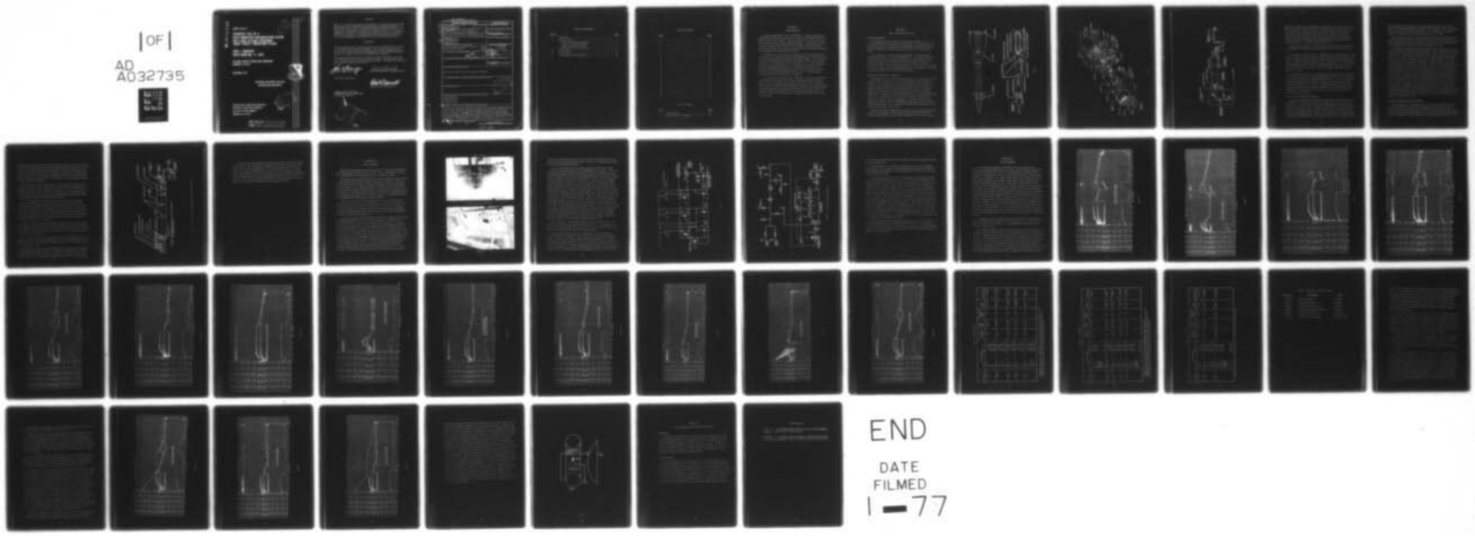
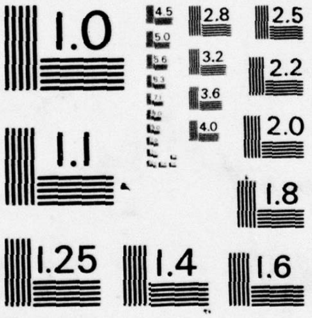
AD-A032 735 AIR FORCE ROCKET PROPULSION LAB EDWARDS AFB CALIF F/G 21/8.1
FEASIBILITY TEST OF A PULSE MODULATED PRESSURIZATION SYSTEM FOR--ETC(U)
NOV 76 J E BRANIGAN, D HAMILTON
UNCLASSIFIED AFRPL-TR-76-73 NL

1 OF 1
AD
A032735



END
DATE
FILMED
1-77



1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

12

AFRPL-TR-76-73

FEASIBILITY TEST OF A PULSE MODULATED PRESSURIZATION SYSTEM FOR A HIGH ALTITUDE SUPERSONIC TARGET VEHICLE PROPULSION SYSTEM

JOHN E. BRANIGAN
DAVID HAMILTON, LT, USAF

AIR FORCE ROCKET PROPULSION LABORATORY
EDWARDS CA 93523

NOVEMBER 1976

APPROVED FOR PUBLIC RELEASE,
DISTRIBUTION UNLIMITED

AIRFORCE ROCKET PROPULSION LABORATORY
DIRECTOR OF SCIENCE AND TECHNOLOGY
AIR FORCE SYSTEMS COMMAND
EDWARDS AFB, CA 93523

NOTICES

FOREWORD

The work reported here was performed in-house at the AFRPL under Job Order No. 469A00RJ, *Bang-Bang Pressurization. The overall objective of the work* was to evaluate the feasibility and performance of a pulse-modulated pressurization system as applied to a High Altitude Supersonic Target Vehicle Propulsion System. The report summarizes the results of this evaluation.

This report has been reviewed by the Information Office/DOZ and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals. This report is unclassified and suitable for general public release.

John E. Branigan
JOHN E. BRANIGAN, Author

David E. Hamilton
DAVID HAMILTON, LT., USAF Author

FOR THE COMMANDER

Robert L Wiswell
ROBERT L. WISWELL, Chief
Systems Evaluation Section

Edward E. Stein
EDWARD E. STEIN, Deputy Chief
Liquid Rocket Division

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

(14) 1. REPORT NUMBER: AFRPL-TR-76-73

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

(6) 4. TITLE *(and Subtitle)*: Feasibility Test of a Pulse Modulated Pressurization System for a High Altitude Supersonic Target Vehicle Propulsion System.

(9) 5. TYPE OF REPORT & PERIOD COVERED: Final rept.,

6. PERFORMING ORG. REPORT NUMBER

(10) 7. AUTHOR(s):
John E. Branigan
David Hamilton

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Air Force Rocket Propulsion Laboratory (LKCA)
Edwards AFB CA 93523

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (16) 469A00RJ (17) 00

11. CONTROLLING OFFICE NAME AND ADDRESS

(12) 48 p.

(11) 12. REPORT DATE: Nov 1976

13. NUMBER OF PAGES: 45

14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*

15. SECURITY CLASS. *(of this report)*: Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; Distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

D D C
DEC 2 1976
C

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Pulse Modulated
Pressure Switch
Pressurization
Pressure Control

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Feasibility testing was conducted on a pulse-modulated pressurization system consisting of a solenoid valve powered directly by a normally closed pressure switch. The system was tested for stability of operation and accuracy of pressure control, using a High Altitude Supersonic Target (HAST) oxidizer tank and high pressure GN_2 storage vessel. Outflow tests which simulated a wide range of HAST vehicle mission duty cycles showed the system to be stable and accurate to approximately the deadband of the pressure switch used, 2 psi.

307 720

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

The High Altitude Supersonic Target (HAST) is a reuseable target vehicle capable of cruise speeds up to Mach 4.0 at altitudes up to 100,000 ft after air launch at Mach 1.5 at 50,000 ft. The target vehicle is intended for tri-service use for training and for weapons systems evaluation. A unique feature of this vehicle is a hybrid rocket propulsion system, which uses a liquid oxidizer (inhibited red fuming nitric acid) and a solid fuel (80 weight percent polybutadiene and 20 weight percent polymethylmethacrylate).

The AFRPL served in a consultant role for the Air Force Armament Test Laboratory (AFATL) development of the HAST propulsion system and conducted a series of limited preliminary flight readiness tests (PFRT). This testing was conducted in a high altitude test facility at the AFRPL. The objectives of the PFRT were to: (1) demonstrate that the propulsion system would reliably perform the intended flight test mission, (2) verify safe altitude ignition and operation, thereby certifying flight safety and (3) obtain performance data at simulated altitudes for selected flight test missions. The PFRT program conducted by the AFRPL is reported in Reference 1.

In the conduct of the PFRT program, difficulties were experienced with the liquid oxidizer tank pressurization system and with maintaining an adequate inlet pressure to the liquid oxidizer pump. The AFATL requested that the AFRPL conduct a minimum effort feasibility test program as an alternate means of controlling the pressure in the liquid oxidizer tank and at the liquid oxidizer pump that would be more responsive to the needs of the system and be less sensitive to anamolous performance by components in the liquid oxidizer tank and feed system.

SECTION II

HAST PROPULSION SYSTEM

SYSTEM OVERVIEW

The inboard profile of the HAST vehicle is shown in Figure 1. The components of the system may be seen in the drawing. These components are part of two major sub-assemblies of the propulsion system, identified as the Oxidizer Management Assembly (OMA) and the Controlled Thrust Assembly (CTA).

Since this report is concerned only with the OMA, the CTA, which is discussed in Reference 1, will not be presented here. The OMA includes all components for the storage and pressurization of the liquid oxidizer. These include the oxidizer tank, the start valve, the directed power unit (DPU - includes the oxidizer pump, electric alternator and ram-air turbine), the nitrogen storage tank, the pressure regulators and the associated plumbing. An isometric view of the propulsion system is presented in Figure 2.

OXIDIZER MANAGEMENT ASSEMBLY

The oxidizer tank is a rolled and welded structure of 17-7 Ph stainless steel. The tank volume is 9,465 cubic inches, with a maximum oxidizer capacity of 496 pounds. The tank is divided into four compartments, as can be seen in Figure 3, so as to move the center of gravity of the vehicle aft as oxidizer is consumed and the vehicle accelerates to higher mach numbers. A surface tension screen located in the liquid communication path between the aft two compartments, coupled with a weighted, flexible, gravity-vector-following outlet tube, serve to provide liquid oxidizer to the CTA during vehicle maneuvers which tend to unport a stationary liquid outlet. The surface tension screen retains liquid oxidizer in the aft compartment by serving as a flow block in the reverse flow direction. The nominal pressure differential across the screen at maximum oxidizer flow rate is 7 psid.

Outflow from the aft compartment takes place through a flexible tube which is termed a "free siphon". This device is weighted on the free end and is flexible enough to follow the local resultant acceleration vector as the vehicle

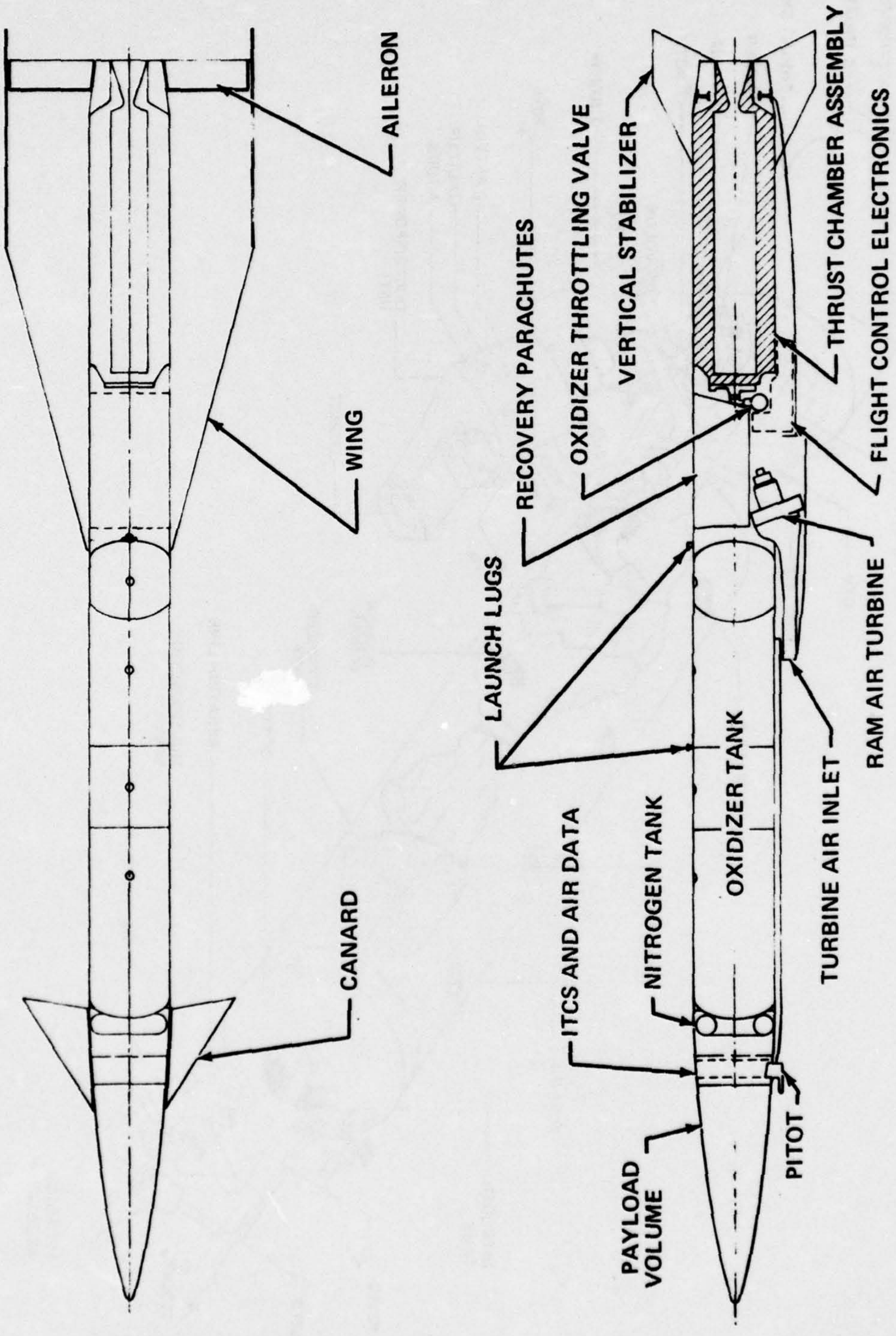

AILERON
WING
CANARD
RECOVERY PARACHUTES
OXIDIZER THROTTLING VALVE
VERTICAL STABILIZER
THRUST CHAMBER ASSEMBLY
FLIGHT CONTROL ELECTRONICS
LAUNCH LUGS
RAM AIR TURBINE
TURBINE AIR INLET
OXIDIZER TANK
ITCS AND AIR DATA
NITROGEN TANK
PAYLOAD VOLUME
PITOT

Figure 1

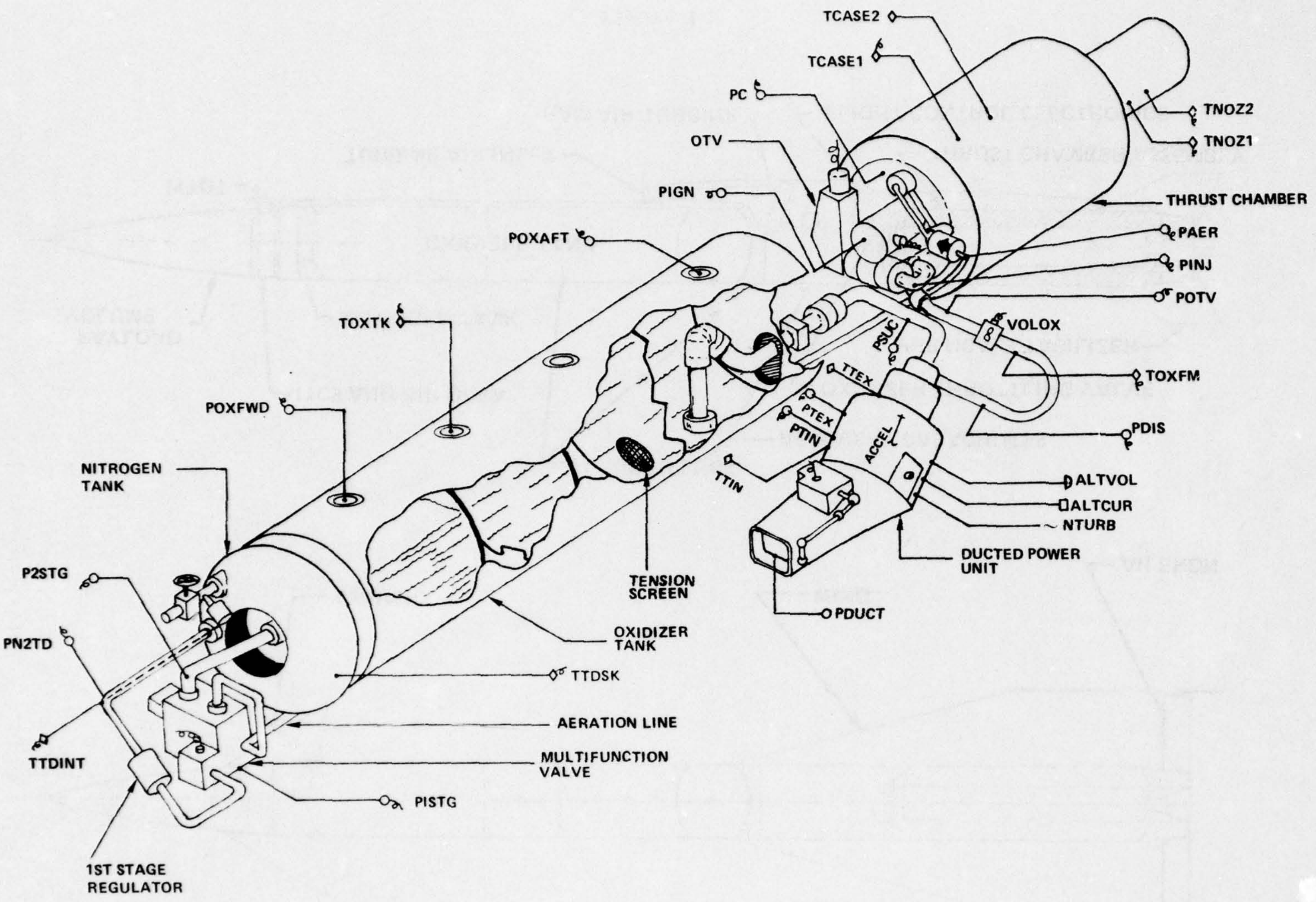

TCASE2
TCASE1
PC
OTV
PIGN
POXAFT
TOXTK
POXFWD
NITROGEN TANK
P2STG
PN2TD
TTDINT
1ST STAGE REGULATOR
TNOZ2
TNOZ1
THRUST CHAMBER
PAER
PINJ
POTV
VOLOX
PSUC
TTEX
PTEX
PTIN
TTIN
ACCEL
TOXFM
PDIS
ALTVOL
ALTCUR
NTURB
DUCTED POWER UNIT
PDUCT
TENSION SCREEN
OXIDIZER TANK
TTDSK
AERATION LINE
MULTIFUNCTION VALVE
PISTG

Figure 2

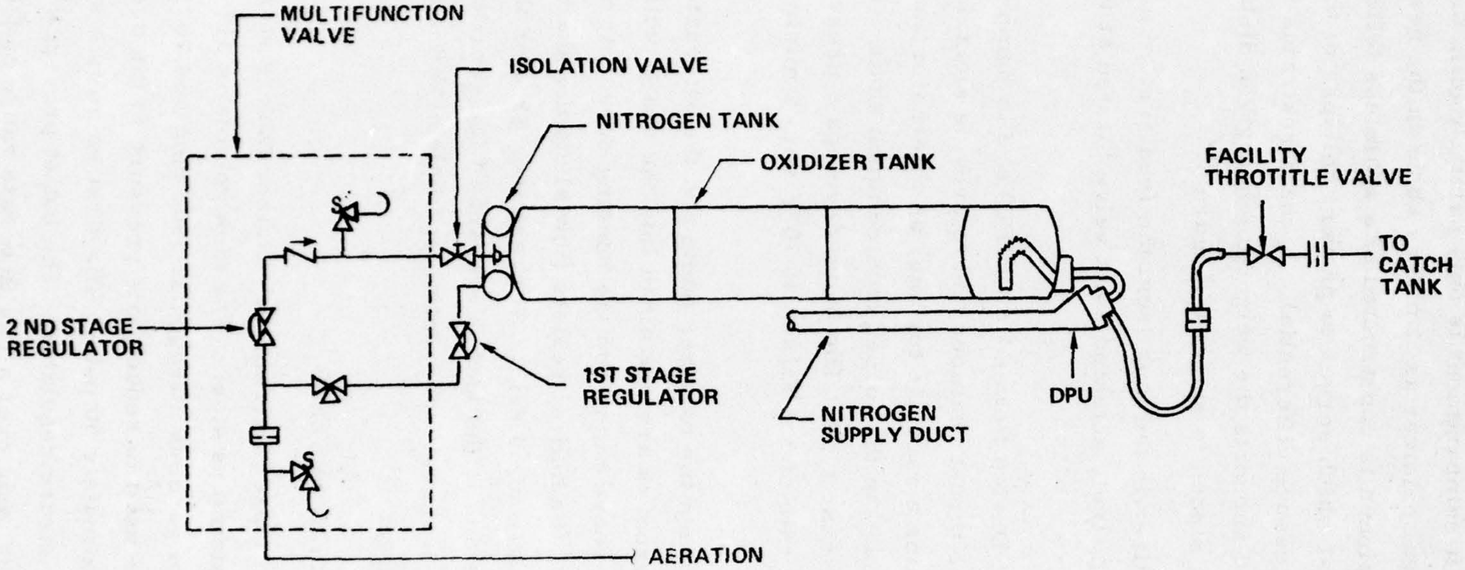

MULTIFUNCTION VALVE
ISOLATION VALVE
NITROGEN TANK
OXIDIZER TANK
FACILITY THROTITLE VALVE
TO CATCH TANK
2 ND STAGE REGULATOR
1ST STAGE REGULATOR
NITROGEN SUPPLY DUCT
DPU
AERATION
S
S

Figure 3

maneuvers. When the aft compartment is only partially full, the free end of the siphon follows the residual oxidizer as it moves about in the nearly spherical aft compartment. The siphon is constructed of a seamless teflon tube heat shrunk over a wire spiral which serves to prevent collapse of the tube by oxidizer flow induced pressure differential. A chain restrains the lengthwise extension of the wire and supports the weighted end a given distance off the compartment wall. The siphon is shown in Figure 2.

Isolation of the oxidizer in the tank from the feed system prior to launch is accomplished by an explosively actuated start valve located at the tank outlet port.

The functions of the Ducted Power Unit (DPU) are to pump the oxidizer to the pressure required by the thrust chamber and to provide electrical power to the vehicle. The unit contains a ram-air turbine, an alternator and a centrifugal oxidizer pump, all mounted in that order on a common shaft. The oxidizer pump is an unshrouded radial vane type. The pump develops a pressure rise of 685 psid at an oxidizer flow rate of 3.6 lb/sec at 70°F with a minimum suction pressure of 30 psia.

A dynamic seal between the oxidizer pump and the alternator uses the visco-seal concept. Helical grooves are machined into the shaft, with a very small clearance between the groove bands and the housing core. At normal operating speed of the pump shaft, the helical resists flow along the shaft toward the alternator up to a pressure of 50 psid. At pressures greater than this value, oxidizer leakage occurs and is dumped overboard of the vehicle through a seal cavity drain. Oxidizer leakage represents lost impluse and hence reduced vehicle mission capability.

FLIGHT PRESSURIZATION SYSTEM

Gaseous nitrogen for pressurizing the oxidizer tank is stored in a toroidal tank made of 17-7 PH stainless steel. The tank volume is 317 cubic inches, containing 3.3 pounds of gaseous nitrogen at 3500 psig and 70°F. Two stages of pressure regulation are used to reduce this pressure to the desired oxidizer tank pressure of approximately 50 psig. The first stage is a spring reference, piston actuated gage pressure regulator. The outlet pressure regulation band is specified as 340 to 280 psig over a gas flow rate range of 1 to 10 scfm. The second stage pressure regulator is contained within the Multi Function Valve (MFV) and is supplied directly from the first stage regulator. The second stage is the same type as the first stage regulator. The required outlet pressure range is 68 to 53 psig over a gas flow rate range of 1 to 8 scfm.

An aluminum burst disc at the oxidizer tank pressurization inlet isolates the regulators from the oxidizer. The disc ruptures when a pressure differential of 20 ± 5 psid exists in the gas flow direction. The burst disc can withstand a pressure differential of 150 psid in the direction opposed to gas flow.

The difficulties experienced during the AFRPL PFRT program were, in part, related to the pressurization system and resulted in below normal oxidizer pump inlet pressure. If this pressure drops below the minimum allowable for pump operation, the result is pump cavitation, a loss of oxidizer flow and ultimately a flame-out in the thrust chamber. If this were to happen in flight, the vehicle would be lost since the propellant combination is non-hypergolic and a second commanded ignition capability is not provided. Hence, even if oxidizer flow were to resume after a flame-out, proper operation of the CTA would not be possible. The most probable cause of below normal pump inlet pressure is an excessive pressure drop across the tension screen between the two aft compartments of the oxidizer tank. This could be caused by foreign matter clogging the screen. Since the pressure regulation system controls the pressure at the regulator outlet, it could neither sense nor accomodate an abnormally high tension screen pressure drop. The result of the pressure drop must be a reduction of pump inlet pressure. Clogging of the surface tension screen was in fact observed during the PFRT program. Other possible causes for below normal pump inlet pressures might be failure of the aluminum burst disc to open completely, thereby introducing an excessive gas pressure drop and a restricted siphon introducing excessive liquid pressure drop.

MODIFIED PRESSURIZATION SYSTEM

The modification to the pressurization system which was tested consists basically of replacing the continuous modulating control of tank pressure, as performed by the second stage regulator, with a pulse modulating control system. This is accomplished by replacing the second stage regulator with a fast response electric solenoid valve directly operated by a pressure sensing switch. The pressure switch is located in the oxidizer feed line between the tank outlet and the pump inlet. By sensing pressure at this location, the tank pressure is controlled so as to provide the minimum required pump inlet pressure independent of the pressure drop in the feed system up to this point. Higher than normal pressure drops in the system are inherently compensated by the pressure switch driving the tank pressure to a higher value. A schematic of the modified pressurization system is presented in Figure 4.

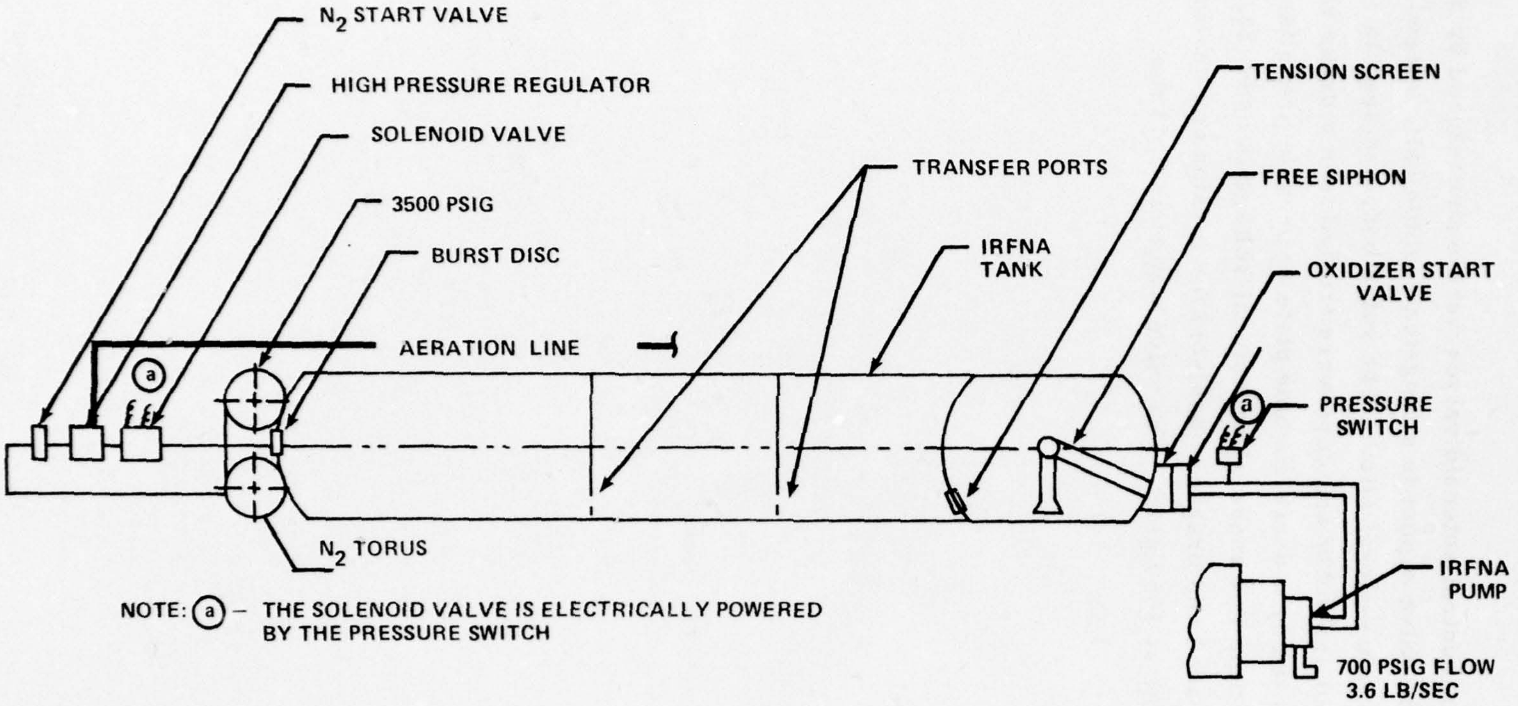
The solenoid valve in the gas supply line to the oxidizer tank also serves to isolate the pressure control components (i.e. the first stage regulator and the pressure relief valves) from the oxidizer in the tank at the end of a mission. In the present system, oxidizer vapors migrate back and cause degradation of the non-compatible elastomeric materials in the components (including the second stage regulator) requiring refurbishment before reuse.

Pulse modulated pressurization systems have been proven feasible by exploratory development efforts (Reference 2) and by use on one Air Force operational launch vehicle, the Martin Marietta Co Transtage. These systems have differed from the system suggested for the HAST vehicle in that the pressure switch senses pressure in either the tank ullage gas or the gas feed line upstream of the pressurized tank. Control of the tank pressure by sensing pressure in the liquid outlet line was considered sufficiently unique to require a feasibility demonstration test program.

The major components of the HAST pulse modulated pressurization system were a pressure switch mounted in the liquid outflow line from the oxidizer tank and a solenoid valve electrically driven directly by the pressure switch, mounted in the gaseous nitrogen feed line. These components are discussed individually in the subsequent paragraphs.

The pressure switch used was the Hydra-Electric part number 572074. Two pressure switches were used in the program and are of identical design, the only difference being the actuating pressure of 40 and 50 psia. The switches are of the normally closed type.

A belleville spring is used to provide snap action actuation, thereby suppressing any tendency for contact chatter. The pressure switch contacts carry the valve current, so secondary switches or relays are not needed. The pressure switch deadband (i.e. the make-break pressure difference) is 2 psia or ±1 psia.



NOTE: ⓐ – THE SOLENOID VALVE IS ELECTRICALLY POWERED BY THE PRESSURE SWITCH

Figure 4. HAST Oxidizer Management Assembly Schematic

The pressurant control solenoid valves were manufactured by Sterer as part number 22130. The valve poppet is a tungsten carbide ball, brazed to the solenoid core with a chrome-nickel alloy. The valve body and seat is 304 CRES steel. The solenoid assembly and core were treated with a dense electrolytic nickel plating followed by a dense chrome plate to provide propellant compatibility. The valve opening time is 8 msec when nominal voltage is used (28. VDC). The poppet is spring loaded and pressure assisted for closing and sealing. Internal leakage is 10 sec/hr at 1650 psig. The valve weight is 0.44 lbs.

SECTION III

TEST FACILITY

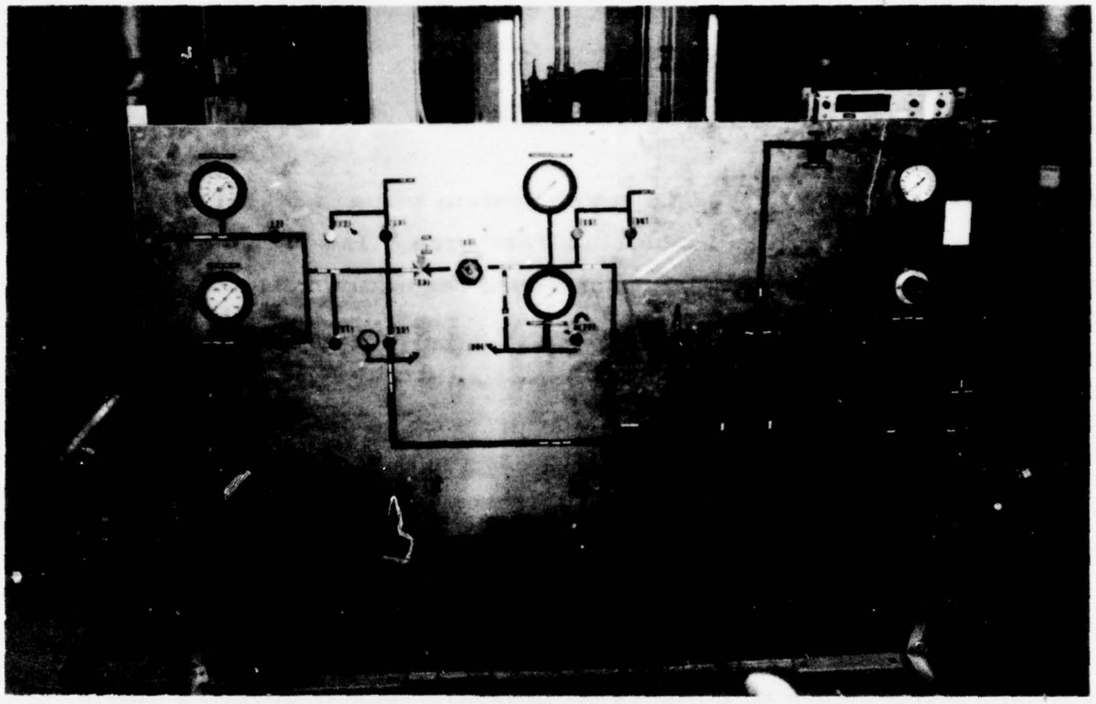
The experimental HAST pressurization system was assembled and tested at the Hydrodynamics Laboratory in the 1-14 Test Area. The purpose of the test was to demonstrate a pulse modulating pressure regulation system.

The pressurization gas used was gaseous nitrogen supplied from the facility nitrogen system and regulated by facility components to 3500 psig. This pressure was used in the later phases of the test program to pressurize the flight gaseous nitrogen tank. A regulated pressure of 1700 psig was used in the first phase of testing to supply a facility regulator, which provided an outlet pressure of 300 psig to the test system solenoid valve. This regulator simulated the first stage regulator in the flight system. Facility type pressure relief valves were used throughout the facility gaseous nitrogen system.

Since the test article was a flight type pressure vessel, special safety precautions were taken to protect test personnel from possible rupturing of the oxidizer tank and the high pressure nitrogen storage tank. These precautions consisted of a blast shield, which also served as a control panel, between the test article and the test personnel, and a 3/8 inch steel shroud surrounding the high pressure torus tank (see Figure 5).

In order to prevent overpressurization of the gaseous nitrogen system or the test tanks, two methods were used. The first method involved the use of facility relief valves. A total of three relief valves were used, one in the test torus tank, set at 3800 psig, one in the system between the 300 psig regulator and the solenoid valve, set at 400 psig, and the third on the oxidizer tank, set at 80 psig. As a back-up method, a pressure transducer output from the oxidizer tank was fed to a strip chart record on which a microswitch was installed. This microswitch, set to trip at 80 psig acted to close the gas supply to the tank and to relieve the pressure in the tank. In addition to these two overpressure protection methods, the test conductor could manually inhibit the action of the pressure switch-solenoid valve combination on the test system to prevent additional pressurization of the oxidizer tank if the pressure were to exceed a safe valve. It should be noted that it was essential that the pressure control

Control Panel



HAST Tank Test Installation

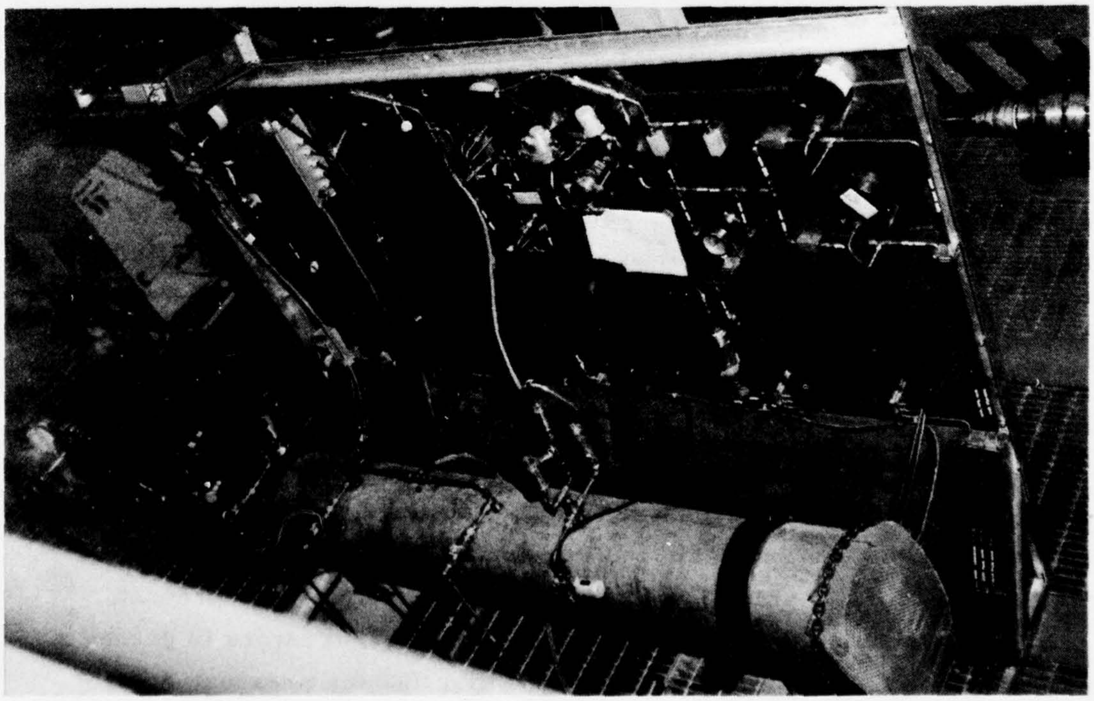


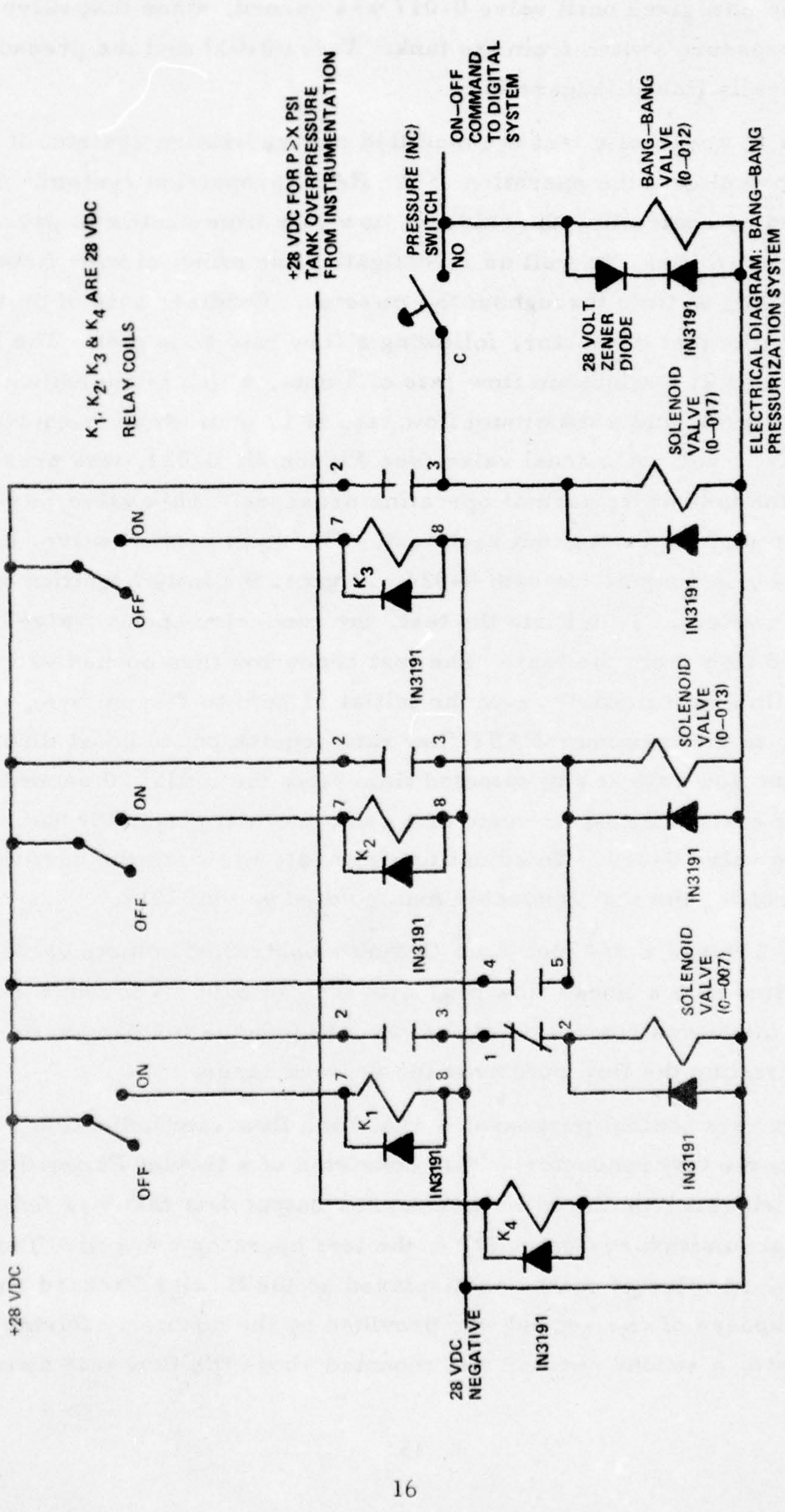
Figure 5

circuit not be energized until valve 0-017 was opened, since that valve would isolate the pressure switch from the tank. Valve 0-017 and the pressure switch were electrically linked (Figure 6).

In order to accurately test the modified pressurization system, it was necessary to duplicate the operation of the HAST propulsion system. This was accomplished by controlling the oxidizer flow rate time profile to preselected HAST mission profiles, as well as investigating the effect of wide flow variations at random points in time throughout the mission. Oxidizer rate of outflow was controlled by the test conductor, following a flow rate time plot. The HAST system operates at a minimum flow rate of 4 gpm, which is equivalent to sustainer thrust level, and a maximum flow rate of 17 gpm which is equivalent to booster thrust level. A manual valve (see Figure 7), 0-024, was preset to flow 4 gpm with the tank at its normal operating pressure. This valve was left open to the preset position throughout each test. The main control valve, 0-019, was preset to flow, in conjunction with 0-024, 11 gpm, the initial ignition flow rate of the HAST system. To initiate the test, the conductor opened valve 0-017, which started flow from the tank. The test conductor then opened valve 0-019 to increase flow rate linearly from the initial 11 gpm to 17 gpm over a 20 second time period, to the maximum HAST flow rate, equivalent to boost thrust level. To reduce the flow rate at any selected time after the initial 20 second time period to the sustain thrust flowrate of 4 gpm, the test conductor had only to quickly close valve 0-019. To adjust the flow rate to match the desired flow rate-time profile, the test conductor manipulated valve 0-019.

Valve 0-019 was a 3/4 inch Anin Domotor controlled remote valve. The valve was fitted with a linear flow plug with a C_V of 6.0. A 1/2 inch line was installed on the downstream side of the valve to provide the proper flow restriction for controlling the flow rate over the desired range.

For flow rate control purposes, a real time flow rate indication was accessible to the test conductor. This consisted of a Hewlet Packard digital counter, which received the same flow-meter output data that was fed to the digital data acquisition system. Thus, the test operator controlled flow rate to a predetermined value of counts as displayed on the Hewlet Packard counter. A flow rate response of one second was provided by the counter. During the last series of tests, a second counter was mounted above the flow rate counter and



ELECTRICAL DIAGRAM: BANG–BANG PRESSURIZATION SYSTEM
2 JUNE 75 J. FREEMAN

Figure 6

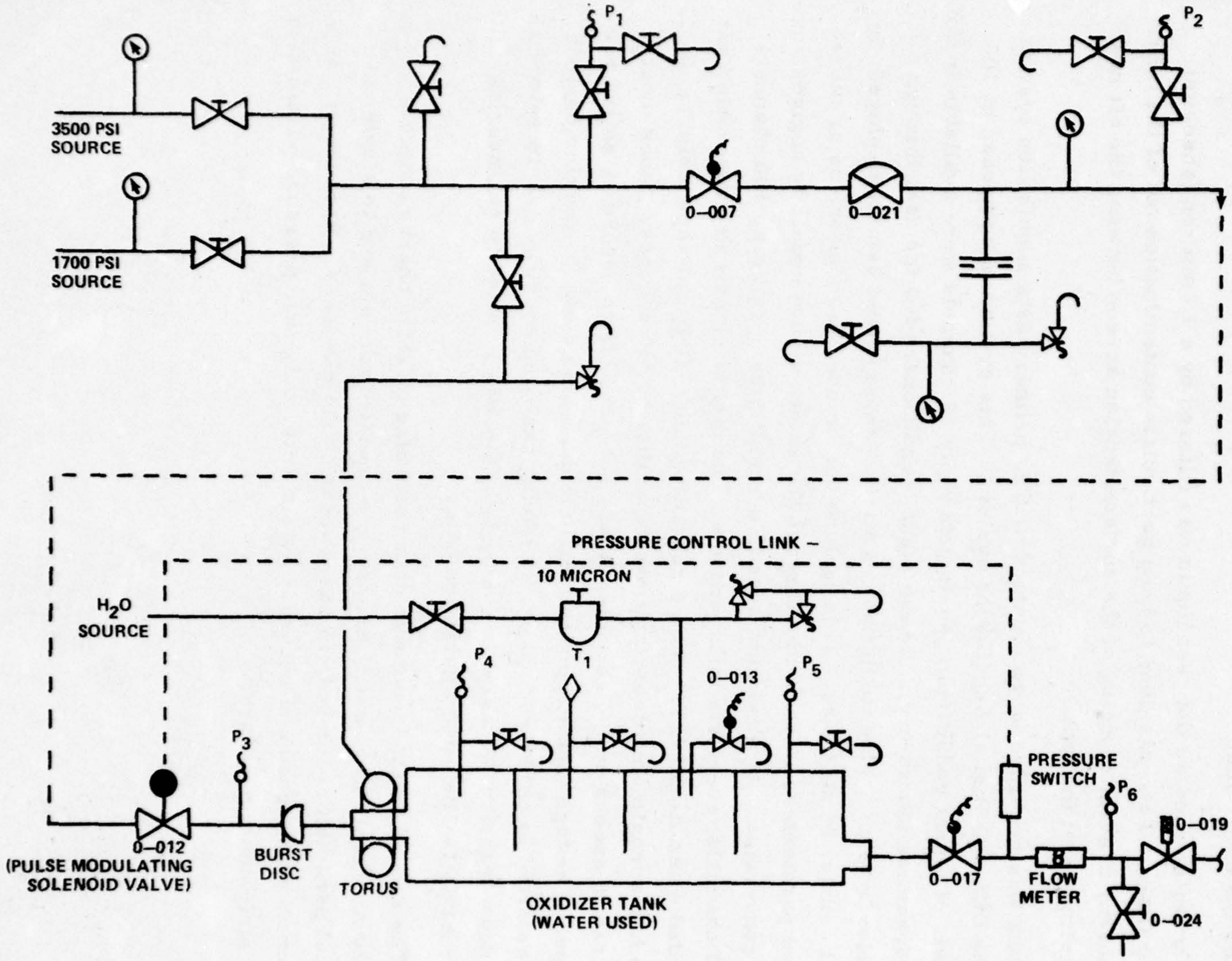


Figure 7. Test Installation Schematic

was used to accumulate the flow meter output counts and thus integrate the flow rate for the entire test.

The water used as the test liquid was filtered by a 10 micron (absolute) facility filter. This was done to keep particulate contamination out of the tank and thereby prevent clogging of the surface tension screen between the aft two compartments of the tank.

Data was recorded by two methods. The primary data acquisition system was the SEL 600 Digital Acquisition system. This system is composed of 100 channels of signal conditioning equipment (only 10 channels were available in the hydrodynamics laboratory). These signal conditioners fed the data through a multiplexer to an analog to digital converter. One channel can be displayed, in digital counts, at all times. This feature can be used to monitor one or more critical parameters in real time through the known digital counts to engineering units conversion. At maximum speed, the multiplexer can scan 100 channels (or 10 channels) every six milliseconds. The digital signals are assembled and recorded on an Amplex/TM-3 tape recording unit. Only one tape could be used, which had a maximum recording time capability of 240 seconds. Since most tests ran in excess of 300 seconds, it was not possible to record an entire run on tape. The tape was stopped during long duration constant condition periods and restarted to either record events during changing conditions or to record the shut-down transient behavior. The digital data was reduced to engineering units by the AFRPL-CDC 6400 digital computer.

The second method used was data recording on strip chart recorders. Four Mosley Autografs were used, primarily as quick-look data and to single out critical parameters for system operational safety purposes. Because of limited equipment rack space and recorder availability, only four pressure parameters were strip chart monitored.

SECTION IV

TEST PROGRAM

The evaluation test program consisted of a series of exploratory or check-out, tank explusions followed by a number of selected HAST flight profile flow rate profile expulsions. The check-out explusions, numbered runs 101 through 103, consisted of a variety of out-flow time profiles, in which the basic initial flow rate ramp of 11 to 17 gpm in 20 seconds was followed by short and long outflow durations with randomly located rapid increases and decreases between sustain and boost flow rates. The purpose of these rapid flow rate excursions was to investigate the pressure control stability and accuracy of the system and to make system configuration changes as necessary. No changes were found to be necessary since the system as originally configured was found to be stable and accurate to approximately the same accuracy dictated by the deadband of the pressure switch. A 50 ± 1 psia pressure switch was used for the check-out explusion tests. The tank ullage pressure was set to 63 psia before the start of outflow. Because of the exploratory nature of these explusions and since they were not preplanned, no data from these tests are presented. Time plots of all critical parameters for the remaining explusion tests are presented in Figures 8 through 20, along with a narrative discussion of selected test runs in the succeeding paragraphs. The nemonics of the test variables are defined in Table 2.

A summary of the test conditions and flow profiles is presented in Table 1. Only selected tests will be specifically discussed as being representative of the entire spectrum of tests conducted. The remaining tests varied only in the outflow rate-time profile.

Tests 104A and 104C were to explore the effect of time at boost flow rate conditions on the control accuracy of the pressurization system. Test 104C was run with a longer period of initial boost flow rate, 120 seconds compared with 20 seconds, to investigate the effect of ullage volume on tank pressure and pump inlet pressure. It may be seen that the result of the longer duration boost flow rate was to increase all system pressures after the flow rate was reduced to sustain flow rate because of the larger ullage volume developed in the tank. This is a fundamental characteristic of a control system which regulates a delivered pressure as opposed to a supply pressure. If the liquid flow pressure drop is

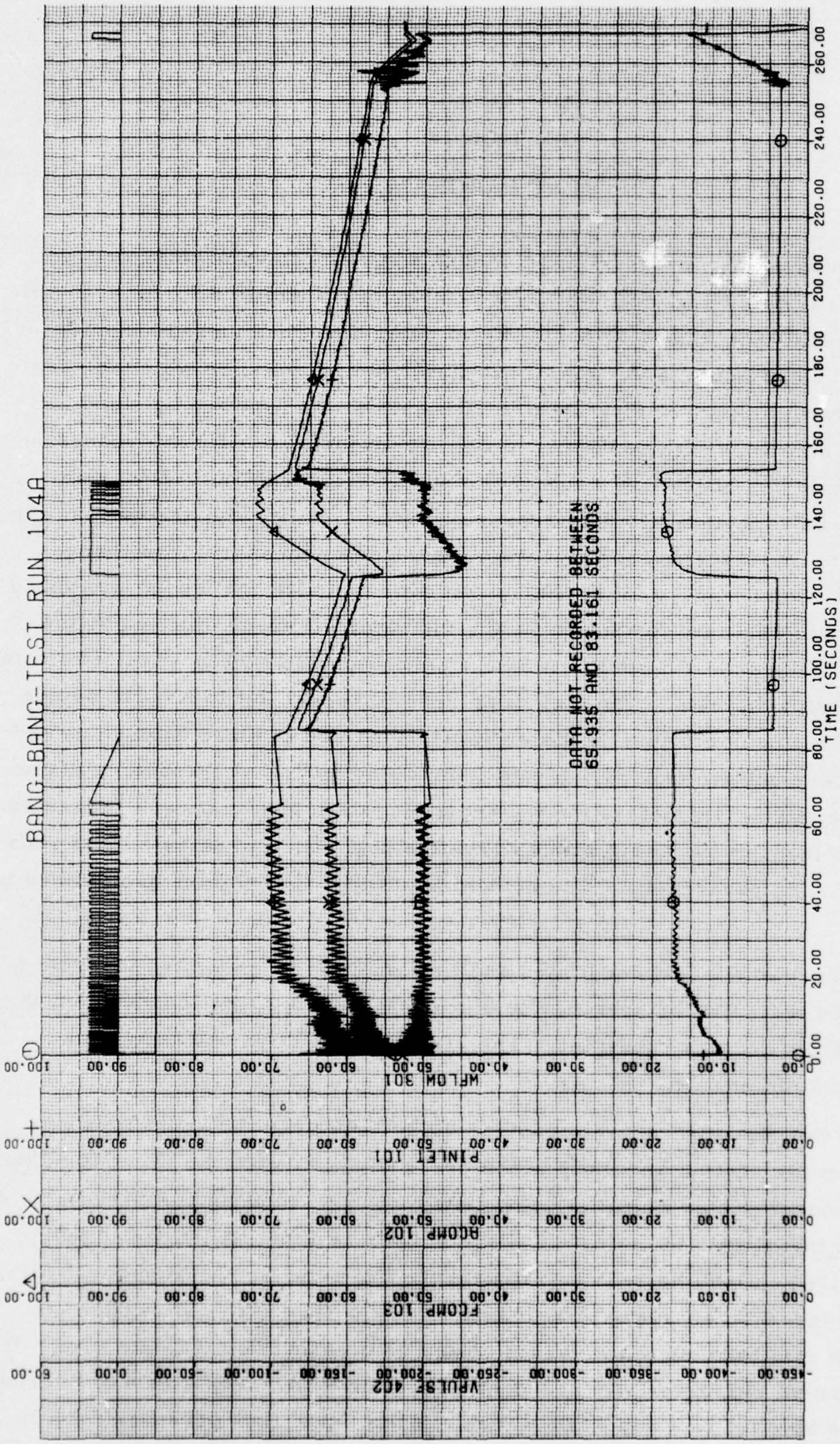

BANG-BANG-TEST RUN 104A
DATA NOT RECORDED BETWEEN
65.93S AND 83.161 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
VPULSE 402
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 8

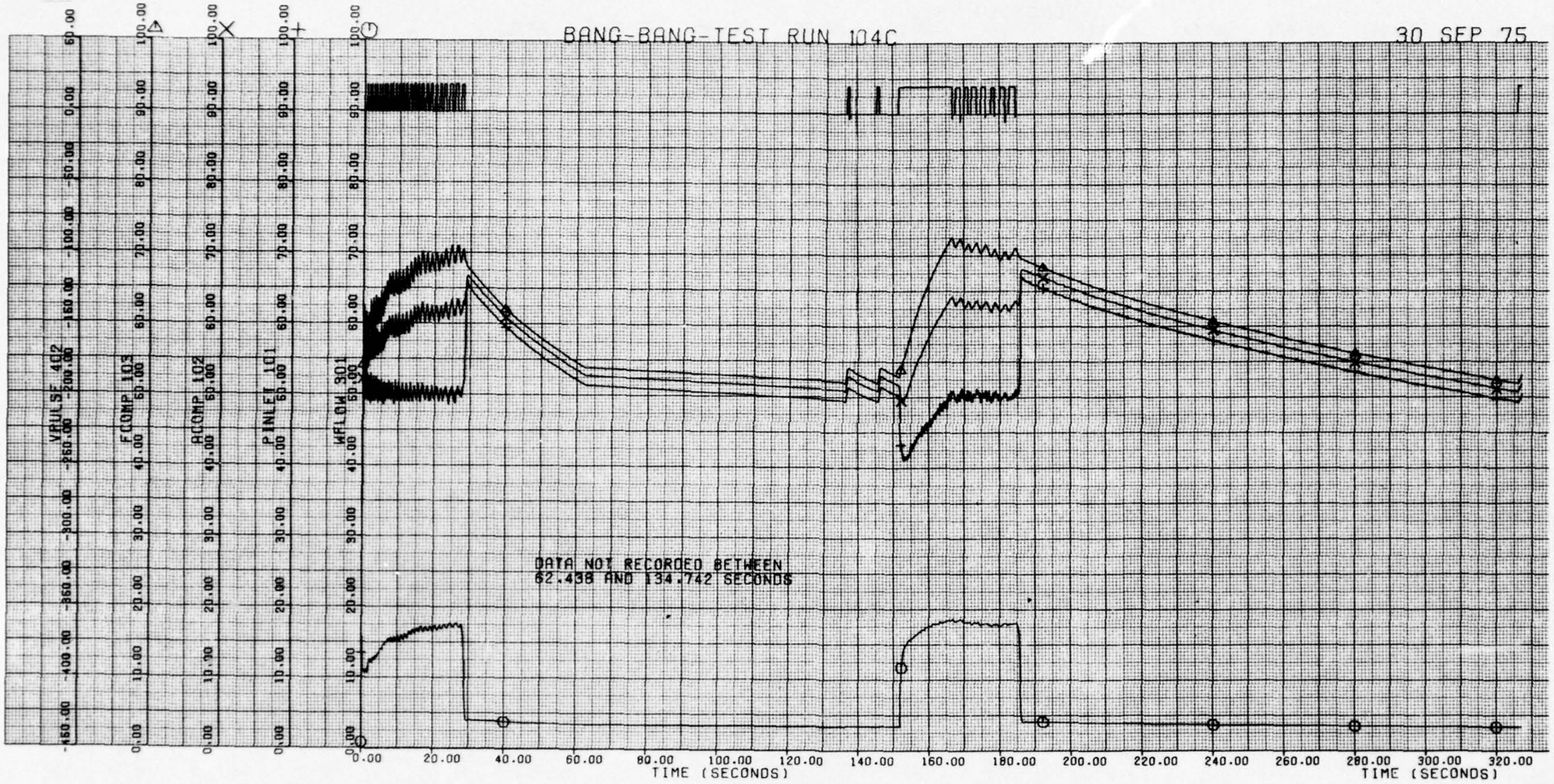

BANG-BANG-TEST RUN 104C
30 SEP 75
VRULSE 402
FCOMP 103
ACOMP 102
PINLET 101
WFLOW 301
DATA NOT RECORDED BETWEEN
62.438 AND 134.742 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
320.00
TIME (SECONDS)
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00

Figure 9

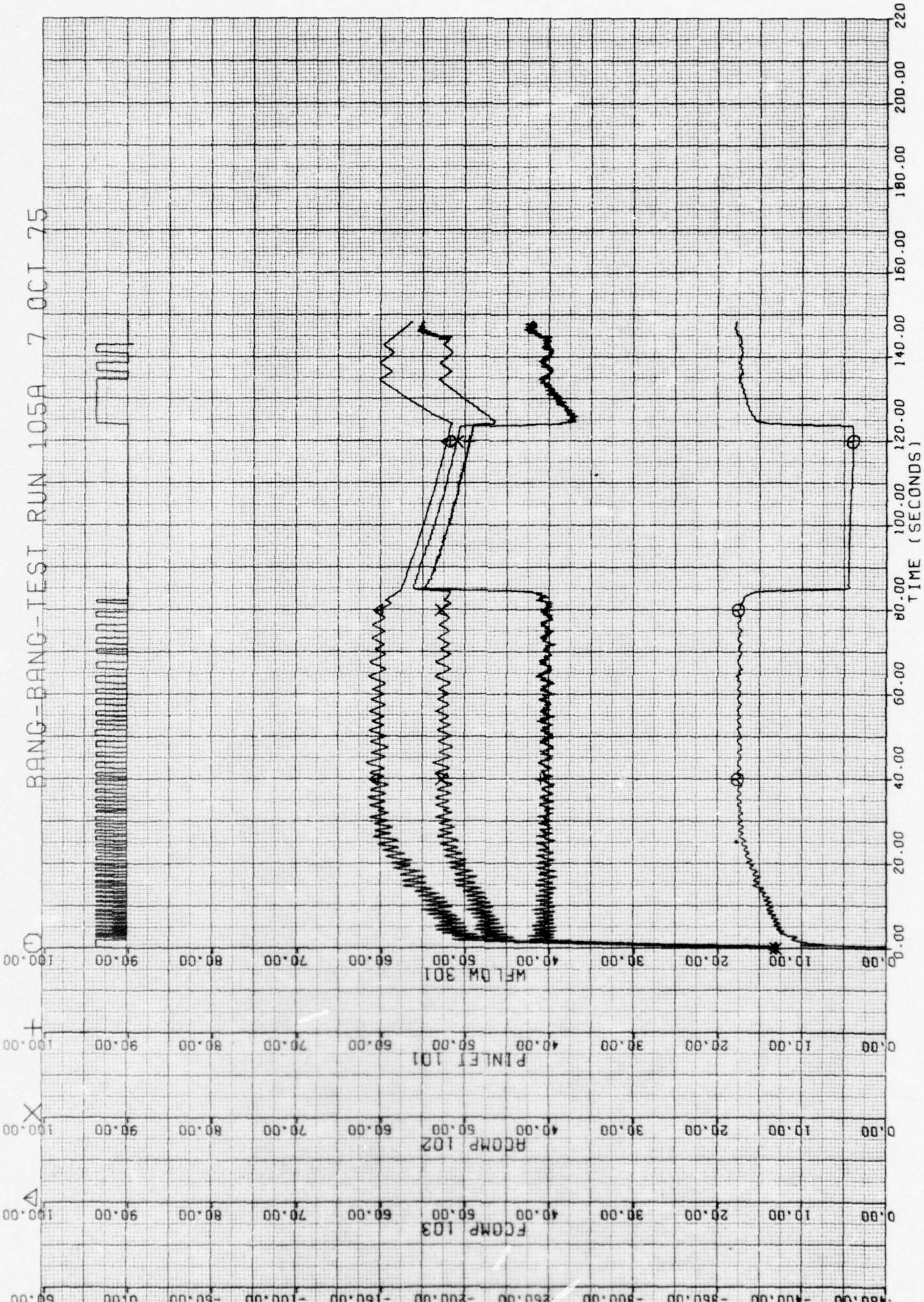

BANG-BANG-TEST RUN 105A 7 OCT 75
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
VPULSE 402
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 10

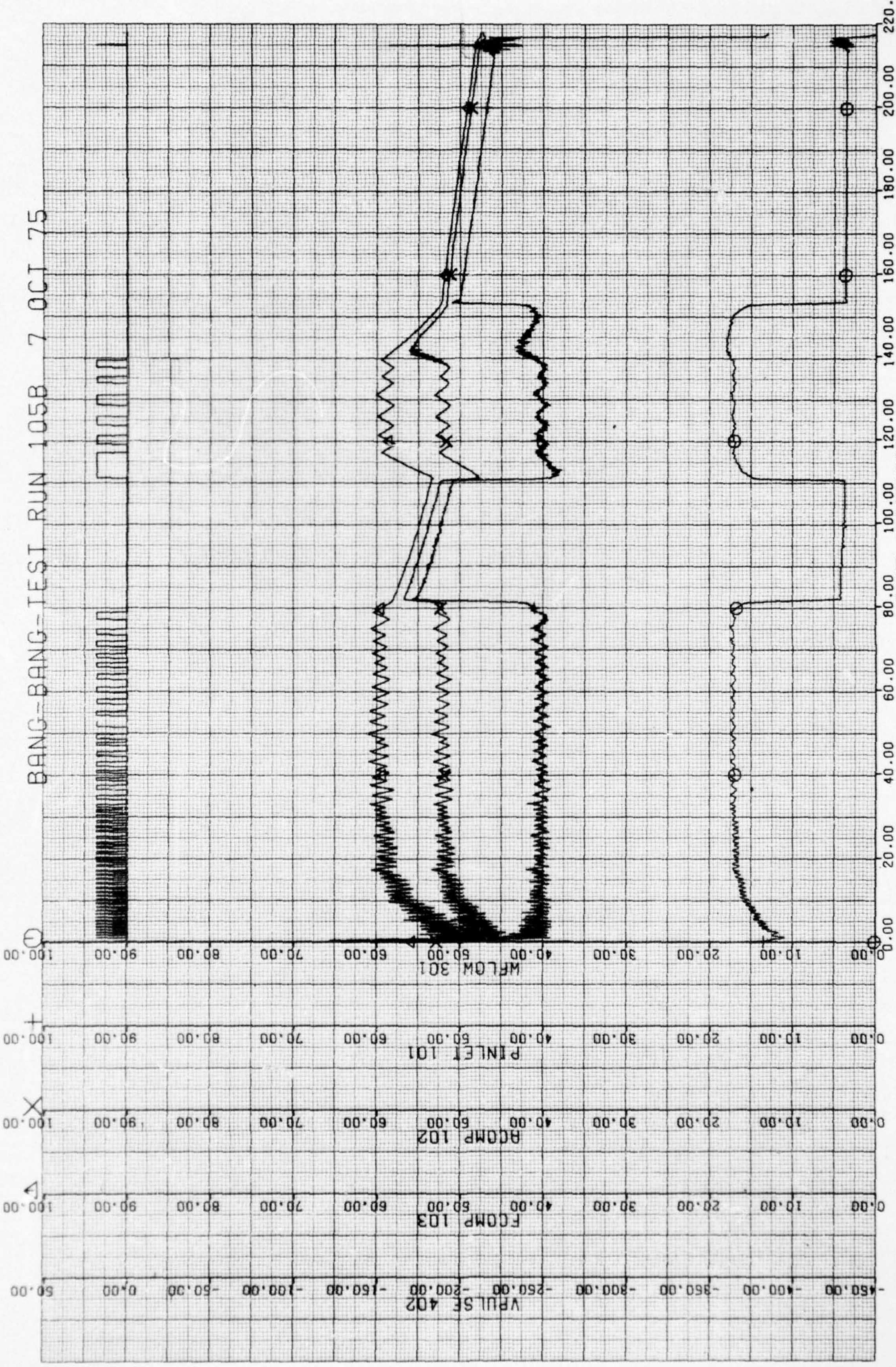

BANG-BANG-TEST RUN 105B 7 OCT 75
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
VPULSE 402
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 11

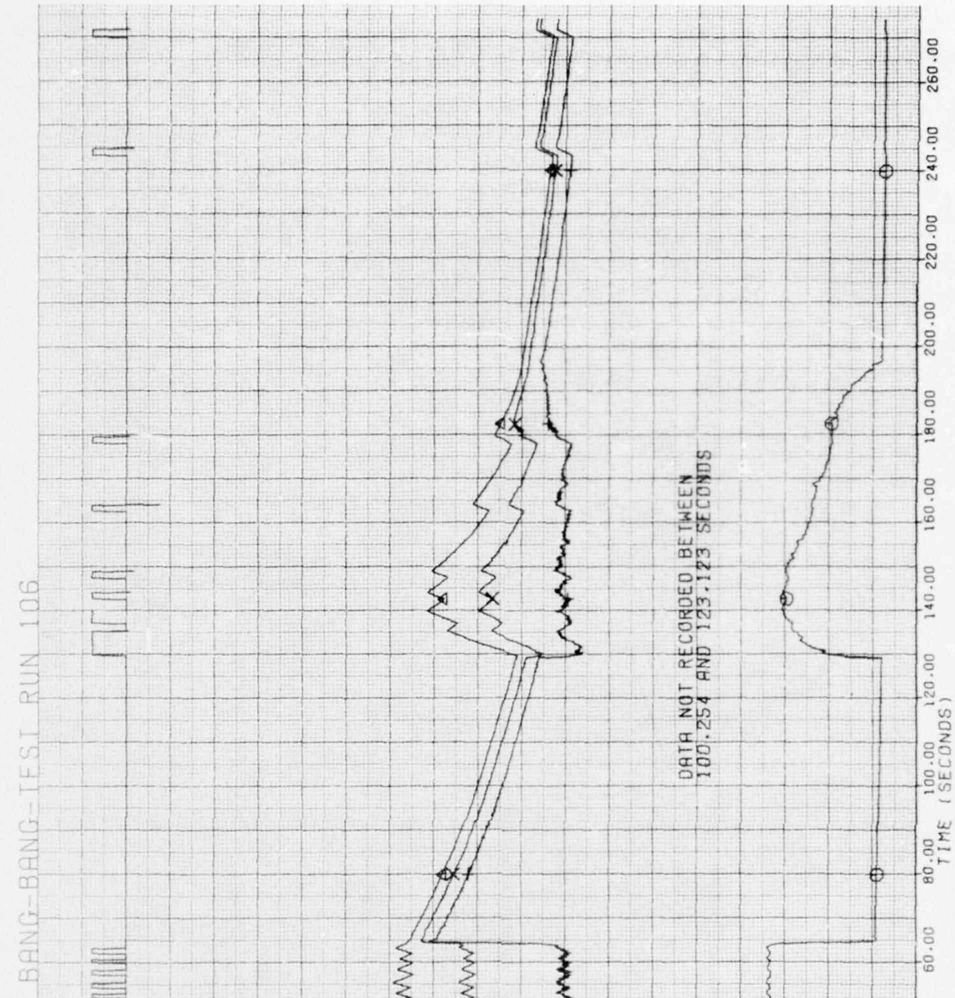

BANG-BANG-TEST RUN 106
DATA NOT RECORDED BETWEEN
100.254 AND 123.123 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
VPULSE 402
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 12

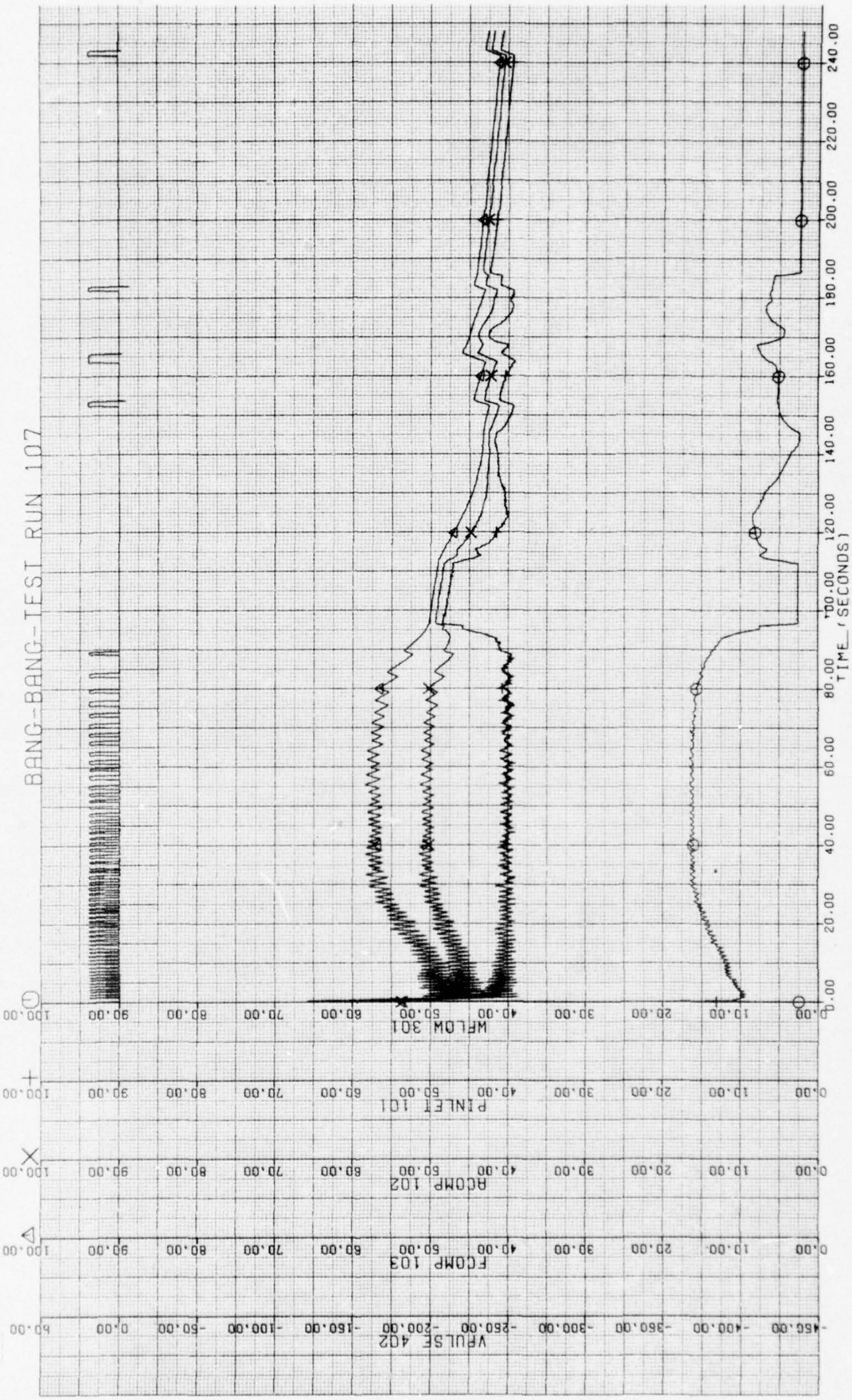

BANG-BANG-TEST RUN 107
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
VPULSE 402
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 13

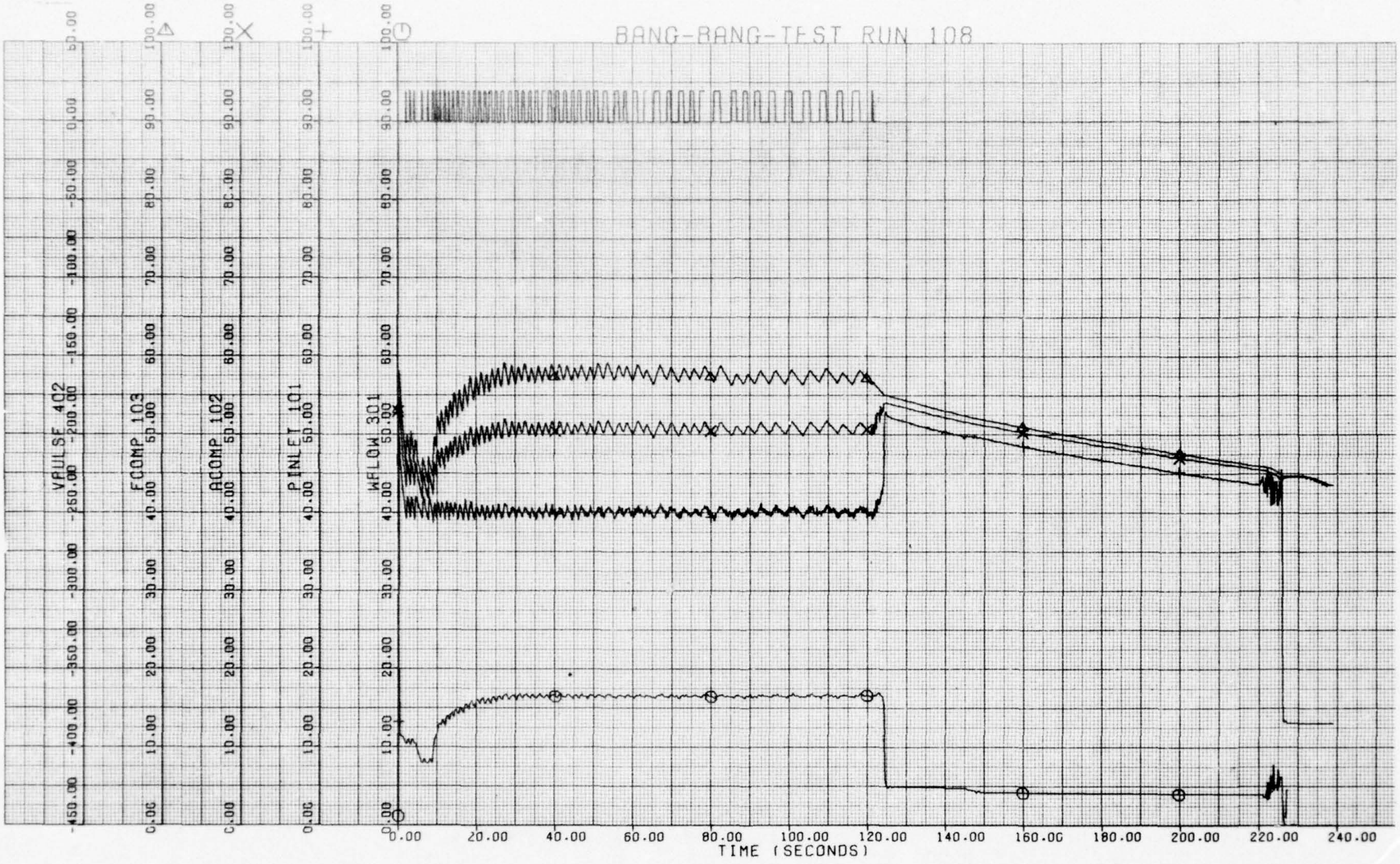
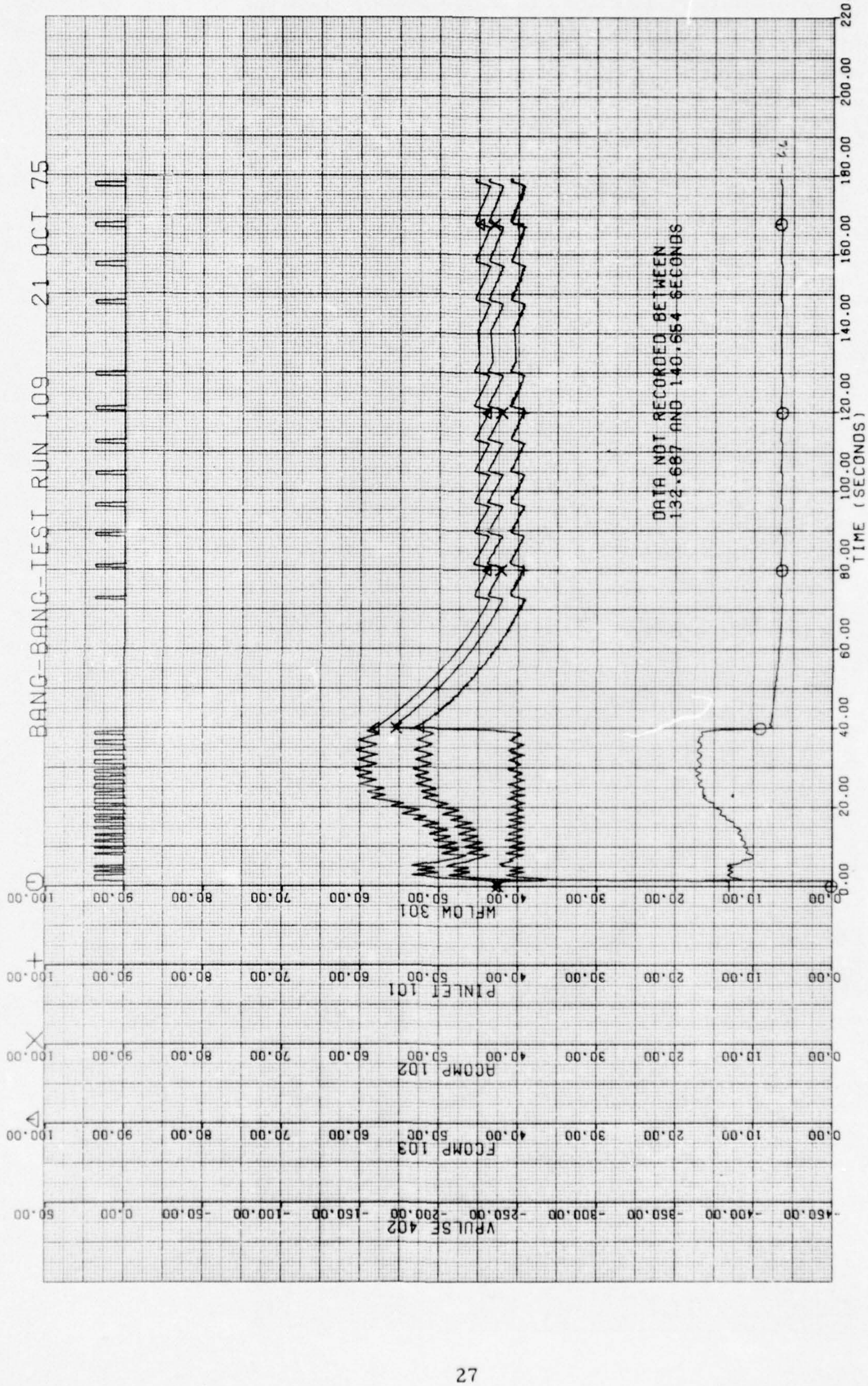

BANG-BANG-TEST RUN 108
VAULSE 402
FCOMP 103
ACOMP 102
PINLET 101
WFLOW 301
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
TIME (SECONDS)

Figure 14



BANG-BANG-TEST RUN 109 21 OCT 75

DATA NOT RECORDED BETWEEN 132.687 AND 140.654 SECONDS

Figure 15

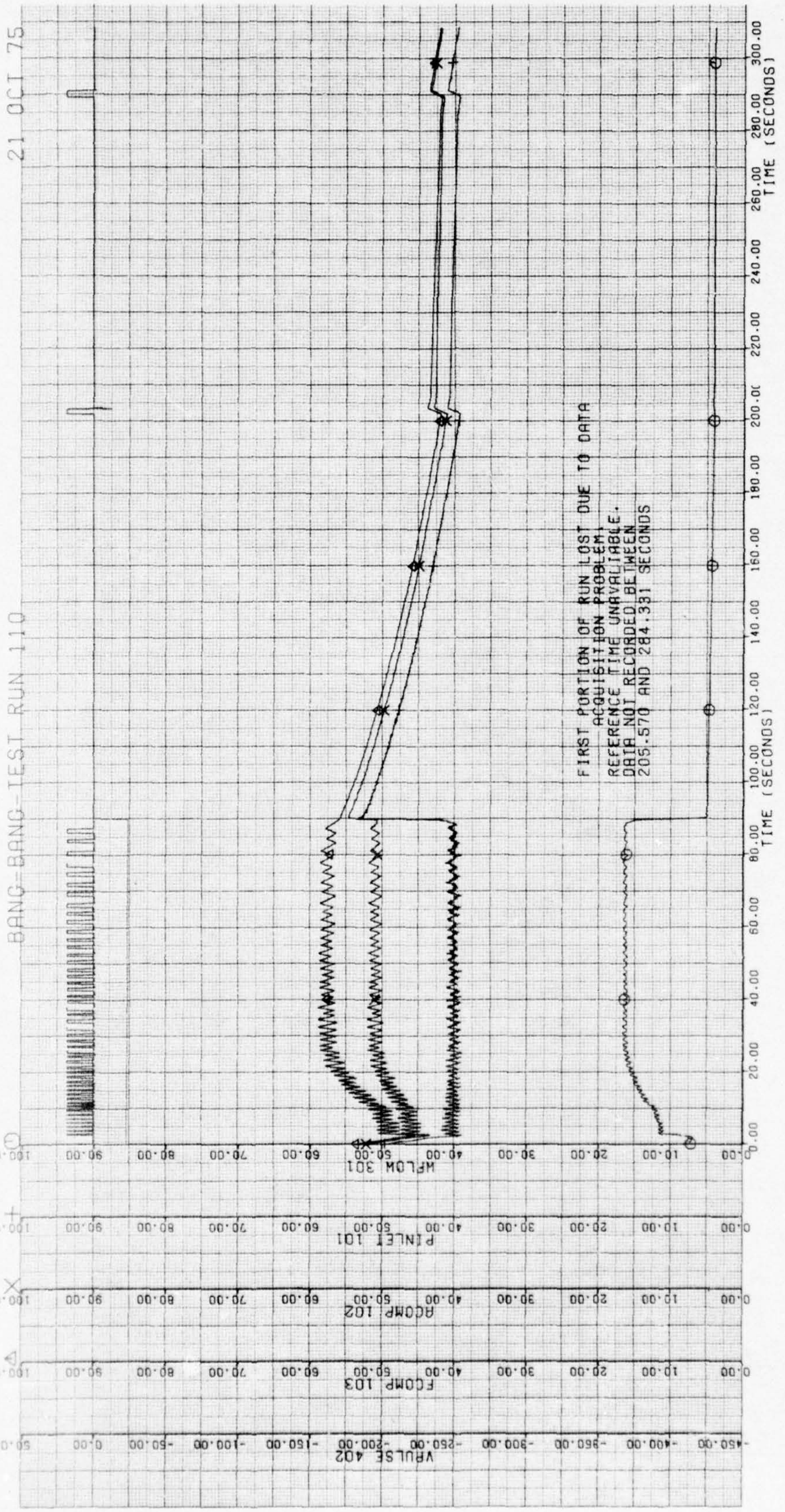

BANG-BANG-TEST RUN 110
21 OCT 75
FIRST PORTION OF RUN LOST DUE TO DATA
ACQUISITION PROBLEM.
REFERENCE TIME UNAVAILABLE.
DATA NOT RECORDED BETWEEN
205.570 AND 284.331 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
0.0
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
VPULSE 402
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.0
50.00

Figure 16

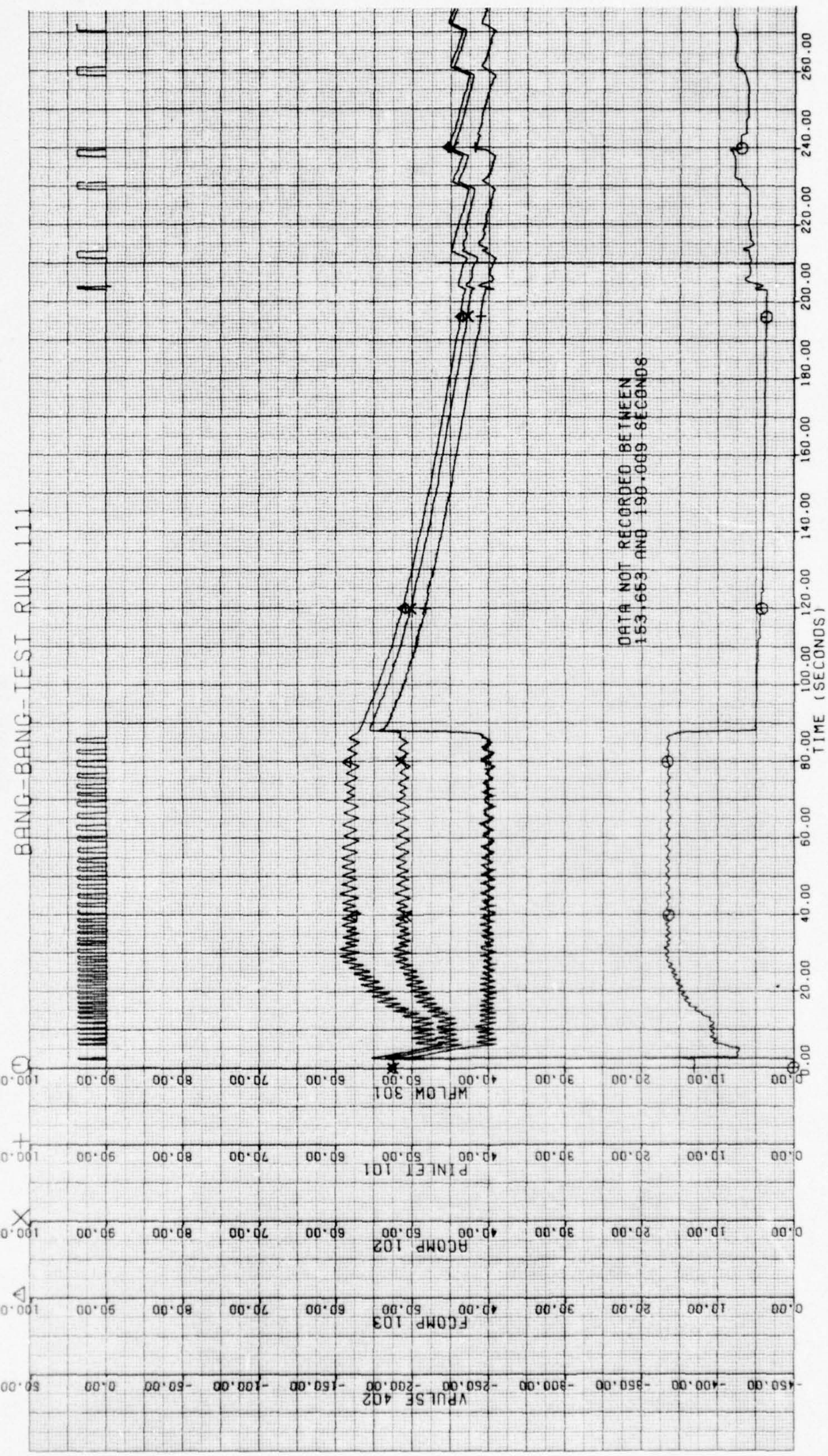

BANG-BANG-TEST RUN 111
DATA NOT RECORDED BETWEEN
153.653 AND 190.009 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
VPULSE 402
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.0
50.00

Figure 17

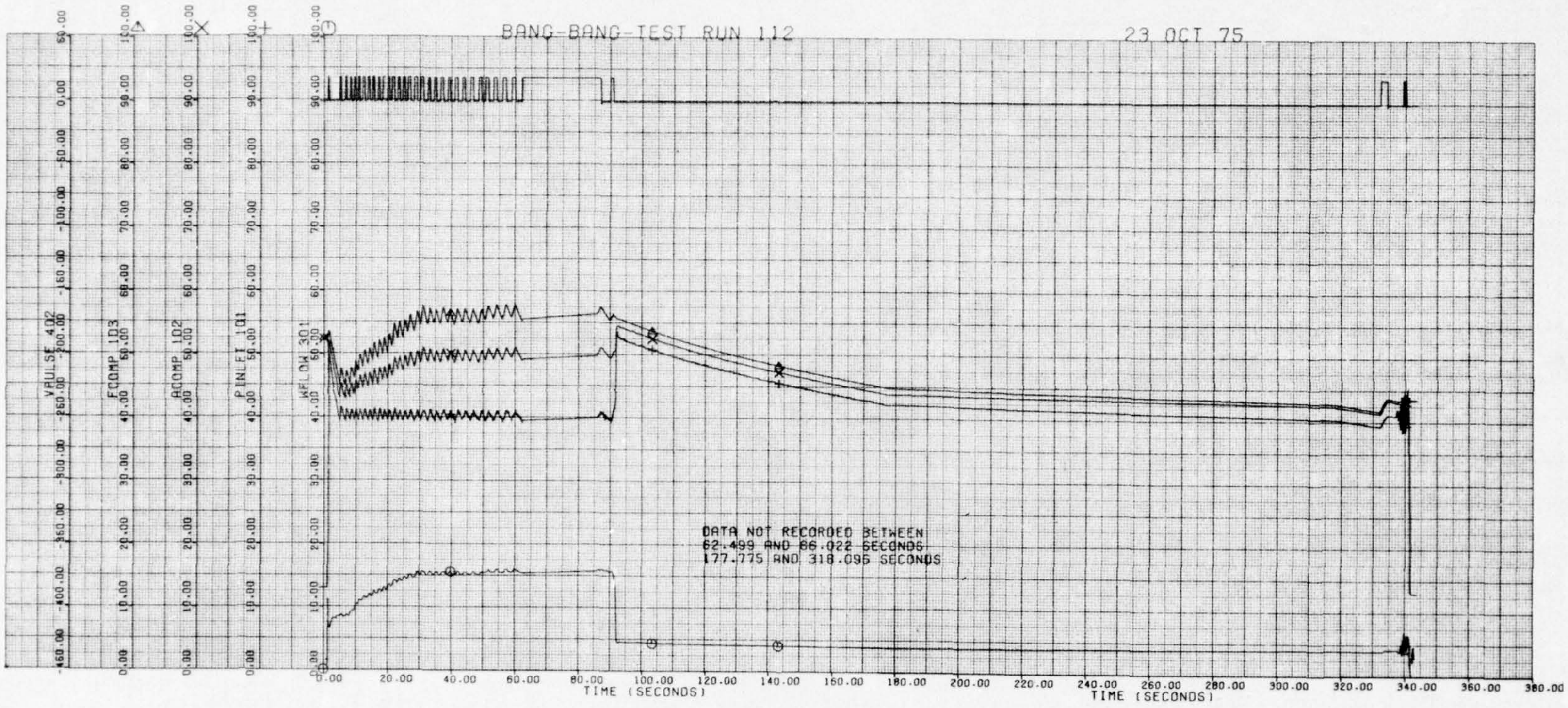

BANG-BANG-TEST RUN 112
23 OCT 75
VPULSE 402
FCOMP 103
ACOMP 102
PINLET 101
WFLOW 301
DATA NOT RECORDED BETWEEN
62.499 AND 86.022 SECONDS
177.775 AND 318.096 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
320.00
340.00
360.00
380.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 18

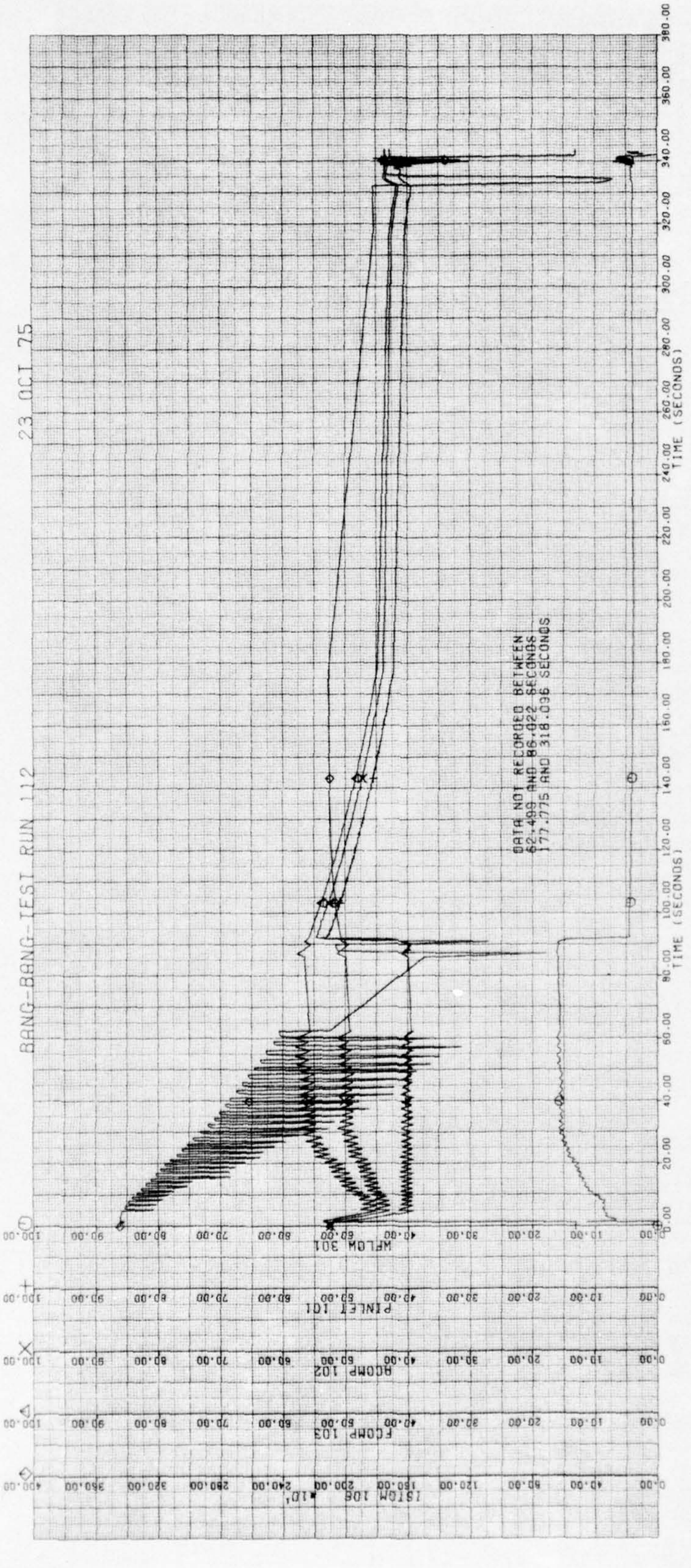

BANG-BANG-TEST RUN 112
23 OCT 75
DATA NOT RECORDED BETWEEN
62.499 AND 86.022 SECONDS
177.775 AND 318.036 SECONDS
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
ISTOM 108 *10¹
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
320.00
340.00
360.00
380.00
10.00
30.00
50.00
70.00
90.00
400.00

Figure 19

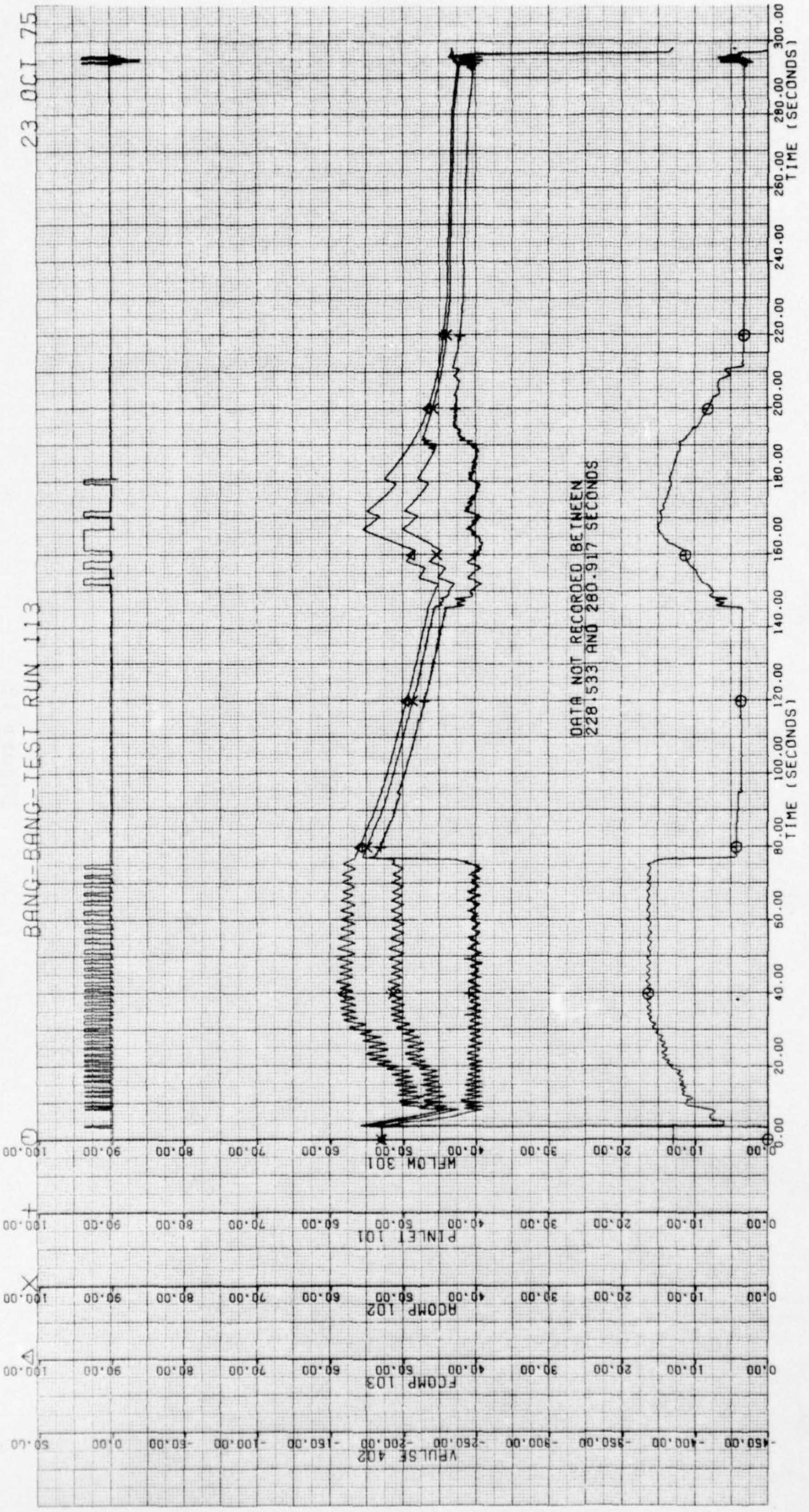

BANG-BANG-TEST RUN 113
23 OCT 75
DATA NOT RECORDED BETWEEN
228.533 AND 280.917 SECONDS
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
VPULSE 402
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
TIME (SECONDS)

Figure 20

Table 1. Test Summary

Test No.	Flow Profile		Run Duration Seconds	Total + Flow Gals.	Pressure Switch Psia	Gas Source	Regulator
	Gpm	Seconds					
104A	11. -17.	0. -20.	253.	40.47	50.	Facility	Facility
	17.	20. -84.					
	4.	84. -125.					
	18.	125. -153.					
	4.	153. -253.					
104B	11. -17.	0. -20.	476. *	40.97 ‡	50.	Facility	Facility
	17.	20. -28.					
	3.5	28. -142.					
	3.5-17.	142. -165.					
	17.	165. -185.					
	4.	185. -476. *					
105A	11. -17.	0. -20.	175.3*	40.97 ‡	40.	Facility	Facility
	17.	20. -85.					
	4.	85. -125.					
	17.	125. -175.3*					
105B	11. -17.	0. -20.	213.	51.06	40.	Facility	Facility
	17.	20. -80.					
	4.	80. -110.					
	17.	110. -140.					
	3.5	140. -213.					
106	11. -17.	0. -20.	285. *	40.97 ‡	40.	Torus	Flight
	17.	20. -63.					
	4.3	63. -129.					
	4.3-15.	129. -143.					
	15. -3.9	143. -197.					
	3.8	197. -285. *					

+ Obtained by numerical integration of flow meter data, unless otherwise noted

* Calculated from tank volume, flow rate and outflow total at end of data

‡ Total tank volume assumed--data tape ended before test ended

Table 1. (Continued)

Test No.	Flow Profile		Run Duration Seconds	Total + Flow Gals	Pressure Switch Psia	Gas Source	Regulator
	Gpm	Seconds					
107	10. -17.	0. -30.	444. *	40. 97 ‡	40.	Torus	Flight
	17.	30. -80.					
	17. -2. 5	80. -97.					
	Random between 2. 5 and 8. 5	97. -186.					
	2. 3	186. -444. *					
108	11. -17. x	0. -30.	221.	39. 32	40.	Torus	Flight
	17.	30. -123.					
	4.	123. -221.					
109	11. -17. x	25.	330. *	40. 97 ‡	40.	Torus	Flight
	17.	25. -39.					
	8. -6. 6	39. -80.					
	6. 6	80. -330. *					
110	11. -16. 5	0. -25.	342. *	40. 97 ‡	40.	Torus	Facility
	16. 5	25. -89.					
	4. 5	89. -342. *					
111	11. -16. 5	0. -30.	327. *	40. 97 ‡	40.	Torus	Facility
	16. 5	30. -86.					
	16. 5-4.	86. -130.					
	4.	130. -203.					
	Random between 4. and 8.	203. -271.					
		271. -327. *					

x Erratic start, flow rate decreased initially then began ramp-up
\+ Obtained by numerical integration of flow meter data, unless otherwise noted
* Calculated from tank volume, flow rate and outflow total at end of data
‡ Total tank volume assumed--data tape ended before test ended

Table 1. (Continued)

Test No.	Flow Profile		Run Duration Seconds	Total + Flow Gals.	Pressure Switch Psia	Gas Source	Regulator
	Gpm	Seconds					
112	12. -15.	0. -30.	341.	38. 34	40.	Torus	Facility
	15.	30. -91.					
	4.	91. -341					
113	11. -17.	3. -40.	296.	38. 85	40.	Torus	Facility
	17.	40. -75.					
	4.	75. -146.					
	4. -15.	146. -166.					
	15. -3. 5	166. -211.					
	3. 5	211. -296.					
114	13. -15. 5	5. -30.	280.	39. 74	40.	Torus	Facility
	15. 5	30. -65.					
	15. 5-2. 5	65. -82.					
	2. 5	82. -98.					
	Random between 2. 5 and 9. 5	98. -200.					
	7. 1	200. -278.					
	7. 1-14.	278. -280.					

+ Obtained by numerical integration of flow meter data, unless otherwise noted

Table 2. Mnemonics of Test Variables

Mnemonic	Description	Range
WFLOW	Water Flow Rate	0-25 gpm
PINLET	Pump Inlet Pressure	0-100 psia
ACOMP	Aft Compartment Pressure	0-100 psia
FCOMP	Forward Compartment Pressure	0-100 psia
ISTGM	GN_2 Delivered Pressure	0-5000 psia
VPULSE	Solenoid Valve Activation	Non Dimensional

high, as with a high flow rate, the supply pressure is maintained high in order to achieve a controlled delivered pressure. When the flow rate and consequently the liquid flow pressure drop is reduced, all system pressures except the oxidizer tank ullage pressure increase by the amount of the pressure drop reduction. This high pressure condition persists until sufficient liquid outflow allows reduction through gas blowdown to the sensing range of the pressure switch. This is true regardless of the ullage volume condition. The effect is seen to persist longer with a larger ullage volume because of the greater volume of higher pressure ullage gas.

The total flow duration of 104A was 253 seconds with an integrated total flow of 40.50 gallons. This compares favorably with a total tank volume of 40.97 gallons. The entire 104C test was not captured on tape so it was necessary to determine the outflow time from total tank volume, outflow volume at the end of the tape, and flow rate from the end of the tape record to depletion, which was held constant. This procedure yields a total flow duration of 476 seconds. The outflow from the tank as a function of time into the run is determined by numerical integration of the flow meter data, Wflow, during data reduction.

The data from tests 104A and 104C are presented in Figures 8 and 9. With regard to the flow rate ramp from 0 to approximately 20 seconds, it should be noted that the controls for the flow valve were manually operated. The flow rate ramp from 11 to 17 gpm is therefore operator technique limited with respect to linearity, which in all tests conducted was satisfactory for the purpose of the testing.

The pressure control bandwidth for both runs, except for the first 10 to 15 seconds of the run is approximately ±2 psi, during periods of steady state flow where the pressure switch and gas supply can exercise control over the pump inlet pressure. After a period of high flow rate during which the system pressures equilibrate at values that satisfy the high pressure drop associated with high flow rate, a reduction in flow rate and therefore pressure drop causes the pressuring action system to lose control. Pump inlet pressure rises to a high value, approaching very closely the tank pressure. The tank pressure will reduce to the control pressure if the low flow rate is sustained, by blowdown. The blowdown process is virtually isothermal, having a polytropic exponent in the order of 1.04 to 1.05. It may be seen that a 50 psia pressure switch was used for these runs.

The operation of the pressure switch and the solenoid valve may be seen by the positive pulses of the VPULSE parameter on the plots.

Tests 107 marked the changeover in gas supply from regulated facility GN_2 to the HAST flight torus. All subsequent testing was performed using this source of GN_2. Tests 107 through 109 were conducted using the HAST flight system first stage regulator as opposed to a facility first stage regulator which was used for all other tests. In this regard, tests 107 through 109 were the most nearly representative of the HAST pressurization system in the flight configuration in that they involved both the high pressure torus gas supply vessel and the first stage regulator.

Tests 107 through 114 were run to flowrate vs time profiles provided by the HAST program office as representative of the envelope of mission flight profiles. Satisfactory performance of the pulse modulated pressurization system (Bang-Bang) system in these tests could be interpreted as indicating a capability of performing satisfactorily for any mission profile within the envelope.

The system is seen to perform well in all the tests, 107 through 114 (Figures 10-23), maintaining pump inlet pressure at ±1 psi of the pressure switch normal setting of 40 psia. The ±1 psi is the deadband of the pressure switch. The only anomalous characteristic of the system, which has been discussed earlier, is the increase in pump inlet pressure that accompanies a reduction in flow rate and hence flow system pressure drop. The early testing in the program was performed with a 50 psia pressure switch because it was not certain that a lower control setting would insure maintaining a minimum of 30 psia at the pump inlet. This setting resulted in driving the pump inlet pressure over 65 psia while maintaining above 40 psia as a minimum. It is seen in the data plots that the maximum pressure reached with a 40 psia setting is in the order of 55 psia while the minimum pressure is never less than 38 psia and then for a very short period. This suggests that a pressure switch setting of say 35 psia would never result in a pressure in excess of 50 psia, the pressure at which viscoseal leakage begins in the HAST oxidizer pump, nor would the pump inlet pressure fall below 30 psia, the minimum pressure to prevent pump cavitation.

The pressure time trace of ISTGM parameter, the inlet to the first stage of regulation shown in Figure 19, run number 112 suggests a potential system improvement possibility. A potentially significant advantage of the pulse

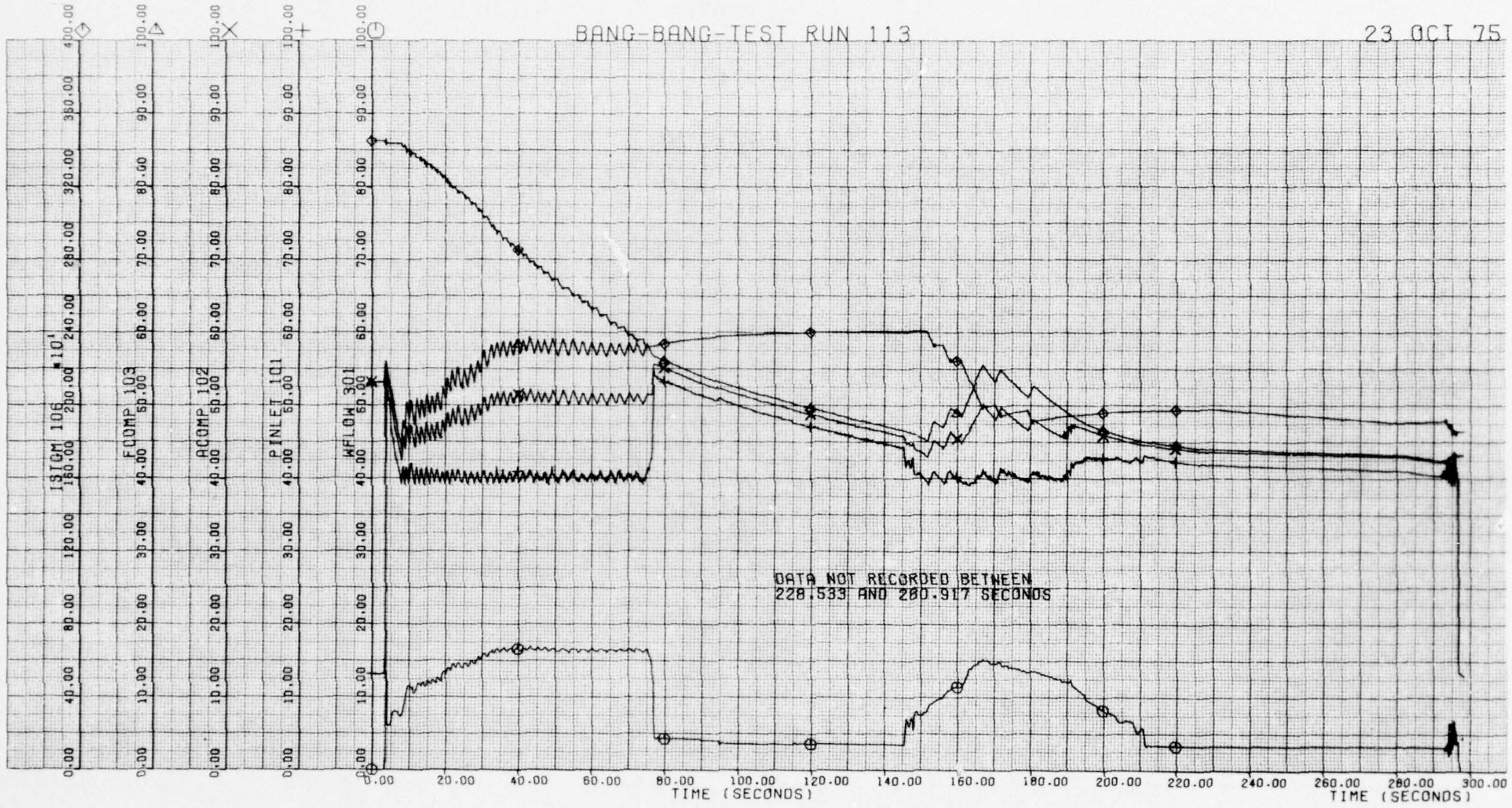
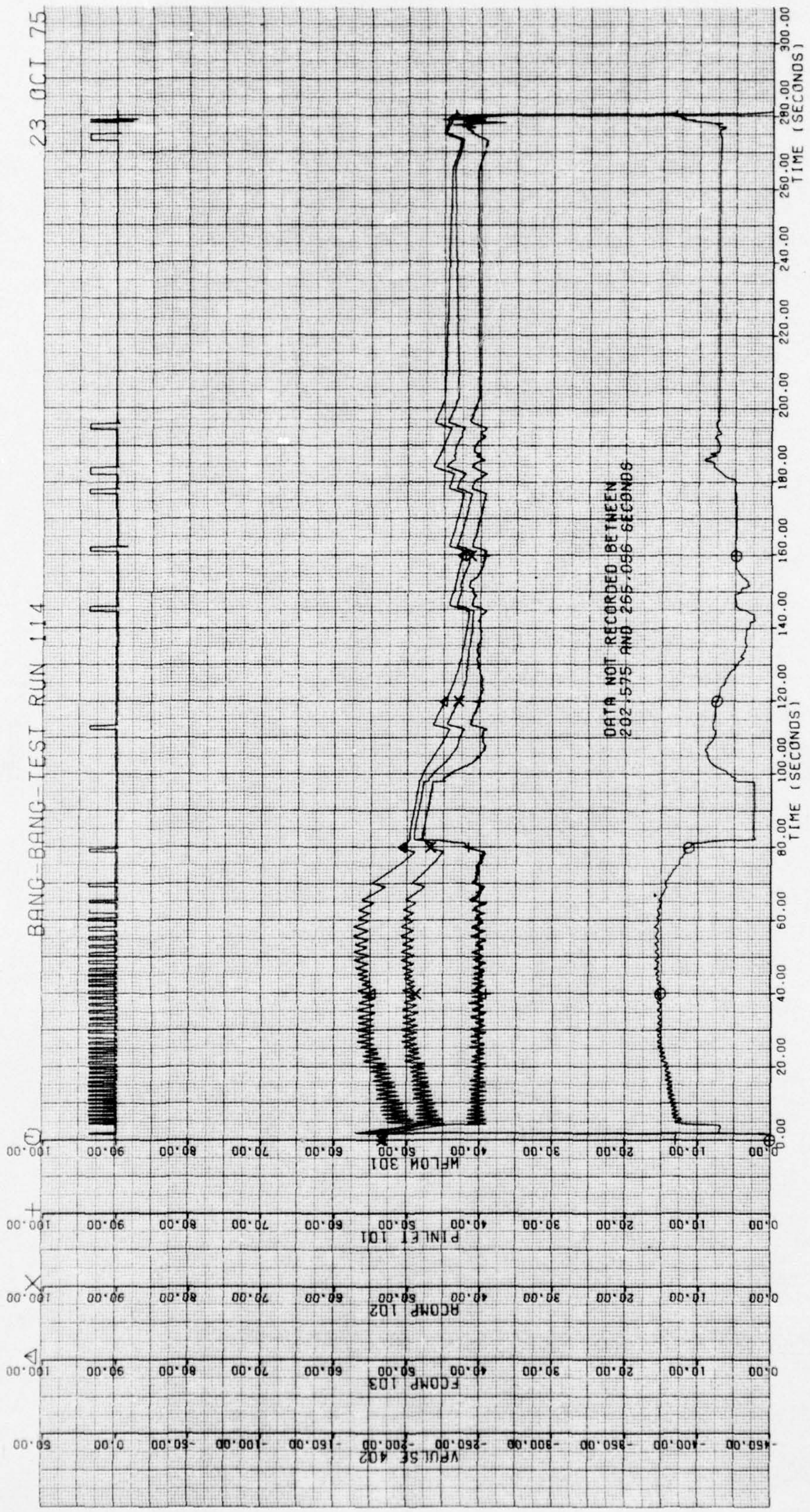

BANG-BANG-TEST RUN 113
23 OCT 75
ISTGM 106 *10¹
FCOMP 103
ACOMP 102
PINLET 101
WFLOW 301
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
400.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
DATA NOT RECORDED BETWEEN
228.533 AND 280.917 SECONDS
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
TIME (SECONDS)
TIME (SECONDS)

Figure 21



BANG-BANG-TEST RUN 114
23 OCT 75
DATA NOT RECORDED BETWEEN
202.575 AND 265.056 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
VPULSE 402
-450.00
-400.00
-350.00
-300.00
-250.00
-200.00
-150.00
-100.00
-50.00
0.00
50.00

Figure 22

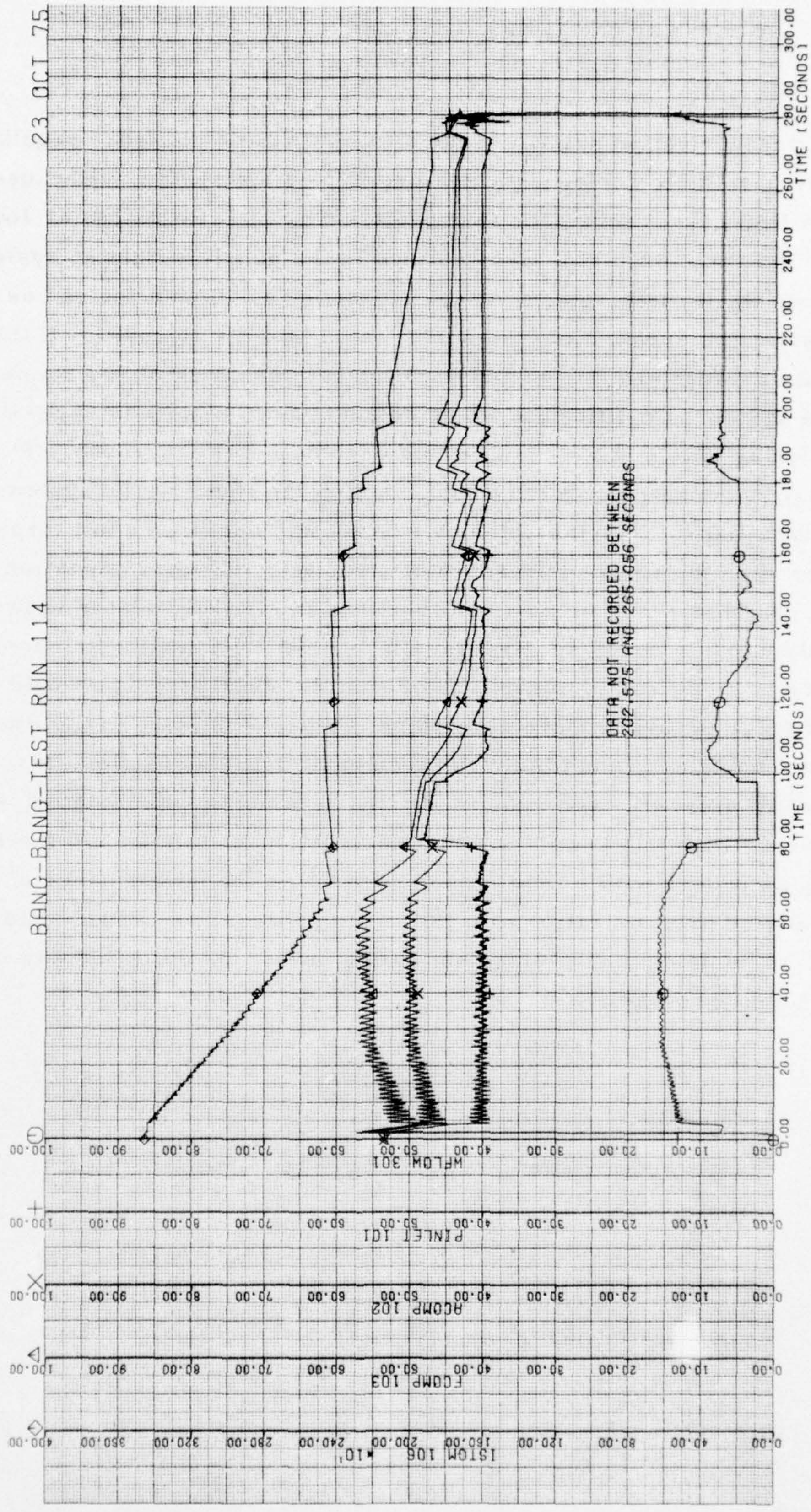

BANG-BANG-TEST RUN 114
23 OCT 75
DATA NOT RECORDED BETWEEN
202.575 AND 265.056 SECONDS
TIME (SECONDS)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
200.00
220.00
240.00
260.00
280.00
300.00
WFLOW 301
PINLET 101
ACOMP 102
FCOMP 103
ISTOM 106 *10'
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
400.00

Figure 23

modulated pressurization system is the elimination of a pressure regulator, one of the most unreliable components in a pressurization system. Because of the need of the HAST thrust chamber to provide a flow of aeration gas at low thrust levels, a first stage regulator was retained in the pulse-modulated system tested. This reduces the torus pressure vessel pressure to 300 psia for use as oxidizer pressurization and aeration of oxidizer injected into the chamber. If the first stage regulator were eliminated and aeration gas furnished at the required condition, a system simplification would be achieved. Figure 19 suggests that a configuration as shown in Figure 24 could accomplish this purpose. The pulse-modulated pressurization system would function the same as the system described in this report, except that the solenoid valve would operate on full torus pressure rather than the reduced pressure of nominally 300 psia. Aeration gas for the thrust chamber would be obtained from the small accumulator shown. When the solenoid valve is open, the pressure in the line between the solenoid valve and the tank is significantly above tank pressure. This pressure would be higher if the first stage regulator were eliminated. The check valve in the line to the accumulator would act to maintain the accumulator pressure close to the maximum transient pressure occurring in the line between the solenoid valve and the oxidizer tank. With this configuration, the aeration system should function essentially as it does with a first stage regulator. The performance of the pulse-modulated pressurization with full torus pressure at the solenoid valve would have to be determined, since no testing under this condition was done under the AFRPL test program.

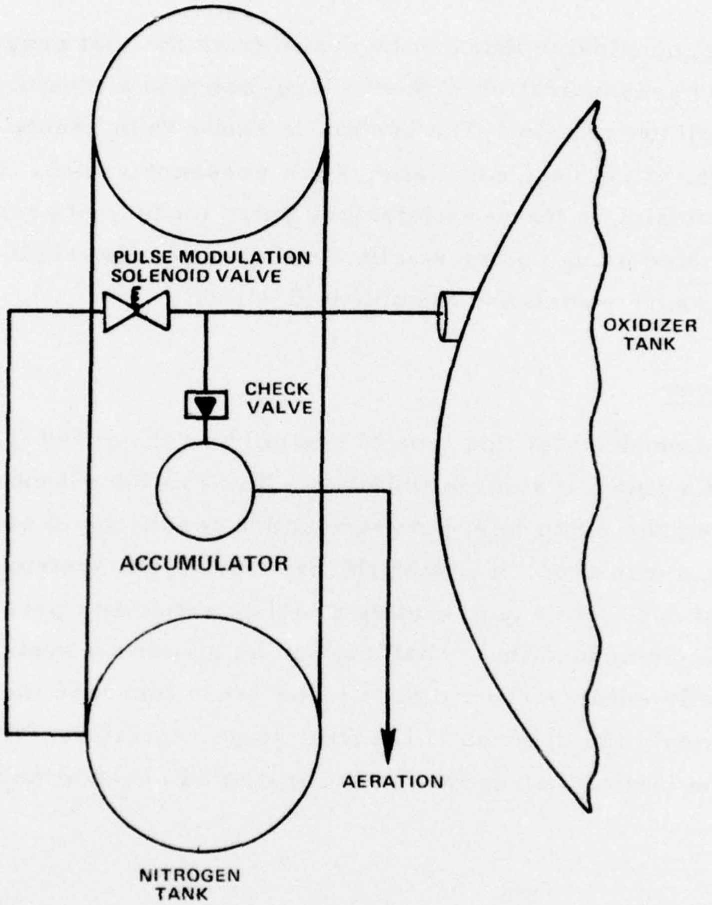

PULSE MODULATION SOLENOID VALVE
OXIDIZER TANK
CHECK VALVE
ACCUMULATOR
AERATION
NITROGEN TANK

Figure 24

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The overall conclusion that can be drawn from the test program is that a pulse modulated pressurization system (Bang-Bang) is a feasible approach for the HAST propulsion system. The system is shown to be stable and accurate, while in control, to the deadband value of the pressure switch. A specific, significant conclusion is that a satisfactory pulse modulated pressurization system was assembled using commercially available, off-the-shelf components, namely the pressure switch and the solenoid valve.

Recommendations

It is recommended that this type of system be considered if engineering development of a HAST system is initiated. It offers the potential advantages of maintaining adequate pump inlet pressure under conditions of abnormally high flow system pressure drop, isolating the pressurization system from the oxidizer after propellant depletion and providing a higher reliability pressurization system. It is further recommended that consideration be given to a system configuration that would greatly enhance the simplicity and hence increase the reliability of the system, namely the deletion of the first stage regulator. The concept is discussed in the text of the report and is illustrated schematically in Figure 24.

REFERENCES

1. Penn, C. D., "Preliminary Flight Rating Tests of the HAST Propulsion System." AFRPL-TR-75-5 (January 1975).

2. DiStephano, D., Ultra-Low-Pressure Rocket (ULPR) Propulsion System Phase II Technical Report - Final, RTD-TDR-63-1082 (November 1963).