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FINAL REPORT

ALL METAL EXPULSION SYSTEM
USING VOLATILE LIQUID
PRESSURIZATION

11 OCTOBER 1968

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TRW
SYSTEMS GROUP



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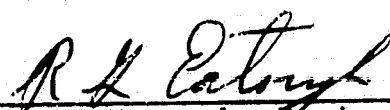
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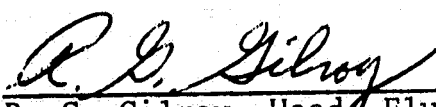
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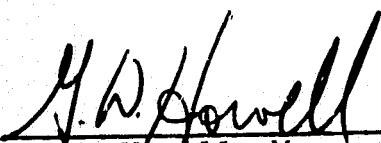
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FOREWORD

This report describes the work conducted by TRW Systems for NASA-MSC under Contract NAS 9-4550 and covers the period from 21 July 1965 through 21 June 1968. Mr. Richard Eatough was the TRW Program Manager. Mr. Darrell Kendrick of NASA Manned Spacecraft Center was the NASA Technical Representative on this program.

ABSTRACT

This report documents the design, development, fabrication, and testing of two flight-weight volatile liquid all-metal expulsion systems. Volatile liquid expulsion pressurization provides an improved method of expelling storable propellants for RCS engines by eliminating the need for a pressurant high pressure storage and distribution capability. The system utilizes the energy resulting from the phase change of a volatile liquid caused by a controlled heat input. Parameters to consider in volatile liquid selection and system design are presented. Typical test expulsion characteristics of subscale and flight-weight systems are described.

CONTENTS

	<u>PAGE</u>
1.0 INTRODUCTION	1-1
2.0 SUMMARY	2-1
3.0 SYSTEM DEFINITION	3-1
3.1 Volatile Liquid System Operation	3-1
3.2 Pressurant Material Selection	3-4
3.3 Heat Source Control System	3-4
4.0 PROPELLANT TANK	4-1
4.1 Tank Design	4-1
4.2 Tank Assembly Fabrication	4-13
5.0 COMPONENT EVALUATION	5-1
5.1 Expulsion Tank	5-1
5.2 System A Heat Control System	5-1
6.0 LOADING METHODS INVESTIGATION	6-1
6.1 Pressurant Loading	6-1
6.2 Heat Storage Material Loading	6-4
7.0 SUBSCALE TEST PROGRAM	7-1
7.1 Test Materials	7-3
7.2 Test Procedure	7-3
7.3 Freon 22 Expulsion Tests	7-8
7.4 Genetron 32 and Heat Storable Material Expulsion Tests	7-14
7.5 Application of Subscale Test Results	7-30
8.0 PRESSURIZATION SYSTEM DEMONSTRATION TESTING	8-1
8.1 Test Procedure	8-3
8.2 Simulated Propellant Testing	8-7
8.3 Propellant Testing	8-45
8.4 Test Problems	8-64

CONTENTS - Continued

	<u>PAGE</u>
9.0 AUXILIARY PROPULSION SYSTEM DEMONSTRATION	9-1
9.1 Test Procedure	9-5
9.2 System B Auxiliary Propulsion System Tests	9-13
9.3 System A Auxiliary Propulsion System Tests	9-23
10.0 CONCLUSIONS AND RECOMMENDATIONS	10-1
REFERENCES	R-1

LIST OF ILLUSTRATIONS

<u>FIGURE</u>	<u>PAGE</u>
3-1 Pressurant Material Comparison	3-5
3-2 External Heat Storage Schematic	3-9
3-3 Transistor Switch Schematic	3-11
4-1 Tank Assembly - Specification Drawing	4-2
4-2 Tank Assembly Design Drawing	4-3
4-3 Pressurant Thermodynamic Diagram	4-8
4-4 Heat Exchanger Configuration	4-8
4-5 System B Oxidizer Tank in Holding Fixture	4-14
4-6 Micro Photo Outside Diameter Weld Bead	4-15
4-7 Micro Photo Inside Diameter Weld Bead	4-15
4-8 Bellows Capsule Assembly	4-16
4-9 Failure of System A Fuel Tank Shell During Leak Check	4-19
4-10 Proof Pressure Failure System A Oxidizer Tank	4-20
4-11 Corrosion Damage on System A Oxidizer Tank	4-22
4-12 Nylon Guide Buttons, Bellows Capsule	4-24
5-1 Location of Weld Configuration Test Samples	5-2
5-2 Closure Weld Tensile Specimen-Failure in Parent Metal	5-3
5-3 Closure Weld Tensile Specimen-Failure in Weld	5-3
5-4 Bellows Segment Load Compression Curve	5-8
5-5 Bellows Test Cycling Fixture	5-9
5-6 Bellows Configuration During Fill Cycle	5-9
5-7 Bellow Capsule Internal Differential Pressure Test	5-10
5-8 Flow Rate Curves Heat Exchanger Bypass Valve	5-13
7-1 Experimental Test Hardware	7-2
7-2 Experimental Test Setup	7-4
7-3 Experimental Test Schematic	7-6
7-4 Continuous Flow Expulsion Characteristics, High Flow With Heat	7-9
7-5 Freon 22 Continuous Flow Expulsion Characteristics, High Flow Without Heat	7-10
7-6 Freon 22 Continuous Flow Expulsion Characteristics, Low Flow With Heat	7-11

<u>FIGURE</u>		<u>PAGE</u>
7-7	Freon 22 Continuous Flow Expulsion Characteristics, Low Flow Without Heat	7-12
7-3	Freon 22 Pulsing Flow Expulsion Characteristics, 4lb 5 oz Freon 22	7-13
7-9	Freon 22 Pulsing Flow Expulsion Characteristics, High Flow	7-15
7-10	Freon 22 Pulsing Flow Expulsion Characteristics, Low Flow	7-16
7-11	Continuous Flow Expulsion Characteristics 1.8 lb Genetron 32	7-18
7-12	Continuous Flow Expulsion Characteristics 0.7 lb Genetron 32	7-19
7-13	Continuous Flow Expulsion Characteristics Genetron 32/ Nonadecane	7-22
7-14	Continuous Flow Expulsion Characteristic Genetron 32/ Lauric Acid	7-24
7-15	Continuous Flow Expulsion Characteristic Genetron 32/ Eicosane	7-26
7-16	Continuous Flow Expulsion Characteristic Genetron 32/ Docosane, 30% Quality	7-27
7-17	Continuous Flow Expulsion Characteristic Genetron 32/ Docosane, 5% Quality	7-29
8-1	System B Fuel Tank and Bellows Capsule	8-2
8-2	Pressurization System Test Schematic	8-4
8-3	Oscillograph Traces - Pressurization System Test Flow Pulse	8-6
8-4	Pulsing Expulsion Characteristics, Freon 22, Five Second Width	8-9
8-5	Pulsing Expulsion Characteristics, Freon 22, Ten Second Pulse Width, Low Flow Rate	8-10
8-6	Pulsing Expulsion Characteristics, Freon 22, Twenty Second Pulse Width, Low Flow Rate	8-11
8-7	Pulsing Expulsion Characteristics, Freon 22, Ten Second Pulse Width, High Flow Rate	8-12
8-8	Pulsing Expulsion Characteristics, Freon 22, Twenty Second Pulse Width, High Flow Rate	8-13
8-9	Continuous Flow Expulsion Characteristics, Genetron 32, Eicosane Without Heat	8-15
8-10	Continuous Flow Expulsion Characteristics, Genetron 32, Eicosane, Without Heat	8-16

<u>FIGURE</u>		<u>PAGE</u>
8-11	Continuous Flow Expulsion Characteristics, Genetron 32 Eicosane, Low Flow Rate With Heat	8-17
8-12	Continuous Flow Expulsion Characteristics, Genetron 32 Eicosane, High Flow Rate with Heat	8-18
8-13	Pulsing Expulsion Characteristics, Genetron 32/ Eicosane, Low Flow Rate	8-20
8-14	Pulsing Expulsion Characteristics, Genetron 32/ Eicosane, High Flow Rate	8-21
8-15	Pressurization System Dual Tank Tests Schematic	8-25
8-16	Dual Tank Test Setup	8-28
8-17	Dual Tank Test System A Duty Cycle Run No. 1	8-29
8-18	Dual Tank Test System A Duty Cycle Run No. 2	8-30
8-19	Dual Tank Test System A Duty Cycle Run No. 3	8-31
8-20	Dual Tank Test System A Duty Cycle Run No. 4	8-32
8-21	Dual Tank Test System A Duty Cycle Run No. 5	8-33
8-22	Dual Tank Test System B Duty Cycle Run No. 1	8-35
8-23	Dual Tank Test System B Duty Cycle Run No. 2	8-36
8-24	Dual Tank Test System B Duty Cycle Run No. 3	8-37
8-25	Dual Tank Test System B Duty Cycle Run No. 4	8-38
8-26	Dual Tank Test, Genetron 32 Only, System B Duty Cycle Run No. 1	8-41
8-27	Dual Tank Test, Genetron 32 Only, System B Duty Cycle Run No. 2	8-42
8-28	Dual Tank Test, Genetron 32 Only, System B Duty Cycle Run No. 3	8-43
8-29	Dual Tank Test, Genetron 32 Only, System B Duty Cycle Run No. 4	8-44
8-30	Dual Tank Test, Genetron 32 Only, Continuous Flow with Heat	8-46
8-31	Dual Tank Test, Genetron 32 Only, Continuous Flow Without Heat	8-47

<u>FIGURE</u>		<u>PAGE</u>
8-32	Schematic Pressurization System Propellant Test	8-49
8-33	Fuel Tank Propellant Expulsion Characteristics System A Run No. 1	8-50
8-34	Fuel Tank Propellant Expulsion Characteristics System A Run No. 2	8-51
8-35	Fuel Tank Propellant Expulsion Characteristics System A Run No. 3	8-53
8-36	Fuel Tank Propellant Expulsion Characteristics System A Run No. 4	8-54
8-37	Fuel Tank Propellant Expulsion Characteristics System A Run No. 5	8-55
8-38	Oxidizer Tank Propellant Expulsion Characteristics System A Run No. 1	8-56
8-39	Oxidizer Tank Propellant Expulsion Characteristics System A Run No. 2	8-57
8-40	Oxidizer Tank Propellant Expulsion Characteristics System A Run No. 3	8-58
8-41	Oxidizer Tank Propellant Expulsion Characteristics System A Run No. 4	8-59
8-42	Oxidizer Tank Propellant Expulsion Characteristics System A Run No. 5	8-60
8-43	Oxidizer Tank Propellant Expulsion Characteristics System B Runs 1 and 2	8-62
8-44	Oxidizer Tank Propellant Expulsion Characteristics System B Runs 3 and 4	8-63
8-45	Fuel Tank Propellant Expulsion Characteristics System B Runs 1 and 2	8-65
8-46	Fuel Tank Propellant Expulsion Characteristics System B Runs 3 and 4	8-66
8-47	Damaged Bellows System B Oxidizer Tank	8-67
8-48	Damaged Bellows Header	8-69
9-1	System A Engine	9-3

<u>FIGURE</u>	<u>PAGE</u>
9-2 System B Engine	9-4
9-3 Auxiliary Propulsion System Test Schematic	9-6
9-4 Fuel Expulsion Tank	9-7
9-5 Oxidizer Expulsion Tank	9-8
9-6 Tank Heat Exchanger Connections	9-9
9-7 Data Acquisition Facility	9-10
9-8 System B Test Setup	9-14
9-9 System B Engine Connections	9-15
9-10 System B Engine Components	9-16
9-11 Pressurant Cavity Volume Loading	9-17
9-12. Operating Performance System B Test B-001	9-21
9-13 Operating Performance System B Test B-002	9-22
9-14 Engine Oscillograph Trace System B Run B-001	9-24
9-15 Engine Case Temperatures Run B-001	9-25
9-16 Engine Case Temperatures Run B-002	9-26
9-17 System A Test Setup	9-27
9-18 System A Engine Connections	9-28
9-19 Reorientation of Fuel Tank	9-29
9-20 Engine Oscillograph Trace, 10% Duty Cycle	9-36
9-21 Engine Oscillograph Trace, 30% Duty Cycle	9-37
9-22 Engine Oscillograph Trace, 67% Duty Cycle	9-38
9-23 Tank Oscillograph, Cycling Heat Exchanger Flow	9-39
9-24 Tank Oscillograph, Intermittent Oxidizer Tank Heat Exchanger Flow	9-40
9-25 Fuel Tank Heat Input Requirements	9-41
9-26 Oxidizer Tank Heat Input Requirements	9-42

<u>FIGURE</u>		<u>PAGE</u>
9-27	Volatile Liquid Vaporization Characteristic Run A-001	9-44
9-28	Volatile Liquid Vaporization Characteristic Run A-002	9-45
9-29	System A Operating Performance	9-46
10-1	Expulsion Characteristics of Genetron 32 in a Pulsing Mode	10-3

LIST OF TABLES

<u>TABLE</u>	<u>PAGE</u>
3-1 System Design Parameters	3-2
3-2 Representative Volatile Liquids	3-6
4-1 System Tank Part Numbers	4-5
4-2 Bellows Design Parameters	4-6
5-1 Tensile Test Data	5-5
5-2 Tensile Tests System A Oxidizer Tank	5-6
5-3 Pressure Margin Levels in System A Oxidizer Tank	5-7
5-4 Tank Acceptance Test Parameters	5-11
7-1 Quality Change Conditions for Freon 22 Tests	7-8
7-2 Quality Change Conditions for Genetron 32/HSM Tests	7-20
7-3 Compatibility and Freezing Points Genetron 32/HSM	7-21
7-4 Pressure Summary for Genetron 32/HSM Tests	7-32
8-1 Tank Loading Requirements	8-8
8-2 System A Duty Cycle Run Conditions	8-23
8-3 System B Duty Cycle Run Conditions	8-24
8-4 System Demonstrations Loading Conditions	8-34
8-5 Pressurant Change During Testing	8-27
8-6 Run and Load Conditions Genetron 32 Only Tests	8-40
8-7 Propellants Utilized in System Testing	8-48
8-8 Fuel Tank Pressurant Conditions	8-61
9-1 Auxiliary Propulsion System Test Parameters	9-2
9-2 Test Parameters Recorded	9-11
9-3 System B Test Loading Conditions	9-18

<u>TABLE</u>	<u>PAGE</u>
9-4 System B Test Duty Cycle	9-19
9-5 Pressurant Change During System B Tests	9-20
9-6 System A Test Loading Conditions	9-30
9-7 System A Engine Checkout Runs	9-31
9-8 System A Test Duty Cycle	9-32
9-9 Pressurant Change During System A Tests	9-33
9-10 Heat Exchanger Operating Pressure Levels	9-33
9-11 Heat Exchanger Usage	9-35

1.0 INTRODUCTION

The projected requirements for future space missions indicate a need for increased reliability of the reaction control propellant expulsion system for long duration flights. The volatile liquid pressurization system provides an increase in reliability by eliminating the need for high pressure pressurant storage, pressure regulators, relief valves, and interconnecting hardware. Elimination of the high pressure components from the pressurization system also results in a significant weight reduction. To avoid the permeation problems associated with nonmetallic materials for long-term storage, an all-metal expulsion device was used. In the volatile liquid system, the pressurant is stored as a liquid and converted to a pressurizing vapor through the application of heat. Since no pressures in excess of the required reaction control system pressure are needed, the pressurization system and propellant storage volume can be made integral and sealed within a common pressure vessel.

The program consisted of the design, fabrication, and test of two flight-weight volatile liquid expulsion systems described briefly below.

System A was an all metal volatile liquid bipropellant expulsion system consisting of an oxidizer tank and a fuel tank capable of feeding a low thrust, long duty cycle pulsed reaction control rocket engine system operating at a nominal 166 psig tank pressure.

System B was an all metal volatile liquid bipropellant expulsion system consisting of an oxidizer tank and a fuel tank capable of feeding an essentially continuous thrust reaction control engine system at a nominal 276 psig tank pressure.

The technical approach used to accomplish the objectives of the program was divided into three phases; design-development, pressurization system demonstration, and reaction control system demonstration.

Phase I - Design-Development

The design-development phase consisted of the design, fabrication, and development testing of all components and materials preparatory to carrying out the full scale flight-weight system demonstration. This phase was sub-divided into four specific areas of investigation:

1. Tank Design and Fabrication

Within the constraints of an all-metal system and a minimum life requirement of 1000 cycles, the expulsion device chosen was a bellows configuration. The tank design parameters and envelope requirements were established to comply with the existing Apollo Command and Service Module designs. The tank design objective was to provide a minimum weight system consistent with the design limitations of an aluminum tank and steel bellows. Four tanks were fabricated, a fuel tank and an oxidizer tank for each system.

2. Component Evaluation

In System A, control of input of the external heat was provided by sensing the pressurant cavity pressure with a pressure switch which controlled the on-off position of a heat exchanger flow valve. Component level tests were conducted as well as sub-system evaluation to assure proper function of the heat control system when incorporated into the full scale flight-weight tanks. A series of functional tests was conducted on each flight-weight tank to assure proper functioning during system demonstration.

3. Pressurant Investigation

Using subscale test hardware, expulsion tests were conducted with various candidate pressurant and heat storage materials. Pressurants investigated were monochlorodifluoromethane and difluoromethane. Heat storage materials included nonadecane, eicosane, docosane, and lauric acid. These tests were

designed to provide a basis for selection of materials to be used in the system demonstration phase.

4. Loading Methods Investigation

An investigation was conducted to determine practical methods for accurately loading the pressurant and heat storage materials into the tank.

Phase II - Flight-Weight, Pressurization System Demonstration

This phase of the program consisted of a series of expulsion tests conducted to demonstrate the capability of the flight-weight Systems A and B Volatile Liquid Pressurization Systems to meet the contract requirements. The purpose of the test was to investigate the limitations of the system including propellant flow rate, magnitude of pressure decay during the expulsion cycle, and rate of pressure recovery. Tests were conducted at various propellant flow rates and duty cycles utilizing a simulated propellant. A series of tests was then conducted, using simulated propellants, to demonstrate bipropellant operation. For the final portion of this phase of testing, a worst-case duty cycle was determined and expulsion tests were conducted with each tank utilizing actual propellants.

Phase III - Auxiliary Propulsion System Demonstration

During the last phase of the program, the volatile liquid pressurization concept was demonstrated during operation of a complete auxiliary propulsion system. A series of engine firing tests was conducted utilizing volatile liquid pressurization for both System A and System B operation. The System A tests were conducted using two Apollo service module 100-lb-thrust radiation engines; the System B tests were conducted using two TRW-manufactured 100-lb-thrust ablative engines.

2.0 SUMMARY

The program described by this report consisted of the design, development, fabrication, and testing of two all-metal volatile liquid positive expulsion systems. The two different pressure level systems considered simulate the RCS bipropellant pressurization systems on the Apollo Service (System A) and Command (System B) Modules. The design of the systems was based on the experience gained during the basic feasibility demonstration phase (Contract NAS 9-1004). Volatile liquid materials were selected for each system. In the low pressure (166 psig) service module system, an existing waste heat loop was utilized to provide the heat source required to maintain a saturation pressure level. For the high pressure (276 psig) command module system the design requirement was for nearly continuous propellant flow. An external heat loop was not considered adequate to provide the heat necessary for pressurant vaporization. An investigation was conducted to determine a suitable heat storage material whereby heat could be stored in the tank and released to the volatile liquid as required during propellant expulsion.

The two volatile liquids selected as pressurant materials for investigation were monochlorodifluoromethane (System A) and difluoromethane (System B). A series of subscale tests was conducted to determine the expansion characteristics of the pressurants during propellant expulsion. Tests were conducted at various flow rates to determine pressure decay rates and magnitudes. Other tests were conducted with various pressurant quantities to determine the effects of varying initial volatile liquid quality on the magnitude of pressure decay.

Various heat storage materials of a family of aliphatic hydrocarbons were mixed with the System B volatile liquid, difluoromethane, and the mix was subjected to expansion to determine equilibrium pressure levels that could be achieved. In this series of heat storage material tests, at the start of expansion, the mix was at a temperature level (and resulting saturated pressurant vapor pressure) just above the freezing point of the hydrocarbon. The temperature decay associated with expansion of the pressurant caused a depression of the temperature of the heat storage

material which resulted in freezing. The heat of fusion given off by the freezing heat storage material was transferred to the pressurant causing continuous vaporization and maintenance of a relatively constant pressure level. Four candidate heat storage materials were investigated and one (eicosane) was selected for use in the System B tests.

A flight-weight fuel and oxidizer bellows and tank assembly was fabricated for each of the two systems. Welding problems were encountered during fabrication of the 2219 aluminum tank shell. Resistance welding of the aluminum alloy 2219 tended to develop weld nugget microcracks, particularly when using material in an annealed condition. This method of fabrication, therefore, was eliminated. Fusion welding and electron beam welding were used successfully.

Component and subsystem tests were conducted to demonstrate compliance with design specifications prior to final assembly of the full-scale system hardware. In addition to the acceptance test conducted on each tank assembly, the heat loop control components were tested individually and jointly to assure proper flow control of the heat exchanger fluid in response to changes in pressurant pressure. A series of tests was conducted to determine a practical method of accurately loading the volatile liquid and heat storage materials into the tank.

A series of pressurization system tests with the full-scale tankage using simulated propellants provided test results comparable to the subscale test performance.

A series of bipropellant expulsion tests (fuel and oxidizer tanks simultaneously) was then conducted using Apollo command and service module duty cycles. Flow pulses were 10 seconds duration for both systems. By varying the off times, a changing duty cycle was established. Tests were conducted at flow rates simulating single and multiple (two and four) 100-pound RCS engine operation. The System B (command module) duty cycle, which was not established until late in the program, required a pulsing performance with only a 50 percent on time. It was found from the

bipropellant test results that the heat storage material, which was developed for use with continuous propellant flow, did not function efficiently in a pulsing mode, particularly at low flow rates. In fact, in some instances, the presence of the heat storage material resulted in reduced performance. For both System A and System B pulsing duty cycle operation best performance was demonstrated using an external heat source.

A series of propellant expulsion tests was then made with each tank. No differences were encountered in expulsion characteristics between the actual propellant and simulated propellant tests.

Finally, the volatile liquid pressurization concept was demonstrated during operation of a complete auxiliary propulsion system. For System A, operation, the flight-weight pressurization system developed was used to provide propellants during operation of two Apollo service module 100-lb-thrust engines. The engines were operated at duty cycles varying between 10 and 67 percent. Throughout these tests the maximum variation in engine chamber pressure resulting from pressurization system operation did not exceed 3 percent.

System B operation was demonstrated during firing of two TRW-manufactured 100-lb-thrust ablative engines. These engines were developed under contract NAS 9-5186. Engine duty cycles between 33 and 75 percent were tested. As was evidenced during the pressurization system tests, the pulsing mode of operation with the heat storage material method of heat input did not provide a continuous pressure plateau. The maximum decay experienced in engine chamber pressure from the plateau pressure was 11 percent.

3.0 SYSTEM DEFINITION

The volatile liquid expulsion system, which provides both a propellant storage volume and integral pressurization within a common pressure vessel, eliminates the need for a high pressure pressurant tank, pressure regulators, check valves, relief valves, and other associated hardware normally found in liquid propellant feed systems. The inherent reliability of the volatile liquid system is high because of its basic simplicity.

The basic system consists of all-metal, positive expulsion fuel and oxidizer tanks capable of providing propellant for operation of up to four 100-lb-thrust bipropellant RCS engines. Each tank has an integral pressurization system which converts a stored saturated fluid into a pressurization gas through the addition of heat. The use of a metal bellows expulsion device reduces the problems of permeability and compatibility common to expulsion systems utilizing plastics or elastomers.

The two different pressure level systems which were developed simulate the RCS pressurization systems on the Apollo Service and Command Modules. A summary of the requirements for the two systems, the Service Module System and the Command Module System, referred to as Systems A, and B, respectively, is given in Table 3-1.

3.1 Volatile Liquid System Operation

The pressurant thermodynamics are such that the fluid exists at a saturated pressure. The desired saturation pressure is determined by the required system operating pressure. The pressurant fluid expands as propellant flow from the tank increases the pressurant cavity volume. The expansion process depends upon the propellant demand and pulse duration. With no energy exchange to or from the pressurant, the pressurant expands adiabatically. As the vapor phase expands there is a corresponding drop in temperature. The temperature differential between the liquid and vapor phase initiates vaporization of the pressurant liquid and causes an increase in the pressurant fluid quality. With no heat

Table 3-1 System Design Parameters

	System A (Apollo Service Module)	System B (Apollo Command Module)
Propellant Supply Pressure (nominal)	166 psig	276 psig
Oxidizer	N ₂ O ₄	N ₂ O ₄
Fuel	Aerozine-50/MMH*	MMH*
Oxidizer Volume	2800 in. ³ (1.62 ft ³)	1760 in. ³ (1.02 ft ³)
Oxidizer/Fuel Ratio by Weight	2.0	2.0
Maximum Tank Diameter (exclusive of heat exchanger)	13.0 in.	13.0 in.
Oxidizer Flow Rate	0.222-0.888 lb/sec	0.222-0.888 lb/sec
Fuel Flow Rate	0.111-0.444 lb/sec	0.111-0.444 lb/sec
Type of Propellant Flow	Pulsing	Continuous**
Operating Temperature	80°-120°F	80°-120°F
Tank Material	Aluminum	Aluminum
Expulsion Device	Stainless steel bellows	Stainless steel bellows
Expulsion Efficiency	98% minimum	98% minimum
Design Cycle Life	1000	1000
External Waste Heat Loop		
Fluid	60% Ethylene glycol/40% water	
Flow Rate	0.0278 lb/sec	0.0278 lb/sec
Temperature	180°F	120°F

*Monomethylhydrazine

**This was subsequently changed to pulsing mode with the establishment of a duty cycle by NASA

addition, vaporization will continue until the fluid stabilizes at a lower level of saturation pressure. By adding heat to the fluid, further vaporization takes place, resulting in an additional increase in quality and a return to the original saturation level. The magnitude of pressure decay in the system will be determined by the pressurant quality at the initiation of flow and the percent increase in the pressurant volume associated with propellant flow. An exact balance between the heat input and the flow work accomplished by the pressurant would result in the maintenance of a constant pressurization level until the pressurant liquid is depleted.

In an attitude control system operating over a period of several weeks, where the average propellant flow rates are relatively low and the level of pressure decay associated with a single expulsion pulse can be tolerated, heat addition can usually be accomplished between pulses by using an available external heat source. However, in reaction control systems where the propellant flow rate is essentially continuous, as might be experienced in an ullage or reentry engine application, the response time for an external heat source may not be capable of meeting the system requirements. In those instances a heat storage material is incorporated in the pressurant cavity of the pressure vessel in intimate contact with the volatile liquid. The heat storage material is selected such that its melting temperature is slightly below the normal system operating temperature associated with saturation pressure of the volatile liquid and system operating pressure. As the pressure in the cavity volume decreases with propellant flow, the temperature will decay to the freezing temperature of the heat storage material. This material will begin to freeze giving off its heat of fusion to the pressurant. As the heat storage material and the volatile liquid are in intimate contact, near instantaneous heat transfer occurs. An equilibrium pressure can be achieved in the pressurant cavity at a level equal to the vapor pressure of the volatile liquid at a temperature equal to the melting temperature of the heat storage material.

3.2 Pressurant Material Selection

Selection of materials with which to pressurize the fuel and oxidizer tanks in Systems A and B was based on the results of testing conducted under the feasibility study contract NAS 9-1004, Reference No. 1. With a specified temperature of 80°F to 120°F and pressures of 166 psig for System A and 276 psig for System B, three materials were considered for use. These materials were ammonia, monochlorodifluoromethane (hereafter referred to as Freon 22*) and difluoromethane (hereafter referred to as Genetron 32**). Assuming an allowable variation in tank pressure of ± 10 percent, as can be seen from the respective vapor pressure curves shown in Figure 3-1, ammonia and Freon 22 are limited to use in System A and Genetron 32 is limited to System B.

The feasibility study established the criteria of a low molecular weight pressurant to minimize total system weight. On this basis, ammonia would be preferred over Freon 22, as shown under the column headed "pounds volatile liquid/cubic foot propellant" in Table 3-2. However, because of the compatibility problems of ammonia with the oxidizer (based on the eventuality of leakage across the expulsion device), ammonia could be recommended for use only with the fuel tank. The optimum volatile liquids for pressurants for the systems are ammonia for the System A fuel tank, Freon 22 for the System A oxidizer tank, and Genetron 32 for the System B fuel and oxidizer tanks. However, in order to simplify system logistics the same pressurant (Freon 22) was used in both System A tanks. This resulted in a fuel tank weight penalty of 4.1 pounds.

3.3 Heat Source Control System

The heat source control system manages the heat addition to the volatile liquid pressurant. The design approach used for the heat source control system was based on the design experience obtained by TRW under Contract NAS 9-1004. In System A, the frequency and duration of the

*Registered trademark of E. I. DuPont de Nemours & Company

**Registered trademark of Allied Chemical Corp.

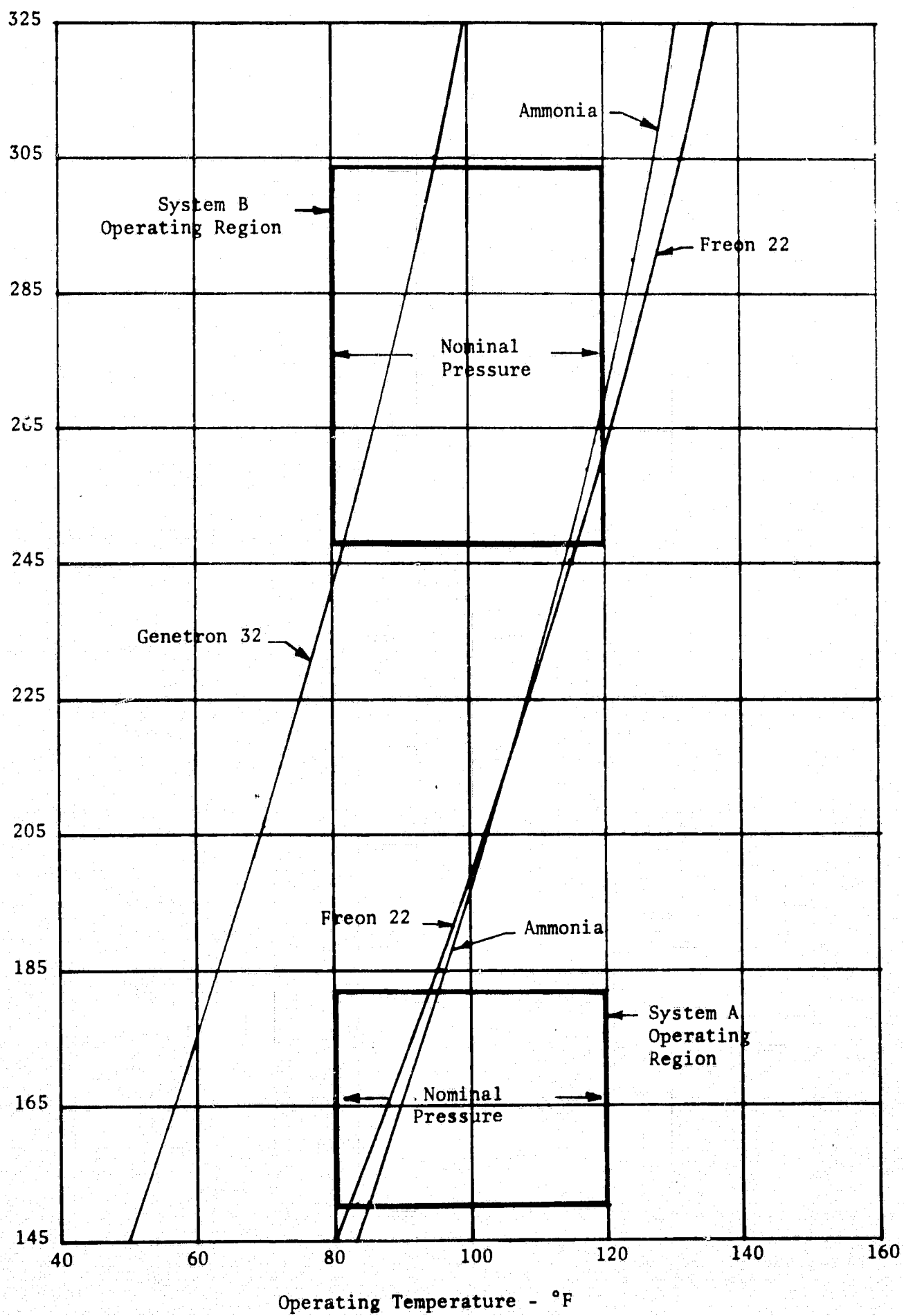


Figure 3-1 Pressurant Material Comparison

Table 3-2 Representative Volatile Liquids

<u>Volatile Liquid</u>	<u>Temperature (°F)</u>	<u>Vapor Pressure (psig)</u>	<u>Pounds Volatile Liquid/ Cu Ft Propellant</u>	<u>Vaporization Heat Input Required/ Cu Ft Propellant (BTU)</u>	<u>Increase In Tank Vol./ Cu Ft Propellant (Ft³)</u>
Ammonia	96	185	0.7	320	.02
	123	285	1.0	450	.03
Monochlorodifluoromethane (Freon 22)	96	185	3.9	425	.05
	126	285	6.3	675	.09
Difluoromethane (Genetron 32)	90	285	3.5	410	.06
	113	385	4.9	510	.09

expulsion pulses is such that there is sufficient time to add the heat required to vaporize the volatile liquid using the water/glycol waste heat loop available on the Apollo Service Module. Heat is transferred from the heat source to the volatile liquid by means of a heat exchanger located on the outside diameter of the tank.

In System B, the external heat source available was not considered adequate to provide the rate of heat input required during continuous expulsion. System B, therefore, was designed such that the heat required to vaporize the volatile liquid is supplied by heat transfer between the volatile liquid and a heat storage material. Under special conditions, i.e., ambient temperature below heat storage material melting temperature, the expulsion system would lose heat to the surrounding environment prior to the time required for system operation. In order to prevent decay of the system temperature below the freezing point of the heat storage material, a means of making up the heat loss to the surrounding ambient was provided. The tank design approach utilized in System B was to provide a heat exchanger and control system, operating with the lower temperature (120°F) Apollo Command Module water/glycol system, similar to that used in System A.

3.3.1 Heat Exchanger

The heat exchanger design consisted of a helical coil of aluminum tubing welded to the outside diameter of the tank. Sizing of the heat exchanger was dependent on the propellant flow conditions to which the unit was subjected. Design of the System A heat exchanger conforms to the thermodynamic relations defined in Reference 2. The heat exchanger configuration for System B was similar in design to the System A heat exchanger, except that the minimum size was determined by heat loss to ambient. To facilitate interchangeability on the development program, it was possible to size the System B heat exchangers for the System A requirements. This provided a backup capability wherein System A tests could be run with System B tanks.

3.3.2 Valve

The flow control valve for the heat exchanger fluid was a three-way valve to allow bypass of the fluid when there was no demand by the volatile liquid, as shown schematically in Figure 3-2. The valve was a 28 vdc direct-acting, three-way solenoid valve. Because of the low temperatures involved, soft seats were utilized to assure minimum leakage.

3.3.3 Control Circuit

Actuation of the switch providing current to the valve controlling heat exchanger fluid flow was determined by sensing the tank pressure. When the tank pressure is within the desired operating region the valve bypasses the water/glycol flow. When the propellant flows from the tank, the pressure level decays. At a predetermined level the control circuit provides current to the valve routing the water glycol to the tank heat exchanger. When the heat input increases the tank pressure to the desired level the current is removed from the valve and water/glycol flow returns to bypass.

3.3.3.1 Pressure Switch

During the pressurization system tests, a pressure switch was used to provide the required control. The pressure switch was designed with a normally open switching element which closed on decreasing pressure and allowed current to flow to the valve. The actuation point of the switch was set at 5 psi below the normal tank operating pressure. The pressure switch was a sealed metal diaphragm acting directly on a snap action switch. The diaphragm was so connected as to sense pressurant cavity pressure. Movement of the diaphragm as a result of decay in pressurant pressure closed the switch contacts. The switch contacts opened when the pressurant cavity pressure reached the nominal operating value.

3.3.3.2 Transistor Switch

During the pressurization system tests, in which bipropellant

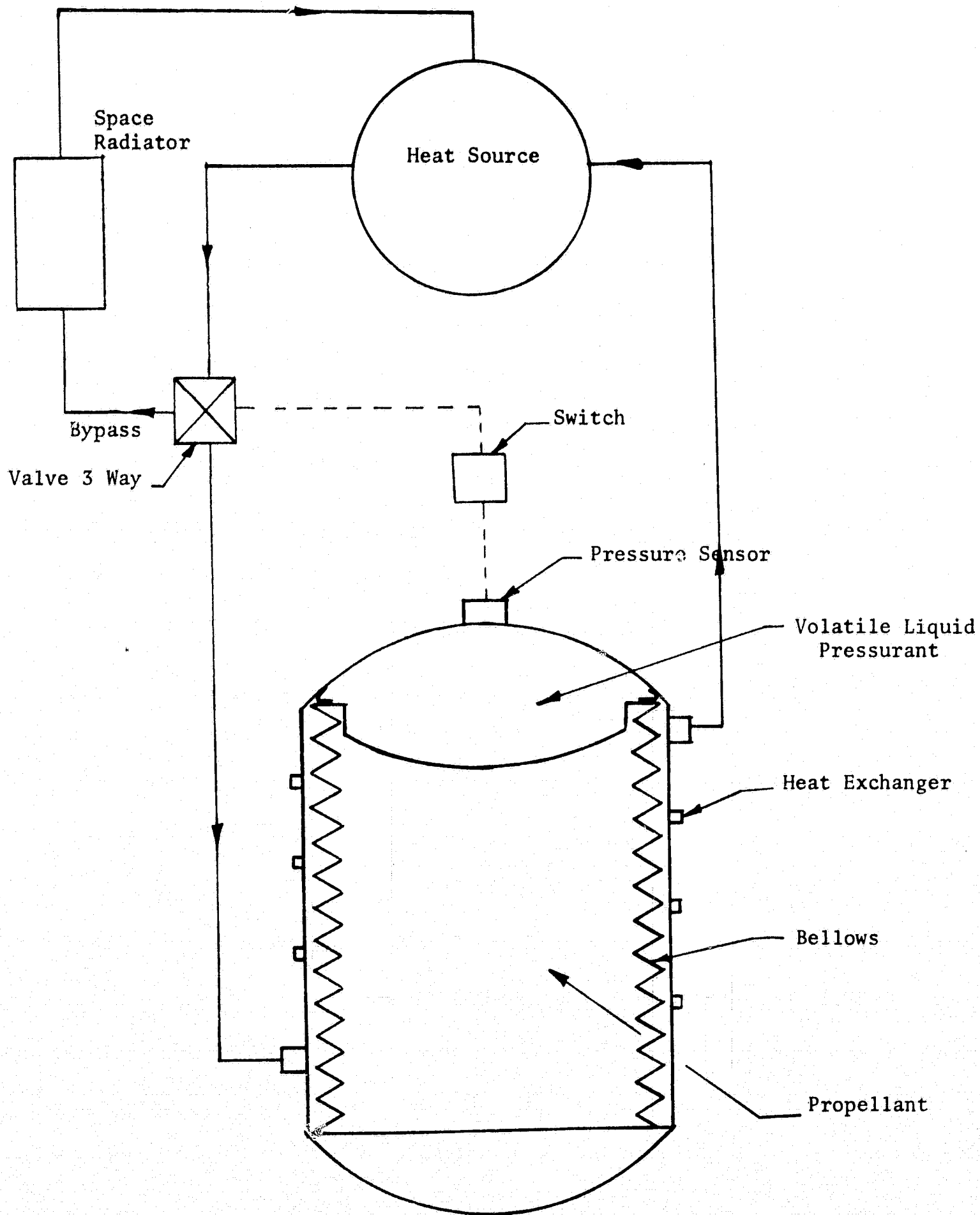


Figure 3-2 External Heat Source Schematic

operation was simulated, the pressure differential between the fuel and oxidizer tanks was noted to vary approximately with the extent of the deadband of the pressure switch used. This variance occurred primarily when one of the tanks initiated heat exchanger flow while the other one did not. By changing to a lower deadband pressure switch, the heat exchanger operation of the two tanks could be made more synchronous. The lower deadband switch which was used in the auxiliary propulsion system tests was a transistor switch which operated on the output voltage of a pressure transducer to control operation of the solenoid valve. The switch had been developed on another program by TRW. In that application, pressure switching deadbands as low as 1/2 percent were achieved.

Two transistor switches were fabricated for use during the reaction control system demonstration tests. These switches allowed operation of the heat control system with a deadband of approximately one psi.

A schematic of the electronic switching circuit is shown in Figure 3-3. The circuit utilizes an operational amplifier with positive feedback for voltage level detection. The output of the amplifier is used to drive a two-stage switch which actuates the flow control valve. The output voltage of the amplifier is locked at either plus or minus 5 volts at the base of the first-stage switch, T1, by the back to back Zener diodes, D2 and D3. The reference voltage on the amplifier at pin 3 is set by both the resistance setting of R1, which is in parallel with the Zener diode D1, and the voltage on the base of T1. For the condition in which the plenum pressure of the feed system is within the required deadband, the output of the control transducer, which is connected to pin 2 of the operational amplifier, will be above the reference voltage at pin 3. The output of the amplifier is a negative 5 volts at the base of switch T1. With a negative base, the switch will not conduct. When T1 is not conducting, the base voltage of switch T2, which completes the valve power circuit, is negative and it too will not conduct. As propellant is expelled from the tank, the output of the transducer will decrease, and when the voltage at pin 2 reaches the value at pin 3, the amplifier output becomes positive. This causes the reference voltage at pin 3 to

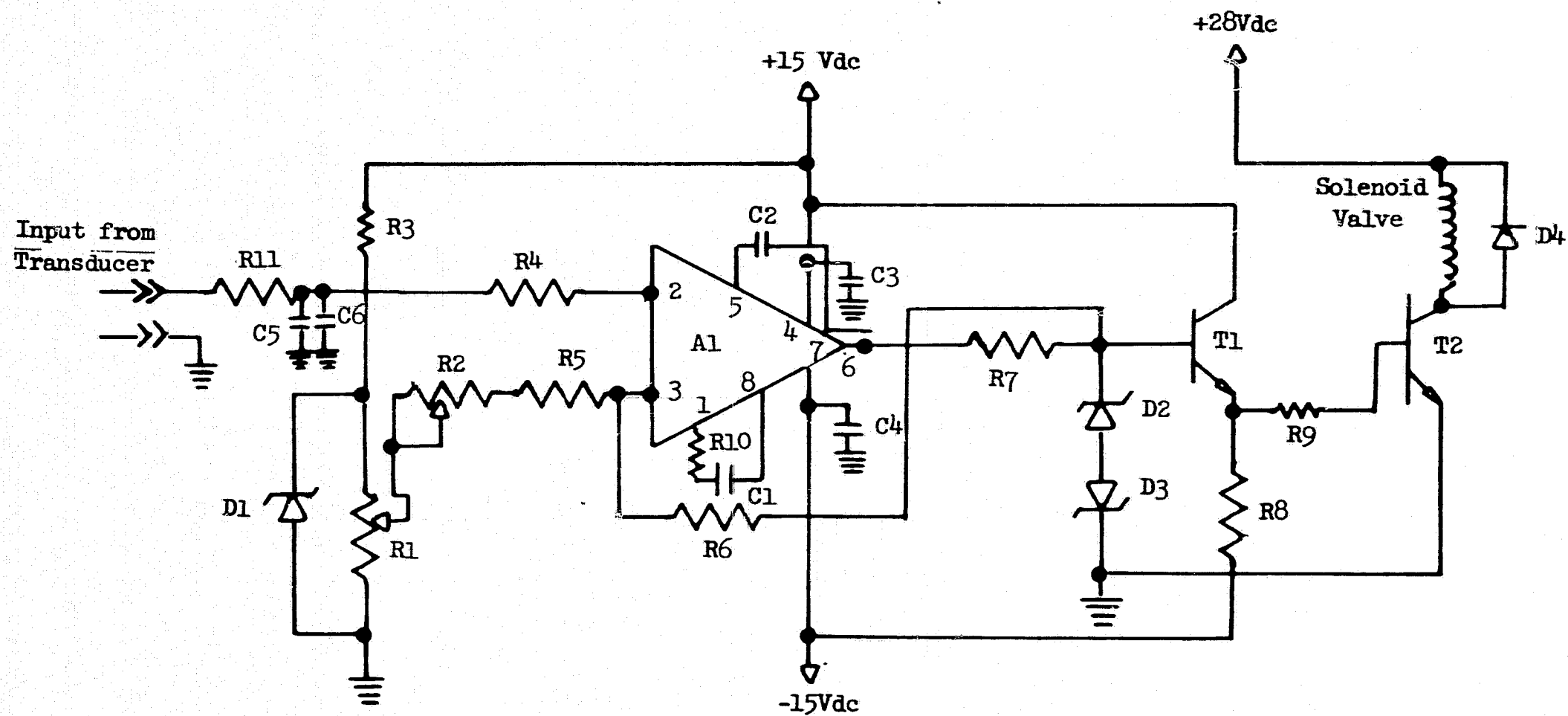


Figure 3-3 Transistor Switch Schematic

assume a higher value which is above the voltage at pin 2. The positive output from the amplifier causes a positive base voltage on switch, T1, and it will conduct.

When T1 is conducting, the base voltage on switch T2 becomes positive and it is also conducting. This completes the valve power circuit causing it to open. Heat exchanger flow is initiated increasing the pressure in the propellant tank and the output signal of the control transducer. The potential at pin 2 of the amplifier increases until it reaches the new voltage level at pin 3. When it reaches this value, the amplifier output becomes negative and the switches become nonconducting resulting in valve closure. The diode, D4, is in parallel with the valve coil and serves as an arc suppressor in T2 at valve closure. With the negative amplifier output, the potential at pin 3 assumes its original lower voltage which is below that at pin 2. The voltage difference at pin 3 between positive and negative amplifier output determines the switching deadband of the circuit. This voltage differential can be varied by adjusting R2. The pressure range in the fuel tank at which switching occurs is varied by adjusting the pick-up position of resistance R1.

4.0 PROPELLANT TANK

This program required the design and fabrication of four propellant tanks with an integral bellows as the expulsion device and an external heat exchanger to provide the heat input during expulsion. A fuel and oxidizer tank were required for each system. The tank fabrication was subcontracted to Metal Bellows Corporation, located in Chatsworth, California. Metal Bellows manufactured the bellows capsule and subcontracted the major portion of fabrication of the tank shell to Spacecraft Welding and Manufacturing Company of Inglewood, California. The design requirements of the tanks are defined in TRW drawing, Figure 4-1.

4.1 Tank Design

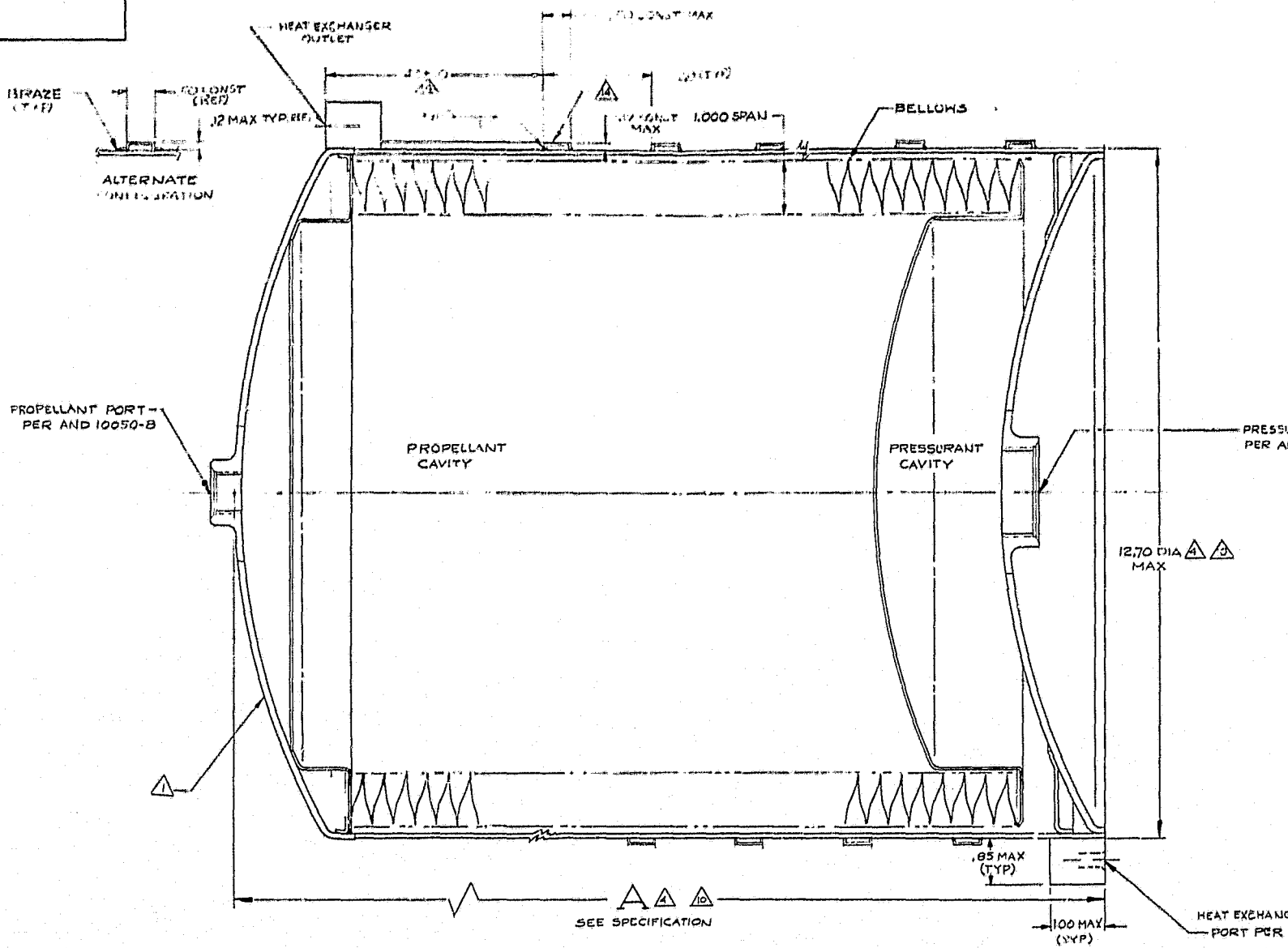
The basic design was a cylindrical tank with essentially elliptical end closures. The tank utilized a welded nesting type of bellows capsule as the expulsion device. The end terminals of the bellows were designed to maximize propellant expulsion efficiency with a design goal of 98 percent. The basic tank design is shown in Figure 4-2. The relation of tank dash number to system identification is shown in Table 4-1.

4.1.1 Tank Shell

A NASA design requirement imposed was fabrication of the tank shell from aluminum. In order to provide a minimum weight system it was decided to fabricate the tank using 2219 aluminum alloy. This relatively new alloy has excellent fusion welding characteristics and is heat treatable. By heat treating subsequent to welding the weight penalty normally associated with a welded aluminum structure can be avoided in all but the closure weld. To minimize the heat affected zone, the closure weld was electron-beam welded. Strength values of 2219 aluminum used in design were obtained from Reference 3.

The design approach utilized was to provide minimum weight. This was accomplished by using optimum cylindrical shell thicknesses and a constant strength header design. The header design was of the Biezeno

THE INFORMATION AND TECHNICAL DATA DISCLOSED BY THIS DOCUMENT MAY BE USED AND DISSEMINATED FOR THE PURPOSES AND TO THE EXTENT AUTHORIZED BY THE SYSTEMS IN ANY PROPOSAL. CONTRACTOR'S OTHER WRITTEN INSTRUMENTS, SUCH AS CONTRACTS AND TECHNICAL DATA, ARE PROPRIETARY TO THE SYSTEMS AND MAY NOT BE USED OR DISSEMINATED EXCEPT AS PROVIDED IN THE FOREGOING SENTENCE.



MMH INDICATES: MONOMETHYLHYDRAZINE
 18. CLEAN PER TRN SPEC PR 2-2.

17. TESTS TO BE CONDUCTED BY SUPPLIER:
1. PROOF PRESSURE EXTERNAL LEAKAGE
 2. BELLOWS LEAKAGE
 3. DETERMINATION OF PROPELLANT VOLUME
 4. BELLOWS OPERATING DIFFERENTIAL PRESSURE
 5. EXPULSION EFFICIENCY

16. ALL MATERIALS OF CONSTRUCTION SHALL BE METALLIC.

ALL SIMILAR METAL JOINTS SHALL BE WELDED. DISSIMILAR METAL JOINTS, IF ANY, MAY BE BRAZED, PROVIDED THE BRAZE MATERIAL IS COMPATIBLE WITH THE CONTACTING MEDIA.

THE EXTERNAL HEAT EXCHANGER WILL BE WRAPPED AROUND THE TANK IN A HELICAL COIL TO THE DIMENSIONS NOTED. THE CROSS-SECTIONAL SHAPE IS OPTIONAL WITHIN THE LIMITS NOTED. A MIN. ROW AREA OF .03 IN² IS REQUIRED. THE HEATING FLUID WILL BE A MIXTURE OF 60% ETHYLENE GLYCOL AND 40% WATER AT 30 PSIA AND 180°F

-1, -2, -3, & -4 ASSEMBLIES TO BE IDENTICAL EXCEPT AS NOTED

THE TOTAL PRESSURE DIFFERENTIAL REQUIRED TO MOVE THE BELLOWS FROM MAXIMUM EXTENDED LENGTH TO MINIMUM STACKED LENGTH SHALL NOT EXCEED THE VALUE SPECIFIED. THE FREE LENGTH OF THE BELLOWS IS TO BE DETERMINED BY THE SUPPLIER

TANK DESIGN TO EXHIBIT PROPELLANT EXPULSION EFFICIENCY OF 98 PERCENT MINIMUM

THE END CAP CONFIGURATION AND TANK CONSTRUCTION DETAILS ARE OPTIONAL AND MAY BE VARIED TO SUIT THE SUPPLIER'S DESIGN WITHIN THE ENVELOPE CONSTRAINTS NOTED

EXTERNAL LEAKAGE AT PROOF PRESSURE SHALL NOT EXCEED 5 SCC/HR OF GASEOUS NITROGEN.

LEAKAGE THROUGH BELLOWS ASSEMBLY SHALL NOT EXCEED 5 SCC/HR OF GASEOUS NITROGEN.

BELLOWS MATERIAL AND WEIGHT TO BE DETERMINED BY THE SUPPLIER.

BELLOWS ASSEMBLY SHALL BE CAPABLE OF WITHSTANDING A PRESSURE DIFFERENTIAL OF 25 PSI WHEN AT THE MAX EXTENDED LENGTH AND A PRESSURE DIFFERENTIAL OF 220 PSI FOR -1 & -2 AND 350 PSI FOR -3 & -4 AT MIN STACKED LENGTH

BELLOWS SHALL BE CAPABLE OF OPERATION IN THE VARIOUS COMBINATIONS OF OPERATING MEDIA FOR A MIN OF 1000 CYCLES FROM MAX EXTENDED LENGTH TO MAX STACKED LENGTH TO MAX EXTENDED LENGTH WITHOUT FAILURE. EXPULSION RATE WILL BE ESTABLISHED TO EMPTY THE TANK IN FIVE MINUTES.

MINIMUM PROPELLANT CAVITY VOLUME SHALL BE AS NOTED AND SHALL BE WITHIN THE ENVELOPE SHOWN.

TANK MAT L SHALL BE 2219 ALUMINUM ALLOY PER MIL-A-8920A. MIN STRENGTH AFTER WELDING SHALL BE EQUIVALENT TO THAT OBTAINED IN HEAT TREAT CONDITION T62 PER MIL-H-6088

OPERATING TEMPERATURE RANGE 80°F TO 120°F

IDENTIFICATION MARKING IN ACCORDANCE WITH STL SPEC, PR 12.1 TYPE II CLASS LA PART NUMBER & TITLE LOCATION ORT

NOTES: UNLESS OTHERWISE SPECIFIED

BELLOWS OPERATING DIFFERENTIAL PRESS.	5.5 PSI	4.5 PSI	3.5 PSI	3.0 PSI
PROPELLANT	N ₂ O ₄	AEROZINE 50	N ₂ O ₄	MMH
PRESSURANT	FREON 22	FREON 22	GENETRON 32	GENETRON 32
DIMENSION A (IN)	32.00	26.08	20.84	17.58
BELLOWS MATERIAL	303	303	303	303
TANK MATERIAL	303	303	303	303
MAX. TOTAL SYST WEIGHT	25.1 LB	24.5 LB	23.6 LB	20.4 LB
BELLOWS WEIGHT (LB)	450 PSIA	450 PSIA	725 PSIA	725 PSIA
BURST PRESSURE	315 PSIA	315 PSIA	510 PSIA	510 PSIA
PROOF PRESSURE	181 PSIA	181 PSIA	291 PSIA	291 PSIA
WORKING PRESSURE	2840 IN ³	2265 IN ³	1760 IN ³	1440 IN ³
PROPELLANT VOLUME	-1	-2	-3	-4
ASSY DASH NO.				

SPECIFICATIONS:

FOLDOUT FRAME

2

1

REVISIONS						
DATE	BY	DESCRIPTION	BY	DATE	CHKD	APPROVAL

PRESSURANT FILL PORT
PER AND 10050-20

HEAT EXCHANGER INLET
PORT PER AND 10050-4 (TYP)

SPECIFICATION CONTROL DRAWING

C110835

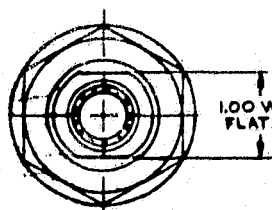
-4	TANK ASSY	13	13	7					
-3		13	13	7					
-2		13	13	7					
-1	TANK ASSY	13	13	7					

RECD PER	NOTED ASSY	PART NO.	PART NAME	STOCK	MATERIAL	SPEC	QTY REQ	CODE	UNIT	TON	ITEM	NO	USED ON	NEXT ASSY	NEXT ASSY	FINAL ASSY

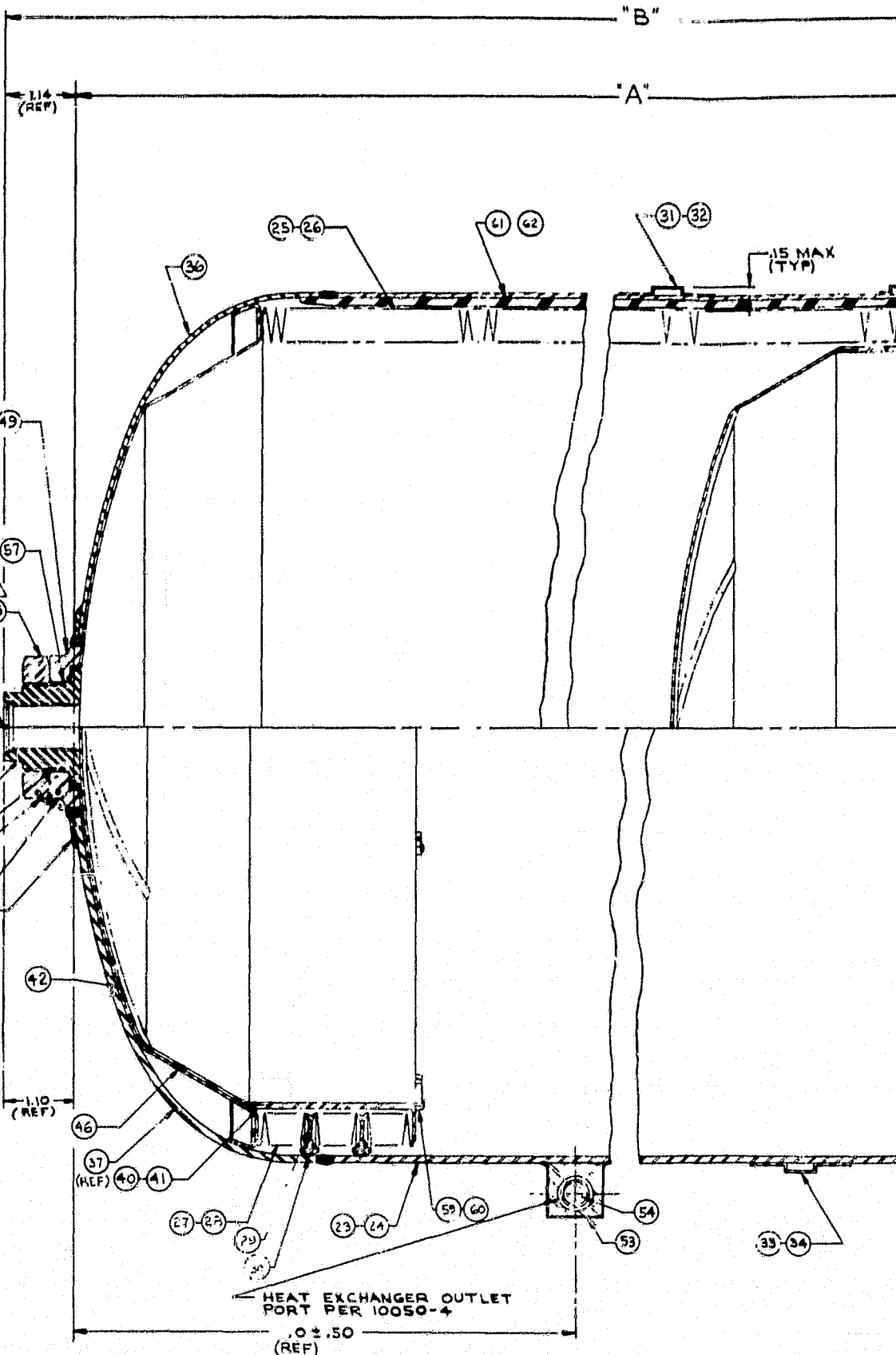
CONFIGURATION	UNLESS OTHERWISE SPECIFIED	FINISH	DO NOT SCALE DRAWING	THE FOLLOWING EQ'S HAVE BEEN ATTACHED TO THIS PRINT
PR 2-2	1 DIMENSIONING & TOLERANCING PER ASME Y14.5-1994		STL APPROVALS	TRW SPACE TECHNOLOGY LABORATORIES THOMPSON RAMP WOODBRIDGE VIC 11982 E C110835 SCALE 1/1 WEIGHT SEC 1.111K SPEC, SHEET 1
PR 12-1	2 DIMENSIONS IN INCHES TOLERANCES		DRAN P. LUGGET	
	3 STD HOLE TOLERANCES PER ANSI/ASME Y14.5-1994		CHECKED	
	4 ALL DIMS TO APPLY AFTER PLATING OR CONVERSION COATING		STRUCTURES	
	5 REMOVE BURRS & SHARP EDGES		MATERIALS & PROCESSING	
	6 SURFACE POLISHNESS PER MIL STD 113			
	7 RIVET COATING PER HAS 323			
	8 WELD SYMBOLS PER AWS A5.1-1992			
	9 THREADS PER MIL STD 1836			
	10 ELECTRICAL & ELECTRONIC SYMBOLS & REFERENCE DESIGNATIONS PER MIL STD 883C			

Figure 4-1 Tank Assembly Specification Control Drawing

PROPELLANT PORT
PER AND10050-8
EXCEPT AS SHOWN



1.00 WRENCH
FLATS (REF)



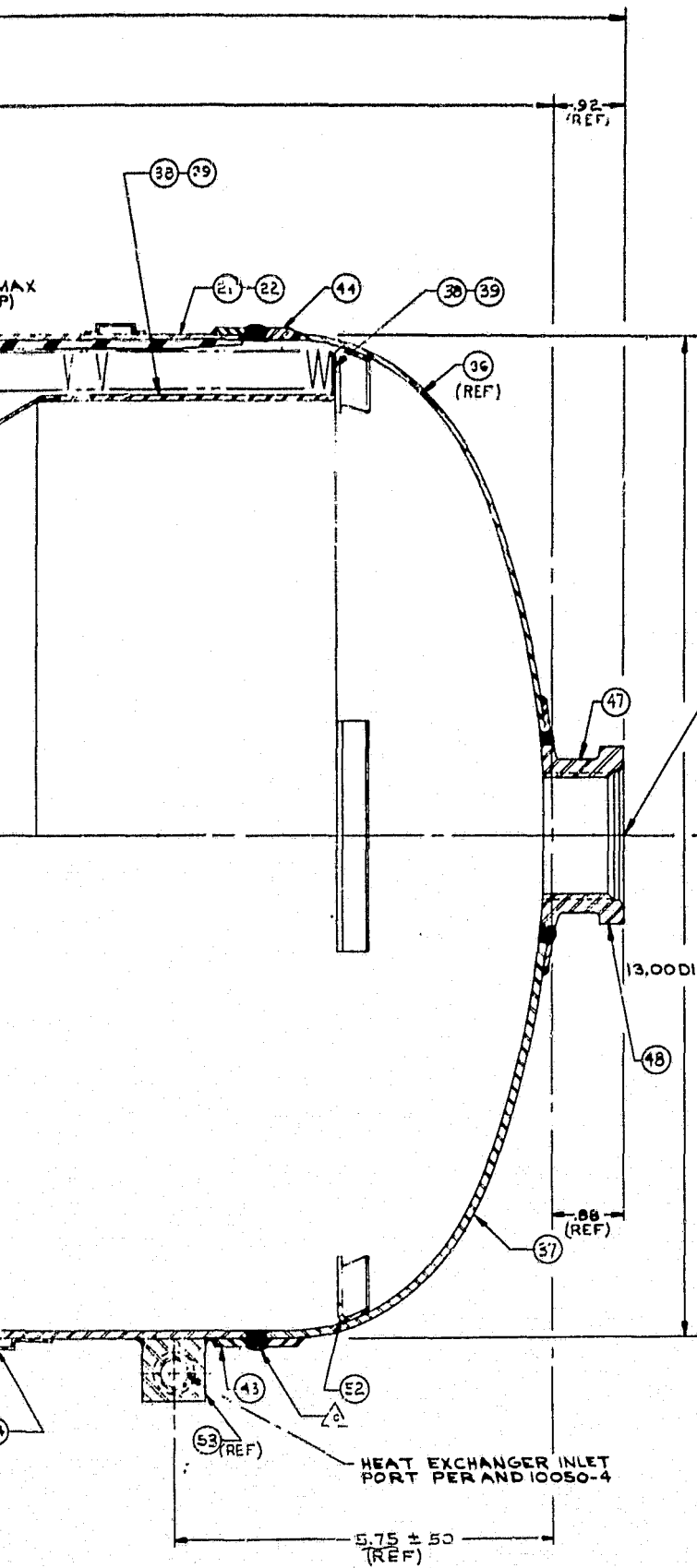
HEAT EXCHANGER OUTLET
PORT PER 10050-4
0.50
(REF)

- 1. ELECTRON BEAM WELD-100% PENETRATION X .050 WIDE (MAX)
- 2. ITEM 35 WILL BE LOCKWIRED TO ITEM 49 OR 50.
- 3. HEAT EXCHANGER FLOW AREA-.03IN² MIN.
- 4. PROPELLANT EXPULSION EFFICIENCY-98% MIN.
- 5. MAX LEAKAGE:
ACROSS BELLOWS-5 SCC HR N₂ AT ΔP = 5 PSI OR EQUIV.
EXTERNAL-5 SCC HR N₂ AT ΔP = PROOF PRESS OR EQUIV.
- 6. BELLOWS SHALL BE CAPABLE OF WITHSTANDING A ΔP AS NOTED
WHEN AT MAX EXTENDED LENGTH & A ΔP OF 220 PSI FOR -1&-2,
AND 350 PSI FOR -3&-4 AT MIN STACKED HEIGHT.
- 7. LIFE: 1000 CYCLES
- 8. OPERATING TEMPERATURE: 80°F TO 120°F
- 9. PART TO BE FREE OF BURRS, SCRATCHES & TOOL MARKS.
- 10. SEE DRAWING 10050-4

ASSEMBLY DASH NO.	-1
PROPELLANT VOLUME (NOM)	2800
WORKING PRESSURE	181 PSIA
PROOF PRESSURE	315 PSIA
BURST PRESSURE	450 PSIA
BELLOWS WEIGHT (NOM)	8.5 LBS
ASSEMBLY WEIGHT (NOM)	32 LBS
DIM "A" IN INCHES (REF)	32.9
PRESSURANT	FRESH 22
PROPELLANT	N ₂ O ₄
BELLOWS OPERATING ΔP	5 PSI
MAX PROP FILL ΔP	25 PSI
NO. OF HEAT EXCH COILS	5
DIM "B" ±.25 (IN.)	34.96

FOLDOUT FRAME /

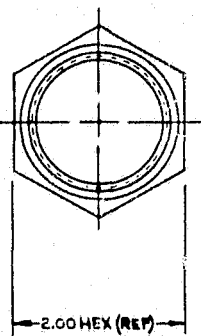
REVISIONS			
REV	DESCRIPTION	BY	DATE
D	REVISED, ADDED SHT 2	JL	12-26-65
E	REVISED - SEE 11646	JL	2-24-66
F	REVISED - SEE ECD 11852	PR	9-8-66 PR
G	REVISED - SEE ECD 11842	PR	8-31-66 PR



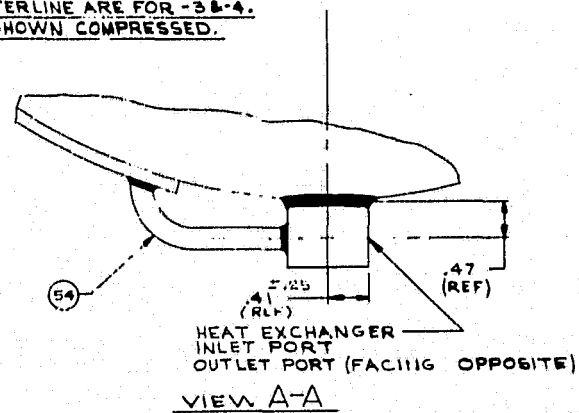
REFERENCE

WALL THICKNESS & ANTI-SAG RINGS
ABOVE CENTERLINE ARE FOR -1 & -2.
BELLOWS SHOWN EXTENDED

PRESSURANT FOR 1
PER AND 10050-20
EXCEPT AS SHOWN



WALL THICKNESS & ANTI-SAG RING
BELOW CENTERLINE ARE FOR -3 & -4.
BELLOWS SHOWN COMPRESSED



57218 G

-1	-2	-3	-4
2800	2235	1760	1440
181 PSIA	181 PSIA	291 PSIA	291 PSIA
315 PSIA	315 PSIA	510 PSIA	510 PSIA
450 PSIA	450 PSIA	725 PSIA	725 PSIA
8.5 LBS	6.8 LBS	5.3 LBS	4.3 LBS
32 LBS	27 LBS	24.7 LBS	22.1 LBS
32.9	27.6	22.9	19.7
FREON 22	FREON 22	GENETRON 32	GENETRON 32
N ₂ O ₄	AEROSINE 50	N ₂ O ₄	MMH
5 PSI	5 PSI	5 PSI	5 PSI
25 PSI	25 PSI	25 PSI	25 PSI
5	4	3	2
34.96	29.61	24.83	21.68

REQD	FEED	REQD	REQD	REQD	PART NO	DESCRIPTION	MATERIAL	MATL SPEC	ITEM
CUST. DWG NO C110835						LIST OF MATERIAL			
TOLERANCES UNLESS OTHERWISE SPECIFIED						DRWN	A. WIZ JHN 4-26-65	 PACIFIC DIVISION 80077 KRAFT ST. • CHATSWORTH, CALIF.	
JES 2.000 .25 .01 2.00						CHK	R. MAZURA 4-26-65		
PILLET 2.000 .25 .01 2.00						PROJ	D. KIRKSEY 4-26-65		
NACH. SURFACES 12/						APPD	P. CAMPBELL 4-27-65		
NACH. DIA. 2.000 .25 .01 2.00						FINISH	SPEC		
NACH. SURFACES 12/						SCALE 1/1			
NACH. DIA. 2.000 .25 .01 2.00						F 57218 G			
NACH. SURFACES 12/						SHT 1 OF 2			
NACH. DIA. 2.000 .25 .01 2.00						DATE 1-6-79			
NACH. SURFACES 12/						SHEET 2			
TOP 12608						HONEY ABBOT J. BOP.			

PROPELLANT
TANK-BELLOWS
EXPULSION

Figure 4-2 Tank Assembly Design Drawing

construction as defined in Reference 4. This allowed the headers to be nearly the same thickness as the tank shell. The headers were fabricated by hydroforming from flat sheet stock in lieu of using forgings.

The only 2219 sheet material available in the gages required for the tank fabrication was clad with 7072 aluminum alloy. Representatives of Alcoa advised that very little, if any, degradation of strength occurs in welded joints using the clad material. A series of weld test specimens was prepared using the same manufacturing techniques and sources used in manufacture of the tanks. These specimens were tensile tested to verify the strength levels expected in the completed tanks.

4.1.2 Bellows

An encapsulating bellows design was utilized. The bellows was manufactured with two full dome headers. The stationary header which was fastened to the tank assembly incorporated the propellant fill fitting. The fill fitting protruded through the aluminum tank header and was mechanically attached to the tank. This design approach provided all welded joints between the pressurant and propellant cavities. A mechanical redundant seal joint was incorporated between the pressurant cavity and ambient. The material selected for the bellows was 347 stainless because of its well defined manufacturing characteristics in bellows fabrication.

The design approach used to allow horizontal operation consisted of segmenting the bellows by providing several stiffening rings in the weldment to break-up the unsupported length of the bellows. Contact with the tank wall was provided by a series of nylon buttons in each insert ring. This design, however, proved troublesome in the System A tanks as described in Section 4.1.4. A summary of the bellows design parameters is shown in Table 4-2.

4.1.3 Heat Transfer Analysis

A thermodynamic analysis was conducted to optimize the heat

exchanger design for System A tanks. The analysis was based on the following system requirements and conditions:

Heat exchanger fluid	-	60% ethylene glycol 40% water
Flow rate	-	0.0278 $\pm$ 0.0166 lb/sec
Inlet temperature	-	160°F $\pm$ 20°F
Pressurant	-	Saturated Freon 22 at 166 psig

The average pressurant heat input requirement is a function of the rate of change from a liquid to a vapor phase and may be expressed in terms of the average propellant flow rate as:

$$H = \frac{\Delta h}{\Delta v} W_p$$

where: H = heat input Btu/min

Δv = change in pressurant specific volume from liquid to vapor phase ft³/lb

Δh = pressurant heat of vaporization Btu/lb

W_p = average propellant flow rate ft³/min

The propellant conditions are the following:

Fuel, Aerozine 50

$\rho_f = 56.1$ lb/ft³

Maximum flow rate, 0.444 lb/sec

Table 4-1 System Tank Part Numbers

	<u>TRW Part No.</u>	<u>Metal Bellows Part No.</u>
System A		
Oxidizer Tank	110835-1	57218-1
Fuel Tank	110835-2	57218-2
System B		
Oxidizer Tank	110835-3	57218-3
Fuel Tank	110835-4	57218-4

Table 4-2 Bellows Design Parameters

	System A		System B	
	<u>Oxidizer</u>	<u>Fuel</u>	<u>Oxidizer</u>	<u>Fuel</u>
Outside Diameter (in.)	12.50	12.50	12.50	12.50
Inside Diameter (in.)	11.50	11.50	11.50	11.50
Effective Area (in. ²)	113.1	113.1	113.1	113.1
Stroke (in.)	24.8	19.8	15.6	12.7
Number of Convolutions	118	94	74	60
Stroke/Convolutions (in.)	0.21	0.21	0.21	0.21
Plate Thickness (in.)	0.006	0.006	0.006	0.006
Solid Height/Convolution (in.)	0.021	0.021	0.021	0.021
Number of Spacer Rings	-	-	2	2
Thickness per Spacer Ring (in.)	-	-	0.15	0.15
Solid Height (in.)	2.48	1.97	1.85	1.56
Spring Rate/Convolution (lb/in.)	1630	1630	1630	1630
Free Length/Convolution (in.)	0.192	0.192	0.192	0.192
Free Length (in.)	22.66	18.05	14.21	11.52
Segments Weight (lb)	.1	6.5	5.0	4.1
Capsule Weight (lb)	14.44	12.70	10.88	9.62

Oxidizer, N₂O₄
 $\rho_o = 90.2 \text{ lb/ft}^3$

Maximum flow rate, 0.888 lb/sec

Pulsing frequency, 0.020 sec/min

Based on the above propellant conditions and pressurant properties from Reference 5, average pressurant heat requirements are:

Fuel Tank

$$H = \frac{75.5}{(0.02955 - 0.01369)} \times \frac{0.444 \times 0.020}{56.1} = 0.042 \text{ Btu/min}$$

Oxidizer Tank

$$H = \frac{75.5}{(0.02955 - 0.01369)} \times \frac{0.888 \times 0.020}{90.2} = 0.053 \text{ Btu/min}$$

In the heat transfer analysis conducted, the following areas were investigated:

- (1) Heating Rate Analysis
- (2) Heat Exchanger Design
- (3) Conduction Analysis

(1) Heating rate requirements for the volatile liquid expulsion system were determined using the following model.

Consider a typical "T-S" diagram (shown in Figure 4-3) and assume that the system stays close to its design range specified by the coordinates for pressure and temperature. The cycle 1-2, 2-3 will adequately describe the physical model within the limits of the following assumptions.

From point (1) to point (2)

$$(S_1 - S_2) = 0$$

If $(P_1 - P_2)$ is small; i.e., the process would be performed in small, ΔP changes. With $\Delta S = 0$ and ΔP small, it may be assumed that the quality at point (1) is equal to the quality at point (2). The work done in expelling the propellant from the tank from (1) to (2) is equal to the change in internal energy of the volatile liquid. But for small volume changes (short duration firing with low propellant flow rates) of the pressurant, the change in internal energy of the liquid may be described by the change in its enthalpy.

$${}_1\Delta_2 U = {}_1\Delta_2 H = \bar{I}W_2$$

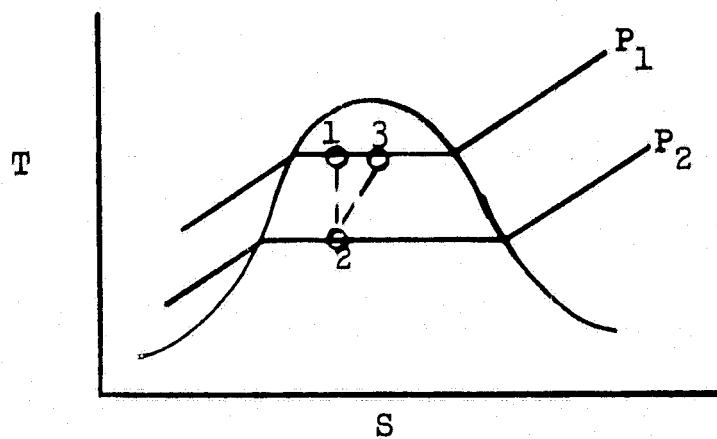


Figure 4-3 Pressurant Thermodynamic Diagram

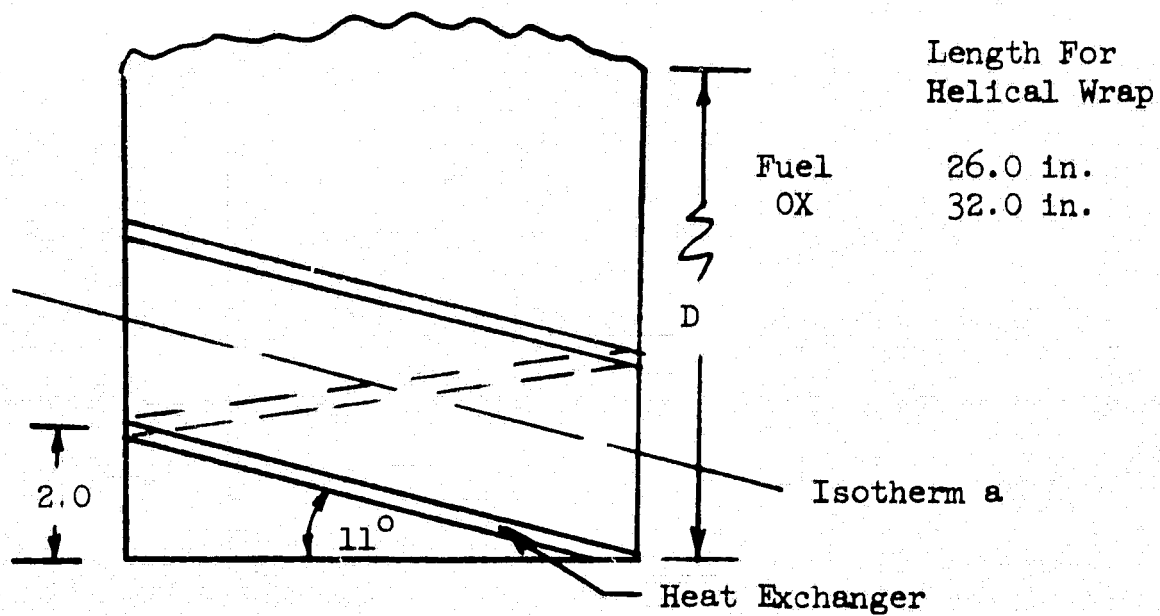


Figure 4-4 Heat Exchanger Configuration

To return to point (3) heat must be added to the liquid and vapor while the volume is held constant. The heat added may be approximated by the change in enthalpy from (2) to (3). The total additive heat requirement may be found by repeating (1), (2) and (3) until the propellant supply is exhausted.

The specific enthalpy change for the first cycle is 1.66 Btu/lb and the total enthalpy change is 9.61 Btu/lb. This energy must be added to the liquid and vapor at a rate determined by the average propellant flow rate. The minimum required heating rate is 0.05 Btu/min.

The total time, sum of the 0.02 second pulses, required to drop the pressure to the sensitivity level ($\Delta P = 5$) of the transducer was 1.72 seconds. The time required to exhaust the complete supply of fuel at the highest flow rate was 145 seconds. Therefore, the number of $\Delta P = 5$ psia cycles required to expel 64.3 pounds of fuel is 84.4 and the total heat addition requirement is 810 Btu.

- (2) The energy source for the volatile liquid is a glycol/water heat exchanger with the capacity to deliver 0.05 Btu/min. The heat exchanger must be designed in such a manner as to heat the liquid and vapor uniformly within a fixed time interval.

The required surface area may be found from,

$$\frac{dQ}{d\Theta}_{Req} = \dot{\omega}_H C (T_{in} - T_{out}) = A_S \left(\frac{T_{in} + T_{out}}{2} - T_2 \right) \bar{h} \quad (1)$$

where,

$$\bar{h} = \frac{h_1 (\rho VC)_L + h_v (\rho VC)_v}{(\rho VC)_L + (\rho VC)_v} \quad (2)$$

and for turbulent-free convection,

$$h_{L,V} = 0.13 K_{L,V} \left[\frac{\rho_{L,V}^2 g \beta_{L,V} T_{L,V} P_R}{\mu_{L,V}^2} \right]^{1/3}$$

which is the energy equation. Assuming the limiting boundary conditions for the system, maximum propellant flow rate and minimum heat exchanger flow rate, the minimum required heating surface area for the fuel tank is 22 in.². The calculation procedure may be modified to include heat loss to the atmosphere by using

$$AS_2 = AS_1 \frac{\bar{h}}{\bar{h} - h_{air}}$$

where

A_{S_1} = uncorrected value of surface area

A_{S_2} = increased surface area to accommodate convections heat loss

h_{air} = heat transfer coefficient for air

The required minimum heating surface area then increases to:

$$A_S = 24 \text{ in.}^2$$

$$L_H \text{ (length of heat exchanger)} = 48 \text{ in.}$$

for the fuel tank.

These design values were increased to ensure proper operation of the system during testing. A minimum heat exchanger contact surface area of 100 in.² was used.

The analysis was performed on the fuel tank. By scaling the results, an estimate of the requirements for the oxidizer tank heat exchanger may be determined.

The ratio surface area of the heat exchangers for the tanks is proportional to the rate of change of pressurant volume and the masses of pressurant to be heated or,

$$\frac{A_{S_{ox}}}{A_{SF}} = \frac{\dot{\omega}_{ox} \rho_F}{\dot{\omega}_F \rho_{ox}} \frac{\omega_{pox}}{\omega_{PF}}$$

Using the above relation and adjusting to the difference in lengths between the tanks, $A_2 = 136 \text{ in.}^2$, $L_H = 272 \text{ in.}$

- (3) An investigation of the temperatures of the tank wall along isotherm (a) (Figure 4-4) and at the heat end of the tank gave the following results.

Using the relation

$$T_a = \frac{A_c K_T T_{in} + 1.083 A h T_L}{1.083 A h - A_c K_T}$$

the wall temperature along (a) was found to be 110°F.

For the head end, the temperature will be between atmospheric (70°F) and operational volatile liquid temperature (90°F). This is equivalent to stating that the heat exchanger's energy will dissipate within a short distance from the water/glycol plumbing. Consider the analysis for isotherm (a) which had two 180 degree energy sources located 2 inches away and had a temperature of 110 degrees. For the head end, there is only one source and it is at a minimum distance of 4 inches from the area of analysis.

4.1.4 Design Problems

During initial loading of the System A fuel tank, a failure of the bellows was experienced. Both sides of the bellows were evacuated and the initial quantity of propellant was to be loaded by slowly

opening the flow control valve and allowing a very small flow rate to occur. During evacuation of the propellant portion of the system, a short section of line between the solenoid shutoff valve and the flow control valve inadvertently was not evacuated and a small amount of Freon 11 remained in the line. The solenoid shutoff valve was then energized. The entrapped Freon 11 (approximately 30cc) vaporized resulting in a relatively loud impact noise in the tank. A subsequent examination indicated a leak across the bellows. The tank was returned to Metal Bellows Corporation for disassembly and examination; report of this investigation is presented in Appendix A.

Initially it was believed that vaporization of the small quantity of entrapped Freon 11 had imposed a dynamic shock load on the bellows and that the damage had occurred when the bellows came to rest against the stops. However, examination of the tank shell and the nylon support buttons (Item 30, Figure 4-2) in the bellows stiffening rings (Item 29, Figure 4-2) indicated that excessive rubbing had occurred between the tank and the buttons. From the position of the bellows on disassembly, it appeared that the bellows had "hung up" and tipped during the fast stroke caused by the vaporizing Freon. This hang up tendency had been noted during the acceptance testing of the System A fuel tank. The bellows appeared to "walk" down the tank during the fill cycle. Because of cycling difficulties encountered during testing, the nylon button support was not considered adequate for the System A tanks.

To adequately guide and support the bellows capsule in the System A tanks during horizontal operation, six longitudinal glass-filled Teflon strips (Item 61, Figure 4-2) were added to the tank shell. The strips were machined after bonding to the tank, to provide a diametral clearance of 0.030 inch with the bellows capsule outside diameter. The strips extended as close as possible to the electron-beam closure weld. In order to provide a lead-in ramp and prevent hang up of the bellows, the exposed end was scarfed for a distance of approximately 3 inches.

The stiffening rings were removed from the System A capsule assemblies. With the close fitting machined diameter, the anti-sag rings were no longer required. A design revision was also made for the System A tanks in the area of the electron-beam closure weld. Metal Bellows Corporation experienced considerable difficulty in removing the waviness of the tank shell resulting from heat treatment. The majority of the difficulties they experienced in electron-beam welding was a result of this problem. The design revision consisted of removing the reinforcing ring and a portion of the tank shell and replacing this with a tapered machined ring (Item 44, Figure 4-2). This revision was incorporated on the dome only in the fuel tank and on both the tank shell and the matching dome in the oxidizer tank. These rings were machined subsequent to heat treat to provide a proper joint configuration for electron-beam welding.

4.2 Tank Assembly Fabrication

In manufacturing the tanks, relatively minor difficulty was encountered with the bellows fabrication. However, several problem areas were encountered in processing and fabricating the tank shell. A completed tank assembly is shown in Figure 4-5 installed in the system test holding fixture.

4.2.1 Bellows Assembly

Fabrication of the bellows capsules by Metal Bellows proceeded satisfactorily with very few problems encountered. The bellows convolutions were fabricated from type 347 stainless steel and the headers from type 321 Cres. A typical convolution outside diameter weld bead is shown in Figure 4-6 and an inside diameter weld bead is shown in Figure 4-7. A spring rate test was conducted on the first segment assembly completed. A completed bellows assembly is shown in Figure 4-8.

4.2.2 Tank Shell Fabrication

In accordance with the NASA design requirements the tank shell was fabricated from aluminum. Aluminum alloy 2219 was selected as the basic tank shell material. Because of limited manufacturing experience

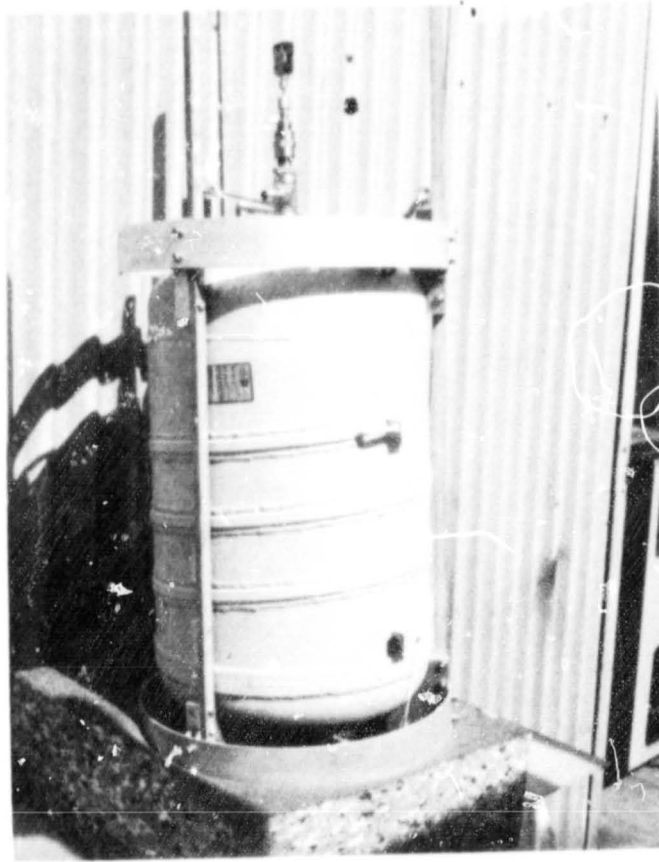


Figure 4-5 System B Oxidizer Tank in
System Test Holding Fixture

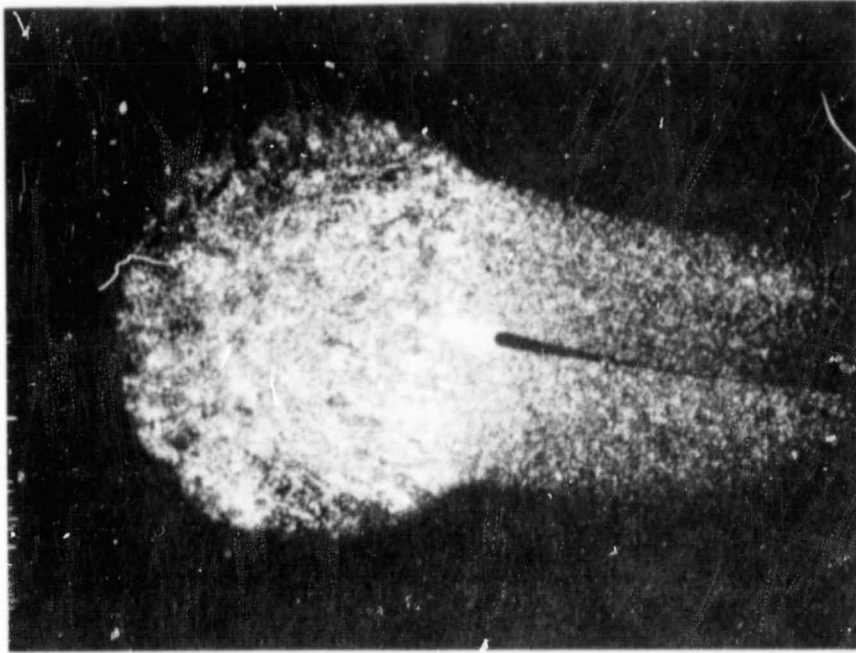


Figure 4-6 Micro Photo of Convolution Outside Diameter Weld Bead. Magnification 100X

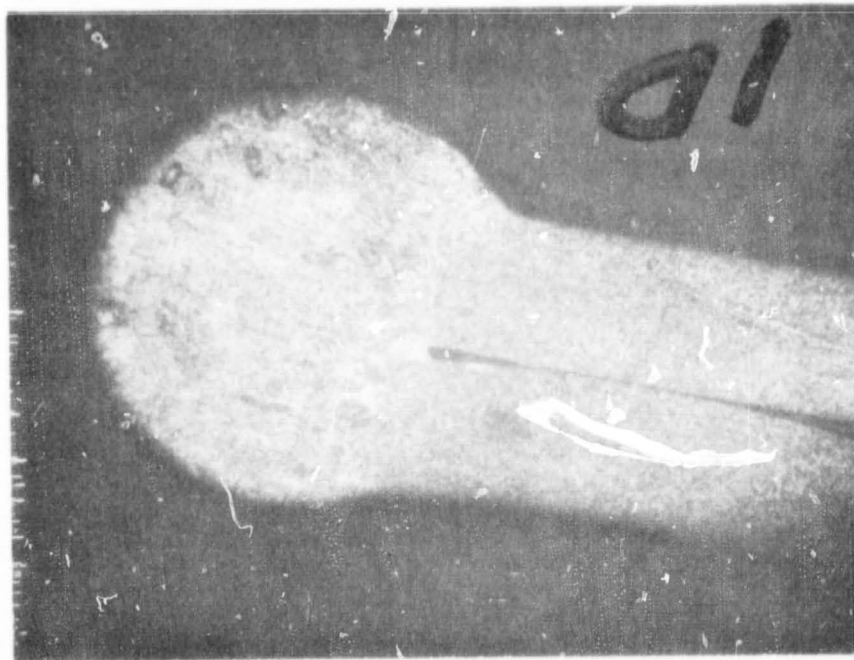


Figure 4-7 Micro Photo of Convolution Inside Diameter Weld Bead. Magnification 100X

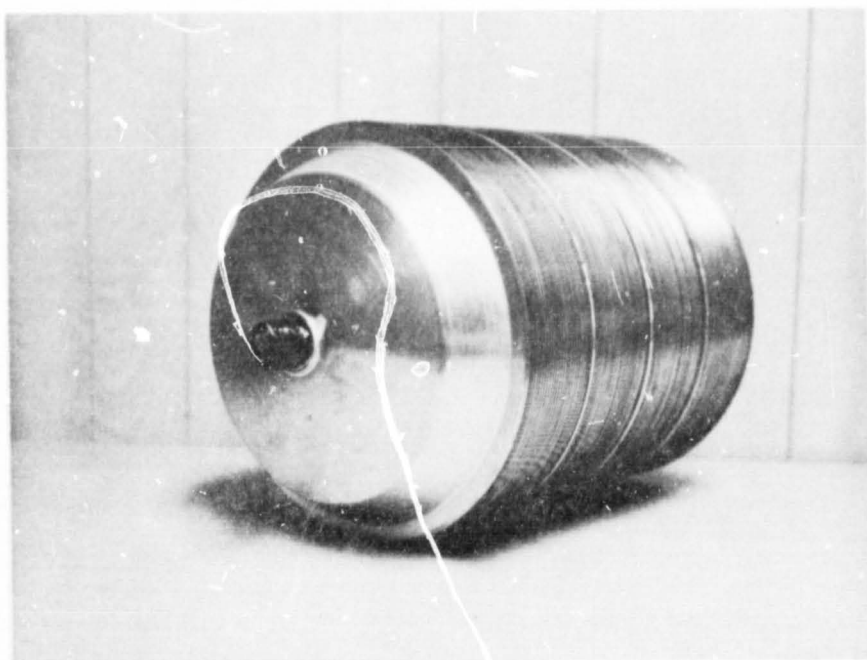
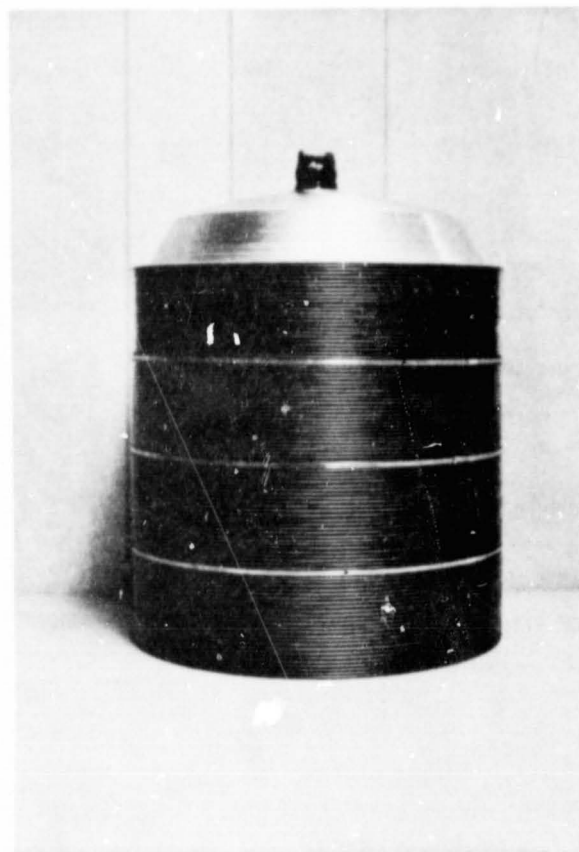
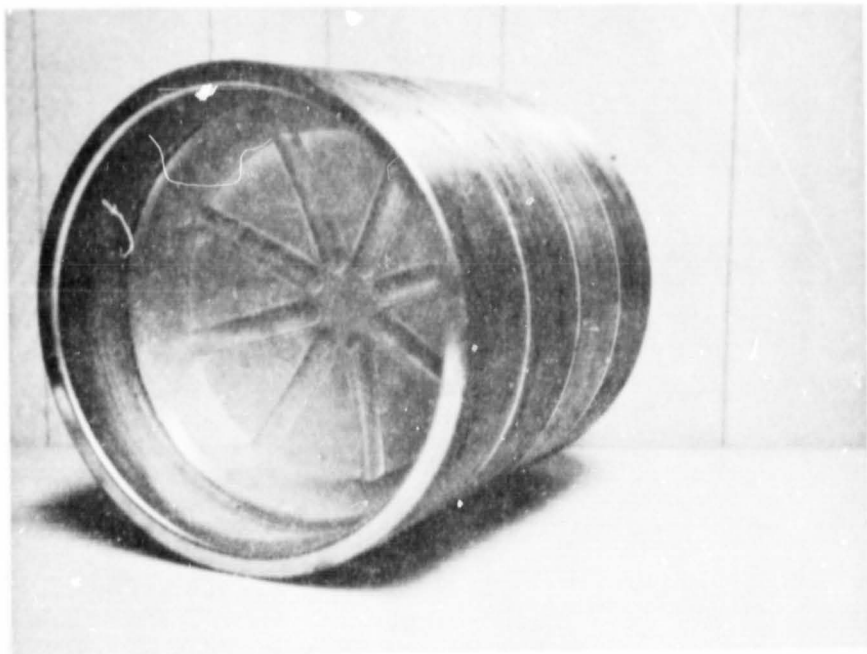


Figure 4-8 Bellows Assembly

with 2219, some fabrication difficulties were experienced by the tank fabricator, Spacecraft Welding and Manufacturing, during manufacture of the tank shell.

In order to form the 2219 heat exchanger tube to the tank contour it was necessary that the material be in an annealed condition. Attempts to resistance weld the annealed heat exchanger tube to the tank cylinder resulted in the presence of microcracks in the weld bead, particularly in the System B tanks where the metal thickness ratio was in excess of 3 to 1. It was felt that satisfactory welds could be obtained if the material was in a heat treated condition. However, the amount of warpage expected in the heat exchanger tube from the heat treat cycle would result in an excessive gap condition for resistance welding. Sample fusion welds were attempted to determine the amount of weld distortion that would be experienced. In the System B tank no distortion was evident on the ID of the tank. However, in the System A tank, weld shrinkage from the fusion weld path caused a slight waviness in the tank shell. This condition was not expected to adversely affect the bellows cycling performance as there were no abrupt changes in contour and the total amount of waviness was small (0.020 in.). Fabrication proceeded using the fusion welded design.

Because of unavailability of 2219 bar stock, 6061 aluminum was originally substituted for 2219 for the end fittings. The weld attaching the 6061 end fitting in each dome developed multiple cracks. Subsequently, a limited quantity of 2219 bar stock of the proper size to allow machining of new bosses was located and a change was made.

For the final trim operation prior to making the closure weld, plug type tooling was used to remove the out of round condition and waviness resulting from the heat treat operations. When the tank was installed in the weld tooling, the external strap-on weld fixture was found to be too flexible to remove the waviness and out of round condition in the tank.

New strap-on tooling was fabricated which was sufficiently rigid to restrain the tank around during the machining operation subsequent to heat treat. The tooling then functioned as the weld fixture during electron-beam welding to maintain the tank in a round condition during the weld process. Prior to installing the tooling, the tank and dome were rolled in the area of the reinforcing to remove the majority of the waviness resulting from the heat treat cycle.

4.2.3 Fabrication Problems

The initial System A oxidizer tank collapsed while in the process of evacuation for leak testing (see Figure 4-9). Although the tank had previously withstood this operation with the skirt unsupported, the replacement of the end fitting in the opposite end dome was believed to have caused the unsupported skirt to go slightly out of round, reducing the hoop strength. On all subsequent units a support disc was inserted prior to evacuation. A stress analysis assured that, in an operational configuration, each of the tanks possessed adequate margin against collapse during evacuation.

A bellows failure occurred at Metal Bellows Corporation during pre-acceptance leakage testing of the System A oxidizer tank. Both sides of the bellows were evacuated to allow helium leak check. The vacuum on the outside of the bellows only was then vented to atmosphere which created a 15 psi differential across the bellows. The high dynamic energy imparted to the bellows during the fast stroke resulted in twisting and warping of the bellows assembly upon impact of the two headers. Two of the bellows segments were damaged.

During proof pressure testing, a rupture occurred in the System A oxidizer tank shell. Failure occurred at an internal pressure of 210 psig, which is less than 50 percent of the required burst pressure (450 psig). The failure occurred in the tank dome to which the bellows capsule is attached. As shown in Figure 4-10, the failure occurred in the approximate area of the angle clips which are installed in the dome to provide a support for the bellows.

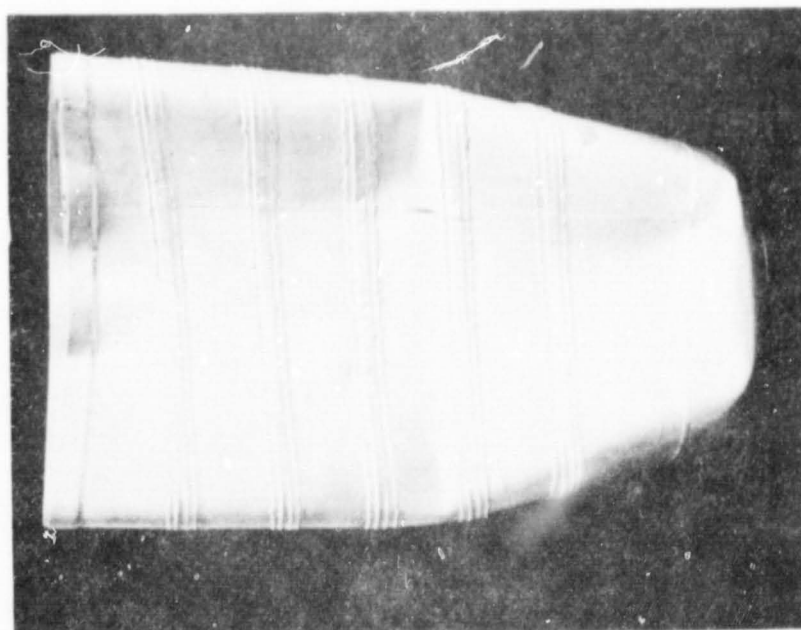
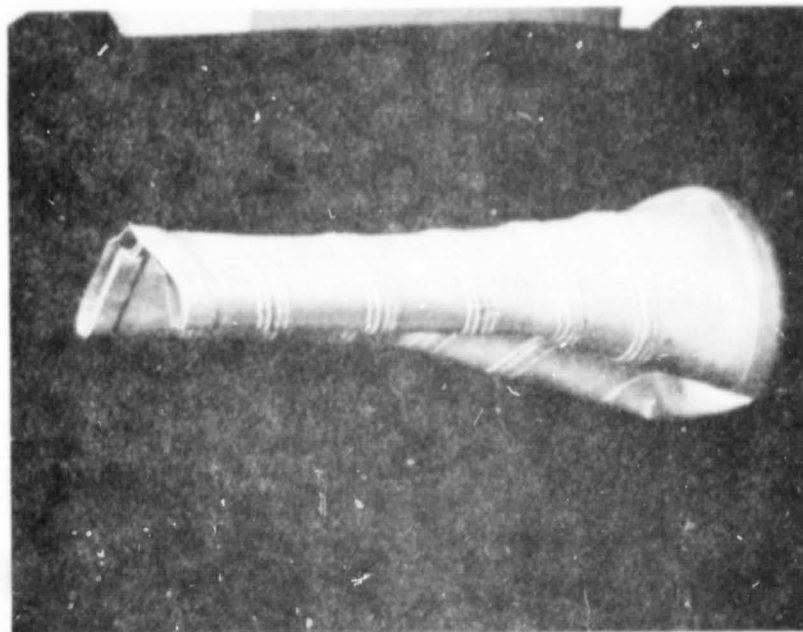


Figure 4-9 Metal Bellows Corporation P/N 57941 (System A fuel tank)
Collapsed During Evacuation for Leak Check

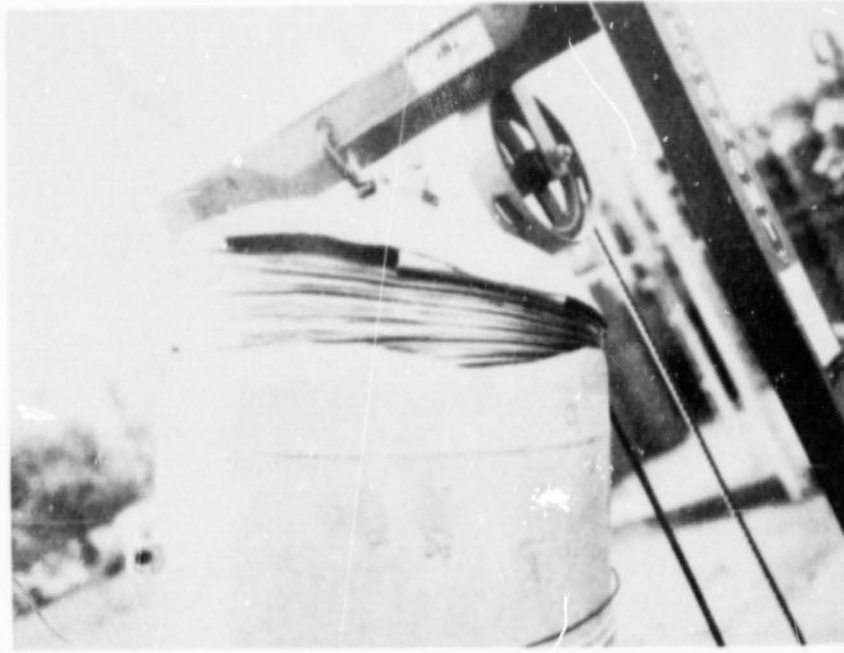


Figure 4-10 Proof Pressure Failure
System A Oxidizer Tank

A review of the hardware was conducted by Metal Bellows Corporation where the cause of the failure was attributed to local annealing of both the dome and the tank shell. Metal Bellows stated that the annealing occurred during removal of a defective Teflon guide strip. The strip was removed by torch heating the tank locally while submerged in water. Although no evidence of overheating was noted during removal, it was concluded that the annealing occurred at that time.

At the conclusion of the pressurization system tests with the System A oxidizer tank, it was discovered that a small pinhole leak was present in the bellows. The leak apparently opened some time during the test cycling. The fail-safe condition of the system design was demonstrated by this leak as on disassembly of the test system N_2O_4 was found in the pressurant cavity of the tank. The leakage, however, had no effect on the pulsing performance of the system.

The N_2O_4 had reacted with the adhesive used to install the Teflon strips in the tank resulting in failure of the bond. The loose Teflon strips were jammed between the tank wall and the bellows resulting in restraint

of the bellows in the expelled position. The presence of the leak in the tank was considered to be the result of a manufacturing defect. Since this tank had been subjected to several rework cycles during the initial assembly, the leak was believed to have been a result of the repair techniques used in the tank rework. The tank was subsequently flushed to clean the residual N_2O_4 out of the system and was then placed in storage. A design change will be required on future tanks in the bonding techniques of the Teflon guide strips to the tank shell.

At the completion of the pressurization system propellant testing, the four propellant tanks were placed in storage. When the System B tanks were removed from storage for incorporation into the engine test stand buildup the System A tanks were inspected at the same time to ascertain their condition after an extended storage period. Corrosion damage was discovered on the System A oxidizer tank in the area of the heat exchanger outlet fitting as shown in Figure 4-11.

The results of the contamination noted after the extended storage indicated residual N_2O_4 was apparently entrapped in the bellows convolutions. This subsequently reacted with moisture in the air and formed nitric acid which in turn attacked the tank shell.

Prior to conducting the auxiliary propulsion system tests, a gaseous nitrogen leak test was conducted to verify the integrity of the System A tank bellows assemblies. Nitrogen was introduced into the inside of the bellows capsule at a pressure of 5 psig. This pressure extends the bellows to a fully open condition. The tank pressurant port was then monitored for leakage. The oxidizer tank was found to be satisfactory. The fuel tank, however, indicated a nitrogen leak rate of approximately 300 cc/min at STP.

The tank was returned to Metal Bellows Corporation for determination of the location and cause of the leak and appropriate corrective action where the tank was cut open. The failure analysis report included as Appendix B described the location and cause of the leak as determined by Metal Bellows Corporation.

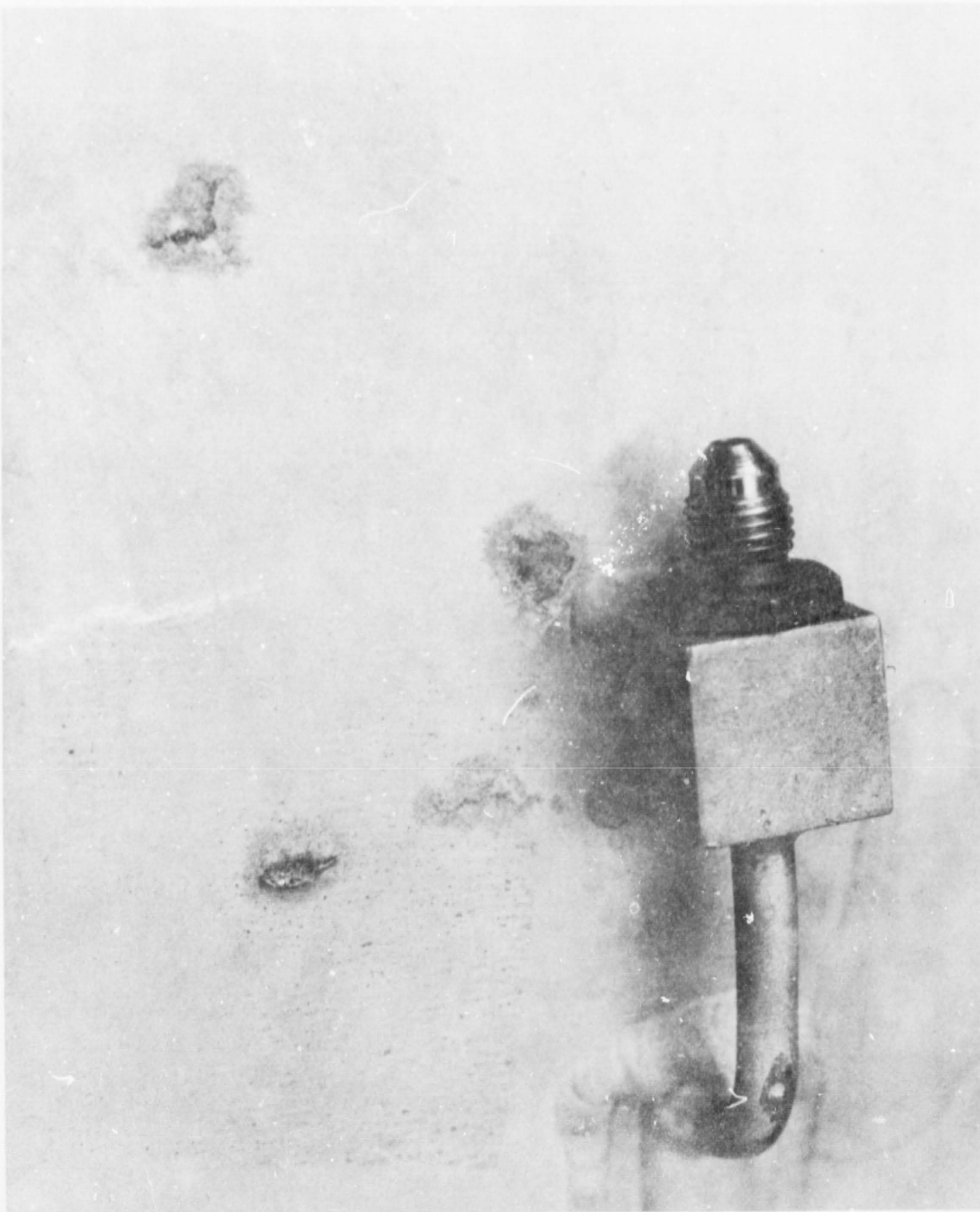


Figure 4-11 Corrosion Damage on System A Oxidizer Tank

The design change which added the guide buttons on the end terminal to supplement the guide provided by the buttons on the support ring was added after the capsule assembly for this tank had been completed. The relative locations are shown in Figure 4-12. In order to hold the assembly during the welding operation the bellows was clamped in the stacked position. Local burn through during attachment of one of the guide button pads resulting in fusion of the adjacent convolution diaphragm to the movable header. The local restraint of the diaphragm caused an excessive stress concentration during cycling which resulted in failure.

It is not known when the failure actually occurred during the approximately 75 cycles accumulated on this unit. No evidence of leakage had been noted during the test program to that point. Metal Bellows advised that this condition could not exist on the other tanks because the guide button pads were welded to the bellows header prior to capsule assembly.

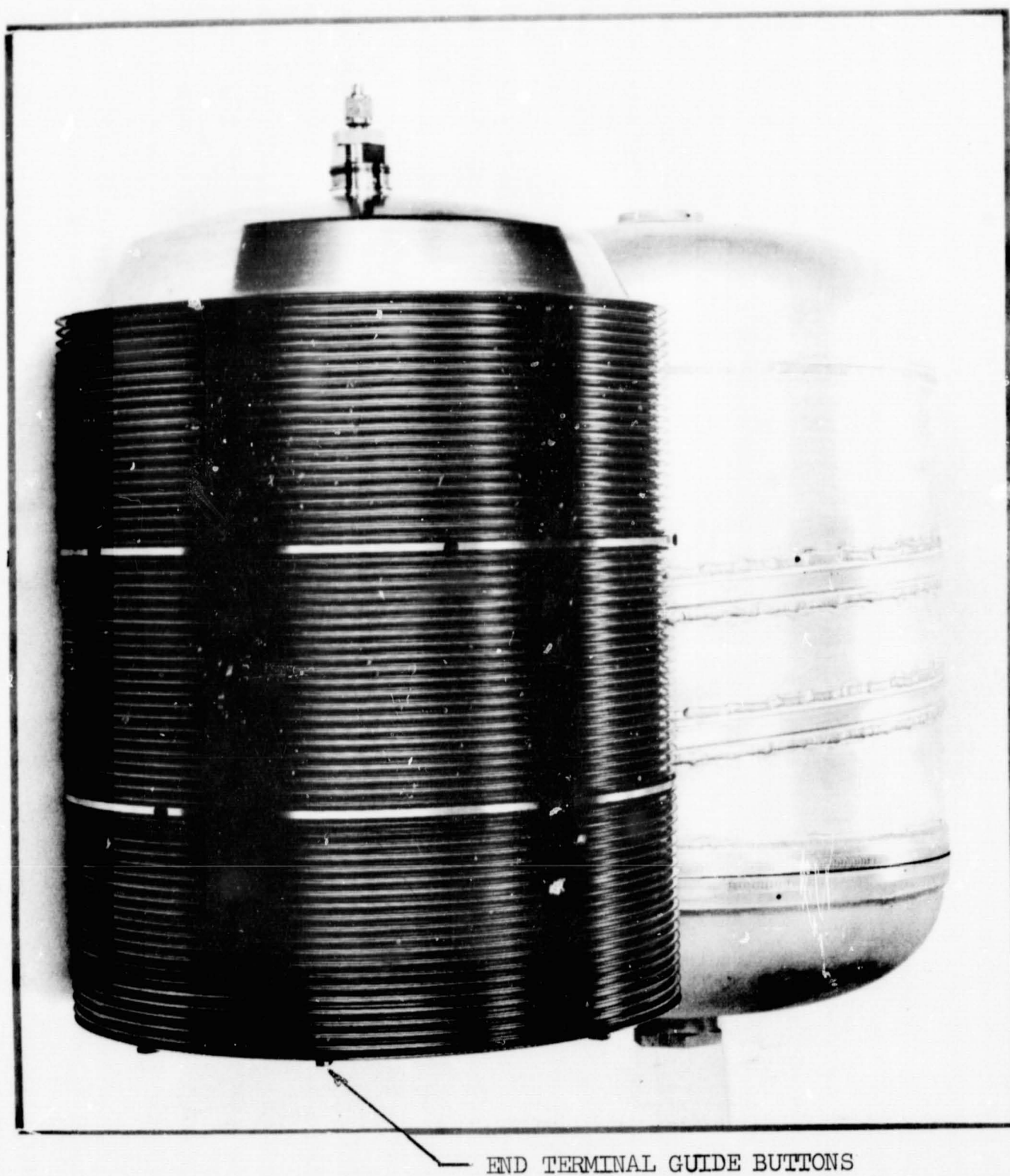


Figure 4-12 Nylon Guide Buttons, Bellows Capsule

5.0 COMPONENT EVALUATION

Component and subsystem tests were conducted to demonstrate compliance with design specifications prior to final assembly of the full scale system hardware. A bellows segment was tested to determine the spring rate expected. Weld specimens simulating the various weld joints in the tank were tensile tested. The pressure switch and solenoid valve were tested individually and jointly to assure proper flow control of the heat exchanger fluid in response to changes in pressurant pressure. Completed tank assemblies were subjected to proof pressure tests and bellows pressure differential to assure conformance to design requirements. Volumetric and expulsion efficiency were determined for each test tank. Volumetric efficiency was determined by the ratio of the amount of propellant remaining in the tank after expulsion to the total amount of propellant loaded.

5.1 Expulsion Tank

The expulsion tank evaluation was divided into three series of tests. A series of weld tensile tests was conducted to verify the strength levels expected in the finished tanks; spring rate and cycling tests were conducted on the bellows segment and capsule; and finally, an acceptance test was conducted on each completed assembly.

5.1.1 Weld Tensile Tests

A series of weld tensile samples were made which duplicated the butt weld joints which are heat treated subsequent to welding. In addition, samples of the parent material in the heat treated condition were tensile tested. These tests verified that the use of a liquid nitrogen quench, instead of a conventional water or oil quench, to reduce warpage, did not adversely affect the material properties.

The stress values obtained during the first series of tests were all within estimated strength values for the 2219 aluminum and in all cases exceeded the calculated stresses of the tank design. The calculated

stresses are as follows:

	<u>Proof Pressure</u>	<u>Burst Pressure</u>
0.100 aluminum (System B)	34,900 psi	49,700 psi
0.063 aluminum (System A)	35,100 psi	48,700 psi

The weld samples duplicated the tank weld configuration shown in Figure 5-1.

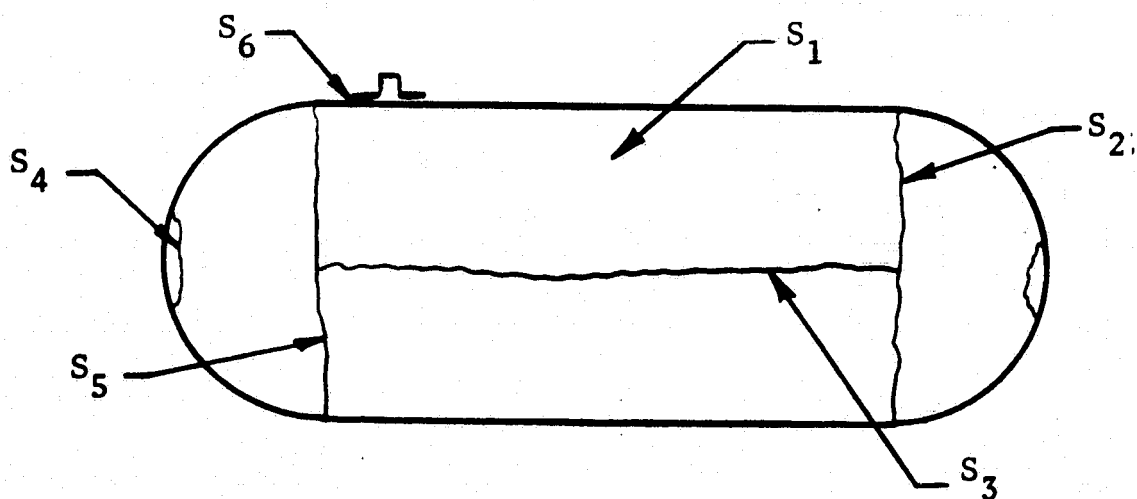


Figure 5-1 Weld Configuration Location of Test Samples

The weld specimens, as shown, represented the following joint areas:

- S₁ - parent material
- S₂ - girth weld joining the dome to the cylinder
- S₃ - longitudinal weld of the cylinder
- S₄ - weld joining the ports to the dome
- S₅ - electron-beam closure
- S₆ - heat exchanger fillet

In evaluating the electron-beam closure weld, two sets of test coupons were prepared. The first set of coupons was of the standard configuration as shown in Figure 5-2. Fracture occurred outside of the reinforced area. This test indicated that any failure would occur in the basic tank shell rather than the closure weld. In order to determine the

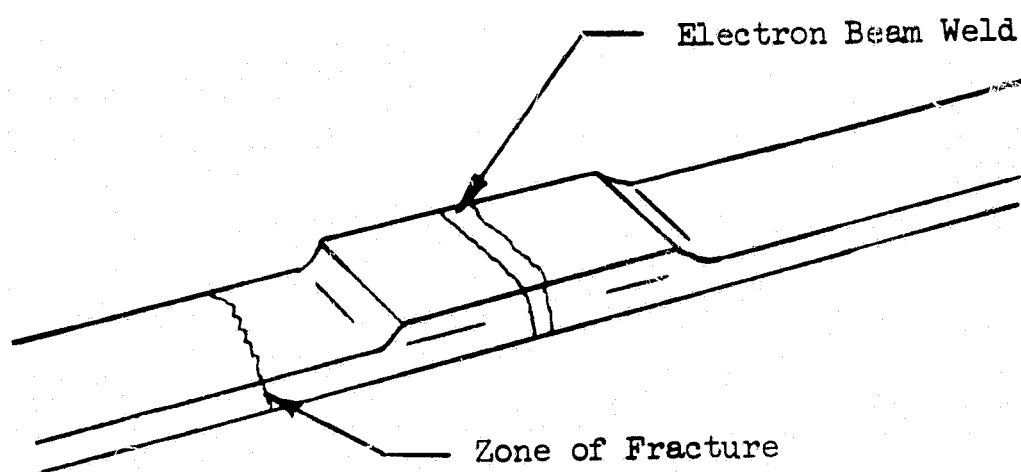


Figure 5-2 Closure Weld Tensile Specimen -
Failure in Parent Metal

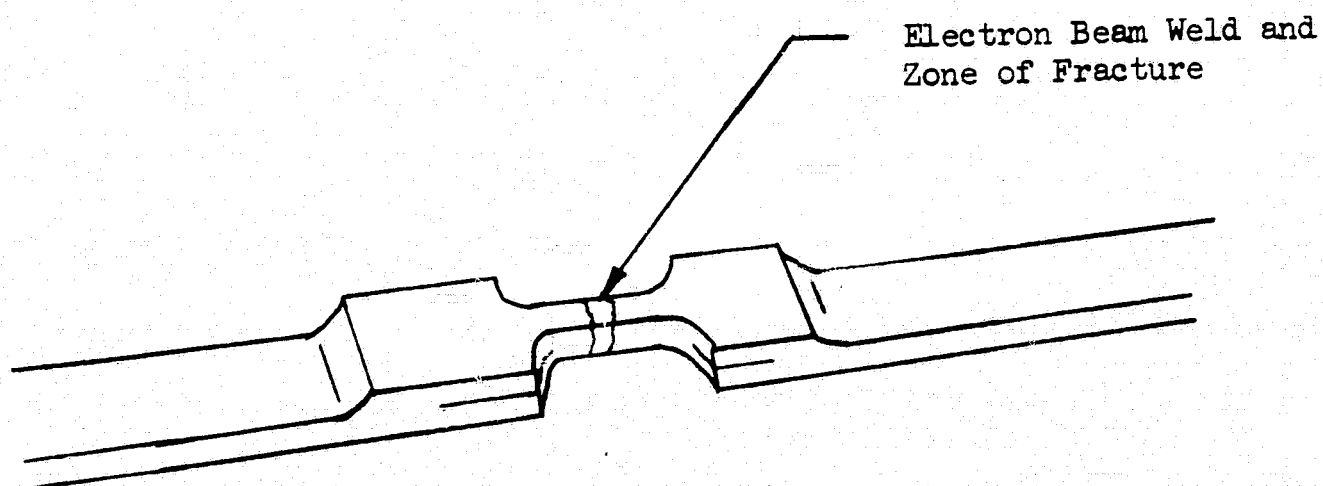


Figure 5-3 Closure Weld Tensile Specimen -
Failure in Weld

actual stress level of the weld joint itself, revised test specimens were prepared as shown in Figure 5-3. Results of the weld tensile tests are listed in Table 5-1.

Failures during fabrication of the System A oxidizer tank resulted in the tank being subjected to three heat treat cycles. The material manufacturer, Aluminum Company of America, recommended that 2219 clad aluminum, of which the tank shell is made, be reheat-treated no more than one time. They indicated that dispersion of the clad material into the base metal resulted in degradation of the material tensile properties with repeated heat treatments. Test coupons were cut from the tank shell during the end trimming operations. These test coupons were subjected to the heat treat cycle with the tank shell and were tensile tested for determination of the properties expected in the tank.

As was expected, some reduction in the tensile properties of the tank shell material was evidenced. The results of the weld tensile test coupons are shown in Table 5-2. Specimen A and B were control coupons of previously unheat-treated material used for the new dome. Specimens C and D were taken from the reworked tank shell.

The tensile values obtained from the tank shell material were lower than the calculated tank stresses as shown in Table 5-3. The proof pressure corresponding to the tensile data was still considered to provide an adequate margin over the working pressure of 180 psia. The burst pressure level provides an even greater margin over proof pressure.

The decision to use the tank with a lower level of proof pressure was based on preliminary information supplied by Metal Bellows. They indicated the test results of the base metal coupons had satisfactory properties. This led to the conclusion that the repeated heat treatment cycles had slightly degraded the tensile properties of the tank shell. However, a subsequent comparison with the test data on the original base metal specimens (reference Table 5-1) showed that the tensile levels of all the new coupons were lower than anticipated. This indicated that

Table 5-1. Tensile Test Data

Specimen No.	Size (in)	Area (in ²)	Yield Load (lbs)	Yield* (psi)	Ultimate Load (lbs)	Ultimate (psi)	Elong-** gation (%)	Weld Configuration (Fig. 5-1)
2-A	.525/.100	.0525	1,880	35,810	2,830	53,900	8.5	S-2, S-3
2-B	.527/.100	.0527	1,945	36,910	2,875	54,550	10.0	S-2, S-3
2-C	.530/.100	.0530	1,985	37,450	2,870	54,150	8.5	S-2, S-3
1-A	.530/.100	.0530	2,050	38,680	3,015	56,890	12.5	S1
1-B	.520/.100	.0520	2,035	39,130	2,965	57,000	12.0	S1
1-C	.524/.100	.0524	2,020	38,550	2,987	57,000	13.0	S1
11-A	.532/.061	.0325	1,205	37,080	1,775	54,620	11.5	S1
11-B	.528/.061	.0322	1,190	36,960	1,750	54,350	11.5	S1
11-C	.525/.061	.0320	1,190	37,190	1,767	55,220	11.5	S1
1	.520/.062	.0322	1,140	35,400	1,705	52,950	9.0	S-4
2	.520/.062	.0322	1,140	35,400	1,685	52,330	6.5	S-4
3	.522/.062	.0324	1,140	35,190	1,700	52,470	6.5	S-4
Control 1	1.065/0.062	0.0660	2,390	36,210	3,000	53,030	11.0	S1
Control 2	1.020/0.062	0.0632	2,200	34,800	3,360	53,160	14.0	S1
HE-1	0.960/0.100	0.0960	3,725	38,800	5,075	52,860	14.0	S-6
HE-2	0.915/0.100	0.0915	3,500	38,250	4,850	53,000	14.0	S-6
HE-3	0.915/0.100	0.0915	3,500	38,250	4,825	52,730	15.0	S-6
C-1	0.505/0.102	0.0515	1,800	34,950	2,703	52,490		S-5
C-2	0.510/0.102	0.0520	1,920	36,920	2,707	52,060		S-5
C-3	0.510/0.102	0.0520	1,865	35,860	2,745	52,790		S-5
C-4	0.142/0.210	0.0298			920	30,870		S-5
C-5	0.164/0.210	0.0344			1,063	30,900		S-5
C-6	0.170/0.210	0.0357			1,183	33,100		S-5

* Yield at 0.2% offset

** In 2 inch gage length

Remarks: 0.005 in./in./min. strain rate

Table 5-2. Tensile Test Data - System A Oxidizer Tank

Specimen No.	Size (in)	Area (in ²)	Yield Load (lb) [*]	Yield (psi) [*]	Ultimate load (lb)	Ultimate (psi)	Elongation (%) ^{**}
A	0.088/0.435	0.0383	1300	34,000	1986	51,900	9.0
B	0.088/0.433	0.0381	1260	33,100	1936	50,800	10.0
C	0.061/0.423	0.0258	840	32,550	1240	48,150	5.0
D	0.061/0.427	0.0260	882	33,940	1319	50,750	8.0

^{*} Yield at 0.2% offset

^{**} In 2.0 inch gage length

Note: 1. 0.005 in/in/min strain rate
 2. Specimens A and B were from new material for dome
 3. Specimens C and D were taken from tank shell

the lower strength levels were a result of incomplete heat treat response rather than diffusion of the clad coat into the base metal.

Table 5-3 Stress and Pressure Level Margins in System A Oxidizer Tank

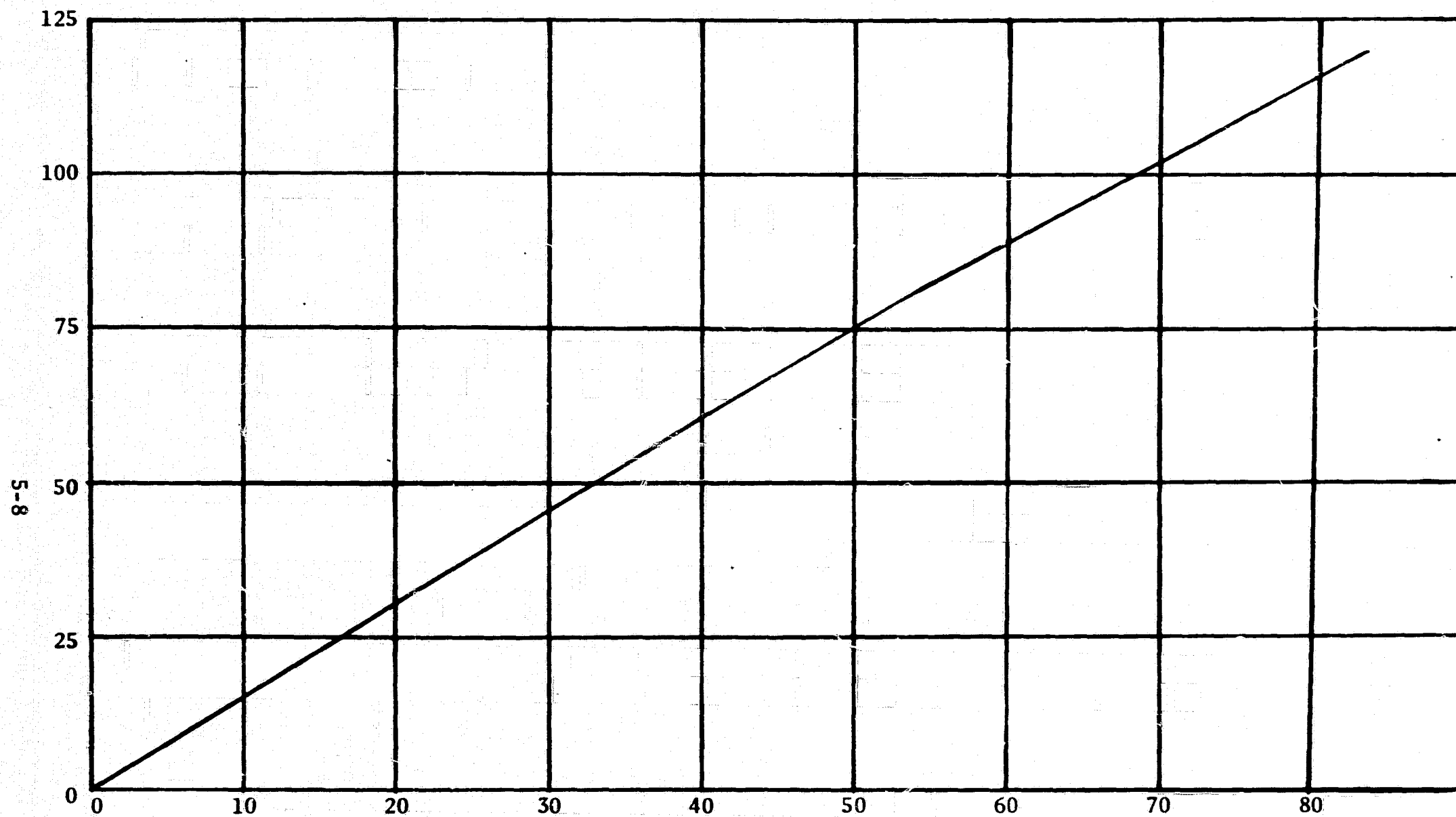
	<u>Yield Stress (psia)</u>	<u>Corresponding Proof Pressure (psia)</u>	<u>Ultimate Stress (psia)</u>	<u>Corresponding Burst Pressure (psia)</u>
Calculated	35,100	315	48,700	450
Minimum Test Value	32,550	292	48,150	446
Average Test Value	33,245	299	49,450	457

5.1.2 Bellows Segment Test

A compression load/deflection test was conducted on the first bellows segment assembly completed. The segment consisted of 20 convolutions and had a free length of 3.37 inches. The resulting curve is shown in Figure 5-4.

5.1.3 Bellows Capsule Cycling Tests

To verify the adequacy of the redesign of Teflon strips to solve the bellows hang up problem encountered in the System A fuel tank (see Section 4.1) a test fixture was fabricated to simulate the redesigned condition. Typical expulsion cycles was conducted using the bellows that had been fabricated for the System A oxidizer tank. The fixture is shown in Figure 5-5. During the cycling tests there was no evidence of the "walking" which had been experienced previously with the nylon button guide configuration. During the fill cycle a slight canting of the bellows header was noted as shown in Figure 5-6. However, operation was smooth throughout the fill cycle. To verify the capability of the bellows capsule without stiffening rings to withstand a 25 psi differential pressure, a test was conducted as shown in Figure 5-7. A slight "snaking" of the bellows was noted indicating some squirming was taking place. However, there was no indication of any indentation of the Teflon guide



$$\text{Compressive Deflection} = \frac{\text{Deflection}}{\text{Free Length} - \text{Stack Height}}$$

Figure 5-4 Bellows Segment Compressive Load Curve

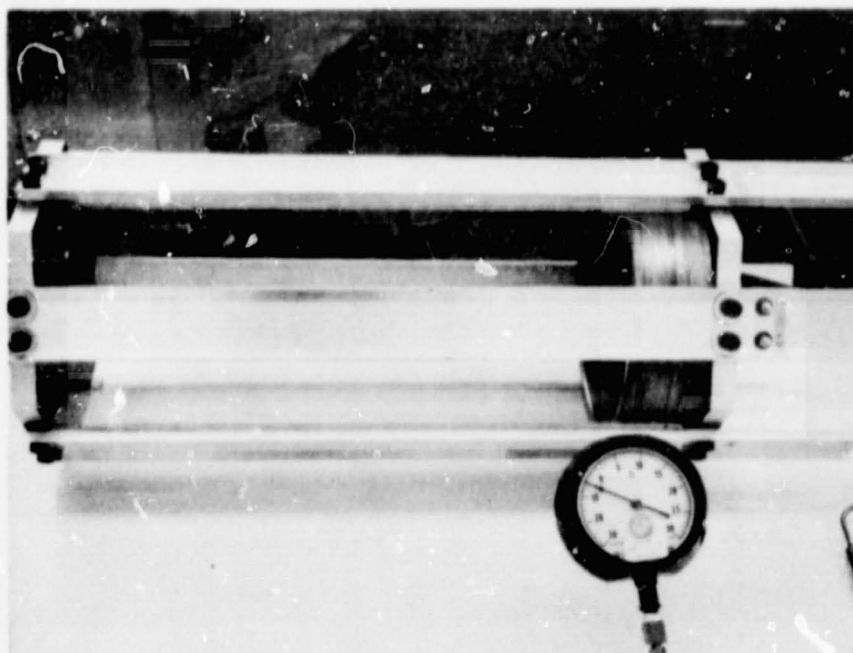


Figure 5-5 Bellows Test Cycling Fixture

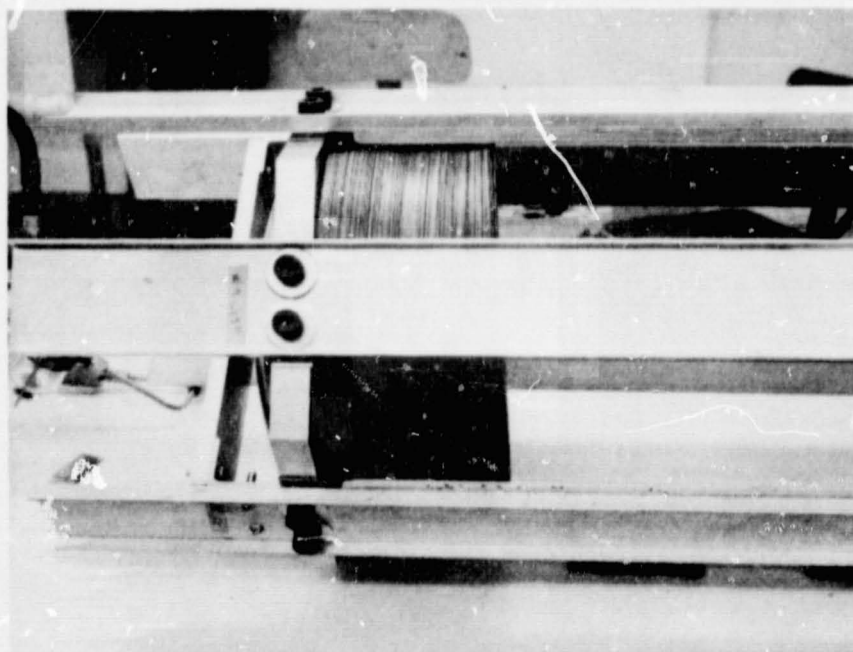


Figure 5-6 Bellows Configuration During Fill Cycle

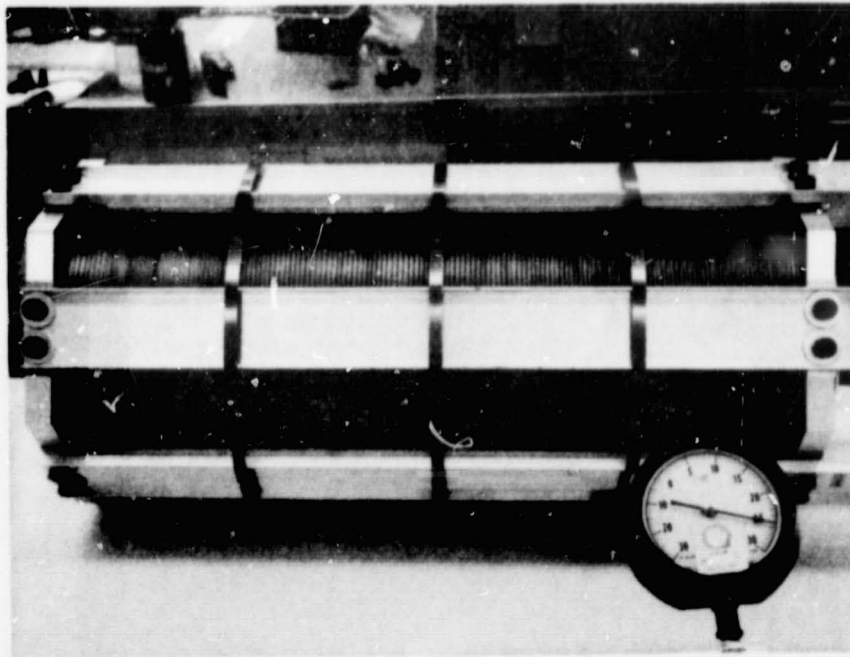


Figure 5-7 Bellows Capsule Subjected to 25 psi
Internal Differential Pressure

strips and no release of the internal pressure movement to the bellows was smooth. The bellows was then filled with Freon 11 and allowed to stand over the weekend. Upon initiation of propellant flow, there was no indication of any cold flow of the Teflon or hang up of the bellows.

5.1.4 Tank Acceptance Testing

Each completed tank assembly was acceptance tested to demonstrate its acceptability in meeting the system requirements. The acceptance test results are summarized in Table 5-4. The test procedure used by Metal Bellows was identical for all tanks. The procedure for the System B oxidizer tank is presented as Appendix C.

Table 5-4 Tank Acceptance Test Measured Operating Parameters

	System A		System B	
	<u>Oxidizer Tank</u>	<u>Fuel Tank</u>	<u>Oxidizer Tank</u>	<u>Fuel Tank</u>
Tank Weight (lb)	29.25	28.25	23.50	20.94
Maximum Propellant Volume (in ³)	2530	2250	1751	1419
Initial Pressurant Volume (in ³)	1328	1074	822	793
Expulsion Efficiency (%)	97.88	98.3	99.2	99.4
Final Pressurant Volume (in ³)	3804	3286	2589	2203
Total Tank Volume (in ³)	3906	3366	2609	2244
Volumetric Efficiency (%)	64.8	66.8	65.6	63.4
Pressure Differential to Stroke Bellows (psi)	5.0	5.0	4.5	4.5
Proof Pressure Test (psig)	315	315	510	510

5.2 System A Heat Control System

The heat input control circuit for System A tests during the pressurant system demonstration consisted of an on-off heat exchanger valve and a pressure switch sensing tank pressure. The use of commercially available hardware was considered adequate for the system requirements for control valves and pressure switches. Barksdale Valves

Co., Part D2T A400SS, was used for the pressure switch and Skinner Electrical Valve Co., Part No. V56LB2100, was used for the three-way valve.

Acceptance testing of the three-way solenoid valves consisted of determining the pressure drop at various flow rates and measuring pertinent electrical characteristics of each of the valves. Typical flow rate curves with 60 percent ethylene glycol solution at 180°F are shown in Figure 5-8.

The four pressure switches were tested for their operating characteristics at both 166 and 284 psig. All four switches were repeatable, both opening and closing pressures, to within 1/2 psi. The deadband range at both the high and low pressure ranges was 6 psi and was repeatable within 1 psi.

The pressure switches were then connected to the flow control valves. Response times of approximately 1 second were encountered between attaining the required pressure level and initiation of flow of the heat exchanger fluid. As a result of this series of tests, each of the valve and pressure switch combinations were considered acceptable for system testing.

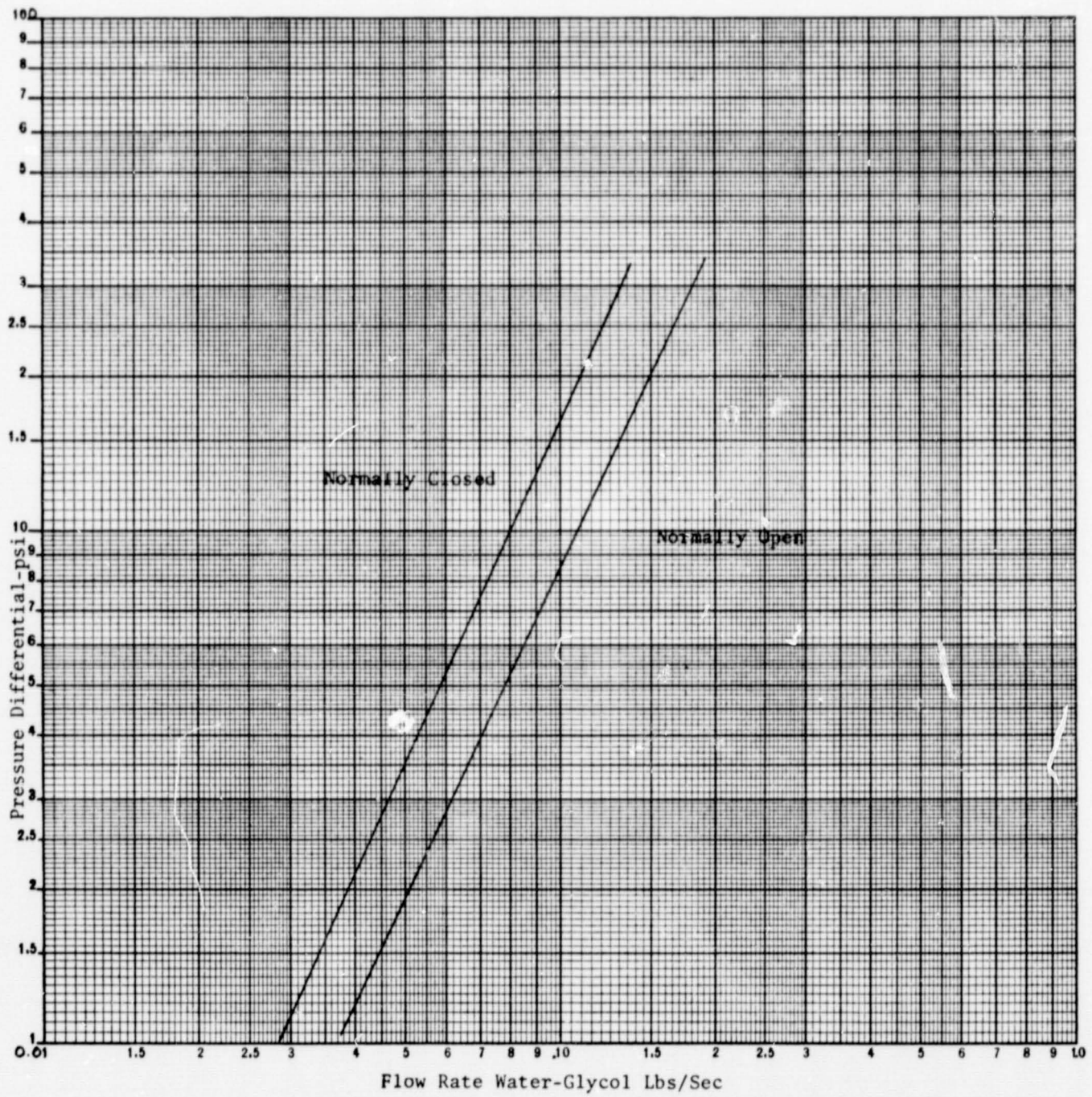


Figure 5-8 Flow Rate of Flow Control Valves

6.0 LOADING METHOD INVESTIGATION

Studies were conducted to determine if improvements could be made in accuracy of loading the materials or possible simplification of the loading procedure. Methods which were investigated included sub-cooling of the volatile liquid prior to loading, liquid versus solid loading of the heat storage material, and the effects of sequence loading of the volatile liquid and the heat storage materials. These investigations were conducted using the subscale tank. The method selected for use in the system testing consisted of the following sequence.

1. The heat storage material (when used) is heated to 100°-150°F, then loaded into the pressurant cavity in a liquid state.
2. Simultaneously the pressurant and propellant cavities of the tank are evacuated.
3. The pressurant was loaded at ambient temperature using the vapor pressure in the pressurant storage container to force the required amount of pressurant into the cavity.
4. Finally, the propellant was loaded at a pressure just sufficient to overcome the pressurant vapor pressure.

However, further modifications to the loading procedure were made as a result of problems encountered during initial system tests as described in Section 8.1

6.1 Pressurant Loading

During the feasibility demonstration, Contract NAS 9-1004, pressurant loading was accomplished by using the ambient temperature vapor pressure to force the liquid phase of the pressurant into an evacuated tank. Minor weight errors were introduced by this method of

loading caused by residual pressurant liquid trapped in the load lines. Studies were conducted to improve the accuracy of loading pressurant.

To determine the possibility of ambient pressure loading of the volatile liquid, several methods of loading of the pressurant were investigated at or below the temperature at which Freon 22 liquifies at ambient pressure (-41°F). No heat storage materials were used during these tests.

Methods investigated were:

1. The expulsion tank was placed in a dry ice bath. Freon 22 was then allowed to flow into the expulsion tank under its own storage pressure from a container at room temperature. During loading the air in the tank was vented to atmosphere. The required weight of Freon condensed inside the bellows. The vent was then capped. No vapor pressure buildup occurred during a 5-minute period. This method of loading, however, allowed air to be entrapped in the pressurant cavity. The amount of air entrapped can be minimized by allowing the pressurant vapor pressure to buildup prior to capping the vent. This would affect the accuracy of the weight loading.
2. The expulsion tank was placed in a dry ice bath for 30 minutes and a predetermined volume of liquid Freon 22 was poured from a graduated beaker which had also be chilled in a dry ice bath. However, there was still air entrapped in the pressurant cavity. In order to determine the effects of the entrapped air, the subscale tank was loaded with 1-1/2 pounds of Freon 22 by the chill and pour method outlined above. The pressurant cavity was sealed off with air entrapped in the system and the fuel was loaded into the tank. The pressure was raised by utilizing the heat exchanger and a series of expulsion test runs was made in a continuous flow mode. The amount of total pressure decay encountered in this series of tests showed a wide range of variation

indicating the presence of air in the system affected the repeatability of operation.

3. A subcooled loading test was then conducted in an attempt to eliminate the problem of entrapped air in the system. Both the expulsion tank and pressurant storage bottle were immersed in the dry ice bath and temperatures were allowed to stabilize at approximately -70°F. The pressurant cavity was then evacuated. The chilled Freon 22 was poured into a previously chilled graduate. A valve was opened and by the pressure differential available Freon was forced into the pressurant cavity. Two pounds of pressurant were loaded. Buildup of vapor pressure in the pressurant cavity was monitored during this period of time. No increase in vapor pressure was noted during the time of loading. Approximately 30 minutes lapsed before a vapor pressure of 5 psi was observed in the tank. This method of subcooled loading proved satisfactory in eliminating entrapped air in the system.

The method of subcooled loading which eliminated the presence of trapped air in the system had the same limitation as the ambient temperature loading (residual liquid in the load lines). As this subcooled loading method was more difficult to incorporate, it was not considered for further use.

To improve the accuracy of weight loading the pressurant, the following technique was utilized. An excess amount of pressurant was loaded into the tank and the load lines disconnected. A method of bleeding the excess pressurant from the tank was developed which resulted in weight loading accuracies of less than 1 percent.

One problem with ambient temperature pressurant loading which was investigated was loading of the propellant subsequent to the pressurant and heat storage material with low (3 to 5%) initial pressurant qualities.

It was anticipated that difficulty could be experienced in loading the last amount of the required propellant into the tank because of the pressure rise associated with compression of the final amount of the pressurant requiring intermediate cooling to condense the pressurant. This problem was investigated in conjunction with the docosane/Genetron 32 tests conducted. The tests which were conducted without intermediate cooling, indicated that the magnitude of pressure rise during re-loading is related to rate of propellant flow. At refuel flow rates approximately one half of the minimum expulsion rate the pressure rise in the tank was only 10 percent. Slower loading rates resulted in even lower increases. This magnitude of pressure rise should present no problem in propellant recycling.

6.2 Heat Storage Material Loading

The loading of the heat storage material as a solid was investigated using the subscale expulsion tank. With the pressurant port positioned upward granulated heat storage material was poured into the pressurant cavity. With a filter installed in the evacuation line to determine if heat storage material would be withdrawn from the tank, the pressurant cavity was evacuated. Freon 22 was then loaded into the pressurant cavity. There was no evidence of any heat storage material being drawn into the filter during the evacuation and pressurant loading process.

Several tests were then conducted where the heat storage material was melted and poured into the tank. Prior to pressurant loading in these tests the heatstorage material was allowed to solidify prior to evacuating the pressurant cavity for pressurant loading. On cooling the heat storage material collected in a solid piece instead of the original flake form. From the results of these tests, the heat storage material could be installed in the tank in either liquid or solid state. For all the system tests conducted, however, the liquid state method was used. The eicosane received had apparently been melted previously (the melting temperature is 99°F) and was solidified in the shipping container. Re-melting was therefore necessary.

A series of tests was conducted in which the pressurant was loaded prior to the heat storage material. In order to introduce the heat storage material into the tank, it was necessary to liquify the heat storage material and pressure load to overcome the Freon 22 vapor pressure. Considerable difficulty was encountered in maintaining the load lines at sufficient temperatures to prevent solidification of the heat storage material. Therefore, this method of loading should only be considered in the event of possible damage to the expulsion device during pressurant loading with solid heat storage material in the pressurant cavity.

7.0 SUBSCALE TEST PROGRAM

The purpose of the subscale test program was to investigate the expulsion characteristics of the selected pressurant for each system, monochlorodifluoromethane (Freon 22) for System A and difluoromethane (Genetron 32) for System B. For System A tests propellant flow was in both a continuous and pulsing modes. For System B tests propellant flow was continuous. A series of heat storage materials was investigated to determine which one would result in an equilibrium pressure (276 psig was desired) when mixed with Genetron 32.

The bellows expulsion tank, as shown in Figure 7-1, was the test hardware used in this program. A simulated propellant (triethylene glycol) was loaded in the tank on one side of the bellows and the required amount of pressurant on the other side. In demonstrating the expulsion characteristics of the pressurant, the basic test procedure used throughout the program was to install a predetermined amount of pressurant in the test tank. The pressurant was then heated to an initial starting condition and flow of the propellant was initiated. By initiating flow of the propellant, the pressurant cavity volume increases. As the pressurant volume increases, the temperature of the vapor which is expanding will decrease and result in a decay in the pressurant cavity pressure. By varying the rate of propellant flow and the amount of pressurant loaded into the test tank, a family of expulsion characteristic curves was generated.

In order to provide the capability of cleaning residual heat storage material from the tanks subsequent to testing, a program was initiated to determine an optimum solvent for eicosane. Two materials, carbon tetrachloride and trichloroethylene, were found which could both be utilized readily. Eicosane has a solubility in carbon tetrachloride of approximately 38 grams per 100 milliliters and in trichloroethylene of 76 grams per 100 milliliters. The relatively high solubility in trichloroethylene indicates a high probability that the tanks could be cleaned using commercial degreasing equipment.

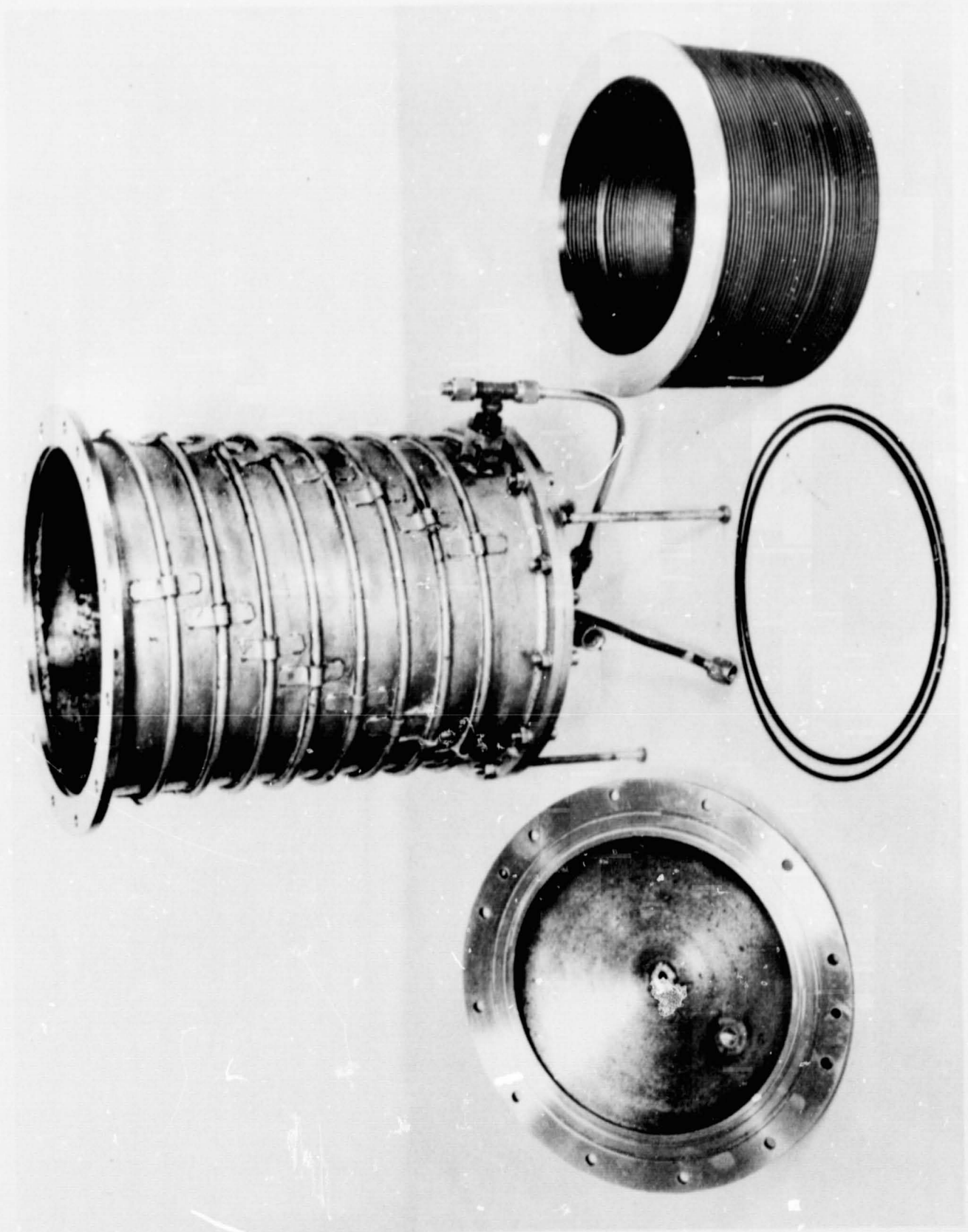


Figure 7-1 Experimental Tank

7.1 Test Materials

Two pressurant materials and four heat storage materials were investigated under this program. The pressurant investigated for the pulsing or low average flow operation (System A) was monochlorodifluoromethane. This material was purchased as E. I. DuPont Company Freon 22 from Arrow-Risco Company in 50-pound lots contained in pressurized steel bottles.

The pressurant material selected for the continuous flow operation (System B) was difluoromethane (methylene fluoride). This material was purchased as Genetron 32 from the General Chemical Division of Allied Chemical Corporation and was obtained in 20-pound lots contained in pressurized steel bottles.

Three of the four heat storage materials were of the saturated hydrocarbon family and carry the general formulation of $C_n H_{(2n + 2)}$. Two of these materials, nonadecane and docosane, were purchased from the Humphrey Chemical Company in North Haven, Connecticut in 5-pound lots. The nonadecane procured was petroleum derived and minimum purity was 99%. The docosane procured was alcohol derived and minimum purity was 97%.

The third hydrocarbon, eicosane, was procured from Eastman Kodak Chemical under their stock No. T6321 in 3 kilogram lots.

The fourth heat storage material investigated was lauric acid which was procured as a technical grade from Armour Industrial Chemicals in a 50-pound lot.

7.2 Test Procedure

The results in the subscale test program were obtained using the test setup shown in Figure 7-2 and represented schematically in Figure 7-3.

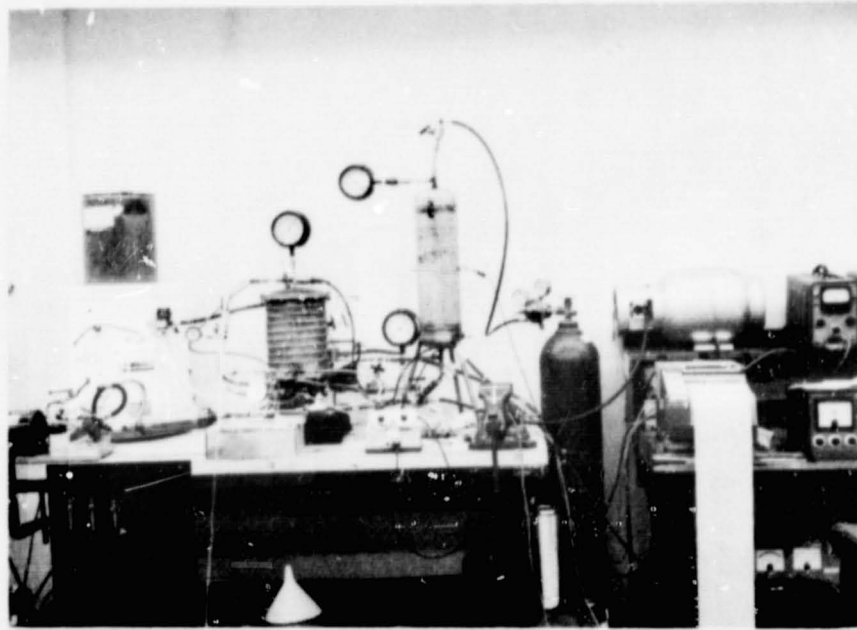


Figure 7-2 Experimental Test Setup

In all tests the basic test procedure was as follows:

1. A leak check was conducted which consisted of pulling a vacuum on the system (both sides of the bellows simultaneously) and monitoring with an appropriate vacuum gage for leaks. Simultaneous with the leak check operation the fuel supply tank was filled with the simulated fuel (triethylene glycol). Upon assurance of a "tight" system, the vacuum pump was closed out and the bellows tank weight was recorded.
2. With the fuel supply tank open to atmosphere, the bypass valve between the bellows tank and the fuel supply tank was open. By virtue of the pressure difference, fuel flowed from the supply tank to the bellows tank. When a total of 2 pounds of fuel had been flowed the bypass valve was closed.
3. The appropriate amount of pressurant was then added to the pressurant cavity. The purpose of adding the initial quantity of fuel was to prevent damage to the bellows assembly when it was subjected to the vapor pressure of the pressurant when it was added.
4. Additional fuel was then added until the bellows tank contained a total of 16 pounds of fuel. The remaining fuel was forced in with a supply of nitrogen applied to the fuel supply tank. The additional nitrogen pressure was required to overcome the pressurant vapor pressure.
5. After the final weight of the system was recorded, the bypass valve was closed, the fuel supply tank pressure was vented off, and the throttle valve was adjusted for the proper flow rate.
6. The heat exchanger pump was then activated to bring the system to an initial operating pressure.

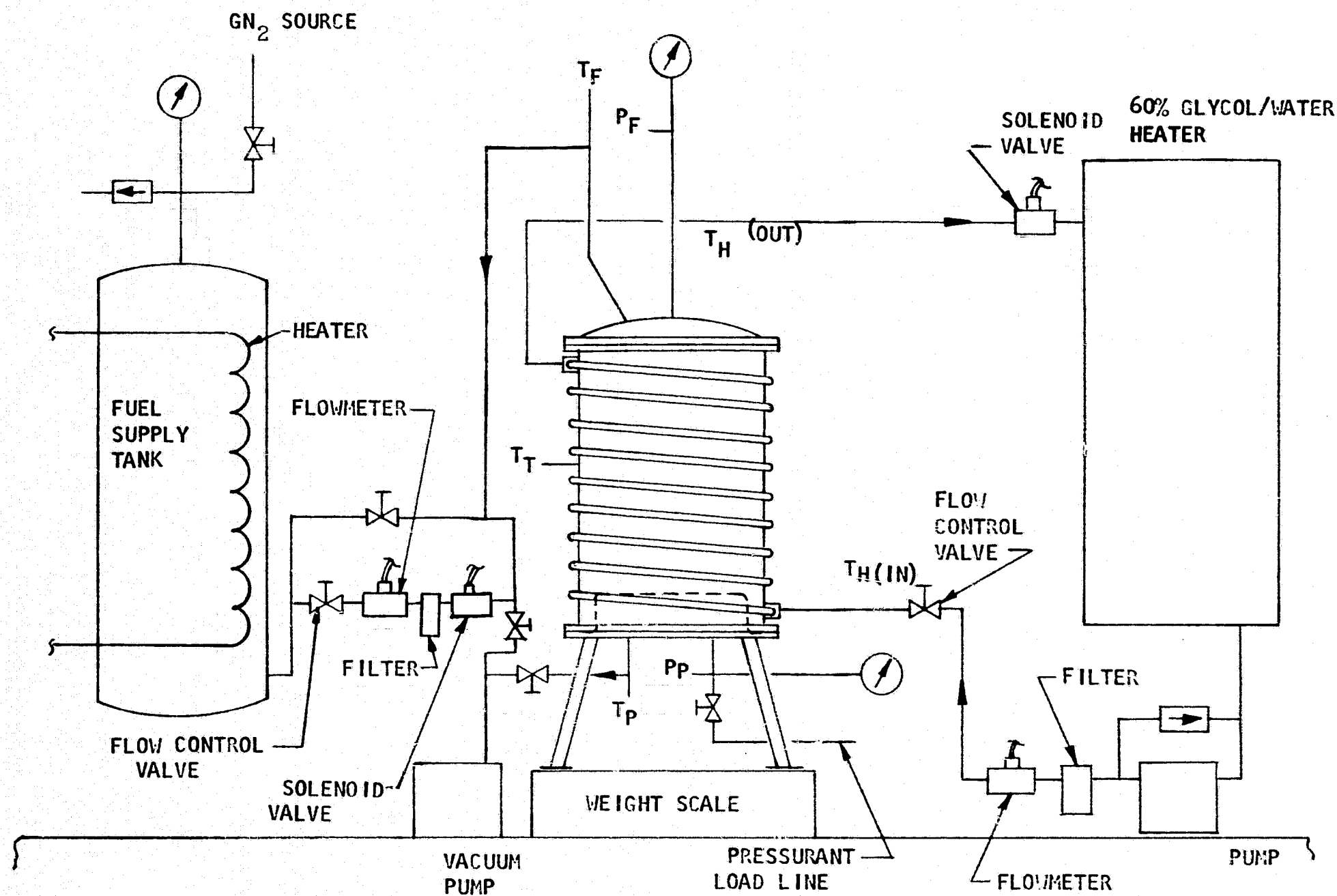


Figure 7-3 Experimental Tank Test Schematic

7. Just prior to the opening of the flow control valve, the oscillograph was activated to record the following parameters during the expulsion test:

Heat exchanger temperature in

Heat exchanger temperature out

Heat exchanger flow rate

Pressurant temperature (liquid)

Pressurant temperature (vapor)

Pressurant pressure

Propellant temperature

Propellant pressure

Propellant flow rate

8. The run was terminated when a total of 10 pounds of fuel had been expelled.
9. The fuel supply tank was then repressurized and the bypass valve opened until the original amount of fuel (16 pounds) was in the bellows tank. The system was then ready for the next test run.

This procedure was repeated for each initial pressurant load. In those runs which were made using a heat storage material in addition to the pressurant, the heat storage material was added to the pressurant cavity prior to performing the leak check.

7.3 Freon 22 Expulsion Tests

Freon 22 test runs were conducted at three different pressurant loadings to simulate various quality conditions as shown in Table 7-1.

Table 7-1 Quality Change Conditions For Freon 22 Expansion Tests

<u>Weight of Freon 22</u>	<u>Cavity Volume</u>		<u>Pressurant Quality</u>	
	<u>Initial (in.³)</u>	<u>Final (in.³)</u>	<u>Initial</u>	<u>Final</u>
4 lb, 5 oz	240	562	0.065	0.220
1 lb, 15 oz	240	562	0.230	0.507
1 lb, 2 oz	240	562	0.400	1.000

A total of 139 runs was conducted at simulated propellant (triethylene glycol) flow rates of 0.10 and 0.40 lb/sec. Three types of expulsion test runs were made at each of the flow rates, (1) continuous flow with the heat exchanger flowing during expulsion (2) continuous flow without the heat exchanger flowing, and (3) flow in a series of 5-second pulses with system pressure being returned to the original level between pulses.

The expulsion characteristics for the continuous flow Freon 22 tests are shown in Figures 7-4 through 7-7. These figures indicate very little difference in the expulsion characteristics, with and without heat addition with the exception of the high pressurant load. This was attributed to the fact that the subscale tank heat exchanger design provided a heat input directly into the liquid phase with the high pressurant load and only into the vapor phase with the lower pressurant loads. In Figure 7-8, typical curves of both high and low flow rate pulsing capability are shown. The system pulsing characteristics are more

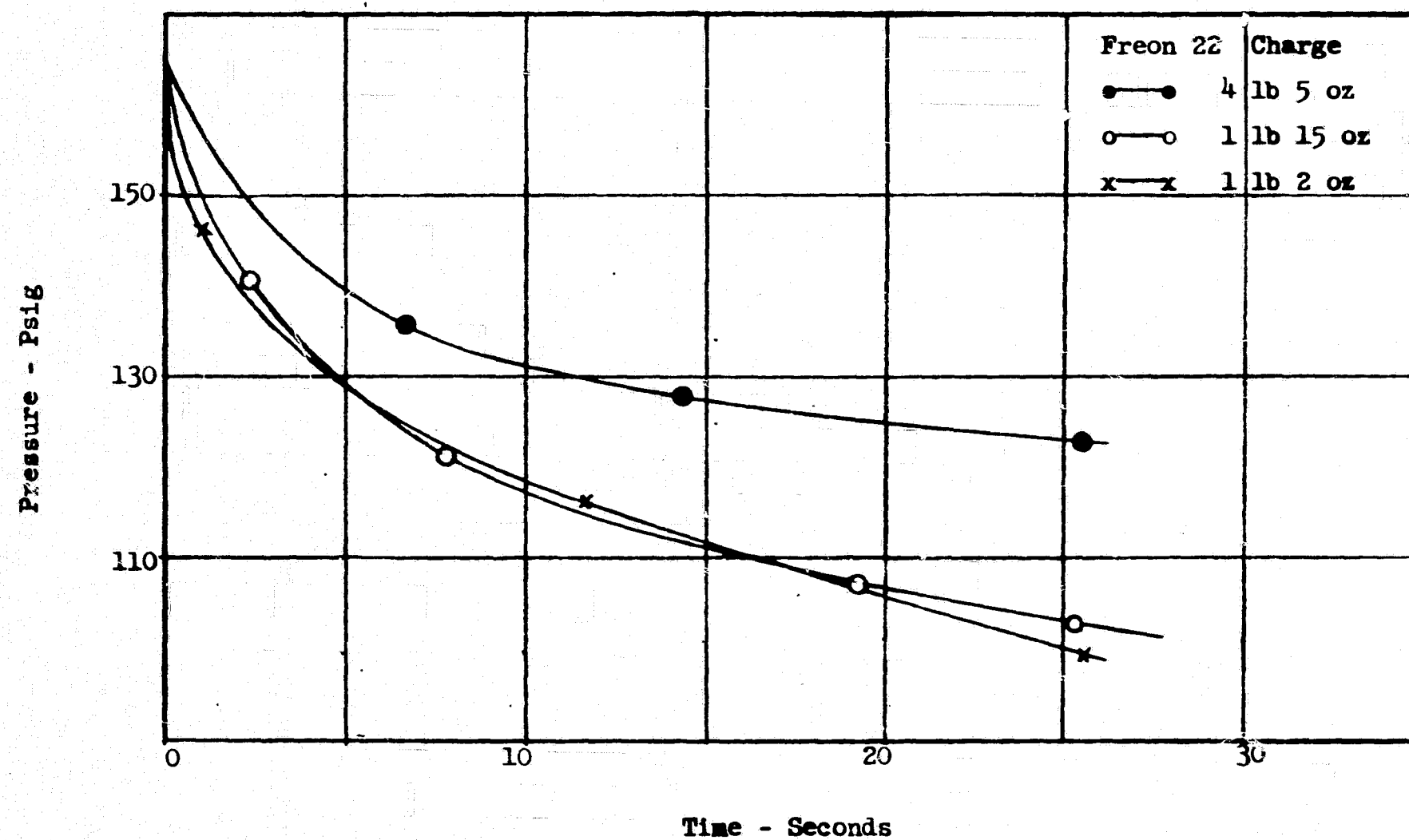


Figure 7-4 Continuous Flow Expulsion Characteristics For Various Freon 22 Charges, High Flow With Heat Addition

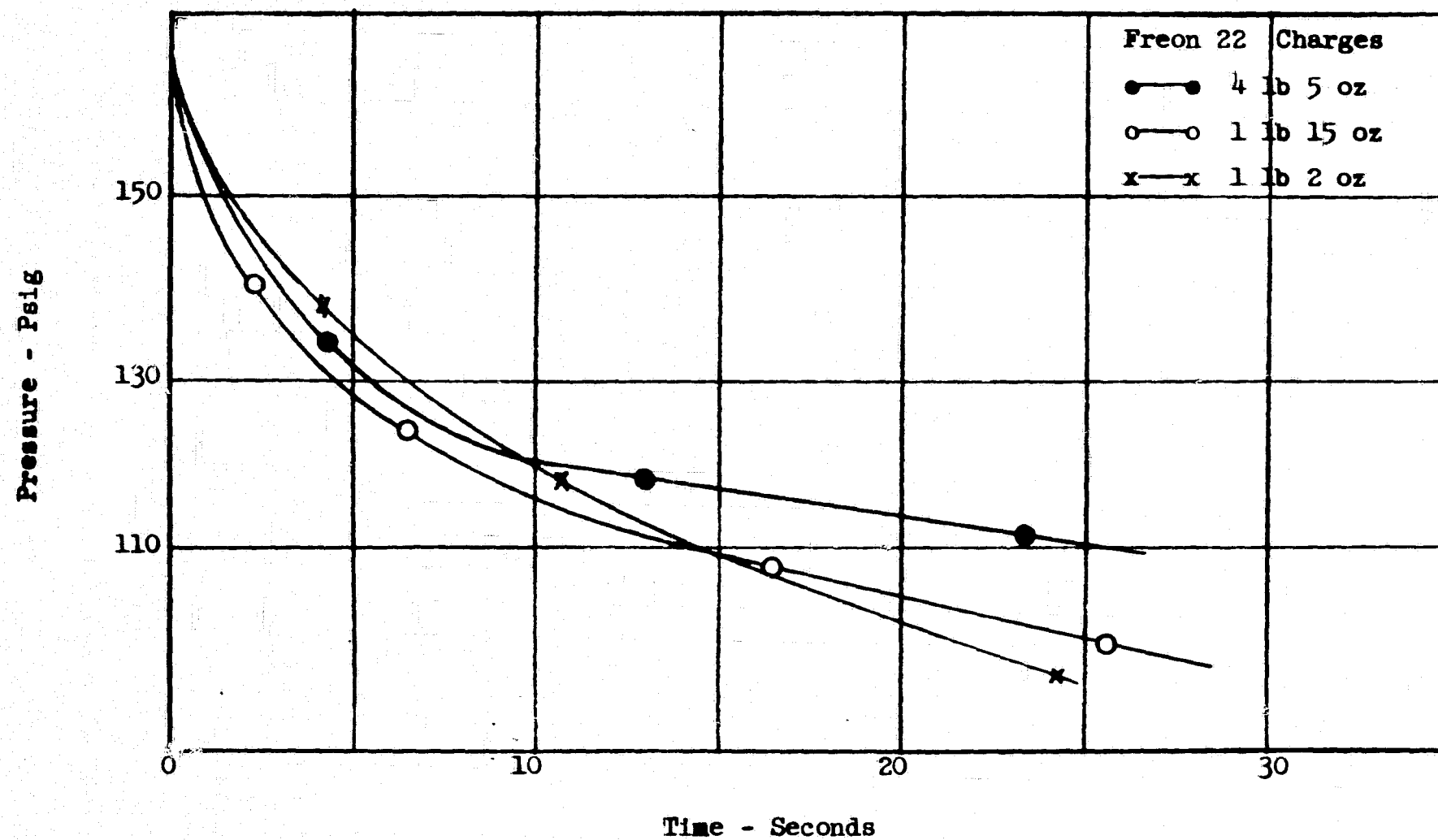


Figure 7-5 Continuous Flow Expulsion Characteristics For Various Freon 22 Charges, High Flow Without Heat Addition.

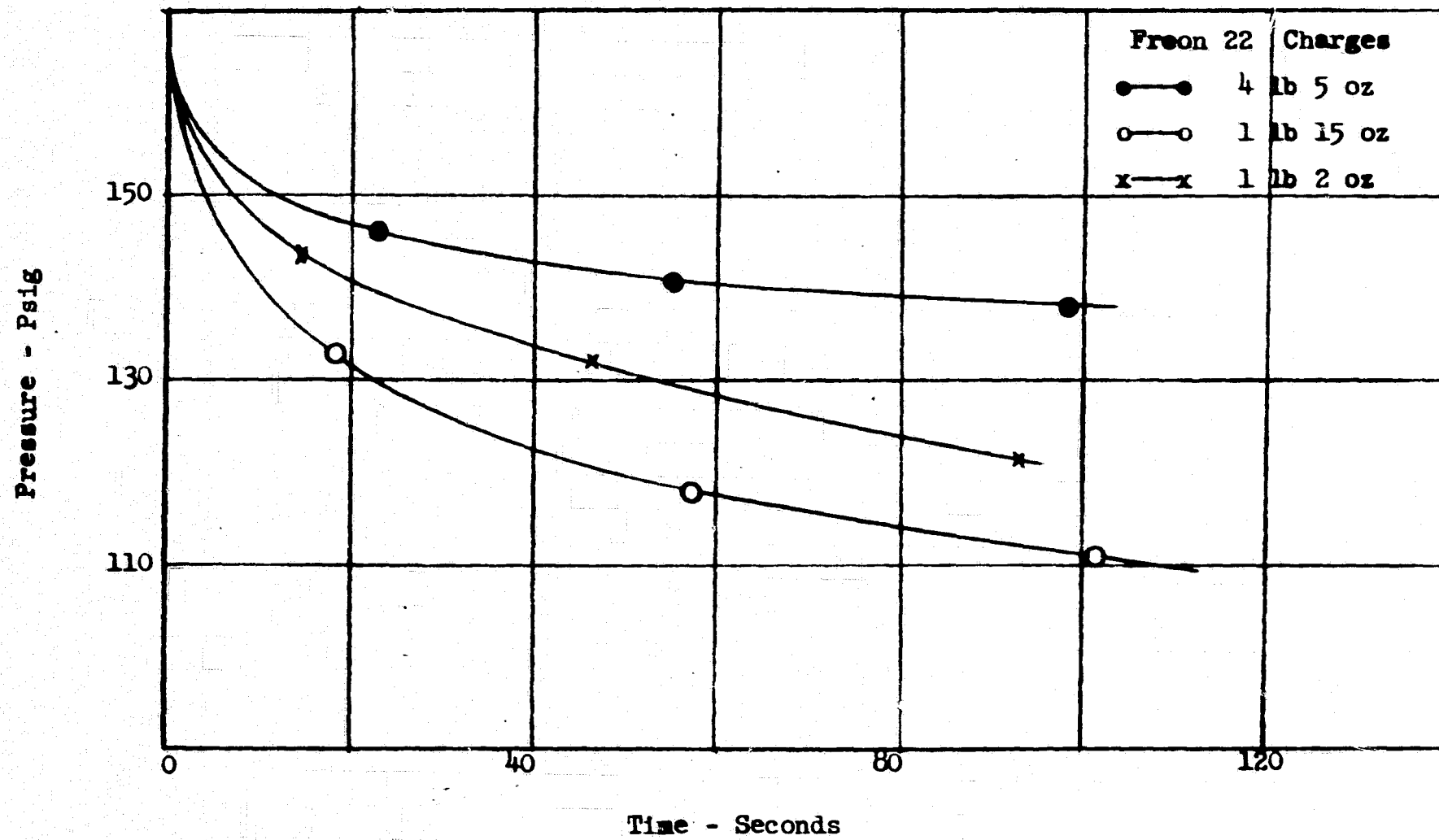


Figure 7-6 Continuous Flow Expulsion Characteristics For Various Freon 22 Charges, Low Flow With Heat Addition

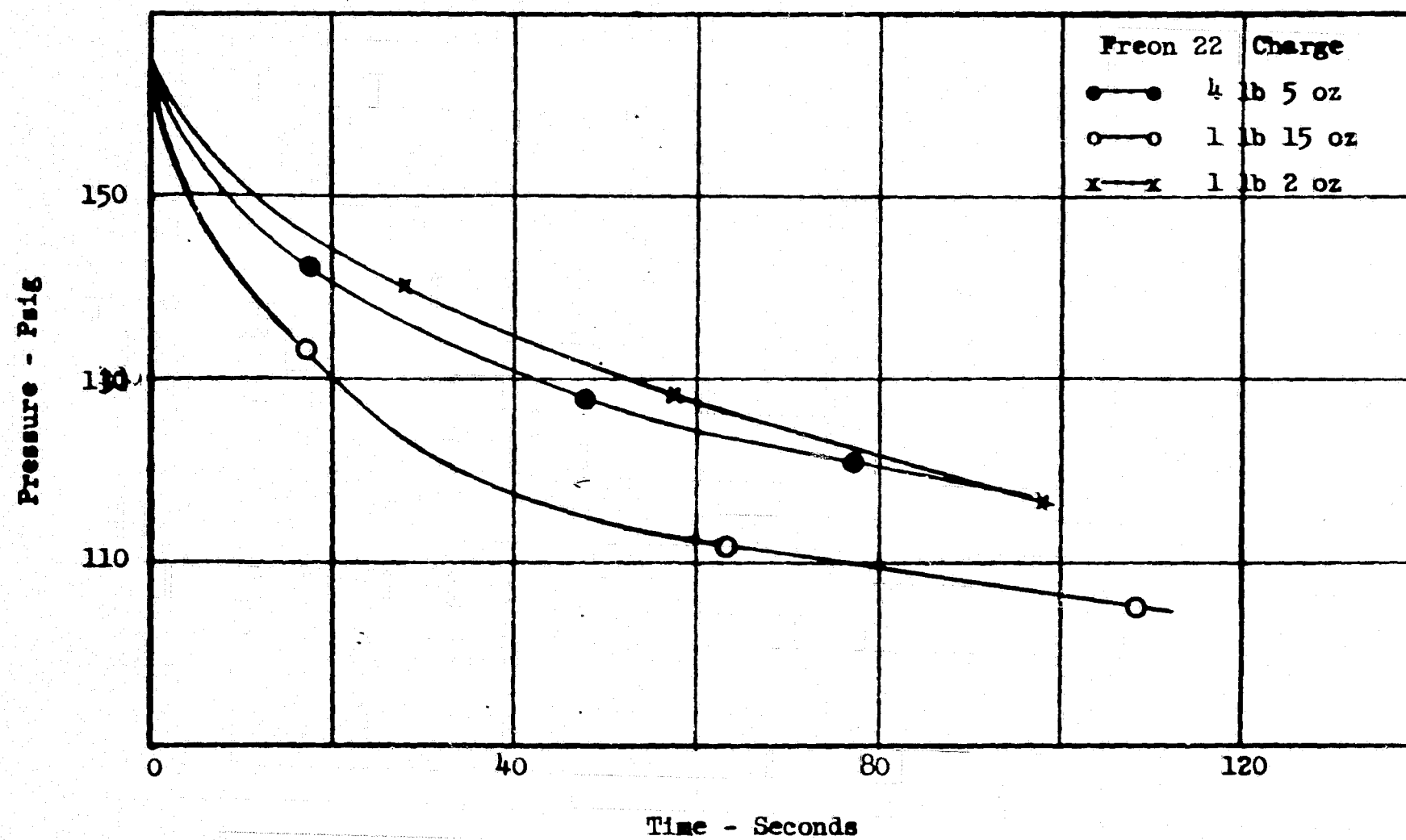


Figure 7-7 Continuous Flow Expulsion Characteristics For Various Freon 22 Charges, Low Flow Without Heat Addition

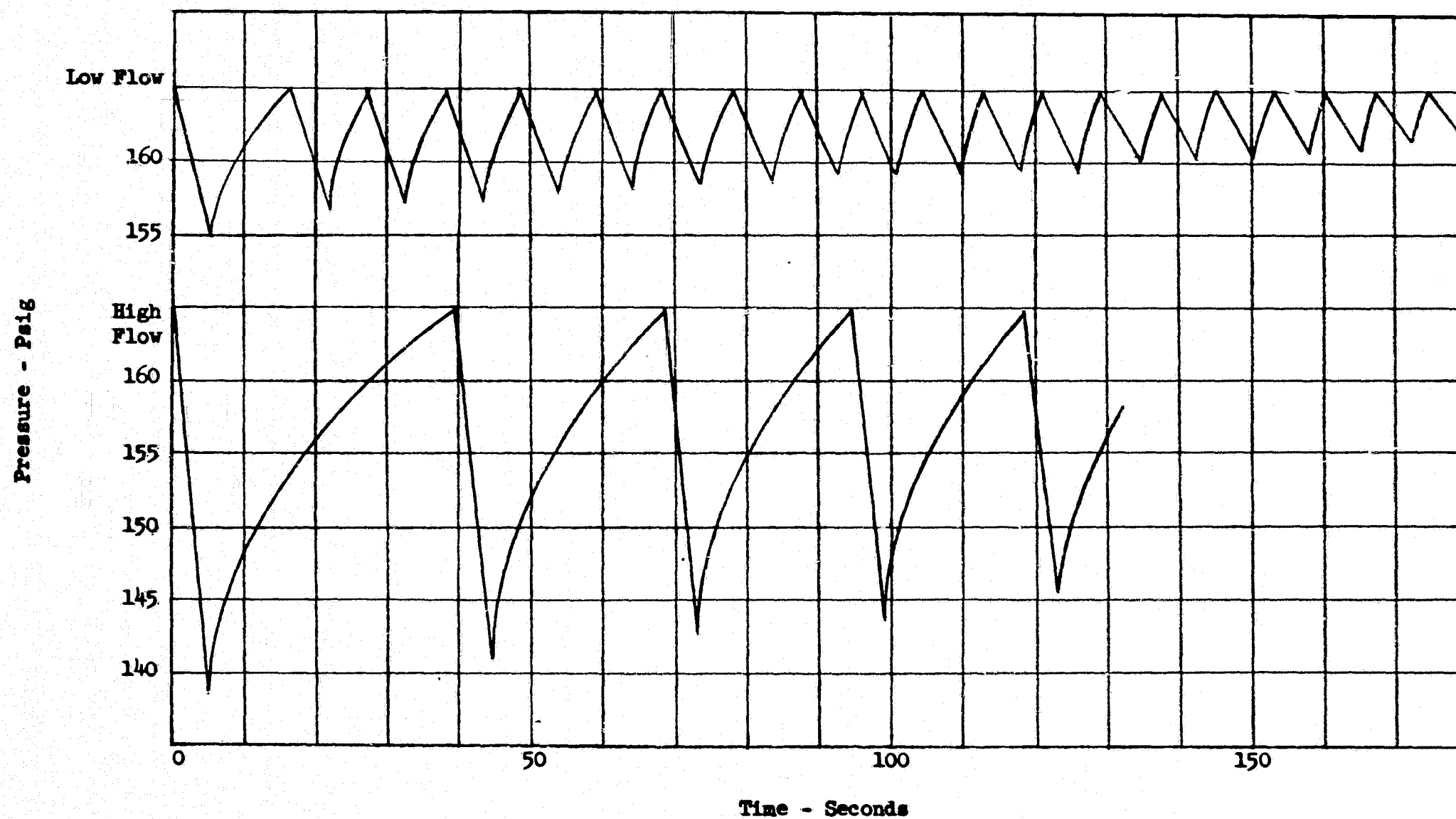


Figure 7-8 Pulsing Flow Expulsion Characteristics
For Freon 22 Charge of 4 lb, 5 oz.

readily seen in Figures 7-9 and 7-10 which show the influence of the quality level on the amount of pressure decay associated with the individual pulse.

With a pressurant loading of 1 lb 2 oz, the time for fuel pressure recovery after pulse expulsion was nearly twice as long as with the 1 lb 15 oz loading. The magnitude of pressure decay was almost identical at the low flow rate for all three loadings. The limiting factor in selecting a minimum acceptable pressurant load is the increase in recovery time. The reason for the longer response was attributed to the fact that at the lower pressurant loads, with the vessel in a vertical position, the portion of Freon in its liquid phase was remote from the tank wall affected by the external heat exchanger and heat transfer was essentially limited to the vapor phase of the pressurant. This was proven by activation of the internal heat exchanger which was immersed in the liquid. Pressurization response was immediate, even with the 1 lb 2 oz pressurant loading.

Four runs were conducted at high (0.4 lb/sec) propellant flow rates to evaluate the effect of expulsion in a horizontal position with 1 lb 2 oz Freon as compared to vertical expulsion. (All previous runs had been conducted with the vessel vertical and expulsion out the top of the tank.) As was expected with liquid Freon in contact with the heat exchanger area, the external heat exchanger was found to be much more efficient with the vessel on its side. The pulse response time was comparable to that experienced with vertical expulsion with the high pressurant load (4 lb 5 oz). The pressure decay associated with continuous flow was lower (44 psi) than any previous test condition. Six test runs were made in an effort to determine whether the point of conversion of all of the Freon to its vapor state (100% quality) could be determined. No definite indication of the transition point could be determined from the test data.

7.4 Genetron 32 And Heat Storable Material Expulsion Tests

The tests conducted with Genetron 32 were intended to determine a heat source material for System B operation in a continuous propellant

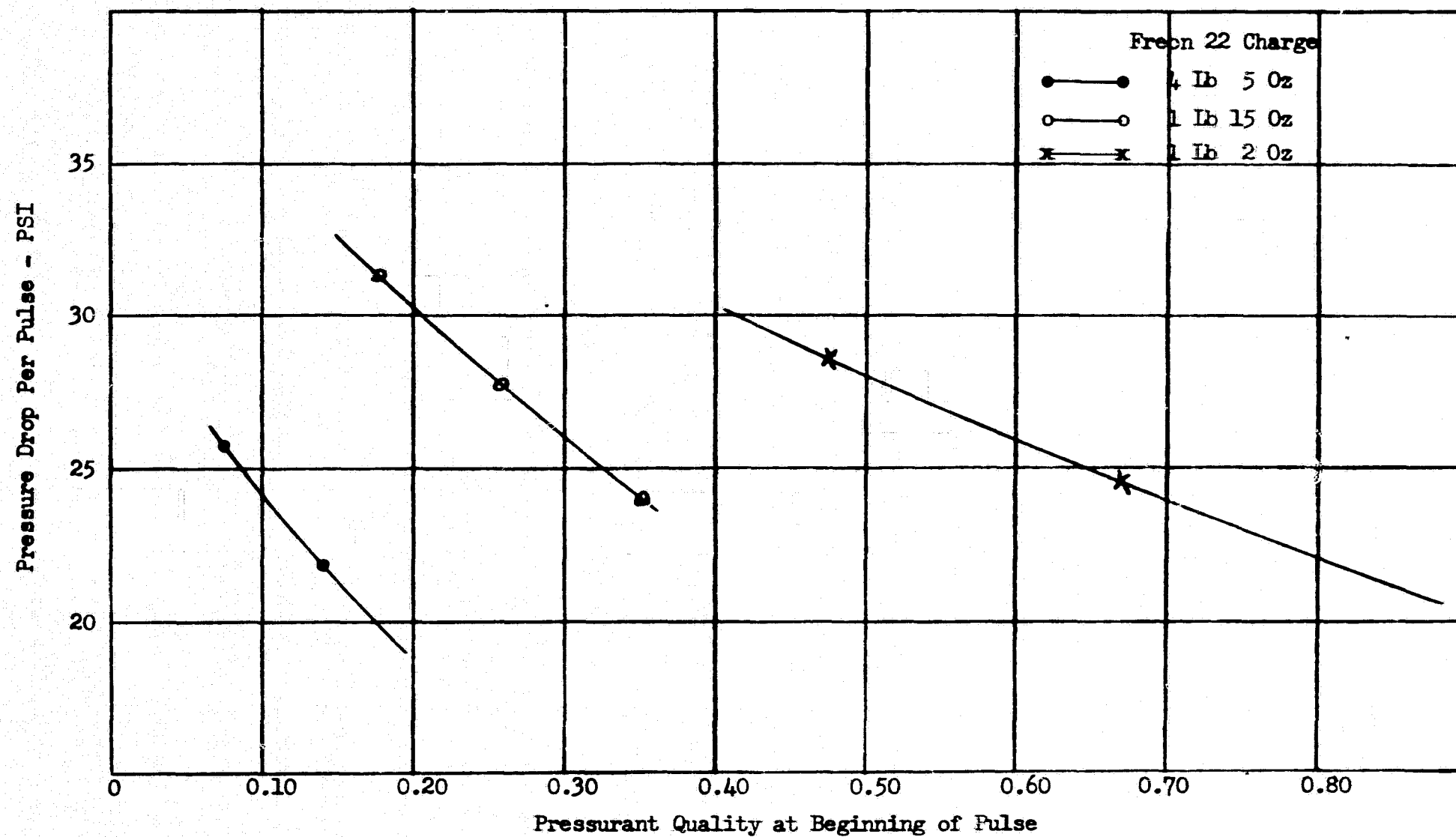


Figure 7-9 Pulsing Flow Expulsion Characteristics for Various Freon 22 Charges, High Flow

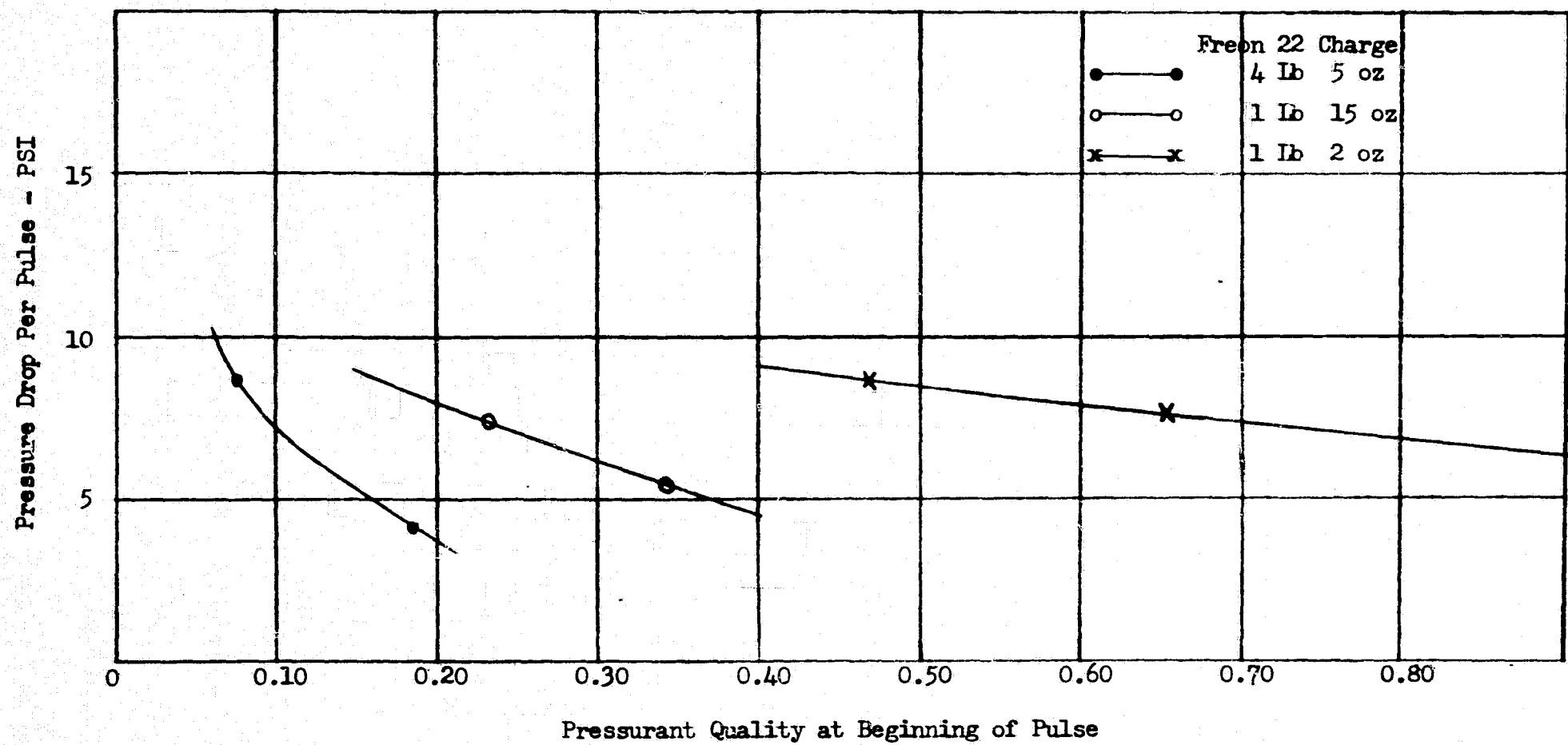


Figure 7-10 Pulsing Flow Expulsion Characteristics for Various Freon 22 Charges, Low Flow

flow mode which would give off heat of fusion to the pressurant and maintain a desired equilibrium pressure level of approximately 276 psig. For comparison purposes, nine test runs were made to establish typical expansion curves at high and low flow rates for Genetron 32 only. The test results are shown in Figures 7-11 and 7-12. For the Genetron 32 series of tests, the low flow rate was reduced to a level of approximately 0.05 lb/sec and the maximum flow rate level was maintained at 0.10 lb/sec. These flow rates simulated the rate of change of the volume of the pressurant cavity expected in the full-scale tests. A summary of the various quality conditions investigated is shown in Table 7-2.

7.4.1 Heat Storage Materials

In using the latent heat of fusion of a heat storage material to provide the energy to vaporize the pressurant, the actual system operating conditions are determined by the interaction of both materials. The system essentially operates at a depressed vapor pressure of the pressurant at a temperature equal to the freezing temperature of the heat storage material. By selection of various heat storage materials having different freezing temperatures, a range of operating conditions can be obtained with a given pressurant. From the results of compatibility and freezing point tests conducted during Contract NAS 9-1004, Reference 1, as shown in Table 7-3, Nonadecane and Lauric acid appeared to be the best choices with Genetron 32, as they exhibited vapor pressures of 285 and 290 psig at the heat storage material freezing point.

7.4.1.1 Nonadecane

Twenty-two tests were made with 1.41 pounds of Nonadecane and 1.81 pounds of Genetron 32 installed in the expulsion tank. An equilibrium pressure was observed at 200 psig in some tests as shown in Figure 7-13. These test runs were made with an initial liquid temperature of 89°F. This represented a decrease of 85 psi from the freezing point results. The reduction in the pressure level was attributed to the differences in heat transfer during a flowing condition and the pressure decay during the time the system temperatures are dropping to the melting temperature of the heat storage material. In other tests, the rate of pressure drop

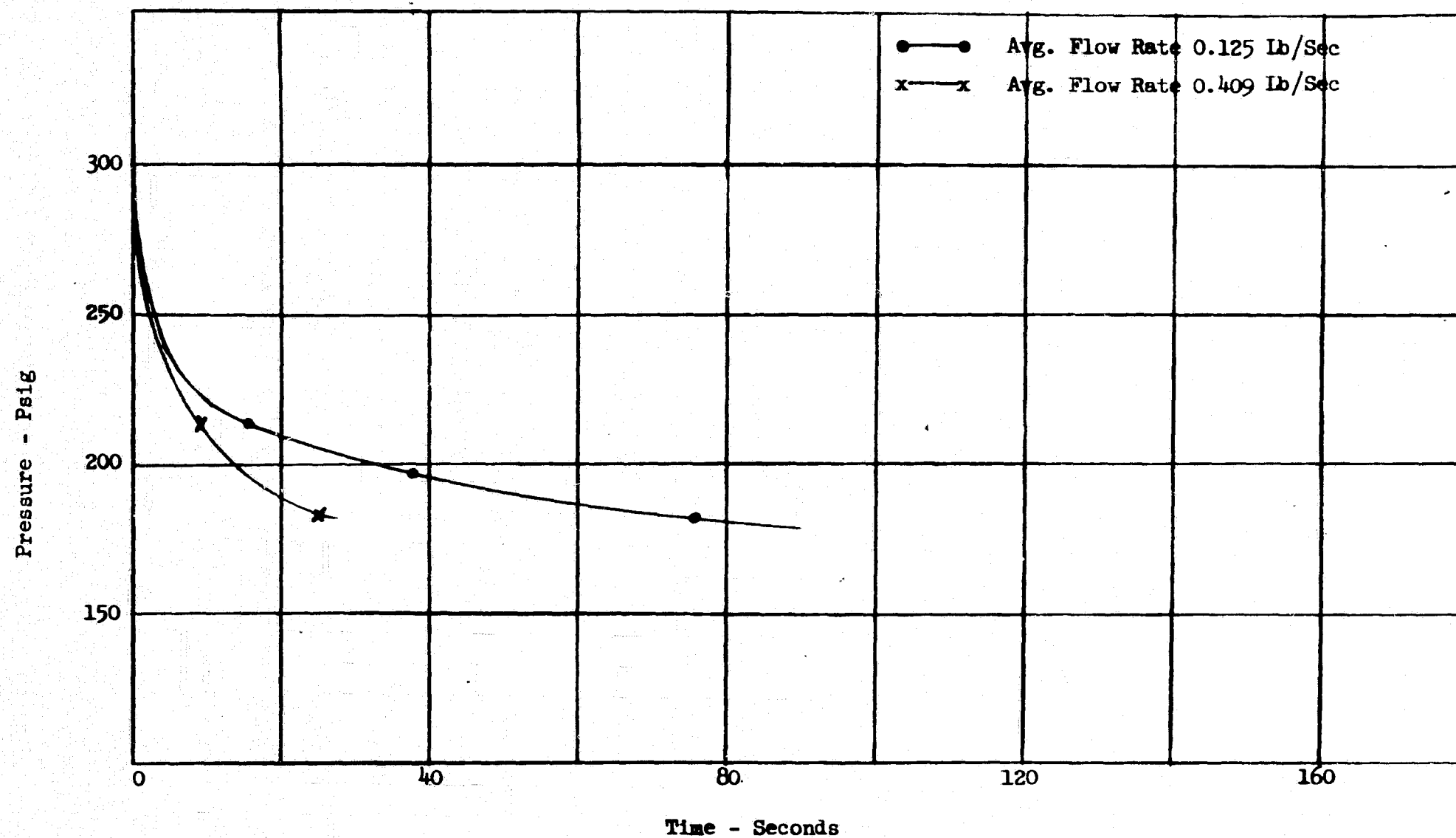


Figure 7-11 Continuous Flow Expulsion Characteristics For
1.8 LB Genetron 32 Without Heat Addition

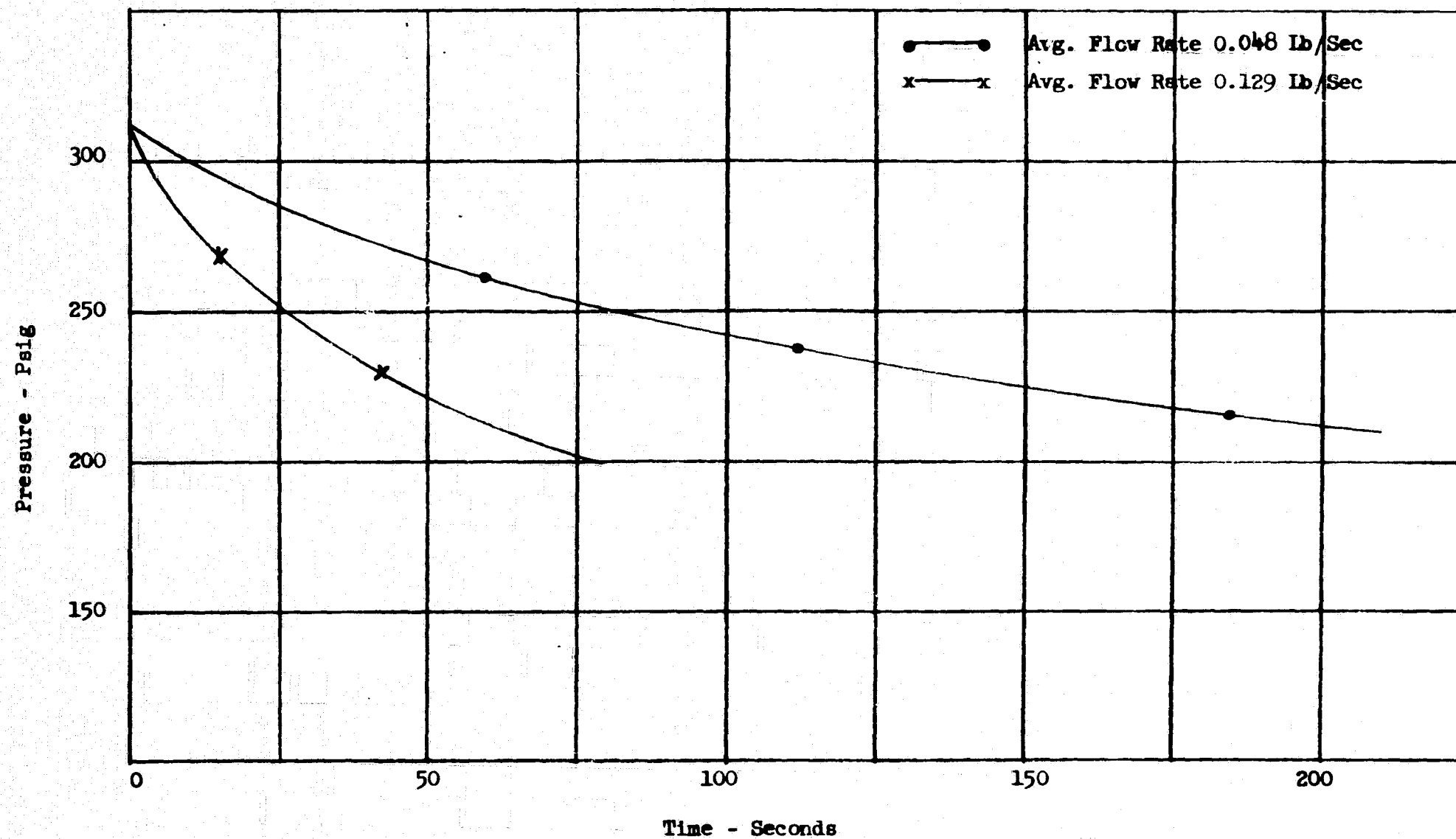


Figure 7-12 Continuous Flow Expulsion Characteristics For
0.7 LB Genetron 32 Without Heat Addition

Table 7-2 Quality Change Conditions For
Genetron 32/HSM tests.

Weight of Genetron 32 (lb)	HSM*	Weight of HSM (lb)	Pressurant Volume		Pressurant Quality	
			Initial (in ³)	Final (in ³)	Initial	Final
0.70	-	-	240	562	0.486	1.000
1.80	-	-	240	562	0.224	0.391
1.80	Nonadecane	1.40	191	511	0.152	0.375
0.70	Eicosane	0.50	222	542	0.434	0.965
0.70	Eicosane	1.00	205	525	0.387	0.935
1.80	Lauric Acid	1.30	205	517	0.195	0.467
0.70	Docosane	.75	214	533	0.413	0.950
2.00	Docosane	4.00	101	420	0.042	0.360

* Heat Storage Material

Table 7-3. Compatibility and Freezing Points
of HSM and Genetron 32

Test No.	Combination	Ratio by Wt.	Initial Conditions		Test Conditions *		Vapor Pressure		Comments
			Pressure (psig)	Temperature (°F)	Pressure (psig)	Temperature (°F)	Freezing Point (°F)	at Freezing Point (°F)	
4	H ₁ /G32	1:1	210	52	325	110	93	305	2 phase separation G-32 bottom
5	H ₂ /G32	1:1	190	50	335	112	93	290	Same
6	H ₃ /G32	1:1	195	62	295	123	79	250	Same
			190	58	270	112	82	240	Same
7	H ₄ /G32	1:1	175	50	345	112	86	285	Same
8	H ₅ /G32	1:1	185	48	345	112	68	230	Same
9	H ₆ /G32	1:1	185	46	370	110	-	-	Not completed be- cause of excessive pressure
10	H ₇ /G32	1:1	225	70	290	110	62	200	2 phase separation G-32 bottom

* Test conditions held at indicated temperature for three hours.

Notes: H₁ - Eicosane H₅ - n-Heptadecane
 H₂ - Lauric Acid H₆ - Docosane
 H₃ - Octadecane H₇ - Cetane
 H₄ - Nonadecane

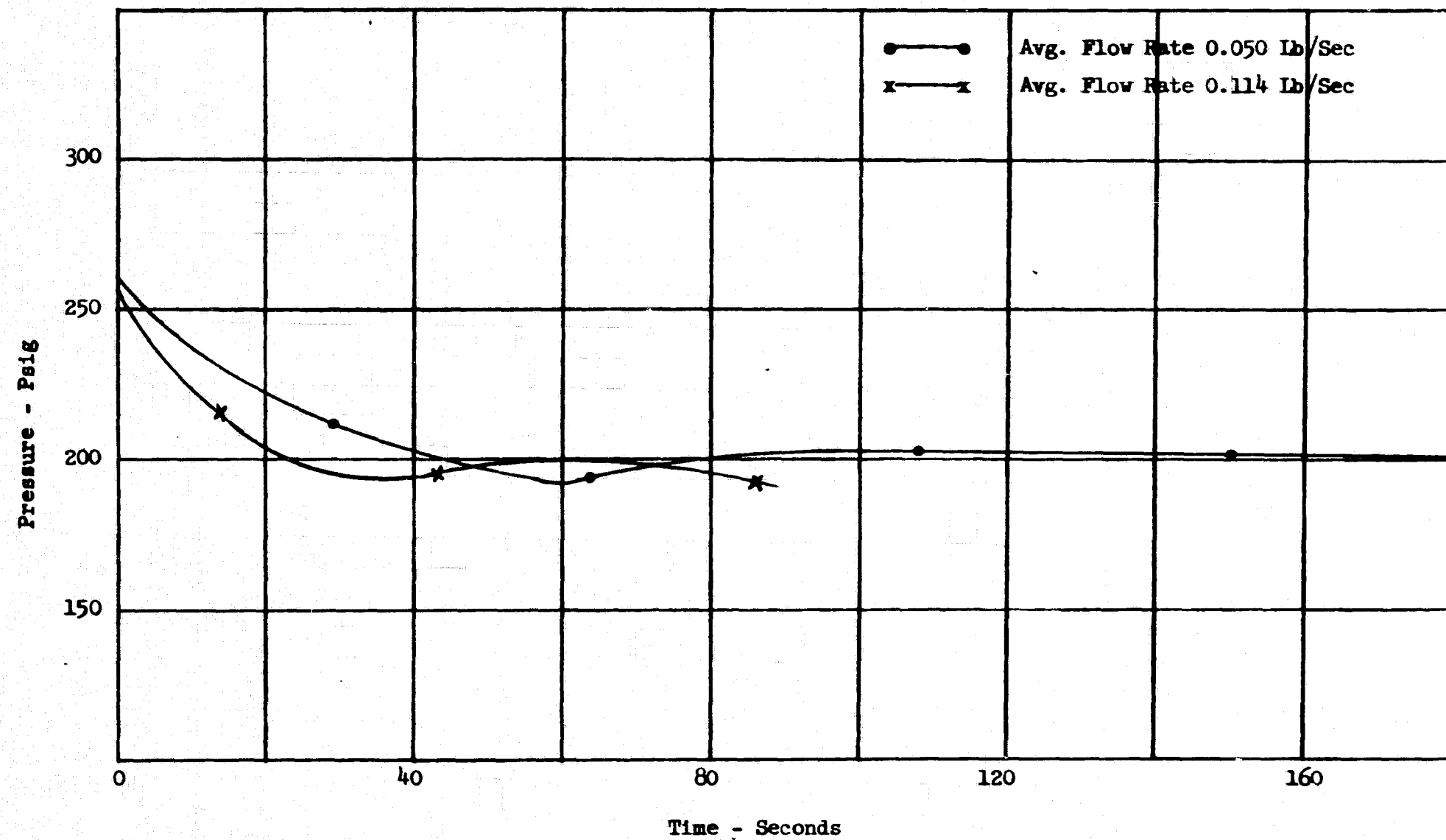


Figure 7-13 Continuous Flow Expulsion Characteristics For
1.8 LB Genetron 32 and 1.4 LB Nonadecane

changed significantly early in the run but did not reverse or plateau. This was apparently caused by incomplete melting of the Nonadecane in some cases and excessive starting temperatures in others. It was evident from this series of tests that temperature stability of the expulsion tank system is required to minimize pressure decay during the early part of the run. In those tests where expulsion was initiated with the vapor temperature higher than the liquid temperature, significant pressure decay was experienced during the time the vapor temperature dropped to the level of the liquid temperature (refer to Figure 7-11, liquid 82°F, vapor 102°F).

7.4.1.2 Lauric Acid

Twenty tests were conducted with 1.3 pounds of Lauric acid and 1.81 pounds of Genetron 32. With the Lauric acid/Genetron 32 combination and equilibrium pressure of approximately 240 psig was achieved as shown in Figure 7-14. In the tests conducted with Lauric acid the plateau at the low flow rate was fairly well defined while the pressure plateau at the higher flow rate was not as well defined although a decrease in the rate of pressure decay was evident.

The equilibrium pressures achieved with these two materials were both lower than the desired system operating pressure.

In an effort to raise the pressures to the System B nominal pressure level, it was decided to investigate heat storage materials with higher melting temperatures. Two additional heat storage materials of the aliphatic family were investigated. The two materials were Eicosane which melts at 97°F (freezing point vapor pressure of 305 psig) and Docosane which melts at 111°F.

7.4.1.3 Eicosane

Sixteen runs were made with the minimum quantities, i.e., final pressurant quality of 1.00, 0.48 pound of Eicosane and 0.73 pound of Genetron 32. Finally, eleven test runs were performed with 1.00 pound

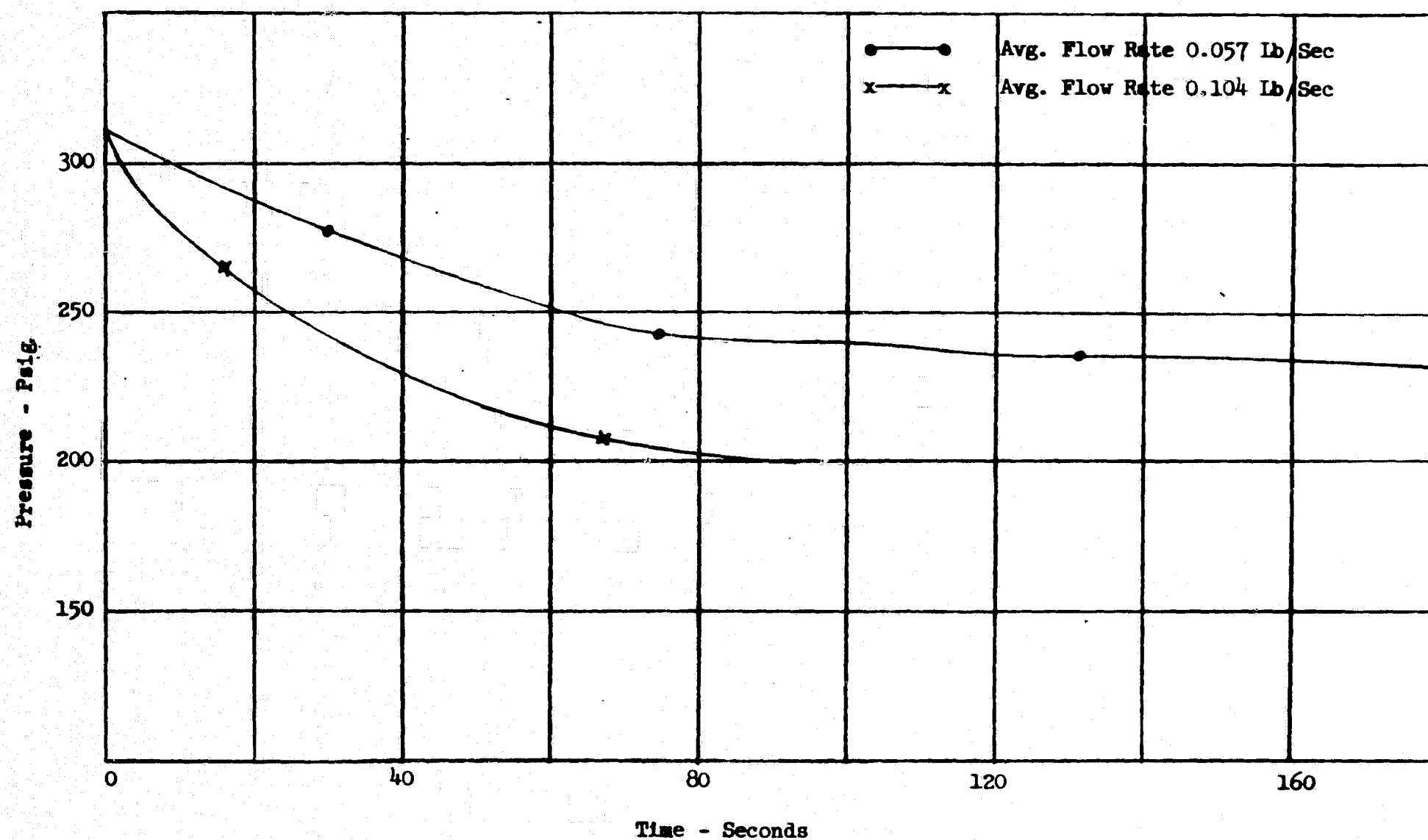


Figure 7-14 Continuous Flow Expulsion Characteristics For
1.8 LB Genetron 32 and 1.3 LB Lauric Acid

Eicosane and 0.73 pound Genetron 32. In conducting the tests with Genetron 32/Eicosane, equilibrium pressures of 250 to 260 psig were obtained as shown in Figure 7-15. The two curves shown are at a relatively low average flow rate. The pressure plateau was not as evident at the higher flow rates with Eicosane as had been exhibited with the previous two materials indicating that the heat transfer process between the heat storage material and the pressurant is not instantaneous and the process therefore is time dependent.

7.4.1.4 Docosane

Twenty-two runs were then made with 0.75 pound of Docosane and 0.75 pound of Genetron 32 and six runs with 0.75 pound of Docosane and 1.5 pounds of Genetron 32. During these runs, no pressure plateau was evident with the Docosane-Genetron material combination. The initial temperature starting conditions (pressurant temperatures at the beginning of the expulsion run) were investigated from 124°F which is 13 degrees above the freestate melting point of Docosane (111°F) down to 93°F. In some cases the overall pressure decay during the expulsion cycle appeared to be slightly lower than experienced with the corresponding expansion of Genetron 32 only. However, there was no evidence of an equilibrium pressure occurring in any of the runs conducted (Figure 7-16).

A review was then made of the results of the subscale tests as well as test data supplied by NASA of volatile liquid expulsion tests they had conducted utilizing an Apollo Command Module bladder tank as the expulsion device. NASA/MSD had run tests using Genetron 32 as the pressurant, in both a continuous and a pulsing mode. They had also made two runs using octadecane as the heat storage material in combination with Genetron 32. This combination was investigated by TRW on Contract NAS 9-1004.

In comparing the NASA and TRW test data, it became apparent that NASA had experienced a much higher rate of initial pressure decay to that point where the heat storage material started freezing than had been achieved in the TRW tests. The associated rapid vapor temperature decay rate (NASA did not monitor temperatures) would provide the temperature

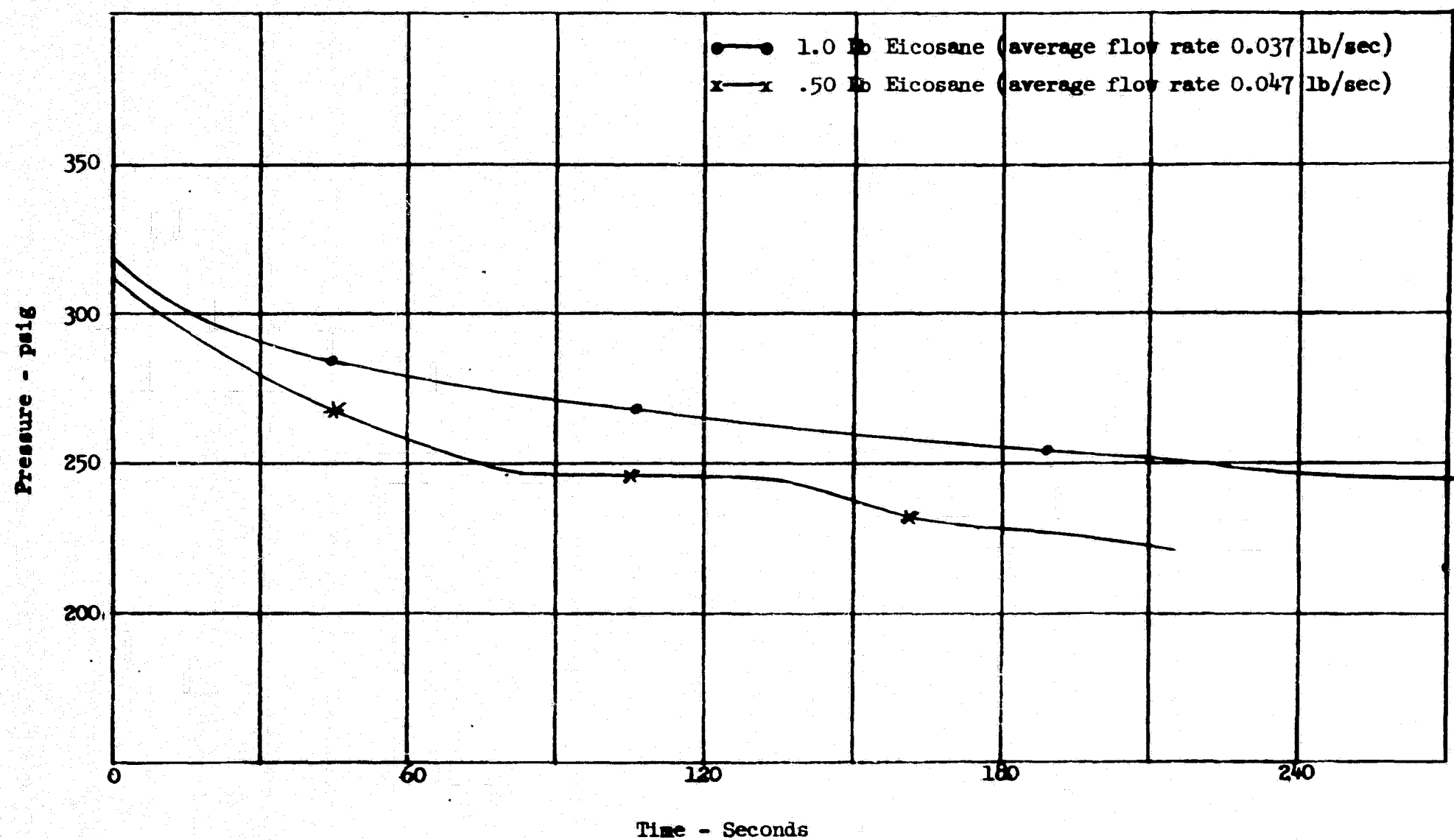


Figure 7-15 Continuous Flow Expulsion Characteristic For
0.70 LB Genetron 32 and Various Amounts of Eicosane

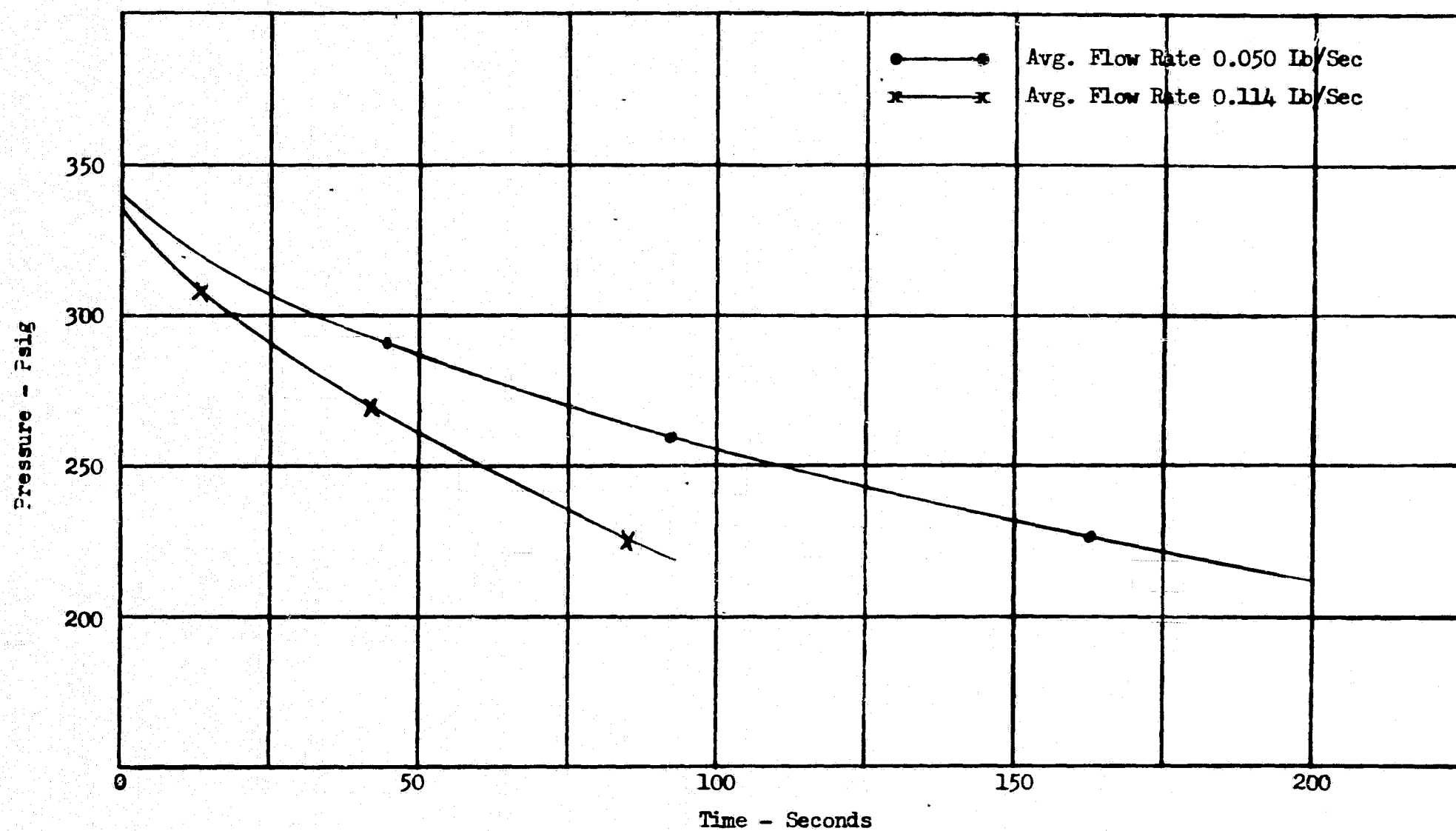


Figure 7-16 Continuous Flow Expulsion Characteristics For
0.7 LB Genetron 32 and 0.7 LB Docosane

differential necessary to drop the heat storage material temperature below its freezing point considerably sooner. A review of the test condition parameters indicated the following:

1. Using the bladder tank system, NASA had been loading the tank with a sufficient quantity of propellant to provide an initial pressurant quality of approximately 5 percent. In the tests which have been conducted by TRW with the subscale bellows tank, the minimum pressurant cavity volume is fixed. Pressurant loads, which had been selected to yield a 100 percent final quality, resulted in an initial quality ranging between 30 and 50 percent.
2. In a pulsing mode of operation, when the pressurant quality in the bladder tank reached approximately 30 percent, the pressure decay rate associated with flow initiation was quite comparable to the values experienced in the bellows tank.

From this review it appeared possible to achieve a pressure plateau with Docosane if the tank was loaded such that the Genetron 32 initial quality was reduced to a very low level.

A series of tests was conducted using a pressurant load of 2 pounds of Genetron 32 and 4 pounds of Docosane. When the tank was loaded with 16 pounds of simulated propellant, the initial quality in the pressurant cavity was approximately 5 percent. Eighteen runs were made at various propellant flow rates. No pressure plateau could be determined at flow rates which would be comparable to those to be experienced on the flight-weight tanks. However, when the flow rate was reduced to approximately one half of the minimum value, a pressure plateau at approximately 300 psig was encountered. The interface heat transfer characteristics are apparently not as efficient for this combination of materials. Typical expansion curves at the low flow rate are shown in Figure 7-17.

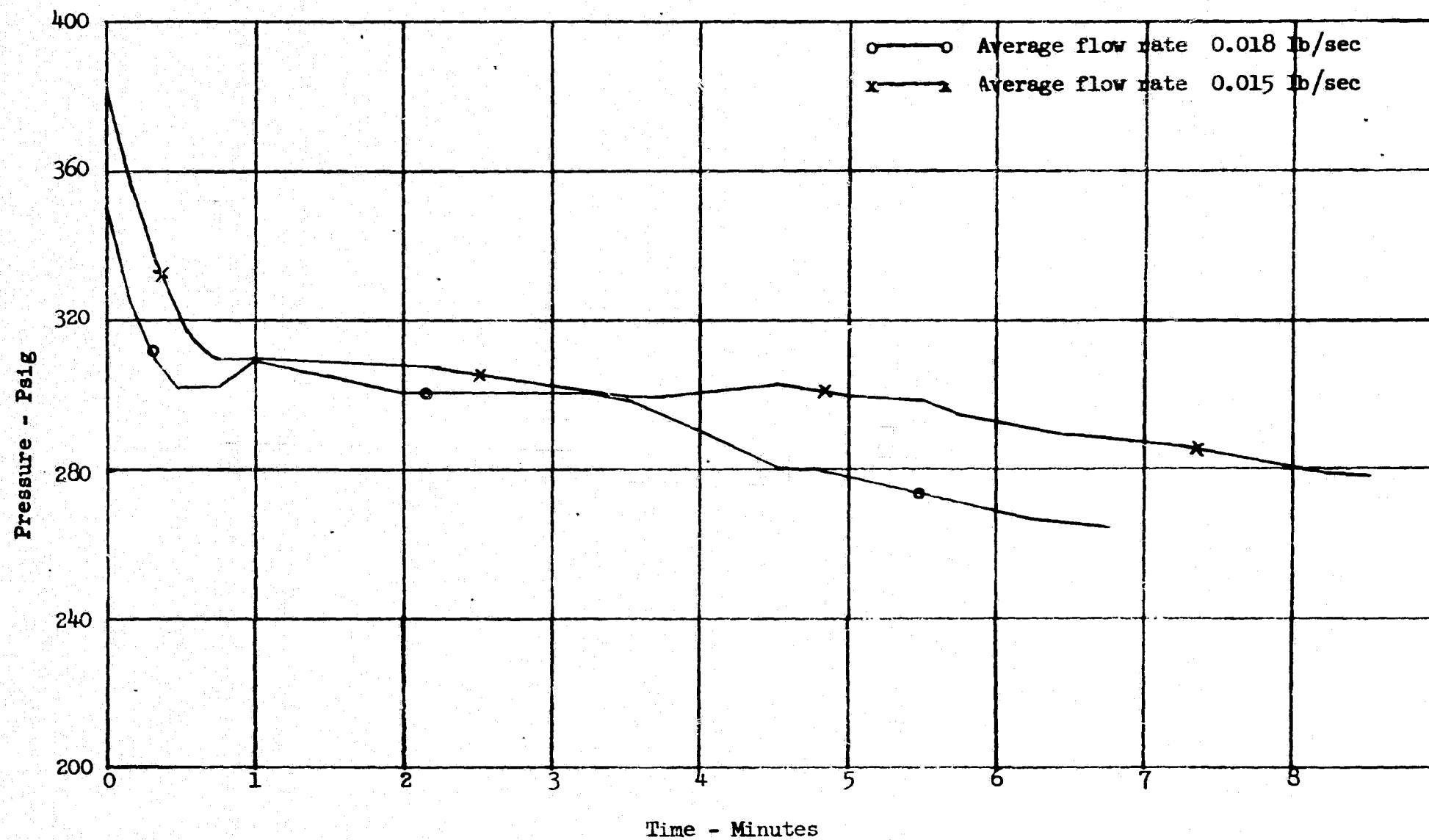


Figure 7-17 Continuous Flow Expulsion Characteristics For
2.0 LB Genetron 32 and 4.0 LB Docosane

7.5 Application of Subscale Test Results

The results of the subscale testing were reviewed and the following decisions were made regarding the system demonstration tests to be conducted:

1. Determination of the amount of pressurant to be loaded into the System A tanks will be based on providing a final quality of 100 percent. With the large initial pressurant volume, the pressure decay on the starting pulse does not become a limiting factor.
2. In the System B tanks it was desirable to achieve as low an initial quality as possible. A reduction in the pressurant cavity size could have been achieved by redesigning the tanks. One approach would have been to invert the tank header on the pressurant cavity side. However, as tank deliveries were already considerably past the original schedule, a redesign, which would impose an excessive amount of slippage, was not considered feasible or desirable.
3. A low initial quality was to be achieved by adding an excess of heat storage and pressurant materials. It was decided to use a 2 to 1 ratio, i.e., 3.5 pounds of pressurant and 7 pounds of heat storage material.
4. The heat storage material to be used will be Eicosane. Extrapolating from the NASA/MSFC test data, the equilibrium pressure expected (260 to 270 psig) was below the system nominal operating pressure but was considered satisfactory to demonstrate the flight-weight system operation. Docosane, which provided a higher equilibrium pressure, was not used because of the flow rate limitation.

It should be noted that only one third of the test runs conducted produced an equilibrium pressure. It became increasingly evident that accurately

controlled starting conditions were required and that the materials themselves will provide considerable influence on operating conditions.

In conducting the investigation into varying starting temperatures, the difference between the free state melting temperature of the heat storage material and the freezing temperature when mixed with the pressurant became a significant factor. As indicated from the compatibility testing conducted during Contract NAS 9-1004, the mixed freezing temperature is depressed between 3 and 17 degrees below the melting temperature. In order to melt the heat storage material, the system temperature must be elevated to a level above the melting temperature. Then in order to avoid an excessive pressure decay during operation, the starting conditions must be reduced to a temperature level just above the mixed freezing temperature. However, even with a desired starting temperature condition, with the initial quality characteristics investigated, as shown in Table 7-4, pressure plateaus were achieved at levels 50 to 85 psi below the apparent pressurant vapor pressure at the heat storage material freezing temperature.

Table 7-4. Pressure Summary for Genetron 32/HSM Tests

Heat Storage Material	HSM Melting Temperature* (°F)	HSM Freezing Temperature* (°F)	Genetron Vapor Pressure at FP* (psig)	Pressure Plateau (psig)
Nonadecane	90	86	285	200
Eicosane	97	93	305	250
Docosane	112	**	***	300
Lauric Acid	110	93	290	240

* Reference 1

**Freezing point not determined during tests.

8.0 PRESSURIZATION SYSTEM DEMONSTRATION TESTING

The purpose of the full-scale pressurization system testing was to demonstrate the capability of the two volatile liquid expulsion systems in meeting the performance requirements for the Apollo Reaction Control Systems. System A operation simulated the Apollo Service Module RCS pressurization system. System B operation simulated RCS pressurization operation in the Apollo Command Module.

The flight configuration hardware used during this series of tests was four flight-weight tanks fabricated to TRW requirements by Metal Bellows Corporation. The System B fuel tank is shown in Figure 8-1.

The testing program was conducted in three phases. During the first two phases simulated propellants were expelled. Actual propellants were expelled during the final phase. During the initial phase, investigative runs were made to provide data similar to that obtained during the sub-scale testing. Utilizing the results of this testing, a duty cycle was established simulating expected Apollo Service and Command Module worst case operation. Phase 2 consisted of a series of bipropellant (simultaneous fuel and oxidizer tank) duty cycle expulsion runs to demonstrate the capability of maintaining equal pressures in the two tanks during operation. The final phase of tests consisted of propellant expulsion with each of the four tanks individually at the worst case duty cycle to determine if any variation existed in expulsion characteristics as a result of the medium being expelled.

Throughout the design-development portion of the program, System B had been considered to operate with a continuous propellant flow mode. The heat input (heat storage material) system had been developed for this mode of operation. The duty cycle, established by NASA, was however a pulsing mode with a 50 to 20 percent propellant flow. The heat storage material was found to be ineffective in this type of flow mode particularly at minimum propellant flow rates. However, System B operation was satisfactorily demonstrated using the available command module waste heat loop.

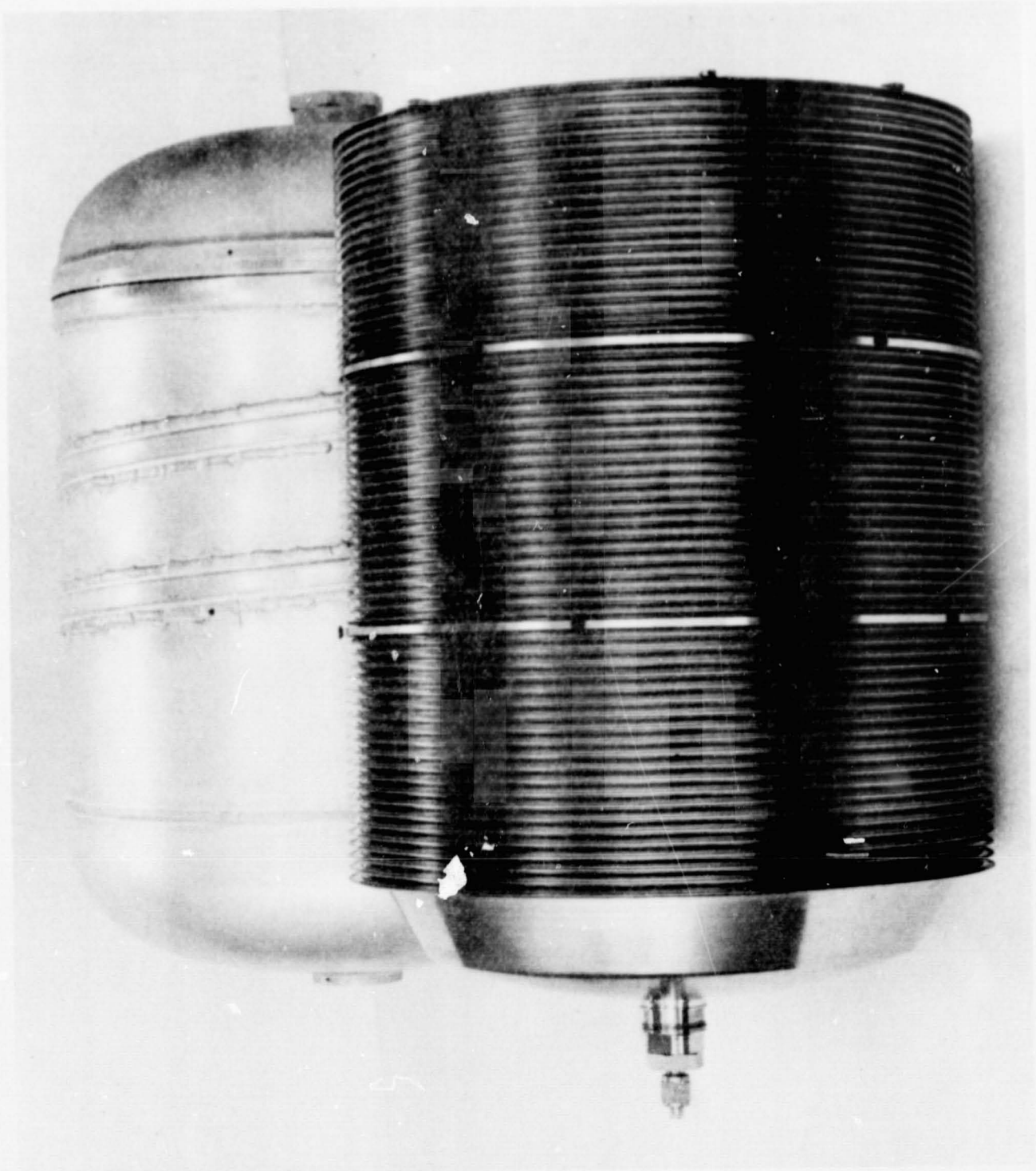


Figure 8-1 System B Fuel Tank and Bellows Capsule (Bellows is in an Expanded Condition)

8.1 Test Procedure

The results in this series of tests were obtained using the tanks installed in the basic test setup shown schematically in Figure 8-2.

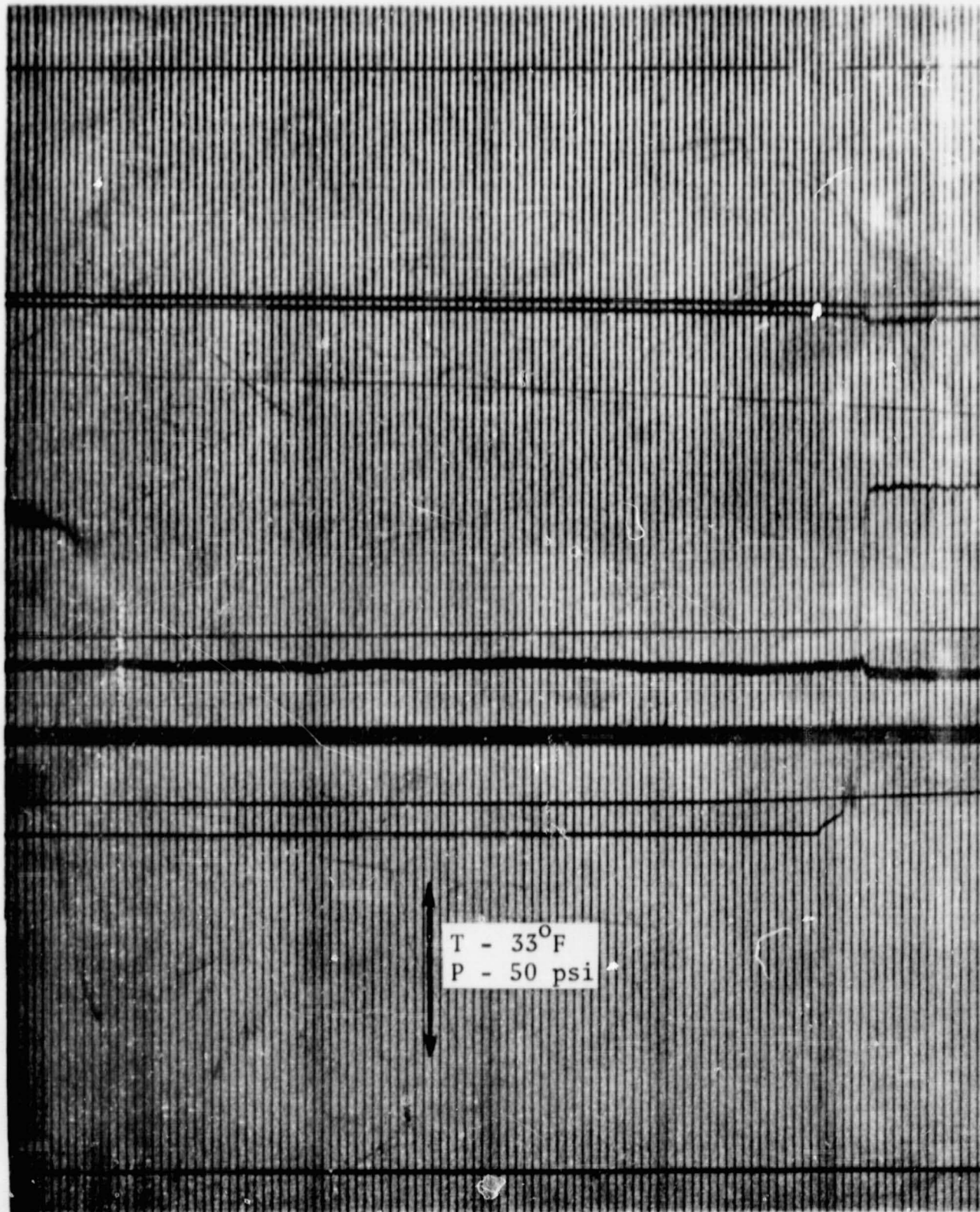
The basic test procedure which was used was identical to the subscale test procedure with minor modifications noted as follows:

1. The heat storage material when used was weighed separately and then loaded into the pressurant cavity in a liquid state. The tank was secured in a vertical position and the heat storage material poured into the movable bellows header and allowed to solidify.
2. The tank was then installed in the test setup and a leak check performed.
3. The propellant cavity of the tank was then evacuated. From the results of the loading studies (Section 6.0), it was intended to evacuate both sides of the bellows simultaneously. However, with both sides of the bellows evacuated, in attempting to load propellant, an excessive amount of propellant vaporization occurred which prohibited loading. The loading procedure was revised to provide a minimal evacuated volume in which to load the propellant. With only the propellant cavity evacuated and the pressurant cavity vented to atmospheric pressure, the pressure differential positions the bellows in a closed position minimizing the propellant volume.
4. With the pressurant cavity vented to atmosphere, a small initial quantity (3 to 4 pounds) of propellant was loaded. It was desired to load the pressurant prior to loading the propellant in order to accommodate propellant depletion and to retain the ability to recycle. However, in attempting to load the propellant, it was discovered that with the

propellant cavity completely empty the load exerted on the movable bellows header by the volatile liquid vapor pressure was sufficient to seal off the inlet port. It was necessary to load a small amount of propellant prior to loading the volatile liquid in order to separate the bellows header and the tank shell. Correcting this condition can be readily accomplished in future tanks through a minor redesign of the bellows header.

5. The pressurant cavity of the tank was then evacuated.
6. The pressurant was then weight-loaded in an ambient condition using the vapor pressure in the pressurant container to force the required amount of pressurant into the cavity.
7. The balance of the propellant was then loaded. It was forced into the propellant cavity by applying gaseous nitrogen pressure as required to overcome the pressurant vapor pressure.
8. After the final weight of the system was recorded, the supply tank was vented off and the throttle valve adjusted for the proper flow rate.
9. The heat exchanger pump was then activated to bring the system to a level slightly above the initial operating pressure. The system temperatures stabilized during the time the pressure decayed to the starting condition.
10. Just prior to opening the flow control valve, the oscillograph was started to record the propellant and heat exchanger flow rates, the pressurant pressure and temperatures of the fuel, pressurant and heat exchanger fluid. A typical oscillograph trace of a single pulse is shown in Figure 8-3.

FOLDOUT FRAME /



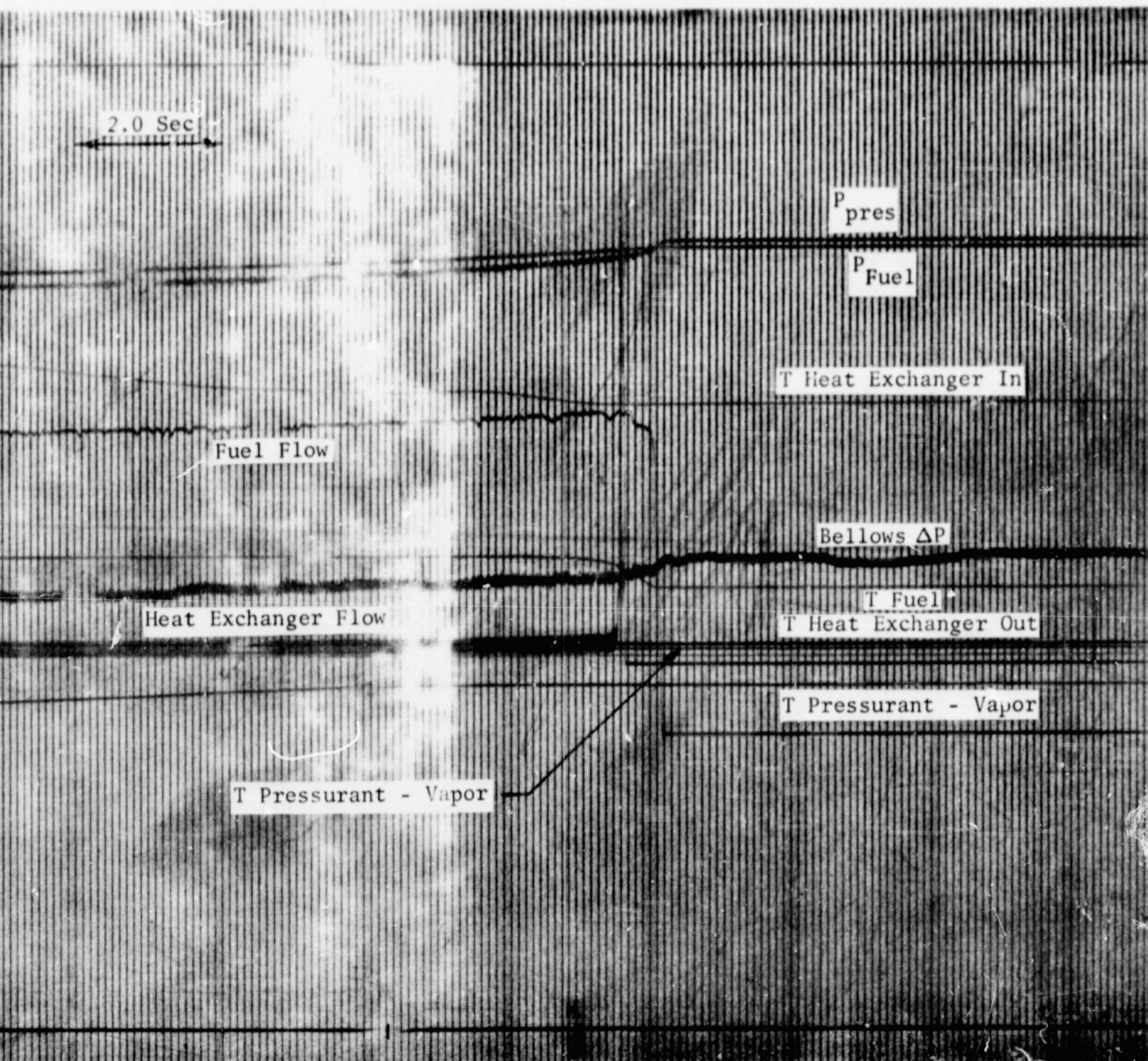


Figure 8-3 Typical Flow Pulse Oscillograph Trace

11. The run was terminated when the required amount of propellant had been expelled or the required number of flow pulses achieved.
12. The propellant supply tank was then repressurized and the bypass valve opened until the original quantity of propellant was in the expulsion tank. The system was then ready for the next run. Care was exercised to assure, that the heat storage material, when used, was in a liquid state during the propellant reloading.

8.2 Simulated Propellant Testing

The subscale tests were conducted using triethylene glycol as the simulated propellant. It was decided to use Freon 11 for the system tests in order to conduct the propellant tests without danger of contamination. As the Freon 11 is a solvent itself, subsequent cleaning was not necessary. The Freon 11 density and heat capacity closely simulate the properties of N_2O_4 . The triethylene glycol, which had been used to date, has properties approximately midway between the fuels used and the oxidizer.

Because of fabrication problems resulting in delays in delivery of the System A tanks, it was decided to conduct the initial investigation tests for both Systems A and B using the System B tanks.

The weight loading and calculated resulting pressurant qualities in the System B tanks are as shown in Table 8-1.

8.2.1 Full Scale Flow Investigation

The System B oxidizer tank was the first tank received. This tank was used for both Systems A and B tests.

For the System A (pulsed flow) tests, a pressurant load of 5.25 pounds of Freon 22 was used. The heat exchanger inlet conditions were set at 180°F

Table 8-1 Tank Loading Requirements for Initial
Systems A and B Tests Using System B Tanks

	<u>Oxidizer Tank</u>	<u>Fuel Tank</u>
Propellant	N ₂ O ₄	MMH
Propellant Capacity (lb)	92.4	44.6
Simulated Propellant (Freon 11) Capacity (lb)	93.7	75.6
Maximum Propellant Flow Rate (lb/sec)	0.888	0.444
Equivalent Maximum Freon 11 Flow Rate (lb/sec)	0.897	0.745
Minimum Propellant Flow Rate (lb/sec)	0.222	0.111
Equivalent Minimum Freon 11 Flow Rate (lb/sec)	0.224	0.186
System A Pressurant Load		
Freon 22 Weight (lb)	5.25	4.5
Pressurant Initial Volume (in. ³)	822.0	793.0
Initial Quality (%)	27.4	31.4
Pressurant Final Volume (in. ³)	2583.0	2203.0
Final Quality (%)	96.5	96.0
System B Pressurant Load		
Genetron 32 Weight (lb)	4.5	4.3
Eicosane Weight (lb)	9.0	8.0
Pressurant Initial Volume (in. ³)	508.0	512.0
Initial Quality (%)	16.6	17.8
Pressurant Final Volume (in. ³)	2251.0	1908.0
Final Quality (%)	92.8	82.6

and a flow rate of 0.03 lb/sec of the water glycol mixture. Freon 11 (simulated propellant) flow rates were established equivalent to the required oxidizer flow rates of 0.222 and 0.888 lb/sec. A total of ten pulsing flow runs was made. At the lower flow rates, runs were made at varying pulse lengths of 5, 10, and 20 seconds. The test results are shown in Figures 8-4 through 8-6. At the high flow rate, pulse lengths of 10 (Figure 8-7) and 20 (Figure 8-8) seconds were used. The flow frequency was determined by the rate of recovery of the system to the original pressure level. A flow pulse was made and the pressure was allowed to recover until the heat exchanger flow was discontinued before the next pulse was initiated.

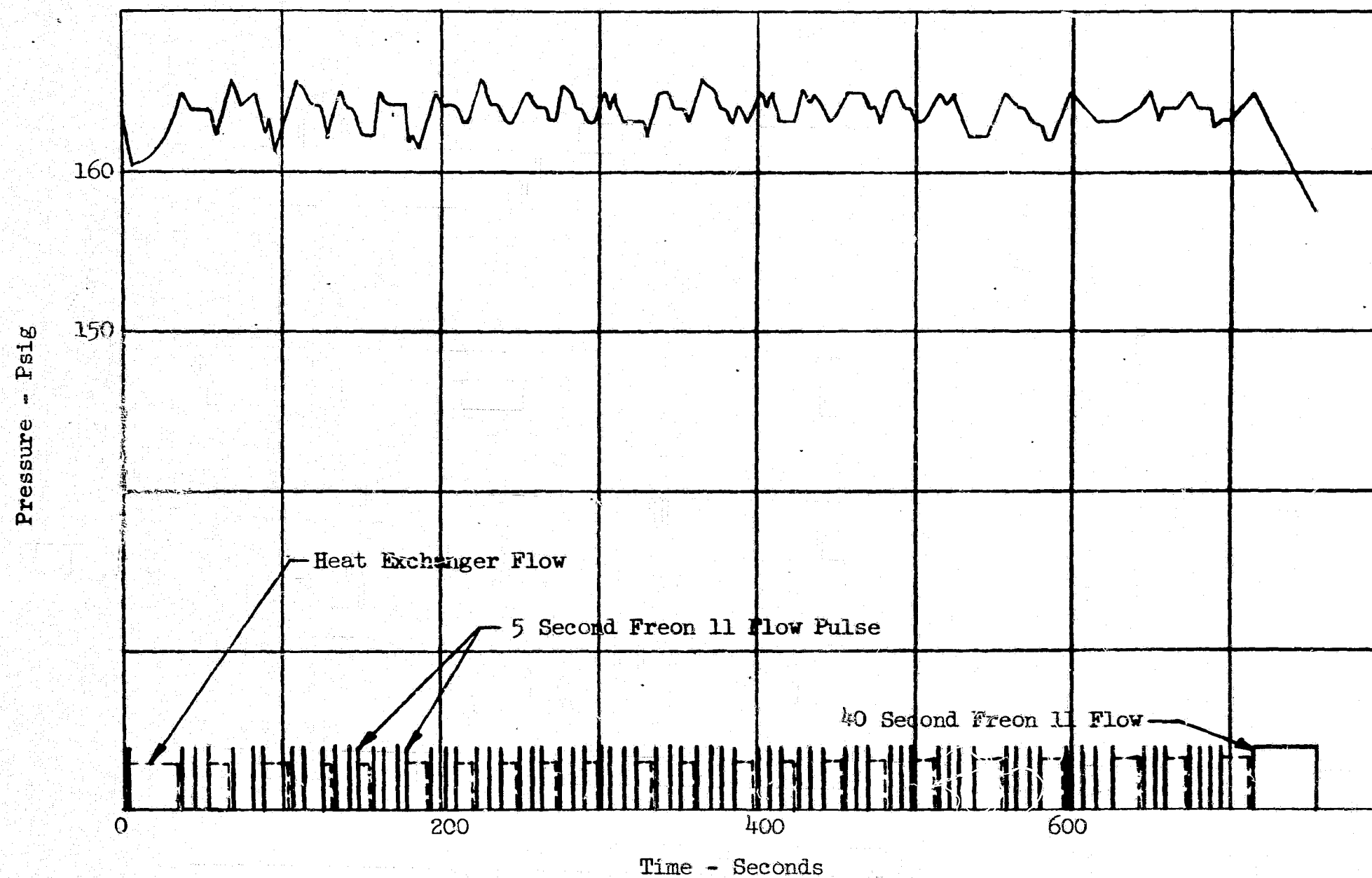


Figure 8-4 Pulsing Flow Expulsion Characteristics for System B
Oxidizer Tank Loaded With 5.5 LB Freon 22. Freon 11
Flow Rate 0.194 LB/Sec - 5 Second Pulses

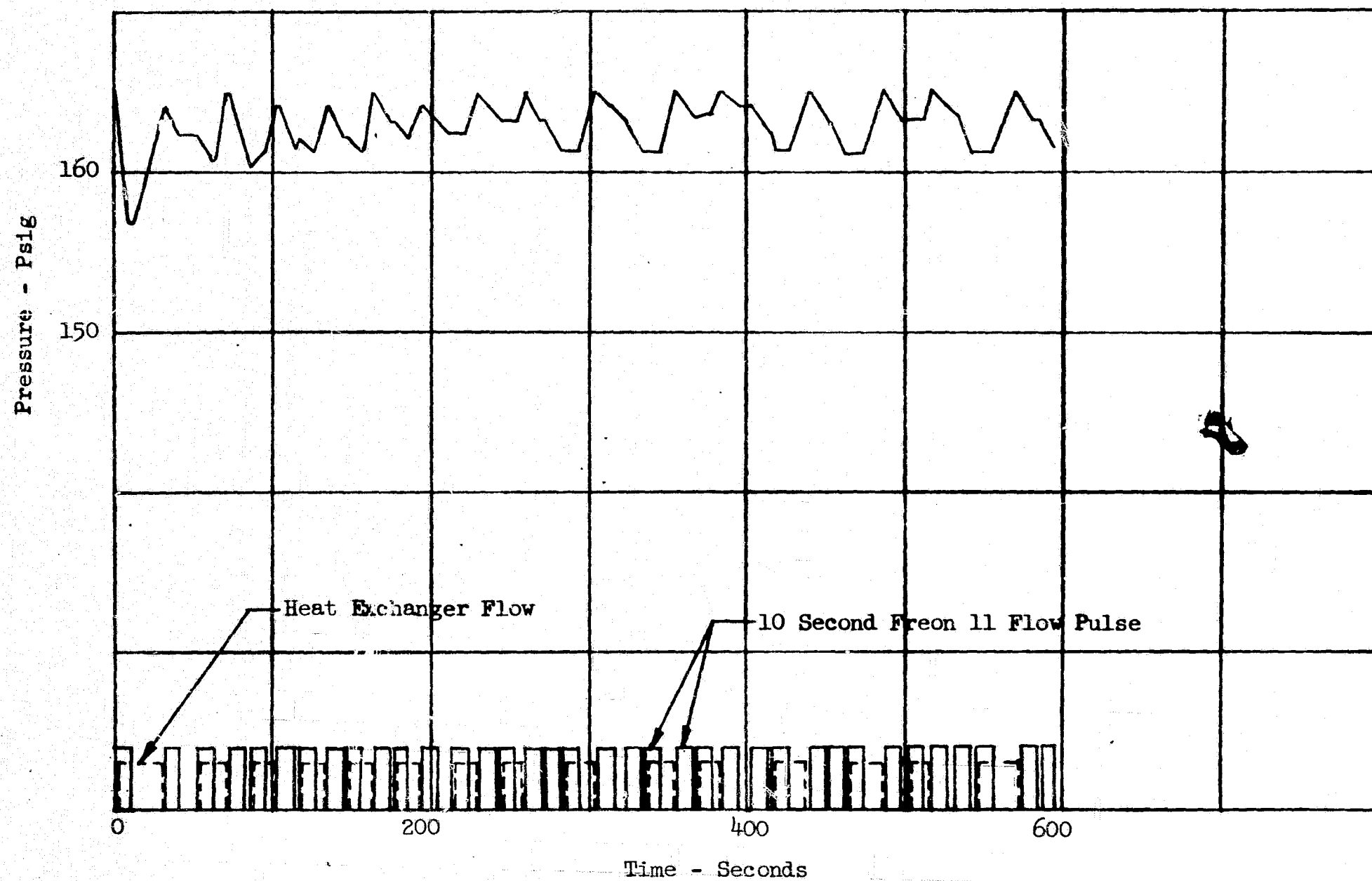


Figure 8-5 Pulsing Flow Expulsion Characteristics for System B
Oxidizer Tank Loaded With 5.5 LB Freon 22. Freon 11
Flow Rate 0.191 LB/Sec - 10 Second Pulses.

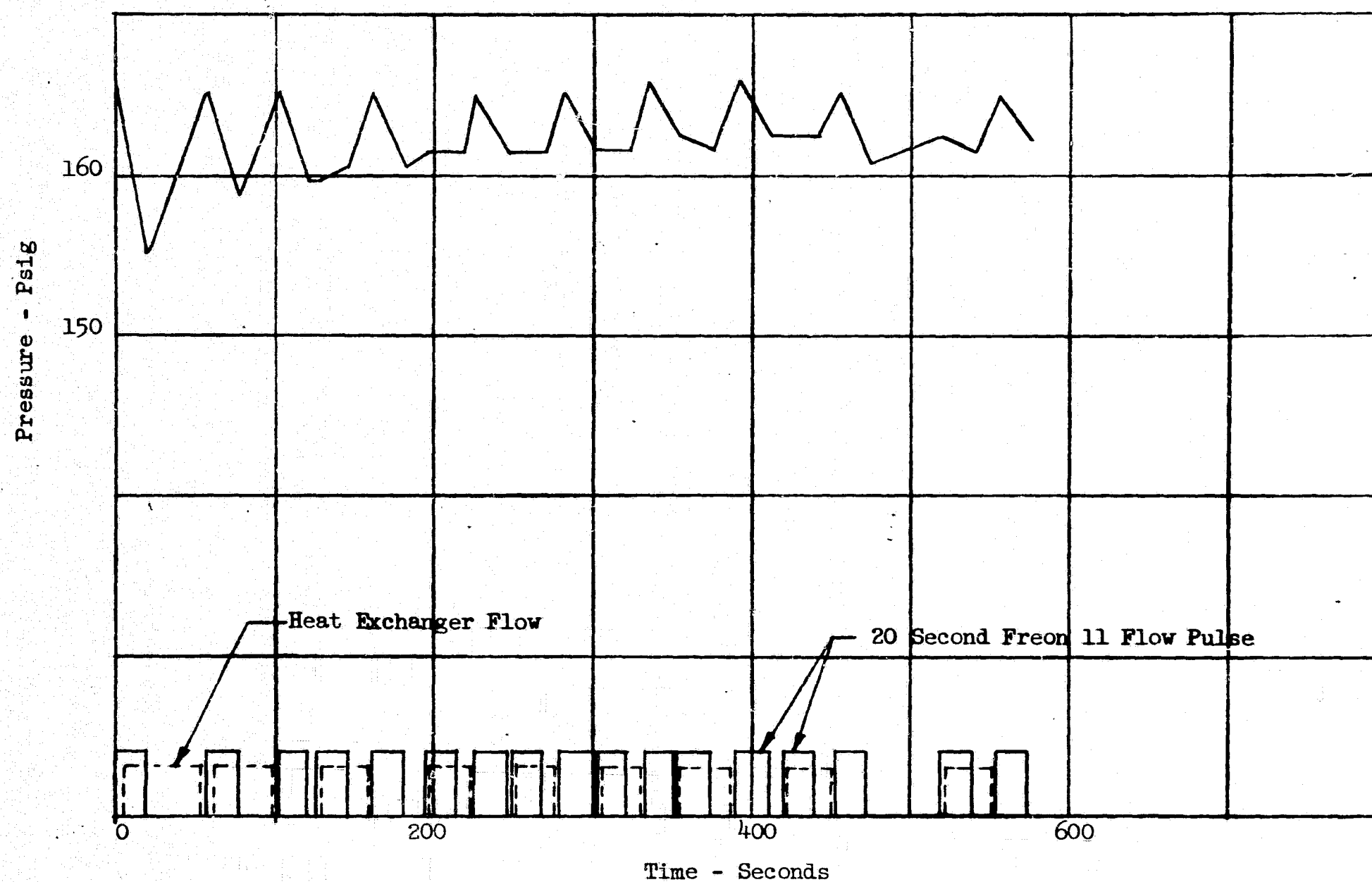


Figure 8-6 Pulsing Flow Expulsion Characteristics for System B
Oxidizer Tank loaded with 5.5 LB Freon 22. Freon 11
Flow Rate 0.198 LB/Sec - 20 Second Pulses

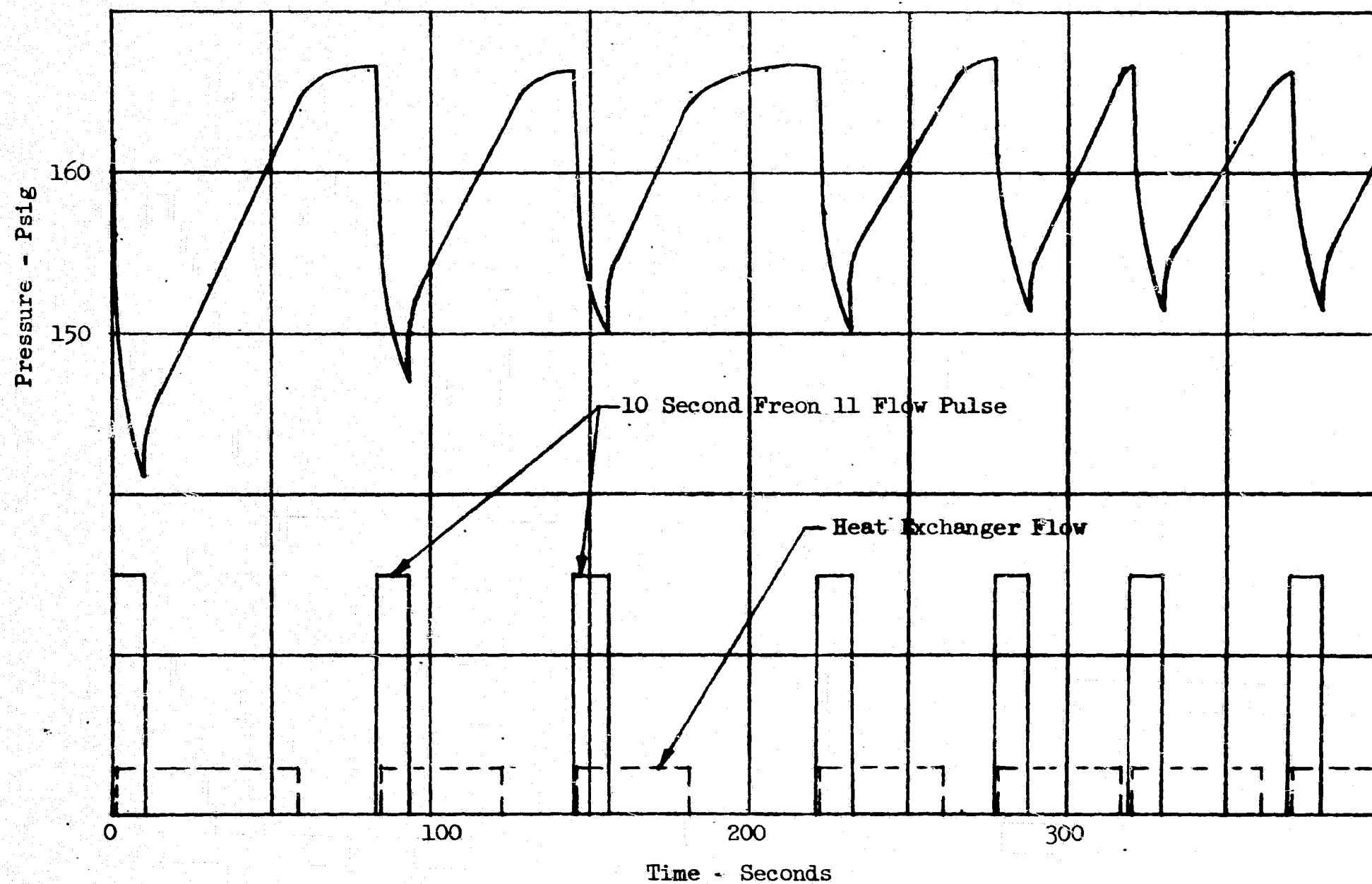


Figure 8-7 Pulsing Flow Expulsion Characteristics for System B
Oxidizer Tank Loaded With 5.5 LB Freon 22. Freon 11
Flow Rate 0.915 LB/Sec - 10 Second Pulses

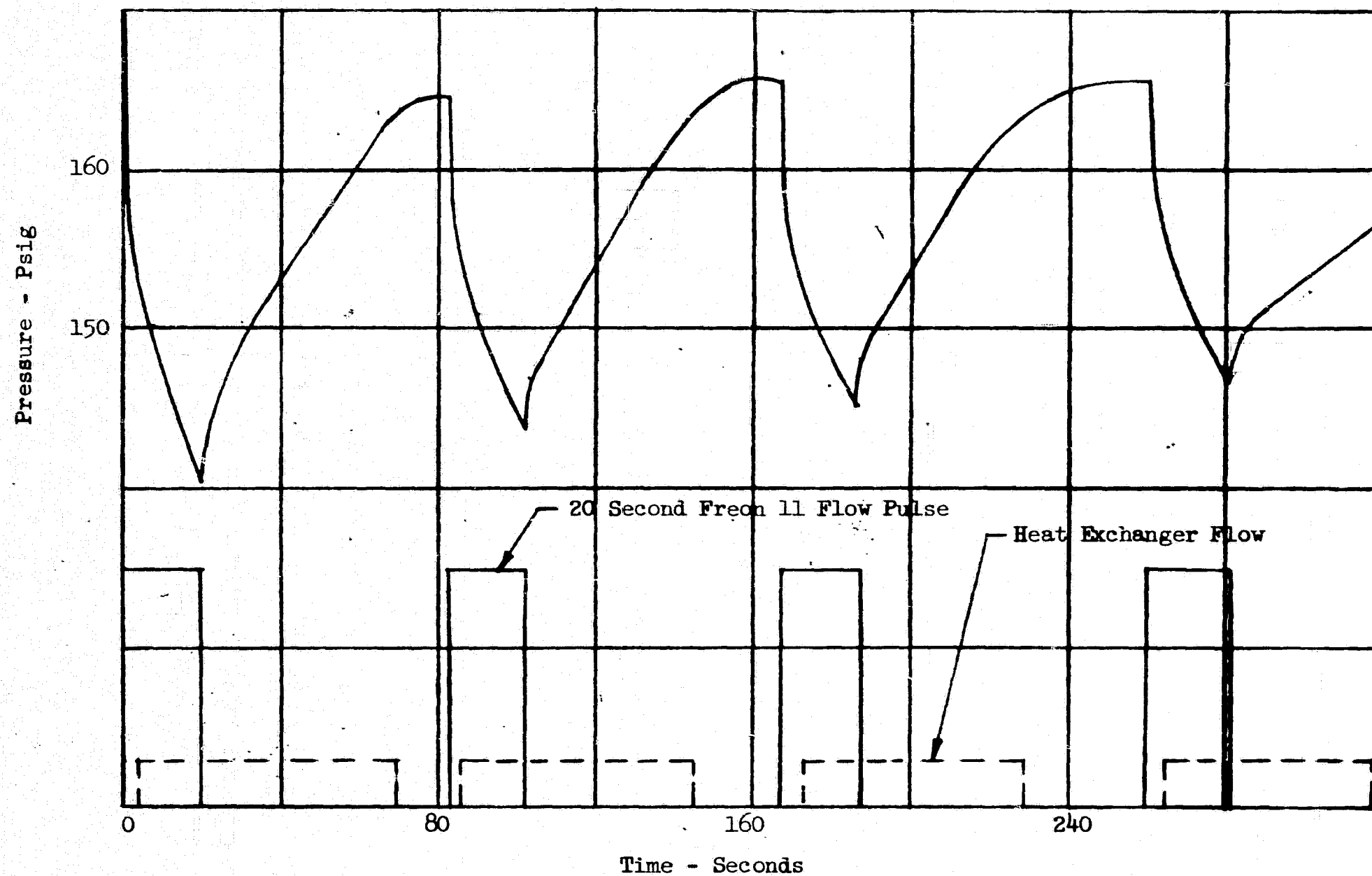


Figure 8-8 Pulsing Flow Expulsion Characteristics for System B
Oxidizer Tank Loaded With 5.5 LB Freon 22. Freon 11
Flow Rate 0.815 LB/Sec - 20 Second Pulses.

The System B oxidizer tank was then prepared for System B (continuous flow) operation. Nine pounds of Eicosane and 4.5 pounds of Genetron 32 were loaded into the tank. A run was made at the low flow rate. Flow was initiated at an initial pressurant temperature of approximately 94°F at 310 psi. The pressure decayed rapidly to approximately 250 psig. At a slower rate of decay, by the end of the run the pressure had dropped to 210 psi as shown in Figure 8-9. A test failure (Section 8.5) prevented further testing in this tank.

A series of five low flow tests was then conducted with the System B fuel tank. The tank was loaded with 8 pounds of Eicosane and 4.3 pounds of Genetron 32. The results, as shown in Figure 8-10, were very comparable to those obtained in the oxidizer tank.

In order to increase the pressure level obtained in the tank several runs were conducted with a higher Genetron 32 weight loading to obtain a lower initial quality. The lower initial quality was expected to provide a more rapid rate of pressure and temperature decay to initiate HSM freezing sooner.

Eighteen additional System B flow investigation runs were made using the System B fuel tank. The tank was loaded with 8 pounds of Eicosane and 9.5 pounds of Genetron 32. This loading resulted in an initial pressurant quality of 5.7 percent and a final quality of 13.3 percent. Continuous expulsion runs were conducted at both the high and low flow rates. Investigative runs were then conducted in which the heat exchanger was used. The heat exchanger flow was triggered at the initiation of propellant flow and was maintained continuous throughout the run. A significant improvement in performance was noted, particularly at the low flow rate. It was then determined that System B operation in the Apollo Command Module would not have a heat exchanger source available at 180°F. However, a 120°F loop was available. Continuous expulsion tests were then repeated using the heat exchanger inlet temperature set at 120°F. Some improvement in performance was still evident. The results of the continuous flow expulsion are shown in Figures 8-11 and 8-12.

SI-8

Pressure - Psig

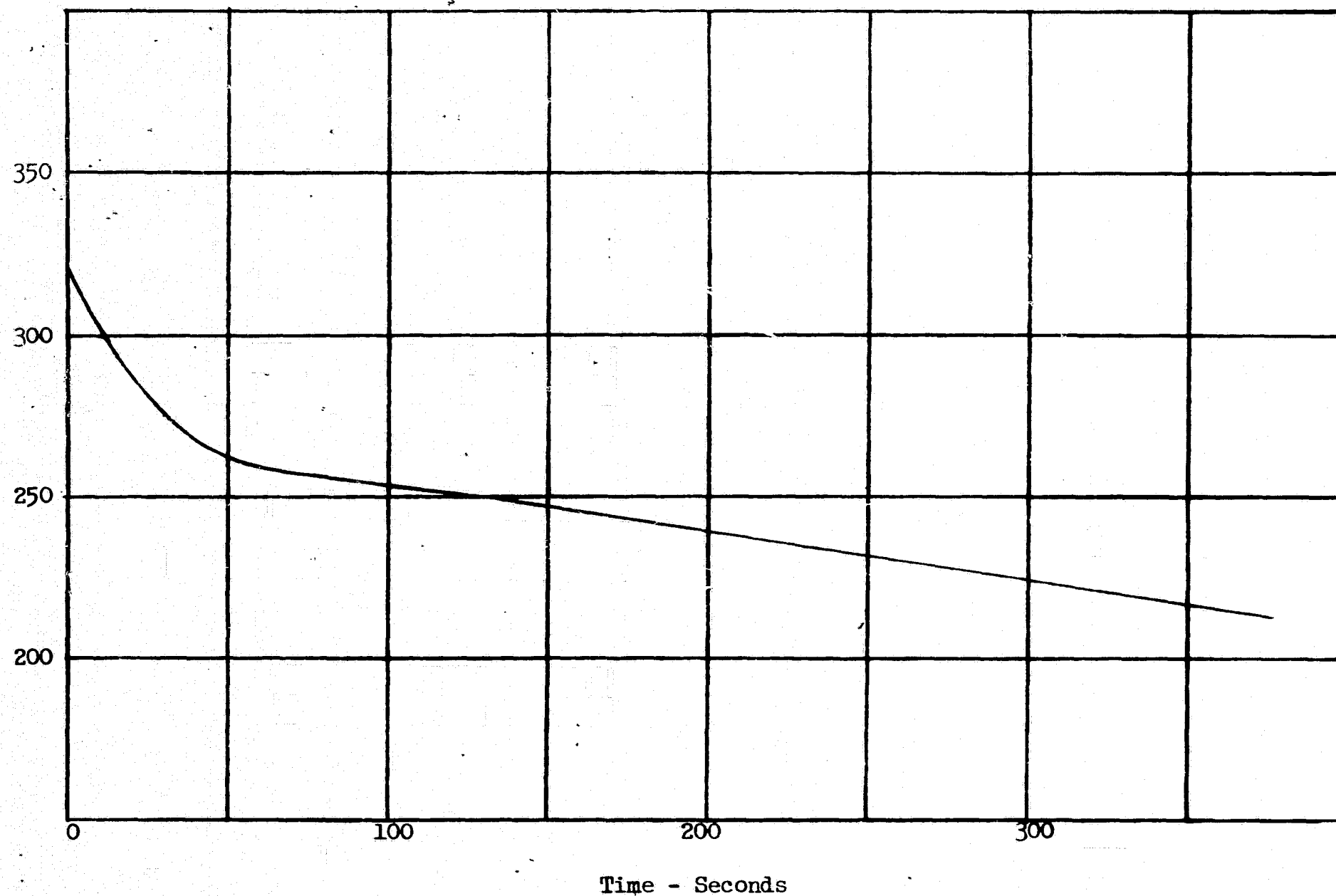


Figure 8-9 Continuous Flow Expulsion Characteristics For System "B" Oxidizer Tank Loaded With 9.0 LB Eicosane and 4.5 LB Genetron 32. Freon 11 Flow Rate 0.207 LB/Sec.

91-8

Pressure - Psig

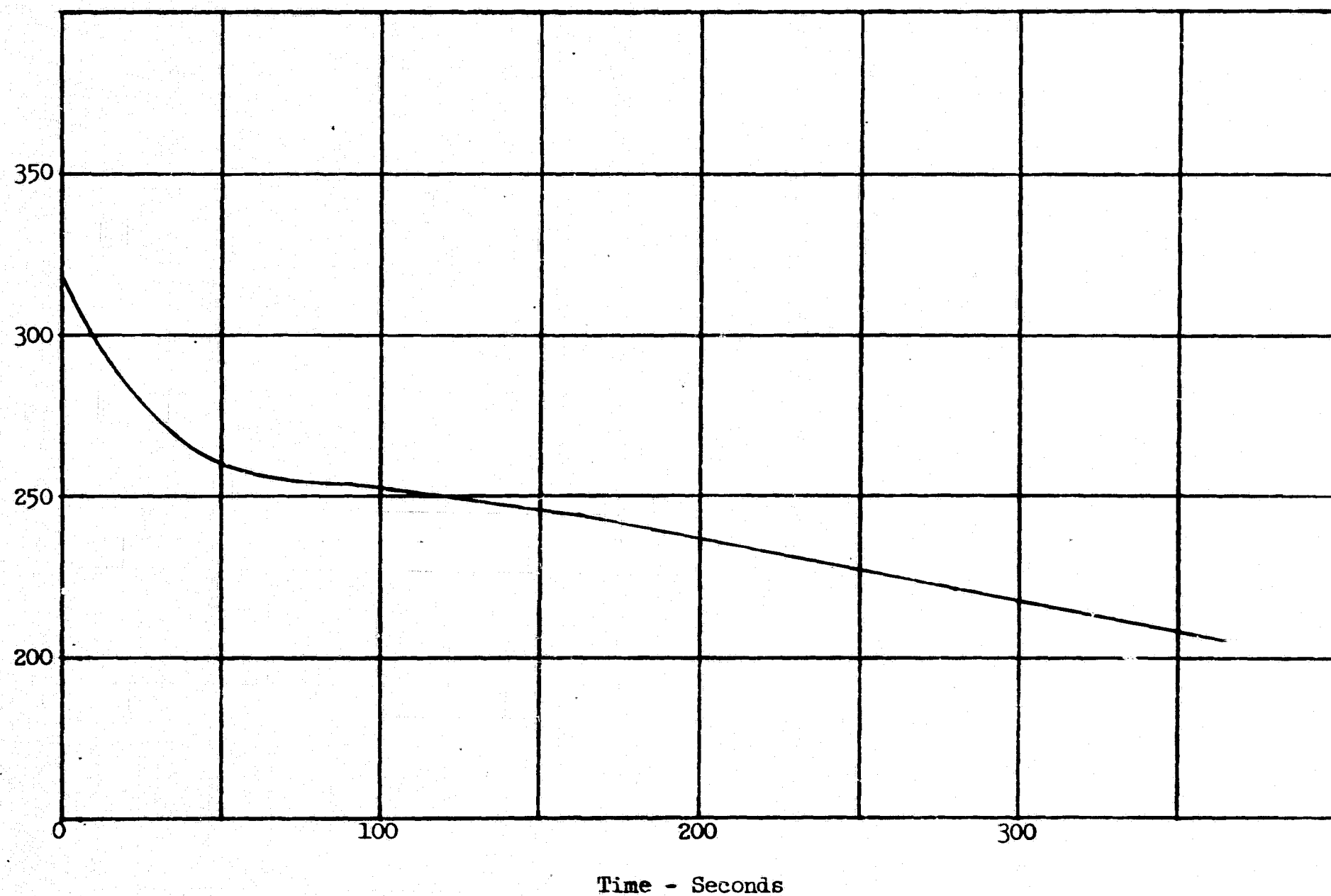


Figure 8-10 Continuous Flow Expulsion Characteristics for System "B" Fuel Tank Loaded With 8.0 LB Eicosane and 4.3 LB Genetron 32. Freon 11 Flow Rate 0.158 LB/Sec

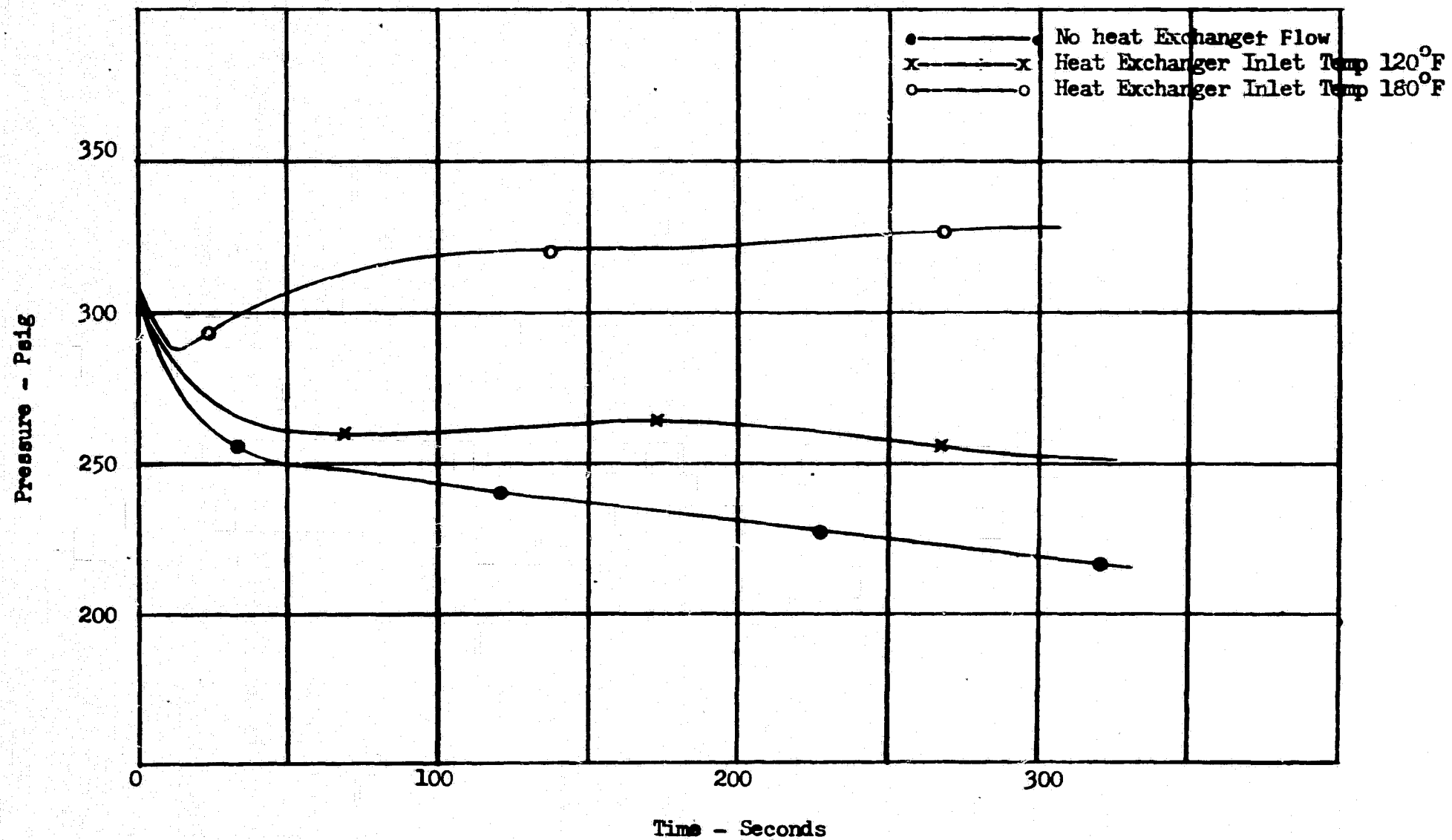


Figure 8-11 Continuous Flow Expulsion Characteristics for System "B" Fuel Tank Loaded With 8.0 LB Eicosane and 9.5 LB Genetron 32. Freon 11 Flow Rate 0.220 LB/Sec.

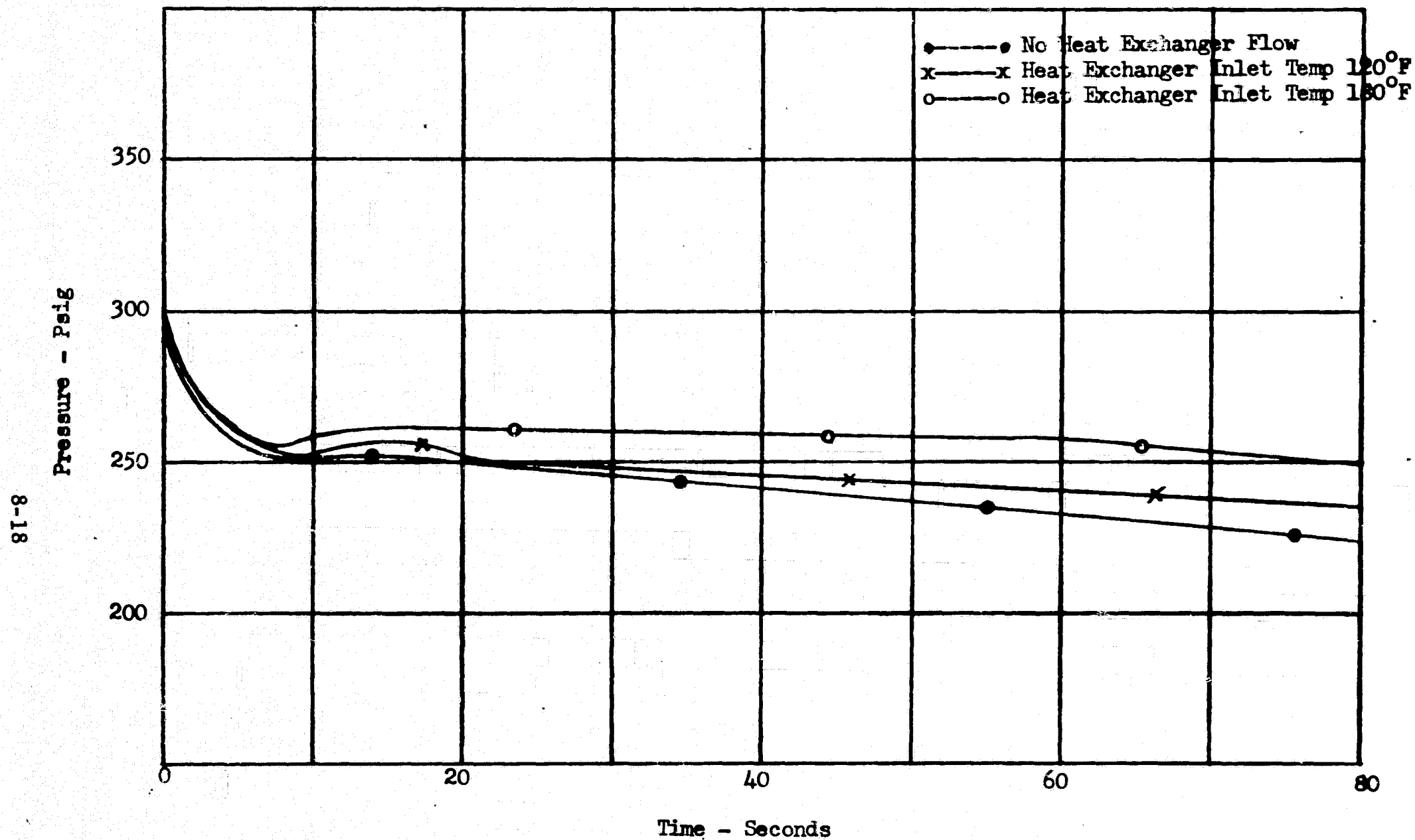


Figure 8-12 Continuous Flow Expulsion Characteristics for System "B" Fuel Tank Loaded With 8.0 LB Eicosane and 9.5 LB Genetron 32. Freon 11 Flow Rate 0.830 LB/Sec.

NASA then requested that pulsing runs be made both with the heat exchanger off and with the heat exchanger inlet set at 120°F. The results are shown in Figure 8-13 for the minimum flow rate, in which the duty cycle was 60 seconds on and 60 seconds off. For the maximum flow rate, the duty cycle was set at 15 seconds on and 15 seconds off. The results are shown in Figure 8-14.

Because of the interest in pulsing performance, further improvements in continuous flow performance by additional reduction in the initial vapor volume were not investigated.

8.2.2 Pressurization System Demonstration Testing Duty Cycle

The results of the flow investigation testing were reviewed and used by NASA in establishing a duty cycle to be used during the balance of the pressurization system demonstration testing.

In establishing a duty cycle to be used, an attempt was made to provide a cycle which was consistent with the expected requirements of the Apollo Service and Command Modules and still allow comparison to the test data already obtained. It was decided that all tests would be conducted using propellant flow pulses of 10 seconds duration. By varying the off times, a changing duty cycle was established.

The duty cycle established for each system consisted of a series of runs to be conducted which provided varying flow rates and various usage cycles. The required minimum flow rate (0.111 lb/sec fuel and 0.222 lb/sec oxidizer) simulates a single 100-pound thrust engine operation and the required maximum flow rate (0.444 lb/sec fuel and 0.888 lb/sec oxidizer) simulates simultaneous four 100-pound thrust engines operation.

System A duty cycle consisted of the following run conditions:

<u>Propellant Flow Rate</u>	<u>Engine Usage Cycle</u>	<u>Heat Exchanger Flow</u>
4 engine	10%	Controlled by Pressure Switch
2 engine	50%	" " "
2 engine	10%	" " "
1 engine	50%	" " "
1 engine	10%	" " "

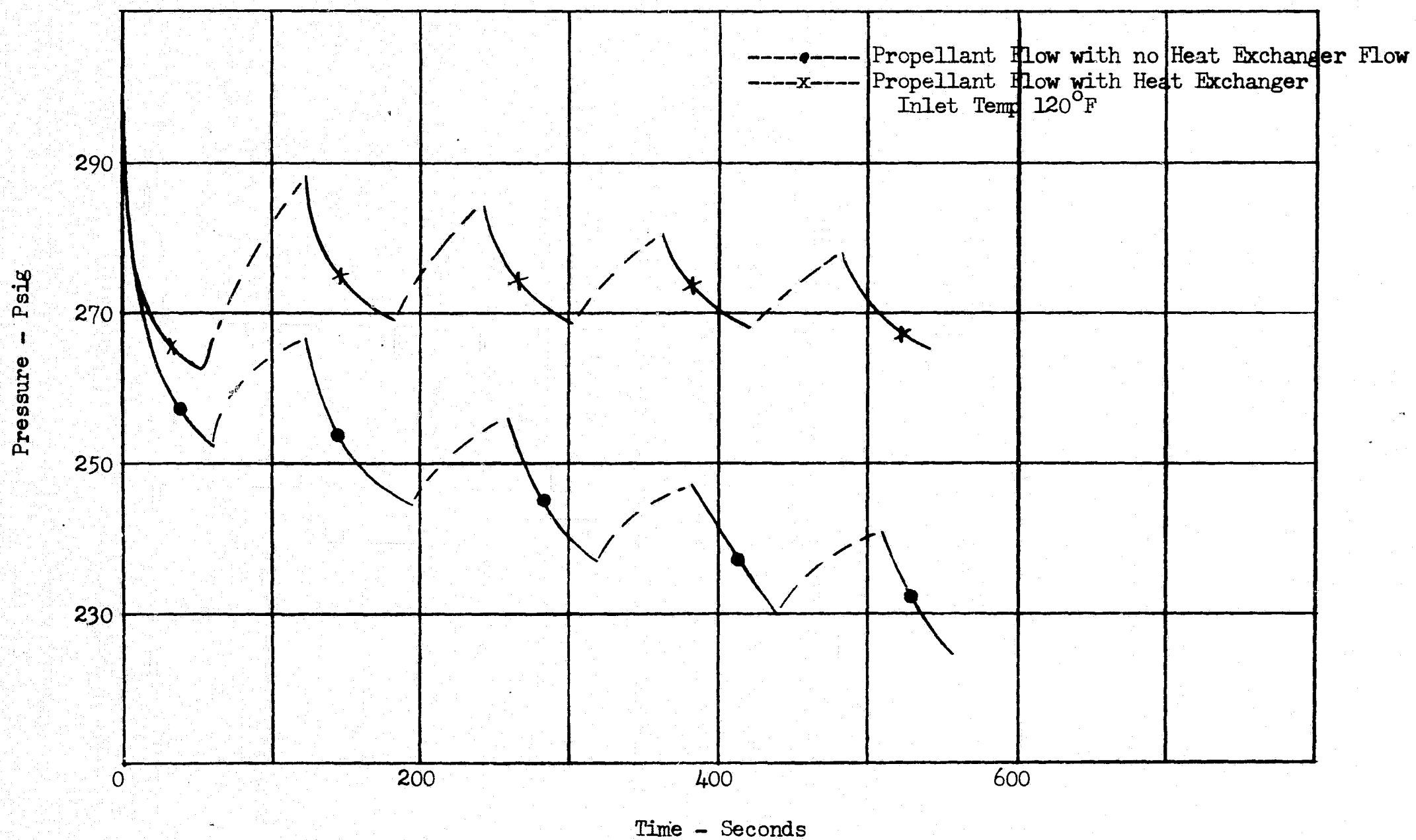


Figure 8-13 Pulsing Flow Expulsion Characteristics for System "B" Fuel Tank Loaded With 8.0 LB Eicosane and 9.5 LB Genetron 32. Freon 11 Flow Rate 0.225 LB/Sec.

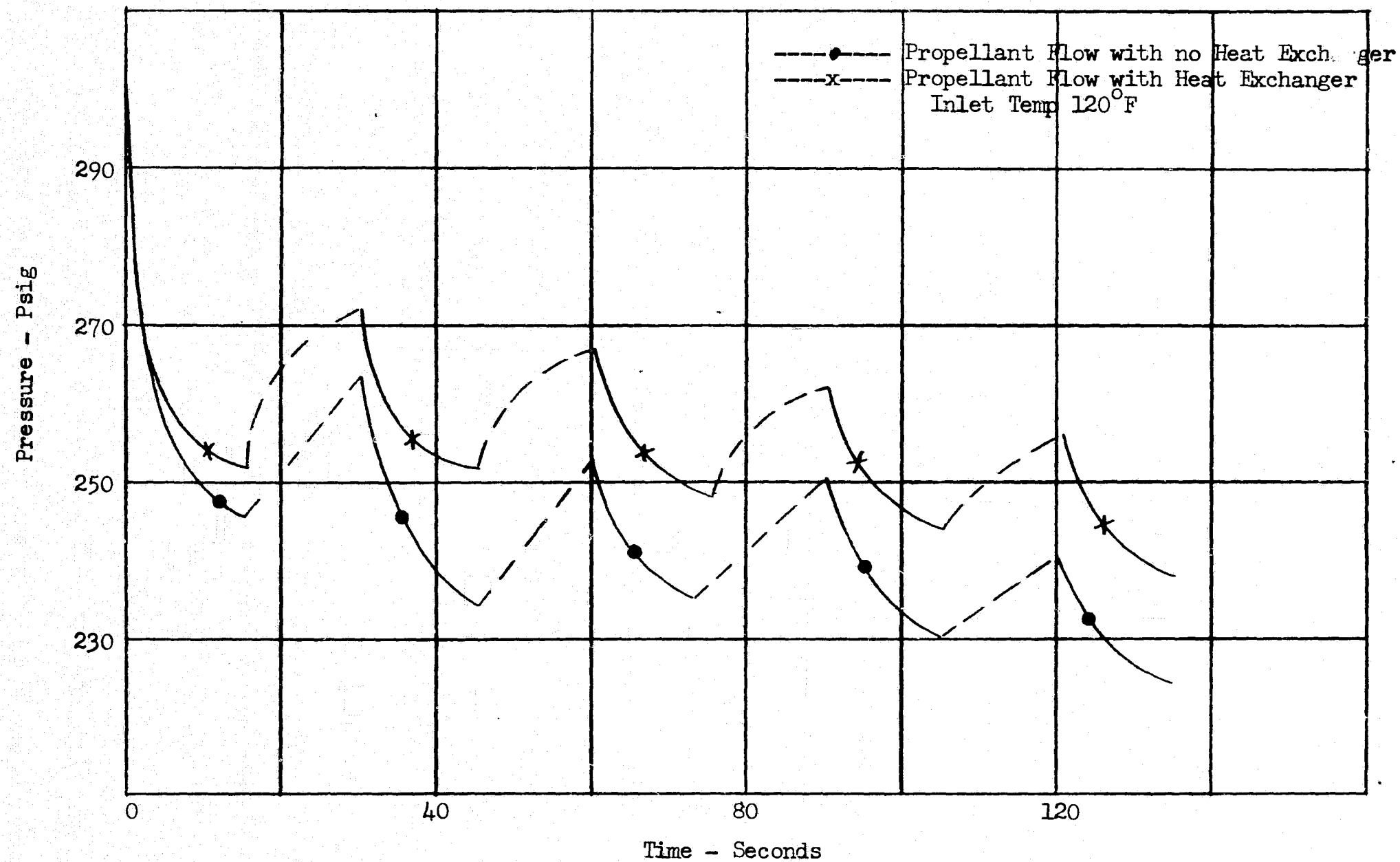


Figure 8-14 Pulsing Flow Expulsion Characteristics for System "B" Fuel Tank Loaded With 8.0 LB Eicosane and 9.5 LB Genetron 32. Freon 11 Flow Rate .822 LB/Sec.

System B duty cycle (the impact of the change of propellant flow from continuous to pulsing was not apparent until later in the program) consisted of the following run conditions:

<u>Propellant Flow Rate</u>	<u>Engine Usage Cycle</u>	<u>Heat Exchanger Flow</u>
4 engine	20%	on
4 engine	20%	off
1 engine	50%	on
1 engine	50%	off

In System B runs in which the heat exchanger was used, heat exchanger flow initiated with propellant flow and was continuous throughout the propellant expulsion.

In all system test runs, the heat exchanger flow rate was established at 0.03 lb/sec for each tank. The heat exchanger inlet temperatures were set at 180°F and 120°F for the Systems A and B operation runs, respectively.

In System A operation, increased pressure decay per pulse occurs with longer duration pulses. The use of 10-second pulses throughout the duty cycle is more severe than is expected in actual service module usage. System B tests are limited to 5 minutes total duration. This duplicates the expected average command module reentry propellant usage. A tabulation of the duty cycle conditions is shown in Table 8-2 for System A. The System B conditions are shown in Table 8-3.

8.2.3. Bipropellant System Expulsion Tests

In order to compare the individual tank response in system operation, a series of tests was conducted expelling simulated propellants from both the fuel and oxidizer tank simultaneously. Because of a delay in delivery of the System A tanks, it was decided to conduct both Systems B and A operational duty cycle tests using the System B tanks.

The test stand was revised to allow dual tank operation. A schematic of the revised test setup is shown in Figure 8-15.

Table 8-2. Duty Cycle Run Conditions System A Simulated Propellant Dual Tank Operation

Run No.	Flow Pulse Length (sec)	Off Time (sec)	No. Pulses	Total Run Time (min)	Heat Exchanger*		Equivalent Freon 11 Flow Rate	
					Flow Rate/Tank (lb/sec)	Inlet Temperature (°F)	Oxidizer Tank (lb/sec)	Fuel Tank (lb/sec)
1	10	10	30	9.8	0.03	180	0.224	0.186
2	10	90	30	48.5	0.03	180	0.224	0.186
3	10	10	15	4.8	0.03	180	0.448	0.372
4	10	90	15	23.5	0.03	180	0.448	0.372
5	10	90	8	11.8	0.03	180	0.896	0.744

* Heat exchanger flow for each tank will be controlled by individual pressure switches sensing the pressurant cavity pressure. Flow will be initiated on decay to 160 psig and terminated on increase to 165 psig.

Table 8-3. Duty Cycle Run Conditions System B Simulated Propellant Dual Tank Operation

Run No.	Flow Pulse Length (sec)	Off Time (sec)	No. Pulses	Total Run Time (min)	Heat Exchanger* Flow Rate/Tank (lb/sec)	Inlet Temperature (°F)	Equivalent Freon 11 Oxidizer Tank (lb/sec)	Flow Rate Fuel Tank (lb/sec)
1	10	10	15	4.8	0.03	120	0.224	0.186
2	10	10	15	4.8	-	-	0.224	0.186
3	10	40	7	5.2	0.03	120	0.896	0.744
4	10	40	7	5.2	-	-	0.896	0.744

* Heat exchange flow for both tanks, when used, will be initiated with propellant flow and be continuous during the run.

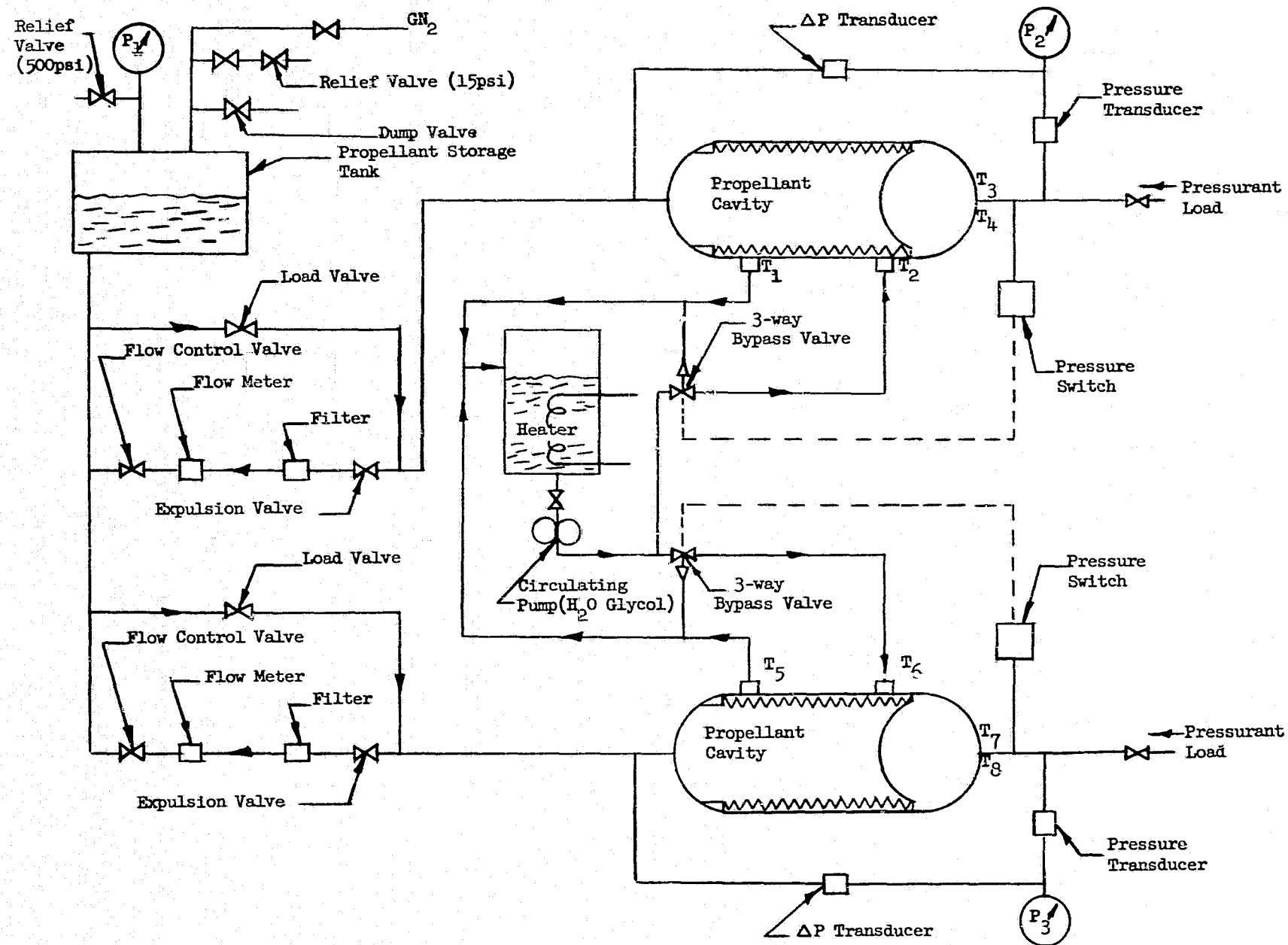


Figure 8-15 Pressurization System Test Schematic Dual Tank Tests

A summary of the loading conditions used during the bipropellant pressurization system demonstration tests is shown in Table 8-4. The calculated pressurant quality changes shown in Table 8-5 are based on the loading conditions in Table 8-4; runs were conducted in accordance with the duty cycles established.

Table 8-4 System Demonstration Loading Conditions
Using System B Hardware

	<u>Oxidizer Tank</u>	<u>Fuel Tank</u>
Simulated Propellant (Freon 11) Load (lb)	90.0	73.0
System A Pressurant Load		
Freon 22 Weight (lb)	5.3	4.5
Initial Quality (%)	29.0	33.1
System B Pressurant Load		
Genetron 32 Weight (lb)	10.0	9.5
Eicosane Weight (lb)	9.0	8.0
Initial Genetron Quality (%)	5.2	5.7

8.2.3.1 System A Bipropellant Expulsion

For the System A runs the tanks were installed in a horizontal position as shown in Figure 8-16. Six System A expulsion runs were conducted. The single engine flow rate runs are shown in Figures 8-17 and 8-18. For dual engine flow rate tests the performance is shown in Figures 8-19 and 8-20. Figure 8-21 shows the four-engine flow rate test results.

The capability of System A operation is clearly demonstrated by this series of tests. Even at the maximum flow rates, the pressure decay was within the design limits. Two system design considerations are indicated, however, which would further improve operating performance.

Table 8-5. Pressurant Change During System Demonstration Testing (Simulated Propellant)

	<u>System A Runs</u> [*]					<u>System B Runs</u> ^{**}			
	1	2	3	4	5	1	2	3	4
System B Oxidizer Tank									
Propellant (Freon 11) Flow (lb)	67.2	67.2	67.2	67.2	71.7	33.6	33.6	54.7	54.7
Propellant Usage (%)	74.7	74.7	74.7	74.7	79.2	37.4	37.4	50.8	60.8
Pressurant Initial Quality (%)	29.0	29.0	29.0	29.0	29.0	5.2	5.2	5.2	5.2
Pressurant Final Quality (%)	78.2	78.2	78.2	78.2	81.5	17.7	17.7	25.6	25.6
System B Fuel Tank									
Propellant (Freon 11) Flow (lb)	55.8	55.8	55.8	55.8	59.7	27.9	27.9	52.1	52.1
Propellant Usage (%)	76.5	76.5	76.5	76.5	81.8	38.2	38.2	71.3	71.3
Pressurant Initial Quality (%)	33.1	33.1	33.1	33.1	33.1	5.7	5.7	5.7	5.7
Pressurant Final Quality (%)	81.2	81.2	81.2	81.2	84.2	16.7	16.7	26.1	26.1

* Run conditions defined in Table 8-2.

** Run conditions defined in Table 8-3.

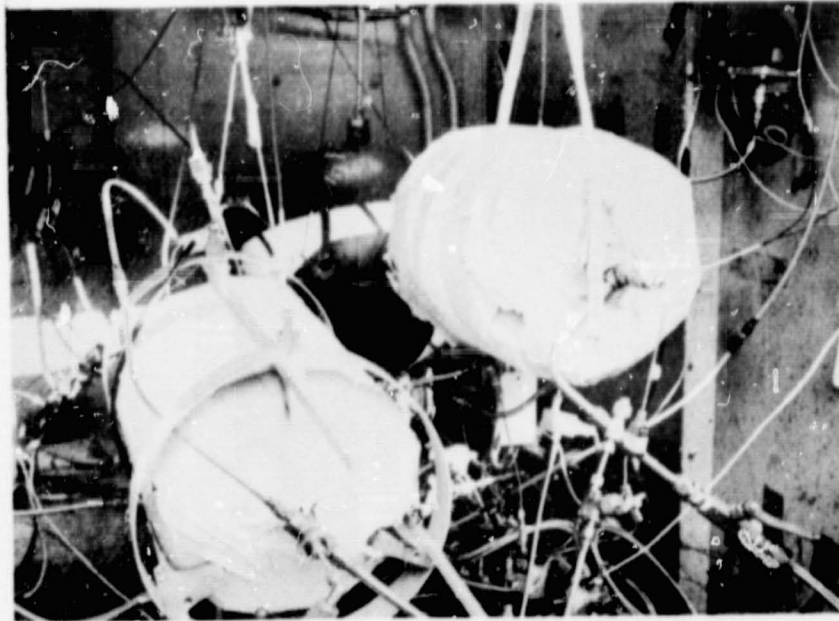


Figure 8-16 Dual Tank Test Setup

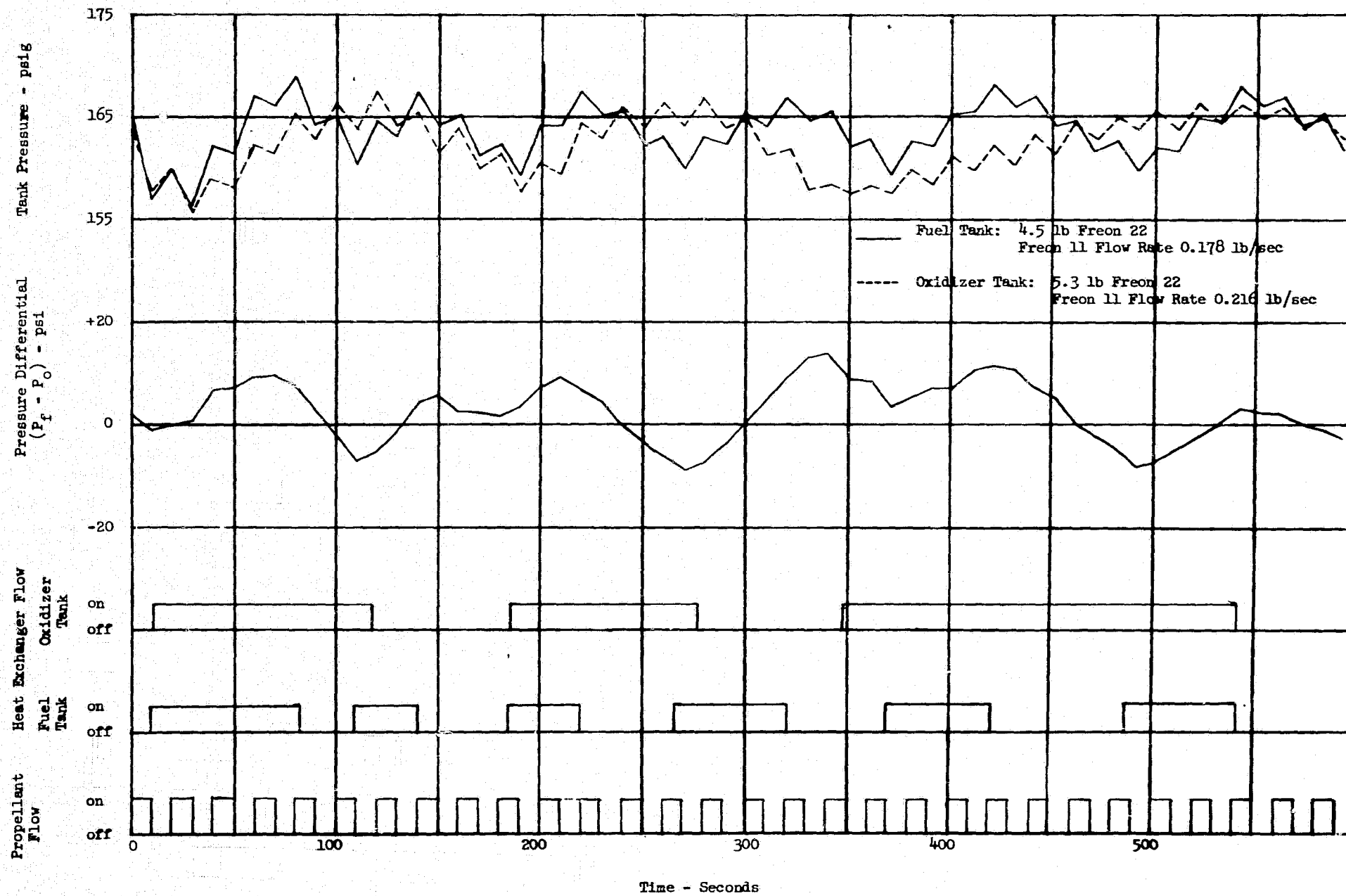


Figure 8-17 Dual Tank Expulsion Characteristics
System A Duty Cycle Run No.1

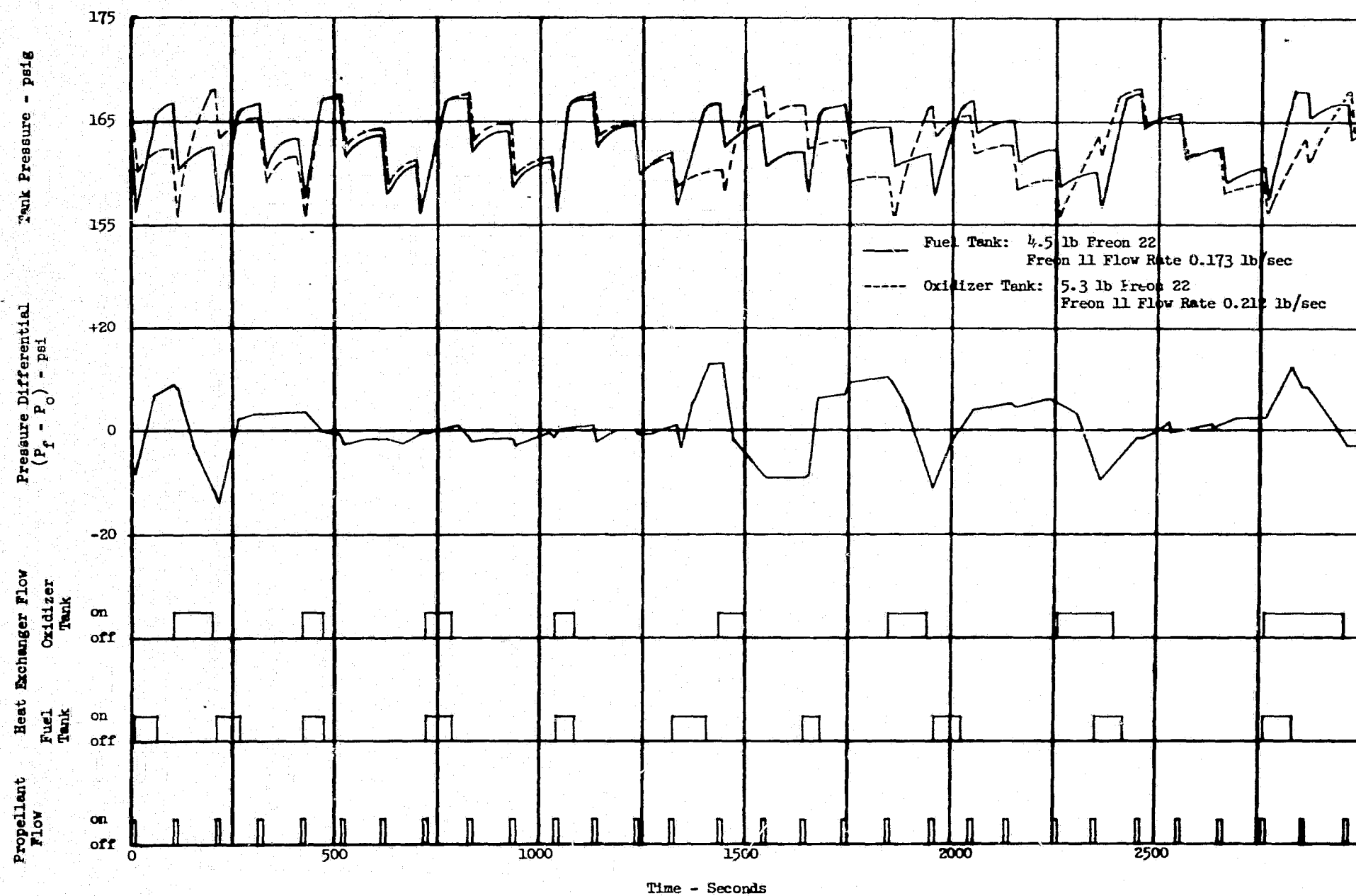


Figure 8-18 Dual Tank Expulsion Characteristics
System A Duty Cycle Run No. 2

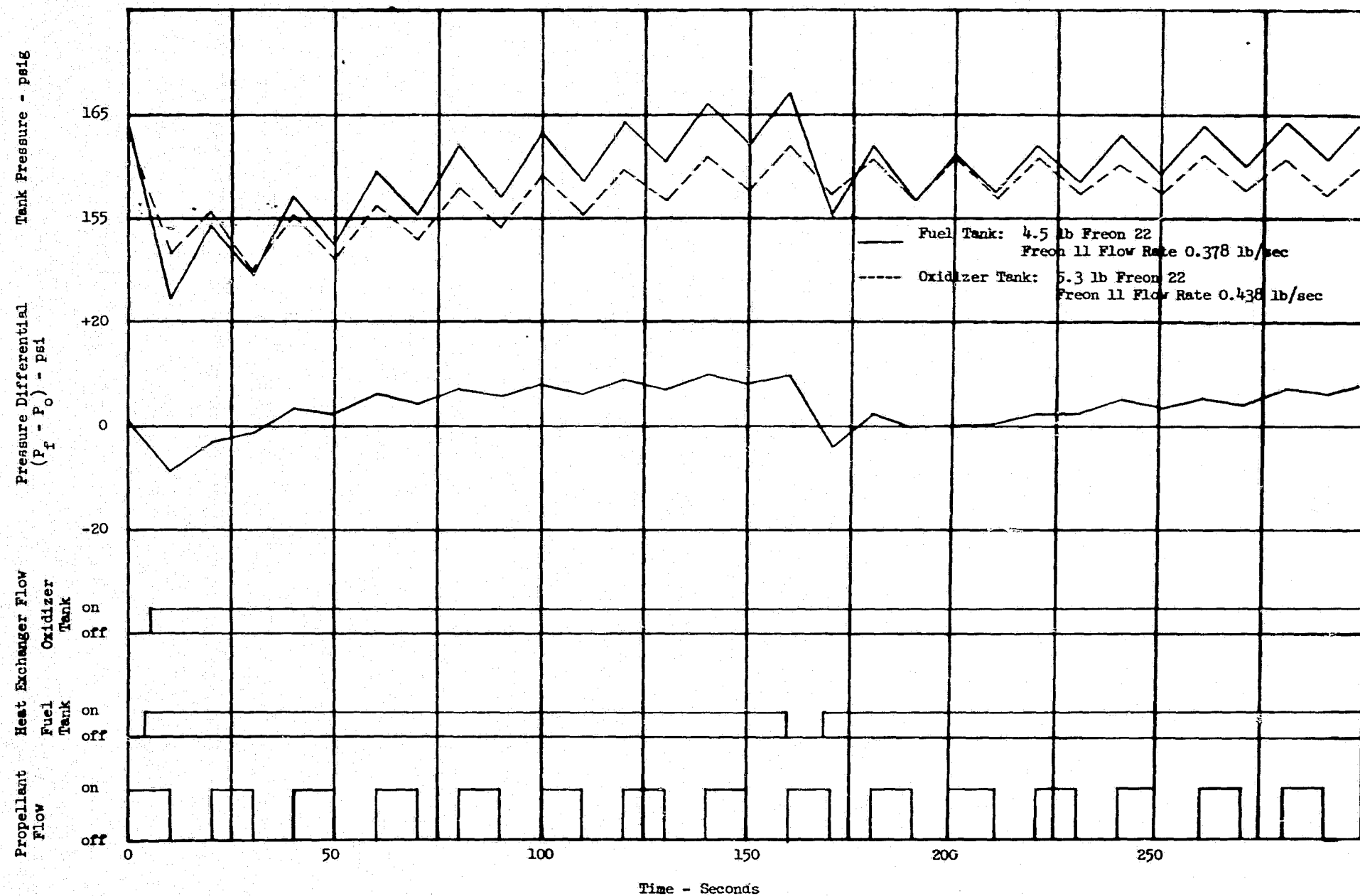


Figure 8-19 Dual Tank Expulsion Characteristics
System A Duty Cycle Run No. 3

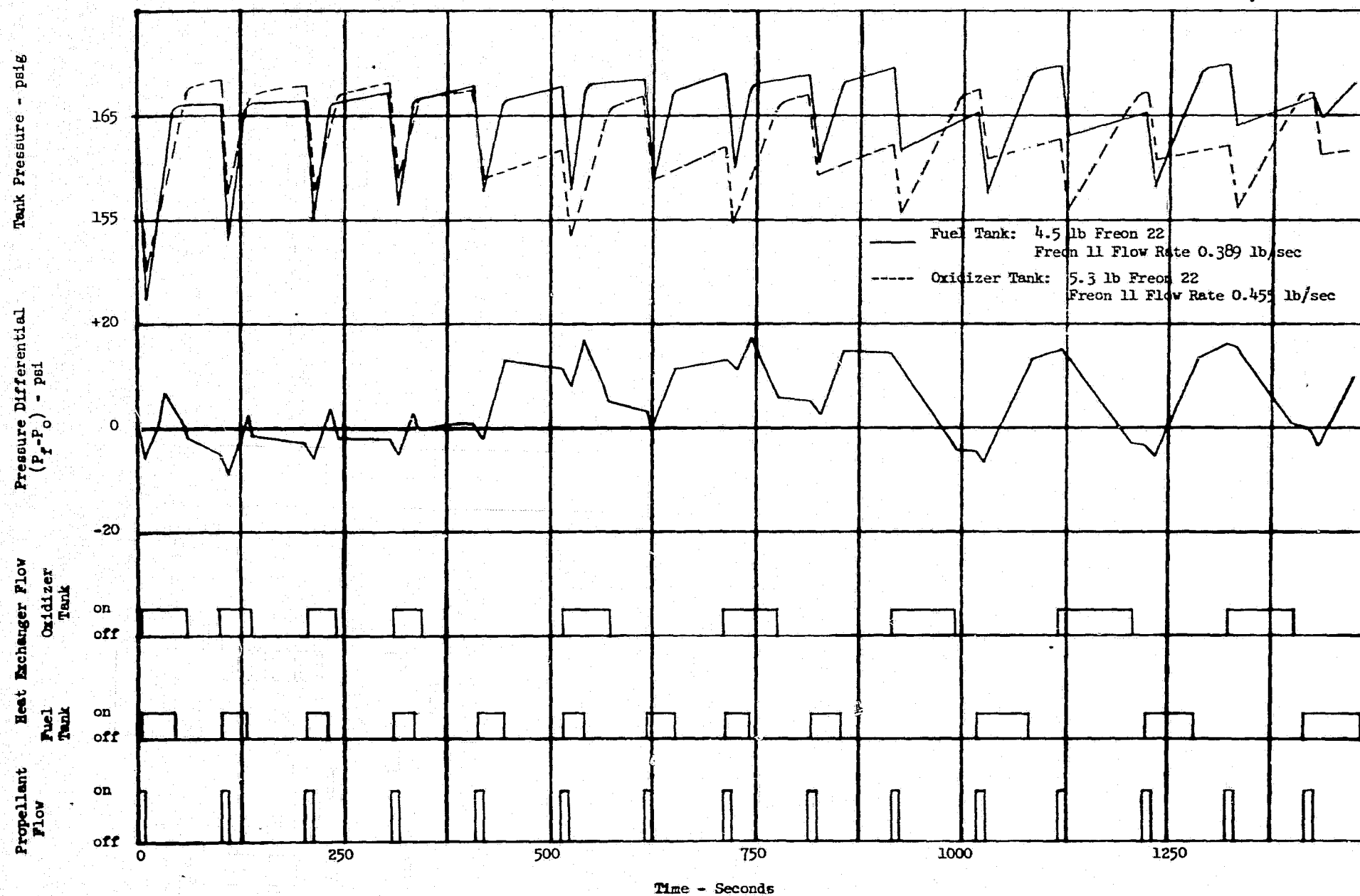


Figure 8-20 Dual Tank Expulsion Characteristics
System A Duty Cycle Run No. 4

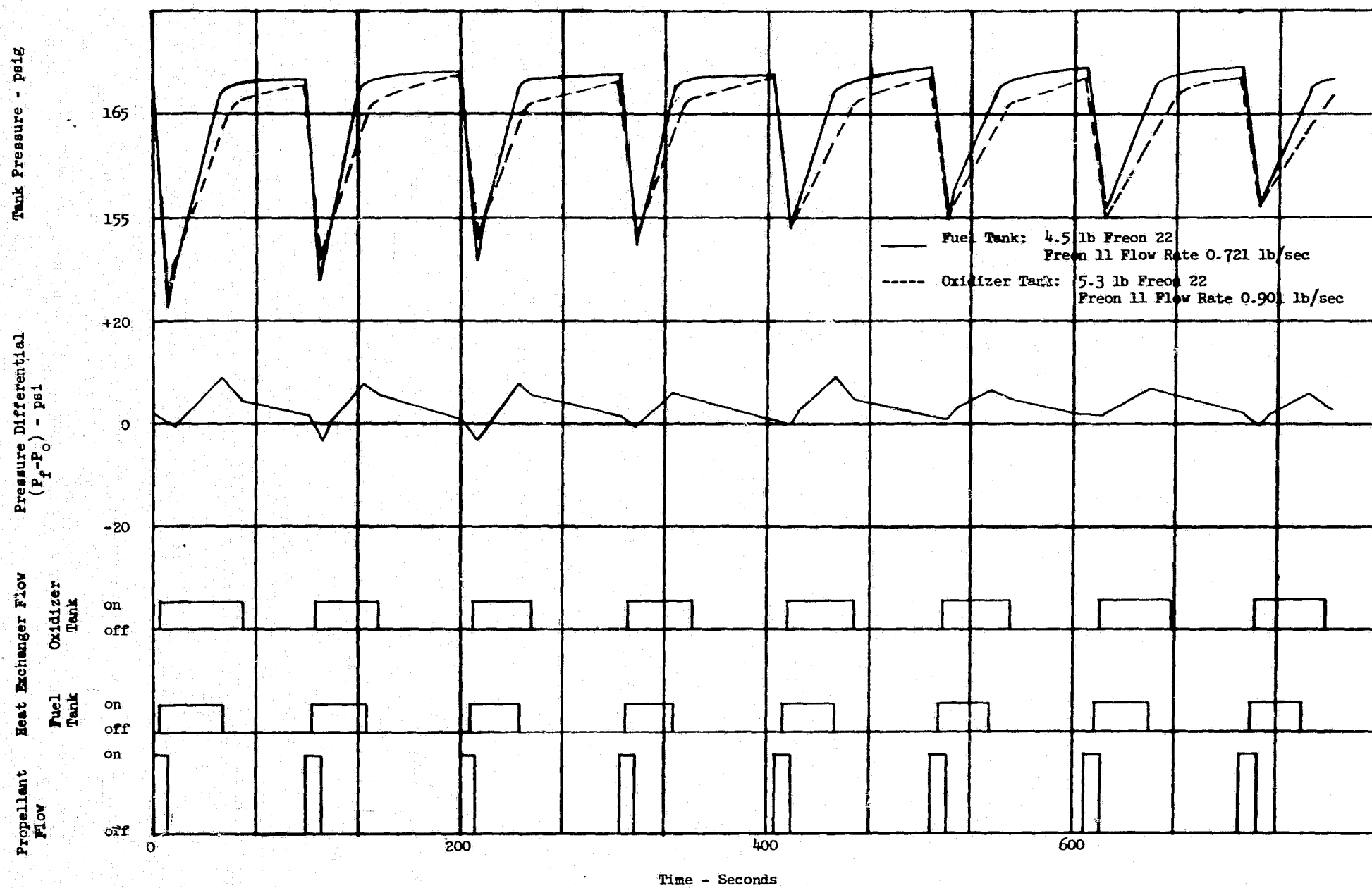


Figure 8-21 Dual Tank Expulsion Characteristics
System A Duty Cycle Run No. 5

The importance of operation of the two heat exchangers synchronously is demonstrated particularly in the four-engine flow rate test. In this test the heat exchanger flow rate for both tanks was initiated on each pulse. Despite the high propellant flow rate, the pressure differential between the two tanks never exceeded 2 psi during propellant flow.

On the balance of the runs, the only time a high (8 psi) pressure differential occurred was when the heat exchanger flow was initiated on only one tank.

The pressure switches used in the tests conducted have a relatively high (7 psi) deadband. A system consideration would be to select a narrower deadband pressure switch to improve initiation of heat exchanger flow on both tanks simultaneously.

A second system consideration is the relative efficiency of the heat exchanger in relation to the required duty cycle. In the two tanks used, the fuel tank has the most efficient heat exchanger. This is demonstrated in the single engine flow rate test, Figure 8-18, where, on the final pulses of the run, two propellant flow pulses were experienced before the oxidizer tank pressure had increased sufficiently to terminate heat exchanger flow. As the fuel tank heat exchanger flow always terminated prior to the next pulse, a pressure differential occurred. However, on the four-engine flow rate test, sufficient time was available between pulses so that the relative efficiency of the heat exchangers was unimportant.

8.2.3.2 System B Bipropellant Expulsion (HSM)

Eight bipropellant System B expulsion tests were conducted with Genetron 32 and Eicosane. The results for the single-engine flow rate with heat exchanger flow are shown in Figure 8-22 and without heat exchanger flow in Figure 8-23. For the four-engine flow rate, the results with heat exchanger flow are shown in Figure 8-24. Without heat exchanger flow, the results were as shown in Figure 8-25.

In all the tests conducted, the oxidizer tank exhibited a higher pressure drop on the initial pulses than the fuel tank. This was attributed to

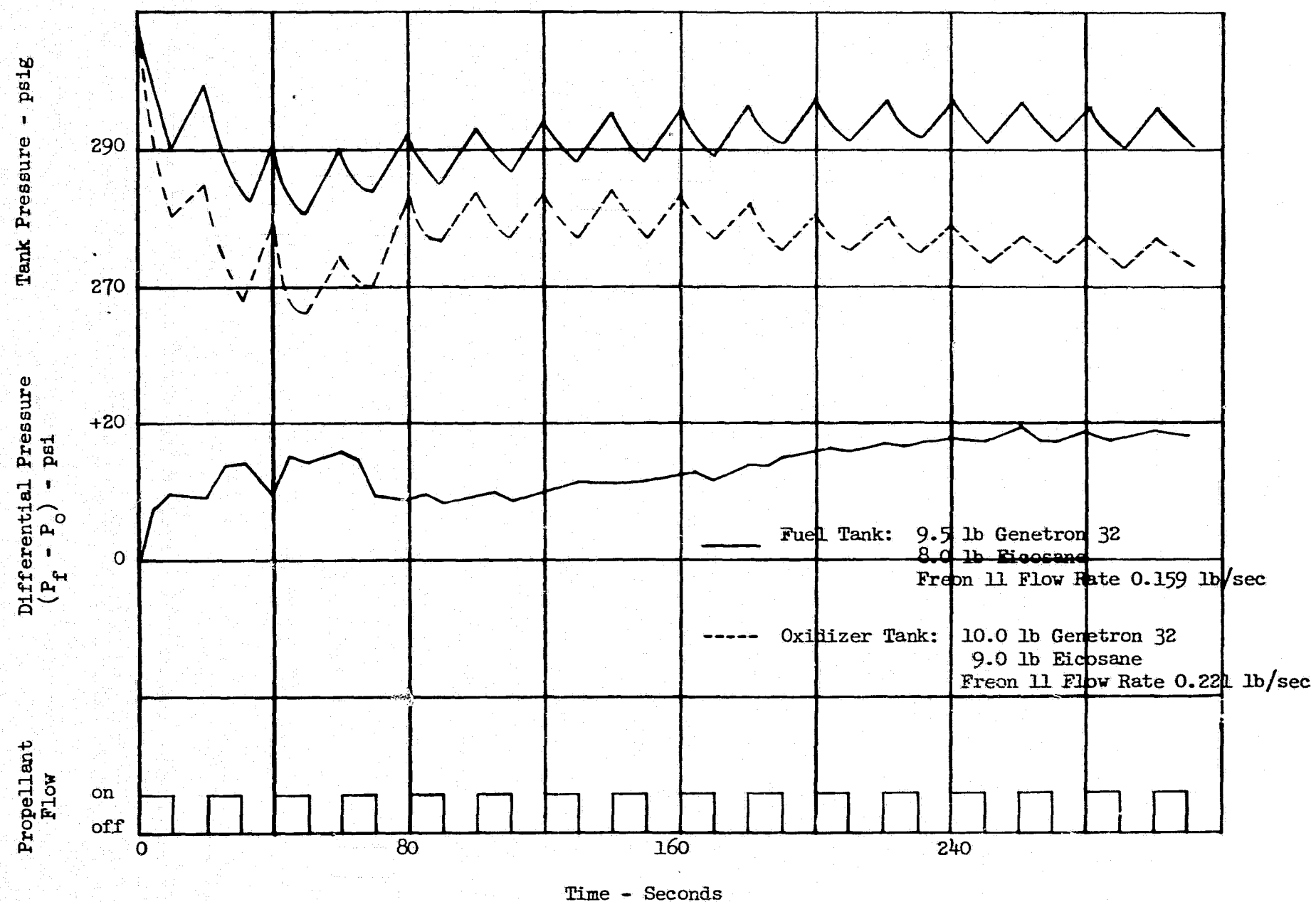


Figure 8-22 Dual Tank Expulsion Characteristics
System B Duty Cycle Run No. 1

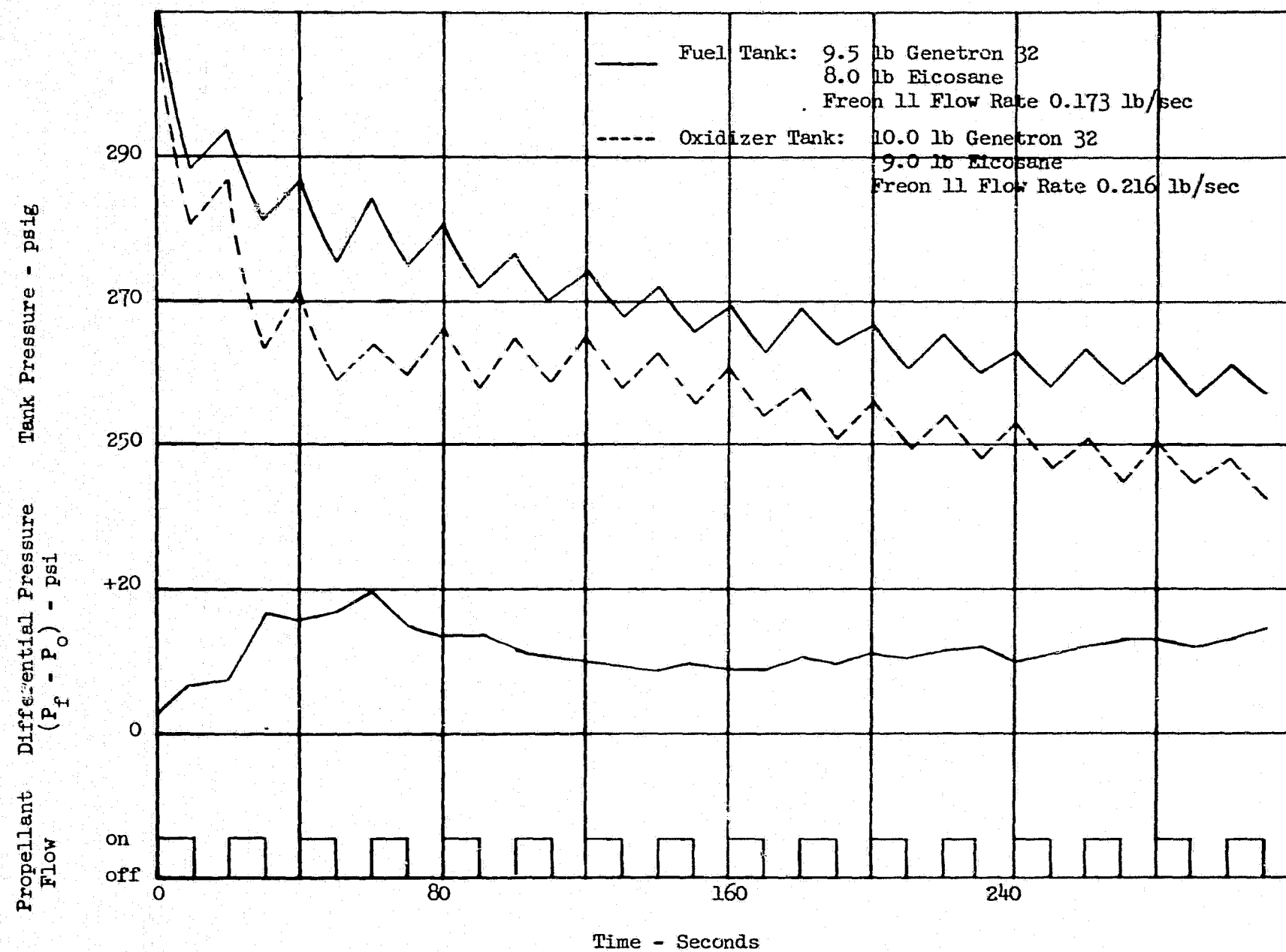


Figure 8-23 Dual Tank Expulsion Characteristics
System B Duty Cycle Run No. 2

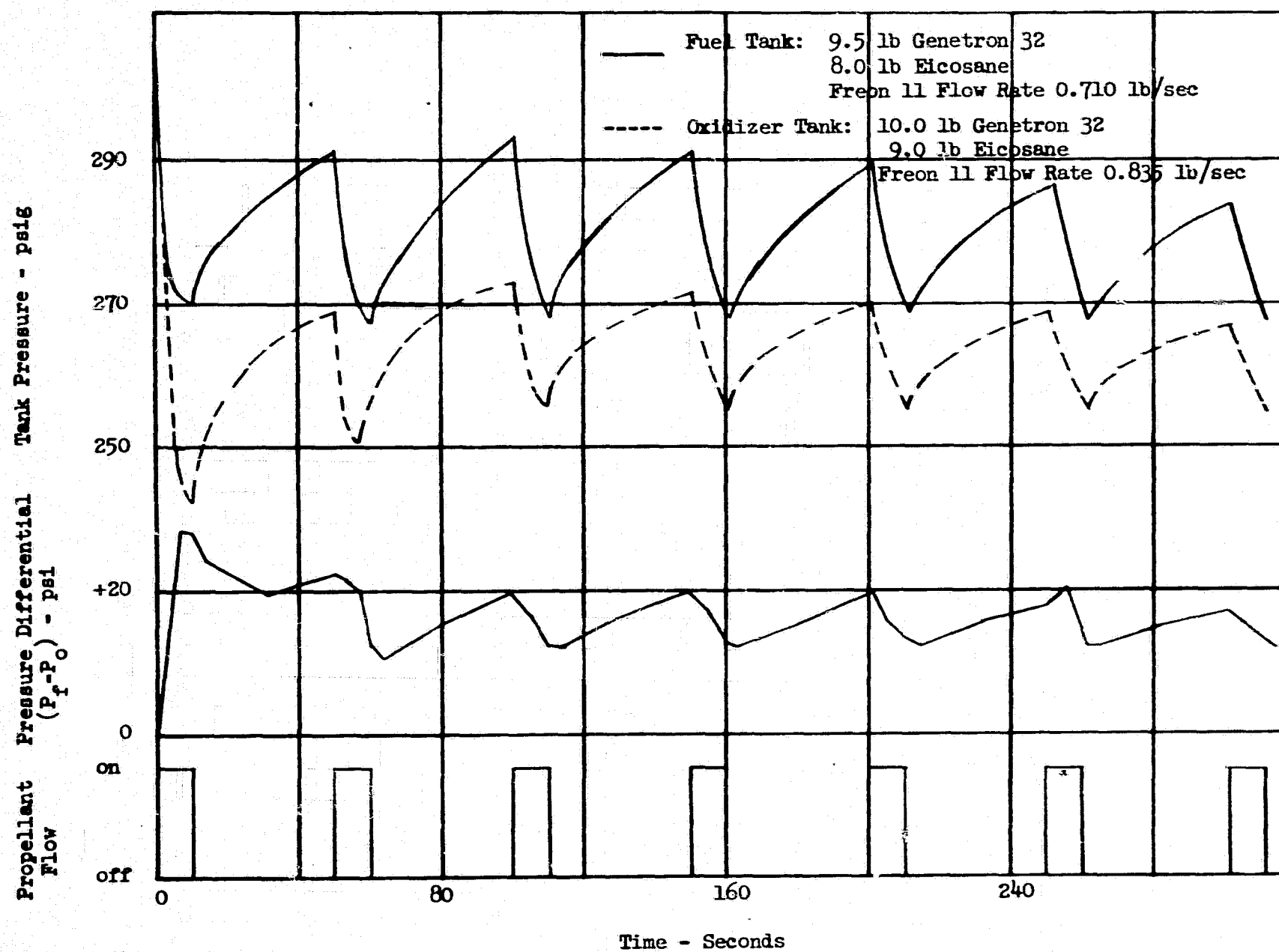


Figure 8-24 Dual Tank Expulsion Characteristics
System B Duty Cycle Run No. 3

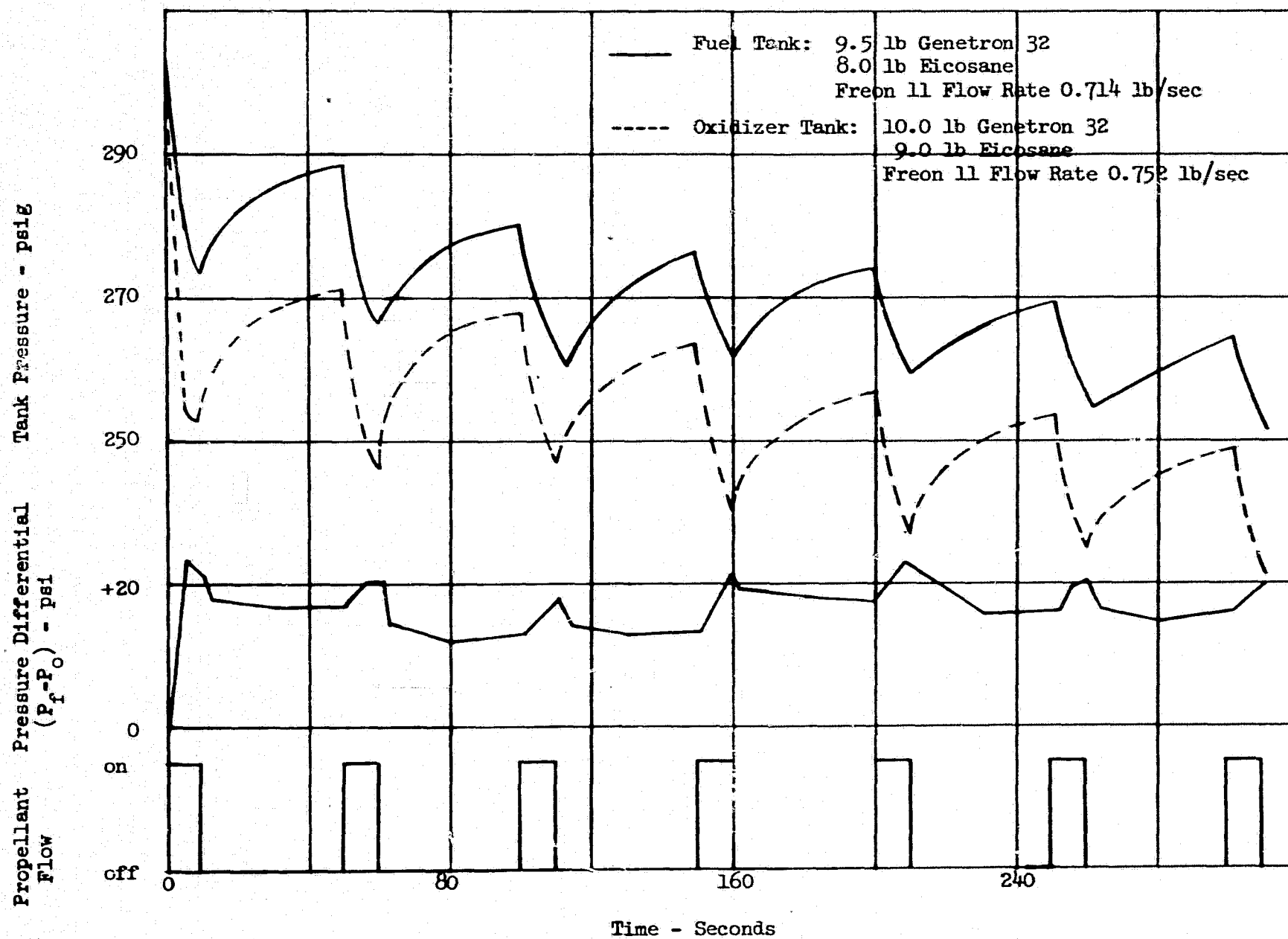


Figure 8-25 Dual Tank Expulsion Characteristics
System B Duty Cycle Run No. 4

the relative starting conditions in the two tanks. In the bipropellant tests, temperature of both tanks was increased until the eicosane was melted. The tanks were then allowed to cool down to the starting conditions (just above freezing temperatures of HSM). The fuel tank, which had a smaller mass of HSM, cooled slightly faster than the oxidizer tank. As a result, the oxidizer tank starting temperatures were slightly higher than the fuel tank. In later propellant expulsion runs where only one tank was used, the starting temperatures and resulting pressure decay were nearly identical with resulting equivalent pressure drop. For actual system usage, a longer preconditioning time, with intermittent heat inputs, would allow a more equal temperature stabilization of both tanks.

The results of these tests indicated that for pulse durations of the magnitude used (10 seconds), the heat storage material alone does not provide proper heat input to the pressurant. This was particularly true with the lower flow rate. However, in those runs conducted with the heat exchanger operating in addition to the heat storage material, the system had no difficulty in maintaining the system pressure within the design limits. It should be noted, however, the the heat exchanger input for both tanks was nearly optimized for both duty cycle conditions investigated, i.e., pressure drop per pulse equal to pressure recovery between pulses.

8.2.3.3 System B Bipropellant Expulsion (Genetron 32 only)

In order to evaluate the effectiveness of the heat storage material when utilized in a pulse mode operation, a series of System B bipropellant tests was conducted using Genetron 32 only in the pressurant cavity. The pressurant loading conditions are shown in Table 8-6. Six runs were conducted. The results for a single-engine flow rate with heat exchanger flow are shown in Figure 8-26 and without heat exchanger flow in Figure 8-27. For a four-engine flow rate with heat exchanger the results are presented in Figure 8-28 and without heat exchanger flow in Figure 8-29. Two runs were conducted at a continuous single-engine flow rate for a duration of 300 seconds. The results with

Table 8-6 Pressurant Run and Load Conditions
Dual Tank Runs - Genetron 32 Only

	System B Duty Cycle Runs*				Continuous Freon 11 Flow 300 Second Runs	
					With*	Without
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	Heat Exchanger	Heat Exchanger
Oxidizer Tank						
Initial Propellant (Freon 11) Load (lb)	90.0	90.0	90.0	90.0	90.0	90.0
Genetron 32 Weight (lb)	10.0	10.0	10.0	10.0	10.0	10.0
Initial Pressurant Quality (%)	11.5	11.5	11.5	11.5	11.5	11.5
Propellant (Freon 11) Flow Rate (lb/sec)	0.211	0.196	0.846	0.823	0.208	0.196
Propellant (Freon 11) Flow (lb)	31.6	29.4	59.2	57.6	62.4	58.8
Propellant Usage (%)	35.1	32.7	65.8	64.0	69.3	65.4
Final Pressurant Quality (%)	23.5	22.6	33.7	33.1	36.2	33.6
Fuel Tank						
Initial Propellant (Freon 11) Load (lb)	73.0	73.0	73.0	73.0	73.0	73.0
Genetron 32 Weight (lb)	9.5	9.5	9.5	9.5	9.5	9.5
Initial Pressurant Quality (%)	11.5	11.5	11.5	11.5	11.5	11.5
Propellant (Freon 11) Flow Rate (lb/sec)	0.167	0.149	0.670	0.659	0.156	0.144
Propellant (Freon 11) Flow (lb)	25.0	22.4	46.9	46.1	46.8	43.2
Propellant Usage (%)	34.2	30.9	64.2	63.2	64.2	59.2
Final Pressurant Quality (%)	23.4	22.3	32.3	32.4	32.1	30.8

*Run conditions as defined in Table 8-3.

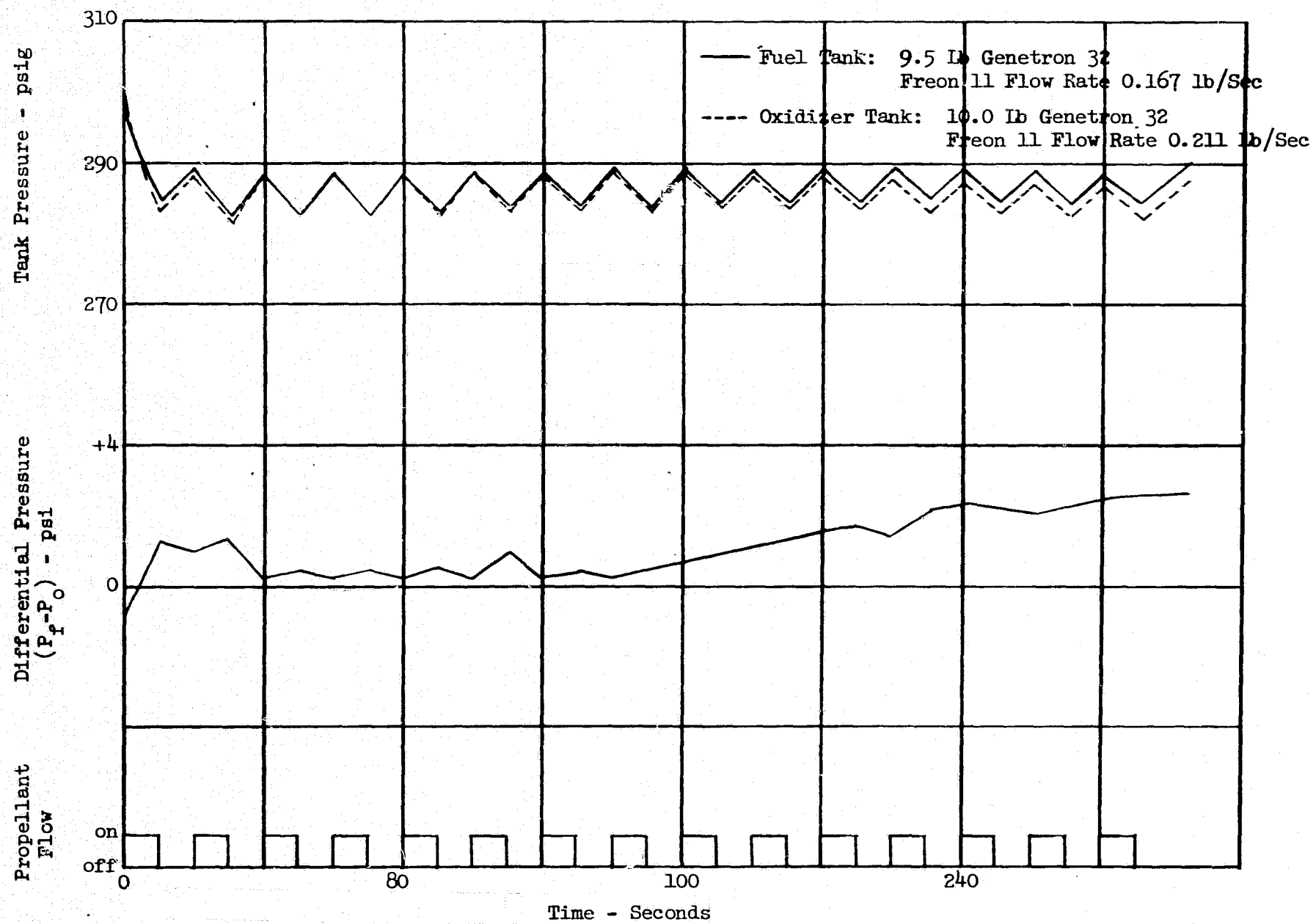


Figure 8-26 Dual Tank Expulsion Characteristics Genetron 32 Only
System B Duty Cycle, Run No. 1

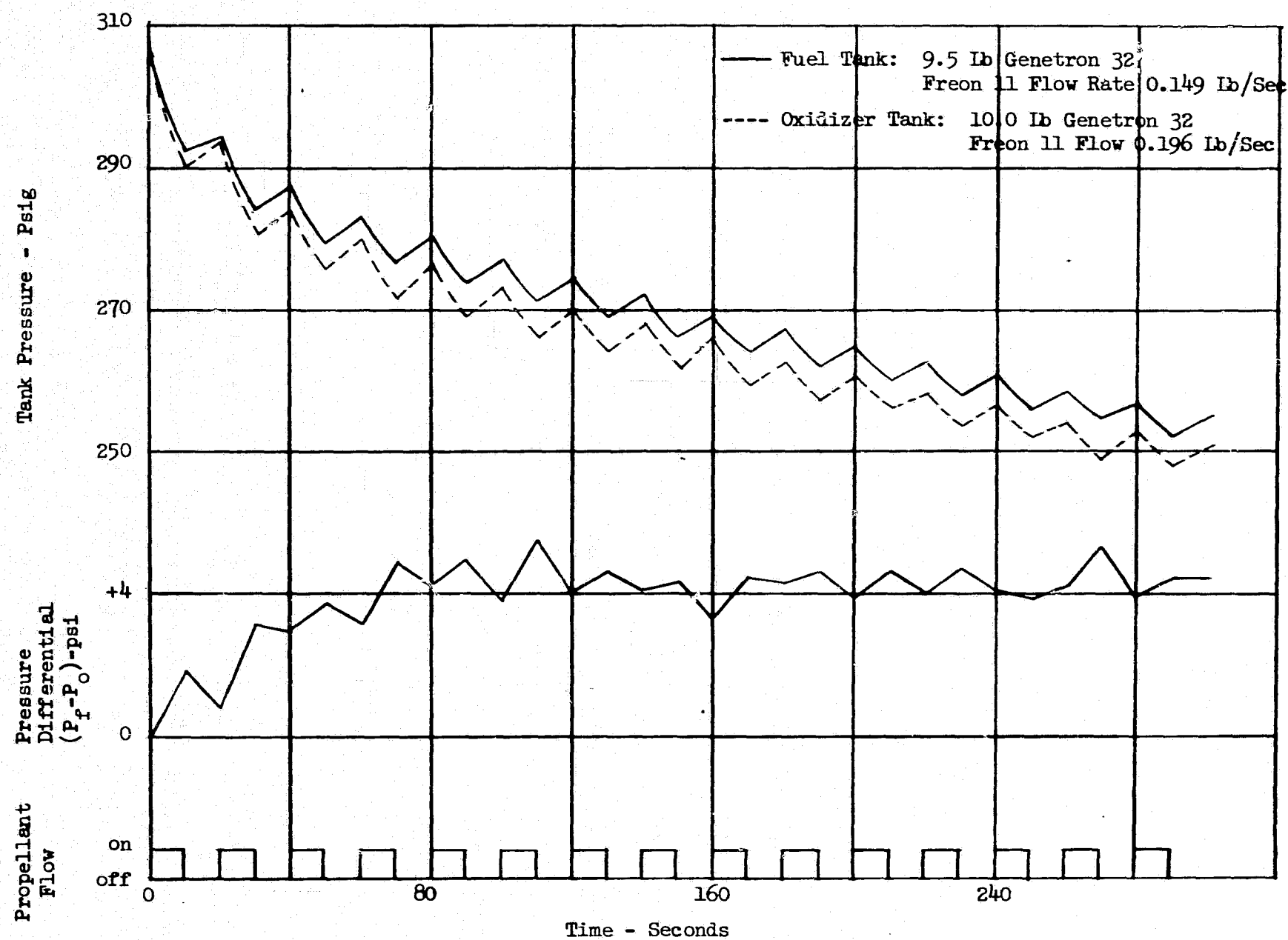


Figure 8-27 Dual Tank Expulsion Characteristics Genetron 32 Only
 System B Duty Cycle, Run No. 2

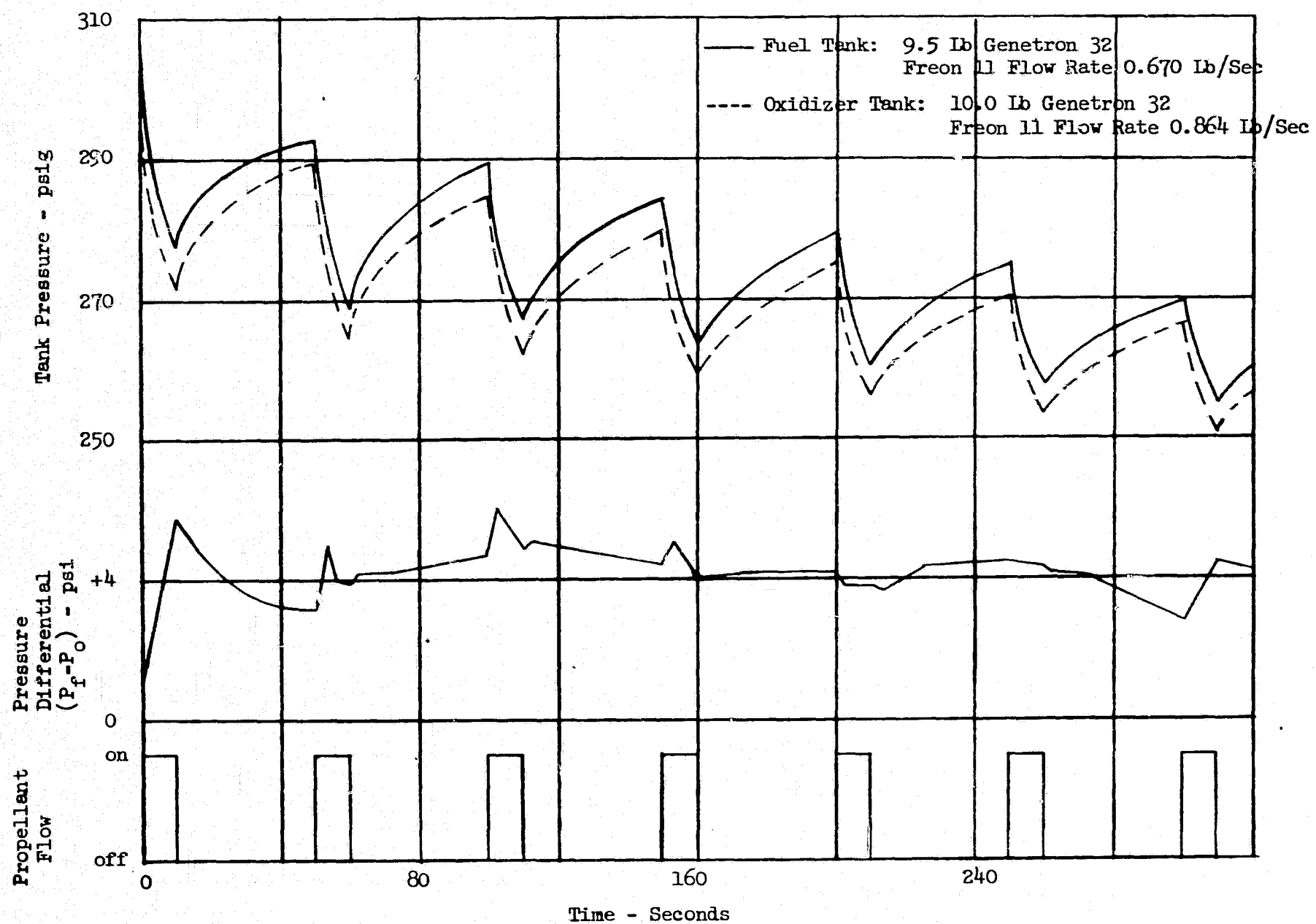


Figure 8-28 Dual Tank Expulsion Characteristics Genetron 32 Only
System B Duty Cycle, Run No. 3

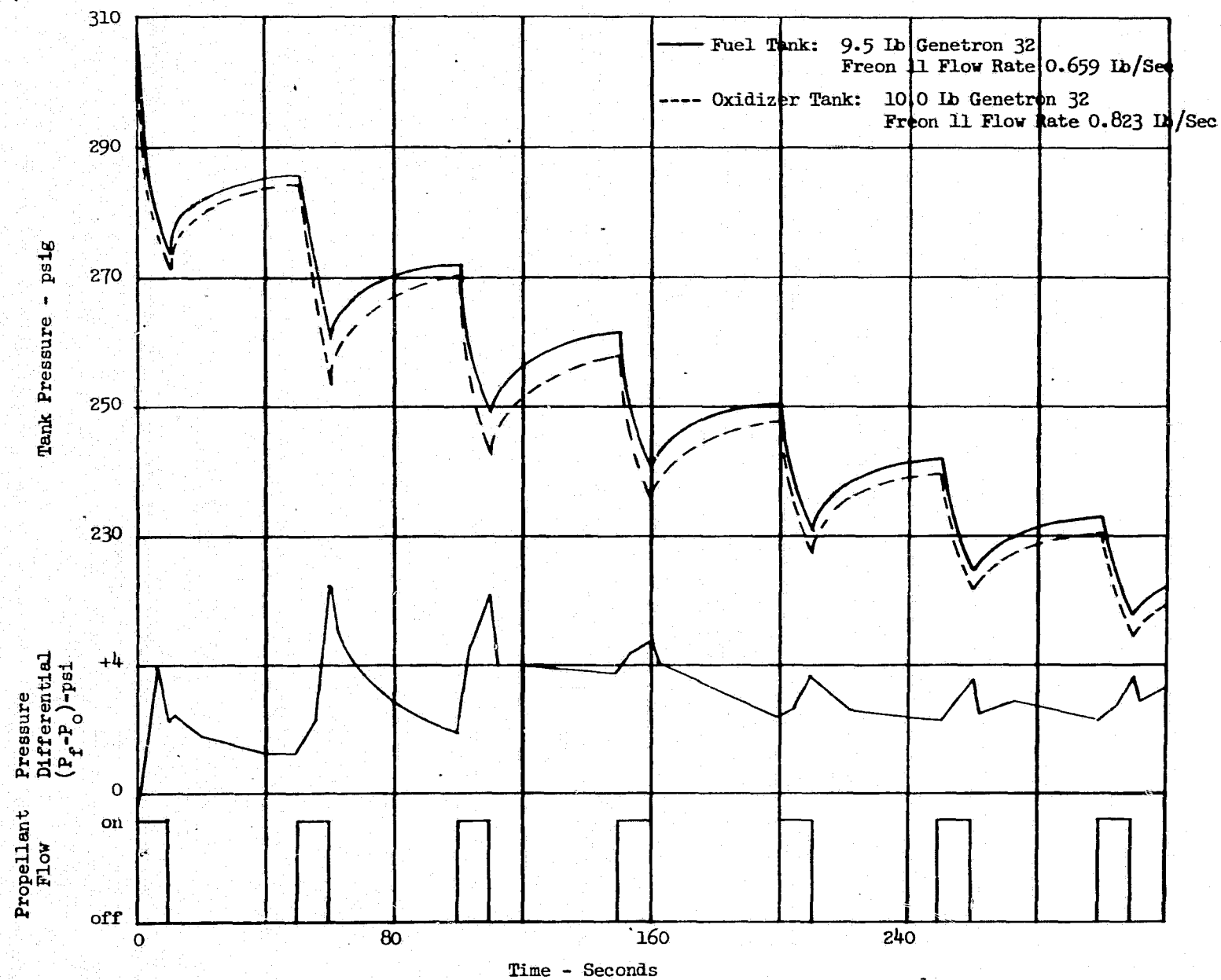


Figure 8-29 Dual Tank Expulsion Characteristics Genetron 32 Only
System B Duty Cycle, Run No. 4

heat exchanger flow are shown in Figure 8-30 and without heat exchanger flow in Figure 8-31.

Comparing the results of these tests with the heat storage material test runs, the initial pressure drop was slightly lower and the tank pressures were maintained closer together than had been experienced with the heat storage material present in the tank. The lower initial pressure drop was as expected with higher initial qualities (11% instead of 5-6%). Without the mass of HSM, simultaneous temperature stabilization of the tanks was simplified. As had been previously noted in the heat storage material runs, the divergence of tank pressures primarily occurred on the initial pulse. Subsequent pulses indicated nearly equal pressure drop in each tank. At the single-engine flow rates, the pulsing performance for both tanks was nearly identical to that experienced with the fuel tank run with HSM. This was true for the run with and without the heat exchanger input and clearly indicated no influence on the pulsing performance by the heat storage material at the lower flow rates. However, at the four-engine flow rates, higher pressure levels were achieved with the heat storage material in the tank than with the Genetron only present. This was attributed to the fact that with the low engine flow rates, the temperature decay in the Genetron is probably not sufficient to trigger solidification of the heat storage material. If the temperature differential is sufficient, as soon as propellant flow is terminated, the temperature of the vapor starts to increase and quickly removes the temperature differential required to solidify the heat storage material. For the four-engine flow rates, the temperature differential occurring is much larger. On termination of flow, it requires a considerably longer period of time before the temperature difference disappears. This allows the heat storage material to solidify over at least a part of the run and results in some heat input into the pressurant.

8.3 Propellant Testing

To investigate whether differences occur between actual propellant expulsion and simulated propellant expulsion, individual tank investigative

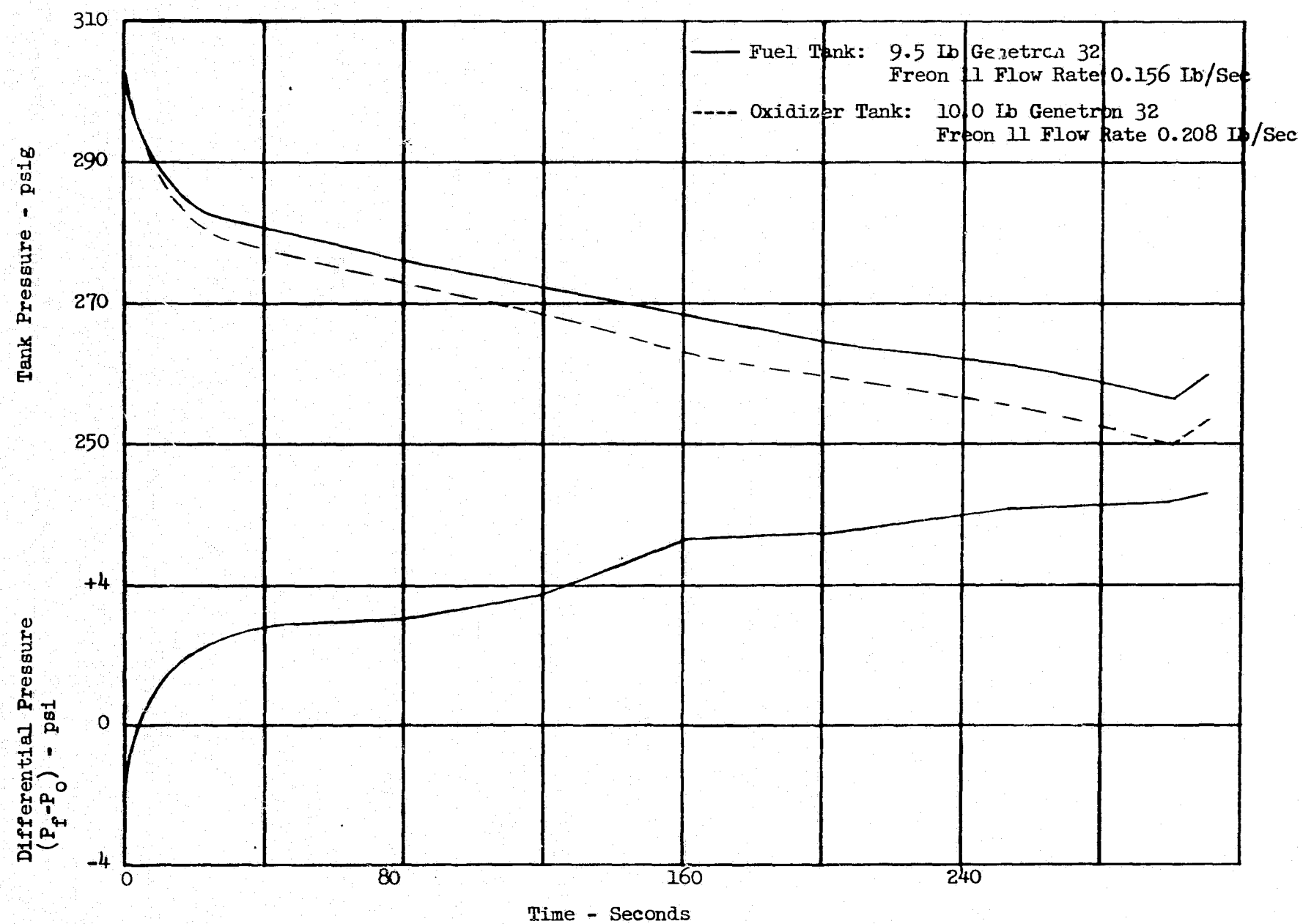


Figure 8-30 Dual Tank Expulsion Characteristics Genetron 32 Only
Continuous Propellant Flow with Heat Exchanger Input

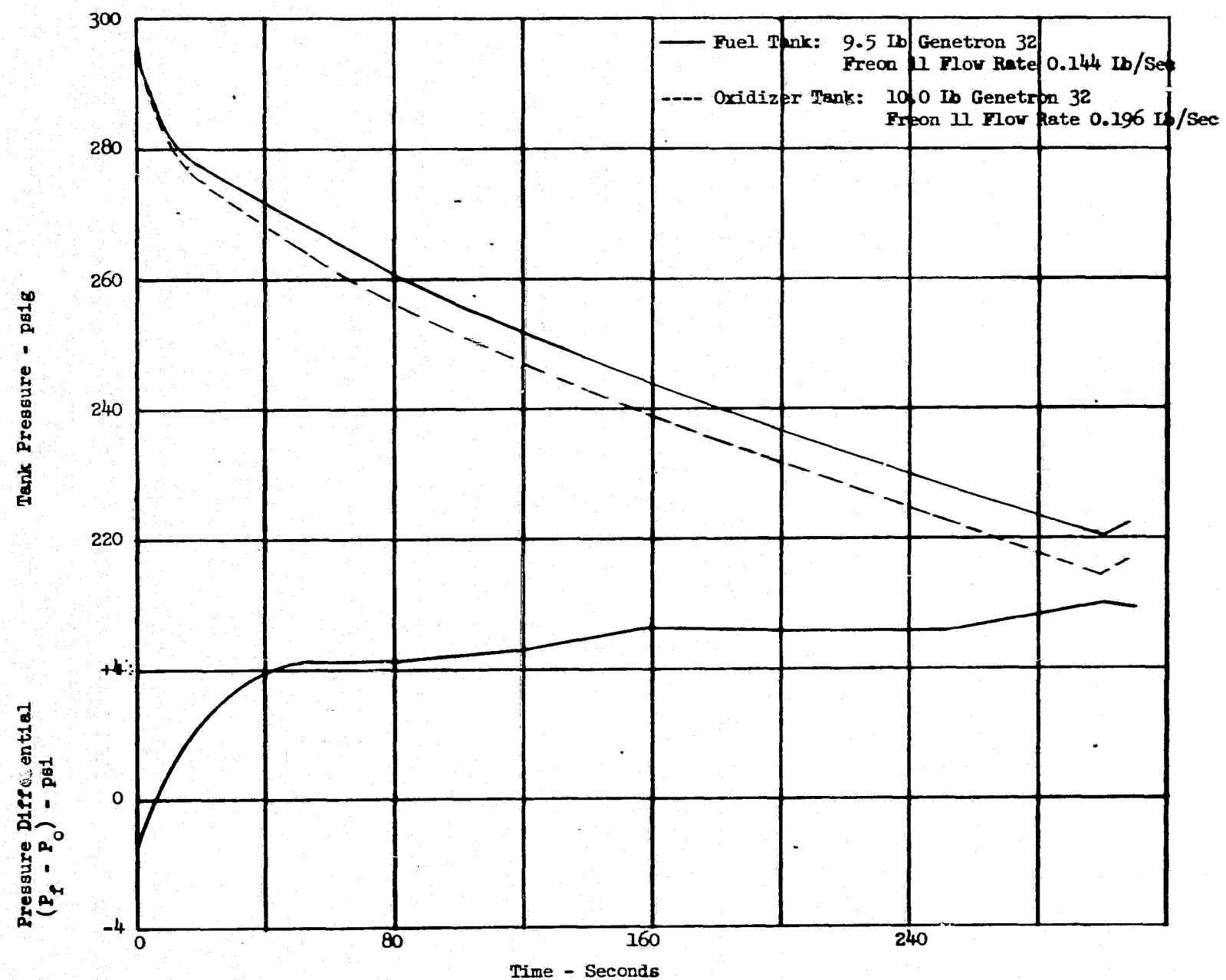


Figure 8-31 Dual Tank Expulsion Characteristics Genetron 32 Only
Continuous Propellant Flow Without Heat Exchanger Input

runs utilizing actual propellants were conducted at the duty cycles used in the bipropellant tank runs.

Expulsion with propellants required a modification to the test setup to provide the safety precautions necessary in handling hazardous materials. The revised test setup schematic is shown in Figure 8-32.

The propellants required for use in each of the tanks are listed below:

Table 8-7 Propellants Utilized in System Tests

<u>Tank</u>	<u>Propellant</u>
System A	
Oxidizer	N_2O_4
Fuel	Aerozine-50
System B	
Oxidizer	N_2O_4
Fuel	MMH

During the propellant testing, loading of the pressurant and the propellant into the tanks was conducted in accordance with the established loading procedure. For the System B tests the required amount of Eicosane was installed in a liquid state and allowed to solidify in the moveable bellows header prior to starting pressurant and propellant loading.

8.3.1 System A Propellant Testing

The System A propellant runs were conducted in accordance with the System A duty cycle running conditions (Table 8-2). Six propellant expulsion runs were made with the System A fuel tank using Aerozine-50 as the propellant.

The single-engine flow rate performance at a 50 percent duty cycle is shown in Figure 8-33 and at a 10 percent duty cycle in Figure 8-34. The performance characteristics of the two-engine propellant flow rate at a

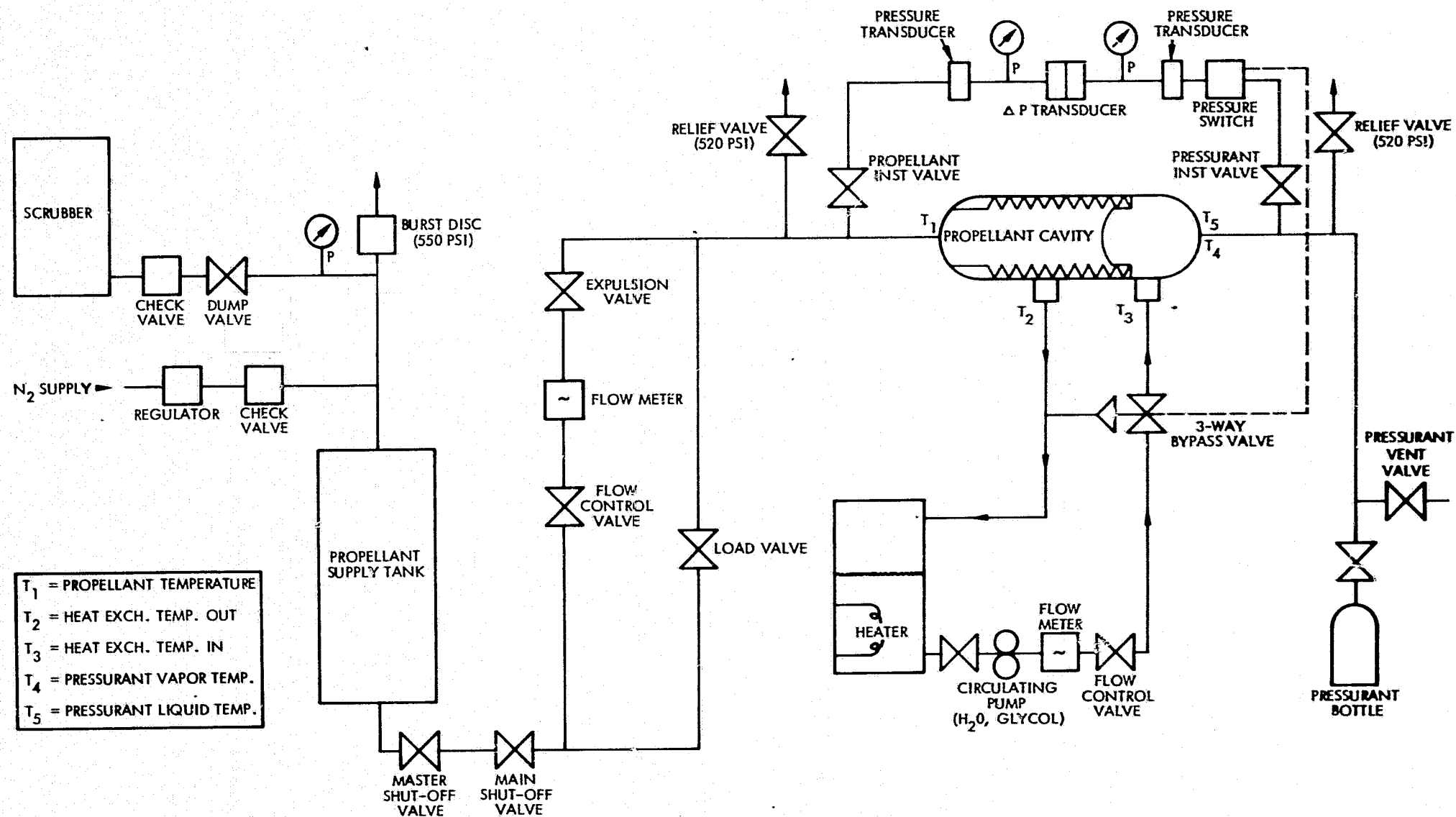


Figure 8-32 Pressurization System Propellant Expulsion Test Setup Schematic

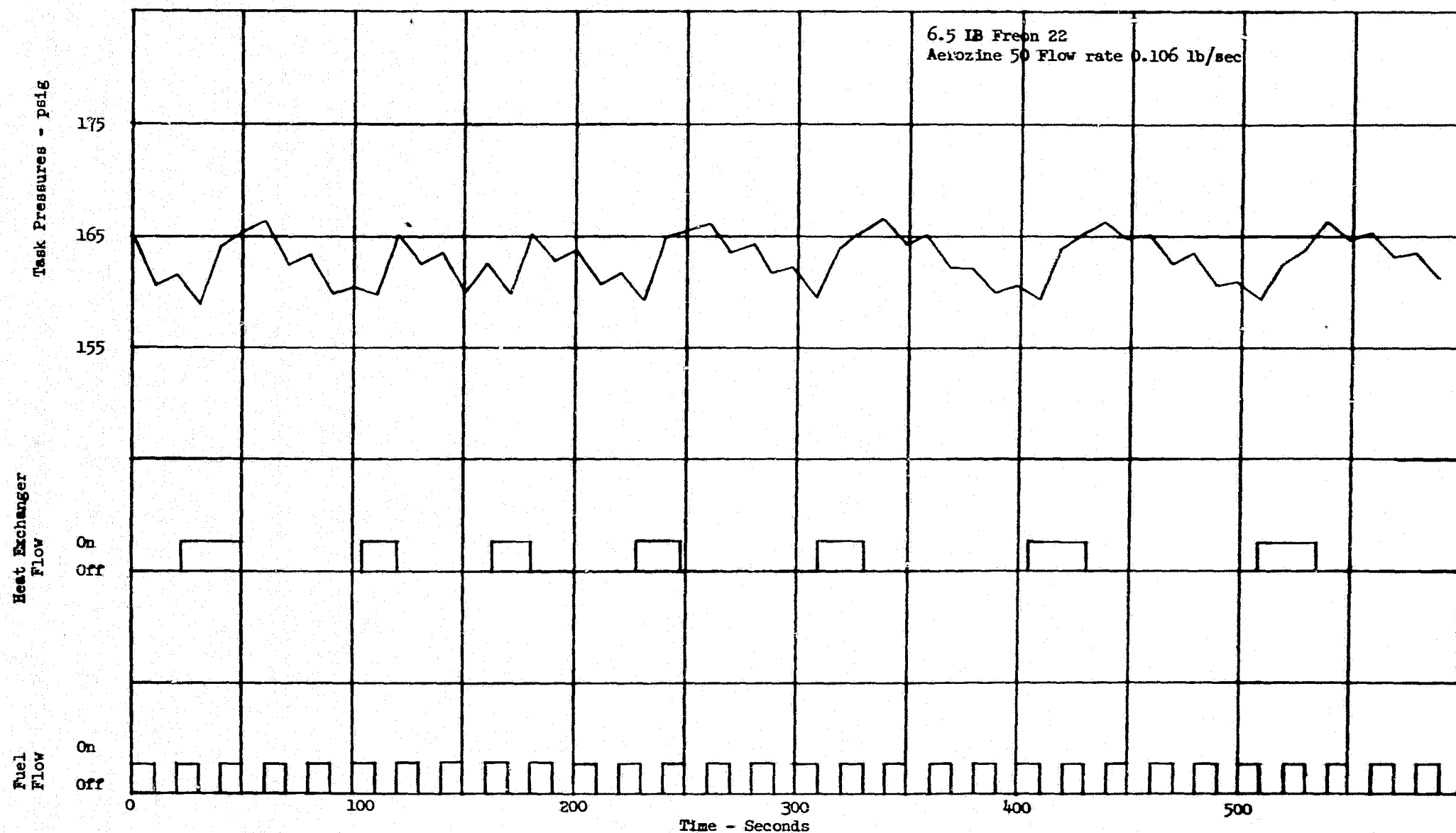


Figure 8-33 Fuel Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 1

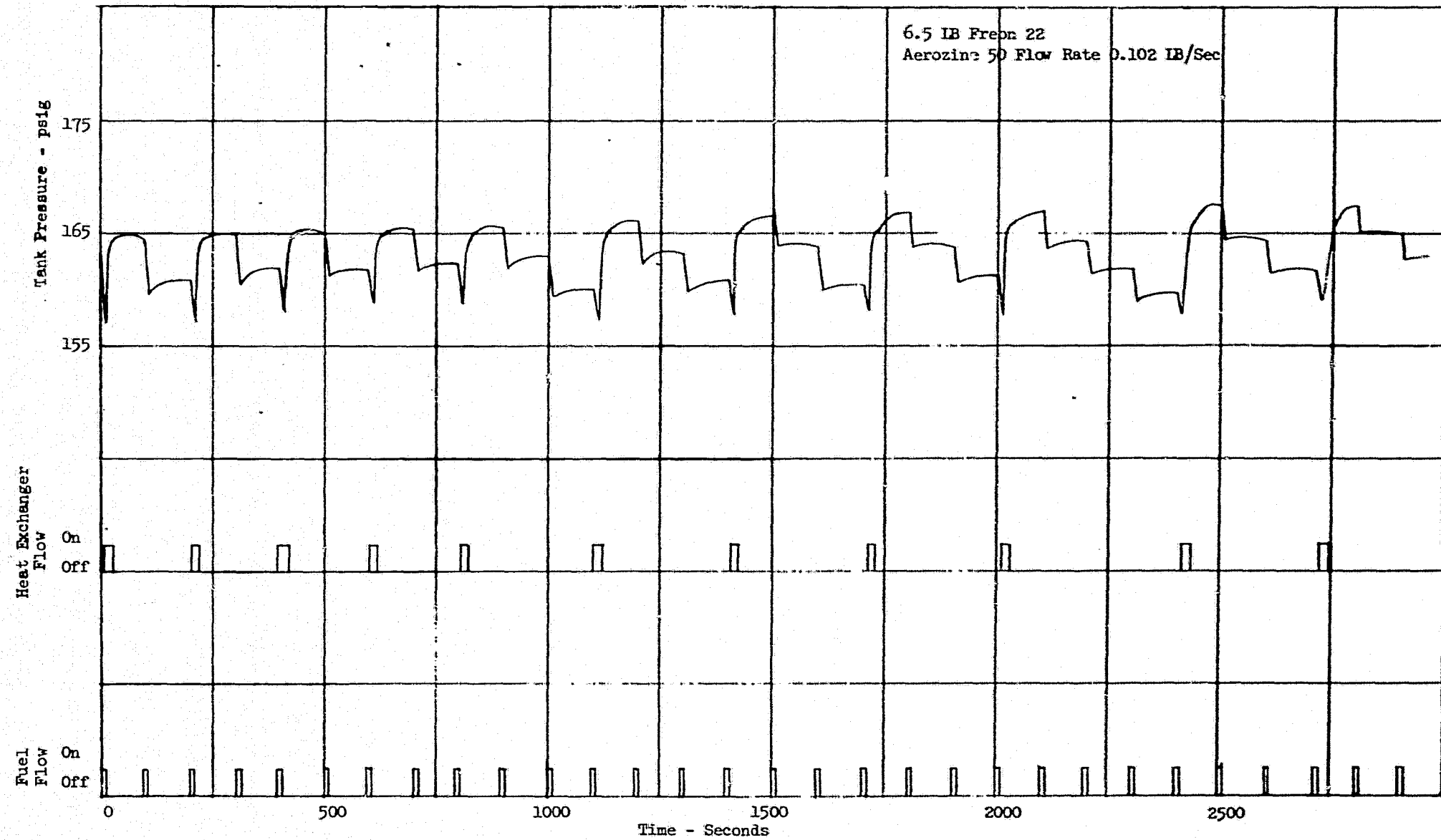


Figure 8-34 Fuel Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 2

50 percent duty cycle are shown in Figure 8-35 and a 10 percent duty cycle in Figure 8-36. The four-engine flow rate at a 50 percent duty cycle performance characteristic are shown in Figure 8-37.

Five propellant expulsion runs were then made with the System A oxidizer tank using N_2O_4 as the propellant. The results of the single-engine flow rate performance at 10 percent duty cycle are shown in Figure 8-38 and 50 percent in Figure 8-39. The results of the two-engine performance are shown in Figures 8-40 and 8-41 for the 10 and 50 percent duty cycles. The four-engine flow run results are shown in Figure 8-42.

The results obtained were quite comparable with the performance obtained during the bipropellant tank testing using the System B tanks. The pressure drop per pulse was slightly smaller than that experienced previously. The System A bipropellant test runs, with the System B tanks, were made using the same flow rates as were used in the propellant tests. This resulted in a slightly smaller percentage of the total tank volume flowed per pulse in the System A tanks over that experienced during System A tests conducted with the System B tanks, and provided a smaller percent change in pressurant quality per pulse. A comparison of the fuel tank pressurant load conditions between the System A bipropellant runs with the System B tanks and the propellant runs with the System A tanks is shown in Table 8-8.

A slight improvement was experienced in the rate of return of the tank pressure to the level where the pressure switch discontinued heat exchanger flow. With the larger tanks, the area of liquid pressurant in contact with the heat exchanger is increased, resulting in improved heat transfer. The tendency for a more efficient heat exchanger on the fuel tank, found in the System B tanks, was also exhibited by the System A tanks.

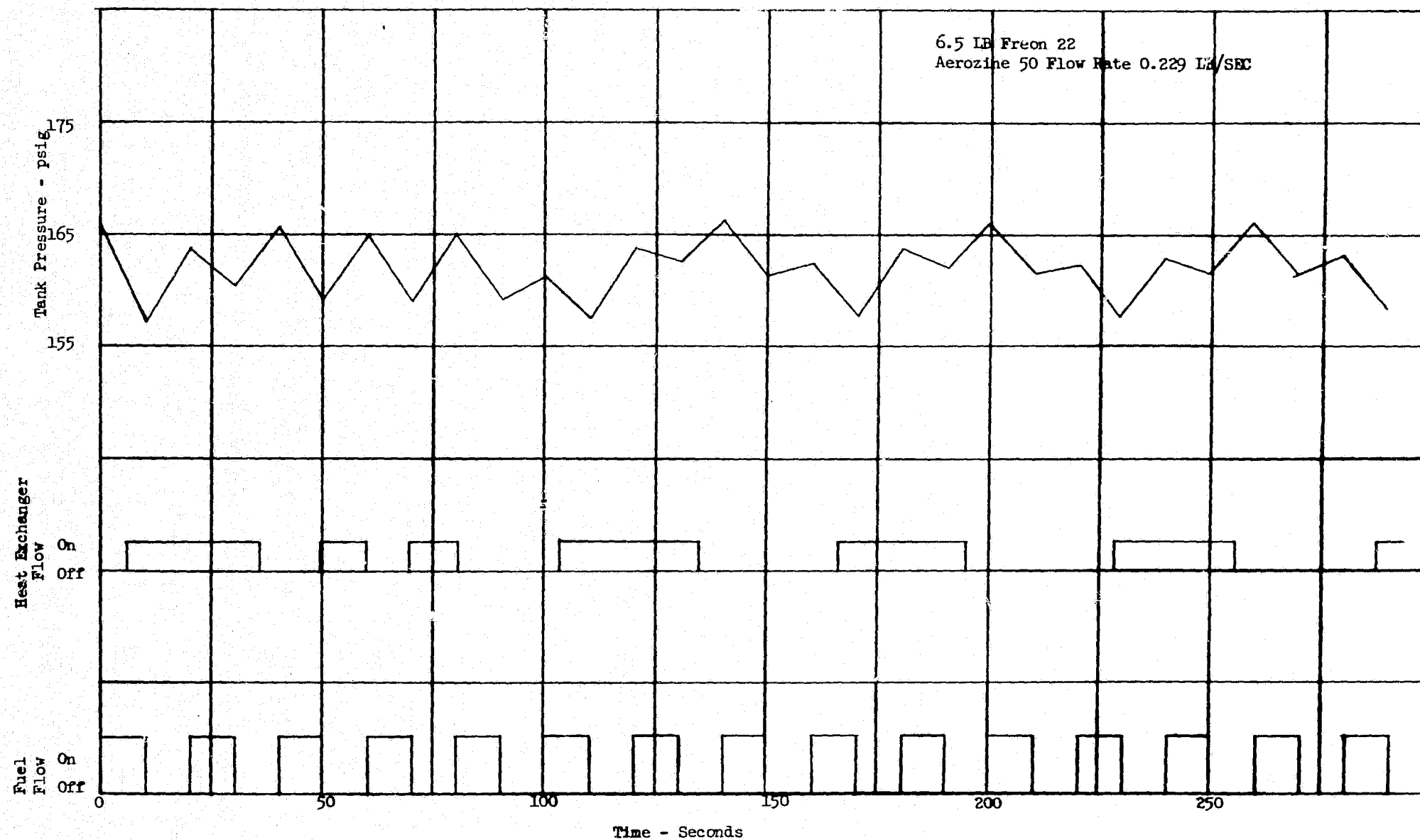


Figure 8-35 Fuel Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 3

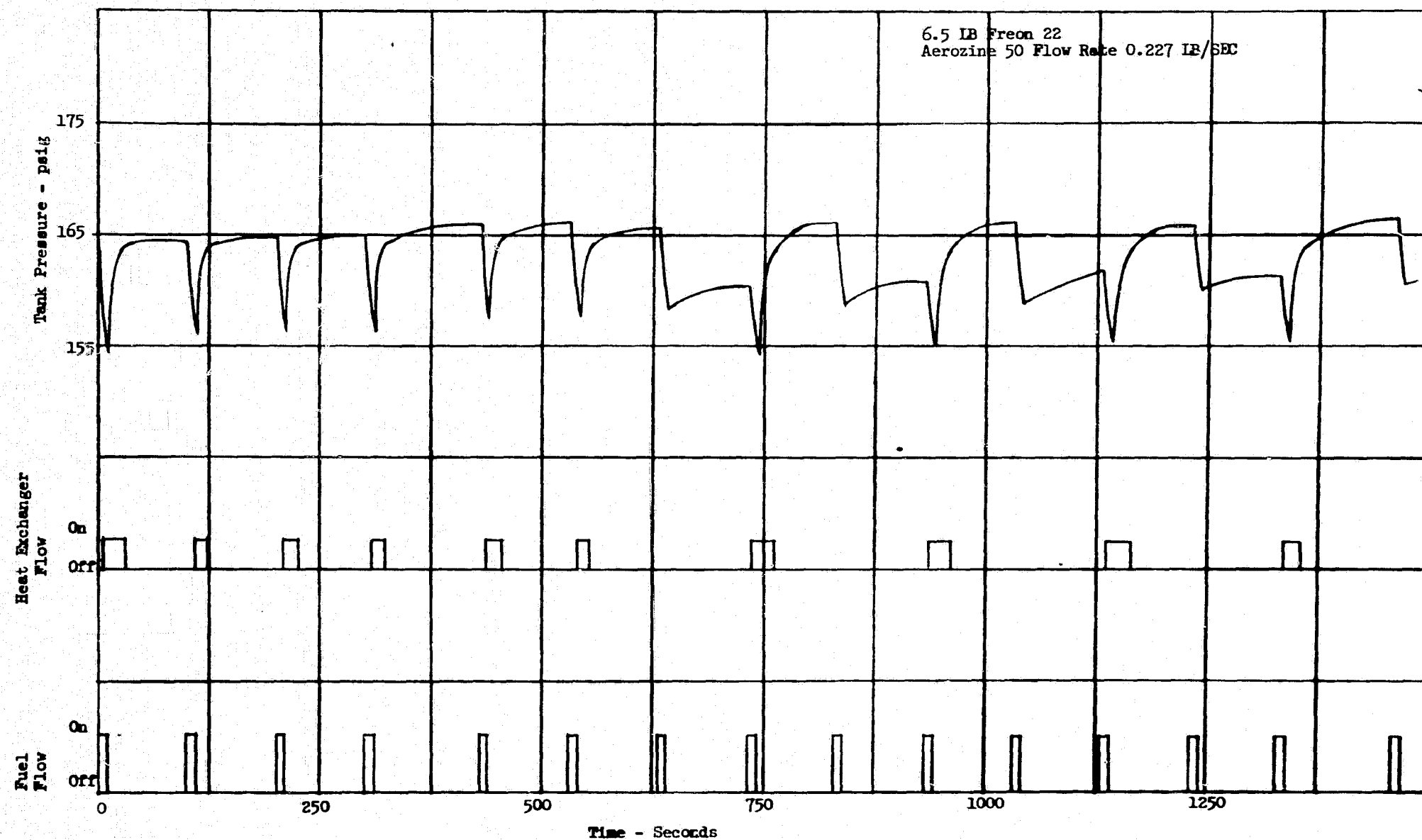


Figure 8-36 Fuel Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 4

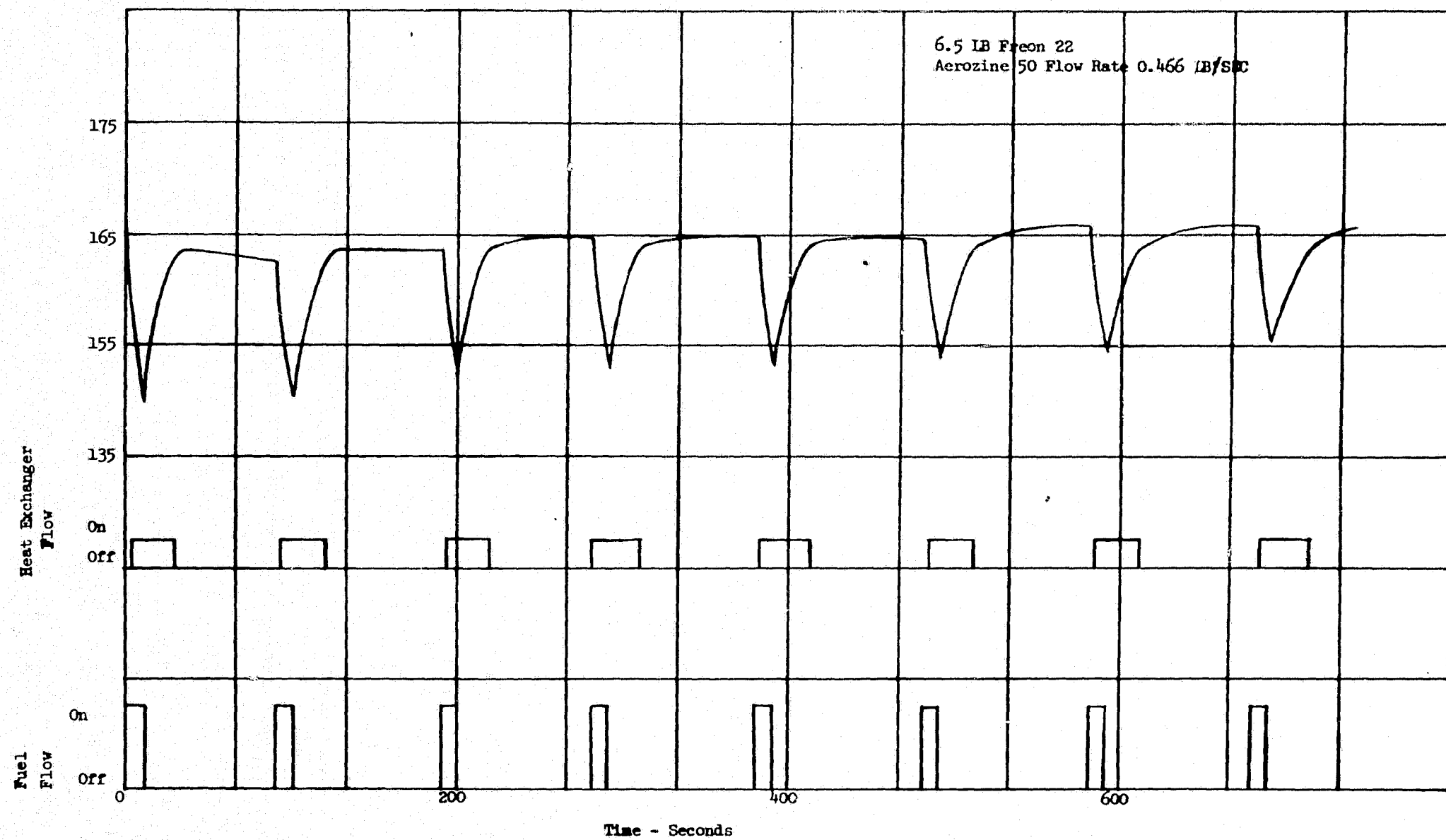


Figure 8-37 Fuel Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 5

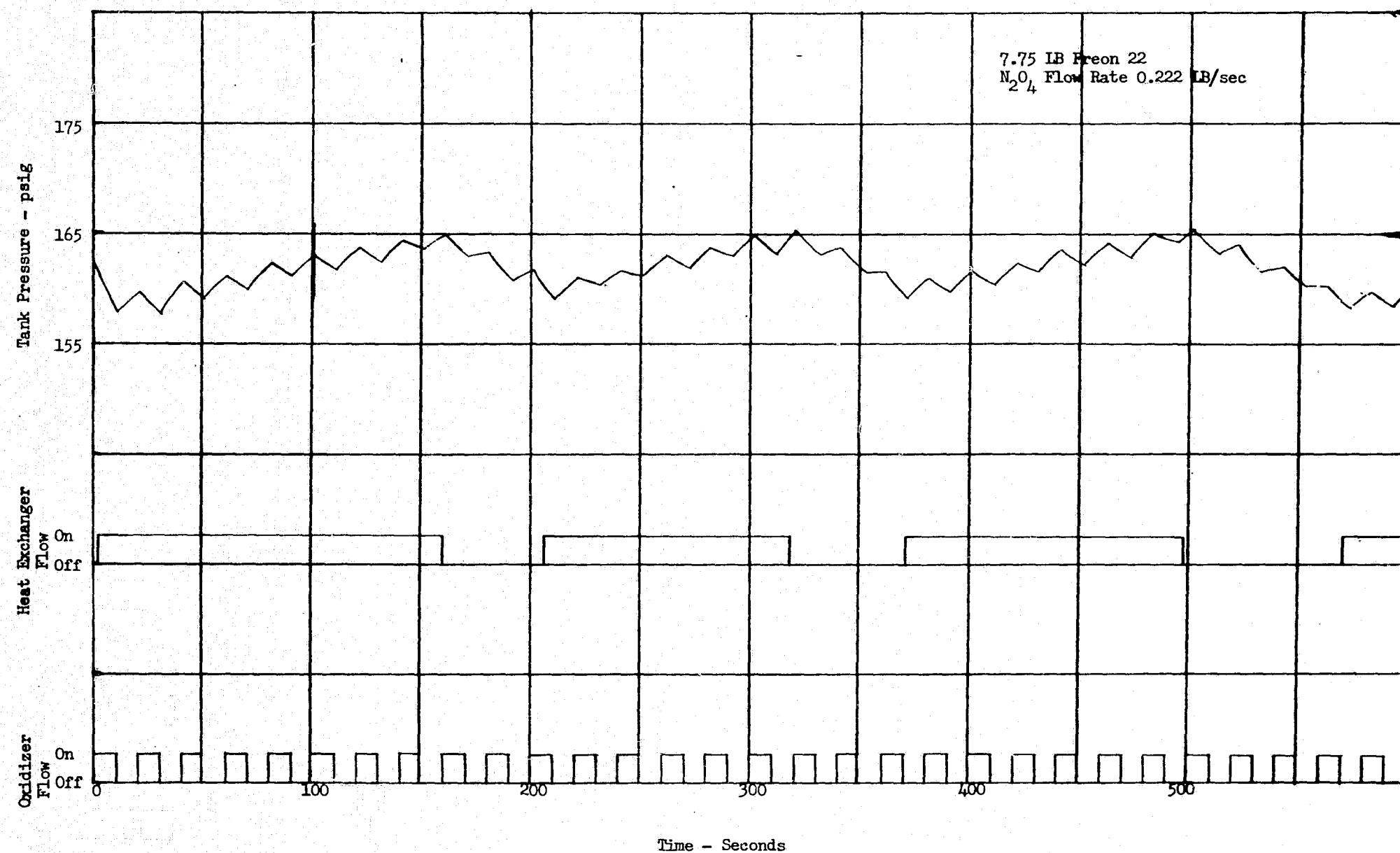


Figure 8-38 Oxidizer Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 1

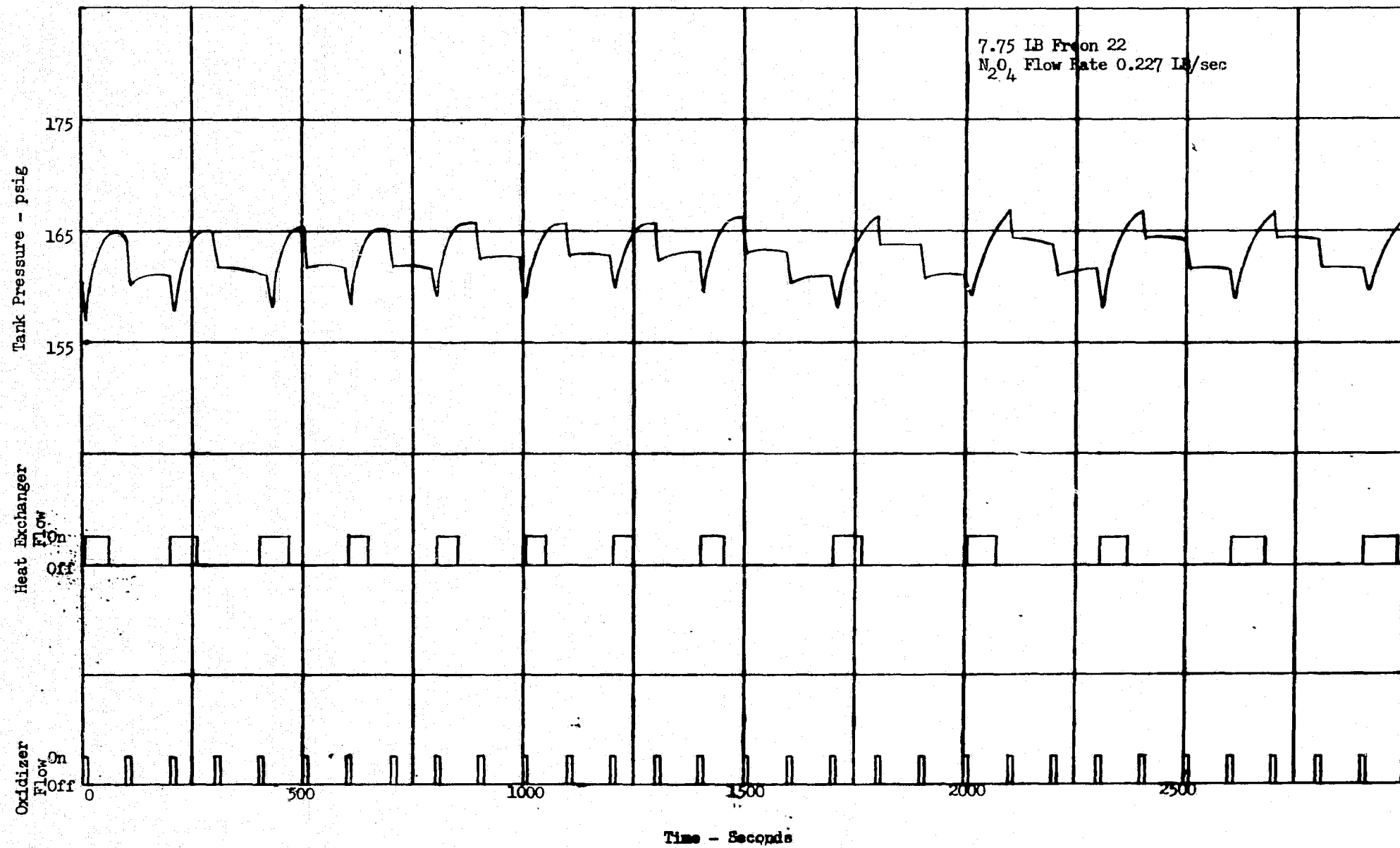


Figure 8-39 Oxidizer Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 2

85-8

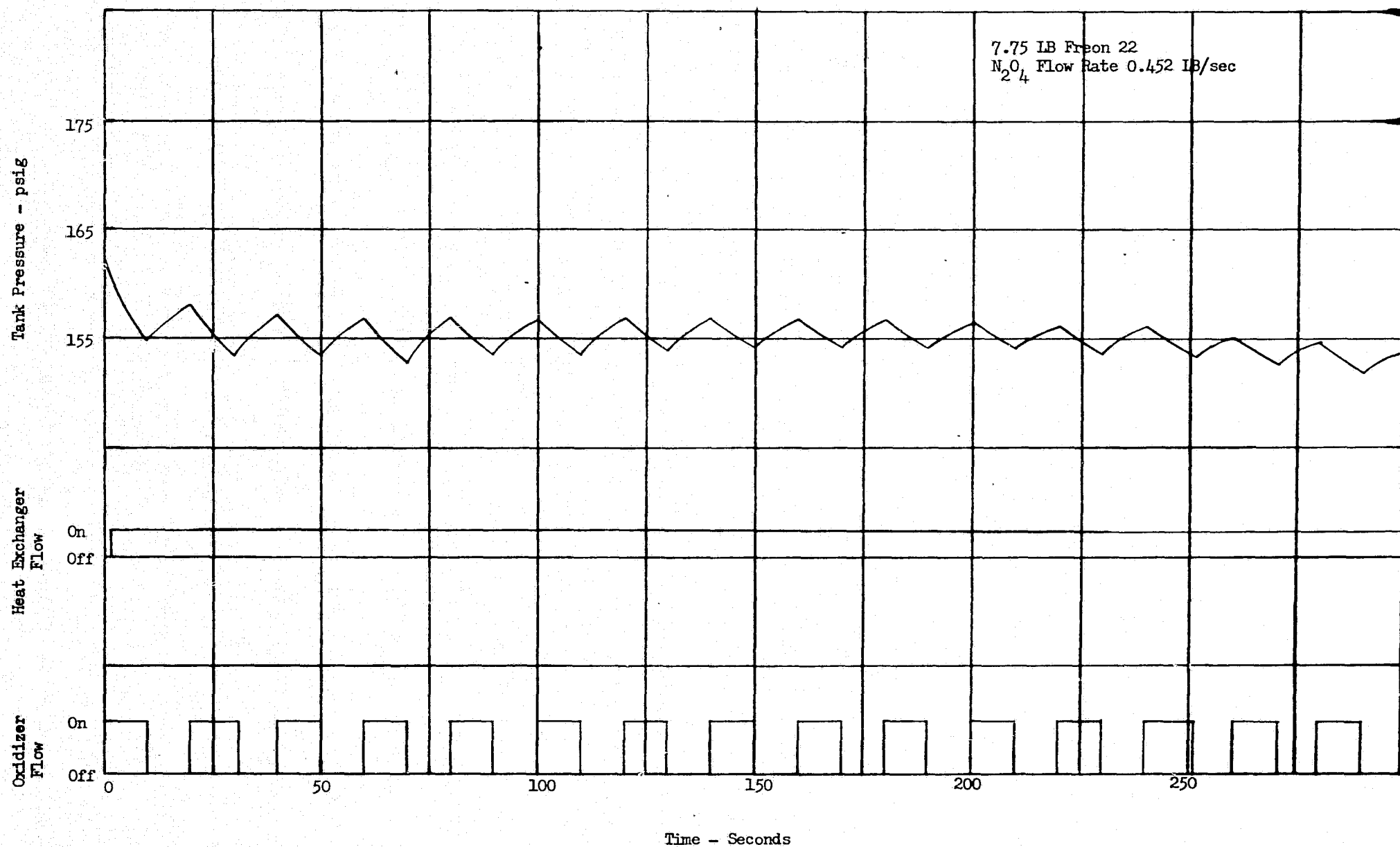


Figure 8-40 Oxidizer Tank Propellant Expulsion Characteristics
 System A Duty Cycle Run No. 3

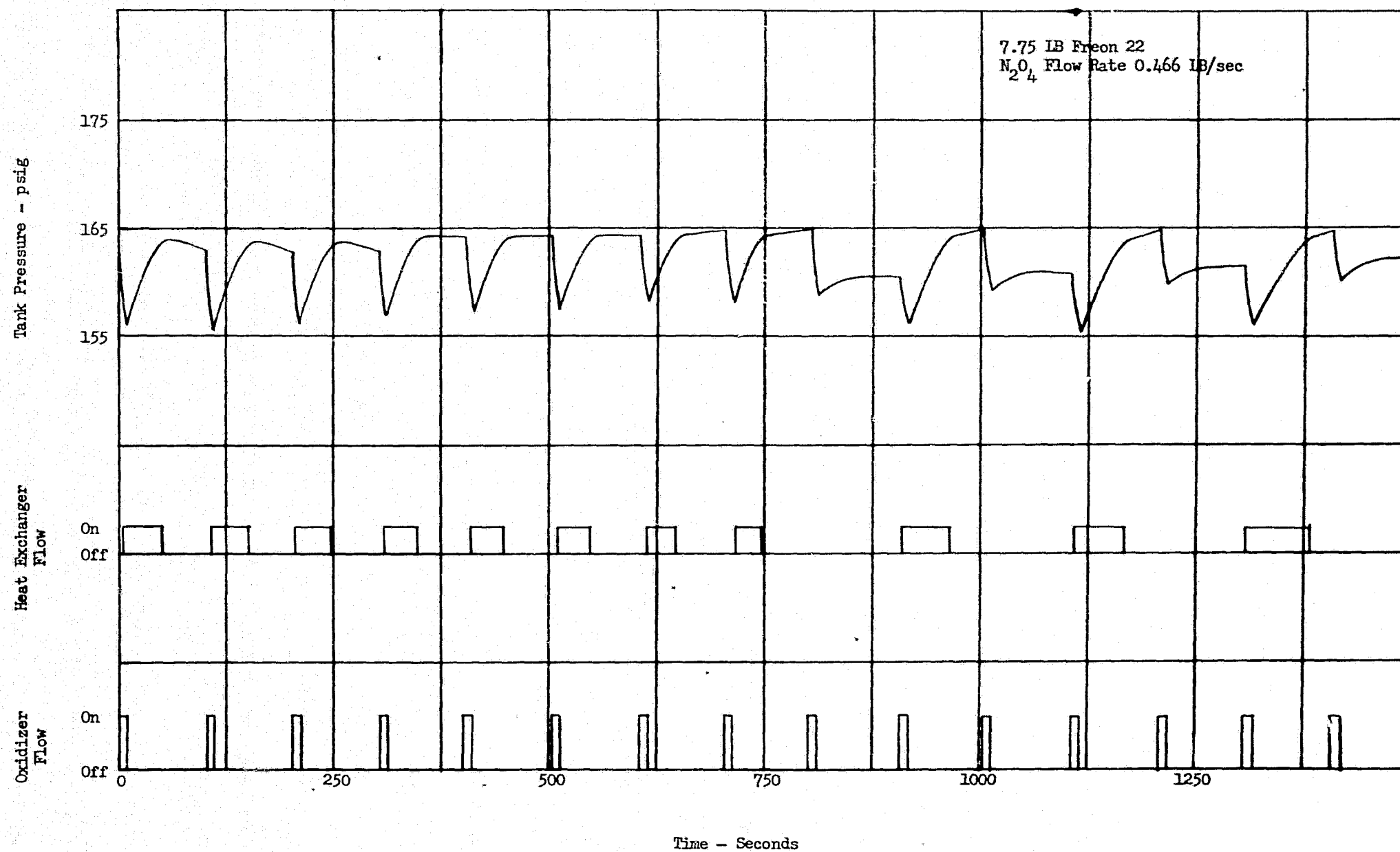


Figure 8-41 Oxidizer Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 4

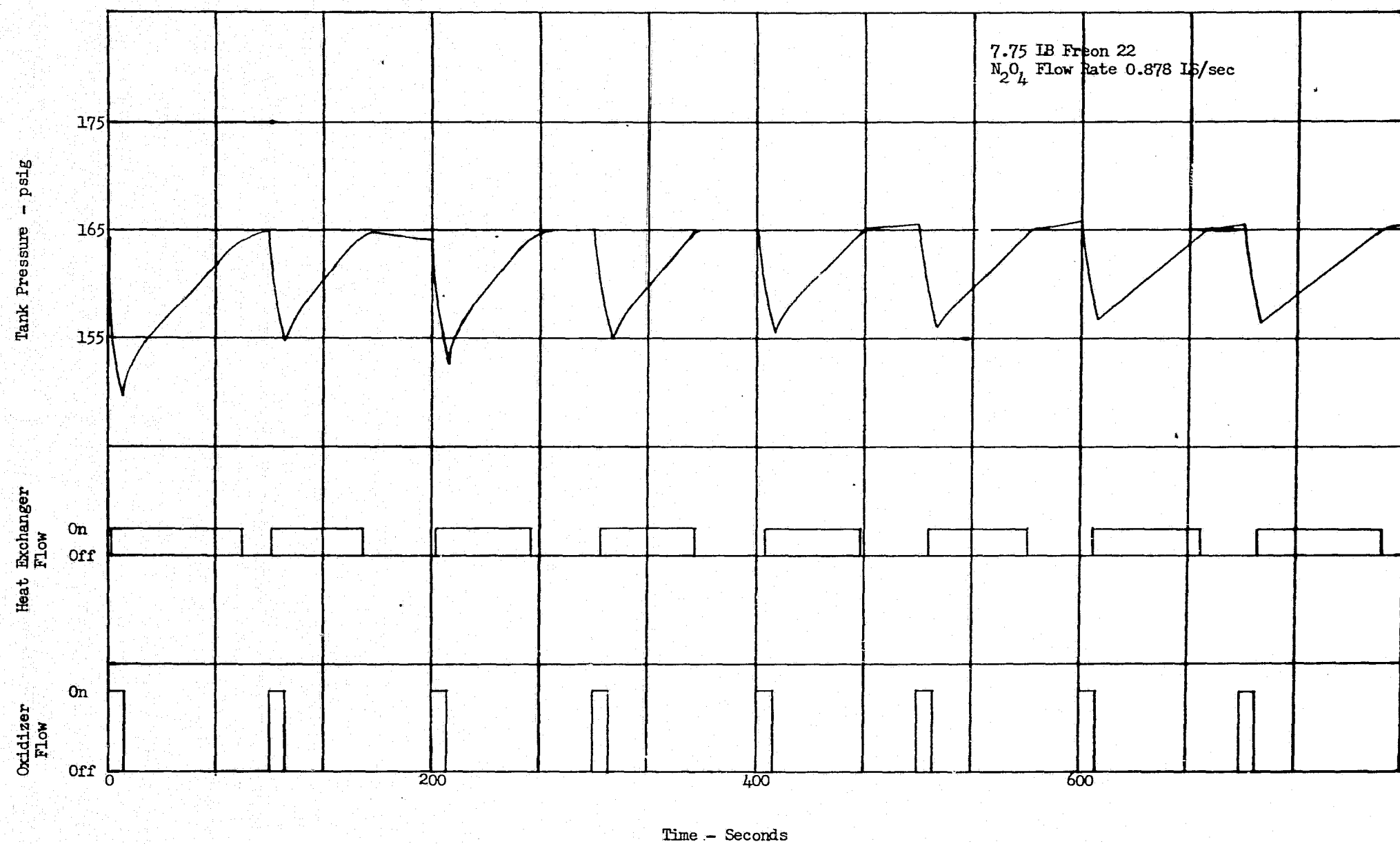


Figure 8-42 Oxidizer Tank Propellant Expulsion Characteristics
System A Duty Cycle Run No. 5

Table 8-8 Fuel Tank Pressurant Conditions During Expulsion Testing

<u>System A Fuel Tank</u>	System A Run No.*				
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
Propellant (Aerozine 50) load (lb)	73.0	73.0	73.0	73.0	73.0
Propellant Flow (lb)	33.3	33.3	33.3	33.3	35.5
Propellant Usage (%)	45.7	45.7	45.7	45.7	48.7
Pressurant (Freon 22) Weight (lb)	6.5	6.5	6.5	6.5	6.5
Pressurant Initial Quality (%)	29.2	29.2	29.2	29.2	29.2
Pressurant Final Quality (%)	61.7	61.7	61.7	61.7	63.7
<u>System B Fuel Tank</u>					
Propellant (Freon 11) load (lb)	73.0	73.0	73.0	73.0	73.0
Propellant Flow (lb)	55.8	55.8	55.8	55.8	59.7
Propellant Usage (%)	76.5	76.5	76.5	76.5	81.8
Pressurant (Freon 22) Weight	4.5	4.5	4.5	4.5	4.5
Pressurant Initial Quality (%)	33.1	33.1	33.1	33.1	33.1
Pressurant Final Quality (%)	81.2	81.2	81.2	81.2	84.2

*Run condition defined in Table 8-2.

8.3.2 System B Propellant Testing

The System B propellant expulsion tests were conducted in accordance with the System B duty cycle conditions (Table 8-3).

The propellant supply tank was loaded with N_2O_4 . Seven expulsion runs were made with the System B oxidizer tank. The results of single-engine flow rates with and without heat exchanger flow are shown in Figure 8-43. The performance characteristics of the tank with four-engine flow rates with and without heat exchanger flow are shown in Figure 8-44.

At both flow rate levels, a performance improvement in the form of a higher pressure level was noted over the results obtained during the bipropellant runs. This improved performance with the oxidizer tank was attributed to a difference in preconditioning of the system prior to starting propellant flow. During preconditioning for the propellant runs, the temperature of the heat storage material was maintained above the melting point for a longer period of time than during the dual system tests. It is felt that incomplete melting of the heat storage material

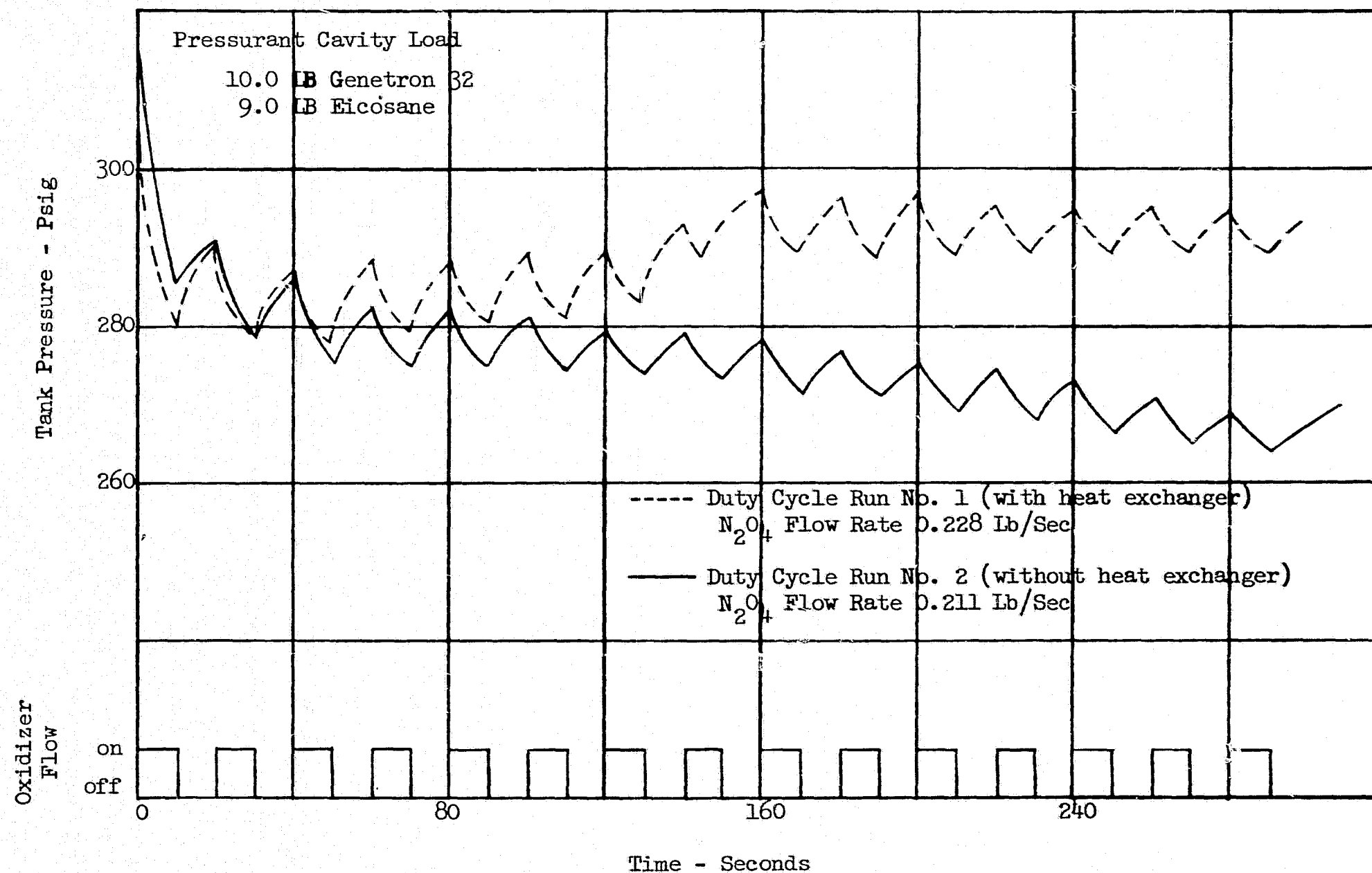


Figure 8-43 Propellant Test Expulsion Characteristics
System B Duty Cycle Runs 1 and 2

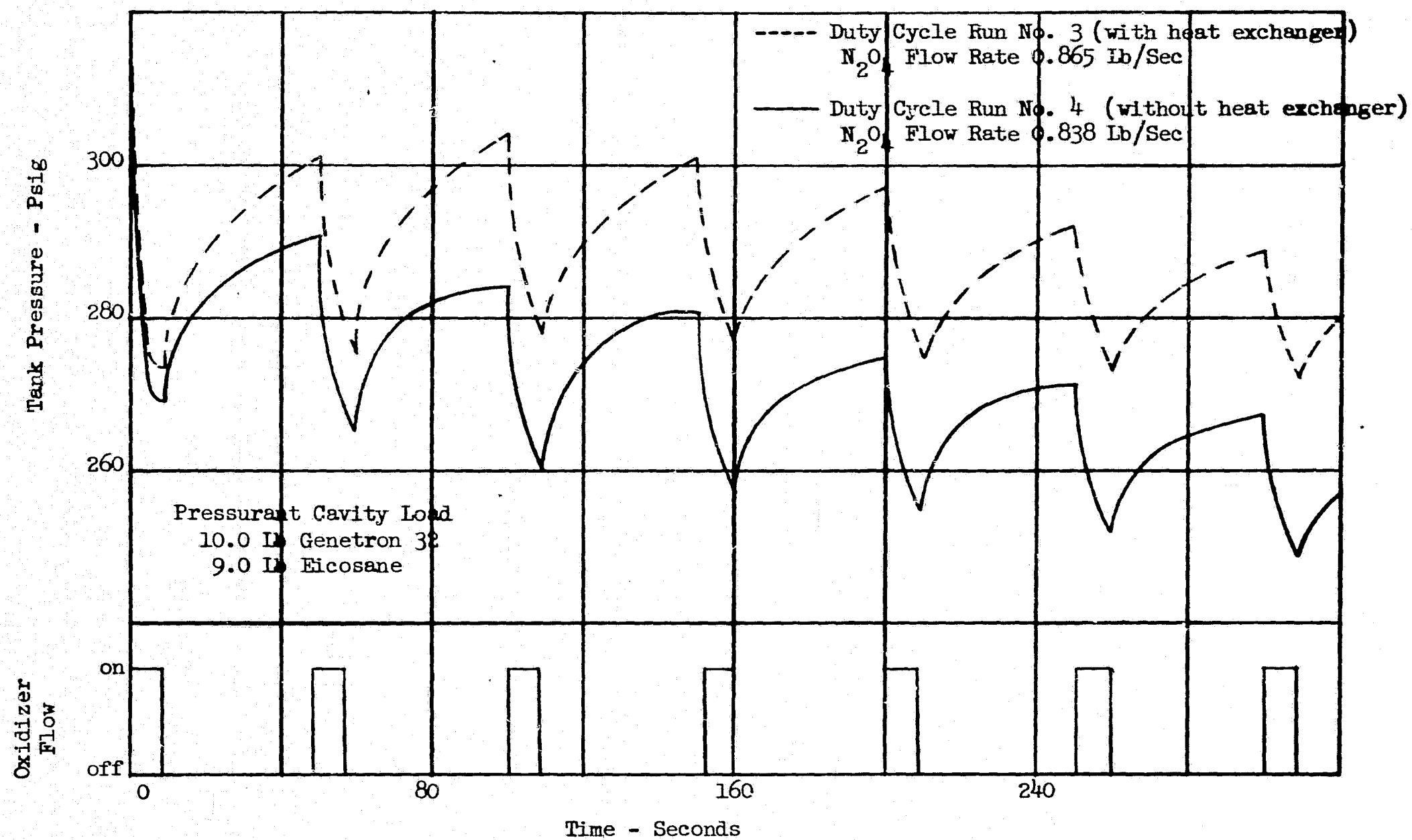


Figure 8-44 Propellant Test Expulsion Characteristics
System B Duty Cycle Runs 3 and 4

or a slightly superheated pressurant condition occurred in the oxidizer tank during the bipropellant tests. This further supports importance of proper preconditioning of the system in order for the heat storage material to be effective during operation.

The propellant supply tank was loaded with MMH and four expulsion runs were made with the System B fuel tank. The results of single-engine flow rates with and without heat exchanger flow are shown in Figure 8-45. The expulsion characteristics of the fuel tank with a four-engine propellant flow rate with and without heat exchanger flow are shown in Figure 8-46.

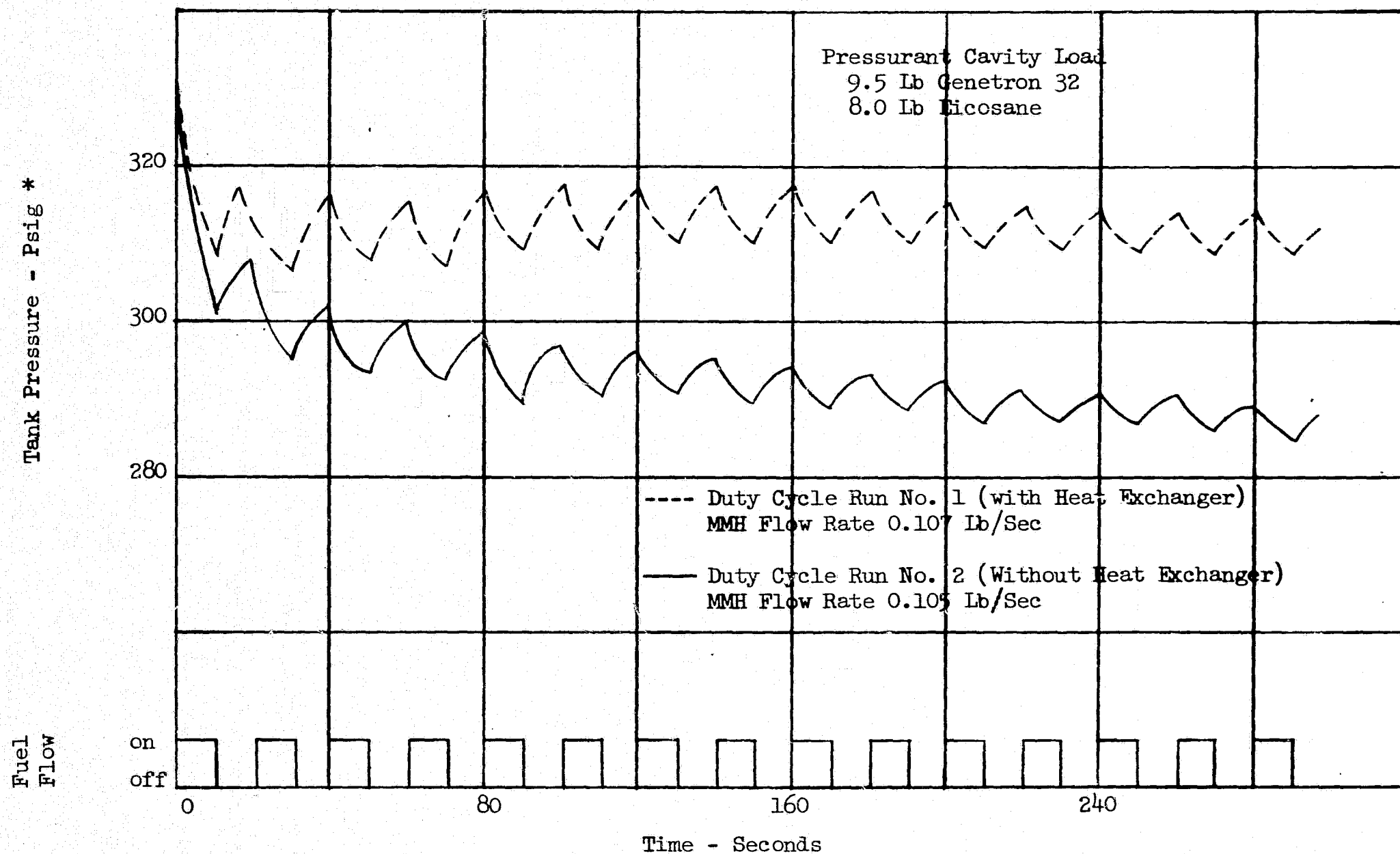
It will be noted that all four fuel tank runs apparently operated at a pressure level of approximately 20 psi higher than had been experienced with any previous System B expulsion runs either with propellants or with the simulated propellant. Although the source could not be determined, it was felt that the apparent increase in pressure operating level was caused by an offset calibration error. Comparison of the pressure drop per flow pulse and the pressure recovery between flow pulses with the results obtained during the oxidizer tank propellant tests indicates very satisfactory performance.

Taking into account the 20 psi data shift, the results without heat exchanger flow showed improved performance over the simulated propellant test results. This was probably a result of preconditioning differences. However, with heat exchanger flow, the amount of pressure decay and recovery rate were almost equal.

8.4 Test Problems

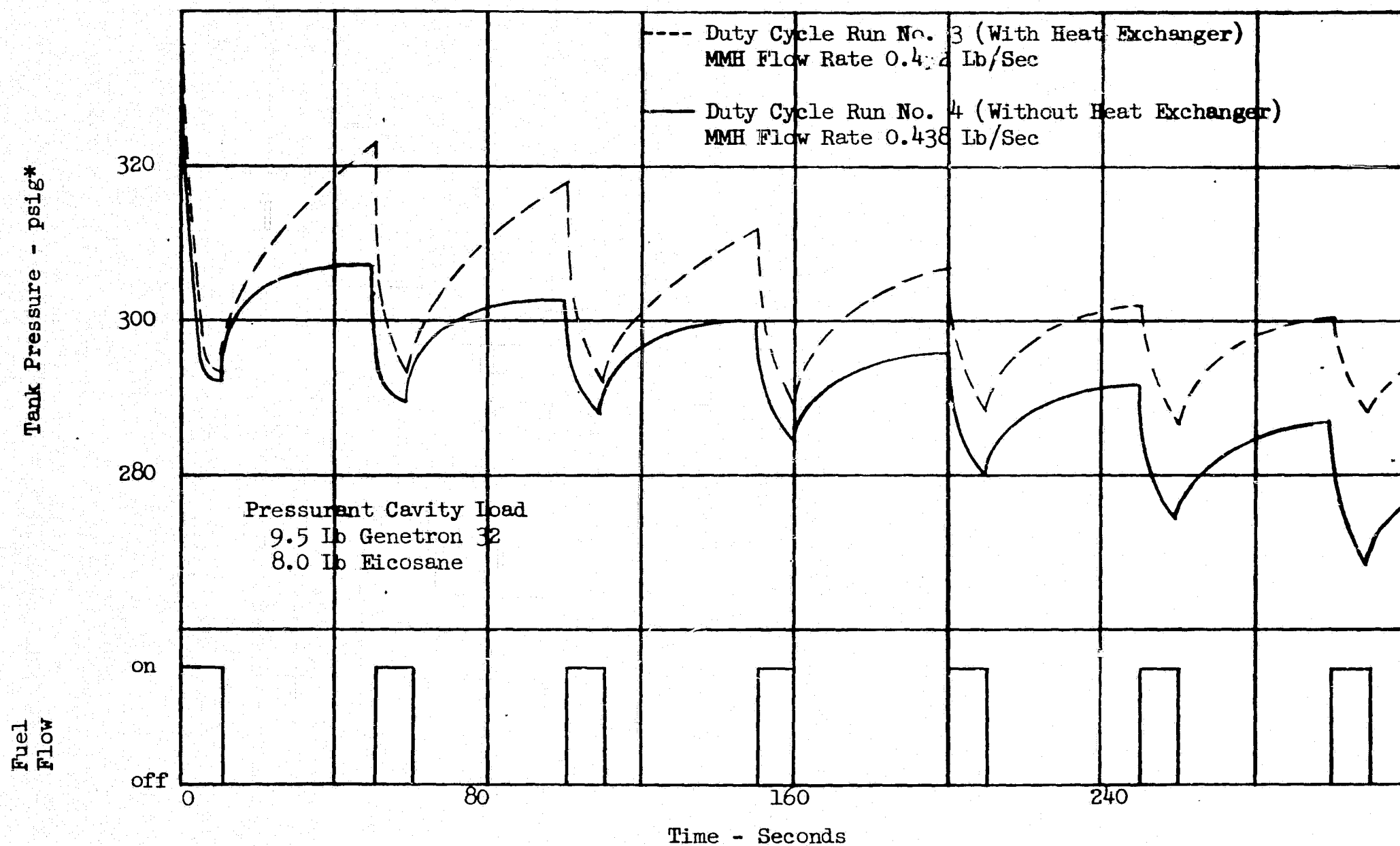
During system demonstration testing the bellows in the System B oxidizer tank was inadvertently subjected to an excessive differential pressure. This resulted in rupture of the bellows. Photographs of damage to the System B oxidizer tank bellows are shown in Figure 8-47.

At the completion of a low flow rate run, the flow control valve was re-adjusted for a high propellant flow rate. The tank was then allowed to



*Pressure level is apparently 20 psi high due to calibration error.

Figure 8-45 Fuel Tank Propellant Test Expulsion Characteristics
System B Duty Cycle Runs - Single Engine Flow Rate



*Pressure Level is approximately 20 psi high due to calibration error.

Figure 8-46 Fuel Tank Propellant Test Expulsion Characteristics
System B Duty Cycle Runs - Four Engine Flow Rate

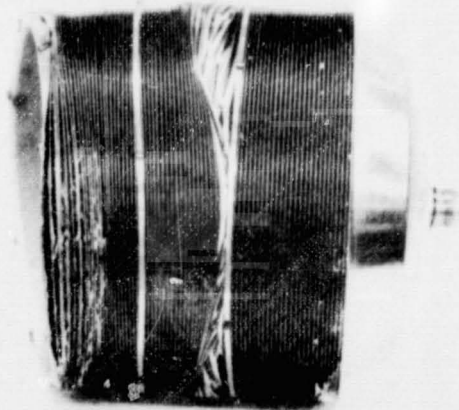
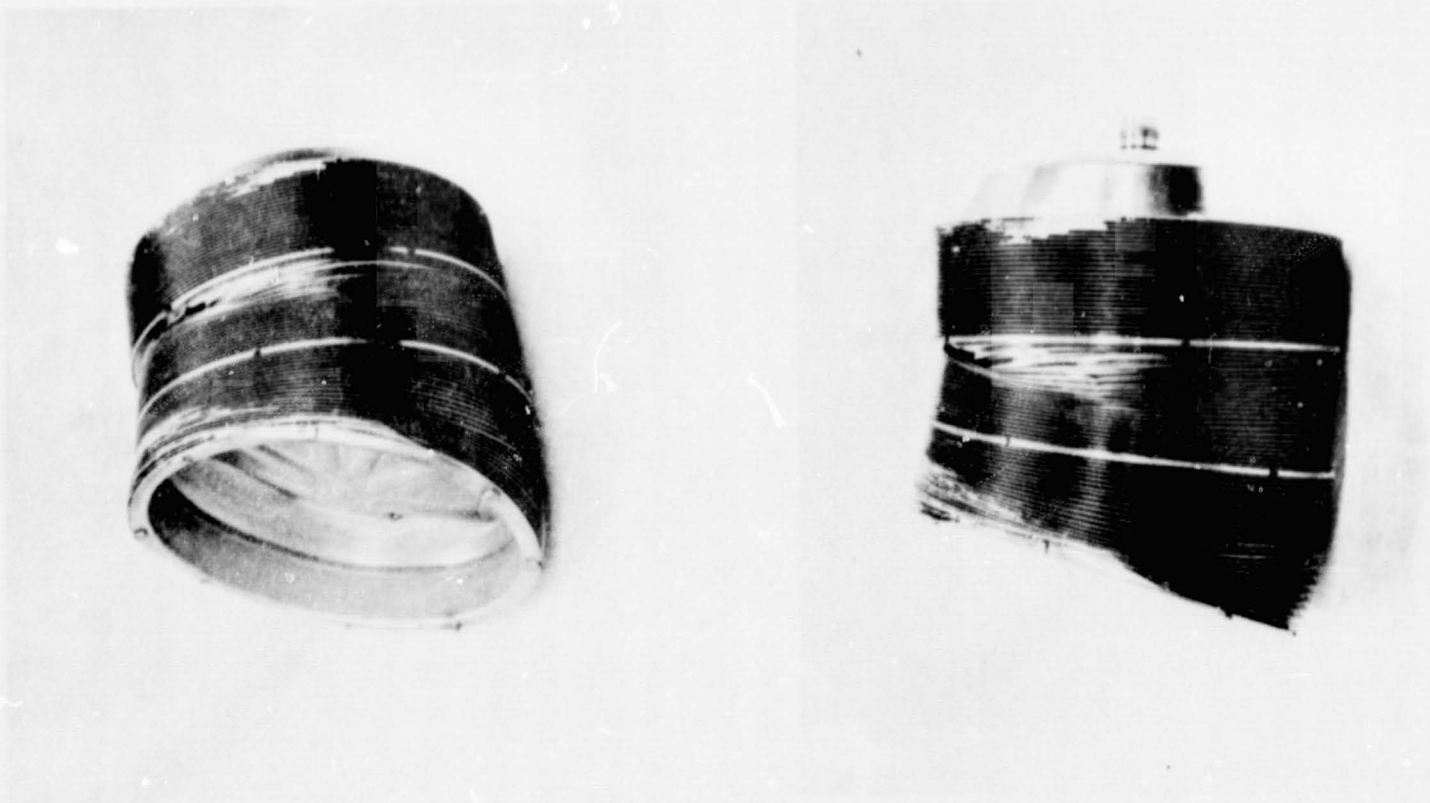


Figure 8-47 Damaged Bellows - System "B"
Oxidizer Tank

stand for approximately 20 minutes with no heat input. Prior to re-initiating the heat exchanger flow, a short pulse was made to verify the flow rate setting. During the shutdown period the Eicosane had been continuing to solidify and apparently became sufficiently solid that it restrained the bellows. With the initiation of the propellant flow, with the bellows in an approximately 10 percent open condition, the pressure in the propellant cavity decayed rapidly. At a differential pressure of approximately 120 psi across the bellows, the pressure in the propellant cavity increased slightly and leveled off for the balance of the flow pulse. Apparently rupture of the bellows occurred allowing leakage of Genetron 32 from the pressurant cavity into the propellant cavity. Not realizing that the bellows had been ruptured, an attempt was made to load the propellant. With a reduction in the amount of Genetron 32 in the pressurant cavity, a high (40 psi) internal pressure differential was induced on the restrained bellows which resulted in collapse of the header as shown in Figure 8-48. The tank was removed from the test stand and returned to Metal Bellows Corporation for repair.

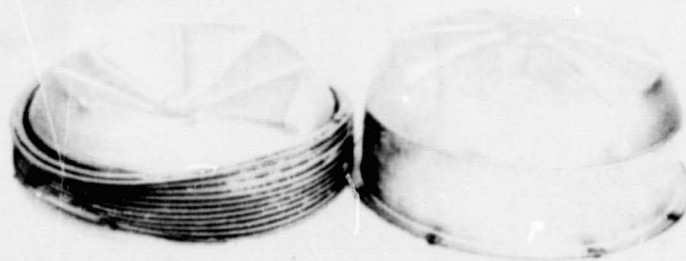


Figure 8-48 Comparison of Damaged Header
From System "B" Oxidizer Tank
With Undamaged Hardware

9.0 AUXILIARY PROPULSION SYSTEM DEMONSTRATION

As a final phase of the program, a series of reaction control engine firings was conducted using the volatile liquid pressurization system and flight-weight bellows tankage to provide positive propellant feed to the engines during operation. These tests were intended to demonstrate the volatile liquid pressurization concept during operation of a complete auxiliary propulsion system and to determine the effects of the reaction imposed by engine operation on the expulsion characteristics.

Because the System A oxidizer tank was not available, both System A and System B tests were conducted using the System B tanks. As a result, the System A tests were conducted at a lower total propellant capacity.

The tests were conducted firing two 100-lb-thrust engines connected in parallel to the propellant tanks. The two engines were operated independently to different duty cycles. This allowed investigation of a wide range of operation conditions. A summary of the test conditions and performance is shown in Table 9-1.

For System A operation two Apollo Service Module engines manufactured by the Marquardt Corporation were used. For System B operation two ablative engines designed and built for NASA by TRW under Contract NAS9-5186 were used. A System A engine is shown in Figure 9-1 and a System B engine in Figure 9-2.

Operating characteristics experienced during these tests were very comparable to the results of the pressurization system demonstration tests. Volatile liquid pressurization performance during operation of a complete auxiliary propulsion system was satisfactorily demonstrated.

Apparently the only effect on the pressurization system performance resulting from the dynamics of engine operation was beneficial and occurred during System A testing. During rapid short pulse operation of only one engine, when the tank heat exchangers were off, the pressure surge from the valve closing appeared to transmit back into the

Table 9-1 Auxiliary Propulsion System Test Operating Parameters

	<u>System A</u>	<u>System B</u>
Oxidizer	N ₂ O ₄	N ₂ O ₄
Average Flow Rate/Engine-Lb/Sec	0.241	0.242
Fuel	MMH	MMH
Average Flow Rate/Engine-Lb/Sec	0.124	0.108
Pressurant	Freon 22	Genetron 32
Heat Storage Material	-	Eicosane
Heat Exchanger		
Fluid	60% ethylene glycol - 40% water	
Inlet Temperature - °F	179	-
Flow Rate - Lb/Sec	0.035	-
Tank Operating Pressure - psig		
Maximum	170.2	311.7
Nominal	168.7*	273.2**
Minimum	163.5	229.5
Engine Pulse Width - Seconds		
Maximum	8.0	30.0
Minimum	0.025	10.0
Engine Pulse Frequency		
Maximum	4 cyc/sec	1 cyc/30 sec
Minimum	1 cyc/15 sec	1 cyc/50 sec
Engine Duty Cycle - % On Time		
Maximum	80	75
Minimum	5	33
Engine Chamber Pressure psig		
Maximum	84.6	150.2
Nominal	84.1*	134.5**
Minimum	82.0	120.3

*Heat Exchanger Flow Termination

**Plateau Pressure from Eicosane Freezing

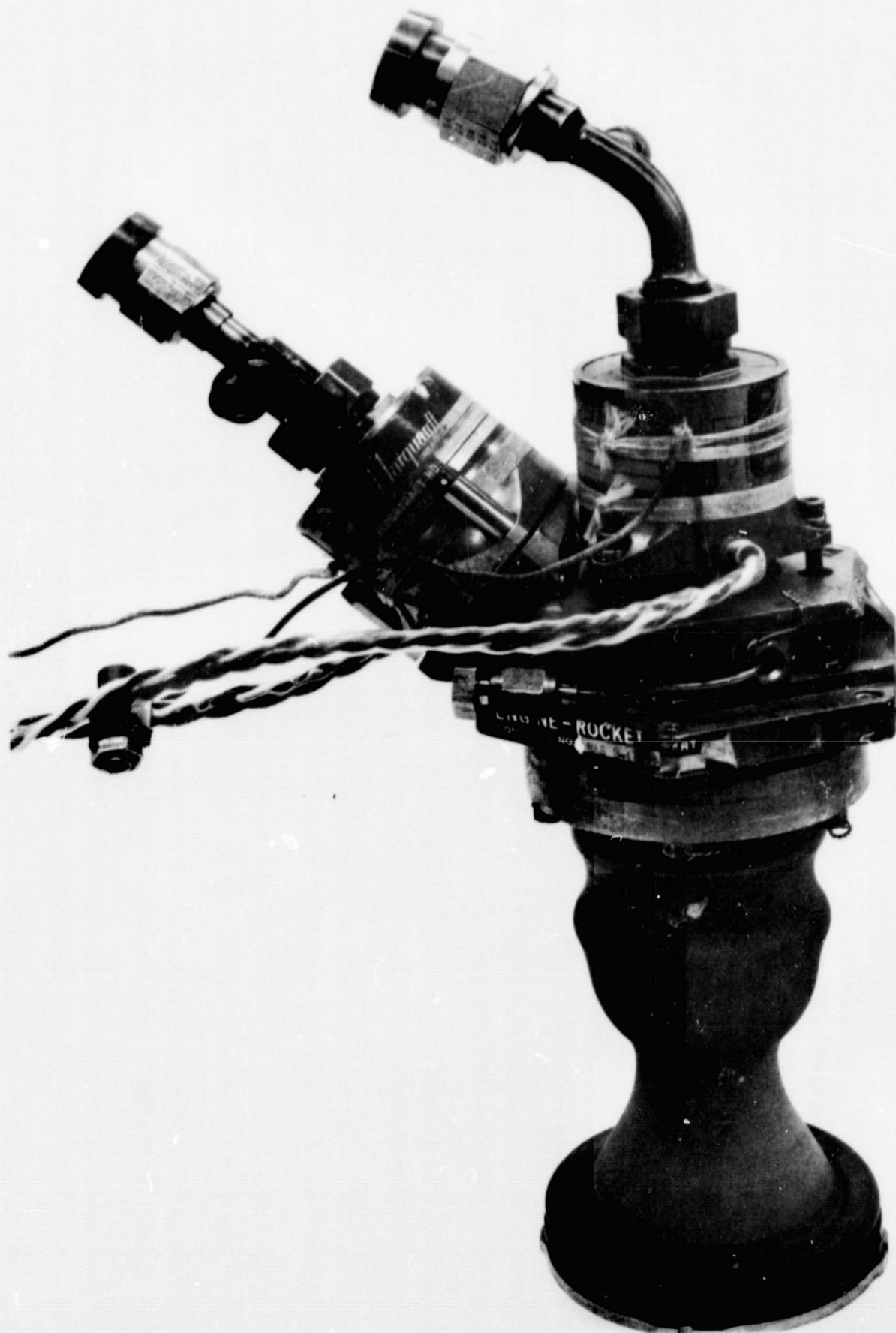


Figure 9-1 System A Engine

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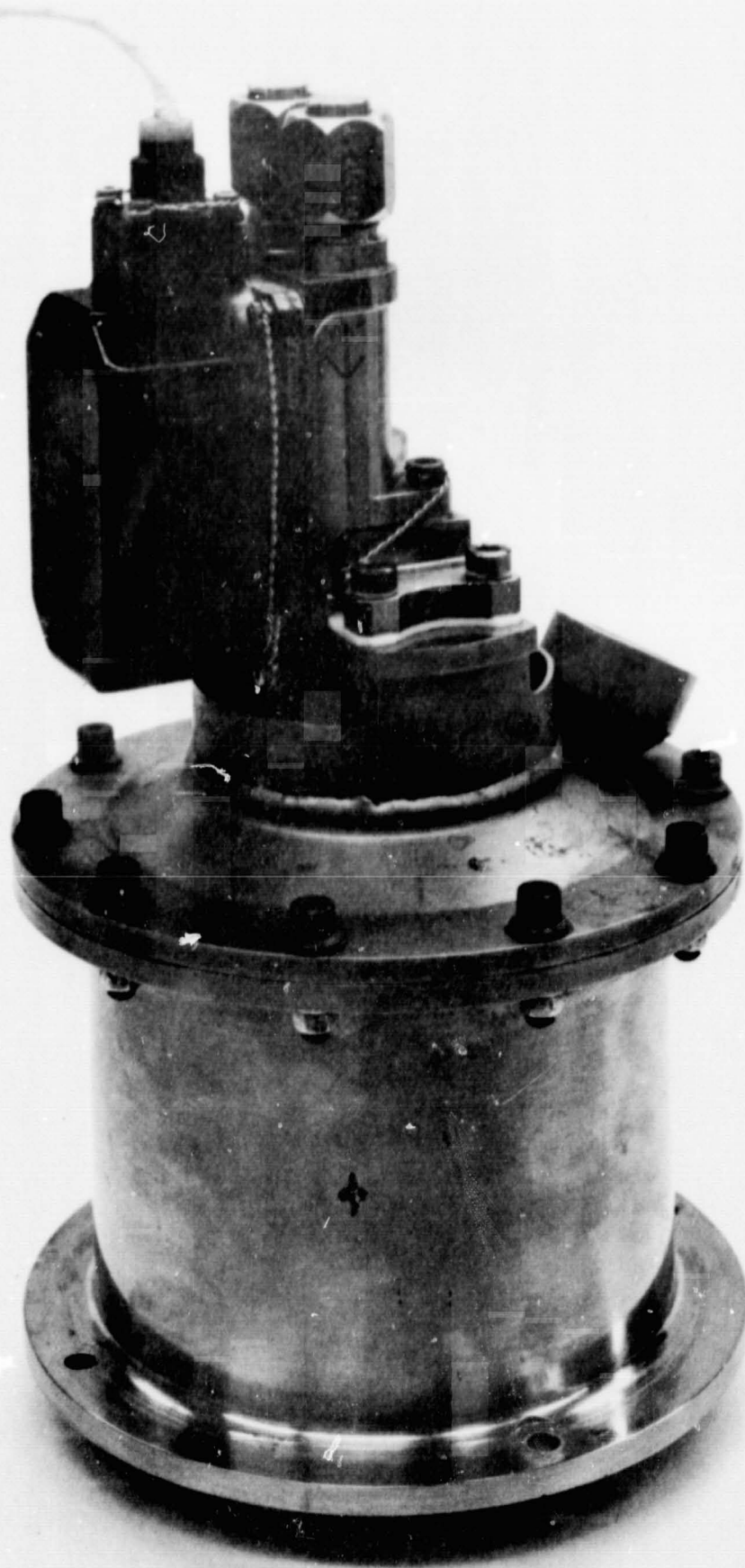


Figure 9-2 System B Engine

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propellant tank. The transducer sensed a pressure impulse and initiated heat exchanger flow prematurely. This had the effect of reducing the operating deadband and tank pressure operating band. With both engines operating, the pressure surges were damped considerably.

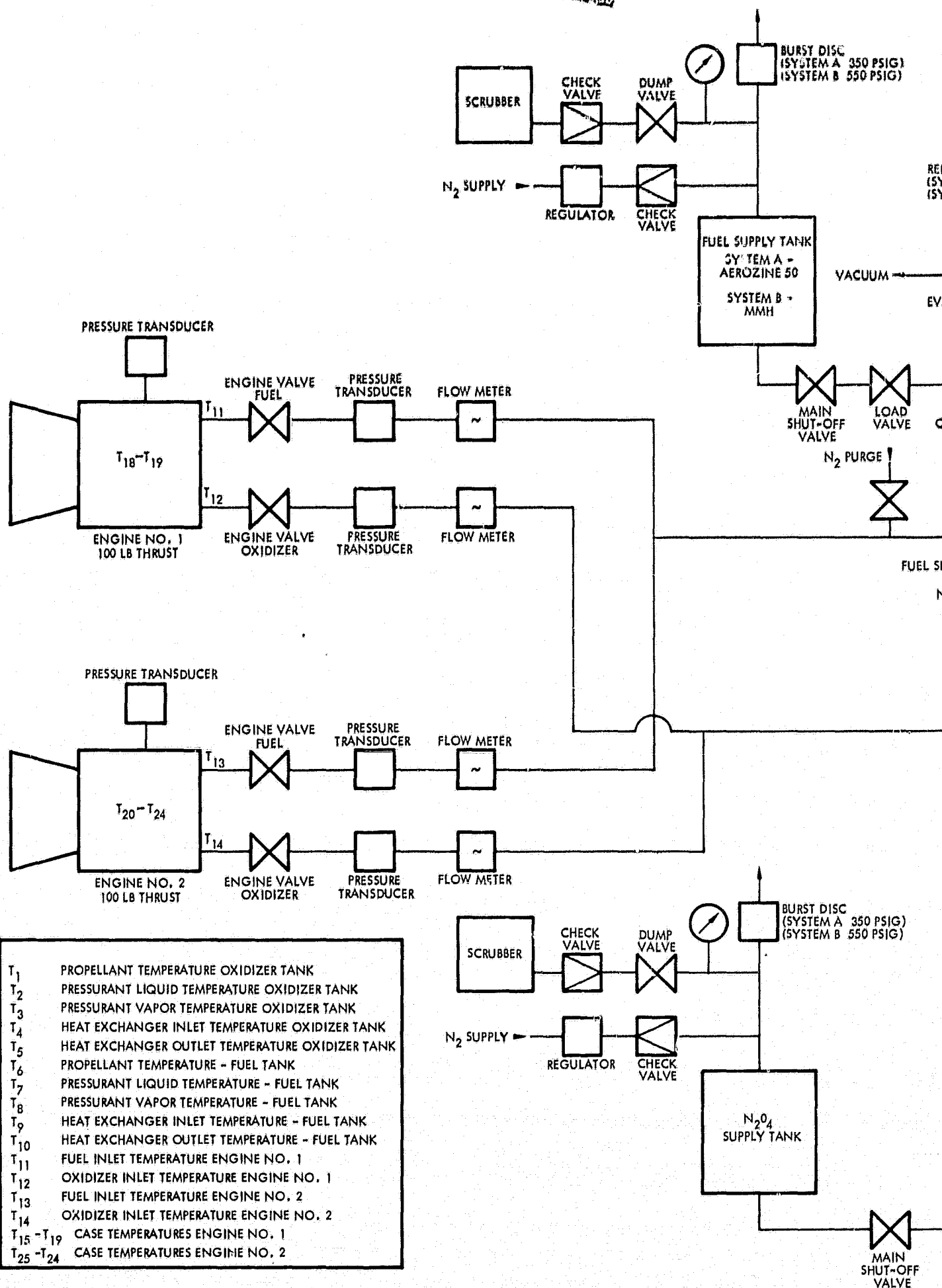
9.1 Test Procedure

In order to conduct the auxiliary propulsion system demonstration it was necessary to buildup a test stand in accordance with the test schematic shown in Figure 9-3. The fuel tank and associated heat input system are shown in Figure 9-4 and the oxidizer tank in Figure 9-5. Typical tank connections to the heat exchanger and pressurant cavity are shown in Figure 9-6.

The basic loading and test conduct procedures used were identical to those used during the pressurization system propellant tests, modified only to accommodate the more complex system. The operating check sheets used are presented in Appendix D.

Just prior to operating the engine valves, the recording equipment was started to reload the parameters listed in Table 9-2. The tank pressures, heat exchanger flows, heat exchanger inlet temperatures, and pressurant vapor temperatures were recorded on one oscillograph. Engine pressures, propellant flows, and engine valve signals were recorded on another oscillograph. The balance of the parameters and selected backup parameters were recorded on strip charts. The recording center is shown in Figure 9-7.

FOLDOUT FRAME 1



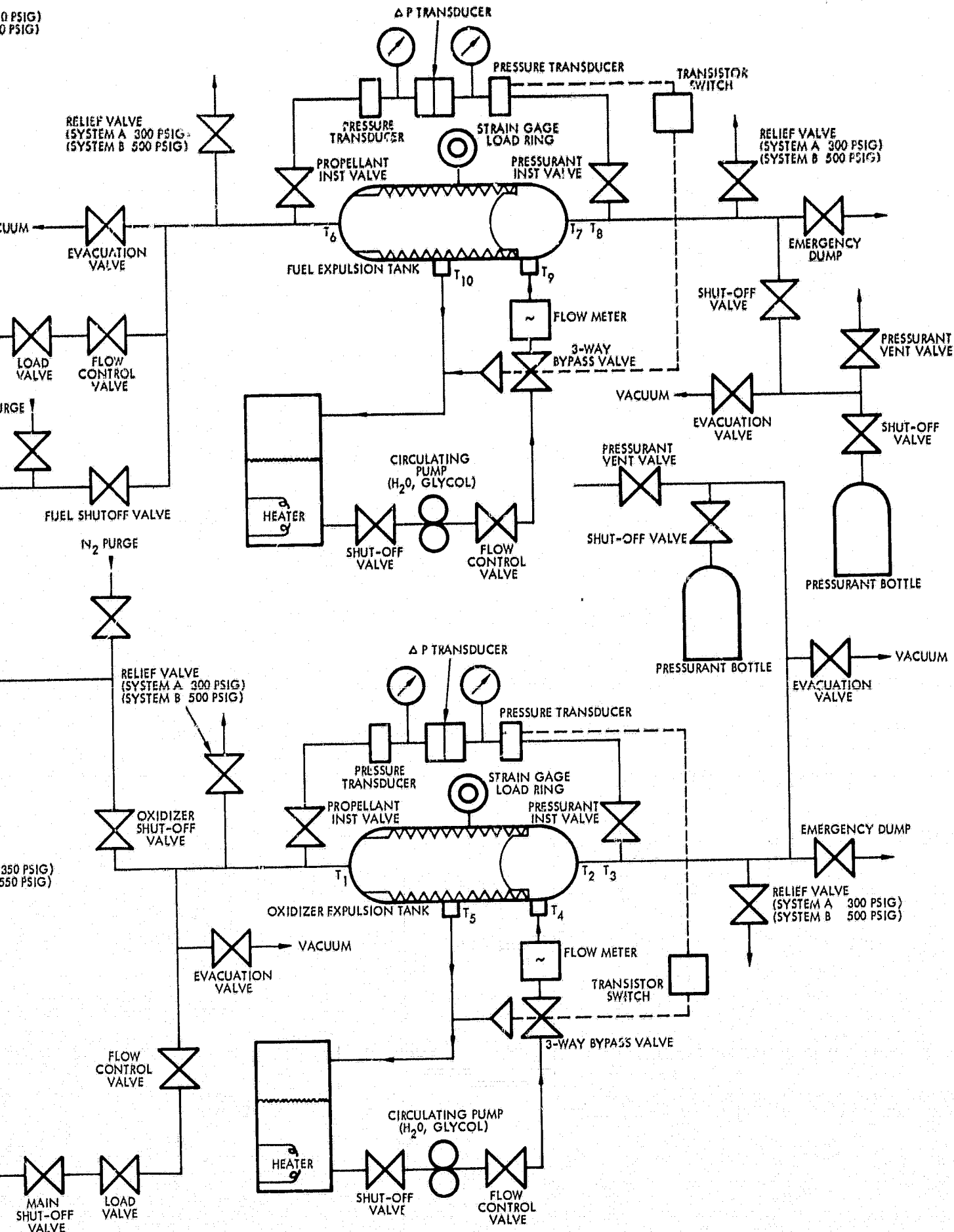


Figure 9-3 Auxiliary Propulsion System Test Schematic

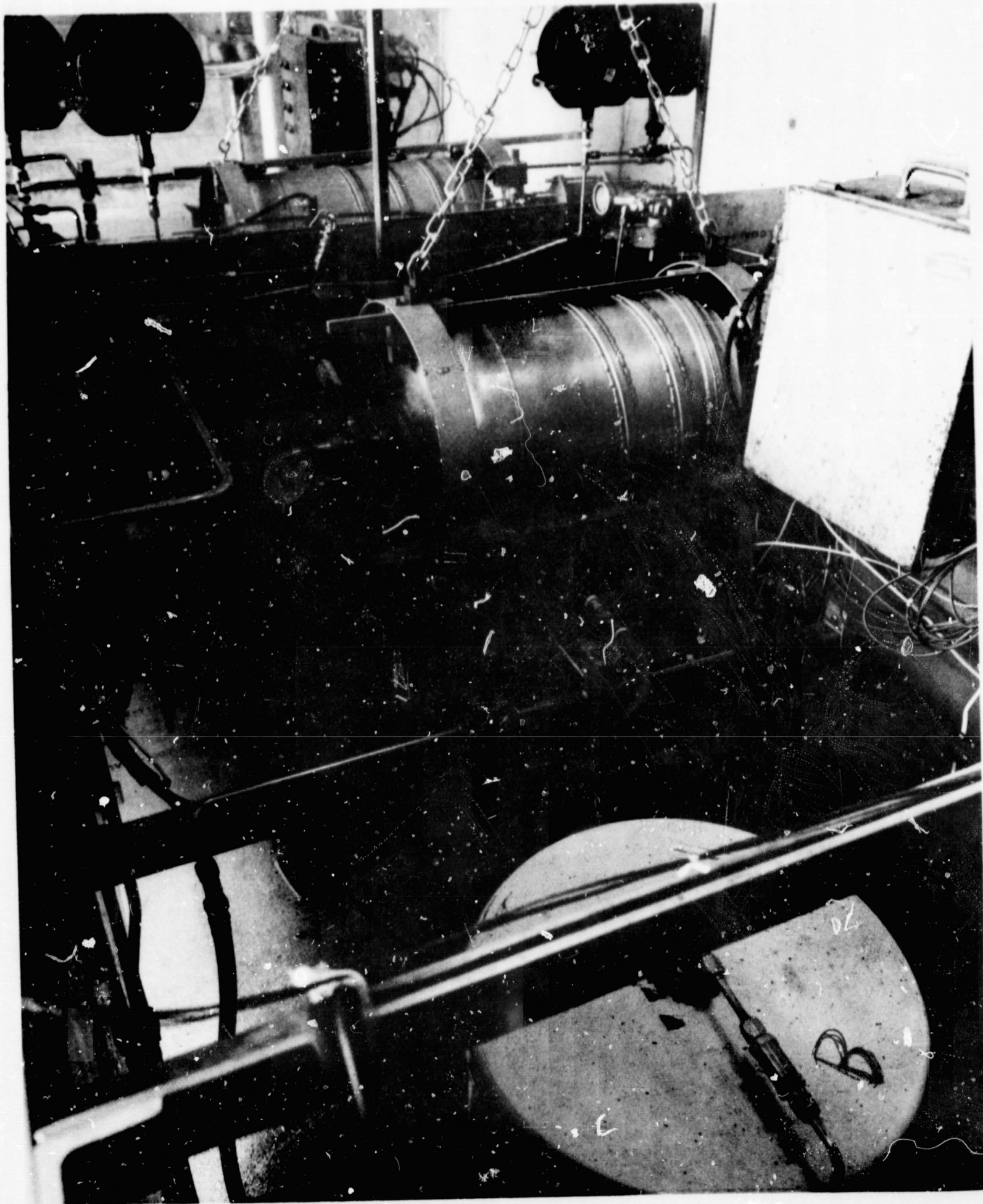


Figure 9-4 Fuel Expulsion Tank

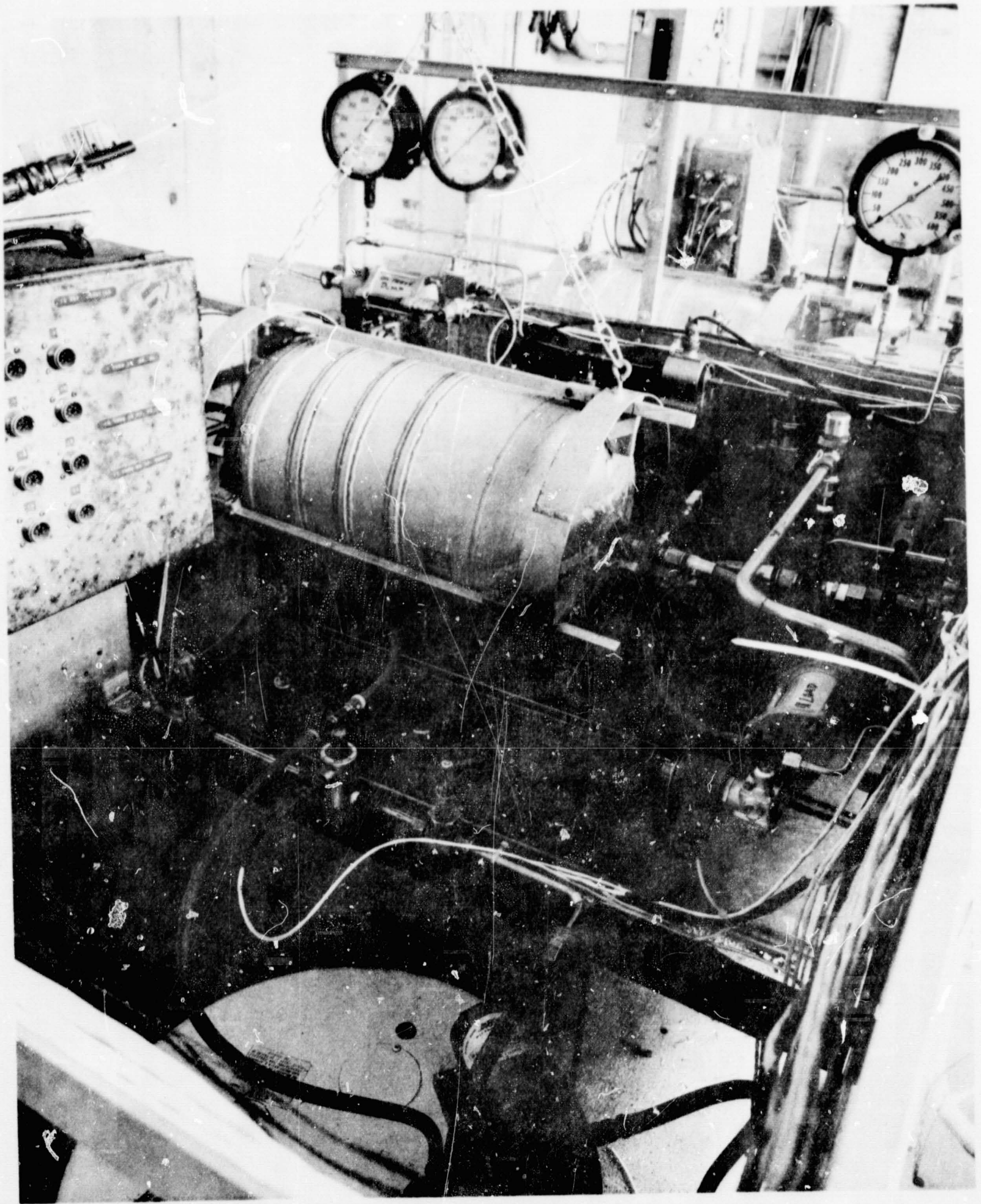


Figure 9-5 Oxidizer Expulsion Tank

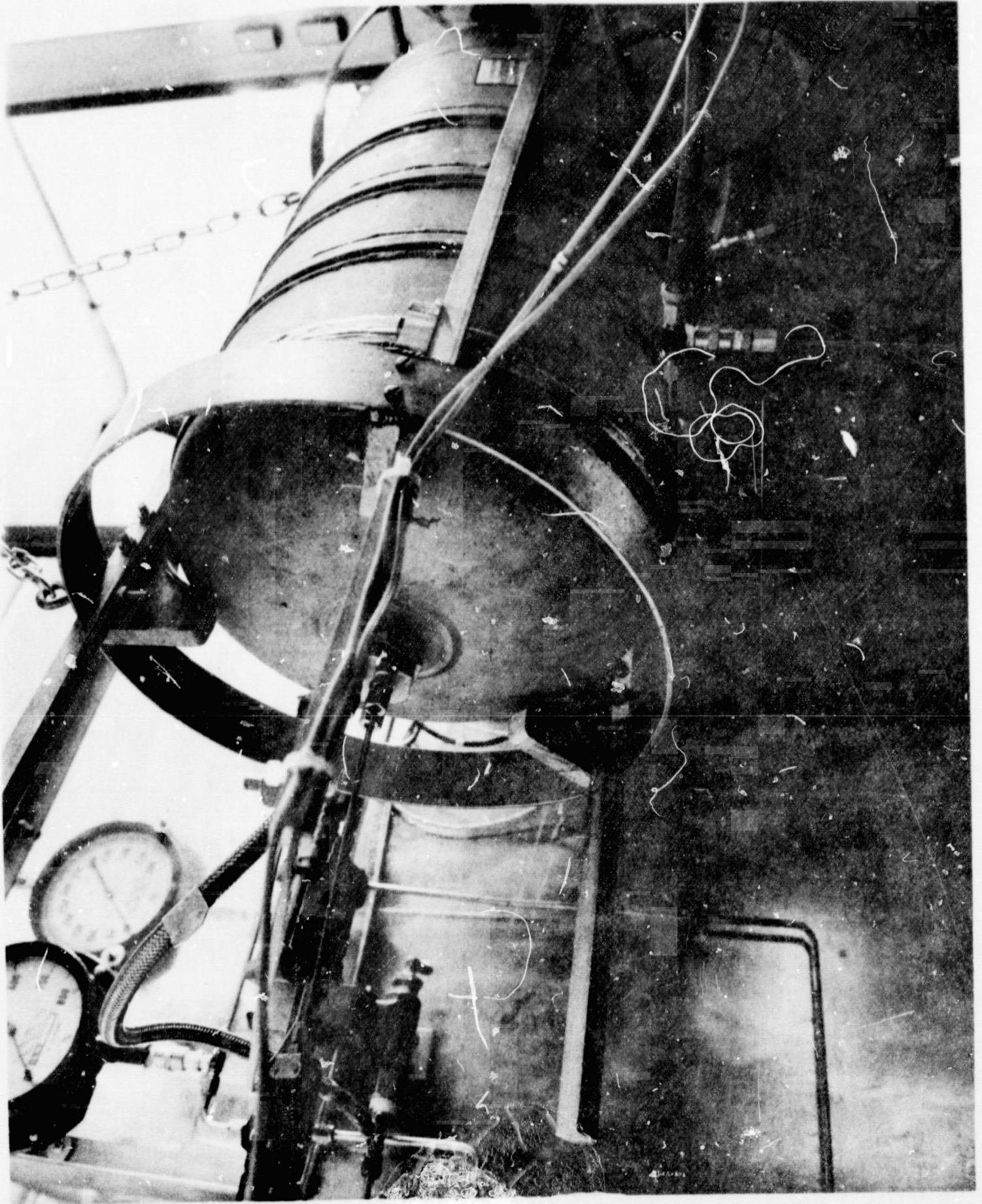


Figure 9-6 Tank Heat Exchanger Connections

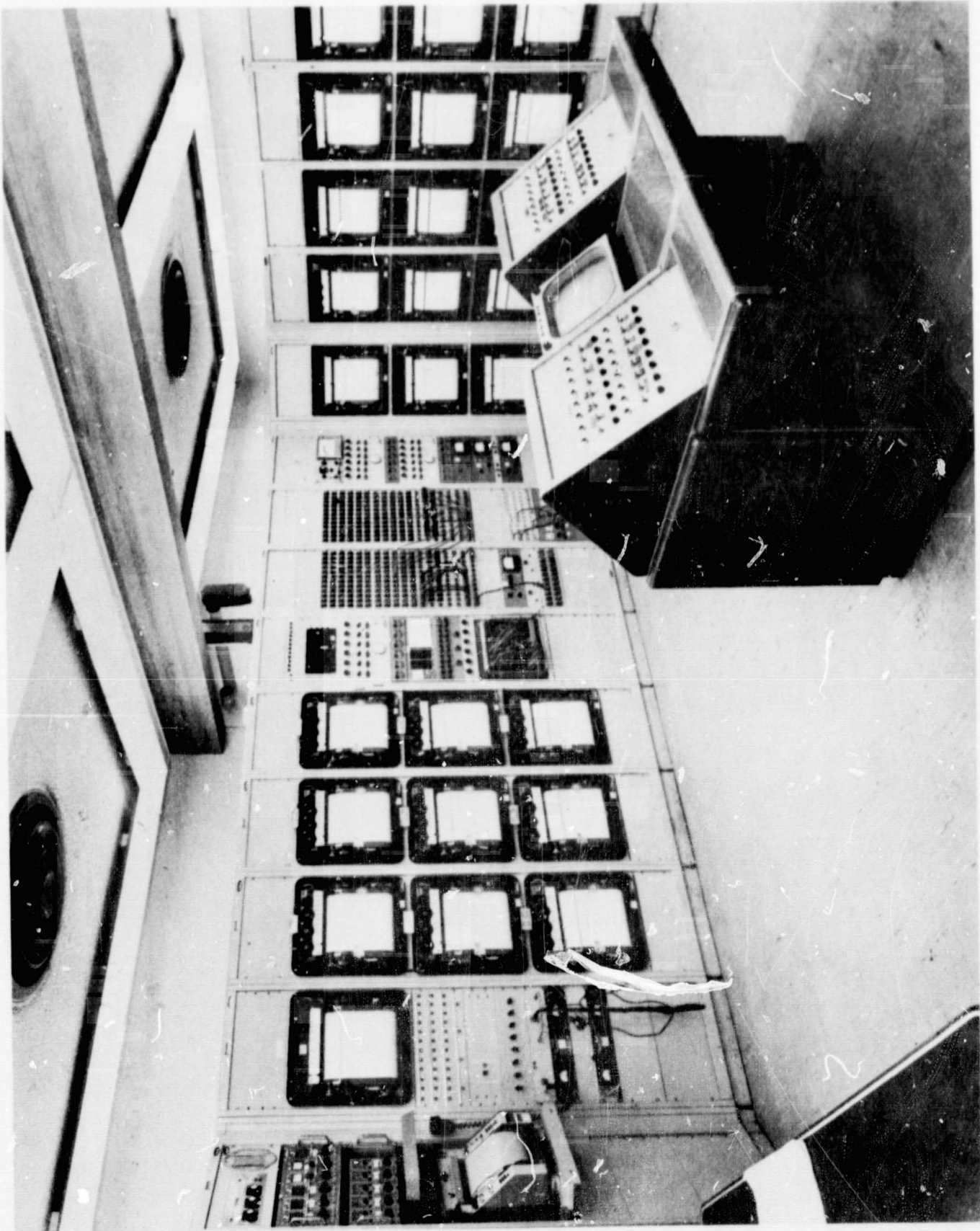


Figure 9-7 Data Acquisition Facility

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Table 9-2 Engine Testing Recorded Parameters

Parameter

<u>Pressures</u>	<u>Type of Record</u>	<u>Operating Range</u>	
		<u>System A</u>	<u>System B</u>
Pressurant Cavity Fuel Tank	Oscillograph and Gage	150-170 psig	250-350 psig
Propellant Cavity Fuel Tank	Oscillograph and Gage	150-170 psig	250-350 psig
Fuel Tank Differential Pressure	Readout Meter	± 25 psi	± 25 psi
Pressurant Cavity Oxidizer Tank	Oscillograph and Gage	150-170 psig	250-350 psig
Propellant Cavity Oxidizer Tank	Oscillograph and Gage	150-170 psig	250-350 psig
Oxidizer Tank Differential Pressure	Readout Meter	± 25 psi	± 25 psi
Fuel Inlet Pressure Engine No. 1	Oscillograph	140-170 psig	230-350 psig
Oxidizer Inlet Pressure Engine No. 2	Oscillograph	140-170 psig	230-350 psig
Fuel Inlet Pressure Engine No. 2	Oscillograph	140-170 psig	230-350 psig
Oxidizer Inlet Pressure Engine No. 2	Oscillograph	140-170 psig	230-350 psig
Fuel Supply Tank Pressure	Gage	0-170 psig	0-350 psig
Oxidizer Tank Pressure	Gage	0-170 psig	0-350 psig
Chamber Pressure Engine No. 1	Oscillograph and Meter	80-110 psig	80-110 psig
Chamber Pressure Engine No. 2	Oscillograph and Meter	80-110 psig	80-110 psig
<u>Flows</u>			
Heat Exchanger Fuel Tank	Oscillograph and Meter	20-40 cc/sec	20-40 cc/sec
Heat Exchanger Oxidizer Tank	Oscillograph and Meter	20-40 cc/sec	20-40 cc/sec
Fuel Engine No. 1	Oscillograph and Meter	0.111 lb/sec	0.111 lb/sec
Oxidizer Engine No. 1	Oscillograph and Meter	0.222 lb/sec	0.222 lb/sec
Fuel Engine No. 2	Oscillograph and Meter	0.111 lb/sec	0.111 lb/sec
Oxidizer Engine No. 2	Oscillograph and Meter	0.222 lb/sec	0.222 lb/sec

Table 9-2 (Cont'd)

<u>Temperatures</u>	<u>Type of Record</u>	<u>Operating Range</u>	
		<u>System A</u>	<u>System B</u>
Fuel in Propellant Tank	Strip Chart	85-95°F	85-105°F
Oxidizer in Propellant Tank	Strip Chart	85-95°F	85-105°F
Pressurant Liquid Fuel Tank	Strip Chart and Meter	85-95°F	85-105°F
Pressurant Vapor Fuel Tank	Oscillograph and Meter	85-95°F	85-105°F
Pressurant Liquid Oxidizer Tank	Strip Chart and Meter	85-95°F	85-105°F
Pressurant Vapor Oxidizer Tank	Oscillograph and Meter	85-95°F	85-105°F
Heat Exchanger Inlet Fuel Tank	Strip Chart	80-180°F	80-120°F
Heat Exchanger Outlet Fuel Tank	Strip Chart	80-170°F	80-120°F
Heat Exchanger Inlet Oxidizer Tank	Strip Chart	80-180°F	80-120°F
Heat Exchanger Outlet Oxidizer Tank	Strip Chart	80-170°F	80-120°F
Fuel Engine No. 1	Strip Chart	85-95°F	85-95°F
Oxidizer Engine No. 1	Strip Chart	85-95°F	85-95°F
Fuel Engine No. 2	Strip Chart	85-95°F	85-95°F
Oxidizer Engine No. 2	Strip Chart	85-95°F	85-95°F
Five Case Temperatures Engine No. 1	Strip Chart	0-600°F	0-600°F
Five Case Temperatures Engine No. 2	Strip Chart	0-600°F	0-600°F
<u>Miscellaneous</u>			
Fuel Tank Weight	Meter	0-170 lb	0-170 lb
Oxidizer Tank Weight	Meter	0-200 lb	0-200 lb
Engine Valve Current (4)	Oscillograph and Meter	0-1.0 amp	0-1.0 amp
Engine Valve Voltage (4)	Oscillograph	0-30 vdc	0-30 vdc

9.2 System B Auxiliary Propulsion System Tests

Because of the availability of engines, the System B tests were conducted first. The System B engine installation is shown in Figure 9-8. The propellant expulsion tanks are located back of the partition shown. Typical engine connections and location of various instrumentation parameters are shown in Figure 9-9.

The engines used were designed and fabricated by TRW for NASA to meet the requirements of the Apollo Command Module.

The engine is characterized by the following major components:

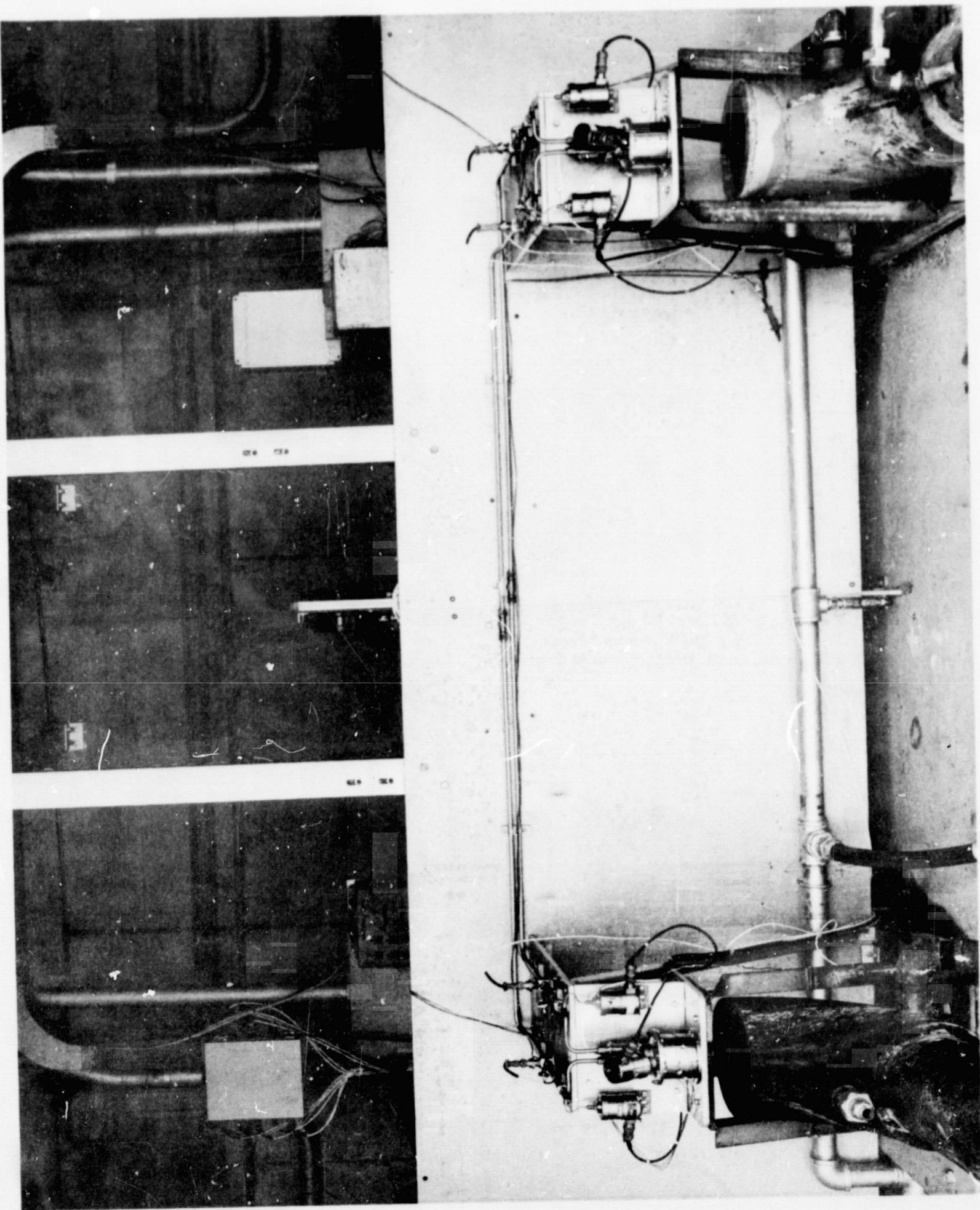
- A capillary tube injector having an injection pattern consisting of eight doublets.
- A silica-phenolic ablative chamber liner with an integrally wrapped tantalum-10 tungsten throat insert having a Durak "MGF" oxidation resistant coating.
- A normally closed bipropellant solenoid valve furnished by Moog Inc.

The major components comprising the engine assembly are shown in Figure 9-10.

In an attempt to improve the performance of System B it was decided to increase the amount of Genetron 32 and Eicosane in the pressurant cavity so that the initial vapor volume would be decreased. The lower initial vapor volume was expected to provide a more rapid temperature decay to initiate early Eicosane freezing. It was decided to reduce the initial vapor volume to 5 percent* of the total tank volume. Figure 9-11 indicates the relationship between Eicosane and Genetron weights required for

*An ullage volume comparable to that used in previous tests conducted by NASA using command module tanks.

Figure 9-8 System B Test Setup



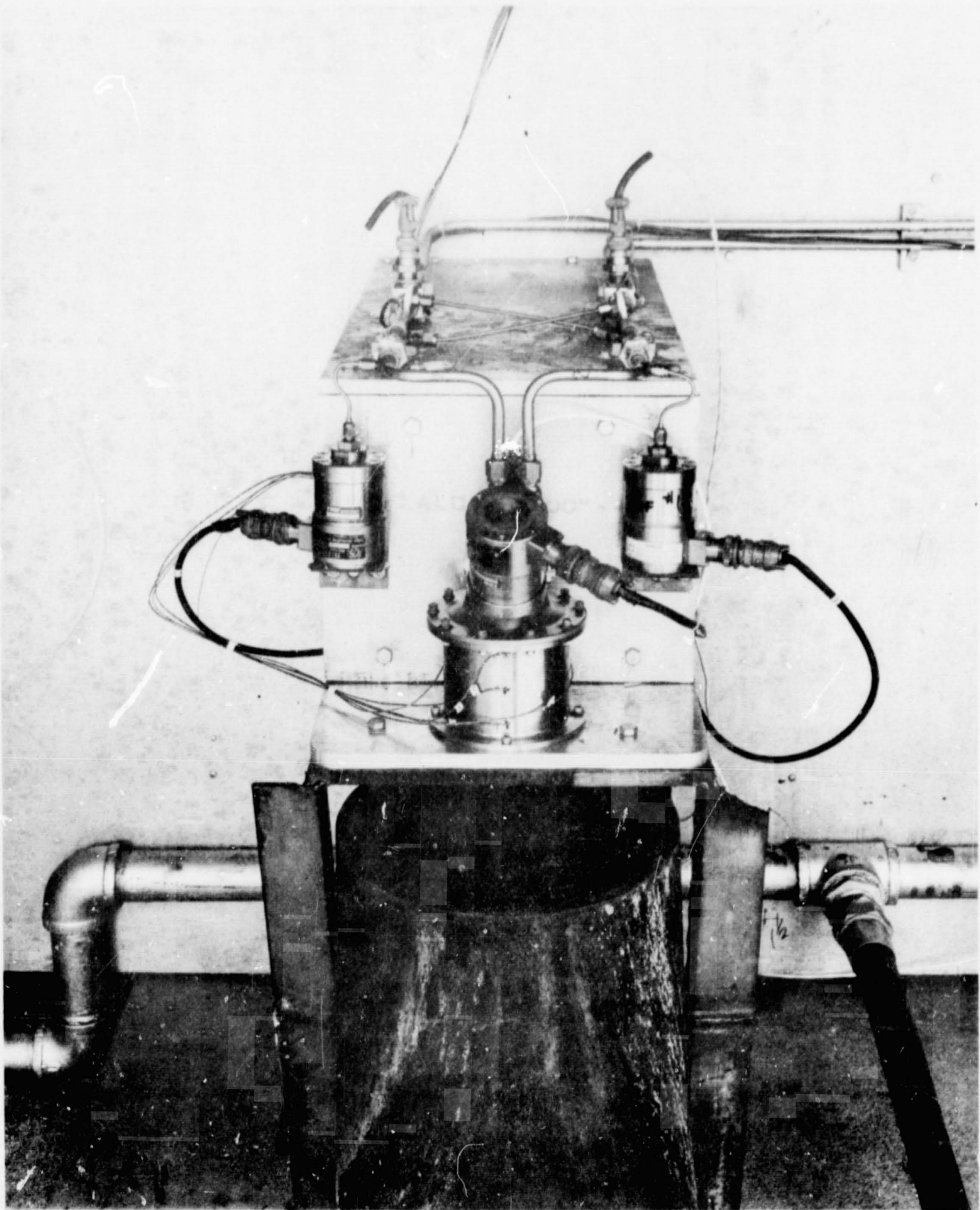


Figure 9-9 System B Engine Connections



Figure 9-10 Components of System B Engine Assembly - Side View

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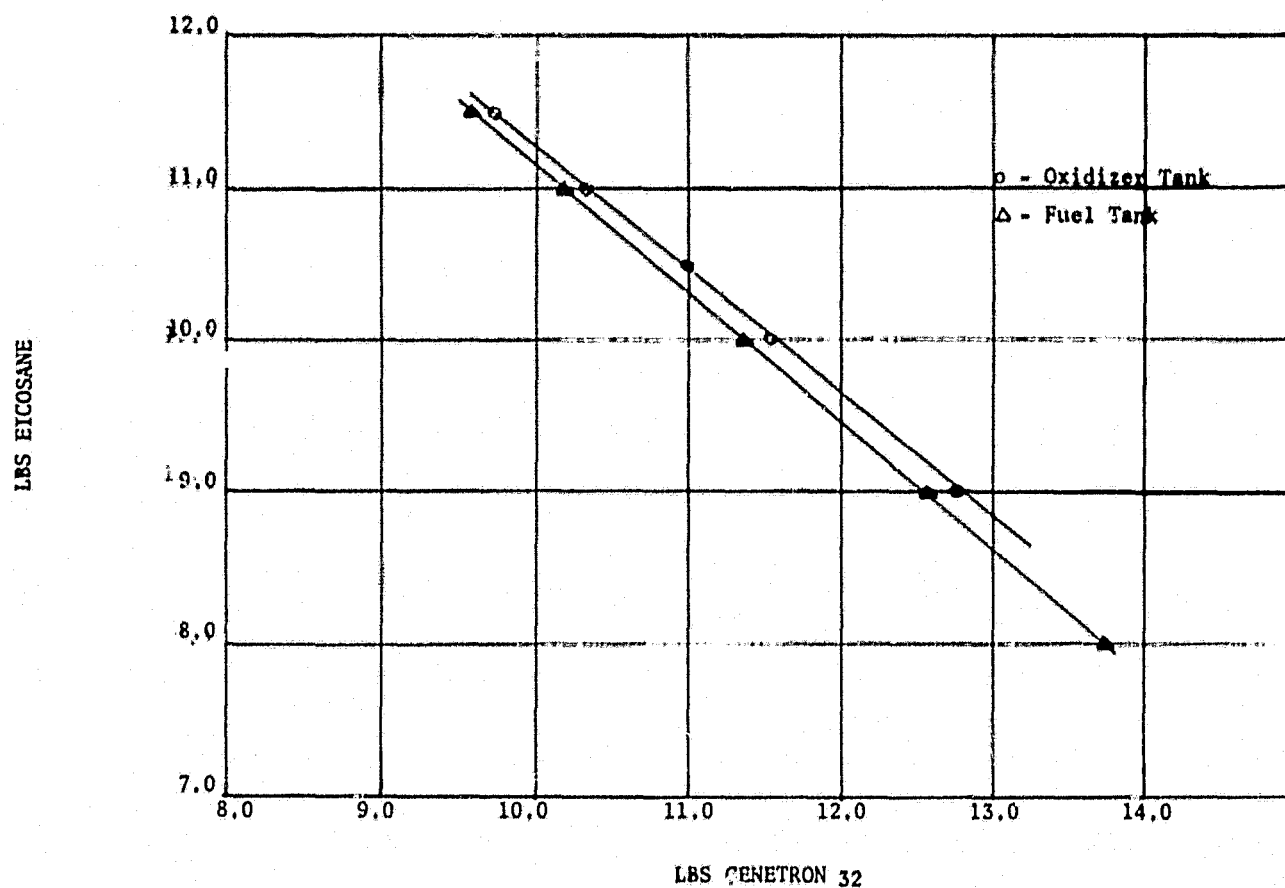


Figure 9-11 Pressurant Cavity Loading for Initial Vapor Volume = .05 Tank Volume

this condition. An Eicosane weight of 9.5 pounds was selected and resulted in the loading conditions shown in Table 9-3. A series of engine checkout runs was made using the facility tanks to provide a basis for measuring performance during the system tests. Two system tests were conducted. The two engines were individually controlled at different duty cycles to provide a variety of flow conditions. The run duty cycles are summarized in Table 9-4.

The system was loaded and tests conducted in accordance with the established test procedures. The engine runs resulted in calculated quality pressurant changes as shown in Table 9-5.

During the second system test, the throat in the engine subjected to the engine No. 1 duty cycle evidenced burn through by extensive spark ejections. This engine was shut down after 187 seconds in run No. 2. The failure was apparently caused by hot gas leakage behind the throat insert resulting in a local hot spot and throat burn through. At the time this failure occurred the engine had accumulated a total of 360 seconds of firing time. This compares favorably with the design life of the engine which is 300 seconds minimum firing time.

Table 9-3 System B Test Loading Conditions

		<u>Oxidizer Tank</u>	<u>Fuel Tank</u>
N ₂ O ₄	(1b)	90.0	-
MMH	(1b)	-	44.0
Genetron 32	(1b)	12.25	12.0
Eicosane	(1b)	9.5	9.5
Initial Genetron Quality (%)		2.0	1.7

Table 9-4 System B Test Duty Cycle

ENGINE CHECKOUT RUNS (BOTH ENGINES)

<u>Run No.</u>	<u>Number of Pulses</u>	<u>Pulse Width (sec)</u>	<u>Oxidizer Supply Pressure (psig)</u>	<u>Fuel Supply Pressure (psig)</u>
C-001	1	3.0	280	280
C-002	1	3.0	260	260
C-003	1	Engine #1 5.0	260	260
		Engine #2 3.0*		

*Firing of Engine No. 2 to lag Engine No. 1 by 3.0 sec.

SYSTEM TESTS

<u>Run No.</u>	<u>Engine No.</u>	<u>Start Time (sec)</u>	<u>No. of Pulses</u>	<u>Pulse Width (sec)</u>	<u>Pulse Period (sec)</u>	<u>Accumulated On-Time (sec)</u>	<u>End of Last Pulse (sec)</u>
B-001	1	0	9	20	35	180	300
B-001	2	0	6	30	50	180	280
B-002	1	0	9	30	40	270	350
B-002	2	0	12	10	30	120	340

Table 9-5 Expected Pressurant Change During System B Testing

	<u>Run B-001</u>	<u>Run B-002</u>
Oxidizer Tank		
N ₂ O ₄ Flow (lb)	80.0	86.6
Propellant Usage (%)	89.0	95.3
Pressurant Initial Quality (%)	2.0	2.0
Pressurant Final Quality (%)	26.7	28.6
Fuel Tank		
MMH Flow (lb)	40.0	43.3
Propellant Usage (%)	91.0	98.5
Pressurant Initial Quality (%)	1.7	1.7
Pressurant Final Quality (%)	22.6	24.4

As can be seen from the performance curves of the two runs, Figures 9-12 and 9-13, initiation of Eicosane freezing occurred on the initial pulse. In one case, this occurred as early as 2.7 seconds. However, as indicated during the pressurization system testing, when operating in a pulsing mode the vapor expansion providing the temperature differential to initiate Eicosane freezing disappears on shutdown. In a nonflow condition the volatile liquid tends to stabilize and the vapor temperature increases. Because of the increasing gas volume it becomes more and more difficult to obtain an adequate temperature drop. As shown in the performance curves there is no definite indication of Eicosane operation beyond the second period of no propellant flow. Pressure is primarily controlled by self vaporization of the Genetron 32. The results of these tests verified the conclusions made during the earlier cold flow tests that the most effective use of a heat storage material is limited to a continuous flow mode of operation.

Very good overall system performance was achieved, however, even with the limited Eicosane heat input. In one run the overall pressure decay from the initial pressure plateau was approximately 35 psi. In the other run the decay was only 20 psi but part of the reduction is attributable to

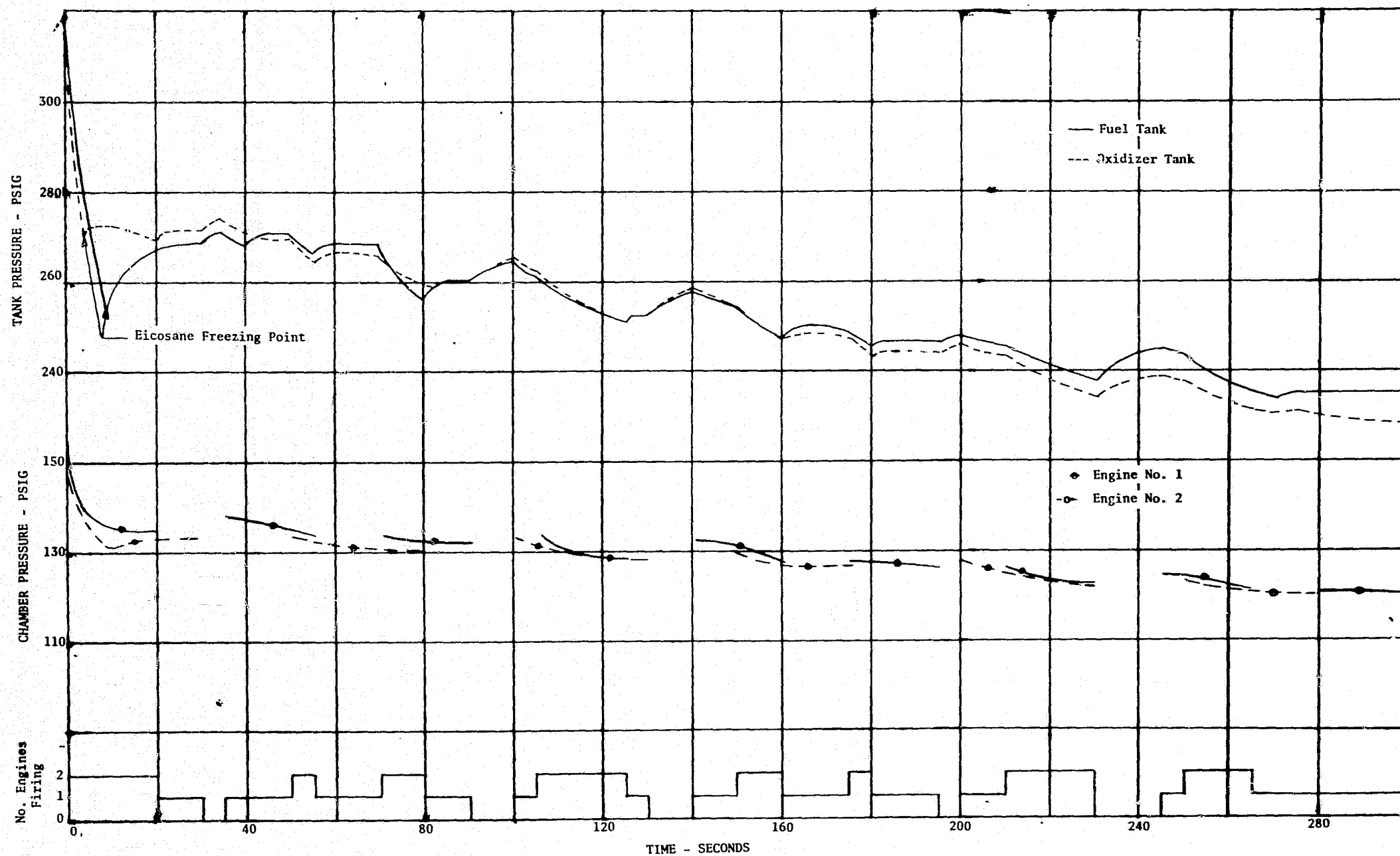


Figure 9-12 Operating Performance System B Test B-001 .

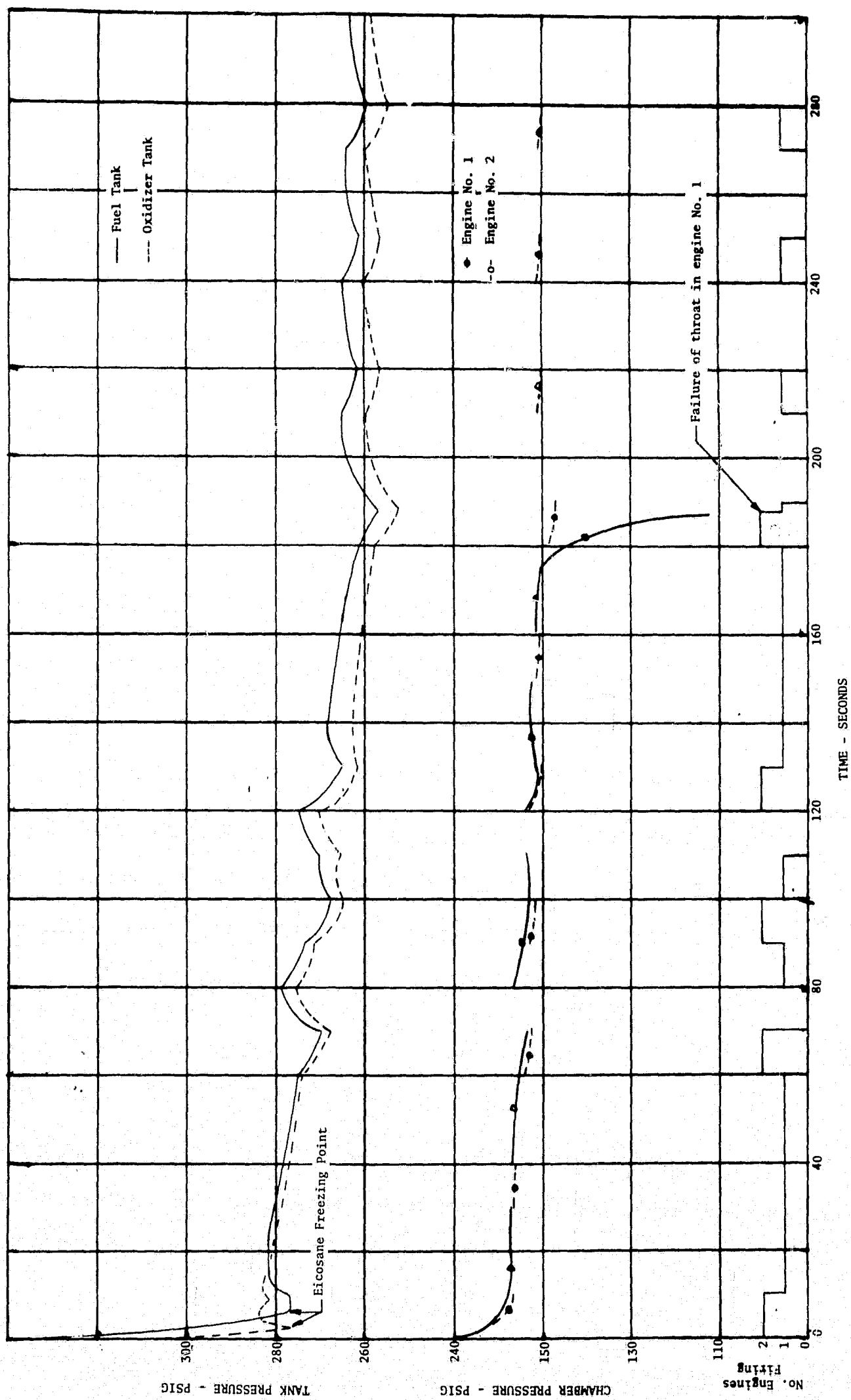


Figure 9-13 Operating Performance System B Test B-002

the fact that only one engine was firing during the latter part of the test. However, in spite of the magnitude of the decay, excellent relative tank pressure levels, which are more important in a bipropellant system, were achieved. The tank pressure levels were maintained within a maximum of 5 psi of each other for nearly the entire run.

The relative tank pressure decay was reflected in the engine chamber pressures which decayed by an equivalent percent.

Operation of the engines was very smooth as shown in a typical oscillograph trace Figure 9-14. The temperature profile of the engines is shown in Figures 9-15 and 9-16.

9.3 System A Auxiliary Propulsion System Tests

The test stand was modified to allow conduct of the System A tests. The two engines supplied by NASA for use in this test were flight configuration Apollo Service Module engines manufactured by the Marquardt Corporation.

The two Marquardt engines were installed as shown in Figure 9-17. Typical engine connections are indicated in Figure 9-18. During removal of the Eicosane from the fuel tank after the System B tests it was noted that the lower nylon guide button on the aft ring of the bellows capsule was bent over. To avoid any problems during the System A tests, the fuel tank was reoriented 180 degrees relocating the heat exchanger inlet and the damaged button on the top of the tank. This allowed the bellows to ride on a different pair of nylon guide buttons during cycling. The reoriented tank with insulation installed is shown in Figure 9-19.

Because the Apollo engines are capable of operation with either Aerozine-50 or MMH as the fuel, it was decided to conduct the System A tests using MMH. This minimized the amount of cleaning required in changing from System B to System A tests.

ENGINE NO. 1 VALVE FIRE SIGNAL

0.20 SEC

PC-2

PC-1
132.5 PSI

20 PSI
(TYP)

P_{OX-1}

P_{FUEL-2}

P_{OX-1}

P_{FUEL-1}

FOLDOUT FRAME /

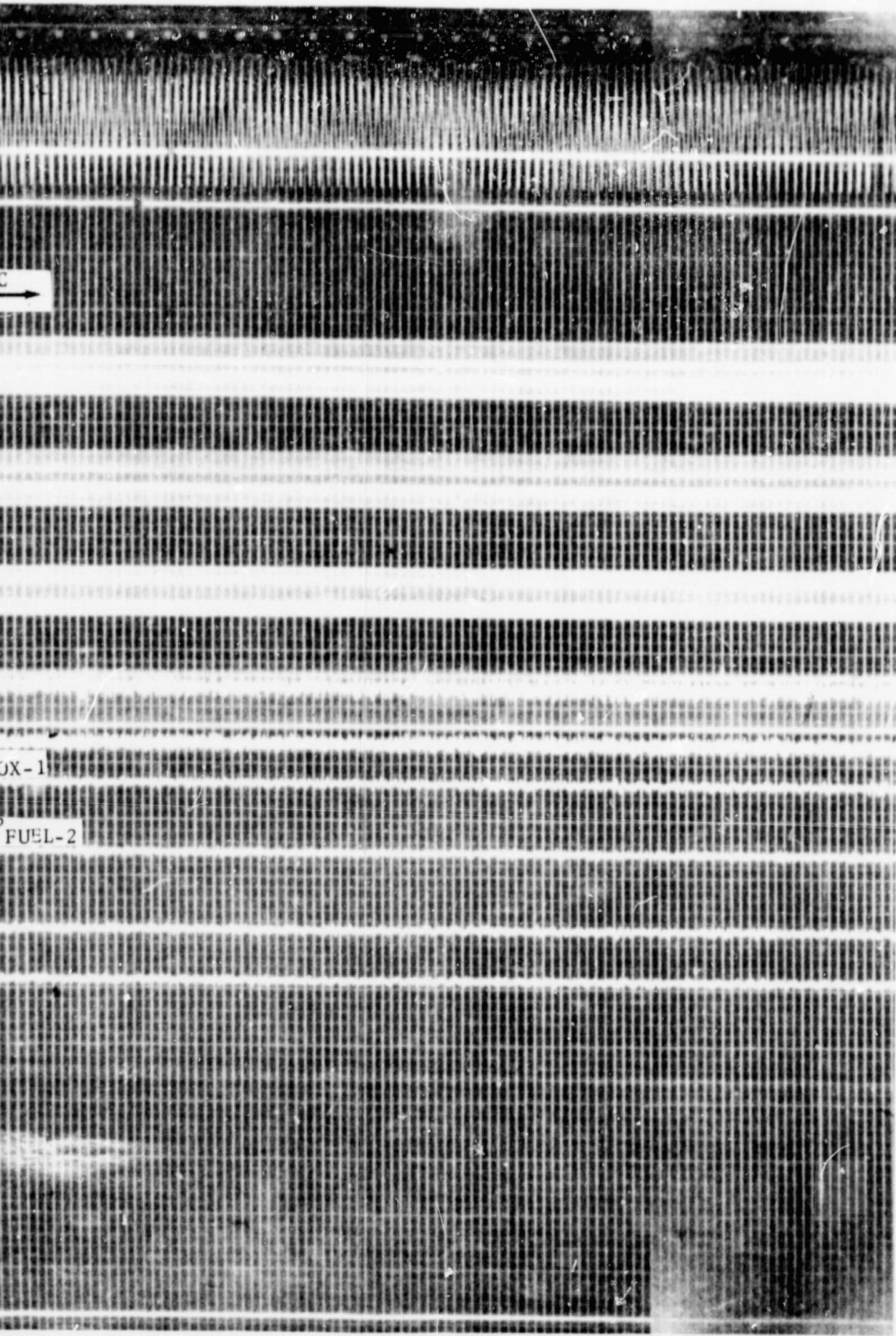


Figure 9-14 Engine Oscillograph Trace System B Run B-001

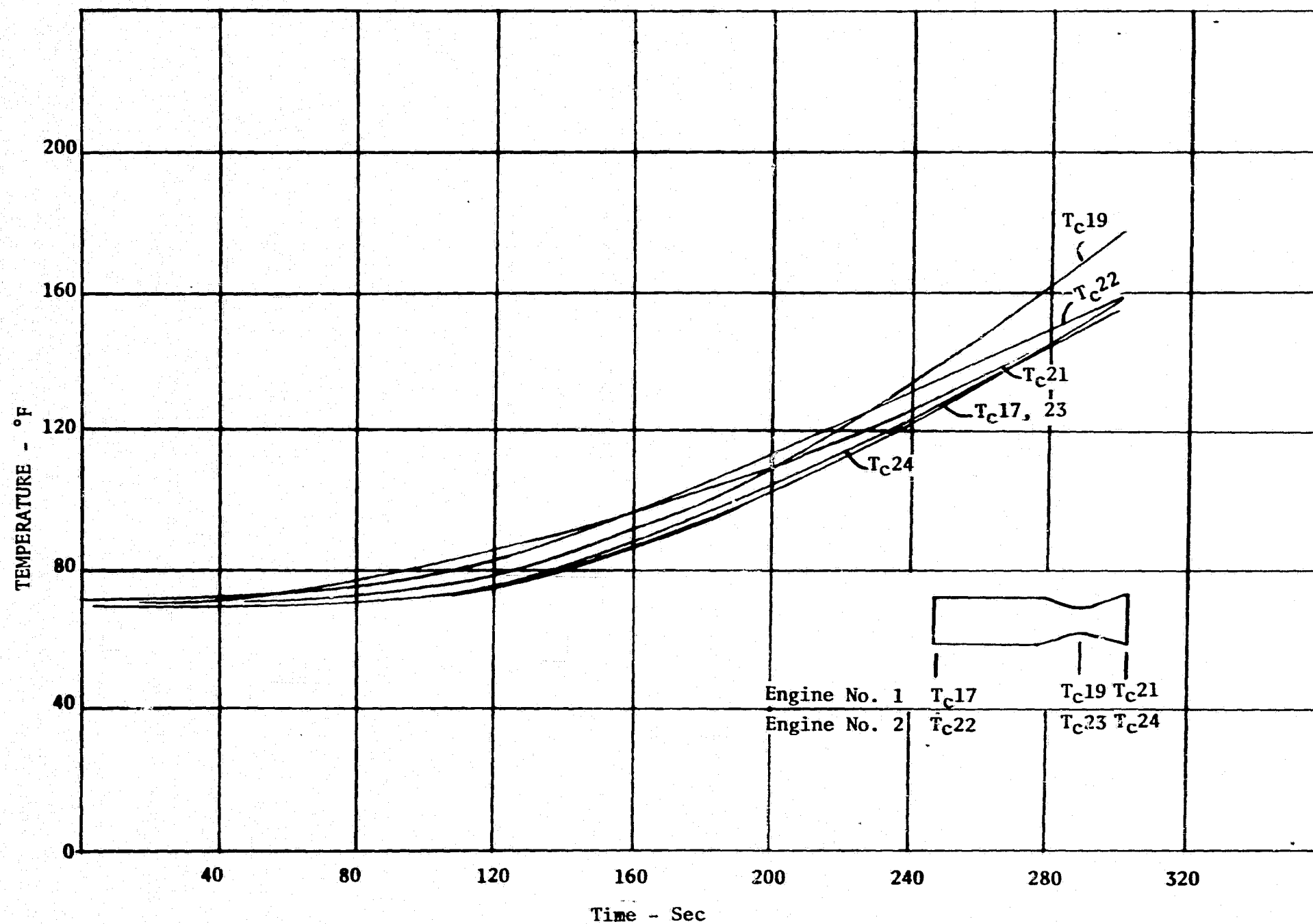


Figure 9-15 Engine Case Temperatures Run B-001

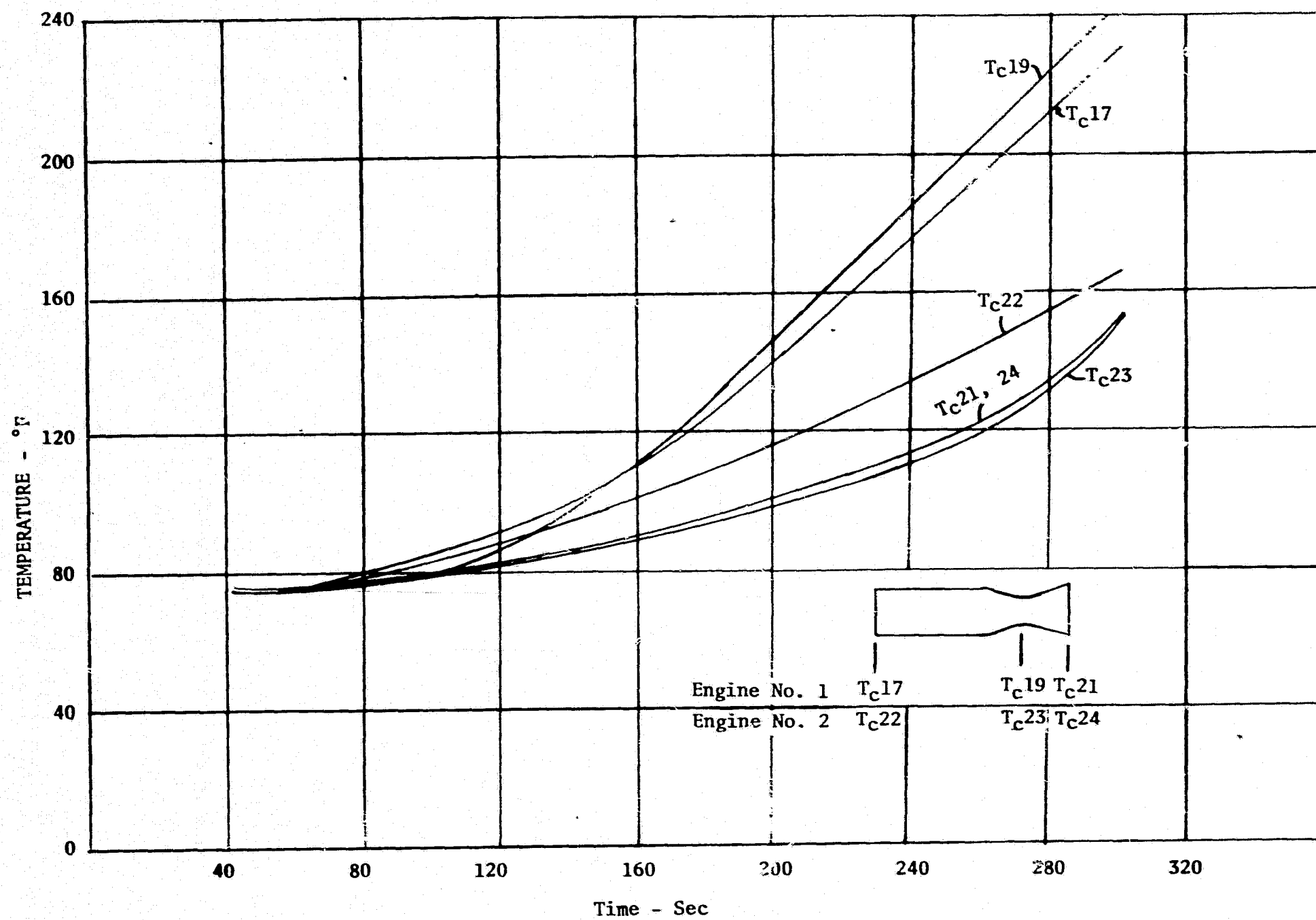


Figure 9-16 Engine Case Temperature Run B-002

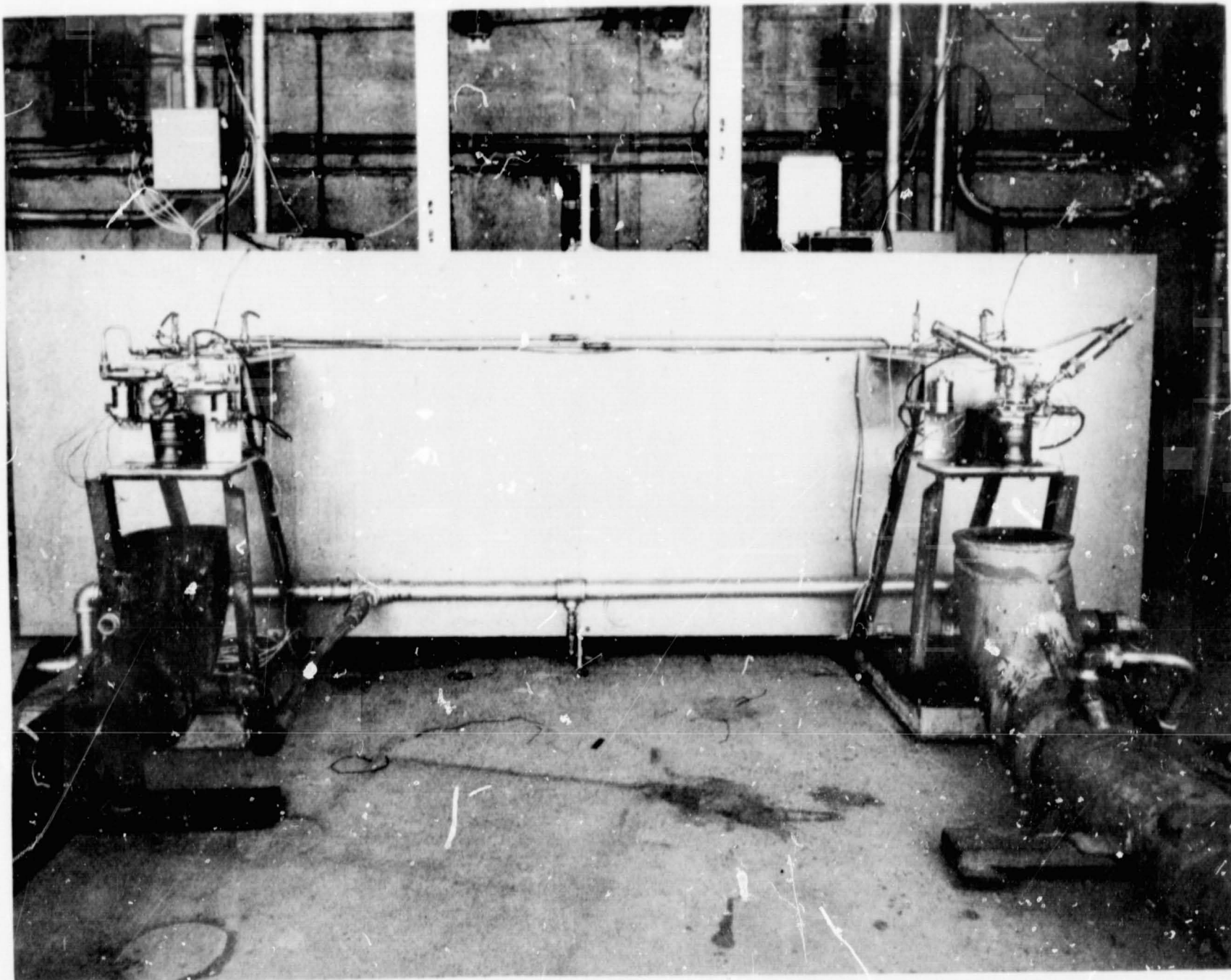


Figure 9-17 System A Test Setup

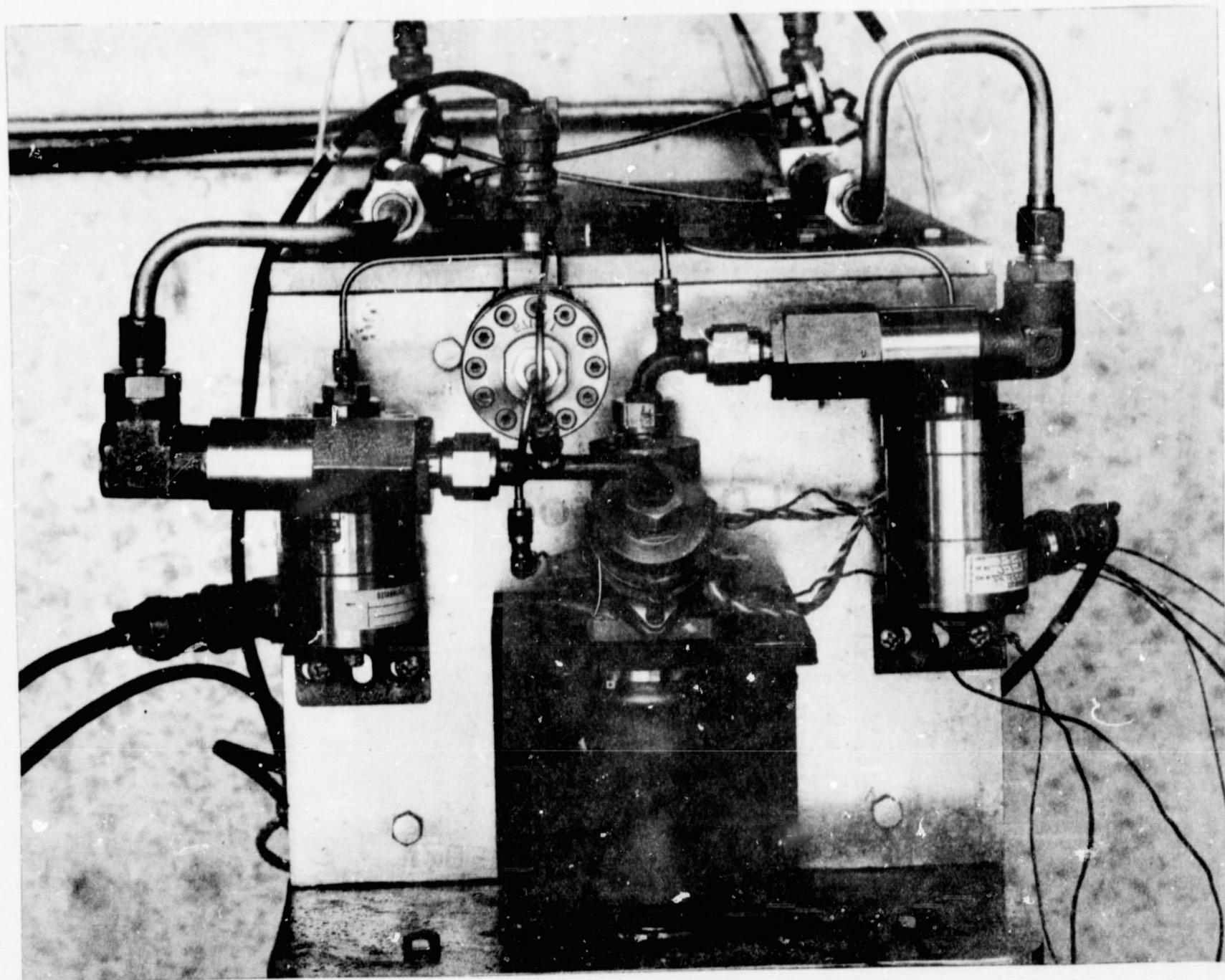


Figure 9-18 System A Engine Connections

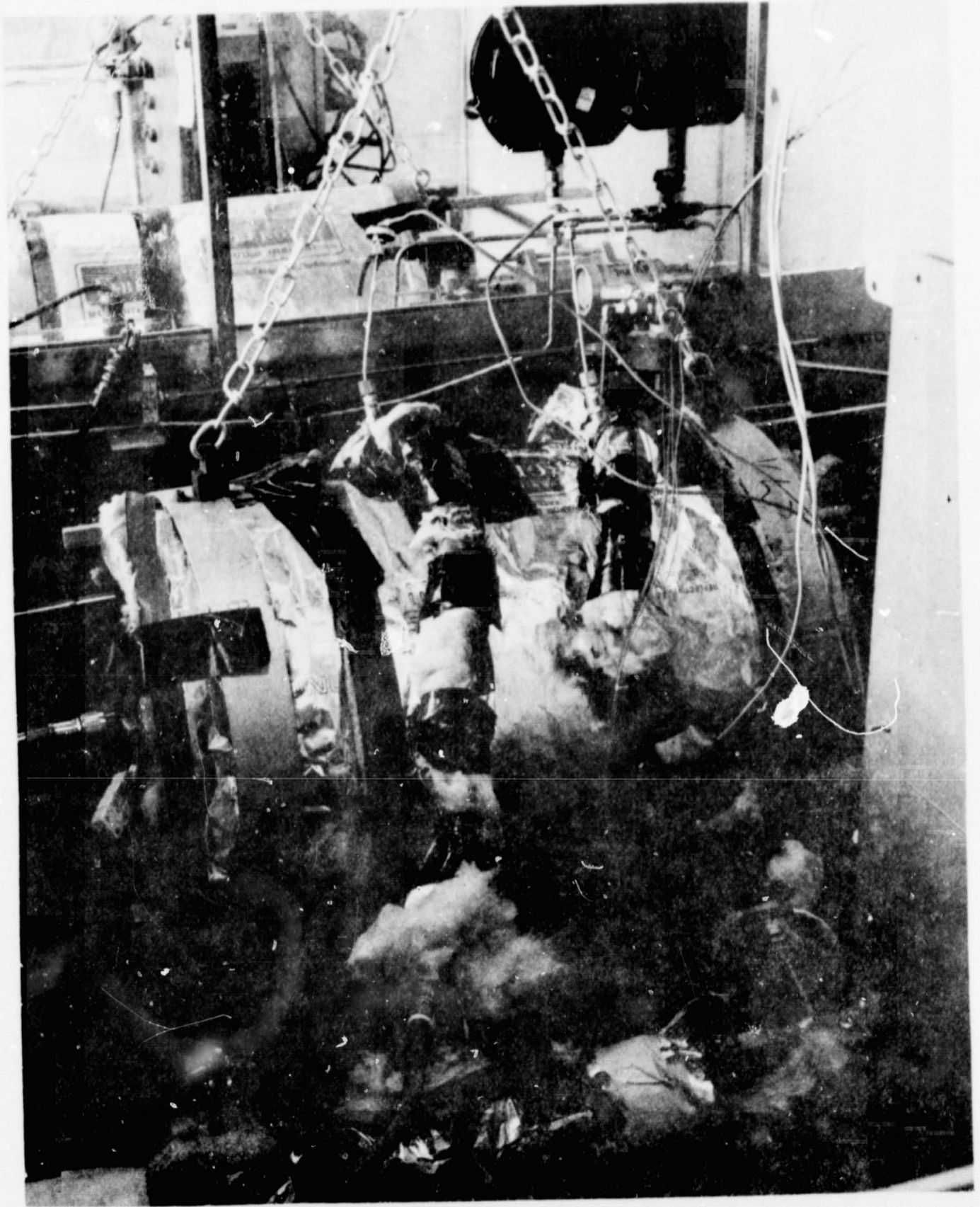


Figure 9-19 Reorientation of Fuel Tank for System A Tests

The pressurant and propellant loading conditions summarized in Table 9-6 are similar to those used during the propellant expulsion testing conducted during the pressurization system tests. In conducting the two system tests, the engine duty cycles were coordinated with NASA to assure compatibility with the limitations of the engines. The engine checkout run cycle conditions used are summarized in Table 9-7, and the system tests in Table 9-8. The calculated resulting pressurant changes in the system tests are given in Table 9-9.

Table 9-6 System A Test Loading Conditions

<u>Run No.</u>	<u>Oxidizer Tank</u>		<u>Fuel Tank</u>	
	<u>A-001</u>	<u>A-002</u>	<u>A-001</u>	<u>A-002</u>
N ₂ O ₄ (lb)	89.90	90.40	-	-
MMH (lb)	-	-	44.15	44.18
Freon 22 (lb)	5.26	5.26	4.54	4.54

The system was loaded and the tests conducted in accordance with the established test procedures. During both runs, the volatile liquid system performed extremely well. The heat exchanger experienced no difficulty in maintaining operating pressure at duty cycles below 50 percent. During the maximum duty cycle tested, 80 percent on one engine and 50 percent on the other, a slight, approximately 5 psi, pressure drop was experienced in tank pressure over the 60 second operating time at this duty cycle.

As expected, the use of the electronic switches to obtain a closer deadband on heat exchanger flow resulted in considerable improvement in system performance.

Table 9-7 System A Engine Checkout Runs

<u>Run No.</u>	<u>Engine No.</u>	<u>Start Time (sec)</u>	<u>No. Of Pulses</u>	<u>Pulse Width (sec)</u>	<u>Pulse Period (sec)</u>	<u>Oxidizer Supply Pressure (psig)</u>	<u>Fuel Supply Pressure (psig)</u>
C-004	1	0	12	0.1	0.5	165	165
	2	0	2	1.0	5.0	165	165
C-005	1	0	8	0.5	1.0	165	165
	2	0	2	2.5	5.0	165	165
C-006	1	0	5	1.0	3.0	165	165
	2	0	2	5	10	165	165

Table 9-8 System A Test Duty Cycle

Test No. A-001

<u>Cycle No.</u>	<u>Engine No.</u>	<u>Start Time (sec)</u>	<u>No. Of Pulses</u>	<u>Pulse Width (sec)</u>	<u>Pulse Period (sec)</u>	<u>On-Time (sec)</u>	<u>Accumulated On-Time (sec)</u>	<u>End Of Last Pulse (sec)</u>	<u>Off Time (sec)</u>
1	1	0	240	0.10	0.25	24.0	24.0	59.85	36.0
	2	0	12	1.00	5.00	12.0	12.0	56.00	48.0
2	1	120	480	0.10	0.25	48.0	72.0	239.90	72.0
	2	120	24	2.50	5.00	60.0	72.0	237.50	60.0
3	1	300	240	0.10	0.50	24.0	96.0	419.60	96.0
	2	300	12	2.50	10.00	30.0	102.0	412.50	90.0
4	1	720	120	0.10	2.00	12.0	108.0	958.10	228.0
	2	720	24	1.00	10.00	24.0	126.0	951.00	216.0
5	1	1020	120	0.50	1.00	60.0	168.0	1139.5	60.0
	2	1020	12	5.00	10.00	60.0	186.0	1135.0	60.0

Test No. A-002

1	1	0	20	1.00	3.00	20.0	20.0	57.0	40.0
	2	0	4	5.00	15.00	20.0	20.0	50.0	40.0
2	1	120	20	1.00	3.00	20.0	40.0	177.0	40.0
	2	120	4	5.00	15.00	20.0	40.0	170.0	40.0
3	1	190	120	0.10	1.00	12.0	52.0	309.1	108
	2	190	12	1.00	10.00	12.0	52.0	301.0	108
4	1	370	30	1.00	2.00	30.0	82.0	429.0	30.0
	2	370	6	8.00	10.00	48.0	100.0	427.0	12.0
5	1	440	60	0.025	0.25	6.0	88.0	449.1	54
	2	440	6	1.00	10.00	6.0	106.0	491.0	54
6	1	840	120	0.10	1.00	12.0	100.0	959.1	108
	2	840	12	1.00	10.00	12.0	118.0	951.0	108
7	1	1020	30	1.00	2.00	30.0	130.0	1079.0	30.0
	2	1020	6	8.00	10.00	48.0	166.0	1077.0	12.0
8	1	1140	300	0.10	1.00	30.0	160.0	1439.1	270
	2	1140	30	1.00	10.00	30.0	196.0	1431.0	270

Table 9-9 Calculated Pressurant Quality Change During System A Testing

	<u>Run A-001</u>	<u>Run A-002</u>
Oxidizer Tank		
N ₂ O ₄ Flow (lb)	84.7	85.1
Propellant Usage (%)	94.2	94.1
Pressurant Initial Quality (%)	28.6	28.2
Pressurant Final Quality (%)	92.0	91.8
Fuel Tank		
MMH Flow (lb)	42.4	44.1
Propellant Usage (%)	94.1	99.8
Pressurant Initial Quality (%)	32.0	31.9
Pressurant Final Quality (%)	89.3	89.5

It was originally intended to adjust the electronic switches to control the water glycol flow initiation on decay of the tank pressure to 165 psig, with the deadband for each tank set at approximately 1.5 psi. Through error, however, the actual operating conditions set by the switches are shown in Table 9-10. The effect of the lower deadband (<1 psi) was higher cycling of heat exchanger operation and narrower total pressure variation. In a system application, the minimum operational deadband may be limited by cycle life of the heat control system.

Table 9-10 Operating Pressure Levels for System A Heat Exchanger

	<u>Oxidizer Tank</u>	<u>Fuel Tank</u>
Heat Exchanger Flow initiated - psig	167.7	168.9
Heat Exchanger Flow terminated - psig	168.0	169.4
Switch Deadband - psi	0.3	0.5

Throughout both runs the engine cycling had little, if any, effect on the volatile liquid pressurization system operation. Typical oscillograph traces indicating engine operation and the magnitude of pressure surge oscillation resulting from valve closure are shown in Figures 9-20 through 9-22. The three figures show the variance in magnitude of the dynamic loads at various engine duty cycles. It can be noted that the influence of engine operation is greatly reduced when the second engine is firing. The transmission of these inputs to the propellant tanks as well as typical heat exchanger operation are shown in the oscillograph traces in Figure 9-23.

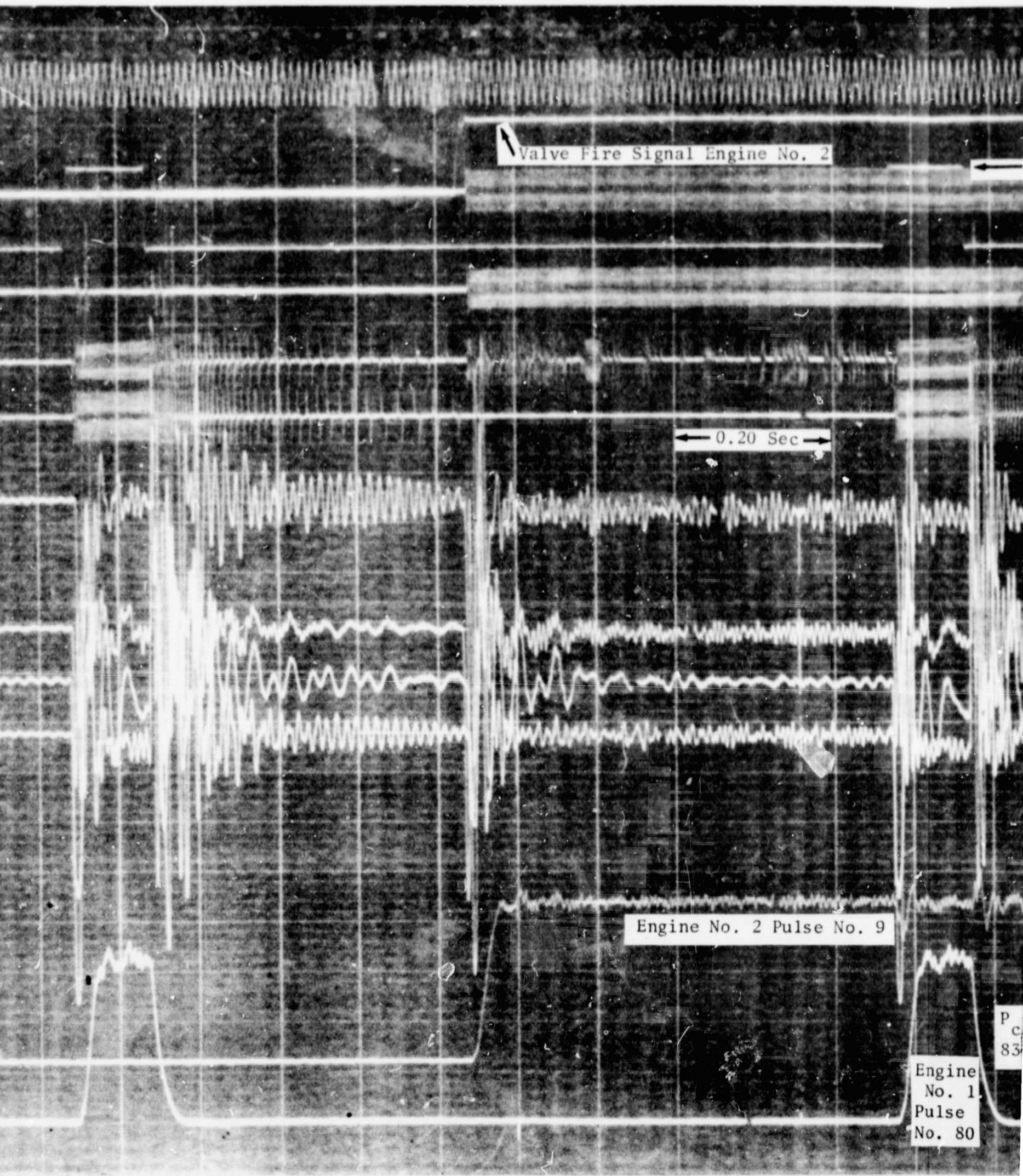
During the two tests the reaction of the two heat input systems was slightly different in the mode of heat exchanger flow. On the fuel tank the heat exchanger flow cycled satisfactorily showing well defined initiation and termination of flow. In general, the fuel heat exchanger operated in conjunction with multiples of the frequency of firing of engine No. 2. On the oxidizer tank, however, this only occurred during cycles in which the pulse width on engine No. 1 was greater than 0.10 second. At all other times the oxidizer tank heat exchanger flow was a series of very short duration pulses as shown in Figure 9-24. This condition occurred over engine duty cycles varying from 7 to 45 percent. This action apparently was the result of a combination of factors. The heat exchanger valves were a commercial three-way valves not designed for fast operation. Because of the short duration pulsing, the magnitude of pressure decay per pulse and the average rate of pressure decay were small. As the pressure level approached the actuation point, the electronic switch only partially closed and allowed a low level of current to flow, cracking the bypass valve. The trickle of heat exchanger fluid flow was sufficient to allow the pressure level to increase slightly, opening the switch and closing the valve. As the pressure change was very small the cycle was repeated with engine pulsing. In relation to overall system performance, however, there were no adverse effects from the two modes of operation as shown in Figures 9-25 and 9-26. The heat exchanger usage, in relation to propellant flow rate, compared very favorably in the two test tanks as shown in Table 9-11.

Table 9-11 Heat Exchanger Usage - System A Tests

Run	Cycle	Engine Usage (%)	Fuel Tank		Oxidizer Tank		Heat Exchanger Operations	Average Time/ Operation (sec)	Accumulated on Time (sec)	Usage (%)
			Heat Exchanger Operations	Average Time/ Operation (sec)	Accumulated on Time (sec)	Usage (%)				
A-001	1	28.7	7	1.8**	19.9	33.4	*	*	20.0	33.6
	2	42.8	22	2.6**	66.2	55.2	*	*	62.2	51.8
	3	22.5	10	2.3**	28.5	23.8	*	*	27.9	23.4
	4	7.5	4	4.5	18.1	7.5	*	*	16.4	6.8
	5	50.2	1	-	127.4	106.5	10	5.9**	78.9	66.0
A-002	1	34.0	3	6.8**	30.2	53.1	4	3.7**	24.1	42.4
	2	33.7	4	7.0	28.0	49.1	4	4.6	18.4	32.4
	3	10.1	4	3.6	13.9	11.7	*	*	6.9	5.8
	4	61.7	1	-	66.2	105.3	4	6.5**	50.3	80.1
	5	9.9	3	-	3.7	6.2	*	*	2.9	4.9
	6	10.2	1	3.9**	16.6	13.7	*	*	16.0	13.2
	7	63.7	-	-	75.9	125.5	1	-	57.2	94.7
	8	10.2	-	4.6	36.7	12.3	*	*	38.3	12.8

*Intermittant or irregular flow.

**The initial heat exchanger operation in the cycle was omitted in determining the average stable operation time. This initial flow was from three to five times the duration of the balance of the operations in the cycle in order to raise the tank wall temperature to the operating level.



FOLOUT FRAME

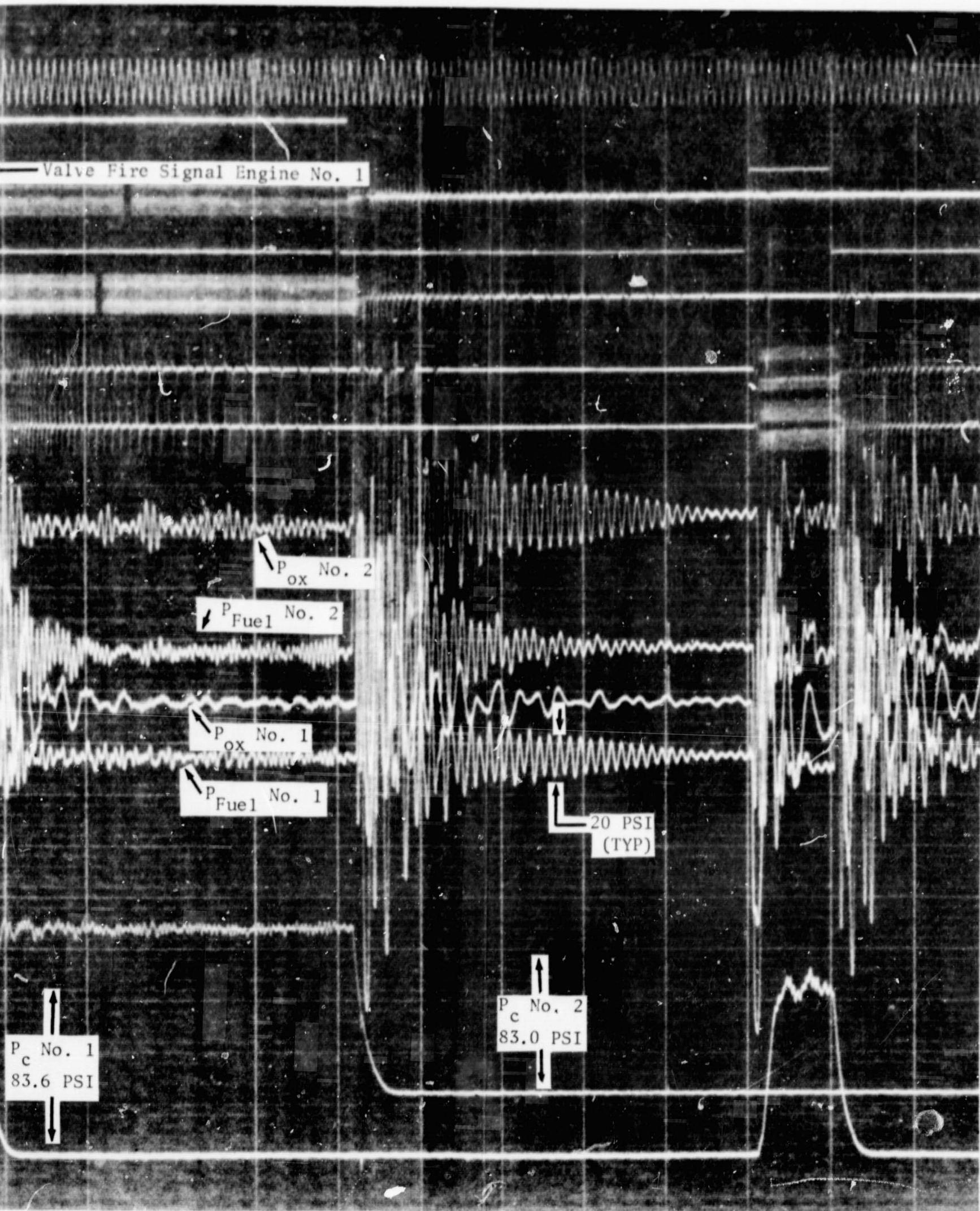
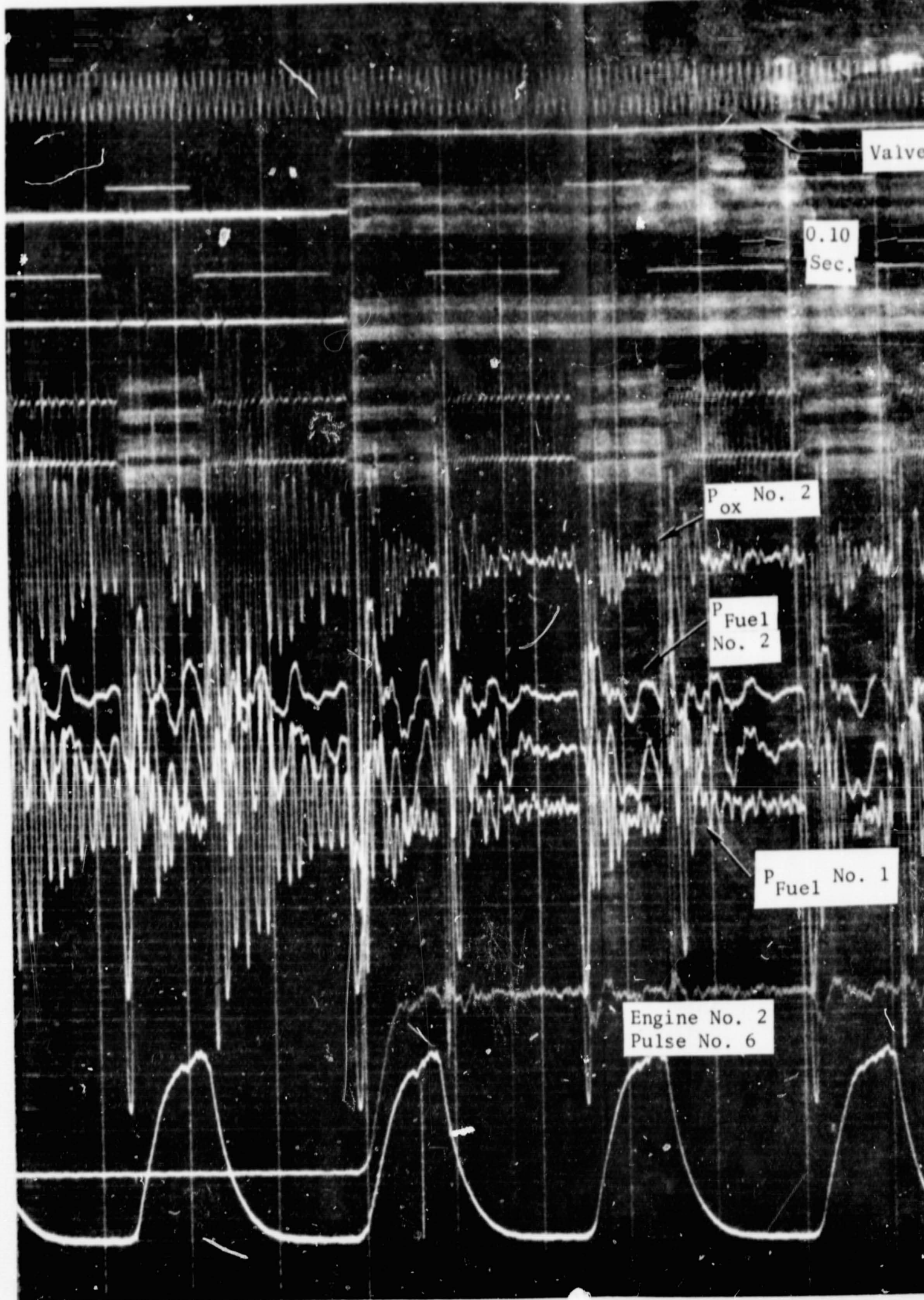


Figure 9-20 Engine Oscillograph Trace - 10 Percent Duty Cycle, Run A-002 Cycle 3

FOLDOUT FRAME

2



FOUR OUT FRAME /

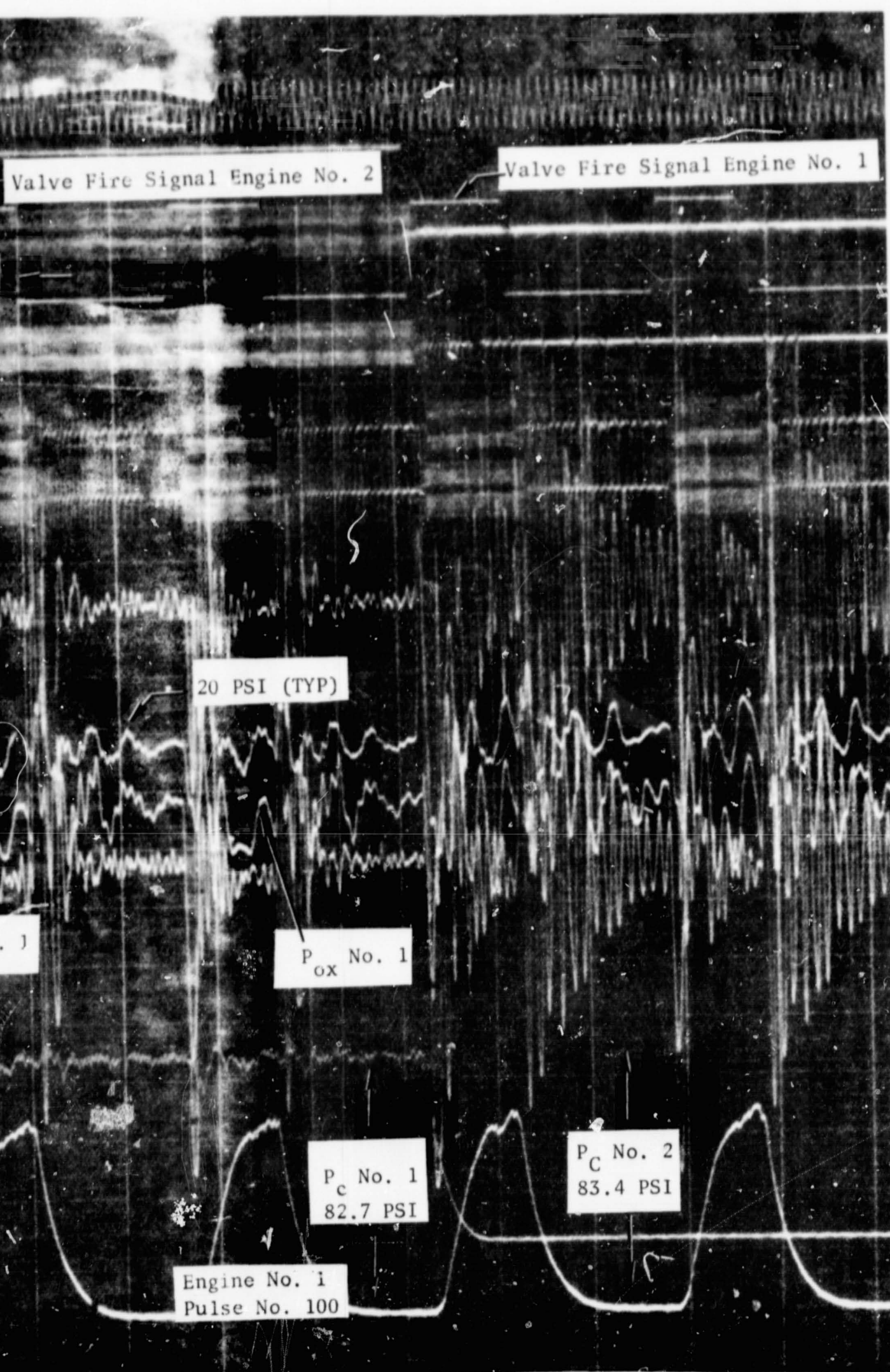
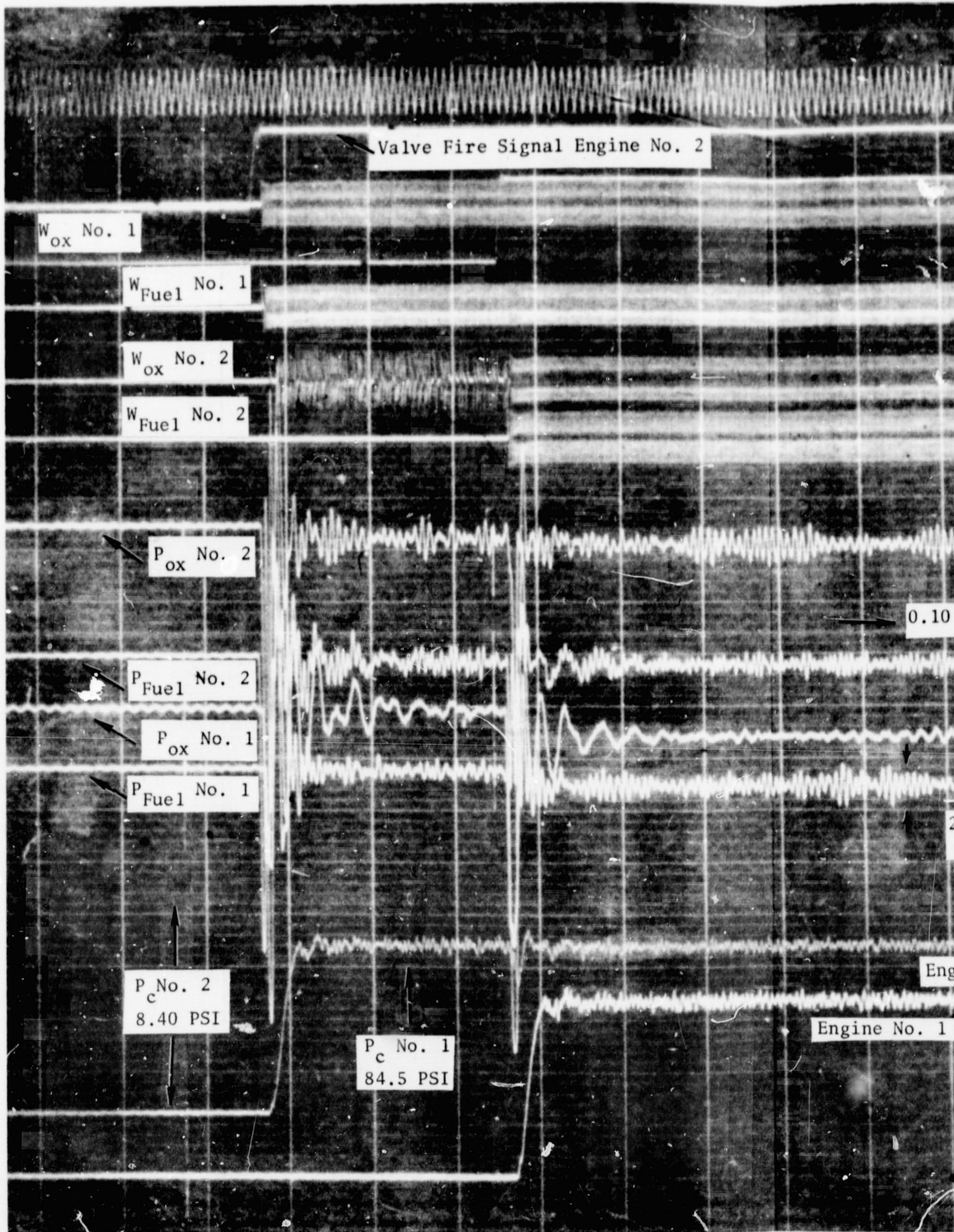


Figure 9-21 Engine Oscillograph Trace - 30 Percent Duty Cycle, Run A-001 Cycle 1
FOLDOUT FRAME 2



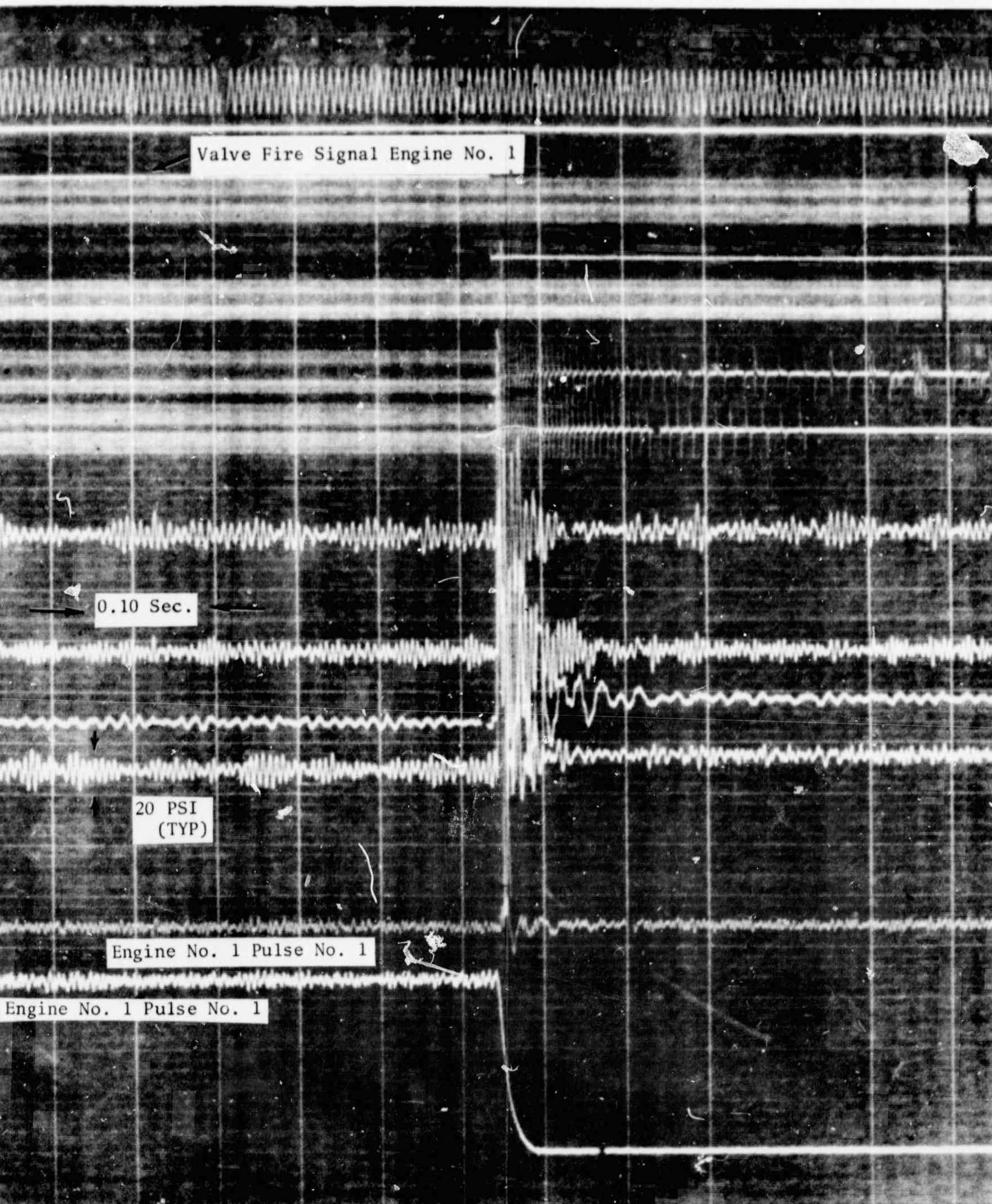


Figure 9-22 Engine Oscillograph Trace - 67 Per-
cent Duty Cycle, Run A-002 Cycle 4

FOLDOUT FRAME 2

Fuel Tank Heat Exchanger

Fuel Tank Heat Exchanger Inlet Temperature

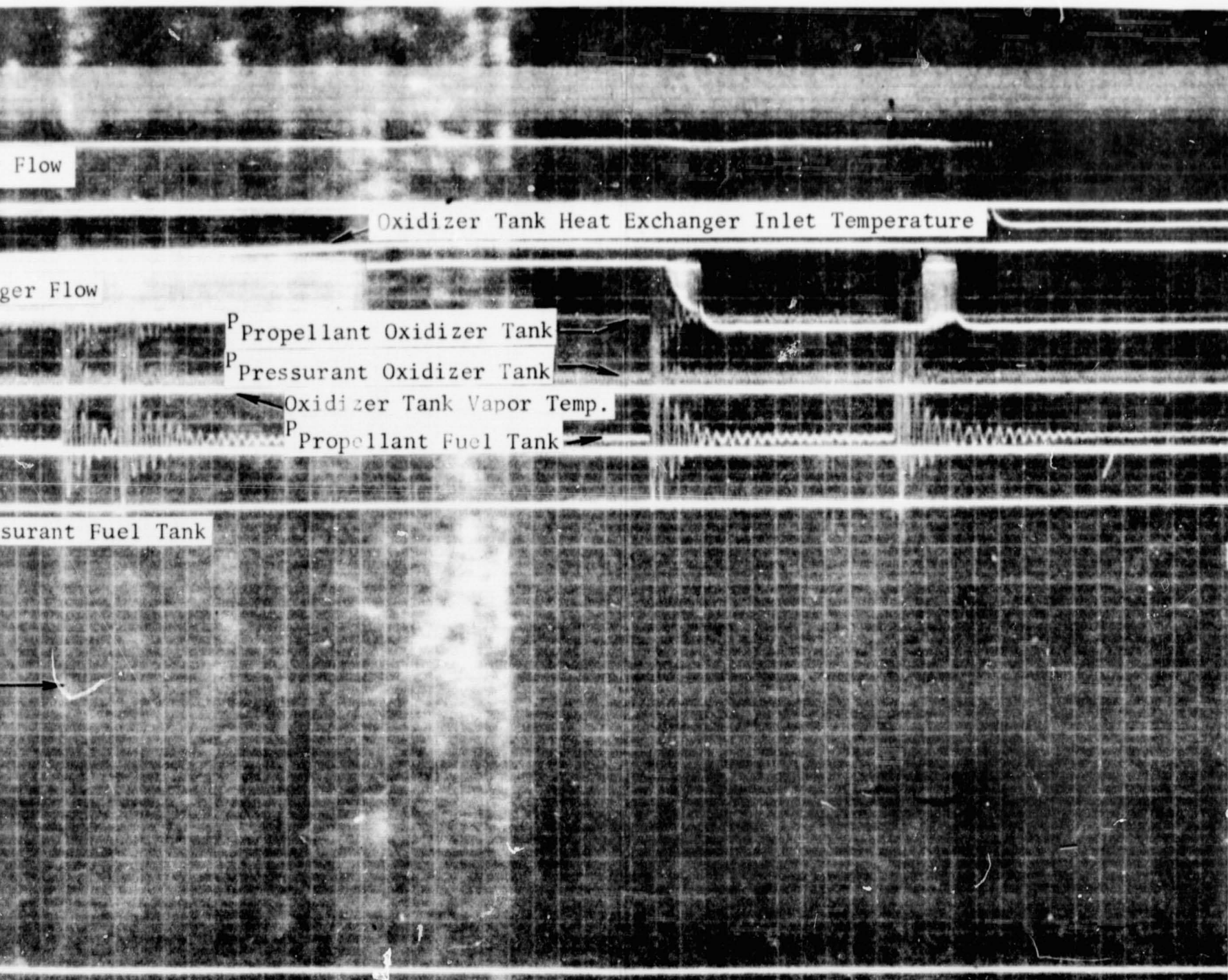
Oxidizer Tank Heat Exchanger

Fuel Tank Vapor Temperature

P_{Pres}

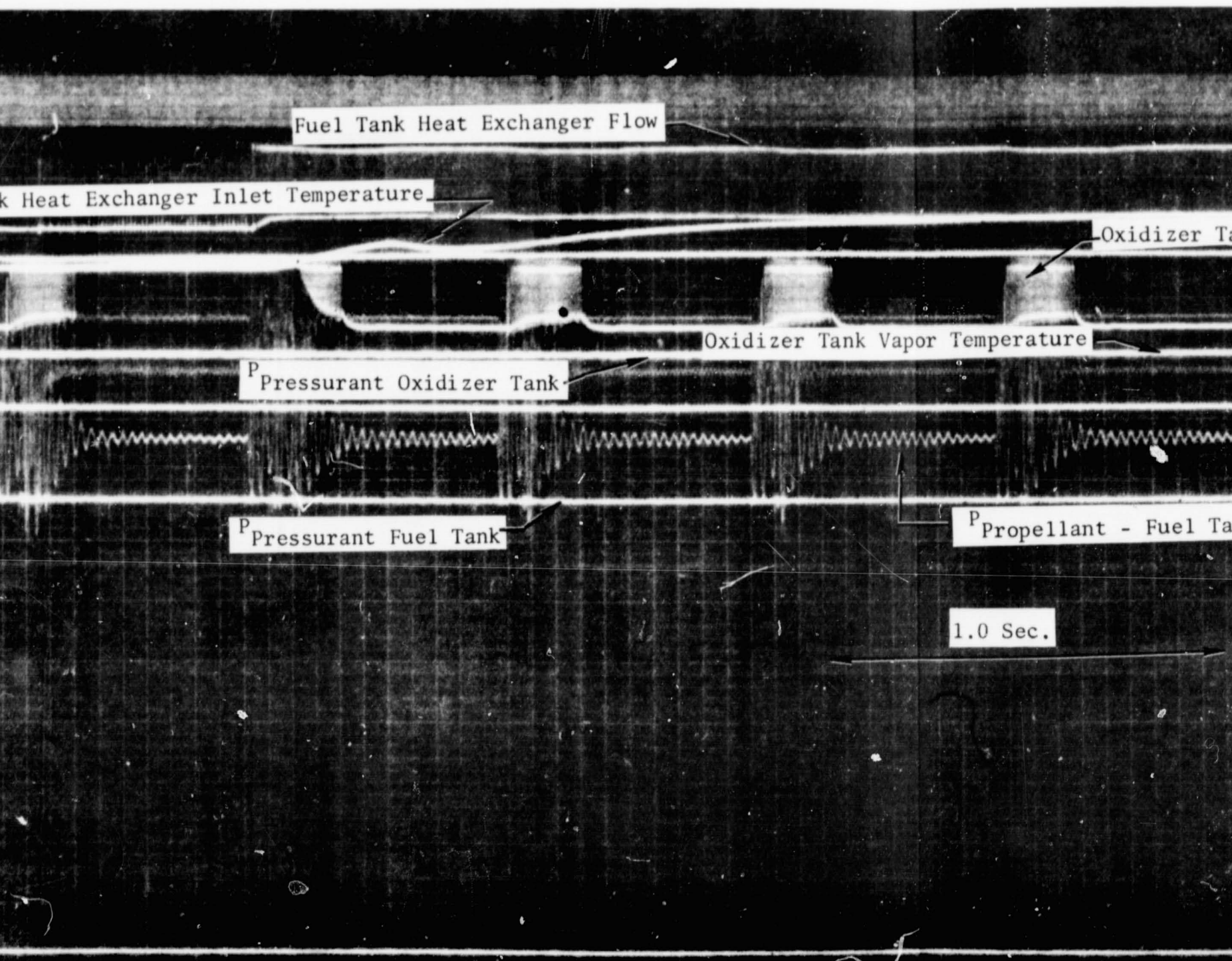
1.0 Sec.

REBOUT FRAME /

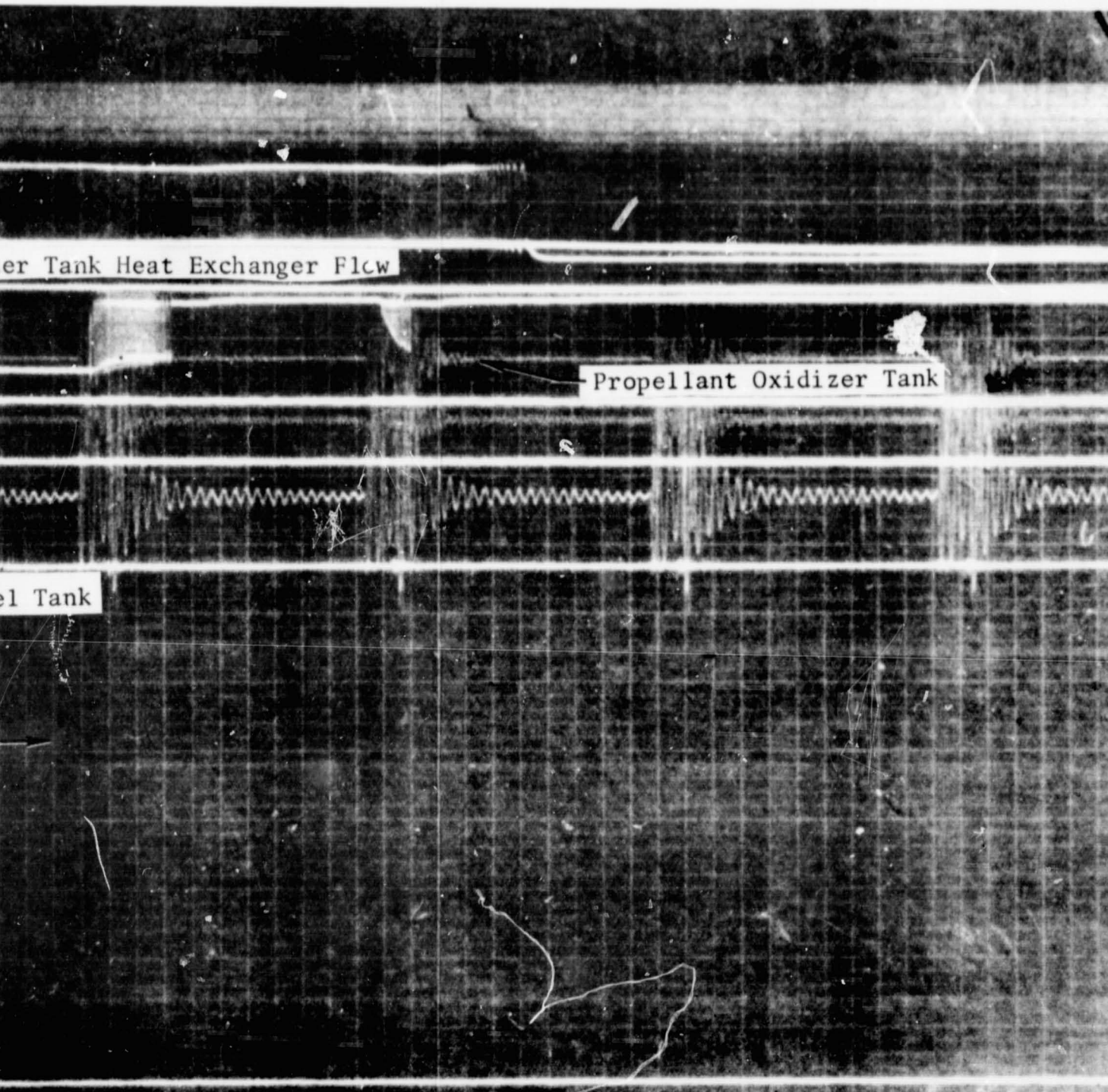


FOLDOUT FRAME

Figure 9-23 System A Tank Oscillograph Cycling Heat Exchanger Flows



FOLDOUT FRAME 1



FOLDOUT FRAME 2

Figure 9-24 System A Tank Oscillograph - Intermittent Oxidizer Tank Heat Exchanger Flow

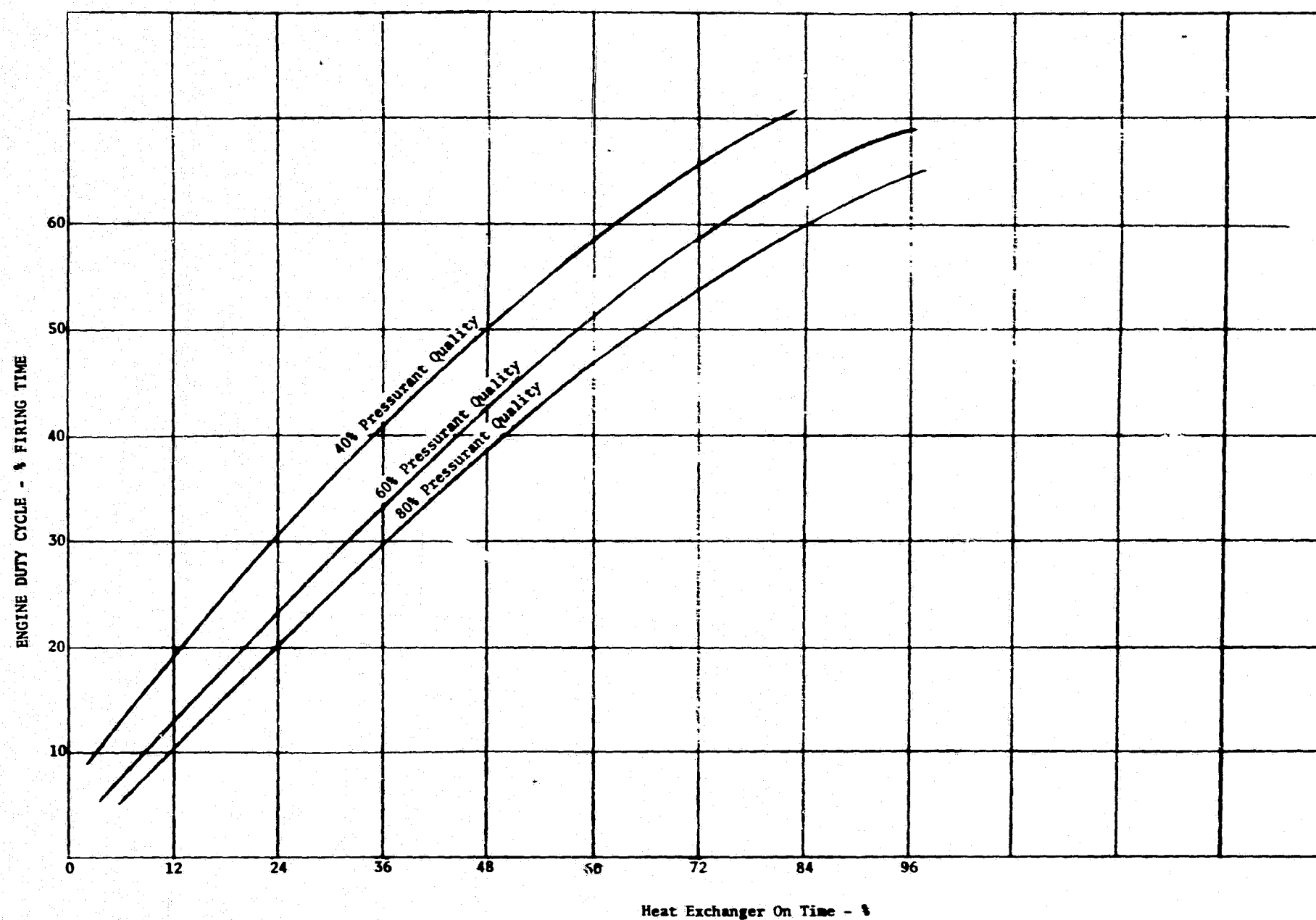


Figure 9-25 Oxidizer Tank Heat Input Requirements

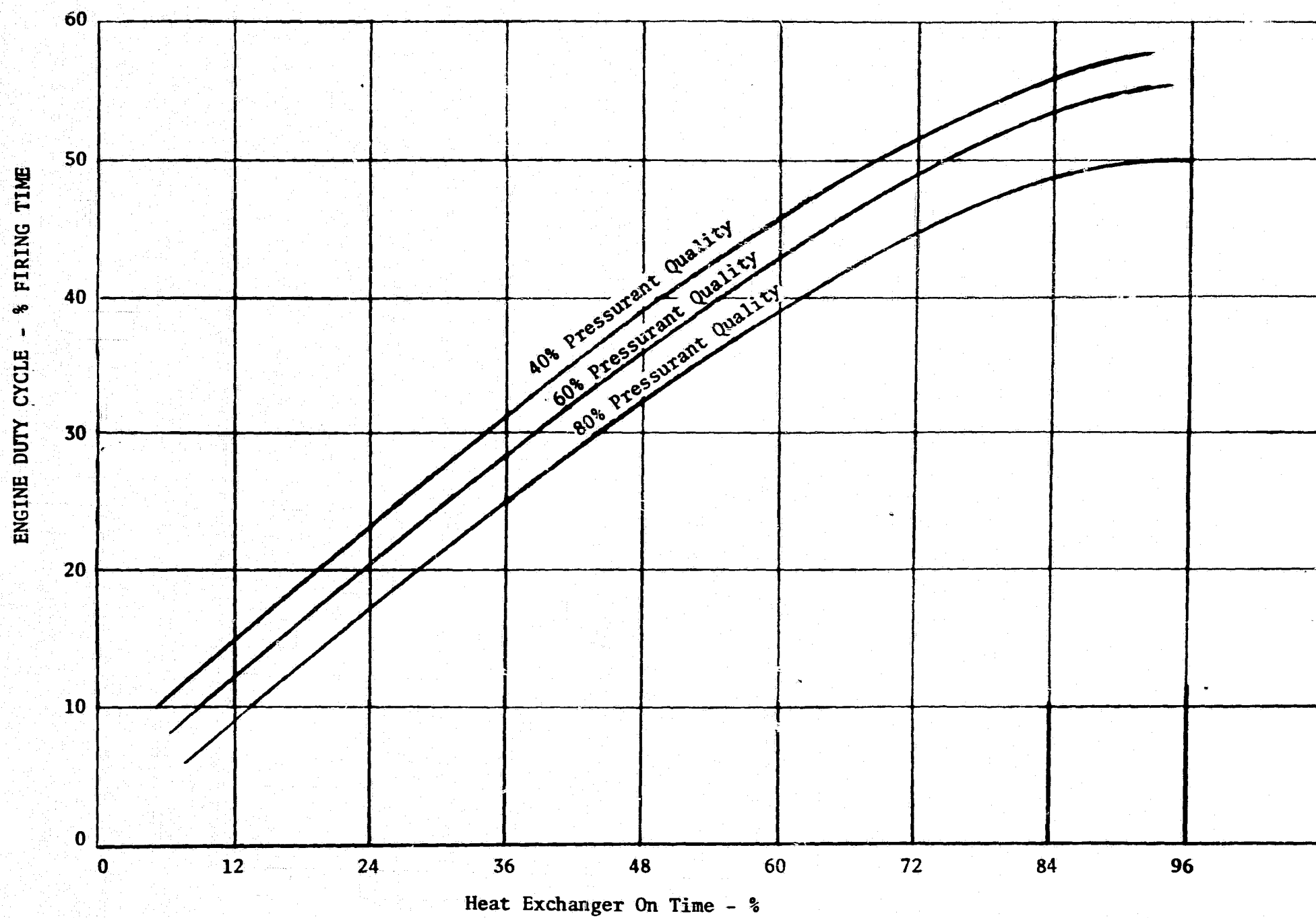


Figure 9-26 Fuel Tank Heat Input Requirements

The relatively stable operation of the volatile liquid pressurization system is shown in Figures 9-27 and 9-28. In a perfect system pressurant saturation would be maintained throughout the expulsion run. The degree of unsaturation would be reflected in the percent quality of the volatile liquid. As can be seen for both runs made, the quality varied almost linearly through the run. The maximum amount of superheat noted in the vapor phase was 6°F. This occurred in both runs at the conclusion of the cycle just prior to the long off time required to change instrumentation recording paper. In both instances the superheat had reduced to approximately 2°F by the time firing was resumed.

The pressure drop performance of the system summarized in Figure 9-29, indicates that a 1/2 psi drop in fuel tank pressure, the switch deadband, results from a single engine flow duration varying from 1.3 seconds at the beginning of the run to 4 seconds at the end of the run. The corresponding flow durations for the oxidizer tank are 2 and 6 seconds. The heat exchanger flow initiation followed this trend, with the exception of the intermittent oxidizer heat exchange cycling previously discussed.

During expulsion operation two conditions occur which would cause the tank pressure to exceed the limits of the switch operating band. On initiation of heat exchanger flow, if engine firing continues a time lag will occur before the heat input results in vaporization of the volatile liquid. During this time, the tank pressure will continue to decay. The amount of pressure drop depends on the magnitude and duration of the engine firing. The maximum value experienced, 5 psi on the fuel tank, occurred during cycle 7 of Run A-002. During this series of engine firings the pressure dropped 4 psi within the first 10 seconds, before the heat input slowed the rate of decay. The oxidizer tank returned to its operating level, however, the fuel tank heat exchanger was incapable of meeting the demand and continued a slow average rate of decay to the end of the cycle at which point an additional heat exchanger flow of 17 seconds was required to return the tank pressure to the operating level.

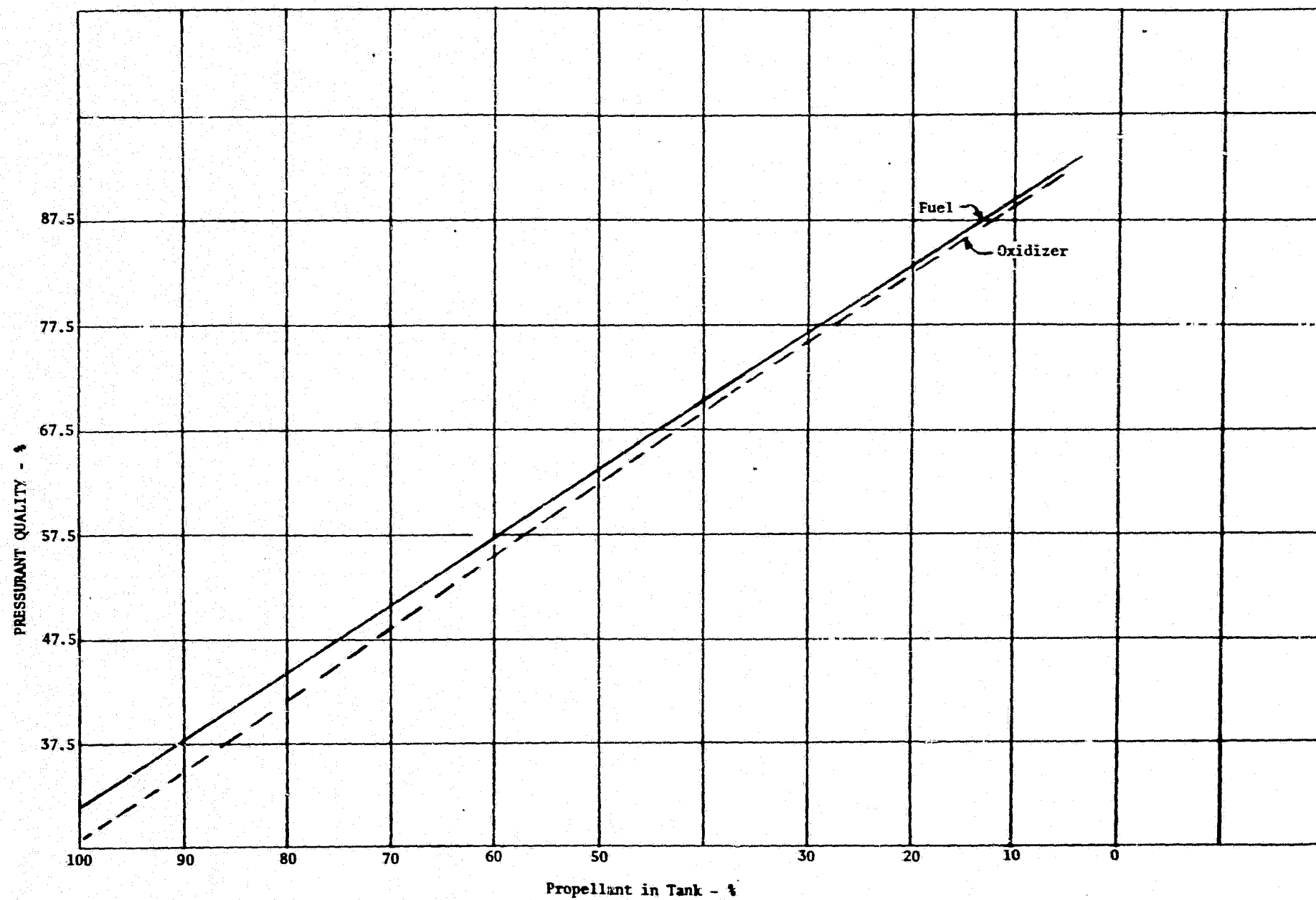


Figure 9-27 Volatile Liquid Vaporization Characteristic Run A-001

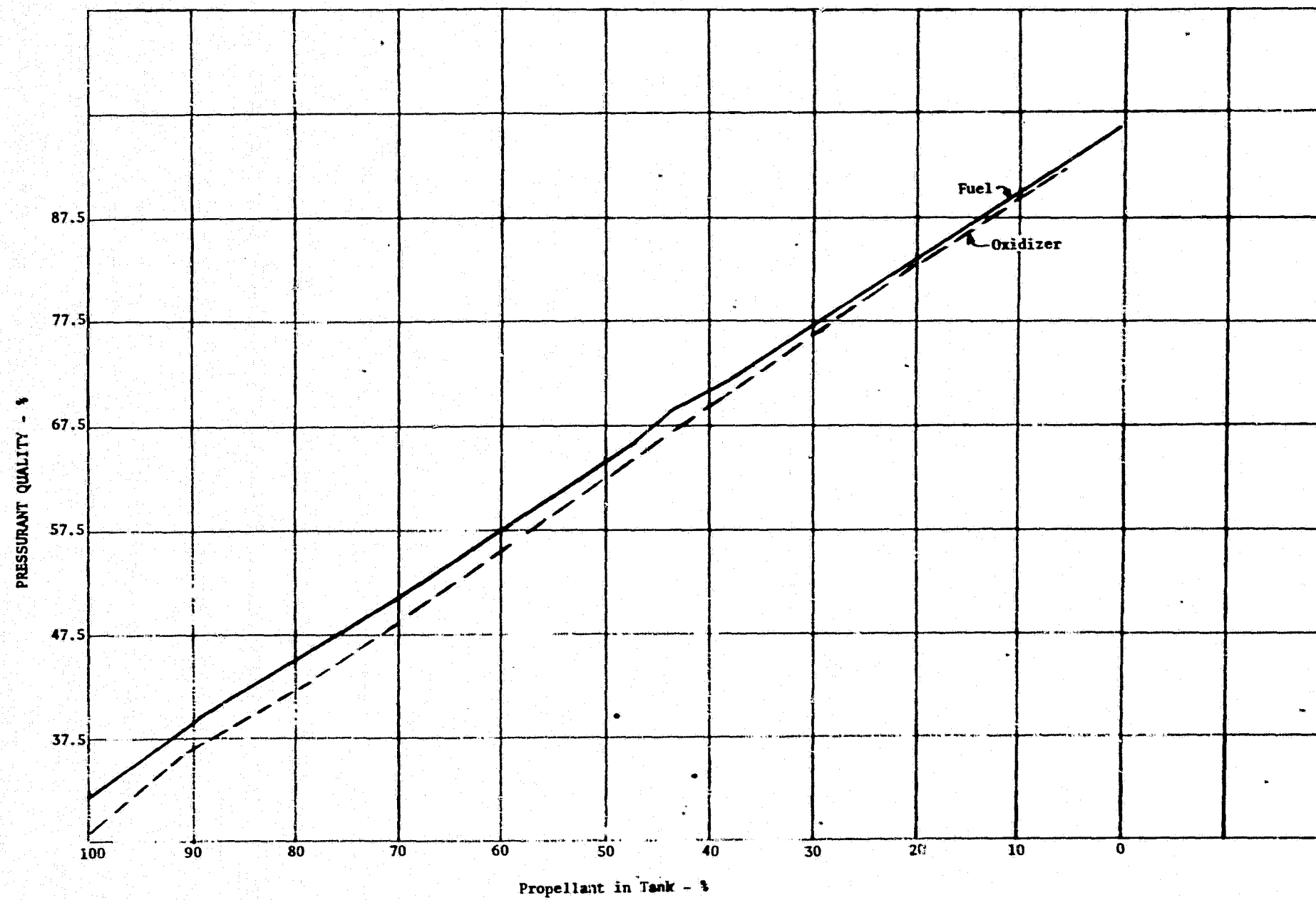


Figure 9-28 Volatile Liquid Vaporization Characteristic Run A-002

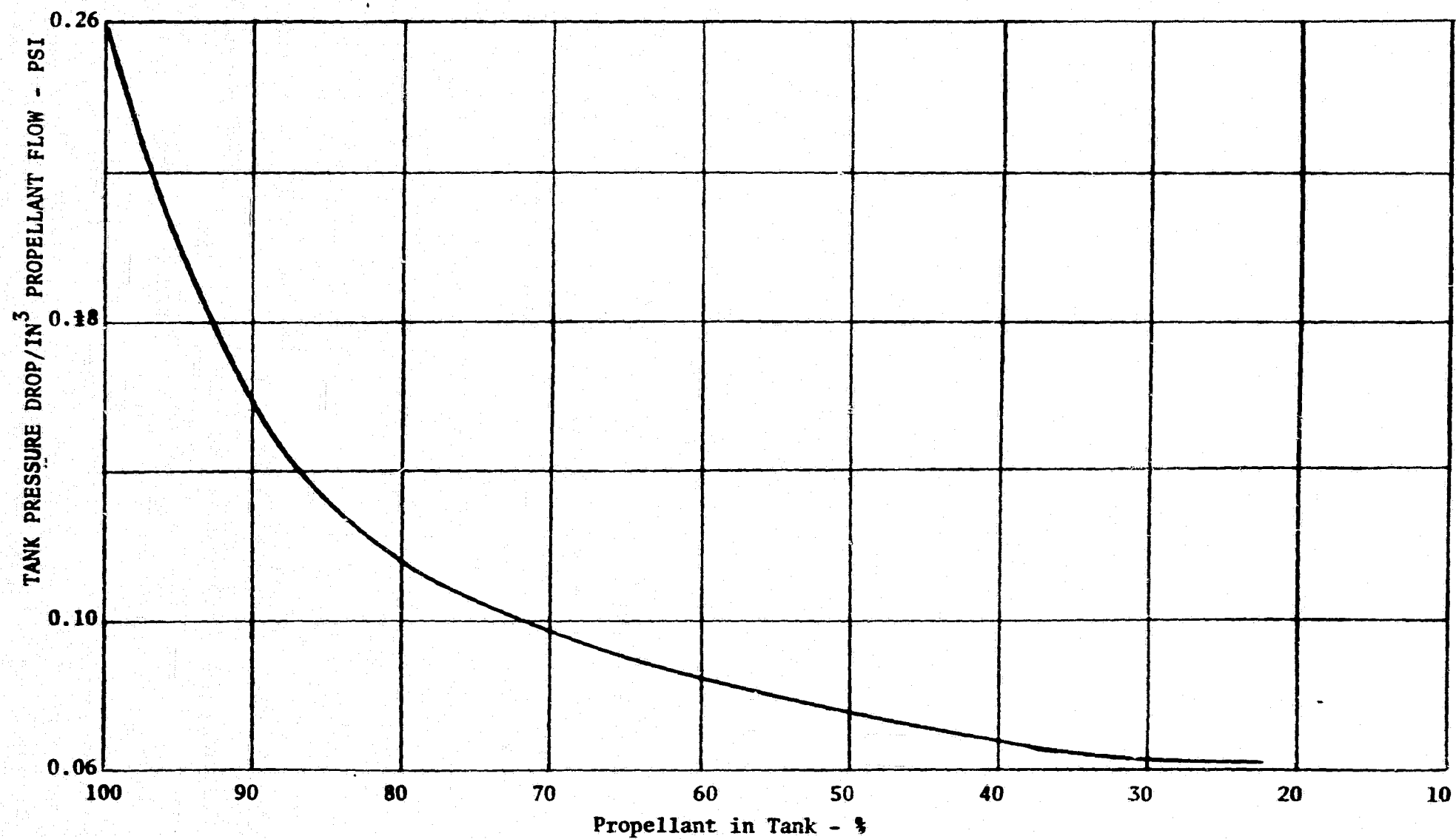


Figure 9-29 Pressurization System Operating Performance

The second area of pressure excursion occurs on termination of heat exchanger operation after engine firing. The residual heat stored in the heat exchanger fluid and tank shell gradually causes an increase in the tank pressure over the operating range. The maximum level noted (2 psi) occurred between cycles 3 and 4 of Run A-001.

The total tank pressure excursion experienced during the test program, therefore, was 8 psi. However, except during the cycle when the fuel tank lagged, the pressure difference between the two tanks did not exceed 2 psi at any time.

10.0 CONCLUSIONS AND RECOMMENDATIONS

This program required the design, development, and testing of two flight-weight volatile liquid expulsion systems. System A simulated the Apollo service module requirements and System B simulated the Apollo command module requirements. The results of the program are considered to have advanced volatile liquid pressurization and bellows tank technology toward a "flight-worthy" condition.

Although considerable fabrication difficulties were encountered in manufacture of the aluminum expulsion tanks, these problems are considered resolved. The basic design and fabrication of the stainless steel bellows, which are well within the state of the art, proceeded without difficulty.

A successful flight-weight demonstration program was conducted where expulsion tests were made with single tanks using storable propellants (N_2O_4 , Aerozine 50, and monomethylhydrazine). The simultaneous expulsion of two tanks with simulated propellants demonstrated bipropellant engine operation. Tests were made at various flow rates to simulate selected duty cycles for single and multiple engine usage. Finally, a series of tests was conducted in conjunction with a complete auxiliary propulsion system. The results of these tests allowed determination of the following system parameters: magnitude of pressure decay in the tank versus propellant flow rate and duty cycle; effectiveness of the pressure recovery during a nonflow condition; effect of a changing quality level of the volatile liquid on the magnitude of pressure decay; capability of the individually controlled tanks in a bipropellant system to maintain equal pressure levels; and the effect of engine dynamic operation on pressurization performance.

Successful System A operation was demonstrated over a wide range of propellant flow duty cycles. The only time a relatively high (4 psi) differential pressure occurred between the two tanks was during a high (67 percent) engine duty cycle when the heat exchanger flow on one tank was incapable of meeting the demand. As this problem occurred only on

the fuel tank, a redesign of the heat exchanger would resolve this problem. There is, however, a maximum duty cycle which can be tolerated by the system without pressure decay. During the balance of the tests, the differential between the tanks did not exceed 2 psi. The total operating band was well within the tolerance range established. The results of this set of tests demonstrated the applicability of volatile liquid pressurization in a pulsing mode of operation.

For System B operation the pulsing mode of expulsion did not result in efficient operation of the heat storage material, particularly on the low (single 100-lb-thrust engine) flow rate runs. As shown in Figure 10-1, the performance was nearly identical between a run made with heat storage material added and another run made using Genetron 32 only indicating no heat input from the eicosane. Some evidence of heat storage material heat input, however, was indicated during the high (four 100-lb-thrust engines) flow rate runs. This was attributed to the fact that with the low propellant flow rates the temperature decay in the Genetron is probably not sufficient to trigger solidification of the heat storage material. If the temperature differential is sufficient at propellant flow termination, the temperature of the vapor starts to increase and quickly removes the temperature differential required to solidify the heat storage material. For the four engine flow rates, the temperature differential occurring is much larger. On termination of flow it requires a considerably longer period of time before the temperature difference appears. This allows the heat storage material to solidify over at least a part of the run and results in a higher pressure level. With the duty cycles established for System B operation, the advantages of a heat storage material were not clearly demonstrated. At the low flow rate and duty cycle an eicosane definitely should not be used. The use of heat storage material at the higher usage rate may be warranted depending on the system requirements.

The results of this program demonstrated that volatile liquid expulsion technology for pressurization of storable propellants is suitable for reaction control system applications. For a pulse mode of operation,

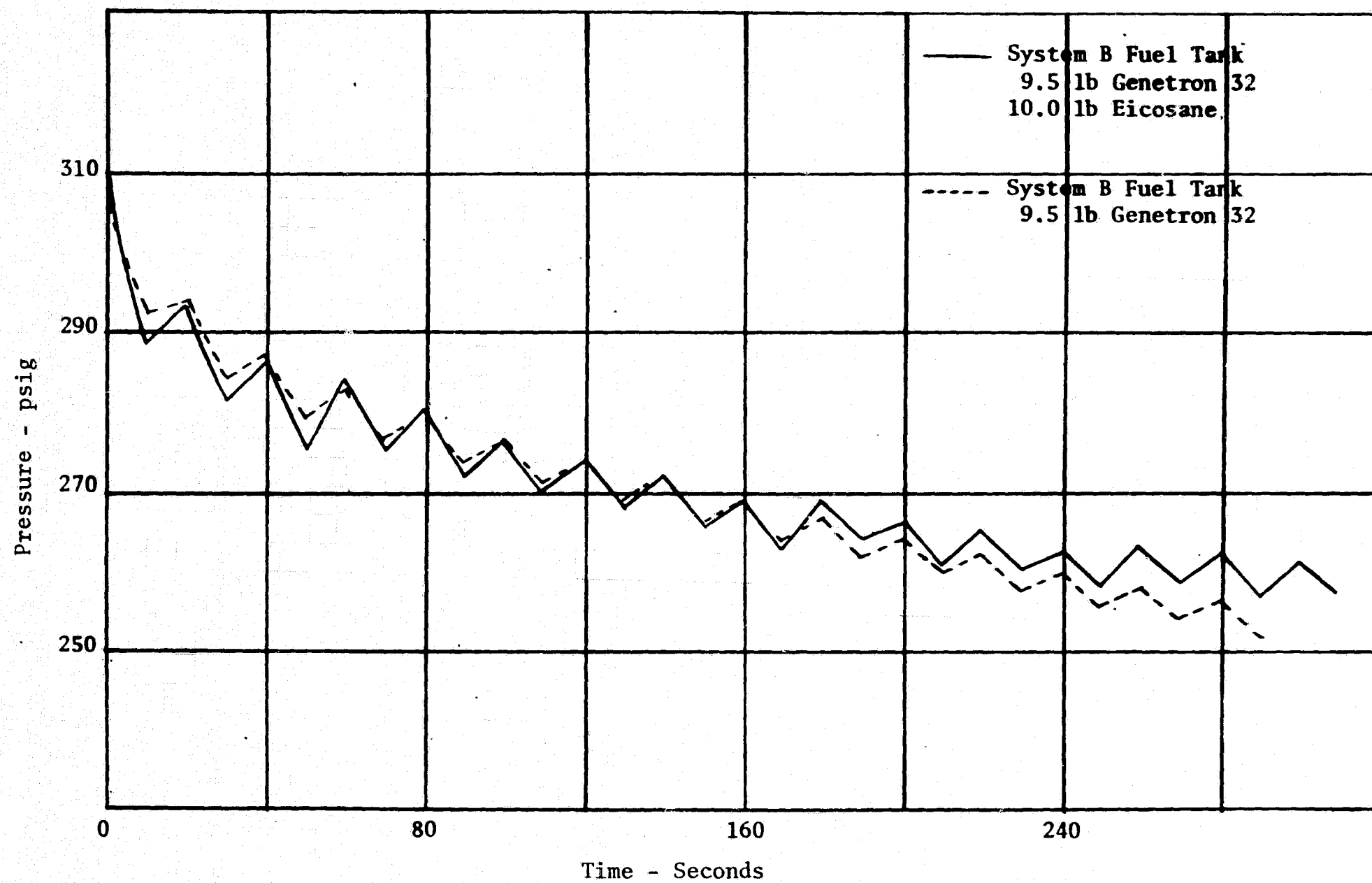


Figure 10-1 Expulsion Characteristics of Genetron 32 in Pulsing Mode - With and Without Eicosane

the use of the waste heat loop as the heat source proved to be very effective in providing adequate system control for all duty cycles tested. The use of a stored heat material is of advantage in continuous expulsion of most of the propellant in a single pulse. The pressure variation experienced during propellant flow is well within the tolerance limits of the present reaction control system engines being used.

Several distinct advantages for a volatile liquid pressurization system over the conventional gas pressurization are indicated including: an increase in reliability through the elimination of several complex components in the pressurization system; improved overall volumetric efficiency through the combination of the pressurization and propellant storage systems in a single container; a potential weight reduction, and a system having an inherent capability of propellant refueling which will be of extreme importance on long duration missions.

The following areas of work are recommended as a continuation of this program to advance volatile liquid expulsion technology to the state where development of a flight system is feasible:

1. An investigation into the manufacture of the bellows using lightweight metals such as aluminum or titanium, to provide a reduction in the overall all-metal system weight.
2. A system optimization study for a specific application of the volatile liquid system. This would necessitate updating the analytical model to include vaporization of the pressurant during expulsion and account for the resulting transient unsaturated condition.
3. The work conducted under this program was limited to investigation of a waste heat loop as the external heat source. For many potential applications where a waste heat loop is not available or of insufficient capacity, an investigation is warranted of alternate heat sources such as electrical, nuclear isotope or radiation from the engines being operated by the system.

REFERENCES

1. Giffoni, S. F.: Final Summary Report, All Metal Volatile Liquid Positive Expulsion System. TRW Electromechanical Division, Cleveland, Ohio. Report ER5980, June 1964.
2. Eatough, R. G.: All Metal Volatile Liquid Positive Expulsion System, Second Quarterly Report. TRW TAPCO Division, Inglewood, California. Report ER5724, July 1963.
3. Mayer, L. W.: Alcoa Aluminum Alloy 2219. Application Engineering Division, Aluminum Co. of America, New Kensington, Pa., November 1963.
4. Den Hartog, J. P.: Advanced Strength of Materials. McGraw Hill Book Co., N. Y. (1952) pp. 83-87.
5. Graham, DP, McHarness,: Thermodynamic Properties of Freon 22. Freon Products Division, E. I. DuPont De Nemours & Co., Wilmington, Delaware. Bulletin T-22A, 1945.
6. Chen, T. Y.: Thermodynamic Properties of Genetron 32. General Chemical Division, Allied Chemical Corp., New York, N. Y., Planning Research Report No. 63-3, May, 1963.
7. Anon: Aliphatic Chemicals Product Bulletin. Humphrey-Wilkinson Inc., North Haven, Conn. 1963.

APPENDIX A



METAL BELLOWS CORPORATION
CHATSORTH, CALIFORNIA

REPORT CR - 67
EXPULSION TANK

THOMPSON RAMO WOOLDRIDGE

P. O. 29279

P/N C 110835

MEC P/N 57218 - 2

JOB NO. 12608

Prepared by: *Paul Rackliffe* PR
Paul Rackliffe,
Project Engineer

Approved by: *Paul B. Campbell*
Paul B. Campbell,
Chief Engineer

Date: August 9, 1966

**A. Before Capsule Removal**

Developed a leak while testing at TRW. Details of the testing cycle and history of performance at TRW are not known at this time. The tank was cut apart on 8-4-66. The close-out weld drop through appears to be heavy. The height appears to vary from .020 to .050. However, this is difficult to determine, due to the heavy burrs induced by cutting the can apart directly in this area. Observations of the visual examination of the exposed bellows, can and dome is as follows:

End Dome

Shows no dings or deformations. There is some evidence of scratching apparently due to the buttons on the end terminal of the bellows. There is one bent stop inside of the dome. This stop is bent inward (I. E. bent toward the end of the dome.) See Picture 1. No other damage is apparent.

Can (With Bellows Still Inside)

The can shows no bulges or gouging in the exposed section. There is some scratching or polishing, I don't know which, due to the buttons on the end terminal and the anti-sag rings. All the buttons seem to have been riding on the side of the tank at one time or another, indicating that the tank has been operated horizontally in several positions. See Picture 2.

End Terminal

The end terminal shows bending of the flange at the 4:00 o'clock and 8:00 o'clock sections. The buttons at these portions are severely deformed. The button at 12:00 o'clock is protruding slightly from its retaining hole. The button at the 6:00 o'clock section appears to have been completely removed.

Action of the Bellows

Movement of the bellows is difficult. The bellows can be pushed in with the heavy dragging occurring somewhere in the middle of the bellows at the top side. Upon release of force, the end terminal cocks by digging in on the bottom. The top moving outward and the middle portion of the bellows moving upward coming in contact with the surface of the tank.

B. After Capsule Removal

Can Examination

The can shows gouging at 4:00 o'clock and 8:00 o'clock in the rear portion of the can. See Picture 3. Light gouging at the 6:00 o'clock portion occurs approximately 3 1/4 inches from the rear stop. The heavy gouging at the 4:00 and the 8:00 section are at approximately five to six inches away from the rear stop.

Examination of the Bellows

The bellows segments appear to be okay with the following exceptions. The second segment from the fixed terminal is heavily damaged with fold-in occurring next to the rear anti-sag ring. The bellows segment is cocked, causing bending of the capsule. The segment next to the moveable terminal shows bending at the end terminal junction due to the terminal flange being bent over the capsule. See Pictures 4 & 5. The anti-sag ring buttons opposite the fold-through on number two segment are flattened due to heavy pressure.

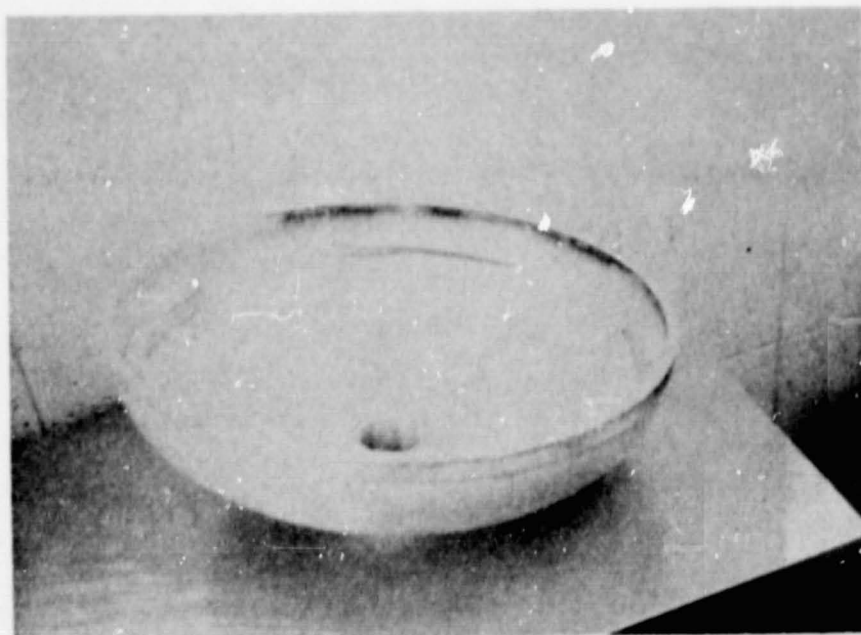


FIGURE 1

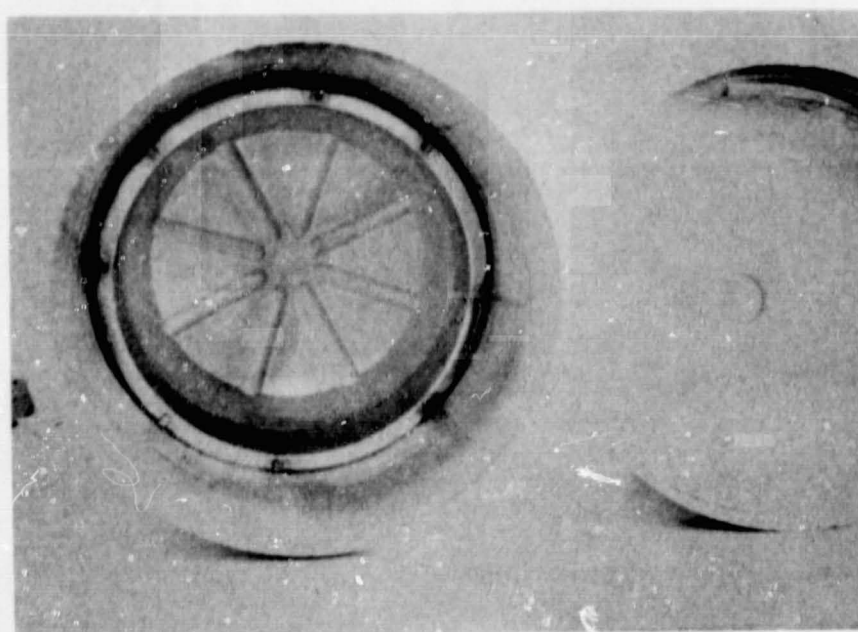


FIGURE 2

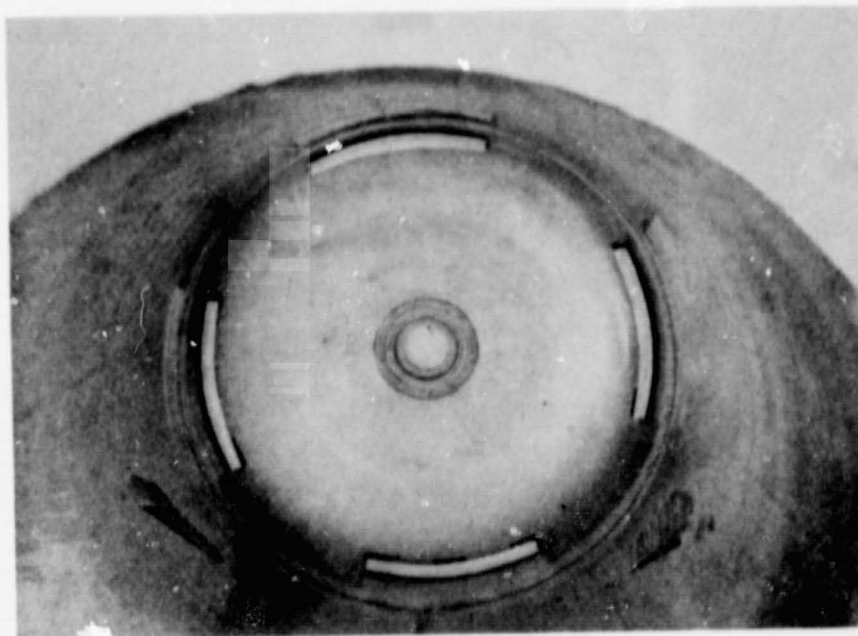


FIGURE 3



FIGURE 4

A-5

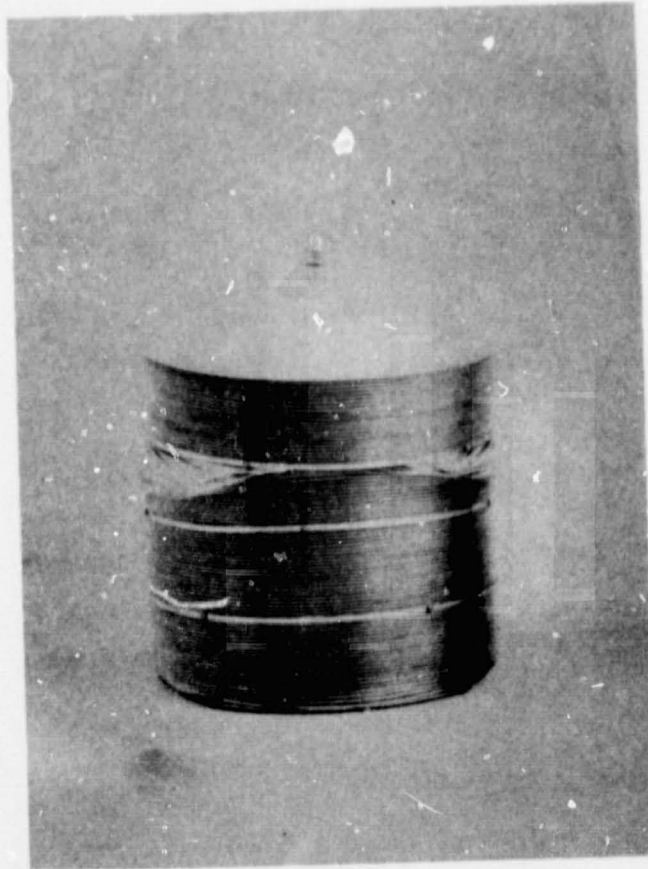


FIGURE 5

APPENDIX B

METAL



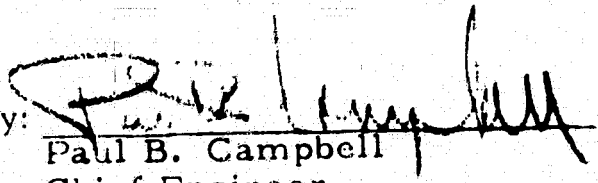
METAL BELLOWS CORPORATION
CHATSWORTH, CALIFORNIA

REPORT CR 105

FAILURE ANALYSIS
OF
PROPELLANT EXPULSION TANK (DASH 4)
FOR
THOMPSON RAMO WOOLDRIDGE

P.O. 29279
P/N C110835-4
MBC P/N 57218
Job No. 12608

Approved by:


Paul B. Campbell
Chief Engineer

Date:

November 9, 1967



Subject tank was removed by TRW, from approximately a years storage, following completion of its initial testing; and examined for usability in a new series of tests. TRW discovered what appeared to be a leak in the bellows expulsion module.

MBC received the tank and installed it in a test set-up to confirm the leakage.

5 PSI of gaseous nitrogen was applied to the port internal to the bellows. A line from the port external to the bellows was submerged in water. Moderate bubbling was detected; confirming the leakage.

The aluminum dome was then parted from the tank through the electron beam weld. The bellows expulsion module was removed from the tank, and examined by again applying gaseous nitrogen through the port, while the bellows was submerged in water.

Leakage was found to be emanating from only one spot on the bellows.

Close examination showed the leak source to be a hole in the middle of the first diaphragm attached to the terminal immediately below one of the guide button pads.

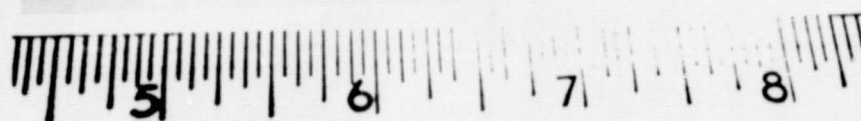
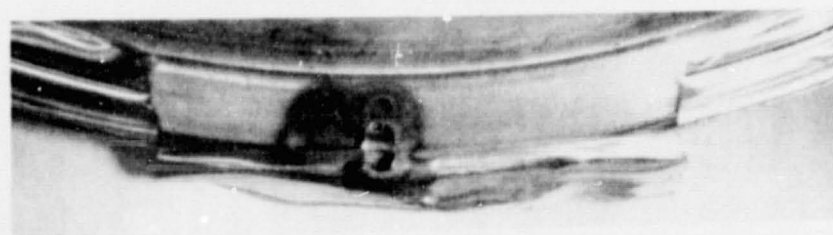
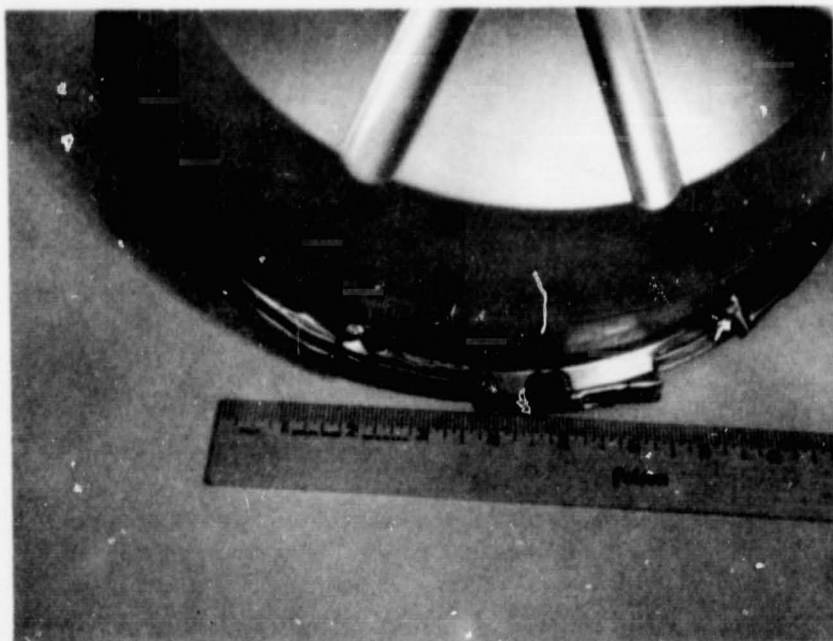
The damaged convolution and terminal were then removed from the remainder of the bellows assembly to determine the cause of the hole.

Examination of the damaged area showed the diaphragm to be fused to the terminal at one spot, which occurred during the welding attachment of the guide button pad to the terminal. The apparent hole was actually a semi-circular crack extending around the periphery of the fused spot. See Photos.

METAL



Page 2 of 2
CR 105
11/9/67



Falcon

APPENDIX C

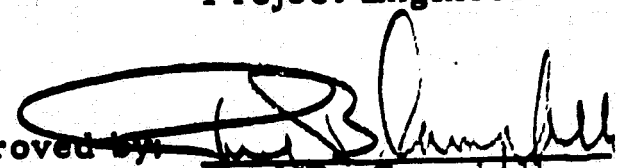
METAL BELLOWS CORPORATION
CHATSWORTH, CALIFORNIA

REPORT CR - 58
EXPULSION TANK

THOMPSON RAMO WOOLDRIDGE SYSTEMS
P. O. 29279
P/N C110835 - 3

MBC P/N 57218 - 3
JOB NO. 12608

Prepared by: 
P. Rackliffe
Project Engineer

Approved by: 
Paul B. Campbell
Chief Engineer

Date: April 19, 1966

The following procedure constitutes the Production Test Procedure for MBC P/N 57218-3

Test Conditions

Ambient and fluid temperatures: $70^{\circ}\text{F} \pm 20^{\circ}\text{F}$.

Fluids: Clean dry Nitrogen
Clean dry Helium
Clean Freon TF

Equipment

Pressure gauges - accuracy $\pm 2\%$ of full scale
C. E. C. Helium leak detector Model 24-120 or equivalent
Test set ups per applicable sketch. Note, the actual test set-up can vary from the figures. However, the intent of the figures must be adhered to.

A. External Leakage

1. Set up per Figure 1. Ports identified by picture only.

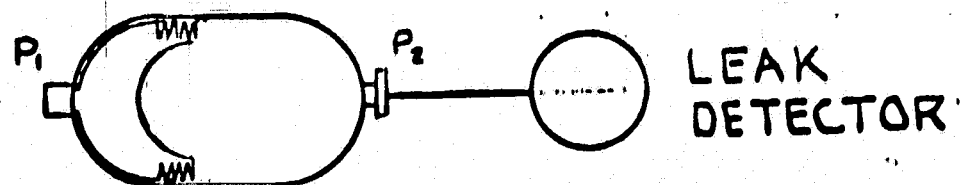


FIG I

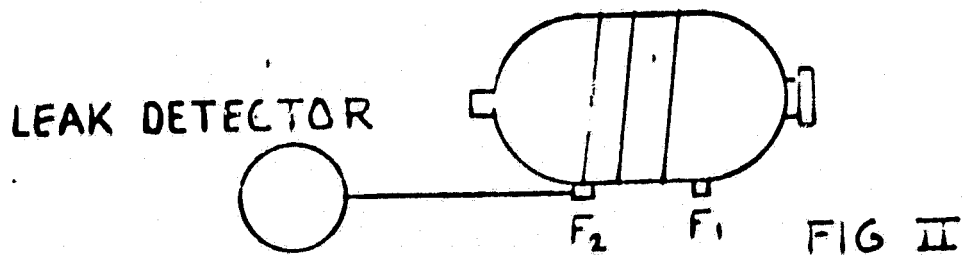
2. Evacuate unit through port P_2 . Plug port P_1 .
3. Apply He to all external joints.
4. Leakage greater than 5×10^{-6} cc/sec He @ any joint shall be cause for rejection. Total leakage greater than 1×10^{-5} cc/sec He shall be cause for rejection.

B. Internal Leakage

1. Leave set up per figure 1.
2. Unplug P_1 and apply He to P_1 . Evacuate unit through P_2 .
3. Leakage in excess of 1×10^{-5} cc/sec He shall be cause for rejection.

C. Tube Leakage

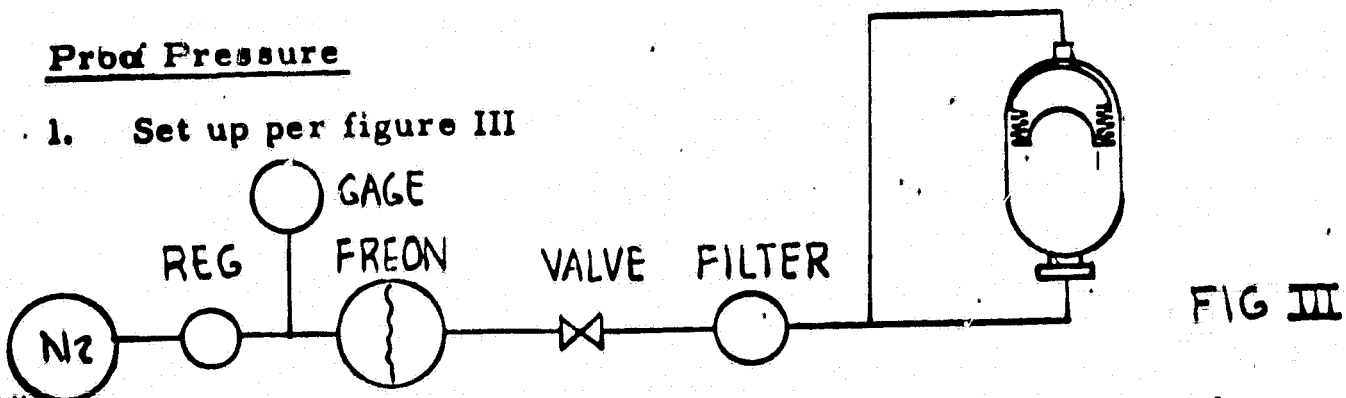
1. Set up per Figure II



2. Plug fitting F_1 , evacuate unit through fitting F_2 .
3. Apply He to heat exchanger tube.
4. Leakage greater than 1×10^{-4} cc/sec shall be cause for rejection.

D. Proof Pressure

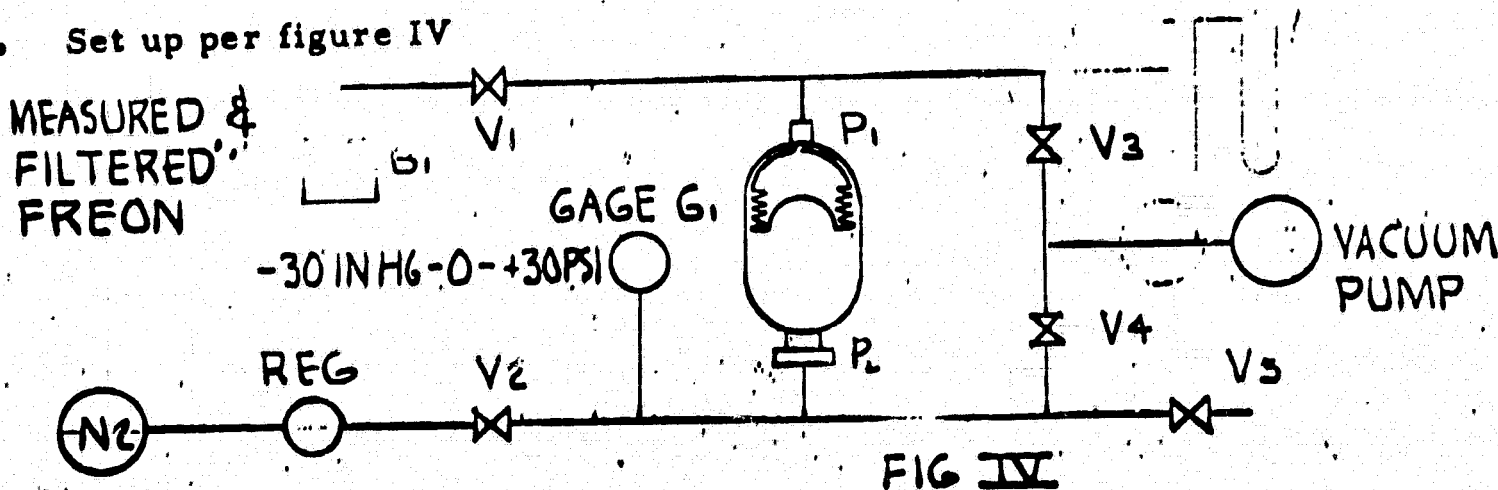
1. Set up per figure III



2. Apply steadily increasing Freon pressure simultaneously to ports P_1 and P_2 up to 510 PSI.
3. Hold press for one minute and then return pressure to zero.
4. Any leakage or permanent deformation shall be cause for rejection.
5. Drain unit.

E. Propellant Volume

1. Set up per figure IV



E. Propellant Volume (Continued)

2. Record volume in beaker B_1 .
3. Close valves V_1 , V_2 & V_4 . Open valves V_3 & V_5 . Evacuate port P_1 .
4. Close valve V_3 . Open valve V_1 . Allow freon to flow into tank.
5. Close valve V_5 and open valve V_2 . Steadily increase N_2 press to port P_2 until flow into beaker B_1 stops. Record volume of freon in beaker B_1 . Record N_2 pressure.
6. Close valve V_2 and slowly open valve V_4 . Evacuate port P_2 until pressure is 5 PSI less than pressure recorded in step E 5. Record volume of freon in beaker B_1 .
7. Close valve V_4 and open valves V_1 & V_2 . Apply N_2 press to port P_2 to the level recorded in step E 5. Record volume of freon in beaker B_1 .
8. Determine and record expelled volume of freon by subtracting beaker volumes of step E 6 from step E 7. Expelled volume less than 1672 cubic inches shall be cause for rejection.
9. Close valve V_2 and open valve V_4 . Evacuate port P_2 until freon stops flowing into tank. Record volume of freon in beaker B_1 .
10. Determine and record total volume of freon in tank by subtracting beaker volumes of step E 7 from E 9.
11. Close valve V_4 and open valve V_2 . Slowly increase N_2 press to port P_2 until freon stops flowing into beaker B_1 .
12. Disconnect tubing from port P_1 . Reduce pressure in port P_2 to zero.
13. Disconnect port P_2 and drain fluid remaining in port P_1 into calibrated beaker. Record volume of freon. Volume in excess of 2% of expelled volume of note E 10 shall be cause for rejection.

APPENDIX D

EICOSANE LOADING PROCEDURE

- ___ 1. Melt 9.5 lbs of eicosane (melting temperature 97.9°F)
- ___ 2. Pressurize the Bellows capsule to 5 psig
- ___ 3. Pour the melted eicosane into the Bellows movable header through the tank pressurant port (pour slowly to avoid spill over of eicosane on Bellows convolutions)
- ___ 4. Allow eicosane to cool and solidify in Bellows header
- ___ 5. Vent the Bellows capsule

Tank _____
Date _____
Propellant Wt. _____
Gen. 32 Wr. _____
Eicosane Wt. _____

EXPULSION TANK
PRESSURANT AND PROPELLANT
LOADING PROCEDURE

- ___ 1. Open pressurant tank vent and isolation valves
- ___ 2. Evacuate the propellant side of the expulsion tank to 30 in of Hg with the following valves in the indicated positions
 1. Main safety valve closed
 2. Propellant shutoff valve open
 3. Flow control valve closed
 4. Load valve closed
 5. Propellant inst. valve closed
 6. Propellant vacuum valve open
 7. Bellows isolation valve open
 8. Engine valves closed
- ___ 3. When the lines are evacuated close propellant vacuum valve
- ___ 4. Close the pressurant vent valve
- ___ 5. Open the main shutoff valve
- ___ 6. Slowly open flow control valve until 3 lbs of propellant are loaded or until flow stops. If flow stops slowly open pressurant vent valve to atmosphere. If required propellant cannot yet be loaded, pressurize supply tank to 3 psig max. When required amount of propellant has been loaded close the propellant shutoff valve, the flow control valve and main safety valve.
- ___ 7. Close pressurant inst. valve and open propellant inst. valve

- ___8. Evacuate pressurant cavity through pressurant vent valve to 30 in of Hg or 15 psi P max., which ever occurs first
- ___9. Cap pressurant vent port
- ___10. Open bottle valve and load pressurant to 10 psig
- ___11. Open pressurant inst. valve and close press vent valve
- ___12. Load remaining required weight of pressurant and close pressurant bottle valve
- ___13. Close pressurant isolation valve and open pressurant vent valve
- ___14. Pressurize supply tank to 5 $\pm$ 5 psi higher than the pressure level in the propellant tank using the N₂ supply
- ___15. Open main valve
- ___16. Open the load valve and load the tank to the required weight
- ___17. Close load valve when tank is loaded
- ___18. Close the main safety valve
- ___19. Turn on the water to the scrubber tank
- ___20. Open the dump valve and vent the supply tank
- ___21. Turn the water off to the scrubber tank after 10 minutes

RUNNING PROCEDURE - SYSTEM A

- ___ 1. Heat the water/glycol mixture to $180 \pm 10^{\circ}\text{F}$
- ___ 2. With the bypass valve on automatic control, turn on the heat exchanger pump
- ___ 3. Let the tank pressure rise until the bypass valve closes
- ___ 4. If liquid and vapor temperatures are not equal within one $^{\circ}\text{F}$, let the pressure in the tank decay until the heat exchanger flow is reinitiated. Continue the cycling process until the temperature conditions are met.
- ___ 5. Expel the propellants in accordance with the desired duty cycle by operating the engine valves.

To Reload Propellants For Additional Run

- ___ 1. Turn heat exchanger pump off
- ___ 2. Pressurize the supply tank to 3 ± 2 psi higher than the pressure level in the propellant tank
- ___ 3. Open the main safety valve
- ___ 4. Open load valve and load the tank to the required weight
- ___ 5. Close the load valve when the tank is loaded to the desired weight
- ___ 6. Close the main safety valve
- ___ 7. Turn on water to the scrubber tank
- ___ 8. Open the dump valve and vent the supply tank
- ___ 9. Turn the water off in the scrubber tank after 10 minutes
- ___ 10. Start running procedure at step No. 2

RUNNING PROCEDURE - SYSTEM B

- ___ 1. Heat the water/glycol mixture to $180 \pm 10^{\circ}\text{F}$
- ___ 2. With the bypass valve on manual control, turn the circulating pumps
- ___ 3. Heat system to 99° and hold for a minimum of 1 hour. If the pressure rises over 360 psig, turn off heat exchanger until pressure drops to 340 psig, then re-initiate heat exchanger flow
- ___ 4. Switch the heat exchanger bypass valve to automatic control
- ___ 5. Let tanks cool until wax temperature is 93 to 94°F . Vapor temperature shall be as close as possible to wax temperature in both tanks at start of run
- ___ 6. Turn off heat exchanger pumps
- ___ 7. Expel propellants according to given duty cycle by operating the engine valves

To Reload Propellants For Additional Run

- ___ 1. Switch the bypass valve to manual control and turn on pumps
- ___ 2. Reheat wax to $98+^{\circ}\text{F}$ and hold for 10 minutes
- ___ 3. Pressurize the propellant supply tank to 5 ± 5 psi higher than the pressure level in the propellant tank
- ___ 4. Open the main safety valve
- ___ 5. Open the load valve and load the tank to the required weight
- ___ 6. Close the load valve when the tank is loaded to the desired weight
- ___ 7. Close the main safety valve
- ___ 8. Turn on water to the scrubber tank

- ___9. Open the dump valve and vent the supply tank
- ___10. Turn the water off in the scrubber tank after 10 minutes
- ___11. Start running procedure at step No. 4

*Caution: - Do not cycle the bellows if the liquid temperature falls below 92°F except as directed by the test engineer