopump Modification Program
Revision A, dated 22 February 1965



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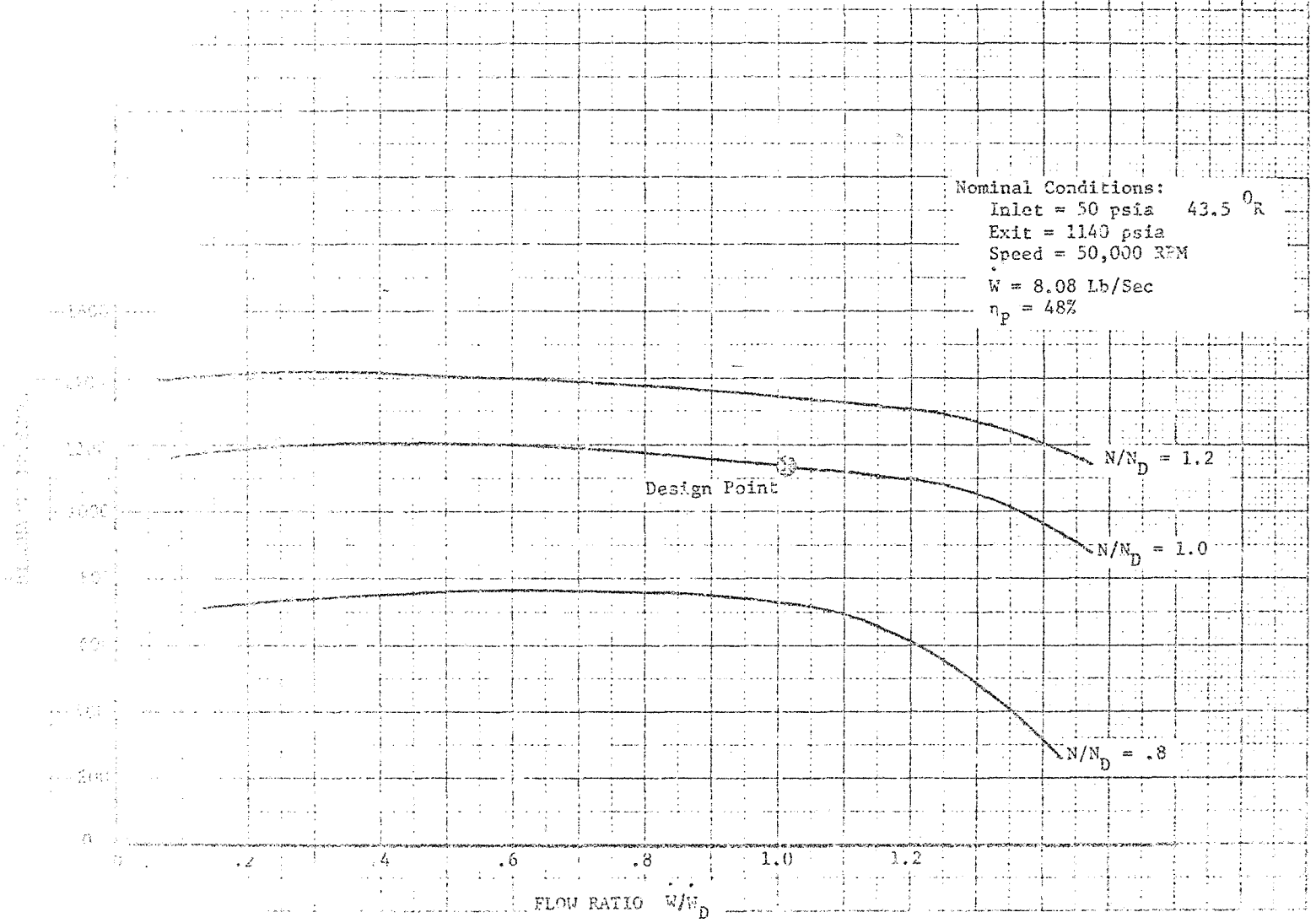
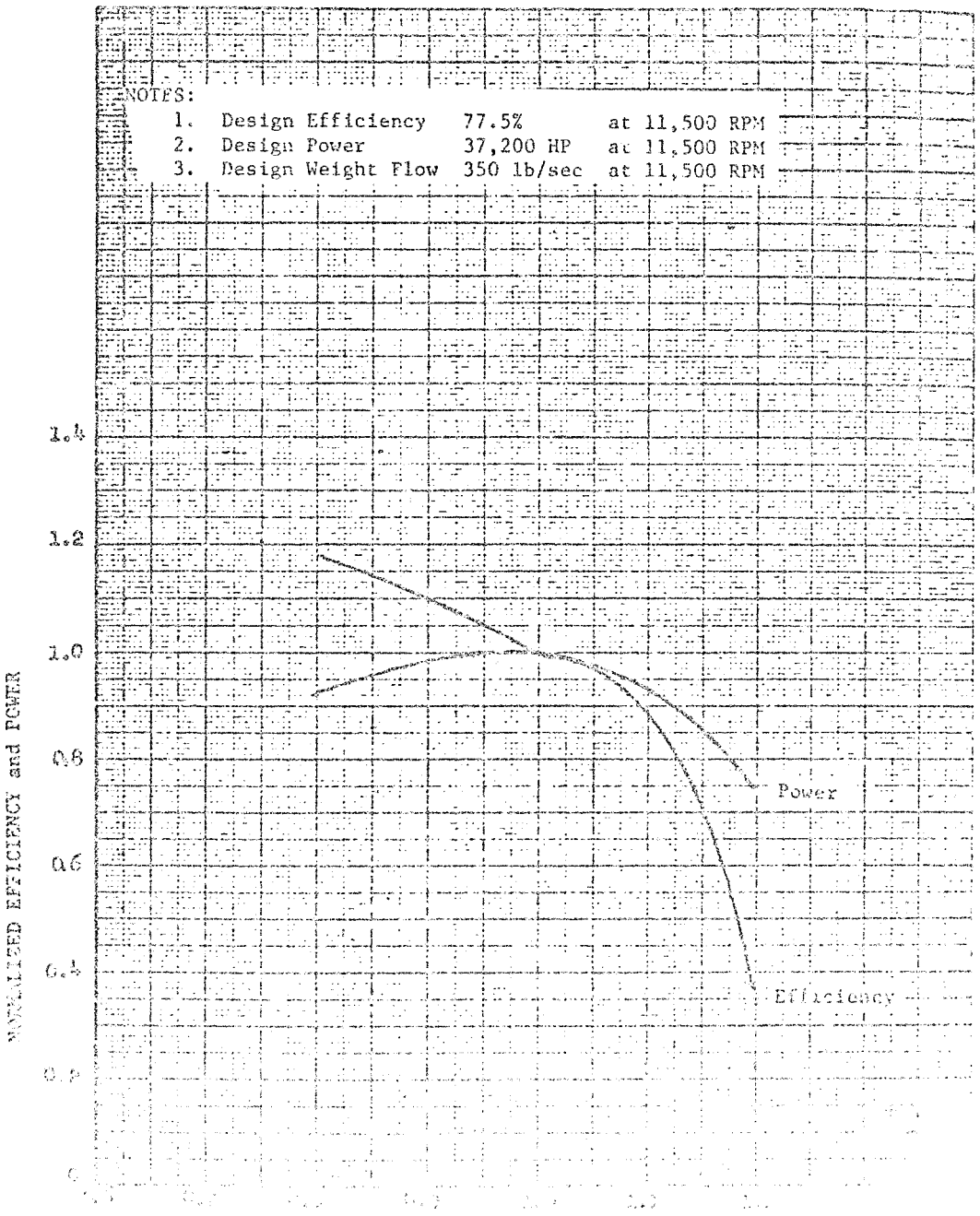
NO. 340R-10, DIETZGEN GRAPH PAPER
10 X 10 PER HALF INCH

EUGENE DIETZGEN CO.
MADE IN U. S. A.

FIGURE 14 TYPICAL PRELIMINARY PUMP PERFORMANCE (HYDROGEN PUMP)



REFERENCE: Aeroject General Corporation
Proposal No. LR650100,
Fuel Turbopump Modification Program
Revision A, dated 22 February 1965



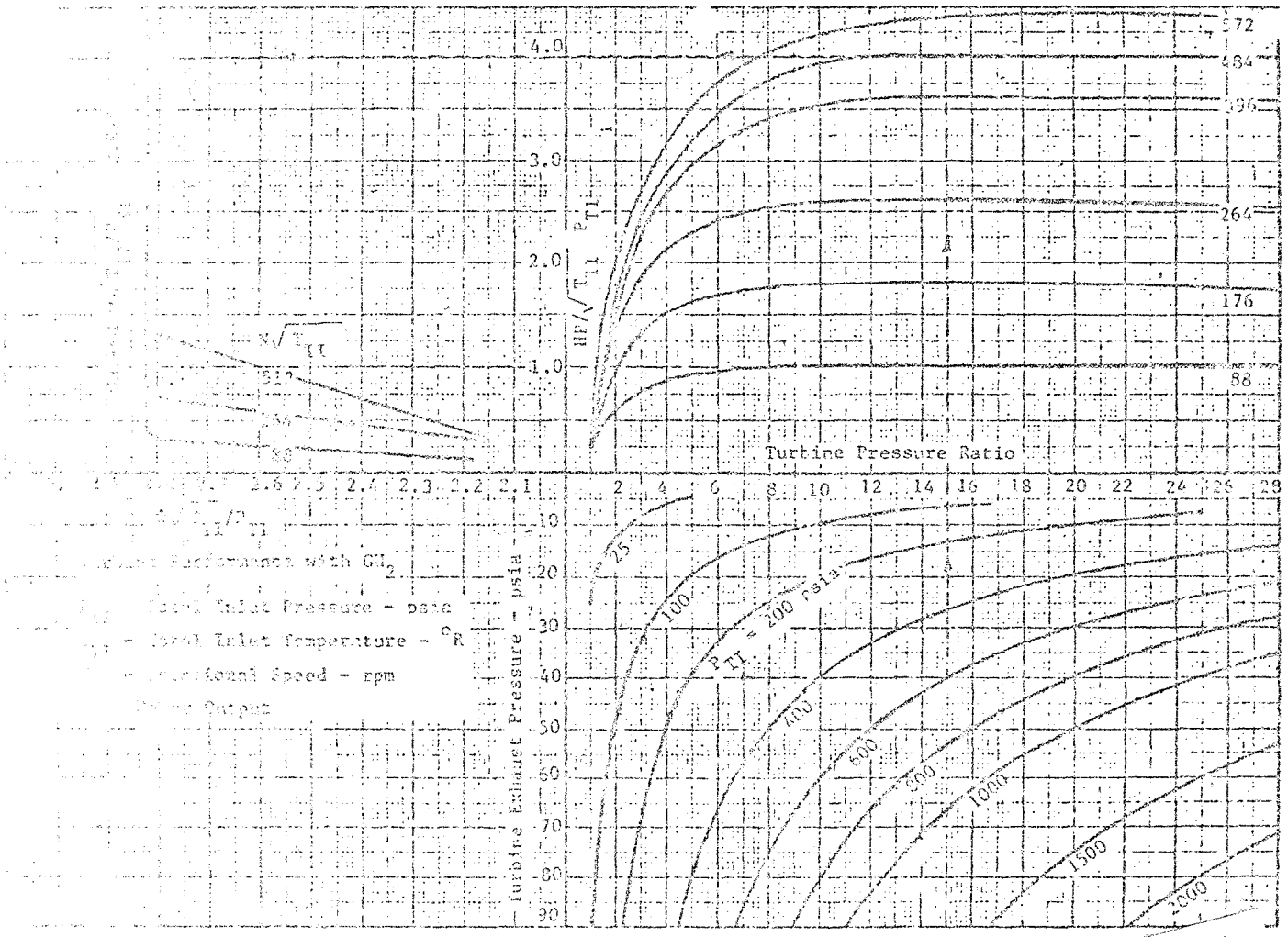


FIGURE 16

TYPICAL TURBINE PERFORMANCE MAP

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3.4.7 Heat Exchanger Transient Model

At the present time it is anticipated that the heat exchanger model will consist of three parts: preheater, boiler, and superheater. When all three subroutines are used consecutively, they will simulate the conditioning of a liquid to a superheated gaseous state. However, each subroutine may be used separately as the simulation of heat exchangers which may start with a fluid at a cool liquid, boiling liquid, or gaseous condition and, for the appropriate initial fluid state, will condition the fluid to either a boiling liquid, cool gas, or superheated gaseous state. This is shown schematically in Figure 17.

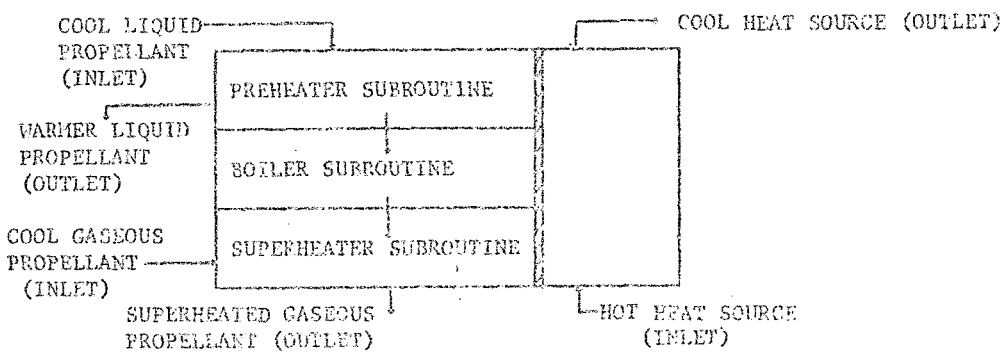


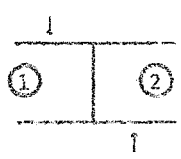
FIGURE 17 - HEAT EXCHANGER BLOCK DIAGRAM

The preheater has the function of elevating the liquid state to a boiling condition. The boiler section accounts for the heat transfer required to vaporize the liquid. The superheater increases the gas to a higher temperature.

An important phase of the [illegible] to a comparison [illegible] empirical data. [illegible] model using data which [illegible]

Figure 17 shows how the counter-flow heat exchanger model will be set up. A slight increase in complexity will result when options are provided in the model for parallel and cross-flow heat exchange. A computer program for the design and performance analysis of Compact Multi-Fluid Heat Exchangers was located in the literature search (Reference Appendix 3, Program N70-10069). This program includes parallel, counter, multi-fluid cross-flow and plates/fins configurations. This program is presently being obtained from MSC and extensive use may be made of it if evaluations indicate it will be useful.

The heat transfer balance equations with counter flow are (see Reference 22);



$$\rho_1 A_1 C_{p1} \frac{\partial}{\partial t} T_1(x,t) = \dot{W}_1 C_{p1} \frac{\partial T_1}{\partial X}(x,t) - h_1 C_1 [T_1(x,t) - \overline{T}_2(t)]$$

$$\rho_2 A_2 C_{p2} \frac{\partial}{\partial t} T_2(x,t) = -\dot{W}_2 C_{p2} \frac{\partial T_2}{\partial X}(x,t) - h_2 C_2 [T_2(x,t) - \overline{T}_1(t)]$$

where

ρ	=	density	1 = conditioned fluid
A	=	flow area	2 = heat source
C_p	=	specific heat	X = length
$\dot{W}$	=	flow rate	t = time
h	=	film coefficient	
C	=	circumference	
T	=	Temperature	
L	=	Total length	

$$\overline{T} = \frac{1}{L} \int_0^L T dx$$

These equations apply to all cases except boiling and will likely form the basis for the model.

For the case of the boiler [illegible] conditioned fluid [illegible]

[illegible]

$$\frac{\dot{W}_1 H}{L} = -U_1 C_1 [T_1 - \overline{T}_2(t)] \qquad H = \text{latent heat of vaporization}$$

3.4.8 Heat Exchanger Steady-State Model

The steady-state equations for heat exchangers are well developed and will be utilized for this application. The principal mechanism for the transfer of heat in the heat exchangers planned for the ACPS is that of convection. The heat transferred by convection is determined from the relation:

$$Q = hA(\Delta T) \tag{1}$$

where Q is the heat transfer rate, h is the film coefficient, and ΔT is the appropriate temperature difference. The film coefficient depends upon the shapes of the exchanger parts and upon whether the convection is natural or forced. Reference 23 gives the following empirically determined relation for natural convection from a cylinder, to a surrounding medium.

$$\frac{hD}{k} = 0.53 \left|(G_R P_R)\right|^{.25}$$

where

$$G_R = \frac{B g \, \Delta T \rho^2 D^3}{\mu^2}, \text{ is the Grashof number.} \tag{2}$$

$$P_R = \frac{C_p \mu}{k}, \text{ is the Prandtl number.}$$

D is the cylinder diameter, k is the fluid thermal conductivity, B is the fluid bulk modulus of thermal expansion, ρ is the fluid density, μ is the fluid viscosity, C_p is the fluid specific heat, and g is the local acceleration.

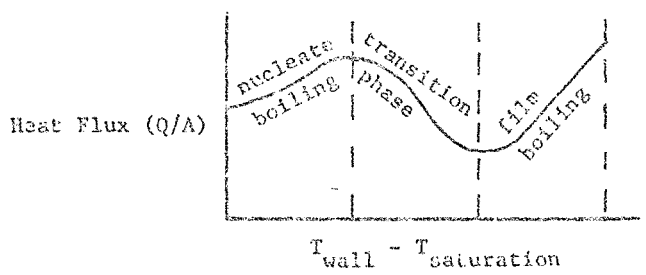
The value of the film coefficient for forced convection to a cylindric [illegible] is a function of the [illegible] and the Prandtl number [illegible] [illegible] gives the following [illegible] [illegible]

[illegible]

NOT REPRODUCIBLE

if the heat flow is from the cylinder wall to the fluid, the Prandtl number exponent is 0.4 rather than 0.3. These relationships, or a similar approach, will likely serve as the basis of development of the model.

The previous heat transfer Equations (2 & 3) are valid strictly for single phase flow. In order to handle the region of two phase flow, in both liquid and gas, three regions of heat exchange must be considered, nucleate boiling, transition phase, and film boiling. The oxygen and hydrogen boiling curves, for example,



will be used to determine the heat transfer coefficient averaging method which will be utilized to model this heat transfer region. The heat transfer entrance and exit effects will be further investigated for possible inclusion in this model.

3.4.9 Accumulators and Pressure Vessel Transients

If an accumulator is long enough so that it would require at least two calculation nodes, and if treated as a distributed parameter line, then the line subroutines described in Section 3.4.3 can be used to simulate it. If the accumulator is so short that the selection of a time interval to give it two nodes results in an impracticably small interval, then a lumped parameter representation will be used. (Figure 18)

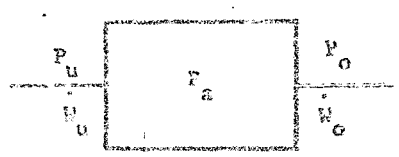


Figure 18 Accumulator

$$\dot{W}_u = f_1 (P_u, P_a) \tag{1}$$

$$\dot{W}_o = f_2 (P_a, P_o) \tag{2}$$

$$\frac{dP_a}{dt} = \frac{\gamma RT}{V_a} (\dot{W}_u - \dot{W}_o) \tag{3}$$

$\dot{W}_u$ is the flow rate into the accumulator, $\dot{W}_o$ is the flow rate out of the accumulator, P_u is the pressure upstream of the accumulator, P_a is the pressure in the accumulator, P_o is the pressure downstream of the accumulator, γ is the ratio of specific heats, R is the gas constant, T is the temperature, and V_a is the gas volume. Equations 1 and 2 are steady-flow relations between [illegible] and existing flow rates and pressure drops and Equation 3 is the [illegible] of the continuity equation.

[illegible]

3.4.10 Accumulators and Pressure Vessels Steady-State

The modeling of the steady-state accumulators and pressure vessels will account for heat transfer through the walls and liquid surface, venting reverse flow and mass/volume changes (Figures 19 and 20, Reference 25). The following approach will be used and the nomenclature is included at the end of this section.

The initial pressure (P) will be obtained from the initial ullage volume (v), gas mass (W) and initial average gas temperature (T) based on the equation of state for a perfect gas.

$$Pv = W R T$$

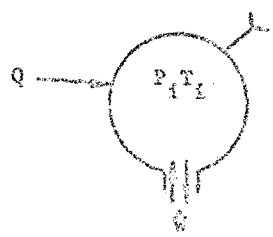


Figure 19 Gas Accumulator

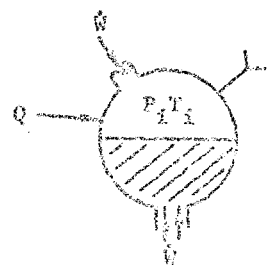


Figure 20 Gas/Liquid Pressure Vessel

If $P_e > P_i$

The entering flowrate, (lbm/sec) is

$$\dot{W}_e = A R \sqrt{\frac{[illegible]}{[illegible]}}$$

If $P_i > P_e$

[illegible]

The volume change, (ft^3) is

$$V_2 = V_1 - \frac{12\,\dot{W}}{\rho A}\,\Delta t; \quad dv = V_2 - V_1 \tag{3}$$

The ullage or accumulator volume change, (ft^3) is

$$dv = \dot{W}_e\,dt \tag{4}$$

The ullage mass (lbm) is

$$W_g = W_{g-1} + \dot{W}_g\,dt \tag{5}$$

If the pressure in the tank is greater than the vent pressure, calculate venting flowrates.

$$\dot{W} = \text{sonic flow} \tag{6}$$

Calculate heat transfer across gas-liquid interface (BTU), if necessary

$$\dot{Q}_{gl} = h\,A_1\,(T_i - T_1) \tag{7}$$

where h = f(Prandtl, Grashof, or Reynolds numbers)

A_1 = liquid surface area

The energy of incoming mass (BTU) is:

$$Em_{in} = C_p\,\dot{W}_{in}\,dt \tag{8}$$

where in = entering

The energy venting mass (BTU) is

$$E_{vent} = \dot{W}_{VR}\,T_u\,C_p\,dt \tag{9}$$

The expansion work (BTU) is

$$E_s = P_i\,|V_t - V_{t-1}| \tag{10}$$

The internal energy is

$$U = C_v\,T \tag{11}$$

[illegible] heat transfer through [illegible] wall is

$$\frac{[illegible]}{dt} = [illegible]$$

[illegible]

The energy balance then yields the ullage temperature (°R)

$$T_u = \frac{U - Em_{in} - Q_{gl} - E_V - E_s - Q_W}{C_V}$$

Final ullage pressure (psia) is

$$P_i = \frac{W\ R\ T_i}{V_i}$$

When the fluids are stored under supercritical conditions, they cannot be treated using thermodynamic relationships based on the ideal gas laws. For quasi-steady flow, it is common to use the thermodynamic functions θ and ϕ which are defined as

$$\phi(P,\rho) = \frac{1}{\rho}\left(\frac{\partial P}{\partial U}\right)_\rho$$

$$\theta(P,\rho) = -\rho\left(\frac{\partial H}{\partial \rho}\right)_P$$

The pressure change in the tank as a function of flowrate out and heat added is then

$$\frac{dP}{dt} = \frac{\phi}{V}\left(\frac{dQ}{dt} - \theta \dot{W}_e\right)$$

The ϕ and θ functions are readily available for oxygen and hydrogen as the result of work on other programs.

NOMENCLATURE

P	Pressure	psia
V	Volume	ft^3
W	Weight gas in bottle	lbm
R	Gas constant	ft-lbf/lbm°R
T	Temperature gas	
	Flowrate	
	[illegible]	

NOMENCLATURE (Continued)

ρ	Density	lbm/ft^3
Aw	Surface area tank walls	ft^2
A	Flow area	ft^2
A_l	Liquid/gas surface area	ft^2
C_p	Specific heat constant pressure	BTU/°R
C_V	Specific heat constant volume	BTU/°R
U	Internal Energy	BTU
EM_{in}	Energy of incoming mass	BTU
Q_{gl}	Heat transfer thru gas interface	BTU
E_V	Energy Venting mass	BTU
E_s	Expansion work on surroundings	BTU
Q_W	Heat transfer thru tank walls	BTU
Q	Total heat added to tank	
H	Enthalpy	BTU
g_c	Conversion constant	$32.2 \frac{lbm\text{-}ft}{sec^2\text{-}lbf}$

Subscripts

e	Exit
i	Internal
t	Time
p	Present
v	Ullage
l	Liquid

3.4.11 Manifold and Injector Transients

A rigorous treatment of the flow downstream of the thrust chamber valve would be a very difficult matter. Even making the assumptions that the flow is one-dimensional, inviscid, and adiabatic would involve solving the continuity and momentum equations, which are partial differential equations, and the algebraic equations of state and the isentropic relationships. In addition, discontinuities in the solution (shocks and interfaces) would have to be followed. A search of the literature has so far revealed no simplified models which are substantiated by experimental data. The proposed simplified model (Figure 21) is typical of the treatment of transient flow through the manifold and injectors.

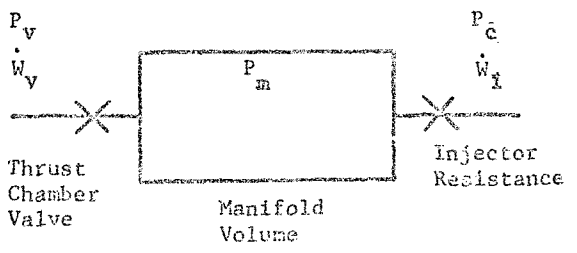


FIGURE 21 - MANIFOLD DIAGRAM

The flow into the manifold is given by

$$\dot{W}_v = P_v A_v C_v \sqrt{\frac{g_c}{RT}\left(\frac{2\gamma}{\gamma-1}\right)\left[\left(\frac{P_m}{P_v}\right)^{\frac{2}{\gamma}} - \left(\frac{P_m}{P_v}\right)^{\frac{\gamma+1}{\gamma}}\right]} \qquad (1a)$$

for unchoked flow, or, if the flow is choked by

$$\dot{W}_v = P_v A_v C_v \sqrt{\frac{g_c \gamma}{RT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (1b)$$

$\dot{W}_v$ is the flow through the valve, A_v is the effective [illegible] C_v is the valve flow coefficient, g_c is a [illegible] constant, γ is the [illegible]

cific heats, P_m is the manifold pressure, and T is the total temperature of the gas. Similarly, for flow from the manifold into the chamber

$$\dot{W}_i = P_m A_i C_i \sqrt{\frac{g_c}{RT}\left(\frac{2\gamma}{\gamma-1}\right)\left[\left(\frac{P_c}{P_m}\right)^{\frac{2}{\gamma}} - \left(\frac{P_c}{P_m}\right)^{\frac{\gamma+1}{\gamma}}\right]} \tag{2a}$$

for unchoked flow, or

$$\dot{W}_i = P_m A_i C_i \sqrt{\frac{g_c \gamma}{RT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{2b}$$

for choked flow. $\dot{W}_i$ is the flow through the injector, and A_i is the injector area.

The pressure in the manifold volume will be found from the differencial equation

$$\frac{dP_m}{dt} = \frac{\gamma RT}{V_m}\left(\dot{W}_v - \dot{W}_m\right) \tag{3}$$

V_m is the volume of the injector. For the valve flow to be unchoked

$$\frac{P_m}{P_v} > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{4}$$

and for the injector flow to be unchoked

$$\frac{P_c}{P_m} > \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{5}$$

Equations 1 and 2 are the steady flow relations for flow through a constriction, and Equation 3 is the continuity equation (see Section 3.4.3, Equation 1) put into finite difference form in the length dimension and the convective terms dropped. In the transient analysis program, Equations 1-5 will be solved in the subroutine MANIFOLD.

3.4.12 Manifolds and Injector Steady-State

The manifolds and injectors will be treated as lines and orifices (Figure 22). The flowrate calculation will be performed as follows

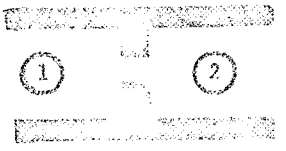


FIGURE 22 - SIMPLIFIED MANIFOLD ORIFICE

$$\dot{W} = \Omega \; K \; (D^2) \sqrt{\frac{(P_1 - P_2) \; P_1 \; (MW)}{T}}$$

where: $K = C \; Y$; $C = \dfrac{Cd}{\sqrt{1 - \left(\frac{d_o}{d_1}\right)^4}}$; $Y = f(\gamma, \frac{dt}{p}, \frac{d_o}{d_1})$;

$$\Omega = \frac{\pi}{4} \sqrt{\frac{2(32.174)}{1545.4}} = \text{conversion factor}$$

NOMENCLATURE

MW	Molecular weight	moles
D	Diameter line	in.
T	Temperature line	°R
$\dot{W}$	Flowrate (assumed)	lbm/sec
P	Pressure	psia
C	Flow coefficient	---
Y	Expansion factor	--
$\dot{W}$	Diversion of flow depending on which is connected to the manifold flowrate	lbm/sec

Subscripts

Unknown

3.4.13 Orifices, Pipebends and Valves Transients

During transients, orifices, pipebends and valves will be represented by quasi-steady flow relations similar to those used in Section 3.4.12. Flows of gases across lumped resistances may be treated as Joule-Thompson expansions. Valve resistances as a function of both position and time will be considered in the simulation. The resistances of orifices, pipebends, and valves will be required as input. The resistances of bends and orifices may be obtained from standard references works. (See Reference 26). Valve resistances are usually provided by the manufacturer and will be put into the program in tabular form.

3.4.14 Orifices, Pipebends and Valves Steady-State

The only difference between the transient and steady-state models will be that the valve positions and thus resistances will not be functions of time.

3.4.15 Gas Generator Transients

The gas generator transient model will be characterised by the fluid flow equations used in the combustor model, Section 3.4.1, and the compressible gas flow relationships.

The initial flow out of the gas generator, when it is operated in a vacuum, will be choked. As the back pressure in the duct leading to the turbine increases, the velocity of the flow will change to subsonic. The following equations will be used:

The velocity at the gas generator for choked flow is:

$$V_t = a^* = (g_c \gamma R T_t)^{1/2} = \left[2 g_c R T_c \left(\frac{\gamma}{\gamma+1}\right)\right]^{1/2} \tag{5}$$

The pressure at the throat is

$$P_t = P_c \left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1} \tag{6}$$

The temperature at the throat is

$$T_t = T_c \left(\frac{2}{\gamma+1}\right) \tag{7}$$

The equations to determine the thermodynamic state at a position downstream in the ducts are:

$$\frac{V_x}{V_t} = \left\{\left(\frac{(\gamma+1)}{(\gamma-1)}\right)\left[1 - \frac{2}{\gamma+1}\left(\frac{P_x}{P_t}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2} ; \tag{8}$$

$$\frac{A_x}{A_t} = \left(\frac{P_t}{P_x}\right)^{1/\gamma}\left(\frac{A_t}{V_x}\right) \tag{9}$$

$$\frac{P_x}{P_t} = \left(\frac{A_t}{A_x}\right)^{\gamma}$$

Substituting Equation 10 into Equation 8, the velocity ratio, and V_x may be solved for

$$\frac{V_x}{V_t} = \left(\frac{\gamma+1}{\gamma-1}\left[1 - \frac{2}{\gamma+1}\left(\frac{A_t V_t}{A_x V_x}\right)^{\gamma-1}\right]\right)^{1/2} \tag{11}$$

The duct pressure is

$$P_x = P_t \left(\frac{A_t V_t}{A_x V_x}\right)^{\gamma} \tag{12}$$

The duct temperature is

$$T_x = T_t \left(\frac{P_x}{P_t}\right)^{\frac{\gamma-1}{\gamma}} \tag{13}$$

For subsonic flow:

The duct pressure is

$$P_x = P_{GG} - \frac{K\,W'^2}{P_{GG}}\,T_{GG} \cdot R \tag{15}$$

The duct temperature is

$$T_x = T_{GG} \tag{16}$$

NOMENCLATURE

V	Velocity	ft/sec
γ	Specific heat ratio	
T	Temperature	°R
R	Gas constant	ft-lbf/lbm°R
a*	Sonic velocity	ft/sec
G	Gravitational constant	ft/sec^2
m	Molecular weight	
C_p	Specific heat at constant pressure	BTU/°R
[illegible]	[illegible]	[illegible]
		[illegible]
		[illegible]

NOMENCLATURE (Continued)

Subscripts

x	duct
c	Critical
t	Throat
GG	Gas generator

3.4.16 Steady-State Modeling - Gas Generator (high & low Pressure)

The gas generator will be a combustor model operating at a different mixture ratio. The model will use the same basic fluid flow equations as the combustor model with some additional calculations to determine the thermodynamic conditions at the gas generator exits (duct entrance). (Reference Section 3.4.2, Steady-State Combustor for Modeling and Basic Input/Output). The combustion equations will be based on curve fits of data calculated with the ICRPG program (Reference 12-16). The gas generator exhaust gas may be ducted to a turbine or to a heat exchanger (in series or separately) and there will likely be a duct connecting the gas generator to the next component. The duct length may vary from negligibly short to rather long; therefore, this simulation requires a duct model to determine the change in thermodynamic state of the fluid between the gas generator exit and the entrance to the next component. Likewise, this same duct simulation may be used between succeeding components (turbine exit to heat exchanger entrance, heat exchanger exit to space vacuum, etc.).

The basic approach to be used is described by the following equations; the nomenclature is found at the end of this section. The combustion temperature, specific heat ratio, specific heat, and molecular weight will be calculated from the following curve fits:

$$T_c = f(MR) \qquad (1)$$

$$\gamma = f(T_c) \qquad (2)$$

$$C_p = f(T_c) \qquad (3)$$

$$(4)$$

The duct temperature

$$T_x = T_{GG} \tag{6}$$

NOMENCLATURE

T	Temperature	°R
MR	Mixture ratio	
γ	Specific heat ratio	
C_p	Specific heat constant pressure	BTU/°R
MW	Moleculer weight	
P	Pressure	psia
K	Duct pressure loss coefficient	$\frac{psia\text{-}sec^2}{lbm\text{-}ft^3}$

Subscripts

x	Duct
GG	Gas generator
c	Combustion

3.4.17 Solution of a System of Implicit Equations

In the steady-state analysis program, it is necessary to have a subroutine or set of subroutines that computes a solution to the system of equations $F(X) = 0$. These routines must be accurate, reliable, and easy to use. They must take a minimum of care and execution as they will be used extensively. During the literature search, a set of subroutines were discovered which meet these specifications.

BEGS is a subroutine that, given N functions $F = (f_1, \ldots, f_N)$ in M variables $X = (x_1, \ldots, x_M)$, computes X such that $||F(X)||^2 = \sum_{i=1}^{N} f_i^2(X)$ is a minimum. If $M = N$, it seeks the solution of the system of equations $F(X) = 0$ using the Newton Method. BEGS requires two auxiliary subroutines. One routine must be provided to compute $F(X)$ for a given value of X. The other is subroutine LEGS. LEGS is used to solve an overdetermined linear system of equations $AX = B$ in the least squares sense, i.e., to solve the normal equations $A^TAX = A^TB$.

These routines have proven to be accurate and reliable. They are in use in several programs at TRW/Houston and TRW/Redondo Beach.

3.4.18 Integration Subroutine

Both the steady-state and transient analysis programs have a need for an integration subroutine for the conductor model. Through the use of the TRW/TSS terminal system, a library integration subroutine was located.

The subroutine is capable of solving a set of N simultaneous, first order, ordinary differential equations of the form

$$y_i' = f_i(t, y_1, \ldots, y_N) \qquad i = 1$$

[illegible] Runge-Kutta method. [illegible]

integration scheme will be evaluated after the ACPS models have been formulated.

This Runge-Kutta method was tested against the Euler method in the combustor transient model for accuracy, stability, and convergence. The Runge-Kutta method proved superior to the Euler method as discussed in Section 3.4.1.

REFERENCES

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APPENDIX I

REQUEST FOR LITERATURE SEARCH

1. Please conduct a literature search on the following subject:

   Rocket propulsion systems using propellant stored as liquid hydrogen and liquid oxygen (cryogenics); and which have these liquid propellants to a gas (gas/gas system) for combustion in the rocket engine.

   The following information is furnished to satisfy TIC requirements:

   A. Specific terms which may be of use in locating items:

   Gaseous Hydrogen/Gaseous Oxygen Rocket Engines.
   " " " " " Injectors,
   " " " " " Valves
   " " " " " Plumbing
   " " " " " Accumulators
   Liquid Hydrogen and Liquid Oxygen Heat Exchangers
   " " " " " Propellant Vaporizers
   " " " " " Propellant Pumps
   " " " " " Propellant Tanks

   B. Terms or subjects to be excluded:

   Thermodynamic properties of liquid hydrogen, liquid oxygen, gaseous hydrogen, and gaseous oxygen.

   C. Additional information of possible assistance: None

   D. Cost Code: 4354 Job Number: 1275-20
   Note: For information purposes only. No charges levied for literature search or bibliographies.

   E. Date results Needed:

   F. Coverage (years): 1960-1970

   G. Number of entries desired:

   H. Level of classified material desired: Unclassified

   I. Computer search by: [illegible] Documentation Center and [illegible]
   (Allow a minimum of [illegible] working days for a computer search.)

   [illegible] conduct a literature search on the following [illegible]

   [illegible]

The following information is furnished to satisfy TIC requirements.

A. Specific terms which may be of use in locating items:

Digital computer simulations; transient rocket engine analysis; steady-state rocket engine analysis; gaseous hydrogen and gaseous oxygen rocket engines; transient flow analysis for gas in pipes and tubes.

B. Terms or subjects to be excluded:

Thermodynamic properties of liquid hydrogen, liquid oxygen, gaseous hydrogen and gaseous oxygen.

C. Additional information of possible assistance: None

D. Cost Code: 4354 Job Number: 1275-20
Note: For information purposes only. No charges levied for literature search or bibliographies.

E. Date results needed:

F. Coverage (years): 1960-1970.

G. Number of entries desired:

H. Level of classified material desired: Unclassified.

I. Computer search by: None

III. It is requested that a literature search be conducted for any dynamic analysis or dynamic math modeling pertaining to the following items:

A. Rocket Engines
B. Propulsion Systems - Auxiliary and Primary
C. Propellant Feed Systems
D. Propellant Tanks and Accumulators
E. Propellant Lines - Liquid and Gas
F. Heat Exchangers and Heaters
G. Valves
H. Injectors
I. Turbopumps and Compressors
J. Manifolds
K. Combustion Chambers
L. Ignition Systems
M. Gas Generators

APPENDIX 2

LITERATURE SEARCH ON MATHEMATICAL MODELING FOR STABILITY OF HYDROGEN AND OXYGEN ROCKET PROPULSION ENGINES RESPONSE

The following bibliography is furnished in response to your request:

N63-18207 Mathematical model and tests of rotation detonation wave rocket engine using hydrogen and oxygen propellants.

N67-37686 Study of random wave phenomena in hypergolic propellant combustion. (analytic model for describing combustion chamber disturbances during start transient and steady state operations for hypergolic liquid rocket engines)

N68-22095 Computer simulation of high frequency combustion instability and its suppression. Final report.

X66-22572 Combustion stability limits calculated utilizing a nonlinear model. (liquid propellant rocket engines)

X67-14913 Generalized steady-state rocket engine performance equations and algorithms of solution. (General equations for constructing mathematical model on steady state liquid propellant rocket engine performance, and algorithms of solution)

X67-22246 Combustion instability analysis at high chamber pressures. (Modification and extension of analytical liquid rocket engine combustion instability model.)

X68-15979 Experimental verification of a double-dead-time model describing chugging in liquid bipropellant rocket engines.

X68-30949 High frequency combustion instability mathematical analysis. Monthly progress report.

X69-17012 An experimental investigation of injection distribution on the stability of hydrogen oxygen engines.

APPENDIX 2 (CONTINUED)

LITERATURE SEARCH ON LIQUID HYDROGEN/OXYGEN
ROCKET PROPULSION SYSTEM RESPONSE

The following bibliography is furnished in response to your request:

A68-21387 (AIAA paper 67-461) M-1 injector development-philosophy and implementation.

A68-23597 The design and manufacture of a liquid hydrogen/oxygen thrust chamber.

A68-28827 Development of high-power rocket engines.

A68-33767 Development of LOX-hydrogen engines for Saturn Apollo launch vehicles.

A69-15064 Design and development of the SEPR HM4 40Kn thrust liquid oxygen/hydrogen rocket motor.

A69-23561 Secondary-injection thrust vector control systems.

A69-31749 Oxidizer injector face configuration for high power variable thrust rocket engine using hydrogen/oxygen propellant.

A69-32759 An analysis of two/phase flow in LH sub 2 pumps for O sub 2/H sub 2 rocket engines.

A69-33345 The SEPR rocket engine - HM4 with liquid oxygen and hydrogen - design and operation.

N68-11043 Effect of combustor parameters on the stability of gaseous hydrogen-liquid oxygen engine.

N68-11044 An experimental on articulate damping in a two-dimensional hydrogen/oxygen combustor.

N68-15879 Design criteria for high-pressure rocket engines.

N68-15939 Development of SEPR-HM4 engine - A40Kn thrust liquid oxygen and hydrogen engine.

N68-21679 Stabilizing effects of several injector face baffle configurations on screech in a 20,000 lb. thrust rocket-thrust hydrogen/oxygen [illegible]

[illegible] Comparative analysis of liquid oxygen-liquid hydrogen [illegible]

[illegible]

APPENDIX 2 (CONTINUED)

N69-33340 Effect of injection element radial distribution and chamber geometry on accoustic mode instability in a hydrogen/oxygen engines.

N69-33584 Analytical performance prediction for high energy spacecraft propellents in the presence of heterogeneous combustion products.

N69-34345 Estimation of the maximum possible pressure in an oxygen-hydrogen engine. (turbopump drive)

Cryogenic ignition of hydrogen and oxygen with Raney Nickel. W.B. Lee. Industrial & Eng. Chem. V6 N1 Mr '67. p59-64.

For all - round propellent performance; 98 per cent H_2 O_2. J.C. Mc Cormick. biblog. Space/Aeronautics 39:101+ Mr '63.

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New combinations of liquid H_2, liquid O_2, flourine, ozone ready for rockets. R.F.Fremed. il. Chem Eng 66:69-74. N2 '59.

Pratt & Whitney picked to build cryogenic rocket engine for late 70's use. H. Taylor. Aerospace Tech 21:15 Ja 15 '68.

Round-up of cryogenic fluids for missile and space propulsion systems. E.L. Mc Candless. SAE J. 68:64-5 S '60.

Theory of liquid propellant rocket combustion instability and its experimental verification. L. Crocco et al. ARS J. 30:159-66 F '60.

This bibliography will be supplemented with a Defense Documentation Center computer search upon receipt.

APPENDIX 2 (CONTINUED)

BIBLIOGRAPHY ON DYNAMIC MATH MODELS OF

PROPULSION SYSTEMS

The following bibliography is furnished in response to your request:

A66-28442 - Probability model for defining explosive yield and spill of liquid propellant.

A66-36889 - Mathematical model of combustion instability in solid propellant rocket engines, noting system dynamic behavior, appearance of limit cycle and effect of large amplitude oscillations on burning rate.

A67-20072 - Nonconventional rocket propulsion systems performance and base environment characteristics evaluated, using separate cold flow and combustion models.

A67-28113 - Model for solid rocket motor instability caused by chamber and propellant combustion characteristics, relating combustion and acoustics instabilities.

A67-39539 - Combustion in solid propellant rocket engines using mathematical model.

A67-41319 - Improvement of high performance liquid fuel rocket engine by optimization of liquid hydrogen/LOX/propulsion mixtures.

A68-15610 - Rocket combustion chamber ignition studied by mass spectroscopy of chemical species.

A68-20743 - Rocket combustion instability studied experimentally using theoretical model characterizing combustion by time lag and interaction index.

A69-18100 - Nonsteady combustion models for gases, liquid fuels and solid propellants, reviewing errors in physics and mathematics.

A69-23806 - Book on rocket propellants covering propulsion fundamentals, liquid, solid and hybrid propellants properties calculations, rocket technology, etc.

A69-32776 - [illegible]

[illegible]

[illegible]

APPENDIX 2 (CONTINUED)

A69-34773 - Chemical relaxation, optimum propellant mixture ratio, combustion chamber pressure, gas jet impulse, mass flow and drive capacity of space propulsion systems.

A70-12007 - Nonlinear combustion instabilities in liquid propellant rockets, considering various combustion models and experimental techniques.

A70-12011 - Three dimensional linear combustion instability in liquid propellant rocket motors using concentrated combustion model, presenting mathematical analysis as boundary value problem.

A70-18671 - Boundary value problems and Cauchy problem considered for mathematical model of turbulent motion in liquid or gas.

A70-20008 - Mathematical model for calculating radiative heat transfer from turbulent diffusion buoyant flame and predicting liquid fuel burning ratio.

AD-502 957 - Combustion model for composite modified low burning rate double base rocket propellants.

AD-505 101 - Mathematical model for combustion tailoring of solid rocket propellants.

AD-842 960 - Analytical model development to study liquid rocket engine combustion instability at high chamber pressures.

AD 845 936 - Absolute reaction rate theory applied to problem of cumulative damage in solid rocket propellants.

AD 851 902 - Analytical model for predicting turbocompressor performance with combined circumferential and radial inlet distortion.

AD 851 905 - Development of turbocompressor rotating stall prediction model.

N66-26000 - FORTRAN II computer program for aerothermodynamic behavior of compact heat exchanger component models for nuclear ramjet and rocket engines based on real gas properties.

N66-32330 - Digital distributed parameter model for computing dynamic response of rocket propellant feed systems to pressure and flow disturbances.

N67-[illegible] - Computer programs for steady-state process and cost optimization of [illegible] flux rear facility heat removal systems using air heat dump.

N67-[illegible] - Test firings and analytical model used to evaluate chemical instability in salircate experiments with LOX gaseous hydrogen combustors.

[illegible] - [illegible] model for operational data of [illegible] based [illegible]

[illegible] - [illegible]

APPENDIX 2 (CONTINUED)

N68-17557 - FORTRAN computer program for predicting aerodynamic and heat transfer characteristics of annular and rectangular gas turbine combustors.

N68-23231 - Analytic model of thermal flow oscillations in heat exchangers for supercritical fluids.

N68-25102 - Double dead-time model for combustion stability analysis in liquid bipropellant rocket engines.

N68-30581 - Mathematical model of cylindrical electric gas dynamic generator.

N68-36861 - Mathematical model for combustion at zero gravity in Spacecraft environments.

N69-10521 - Computer programs for analysis of liquid heat exchangers for convective and radiative systems of ducts and fins.

N69-11891 - Mathematic model describing dynamic behavior of high speed reciprocating compressors.

N69-25539 - Mathematical model for calculating heat exchange capability of tubular spacecraft radiator with meteorite shielding. (AD 683 578)

N69-27561 - Computerized simulation of optimal hydraulic control system with dynamic pressure feedback servovalve for positioning gimbal engine.

N69-31489 - Computer analyzed hydrogen reliquefier cycles for selection of optimal cycle, rates and heat exchangers.

N69-33319 - Analytical model for use in design of pump inlet accumulators for prevention of liquid rocket longitudal oscillation.

N69-39420 - Computer models for inducer system of hydraulic turbine drive for liquid hydrogen.

N69-40186 - Linearized mathematical models of feed system coupled combustion instability of liquid propellant rocket engines.

X64-15681 - Mathematical model for liquid hydrogen propellant temperature rise prediction in reactor in-flight test/Rift/Vehicle - Stratified flow model.

X65-15223 - Digital computer programs to calculate behavior of nozzle and chamber material [illegible] to solid propellant rocket [illegible] environment.

[illegible]

[illegible]

APPENDIX 2 (CONTINUED)

X66-11722 - Mathematical mass spring models of partially filled thin wall propellant tanks.

X66-12015 - Mathematical model for hypergolic ignition and ignition propagation across solid propellant surface in dynamic flow-hypergolic propellant studies.

X66-13777 - Stress analysis mathematical model for tubular thermoelectric generator for isotopic power systems.

X66-21998 - Development and state-of-art in analytical steady-state liquid propellant rocket combustion models.

X66-22572 - Nonlinear model for calculating combustion stability in liquid propellant rocket engines.

X66-23901 - Theoretical propellant combustion model for rapid depressurization effects.

X67-11406 - Mathematical model of hypergolic ignition delay in space-ambient engines.

X67-14913 - General equations for constructing mathematical model on steady state liquid propellant rocket engine performance, and algorithms of solution.

X67-17396 - Analytical model for predicting combustion wave instability characteristics of solid propellants.

X67-18780 - Mathematical model for steady state combustion of solid propellant rocket engine.

X67-18791 - Computer model of solid rocket motor ignition transient.

X68-12281 - Digital computer programs, mathematical models and propulsive system disturbance functions for integrating engine and inlet dynamic controls in turbine engine design.

X68-12882 - Mathematical model for computerized simulation of multiengine, liquid propellant stage by means of linearized engine coefficients.

X68-17523 - Experimental verification of mathematical models for predicting lateral forces induced by secondary injection into rocket engine nozzles.

X68-[illegible] - Analytical model describing steady state combustion of [illegible] for [illegible].

X68-[illegible] - Mathematical development of [illegible] [illegible].

APPENDIX 2 (CONTINUED)

X69-17008 - Mathematical model for solving 3-dimensional combustion instability in liquid propellant rocket engines.

X70-12673 - Combustion stability model of advanced injector for use on high pressure hydrogen oxygen engines.

Approximate but complete model for ignition response of solid propellants. A. D. Baer, N. W. Ryan. AIAA J. v.6, n.5 May 1968 P. 872-7.

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Development of fundamental model of hypergolic ignition in space-ambient engines. T. F. Seamens, M. Vanpee, V. D. Agosta. AIAA J. v.5, n.9 Sept. 1967. p. 1616-24.

Digital computer methods in dynamic-response analyses of turbogenerator units. W. D. Humpage, T. N. Soha. bibliog. flow diags. Inst. E. E. Proc. 114:1115-30 ag'67: Discussion 115:1498-500: Reply. 1500-2 O'68.

Electric space heating with active boundary members. W. K. Roots. bibliog. Inst. EE proc. 114:1018-1019 Jl'67.

Fluid and thermodynamic modeling of nuclear rocket vehicle. D. W. Westerheide, R. C. Erickson, F. P. Kirkland; SAE Paper 690201 for meeting January 13-17, 1969. 11p.

Mathematical model of a packed-bed heat-exchanger reactor for dehydrogeneration of Mathylcyclohexane; comparison of predictions with experimental results. R. D. Hawthorn and others. bibliog. diags. AICHE J 14:69-76 Jan.'68.

Measurement of hydrogen utilization in the blast furnace by steam pulse and oil injection techniques. C. Rhicmond and G. Wilson. diags. Iron and Steel Inst. J. 205:630-6 Jl'67.

Mechanism of heat transfer in a spray column heat exchanger. R. Letan & E. Kehat bibliog. diag. AIAA J. 7:497-502 Mr. '69.

Optimization and design of fin-tube heat exchangers by experiment and computer technique. T. F. Joyce. Inst. Heating and Vent Engrs. J. V. 35 Apr. 1967. p. 8-16.

Testing of polymeric materials for use in multiply-impulse bladders for [illegible] liquids. [illegible] and J. [illegible] [illegible] 5:253-64 Mr. '68.

Theory for [illegible] and drill [illegible] of fast [illegible] [illegible] [illegible] [illegible] [illegible]

[illegible]

APPENDIX 3

PROGRAMS FOR POTENTIAL USE

PROGRAM NO.	PROGRAM NAME	DESCRIPTION
F MSF 554070	Heat Exchanger	S.S. performance at specified intervals along heat exchanger tubes.
F MSF 554630	Heat Transfer to a Spherical Container	Transients for sphere with cryogenic gas.
F MSF 545420	Heat Transfer Sphere	Gas inside a spherical container.
F MSF 566030	SIV Pump Cooling	Heat-up and chill-down characteristics for turbopumps.
H MSC H080	Tank Pressurization Program	Gas pressures, volume, weight.
H MSC H094	Propellant Feedline Heat Exchanger	S.S. heating of a gas by a liquid.
H MSC H095	Analysis of Propellant Tank Pressurization	Liquid propellant tank thermodynamics.
H MSC H116	Axisymmetric Two-Phase Perfect Gas Program	Propellant systems having both gaseous and condensed exhaust products.
H MSC H120	Lunar Module Reaction Control System Engine Injector	Simulates Fluid Dynamics. Requires analog/digital computer.
B MSC B086	Fifth Order Runge-Kutta Integration Subroutine	1st order differential eqs.; 25 simultaneous eqs; variable step size.
B MSC B120	Newmca Real Root Approximation Subroutine	Newton-Rhapson
B MSC B122	Non-Linear Simultaneous Equations Solver	Solves system on non-linear eqs. without using derivatives
F MSC [illegible]	Spacecraft ECS Heat Exchanger Program	Gas to gas heat exchanger.
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

APPENDIX 3 (Cont'd)

PROGRAM NO.	PROGRAM NAME	DESCRIPTION
M70-10069	Computer Programs for the Design & Performance Analysis of Compact Multi-Fluid Heat Exchanger	Parallel, counter, multi-fluid cross flow; plates/fin configuration.
M69-10241	Radial Turbine Syntehetic (sic) Mapping Program	Provides method of calculating an estimated radial turbine performance map when turbine geometry, inlet conditions, and gas properties are known
MSF-443	Solution of Compressible Flows in Piping Systems	Description not available.
MSF-2129	Heat Exchanger Program	Not Available.
NUC-10328	Actuation Timing of a Linear Actuated Valve	Not Available.
NUC-10189	Transient and/or Steady State Thermal Analysis with Coupled Fluid Flow and Heat Conduction	Not Available.
MSF-1675	Orifice Sizing for Fluid Systems	Not Available.
MSF-3602[illegible]	Heat Transfer and Thermal Problems	Transient, compressible, subsonic.
F MFC 158	Generalized Explicit Two-Phase Flow Finite Difference Generalized Heat Exchanger	Apollo fuel cells.
MSF-584	Computer Program for the Prediction of Flow Distribution in a Ring Injector	Not Available.
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

APPENDIX 3 (Cont'd)

PROGRAM NO.	PROGRAM NAME	DESCRIPTION
H NAA APD 153	RCS Steady State Analysis	Flow rate, pressure drops, engine performance.
J MSC J067	Design and Performance Analysis of Compact Heat Exchangers	Description not available.
J MSC J071	Fan, Blower, and Pump Design	Predicts performance curves, size, and wt. required to operate at a given set of design point conditions.
H NAA AP 237	SPS Feed Lines	Description not available.
J MSC J197	Optimization/Evaluation of Fans, Compressors, and Pumps	Description not available.
F MSC F231	Oxygen Cryogenics Program	Description not available.
F MSC F246	Nuclear Shuttle Hydrogen Tank Program	Description not available.

APPENDIX A

UNAVAILABILITY OF PROGRAM DOCUMENTATION REQUESTED FROM THE ADP PROGRAM SHARING LIBRARY

Four of the computer program descriptions requested were not available for one or more of the following reasons:[1]

No formal documentation was prepared.
Personnel turnover caused incomplete programs or documentation.
Program is now obsolete and documentation on it has been destroyed.
Program was not perfected and therefore withdrawn from circulation.

The ADP Program Sharing Library was unable to say which reason applied to to the following programs:

F MSF 554070	Heat Exchanger (cancelled December 6, 1969)
F MSC F 192	Spacecraft ECS Heat Exchanger Program (cancelled February 9, 1970)
F MSF 360 380	Duct Flow FL/D, Q, DA (project probably not completed)
F MSF 361 440	Transient Start-up (cancelled December 6, 1969)

[1] Queries were directed to the cognizant MSC personnel as to what individual determined the status of a given program (i.e., as to whether it was "Obsolete" or not, etc.). MSC's reply to this question was - we do not have this information and cannot obtain it.

APPENDIX 5

APS TRANSIENT COMPUTER PROGRAM LISTING

```
[illegible],[illegible],3198P,F2C6,C,5,5                    PRINGLE,R.W.
[illegible] REQ.  TAPE  1 FH432 4   FSTRN  2

[illegible]
[illegible]
[illegible]          FOR  PIPE,PIPE
[illegible]
[illegible]
[illegible]KAY1,KAY2,KAY3,KAY4,KAY5,KAY6,KAY7,KAY8,KAY9,KAY10
[illegible]LPHA(20),BK(2),DELXL(20),EL(2),TH(20),XLENGL(20),ZO(20)
[illegible]TEMPS(2,6)
[illegible]AL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
[illegible]JUNCL(10,3),IPB(10),LVDN(10),LVUP(10),NODEL(20),
[illegible](20),PL(20,100),PTEMP(20,100),RHOL(2),SINALP(20),THETA(20),
[illegible](20,100),HTEMP(20,100),XK(20),Z(20,100)
[illegible]/AREA(6,2),AREAC(6),CSTAR(6),CV(6,2),DELTF,DWCHAM(6),
[illegible],IENO,KAY,KAY1,KAY2,KAY3,KAY4,KAY5,KAY6,KAY7,KAY8,KAY9,
[illegible],NCHAM(6),RGAS(6,2),RGASC(6),TEMPC(6),TGAS(6,2),
[illegible],WCHAM(6),WNOZ(6),WSWDOT(6)
[illegible]/ALPHA,AREA,AREAC,BK,CSTAR,CV,DELT,DELTF,DIAL,EL,
[illegible],G,GC,ICHAM,IEND,IFBL,IJUNCL,IPB,KAY,LVDN,LVUP,NCHAM,
[illegible]C,NPBL,NPIPL,NPLINE,NVALL,PZOO,RGAS,RGASC,RHOL,
[illegible],TIMEND,XLENGL,VOLC,ZO
[illegible],I=1,17)/5HNODEL,4HIEND,3HIPB,4HLVDN,4HLVUP,6HNPLINE,
[illegible],4HIFBL,5HAREAL,2HCL,4HDIAL,3HFRL,6HSINALP,5HTHETA,2HPL,
[illegible]
[illegible] (6HDECKEN,12,60,5,6)
[illegible]DATA
[illegible]ATIONS
```

NOT REPRODUCIBLE

```
      OL(II)
      (II)/DELX +1.
      (II)/(NODEL(II) -1.)
      3.14159927 * DIAL(II)**2/4./144.
      SIN (ALPHA(II)/57.295780)
      DELXL(II)
      (JJ-1)*DELXL(II)*SINALP(II)

      STARTING CONDITIONS - TEMPORARILY BASED ON STARTING .
      - PRESSURE IS SPECIFIED AT LOWEST POINT IN

      -1287.3469
      - G/GC *RHOL(IPROP) *Z(II,JJ)

      ((PL(I,J),I=1,NPIPL),J=1,NNODEL)
      ((XDOTL(I,J),I=1,NPIPL),J=1,NNODEL)
      NJUNC( ,NFBL,IPROP,NCHAM,DELT,G,GC,
      SK(1),SK(2),DELTF,TIMEF
      (NODEL(I),I=1,NPIPL)
      I=1,NPIPL)
      I=1,NPIPL)
      I=1,NPIPL)
      I=1,NPIPL)
```

```
[illegible] (NPLINE(I),I=1,NPIPL)
[illegible] GO TO 45
[illegible] (IJUNCL(I,J),J=1,3),I=1,NJUNCL)

[illegible] GO TO 46
[illegible] (IPPL(I),I=1,NPBL)

[illegible] (AREAL(I),I=1,NPIPL)
[illegible] (CL(I),I=1,NPIPL)
[illegible] (DIAL(I),I=1,NPIPL)
[illegible] (FRL(I),I=1,NPIPL)
[illegible] (SINALP(I),I=1,NPIPL)
[illegible] (THETA(I),I=1,NPIPL)
[illegible] (EL(I,J),I=1,NPIPL),J=1,NNODEL)
[illegible] (NOUTL(I,J),I=1,NPIPL),J=1,NNODEL)
[illegible] (X(I,J),I=1,NPIPL),J=1,NNODEL)

[illegible] DELT
[illegible]
[illegible]

[illegible] GO TO 33
[illegible]
[illegible]

[illegible] GO TO 34
[illegible]
[illegible]

[illegible] GO TO 36
[illegible]

[illegible] GO TO 38
```

NOT REPRODUCIBLE

```
      [illegible] GO TO 61
      [illegible] I=1,NCHAM
      [illegible]
      [illegible] I=1,NN
      [illegible] (I,DELTF,TIMEF,WCHAM,DWCHAM,CHAM,TEMPS)
      [illegible]
      [illegible]
      [illegible] II=1,NPIPL
      [illegible] = NODEL(II)
      [illegible] JJ=1,NNODEL
      [illegible] WTEMP(II,JJ)
      [illegible] = PTEMP(II,JJ)
    [illegible]
      [illegible] = NODEL (NPIPL)
      [illegible] (8) 101,NW1,TIME,((PL(I,J),I=1,NPIPL),J=1,NNODEL)
      [illegible] (9) 103,NV3,TIME,((NDOTL(I,J),I=1,NPIPL),J=1,NNODEL)
      [illegible] 300)TIME,TIMEF
      [illegible] 500)NAME(15),((PL(I,J),I=1,NPIPL),J=1,NNODEL)
      [illegible] 500)NAME(16),((NDOTL(I,J),I=1,NPIPL),J=1,NNODEL)
      [illegible] .GT. TIMEND) GO TO 50
      [illegible] 2
   50 [illegible]
      [illegible] FILE 0
      [illegible]
      [illegible] 'CNPIPL =',I4,' NVALL =',I4,' NPBL =',I4,' NJUNCL =',I4,' N
      [illegible] I4,' IPROP =',I4,' NCHAM =',I4/' DELT =',E14.8,' G =',E14.8
      [illegible] =',E14.8,' DELX =',E14.8,' TIME =',E14.8/' RHOL(1) =',E14.8,
      [illegible] =',E14.8,' BK(1) =',E14.8,' BK(2) =',E14.8,' DELTF =',
      [illegible] TIMEF =',E14.8)
   [illegible] ',2016/(10X,2016))
   [illegible] ',8E14.8/(10X,8E14.8))
   [illegible] TIME =',E14.8,' TIMEF =',E14.8)
      [illegible]
```

```
C*C          FOR CHAM,CHAN
      CHAM,CHAM
      DIMENSION CHAM
      KAY,KAY1,KAY2,KAY3,KAY4,KAY5,KAY6,KAY7,KAY8,KAY9,KAY10
      DIMENSION C(6,2),C1(6,2),C6(6,2),C7(6,2),C8(6,2),C9(6,2),C10(6,2),
     CELP(6,2),CELP(6,2),PCRIT(6,2),PRAT(6,2)
      DIMENSION AREAL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
     (10),IRUNCL(10,3),IPD(10),LVOM(10),LVUP(10),NODEL(20),
     (20),PL(20,100),PTEMP(20,100),RHOL(2),SINALP(20),
     (20),TIME,VDOTL(20,100),WTEMP(20,100),XK(20),Z(20,100)
     CHAMBR/AREA(6,2),APEAC(6),CSTAR(6),CV(6,2),DELTF,DHCHAM(6),
     (6,2),IESG,KAY,KAY1,KAY2,KAY3,KAY4,KAY5,KAY6,KAY7,KAY8,KAY9,
     (2),PCHAM(6),RGAS(6,2),RGASC(6),TEMPC(6),TGAS(6,2),
     (6),WCHAM(6),WNUZ(6),WSWDOT(6)
     COMMON/VALVES/ARHO,GRHO,WR,ZRPR,WS,ZS,PS
      DO 8 I=
      DO(I,1)
      IF(I.EQ.0
      DO 1 I=1,NVLC
      IF(IPROP.EQ.0)
      DO 1 J=1,
      IF(IPROP.EQ.1)
      IF(WR.GT.0.0)
      IF(I.EQ.1.AND.J.EQ.1.AND.IPROP.
      AREAL(II)/CL(II)*(G*RHOL(IPROP)*Z(II,JJ)-GC*PR*144.-G*
     (IPROP)*PR)+G/CL(II)*WR*SINALP(II)*DELTF+FRL(II)*WR*ABS(WR)/
     (II)*12./RHOL(IPROP)/AREAL(II)*DELTF
      AREAL(II)/CL(II)*144.*GC
      ELSE...
      (I)=WCHAM(I)*RGASC(I)*TEMPC(I)/VOLC(I)*12.
      (I)=PCHAM(I)*AREAC(I)*GC/CSTAR(I)
      IF(PRESS RATIO GE CRIT, USE SONIC FLOW 1ST GUESS...
      DO 88
      DO 88 N=1,2
      (I,N)=AREAC(I,N)*CV(I,N)*SQRT(GC*KAY/(RGAS(I,N)*TGAS(I,II)))
      ENDIF
      ELSE...
      (I,N)=CL(II,N)*PL(II,JJ)-PL(II,JJ)*C6(I,N)*SQRT(KAY10*((
      (II,JJ)**KAY9-(PCHAM(I)/PL(II,JJ))**(KAY2/KAY)))
      (I,N)*SQRT(KAY10)
      (I)/PL(II,JJ)
```

```
[illegible]*[illegible](C9(I,N)**KAY9-C9(I,N)**(KAY1/KAY))
[illegible] PRESS EQUATION ONE ABOVE AND PERFORM N/R ITERATIONS
[illegible](I,N)-C8(I,N)*C10(I,N)-PL(II,JJ)*C8(I,N)/2./C10(I,N)*
[illegible](II,JJ)*(KAY9*(C9(I,N))**KAY8-KAY6*(C9(I,N))**KAY7)
[illegible]-[illegible](I,N)/DELP(I,N)
[illegible](I,N)),LE.0.001)GO TO 25
[illegible]PL(II,JJ)-DELP(I,N)
[illegible]
[illegible]
[illegible](II,JJ)=C(I,N)-C1(I,N)*PL(II,JJ)
[illegible](II,JJ)=WTEMP(II,JJ)
[illegible]
[illegible]
[illegible]AREA(I,N)*CV(I,N)*SQRT(GC/(RGAS(I,N)*TGAS(I,II))*
[illegible]
[illegible] LINE PRESSURES FOR SONIC FLOW
[illegible]C(I,N)/(C1(I,N)*WTEMP(II,JJ))
[illegible] SONIC FLOW ASSUMPTION CORRECT
[illegible]KAY5
[illegible]C10(I)/PTEMP(II,JJ)
[illegible].GE.PCRIT(I,N))GO TO 23
[illegible]
[illegible]TL(II,JJ)+WSNDOT(I)
[illegible]
[illegible]SNDOT(I)-WNDZ(I)
```

NOT REPRODUCIBLE

```
          FOR CR2TAP,CR2TAP
        CR2TAP,CR2TAP
 DEFINE CR2TOP (IOPTRM,INDATA,IMAGES,INSYS,IOSYS)
 ALL PARAMETERS ARE ---                                                 CR2T0001
 IOPTRM - CARD TO TAPE OPERATION TERMINATOR.  EXPECTED IN COLUMNS       CR2T0002
          1 THRU 6.                                                     CR2T0003
 INDATA - NUMBER OF I/O DEVICE TO PUT CARD IMAGES ON.                   CR2T0004
 IMAGES - NUMBER OF CARD IMAGES PER PRINTED PAGE, NORMALLY NUMBER       CR2T0005
          OF LINES PER PAGE - 3.                                        CR2T0006
 INSYS  - SYSTEM INPUT TAPE.                                            CR2T0007
 IOSYS  - SYSTEM OUTPUT TAPE.                                           CR2T0008
 DIMENSION                    IDATA (14)                                CR2T0011
 DATA(A,B,C)                                                            CR2T0012
 (1H1,2H,*,13A6,A2,1H*)                                                 CR2T0013
 (1H1,* CARD COL. 17,T110/7H   NO.*,8(10H1234567890),1H*)               CR2T0014
 (1H   NO.*,8(10H1234567890),1H*/1H1)                                   CR2T0015
 (1H   NO.*,8(10H1234567890),1H*)                                       CR2T0016
 INITIALIZE CARD COUNTER...

 READ THE ALTERNATE INPUT DATA FILE...                                  CR2T0017
 READ INDATA                                                            CR2T0018
 THIS SUBRT PRELIMINARY TO WRITING THE RECORDS IN THE CARD              CR2T0019
 IMAGE FORMATION PLUS COLUMN INDICATORS...                              CR2T0020
 DO 10                                                                  CR2T0021
 WRITE (IOSYS,30) (I,I=1,8)                                             CR2T0022
 I = 1 , IMAGES                                                         CR2T0025
 READ INPUT DATA CARD...                                                CR2T0026
 READ(INDATA,40) (IDATA(J),J=1,14)                                      CR2T0027
 IF END OF THE ALTERNATE DATA INPUT FILE...                             CR2T0028
 IF (EOF,DATA,10) (IDATA(J),J=1,14)                                     CR2T0029
 IF IOPTRM TEST...                                                      CR2T0032
 IF (IDATA,60) 99,(IDATA(J),J=1,14)

 IF IOPTRM TERMINATOR, CEASE PROCESSING...                              CR2T0034
 IF (IOPTRM) GO TO 80                                                   CR2T0035
                                                                        CR2T0036
 WRITE LINE...                                                          CR2T0037
 WRITE(IOSYS,50)                                                        CR2T0038
                                                                        CR2T0041
                                                                        CR2T0042
```

```
[illegible] TRAILER LINE...                                          CR2T0043
[illegible]                                                          CR2T0044
[illegible] FILE ALTERNATE INPUT DATA FILE...                        CR2T0047
[illegible] FILE INDATA                                              CR2T0048
[illegible] ALTERNATE INPUT DATA FILE...                             CR2T0049
[illegible] INDATA                                                   CR2T0050
[illegible]                                                          CR2T0051
                                                                     CR2T0052
```

```
C          FOR FBL,FBL
[illegible]
[illegible] FBL(I)
[illegible] AREAL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
[illegible],IJUNCL(10,3),IPB(10),LVDN(10),LVUP(10),NODEL(20),
[illegible],PL(20,100),PTEMP(20,100),RHOL(2),SINALP(20),THETA(20),
[illegible](20,100),WTEMP(20,100),XK(20),Z(20,100)
[illegible]/[illegible]/[illegible],ARHO,WR,ZR,PR,WS,ZS,PS
[illegible]
[illegible]
[illegible] GO TO 8
[illegible]
[illegible]
[illegible] (II,JJ,IPROP)
[illegible]/CL(II) *(G *RHOL(IPROP)*Z(II,JJ) -GC*PS*144.
[illegible]*ZS) -G/CL(II)* WS* SINALP(II)*DELT  +
[illegible] WS*ABS(WS)*DELT/2./DIAL(II)/RHOL(IPROP)/AREAL(II)
[illegible]
[illegible]*GC*144./CL(II)
[illegible]
[illegible] = -C1/C2 -W/C2
[illegible]
[illegible]
[illegible]
[illegible] = [illegible]
[illegible](II,JJ,IPROP)
[illegible]/CL(II)* (G* RHOL(IPROP)*Z(II,JJ) -GC*PR*144.
[illegible]*ZR)  +G/CL(II)*WR *SINALP(II) *DELT  +
[illegible]*ABS(WR)/2./DIAL(II)*12./RHOL(IPROP)/AREAL(II)
[illegible]
[illegible]*CL/CL(II)*144.
[illegible] = -C3/C4 -W/C4
[illegible]
```

```
[illegible]          FOR INTERP,INTERP
[illegible] INTERP,INTERP
[illegible] INTERP (DEPTAB,INDTAB,IB,NP,INDP,DEPP)
[illegible] INDTAB,INDP
[illegible] DEPTAB(1,1),INDTAB(1,1)
[illegible] .LT. INDTAB(IB,1) .OR. INDP .GT. INDTAB(IB,NP)) GO TO 50
[illegible] NP
[illegible] .GT. INDTAB(IB,K)) GO TO 10
[illegible] INDP - INDTAB(IB,K)) .LE. 1.0E-6) GO TO 20
[illegible] INDP - INDTAB(IB,K-1)) .LE. 1.0E-6) GO TO 30
[illegible] = INDTAB(IB,K) - INDTAB(IB,K-1)
[illegible] = INDP - INDTAB(IB,K-1)
[illegible] = DEPTAB(IB,K) - DEPTAB(IB,K-1)
[illegible] = DEPTAB(IB,K-1)
[illegible] = BIGY * SMLX / BIGX + SMLY
[illegible]
[illegible]
[illegible]
[illegible]
[illegible] DEPTAB(IB,K)
[illegible]
[illegible]
[illegible] = DEPTAB(IB,K-1)
[illegible]
[illegible]
[illegible]
[illegible] INDTAB(IB,1),INDTAB(IB,NP),INDP
[illegible] THE LIMITS OF THE INDEPENDENT TABLE, WHICH ARE ',2E16.8/
[illegible] EXCEEDED BY THE INDEPENDENT CALLING PARAMETER WHOSE VALUE 1
[illegible] THE DEPENDENT VARIABLE WAS SET EQUAL TO ZERO.')
[illegible]
[illegible]
[illegible]
```

NOT REPRODUCIBLE

```
[illegible]          FOR JUNCL,JUNCL
[illegible] JUNCL
[illegible] JUNCL(I)
[illegible] CN(3),CD(3)
[illegible] AREAL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,TEND(10),
[illegible] JUNCL(10,3),IPS(10),LVON(10),LVUP(10),NODEL(20),
[illegible] (20),PL(20,100),PTEMP(20,100),RHCL(2),SINALP(20),THETA(20),
[illegible] (20,100),WTEMP(20,100),XK(20),Z(20,100)
[illegible] ALUES/GRHO,ARHO,WR,ZR,PR,WS,ZS,PS
[illegible]
[illegible] (I,J)
[illegible] .GT. 0) GO TO 4
[illegible]
[illegible]
[illegible]
[illegible] (II,JJ,IPROP)
[illegible] S-AREAL(II)/CL(II) *(G *RHOL(IPROP)*Z(II,JJ) -GC*PS*144.
      [illegible] RHOL(IPROP)*ZS) -G/CL(II)* WS* SINALP(II)*DELT  +
       [illegible] WS*ABS(WS)*DELT/2./DIAL(II)/RHOL(IPROP)/AREAL(II)
       *12.
[illegible] AREAL(II)*GC*144./CL(II)
[illegible]
[illegible]
[illegible]
[illegible] (II,JJ,IPROP)
[illegible] AREAL(II)/CL(II)*(G*RHOL(IPROP)*Z(II,JJ)-GC*PR*144.
      [illegible] RHOL(IPROP)*ZR)  +G/CL(II)*WR *SINALP(II) *DELT  +
      [illegible] WR *ABS(WR)/2./DIAL(II)*12./RHOL(IPROP)/AREAL(II)
      [illegible] DELT
[illegible] GC/CL(II)*144.
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible] (I,J)
```

```
[illegible] GO TO 11
[illegible]

[illegible] = -[illegible] -CD(J)*P
[illegible] = P
[illegible]
[illegible]
[illegible]
[illegible] = -[illegible] -CD(J)*P
[illegible] =P
[illegible]
```

```
[illegible]          FOR  PBL,PBL
[illegible]  PBL,PBL
[illegible] PBL(I)
[illegible] AREAL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
[illegible],IJUNCL(10,3),IPA(10),LVON(10),LVUP(10),NODEL(20),
[illegible],PL(20,100),PTEMP(20,100),RHOL(2),SINALP(20),THETA(20),
[illegible],20,100),WTEMP(20,100),XK(20),Z(20,100)
[illegible] VALUES/ORHO,ARHO,WR,ZR,PR,WS,ZS,PS
[illegible] IS TABLE OF PRPBL(IPO,I) VS TIPBL(IPB,I), NPBL IS THE
[illegible] OF POINTS IN THE TABLE
[illegible]
[illegible] = 100.0
[illegible]
[illegible] GO TO 11
[illegible]
[illegible] (II,JJ,IPROP)
[illegible] = [illegible]*AREAL(II)/CL(II)*(GC*PTEMP(II,JJ)*144.+G*RHOL
     (IPROP)*Z(II,JJ)-GC*PS*144.-G*RHOL(IPROP)*ZS)+G*WS/
     CL(II)*SINALP(II)*DELT-FRL(II)*WS*ABS(WS)*DELT/2./
     ARHO/DIAL(II)*12.
GO TO 12
[illegible]
[illegible]
[illegible] = 14.7
[illegible] (II,JJ,IPROP)
[illegible] = WR -AREAL(II)/CL(II) *(GC*PTEMP(II,JJ)*144.  +
     G * RHOL(IPROP) * Z(II,JJ) - GC * PR * 144. - G * RHOL(IPROP)
     [illegible] - G * WR / CL(II) * SINALP(II) * DELT - FRL(II) * WR *
     [illegible] * DELT / 2. / ARHO / DIAL(II) * 12.
[illegible]
[illegible]
```

```
[illegible] FOR PIPEL,PIPEL
[illegible] PIPEL
[illegible] PIPEL (II)
[illegible] AREAL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
[illegible] (10,3),IPB(10),LVDN(10),LVUP(10),NODEL(20),
[illegible] (20,100),PTEMP(20,100),RHOL(2),SINALP(20),THETA(20),
[illegible] (20,100),WTEMP(20,100),XK(20),Z(20,100)
[illegible] GRHO,ARHO,WR,ZR,PR,WS,ZS,PS
[illegible]
[illegible] NODEL(II) - 1
[illegible]
[illegible] IPROP)
[illegible] = 0.5 * (WR+ WS + AREAL(II)/CL(II) * (GC *PR*144. +
[illegible] IPROP)*G*ZR - GC*PS*144. - RHOL(IPROP)*G*ZS) -
[illegible] * DELT* SINALP(II) *(WR-WS) - FRL(II)*DELT/2.
[illegible] *12./ARHO * (WR *ABS(WR) + WS *ABS(WS)))
[illegible] = 0.5*(PR+GRHO*ZR+PS+GRHO*ZS+CL(II)/GC/AREAL(II)*
[illegible] -DELT*G/GC/AREAL(II)*SINALP(II)*(WR+WS)/144.-CL(II)*
[illegible] /GC/2./DIAL(II)*12./ARHO/AREAL(II)*(WR*ABS(WR)-WS*
[illegible] /144.)-GRHO*Z(II,JJ)
[illegible]
```

```
C          FOR VAL,VAL
[illegible] VAL,VAL
[illegible] VAL (II,JJ,IPROP)
[illegible] AREAL(20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
[illegible] (JUNCL(10,3),IPB(10),LVDN(10),LVUP(10),NODEL(20),
[illegible] (20),PL(20,100),PTEMP(20,100),RHOL(2),SINALP(20),THETA(20),
[illegible] (20,100),WTEMP(20,100),XK(20),Z(20,100)
[illegible] /GRHO,ARHO,WR,ZK,PR,WS,ZS,PS
[illegible] (IPROP)/GC/144.
[illegible] (IPROP) * AREAL(II)
[illegible] (II,JJ) - THETA(II) * CL(II) * (WDOTL(II,JJ) - WDOTL(II
[illegible] / (1. - THETA(II) * (WDOTL(II,JJ) - WDOTL(II,JJ+1))/
[illegible] (IPROP) / AREAL(II))
[illegible] (THETA(II)*(WS/ARHO -CL(II))*(Z(II,JJ) -Z(II,JJ+1))
[illegible] CL(II,JJ) + GRHO * Z(II,JJ) + THETA(II) * (WS/ARHO - CL(II))
[illegible] + GRHO * Z(II,JJ) - PL(II,JJ+1) - GRHO* Z(II,
[illegible] - GRHO*ZS
[illegible] (II,JJ) - THETA(II) * CL(II) * (WDOTL(II,JJ) - WDOTL(II
[illegible] / (1. + THETA(II) * (WDOTL(II,JJ) - WDOTL(II,JJ-1))/
[illegible] (IPROP) / AREAL(II))
[illegible] -THETA(II)*(WR/ARHO +CL(II))*(Z(II,JJ) -Z(II,JJ-1))
[illegible] + GRHO * Z(II,JJ) - THETA(II) * (WR/ARHO + CL(II))
[illegible] + GRHO * Z(II,JJ) - PL(II,JJ-1) - GRHO* Z(II,
[illegible] - GRHO * ZR
[illegible]
[illegible]
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[illegible]          FOR VALVEL,VALVEL
[illegible]VALVEL,VALVEL
[illegible] VALVEL (I)
[illegible] [illegible](20),CL(20),DELT,DIAL(20),FRL(20),G,GC,IEND(10),
[illegible] [illegible](10,[illegible]),IPR(10),LVDN(10),LVUP(10),NODEL(20),
[illegible],PL(20,100),PTEMP(20,100),RHCL(2),SINALP(20),THETA(20),
[illegible](20,100),WTEMP(20,100),XK(20),Z(20,100)
[illegible]VALUES/[illegible],ARHO,WR,ZR,PR,WS,ZS,PS
[illegible]

[illegible] NOLINE(II)
[illegible] [illegible](II,JJ,IPROP)
[illegible] [illegible]/CL(II) *(G *RHOL(IPROP)*Z(II,JJ) -GC*PS*144.
[illegible] RHOL(IPROP)*ZS) -G/CL(II)* WS* SINALP(II)*DELT  +
[illegible](II)* WS*ABS(WS)*DELT/2./DIAL(II)/RHOL(IPROP)/AREAL(II)
[illegible]
[illegible](II)*GC*144./CL(II)
[illegible]
[illegible] NODEL(II)
[illegible] (II,JJ,IPROP)
[illegible] AREAL(II)/CL(II)* (G* RHOL(IPROP)*Z(II,JJ) -GC*PR*144.
[illegible] RHOL(IPROP)*ZR)  +G/CL(II)*WR *SINALP(II) *DELT  +
[illegible] *ABS(WR)/2./DIAL(II)*12./RHOL(IPROP)/AREAL(II)
[illegible]
[illegible]*GC/CL(II)*144.
[illegible] * 2 * 2. * GC * RHOL(IPROP) * 144. * (1. / C4 - 1. /
[illegible]
[illegible]RHOL(IPROP)*144.0*(C5/C4-C1/C2)*XK(I)**2
[illegible] 0.0) GO TO 3
[illegible] =  -C5/2.0 + SQRT(C5**2 -4.0*C6)/2.0
[illegible]
[illegible]
[illegible] =  C5/2.0 - SQRT(C5**2 + 4.0*C6)/2.0
[illegible]
[illegible] =WTEMP(II,JJ)/C4 - C3/C4
[illegible]
[illegible]

[illegible]
[illegible] = - WTEMP(II,JJ)/C2 - C1/C2
```

NOT REPRODUCIBLE

[illegible]

[illegible]OUST
[illegible] OF PL NODE 1

[illegible]OUST
[illegible] OF PL NODE 7

[illegible]OUST
[illegible] OF PL NODE 14

[illegible]OUST
[illegible] OF WDOTL NODE 1
[illegible]OTL

[illegible] OF WDOTL NODE 7
[illegible]OUST

[illegible]OUST
[illegible] OF WDOTL NODE 14

NOT REPRODUCIBLE