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REPORT NO. RN-S-0294
TO
AEC - NASA SPACE NUCLEAR PROPULSION OFFICE

MASTER

CFDTS DATA ANALYSIS FINAL REPORT

NERVA PROGRAM
CONTRACT SNP-1
JUNE 1966

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ROCKET ENGINE OPERATIONS - NUCLEAR

NERVA PROGRAM

CONTRACT SNP-1

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ABSTRACT

This is a data analysis report of the 25 tests conducted with the Cold Flow Development Test System during October and November of 1965. These tests further demonstrated the ability of the NERVA engine to bootstrap under a wide range of tank pressures and turbine and nozzle back pressures, including the test conditions for the NRX/EST program and the ETS-1 design conditions. Bootstrapping with the pump in a prechilled (wet) as well as a warm ambient (dry) condition was demonstrated. A period of oscillations in the pump performance was encountered in the tests with a dry pump at start; however, the oscillations did not affect the ability of the system to bootstrap or produce any critical condition during the CFDTs tests. Closed-loop control of the turbine power control valve to control nozzle chamber pressure during start was effected, pointing the way to future system simplification through elimination of the TPCV programmed position control.

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I. INTRODUCTION

The Cold Flow Development Test System (CFDTS) shown schematically in Figure 1 was the first test system to incorporate all the major components of the NERVA engine. It was an unfueled cold flow prototype of the NRX/EST and the X-Engine systems. The CFDTS consisted of an unfueled graphite reactor, pressure vessel and nozzle, turbopump assembly, thrust structure, propellant feed lines, controls and instrumentation. It simulated almost exactly the heat capacity and flow passages of the NRX/EST and X-Engine Systems. It did not include the external radiation shield, remote disconnects and radiation-hardened components which will be present on the latter systems, but which did not affect the system dynamics. The hardware of the CFDTS is described in the CFDTS Test Plan, Reference 1 and the CFDTS Test Specification, Reference 2.

The general objectives of the CFDTS test program were to provide data related to the behavior of the NERVA engine system during chilldown and the initial phase of the start transient. The tests were also intended to obtain data necessary for the development of the engine controls and to help define the start procedures for the NRX/EST and X-Engines. The start technique considered for the latter systems is based on a bootstrap concept in which the propellant initially flowing into the engine system under tank pressure will absorb sufficient energy from the engine components (initially at ambient temperature) to provide enough driving energy to the turbopump assembly from a bleed through the dome and nozzle chamber to start pumping propellant into the engine. Power would then be provided by the reactor to continue bootstrapping the system to the desired power level.

The CFDTS test program consisted of 31 tests which were conducted in three series of 6, 21 and 4 tests between April and November 1965. The first series of runs, runs 001 through 006, achieved system and facility checkout, demonstrated the ability of the system to bootstrap at various tank pressures and obtained component chilldown information. The results and data analysis of these tests were published in Report RN-S-0250, CFDTS Data Analysis, CY 1965, Year End Report (Reference 3). The present report covers the analyses of the test data from the second and third series of tests.

Figure 1

Schematic of CFDTS

After completion of the first series of tests, modifications were made to the turbopump to provide improved performance and the turbine exhaust manifold replaced with an improved version which more nearly simulated the NRX/EST and X-Engine design. The remaining CFDTs tests were run with these component modifications.

The objectives of the second and third series of tests, established in Reference 4, were to provide the following data:

- (1) Performance differences using the modified turbopump and exhaust manifold.
- (2) Data on the performance at NRX/EST back pressure and tank pressure conditions.
- (3) Data on the performance of the X-Engine at ETS-1 operating conditions.
- (4) Data on the effects of reduced tank pressure with minimum back pressures.
- (5) An evaluation of the automatic pressure controller performance during initial engine startup operation.
- (6) Dry pump start information.

II. SUMMARY

This report presents a discussion of analysis of the results of the second and third series of tests with the Cold Flow Development Test System.

The tests demonstrated that the CFDTS will bootstrap with either a wet or dry pump condition at start. With a wet pump, the data indicate that peak pump speeds in excess of 5000 rpm can be achieved with run tank pressures as low as 45 psia at NRX/EST back pressure conditions of 12.7 psia and run tank pressures as low as 30 psia at ETS-1 facility design back pressure conditions of 7.5 psia. Peak speeds of 8000 rpm and greater were obtained on tests with higher tank pressures. With back pressures of 0.25 psia, a peak speed of about 8600 rpm was obtained with a tank pressure of 30 psia. Tests at this back pressure, in both a wet and dry pump condition, were attempted at a tank pressure of 20 psia; however, limitations of the facility in maintaining the low back pressure resulted in a deviation from the test conditions before any conclusive data were obtained on the ability of the system to bootstrap at these conditions. The test data indicated that at back pressures of 12.7 psia and 7.5 psia, a reduction in the tank pressure below about 45 psia and 30 psia, respectively, results in a sharp reduction in peak pump speed to below 3000 rpm. The peak performance obtained with a dry pump at start was similar to that obtained with a wet pump, at the same test conditions. The dry pump run did require a considerably longer run time to reach the peak performance. At a back pressure of 7.5 psia and a tank pressure of 35 psia, peak performance was achieved with the wet pump after a run time of about 30 seconds. However, with a dry pump, the run time to the peak conditions was about 70 seconds.

An interval during which pump-induced oscillations occurred existed just prior to the final pump acceleration to peak performance during the dry pump starts. These oscillations exhibited an increasing amplitude with a period of 1.5 to 5.5 seconds. It is theorized that the oscillations are associated with a two-phase fluid condition existing in the pump and the pump discharge circuit and are triggered by the pump encountering low speed cavitation. Delaying the

opening of the TPCV valve up to 18 seconds from the beginning of the test had the effect of decreasing the run time and the duration of the period during which the oscillations occurred without having any significant effect on the peak performance characteristics.

During the CFDTS tests, temperature asymmetries were noted in the nozzle manifold, reflector inlet and outlet, shield dome end and nozzle chamber plenums during certain phases of the runs. Some of these were concluded to be measurement errors caused by instrument lag and inaccuracies while others appeared to be true asymmetries related to a two-phase flow condition in conjunction with a nozzle manifold design with a single inlet and the hot bleed port.

Evaluation of the test data with respect to other objectives of the test program indicated the following results:

(1) The improvements to the turbopump and exhaust manifold made prior to the second series of CFDTS tests resulted in an indicated improvement in bootstrap performance of about 40%.

(2) The automatic pressure controller operated satisfactorily. When used, it opened the TPCV full open at the start of the test and controlled the valve position during the run so as to attempt to maintain the pre-set chamber pressure demand.

(3) Removal of the orifice in the diluent line reduced the diluent line loss factor by about 50% with a system performance improvement of less than 4%.

III. DESCRIPTION OF TESTS

The second and third series of CFDTs tests consisted of 21 and 4 runs respectively. The objectives and the test conditions for each run are presented in Table I while the results of each run are summarized in Table II. Runs 007 and 008 were made to evaluate the difference in system performance with the modified turbopump assembly. Test 007 was not a useful test because the TPCV position was lost. An objective of the majority of the runs was to provide information on the effects of tank pressure and back pressure on the bootstrap characteristics. Runs 009, 010, 011 and 017 were made at NRX/EST back pressure conditions of 12.7 psia while runs 015, 021, 022, 024 and 026 provided data at ETS-1 back pressure conditions of 7.5 psia and Runs 016, 018, 023, 027 and 031 provided data at a minimum back pressure of 0.25 psia. Information on dry pump starts and the effect of TPCV opening times on dry pump starts was provided by runs 019, 020, 021, 022, 024, 027 and 030. The operation and response of the automatic pressure control system was evaluated in runs 012, 013, 028, 029 and 030. Tests 014 and 025 had special objectives of evaluating the effect of blanketing the turbopump assembly in helium instead of nitrogen and the effect of removing the diluent line orifice.

Each test was conducted in four operating steps. They were (1) pre-test chilldown, (2) test start, (3) test stop and (4) post test shutdown.

1. Pre-Test Chilldown

For wet pump starts the run tank propellant line and pump were pre-chilled by opening the tank safety valve, propellant shut-off valve and pump discharge bleed valve, and bleeding liquid hydrogen through the line, pump and bleed valve, with the pump discharge valve closed until the fluid temperature stabilized at a minimum. For dry pump starts the run tank propellant line was chilled to the closed propellant shut-off valve by opening the tank safety valve until the fluid temperatures stabilized at a minimum. The pump discharge valve was maintained in an open position during the entire run with a dry pump start.

TABLE I

CFDTS SERIES II AND III TEST OBJECTIVES AND TEST CONDITIONS

TEST NO.	TEST OBJECTIVE AND DESCRIPTION	PUMP START CONDITION	TANK PRESS. PSIA	BACK PRESS. PSIA	DILUENT VALVE POSIT.	TPCV PROGRAM
7	Evaluate difference in system performance with turbine modified to NRX/EST configuration.	Wet	70	14.2	Open	Step and ramp to 80° at test start.
8	Evaluate difference in system performance with turbine modified to NRX/EST configuration.	Wet	70	14.2	Open	Step and ramp to 80° at test start.
9	Evaluate performance at NRX/EST back pressure and tank pressure conditions.	Wet	70	12.7	Open	Scheduled opening to 80° at test start.
10	Investigate effect of lower tank pressure with NRX/EST back pressure.	Wet	50	12.7	Open	Scheduled opening to 80° at test start.
11	Investigate minimum tank pressure for bootstrap start with NRX/EST back pressure.	Wet	35	12.7	Open	Scheduled opening to 80° at test start.
12	Evaluate performance of automatic pressure control system during initial engine start-up operation using closed loop at test start in support of NRX/EST.	Wet	70	12.7	Open	Close loop at test start. Set chamber pressure demand at value based on results of Test 9.
13	Evaluate performance of automatic pressure control system during initial engine start-up operation. Close loop subsequent to test start to verify alternate method of closing pressure loop for NRX/EST.	Wet	70	12.7	Open	Step open to 50° at test start. Close pressure loop at chamber pressure of 35 psia. Set chamber pressure demand at 35 psia.

TABLE I

TEST NO.	TEST OBJECTIVE AND DESCRIPTION	PUMP START CONDI-TION	TANK PRESS. PSIA	BACK PRESS. PSIA	DILUENT VALVE POSIT.	TPCV PROGRAM
14	Determine effect of blanketing TPA in helium on pump performance and system start-up characteristics in support of NRX/EST and XE.	Wet	35	12.7	Open	Scheduled opening to 80° at test start.
15	Investigate start-up characteristics with ETS-1 back pressure. Basic information on effect of lowering back pressure. Check out ejector system under operating load at ETS-1 back pressure conditions.	Wet	35	ETS-1	Open	Step and ramp to 80° at test start.
16	Investigate start-up characteristics with a minimum back pressure. Additional basic information on effect of lowering back pressure. Check out ejector system under operating load at minimum back pressure.	Wet	35	Min.	Open	Step and ramp to 80° at test start.
17	Evaluate bootstrap performance at NRX/EST back pressure and intermediate tank pressure conditions.	Wet	40	12.7	Open	Step and ramp to 80° at test start.
18	Obtain additional basic data on effect of lowering tank pressure to a minimum at minimum back pressure.	Wet	30	Min.	Open	Step and ramp to 80° at test start.
19	Evaluate dry pump start under X-Engine operating conditions using conservative TPCV program.	Dry	35	ETS-1	Open	Open TPCV when pump discharge temperature reaches 43.5°R. Step to 60° and ramp to 80°.

TABLE I

TEST NO.	TEST OBJECTIVE AND DESCRIPTION	PUMP START CONDITION	TANK PRESS. PSIA	BACK PRESS. PSIA	DILUENT VALVE POSIT.	TPCV PROGRAM
20	Determine effect of reducing pump chilldown time (time between opening PSOV and TPCV) on system start-up characteristics with dry pump start at X-Engine operating conditions.	Dry	35	ETS-1	Open	Open TPCV 9 seconds after opening PSOV. Step to 63° and ramp to 80°.
21	Determine effect on start-up characteristics with dry pump of reducing pump chilldown time to minimum at X-Engine operating conditions.	Dry	35	ETS-1	Open	Open TPCV simultaneously with opening of PSOV. Step to 60° and ramp to 80°.
22	Determine effect of higher tank pressure on bootstrap start-up characteristics of system using a dry pump start.	Dry	50	ETS-1	Open	Open TPCV and PSOV simultaneously. Step and ramp to 80° at test start.
23	Obtain additional basic data on effect of lowering tank pressure to a minimum at minimum back pressure.	Wet	25	Min.	Open	Step and ramp to 80° at test start.
24	Investigate effect of lowering tank pressure at ETS-1 back pressure with dry pump start.	Dry	30	ETS-1	Open	Step and ramp to 80° at test start.
25	Investigate effect of diluent flow on system bootstrap start characteristics by removing orifice restriction in diluent line.	Wet	70	12.7	Open	Step and ramp to 80° at test start.

TABLE I

TEST NO.	TEST OBJECTIVE AND DESCRIPTION	PUMP START CONDITION	TANK PRESS. PSIA	BACK PRESS. PSIA	DILUENT VALVE POSIT.	TPCV PROGRAM
26	Obtain additional basic data on effect of lowering tank pressure to a minimum at ETS-1 back pressure conditions.	Wet	25	ETS-1	Open	Step and ramp to 80° at test start.
27	Obtain additional basic data on effect of lowering tank pressure to a minimum at ETS-1 back pressure.	Dry	20	Min.	Open	Step and ramp to 80° at test start.
28	Evaluate performance of automatic pressure control system with closed loop at test start and NRX/EST conditions.	Wet	70	12.7	Open	Close pressure loop at test start. Set chamber pressure demand at 50 psia.
29	Evaluate performance of automatic control system with closed loop at test start using intermediate tank pressure and reduced chamber-pressure demand.	Wet	55	12.7	Open	Close pressure loop at test start. Set chamber pressure demand at 35 psia.
30	Evaluate performance of automatic pressure control system with pressure loop closed at test start under dry pump start conditions.	Dry	70	12.7	Open	Close pressure loop at test start. Set chamber pressure demand at 35 psia.
31	Obtain additional basic data on effect of lowering tank pressure to a minimum at minimum back pressure with a wet pump start.	Wet	20	Min.	Open	Step to 60°, ramp to 80° at test start.

TABLE II
CFDTS Test Data Summary
Series II and Series III Tests

TEST CONDITIONS										TEST RESULTS										REMARKS	
TEST NO.	TEST DATE	TANK PRESSURE	BACK PRESSURE		DILUENT VALVE POSITION	PUMP CONDITION AT START	TPCV PROGRAM	RUN DURATION SEC	MAXIMUM PUMP SPEED		MAXIMUM PROPELLANT LINE FLOW	MAXIMUM PUMP DISCHARGE PRESSURE	MAXIMUM PRESSURE RISE ACROSS PUMP	MAXIMUM CHAMBER PRESSURE		MAXIMUM TURBINE INLET PRESSURE	MAXIMUM TURBINE FLOW				
			NOZZLE	TURBINE					RPM	AT SEC				LB/SEC	PSIA			AT SEC	PSIA		LB/SEC
007	10/ 6/65	69.5	14.0	14.2	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	37.5	3460	18.8	19.0	92.3	23.0	32.3	20.8	22.8	0.5	TPCV POSITION LOST COMPARISON WITH OLD TPA			
008	10/ 9/65	69.3	13.9	14.1	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	27.2	7445	12.6	29.2	175.1	109.2	63.3	13.9	55.5	1.4				
009	10/11/65	68.4	12.8	12.6	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	24.0	7700	11.6	30.4	181.6	115.8	64.4	12.4	56.5	1.4				
010	10/12/65	49.0	12.7	12.5	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	40.9	6900	25.8	25.7	136.5	92.5	52.5	25.8	45.9	1.1				
011	10/12/65	33.3	12.7	12.5	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	99.5	1665	54.4	9.5	39.5	5.0	14.9	80.4	14.3	0.2				
012	10/13/65	69.4	12.7	12.5	OPEN	WET	CLOSE PRESSURE LOOP AT START SET P _c DEMAND AT 45 PSIA	25.4	7740	12.5	30.4	184.1	118.0	65.2	12.6	57.1	1.4				
013	10/13/65	68.9	12.7	12.5	OPEN	WET	STEP TO 50° AT START SET P _c DEMAND AT 35 PSIA	33.1	4650	14.3	22.3	111.0	42.8	38.2	14.3	26.4	0.7	CONTROLS TEST			
014	10/14/65	34.1	12.7	12.5	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	93.2	1610	61.7	8.0	39.0	5.0	14.7	26.8	14.4	0.2	H _e BLANKET ON TPA			
015	10/15/65	34.4	7.5	7.5	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	43.8	8210	29.5	27.6	162.4	130.7	60.4	29.5	52.9	1.3				
016	10/15/65	34.7	0.25	0.3	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	30.8	8700	14.9	26.0	177.7	145.3	59.5	15.5	52.2	1.25				
017	10/16/65	39.5	12.7	12.7	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	76.3	1995	52.8	10.2	47.0	7.0	16.6	78.0	15.9	0.25	SLUG OF WARM FLUID IN RTPL DURING TEST 1 CPS OSCILLATIONS DEVELOPED IN RUN TANK DURING TEST			
018	10/16/65	29.7	0.25	0.3	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	29.3	8700	14.6	27.0	170.0	144.0	61.0	16.1	53.5	1.3				
019	10/18/65	35.4	7.4	7.0	OPEN	DRY	OPEN TPCV WHEN THPD REACHES 43.5°R STEP AND RAMP TO 80°	73.2	7850	64.3	29.8	149.0	119.0	59.2	64.3	52.0	1.25				
020	10/18/65	34.5	7.3	7.3	OPEN	DRY	OPEN TPCV 9 SEC. AFTER PSOV OPENS STEP AND RAMP TO 80°	77.9	7820	65.4	29.2	149.0	119.5	59.2	65.4	52.0	1.3	TPCV OPENED 13.2 SECONDS AFTER PSOV OPENED			
021	10/19/65	34.4	7.3	7.3	OPEN	DRY	OPEN TPCV SIMULTANEOUSLY WITH PSOV STEP AND RAMP TO 80°	80.7	7700	71.0	29.3	143.6	114.6	57.5	71.0	50.7	1.3				
022	10/19/65	49.5	7.4	7.4	OPEN	DRY	STEP AND RAMP TO 80° AT START	36.2	8700	30.1	32.5	190.8	147.8	70.2	30.1	61.7	1.5	PDBV FROZE OPEN DURING RUN PARTIAL PUMP CHILLDOWN PRIOR TO TEST DILUENT LINE ORIFICE REMOVED FOR THIS AND SUBSEQUENT TESTS			
023	10/20/65	25.1	0.3	0.3	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	64.0	4600	36.7	19.8	64.0	40.6	22.0	38.0	19.2	0.5				
024	10/20/65	29.5	7.4	7.3	OPEN	DRY	STEP AND RAMP TO 80° AT START	71.8	7400	61.4	27.0	132.0	106.5	54.2	61.4	47.2	1.2				
025	10/21/65	69.3	12.7	12.7	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	27.7	8000	12.3	31.0	191.0	127.0	68.2	12.8	60.0	1.5				
026	10/22/65	24.3	7.6	7.5	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	152.3	2850	129.9	7.4	38.7	13.7	13.8	129.9	12.2	0.3				
027	10/22/65	19.7	0.3	0.3	OPEN	DRY	STEP AND RAMP TO 80° AT START	115.3	6550	108.8	18.5	85.0	67.0	33.5	109.3	30.0	0.75				
									(15930	53 - PUMP UNLOADED)											
028	11/9/65	69.2	12.7	12.7	OPEN	WET	CLOSED PRESSURE LOOP AT START SET P _c DEMAND AT 50 PSIA	25.5	7550	12.0	28.7	178.0	113.8	63.0	12.4	55.7	1.3	CONTROLS TEST			
029	11/9/65	54.4	12.7	12.7	OPEN	WET	CLOSED PRESSURE LOOP AT START SET P _c DEMAND AT 35 PSIA	36.1	6840	20.5	25.0	144.0	93.0	53.0	20.3	48.0	1.2	CONTROLS TEST			
030	11/11/65	69.4	12.7	12.7	OPEN	DRY	CLOSED PRESSURE LOOP AT START SET P _c DEMAND AT 35 PSIA	32.5	7430	23.0	28.6	172.0	108.0	64.0	23.2	54.0	1.3	CONTROLS TEST			
031	11/12/65	19.5	0.2	0.2	OPEN	WET	STEP TO 60°, FAST RAMP TO 80°	103.9	5900	96.6	16.0	70.0	52.0	27.0	96.6	25.0	0.6	EJECTORS UNBALANCED AT 43 SECONDS			
									(14520	57 - PUMP UNLOADED)											

2. Test Start

Following the pre-test chilldown the run tank pressure was set at the test pressure and the bleed continued until the temperature again stabilized at a minimum. The ejectors were then turned on and adjusted to the test back pressure and the test start initiated through the CFDTS sequencer. The sequencer closed the pump discharge bleed valve and opened the pump discharge valve for a wet pump start or closed the run tank propellant line bleed valve and opened the propellant shut-off valve for a dry pump start. The turbine power control valve was opened as programmed for each test.

3. Test Stop

The tests were terminated by closing of the propellant shut-off valve when the nozzle chamber temperature decreased to 160°R. An interlock in the sequencer closed the TPCV prior to the closing of the shut-off valve to prevent overspeeding of the pump.

4. Post Test Shutdown

Following the termination of the test the ejectors were turned off and the engine purged with gaseous hydrogen followed by gaseous nitrogen.

IV. MEASUREMENTS EVALUATION

In the second series of tests, considerably more measurements were made, particularly measurements of fluid temperatures, than in the first series. These additional measurements provided information to clarify some of the questions raised in the analysis of data from the first series (Reference 3).

A. PRESSURES

Pressure measurements were generally quite consistent. The only pressure measurement anomaly was that the nozzle tube outlet plenum pressure measurement showed the same pressure as the reflector outlet plenum. The reason for this apparent inconsistency was not established.

B. TEMPERATURES

In the first series of tests, it was noticed that a difference of up to 80°R existed in the two temperature measurements in the nozzle tube outlet plenum (reflector inlet plenum). It was suspected that the hot bleed port manifold may have caused this difference.

An additional resistance thermometer plus eight thermocouples were installed for the second series of tests. Typical resistance thermometer measurements are shown in Figure 2 and the thermocouple measurements are shown in Figure 3. Seven of the eight thermocouples gave valid readings.

The additional measurements in the second series of tests showed that the hot bleed port manifold did not greatly influence the reflector inlet plenum temperatures. The resistance thermometer measurements indicated that there was a variation among the three measurements, but the measurement in line with the hot bleed port, THNT0-2, was not consistently higher than the other two. Furthermore, the thermocouple measurements did not show much variation, at least in the first three seconds. THNT0-5 appeared to be questionable, although the reason for its

Figure 2

Reflector Inlet Plenum Fluid Temperatures Resistance Thermometers

Figure 3
Reflector Inlet Plenum Fluid Temperatures
C/C Thermocouples

deviation from the other measurements is not apparent. The variations after three seconds were probably caused by temperature asymmetry resulting from two-phase flow conditions, as is discussed in Section V.H, below.

A comparison of the resistance thermometer measurements with thermocouple measurements indicate that there was a possible difference in response times between the two types of instruments. Figure 4 shows the comparison. That the difference between the temperature was greatest during the initial two seconds of the run, when the temperature change with time is the most rapid, is an indication of response-time discrepancy between the instruments.

Reflector outlet plenum temperature measurements in the first series of tests were sparse and erratic. The additional measurements taken in the second series provided sufficient information to determine whether temperature asymmetry existed in this plenum. Section V.H, below, discussed temperature asymmetry.

There were some uncertainties concerning the nozzle chamber temperature measurements in the first series of tests. A temperature probe was inserted into the center of the chamber in an attempt to obtain more information on the chamber temperature. However, a thermocouple instead of a resistance thermometer was used on the probe because of physical constraints. Therefore, it was difficult to compare this measurement directly with the other measurements made with resistance thermometers. Figure 5 shows a typical plot of nozzle chamber measurements. THNC-4 is the center measurement.

As was observed in the first series, the measurement near the hot bleed port, THNC-2, recorded lower temperatures than the other two RTT measurements. Previous analysis of flow rates (Reference 3) indicated that perhaps the lower measurement, THNC-2, was more representative of the mixed mean chamber temperature.

Comparison of measured flow rate with calculated flow in the second series of tests gave similar results as were obtained previously in Reference 3. Nozzle flow rate was calculated from the choked flow relation in the nozzle.

Figure 4

Comparison of Nozzle Tube Outlet Fluid Temperature Measurements with
RTT's and Thermocouples

NOZZLE CHAMBER TEMPERATURE (CFDTS TEST NO. 008)

Figure 5

Nozzle Chamber Temperature

Turbine inlet flow rate was added to the calculated nozzle flow rate to check against the measured flow rate in the feed line. Table III presents a comparison of the calculated flow rates from two different measured nozzle chamber temperatures with the measured feed flow rate. Analysis of system mass storage presented in Reference 3 indicates that the mass storage may account for the difference between WRTPL and $\dot{W}_2$, but cannot account for all of the difference shown between WRTPL and $\dot{W}_1$.

While the two measurements THNC-1 and THNC-3 agreed fairly well with each other, thus providing a basis for confidence in their accuracy, it is significant to note that THNC-3 remained about 20°R higher than THNC-2 after flow shutdown, while THNC-1 gradually approached the temperature of THNC-2. These temperature probes should have measured the same temperature after flow shutdown since any temperature asymmetry which existed in the nozzle chamber should have gradually disappeared after flow shutdown. From this observation, it can be concluded that the temperature measurement indicated by THNC-3 was somewhat biased.

One possible reason for the discrepancies in the measurements is that THNC-2 was responding faster than THNC-1 and THNC-3. Turbulent flow conditions are expected at the inlet and in the periphery of the hot-bleed port because of the convergence of flowing streams toward the hot-bleed port. THNC-2 was installed on the periphery of the hot-bleed port at an angular location equal to theta of 168 degrees, while THNC-1 and 3 were installed at locations further away from the hot-bleed port. Under these conditions, THNC-2 would respond faster than THNC-1 and 3 to the changing fluid temperature. The fact that the measurement with the thermocouple, THNC-4, which is known to have faster response than RTT's, initially followed THNC-2 lends support to this postulate. However, calculations indicated a time constant of approximately 0.5 second could be possible for THNC-1 and 3, while a lag of approximately one second in time constant was necessary to account for the entire difference in temperature measurements. Therefore, inability of THNC-1 and 3 to respond to the changing fluid temperatures could explain at least part of the observed temperature discrepancies in the nozzle chamber. The possibility of the existence of actual temperature asymmetries in the chamber will be discussed in a subsequent section.

TABLE III

COMPARISON OF CALCULATED FLOW RATE FROM NOZZLE
CHOKED FLOW RELATION AND MEASURED FLOW RATE
(CFDTS TEST NO. 008)

	PNC	THNC-1	THNC-2	WTi	WRTPL	$\dot{w}_1$	$\dot{w}_2$
<u>Run Time</u>	<u>(PSIA)</u>	<u>(°R)</u>	<u>(°R)</u>	<u>(LB/SEC)</u>	<u>(LB/SEC)</u>	<u>(LB/SEC)</u>	<u>(LB/SEC)</u>
382	52.8	511.1	504.2	1.1	21.9	19.7	19.9
384	62.6	476.1	444.3	1.3	28.0	24.2	25.1
386	60.2	392.0	332.0	1.3	28.8	25.5	27.7
388	50.4	296.9	240.6	1.2	26.7	24.6	27.1
390	39.7	231.0	189.2	1.0	24.0	21.8	24.0

NOTES:

PNC = Measured nozzle chamber pressure, psia.

THNC-1 and -2 = Measured nozzle chamber temperatures, °R.

WTi = Calculated turbine inlet flow rate, lb/sec.

WRTPL = Measured suction line flow rate, lb/sec.

$\dot{w}_1$ = Calculated flow rate, lb/sec

$\dot{w}_1$ = Turbine flow and chamber flow = $WTi + 7.97 (PNC) / (THNC-1)^{0.5}$

$\dot{w}_2$ = Turbine flow and chamber flow = $WTi + 7.97 (PNC) / (THNC-2)^{0.5}$

Typical diluent and turbine inlet fluid temperatures are shown in Figure 6. As indicated by the increase in fluid temperature from the diluent inlet, THDL-1 to the diluent outlet THDJ-1, there was considerable heat transfer to the fluid in the diluent line. The turbine inlet temperature was low at the beginning of the run because of the chilldown effect of the bearing coolant flow. During the pump chilldown, some of the bearing coolant backed into the turbine inlet line. In a dry pump start, this leakage is prevented by the flow of hot gases into the turbine after the opening of the TPCV.

V. DATA INTERPRETATION

A. TURBOPUMP PERFORMANCE

1. Effect of Revised TPA Assembly and Exhaust Manifold

Following the completion of the Series I tests the turbopump assembly was modified to provide an improved design with better performance and the exhaust manifold was replaced with a later design that provided better flow characteristics and more nearly simulated the X-E design. The second and third series of tests were run with the revised system. Test 008, run at the same test conditions as Run 003, provided a comparison of the CFDTS bootstrap performance with the original and the modified TPA assembly and exhaust manifold. The pump speed and chamber pressure measured during the two runs are plotted in Figure 7. Run 008 resulted in about a 40% increase in peak pump speed and peak chamber pressure with the peak performance occurring sooner, at a run time of 12.6 seconds instead of 16 seconds.

2. Pump and Turbine Performance

A report on the application of CFDTS to the X-engine startup is being prepared. This will include a detailed analysis of the pump and turbine performance.

B. BOOTSTRAP PERFORMANCE WITH WET PUMP

Information on the bootstrap characteristics of the CFDTS with a wet pump condition at start and the effect of tank pressures and chamber nozzle and turbine exhaust back pressures was provided by Runs 009, 010, 011, 012, 015, 016, 017, 018 and 026. Tests were conducted at back pressures corresponding to the NRX/EST, ETS-1 and minimum back pressure conditions of 12.7 psia, 7.5 psia and 0.2 psia, respectively, and at tank pressures varying from 25 to 70 psia. The results of these tests were included in Table II, CFDTS Test Data Summary.

Time histories of various parametric measurements during Run No. 010 are presented in Figures 8, 9, 10 and 11. The trends shown in these figures are typical of the wet pump bootstrap runs with only the values of the measurements and the peak performance levels and the run time varying with the different test conditions of back pressure and tank pressure. The data show that the system performance, as indicated by pump speed, flow and discharge pressure and nozzle chamber flow and pressure, followed a distinct pattern during the bootstrap runs with a steady build-up culminating in a final acceleration to a peak performance condition. After the system performance peaked it then steadily decayed to the point at which the test was terminated with flow shutoff.

The effects of tank pressure and back pressure on the pump peak speed, pressure rise and flow rate achieved during bootstrapping are shown in Figures 12, 13 and 14. The curves show a general "S" shape variation of the pump performance parameters with tank pressure. With a back pressure of 12.7 psia, corresponding to the NRX/EST conditions, the peak speed increases gradually with tank pressure to a value of 2000 at a tank pressure of about 40 psia, at which point it begins increasing very rapidly and "steps up" to a peak speed of 7000 with a tank pressure of 50 psia. At higher pressures, the increase of peak speed with tank pressure again becomes gradual. At the ETS-1 back pressure condition of 7.5 psia the effect of tank pressure on peak speed was similar except the sharp increase occurred between tank pressures of 25 and 35 psia. Not enough data were available to define the tank pressure range over which the sharp increase in peak performance will occur with the minimum back pressure.

An objective of these tests was to provide start transient information with the back pressure conditions for NRX/EST testing and ETS-1 facility and at minimum back pressures of 0.25 psia. The results, however, also provide a general picture of the effect of back pressure on bootstrap performance. The pump performance data presented in Figures 12, 13 and 14 show that with a constant tank pressure, higher peak bootstrap performance was obtained with lower back pressures. There was a large increase in performance when the back pressure was reduced from the NRX/EST pressure of 12.7 psia to the ETS-1 design pressure of 7.5 psia. Of more

Typical Profile of Pump and Turbine Parameters -
Performance CDDTS Wet Pump Bootstrap Test

Figure 8

Figure 9

TEST NO. 010
TANK PRESSURE - 50 PSIA
BACK PRESSURE - 12.5 PSIA

Figure 10

Typical Profile of System Pressures -
CFDTS Wet Pump Bootstrap Test

Figure 11

Figure 12

Variation of Pump Peak Speed with Tank Pressure and Back Pressure

Figure 13

Variation of Pump Peak Pressure Rise with Tank Pressure and Back Pressure

IPCV STEPPED AND RAMPED TO 80 DEG AT FS-1

Figure 14

Variation of Pump Peak Flow with Tank Pressure and Back Pressure

interest is the fact that bootstrapping at the same relative location on the "S" shaped curves was achieved with a tank pressure about 15 psia lower with the latter back pressure. The "top of the knee" on the pump performance curves occurs at a tank pressure of about 50 psia with a back pressure of 12.7 psia; whereas, with the back pressure of 7.5 psia it occurs with a tank pressure of only about 35 psia. The data indicate higher pump performance when the back pressure is further reduced to 0.25 psia. However, because of the limited data at this test condition, it is not evident what minimum tank pressure would define the "top of the knee" on the pump data curves, the point at which the maximum gain would be achieved with the lower back pressure. Starting the NERVA engine at tank pressures lower than 25 to 30 psia is probably not practical, as lower NPSP at the pump will become a problem with low tank pressures. The effect of reduced back pressure at the same tank pressure is shown in Figure 15 to be to decrease the time to peak performance. For example, with a tank pressure of 35 psia the data indicates a time to peak speed with a back pressure of 12.7 psia of about 65 seconds. With a back pressure of 7.5 psia, however, the time would be reduced to about 30 psia, while reduced back pressure to 0.25 psia would shorten the time to about 5 seconds. However, at the tank pressures corresponding to the "top of the knee" area on the pump speed, flow rate and pressure rise curves in Figures 12, 13 and 14, the time to peak speed is nearly constant, about 25 to 30 seconds, with back pressures of either 7.5 or 12.7 psia. At lower tank pressures the time to peak performance becomes longer at an increasing rate.

An attempt was made to run a bootstrap test with a tank pressure of 20 psia at a back pressure of 0.25 psia. The facility has the ability to maintain this low back pressure for only about 45 seconds after which the nozzle chamber back pressure returns to near ambient. At the time back pressure was lost the pump operation was oscillating and the system was not exhibiting bootstrap characteristics. However it was not possible to determine if the system would have eventually bootstrapped if the low back pressure had been maintained. A similar test was run with a dry pump condition at start with the same inconclusive results.

TPCV STEPPED AND RAMPED TO 80 DEG. AT FS-1

Figure 15

Variation of Time to Peak Pump Performance with
Tank Pressure and Back Pressure

C. BOOTSTRAP CHARACTERISTICS WITH DRY PUMP AT START

One objective of the CFDTS test program was to evaluate the possibility of a dry pump engine start. In this condition, the pump and pump inlet line are not pre-chilled. The run is initiated (FS-I) by opening the propellant shutoff valve with the opening of the turbine power control valve programmed from the same time. The chilldown of the inlet line and pump thus occurs during the system start transient. This start sequence would eliminate the need for the pump discharge valve and its controls from the engine system.

Six tests with a dry pump condition at start were conducted during the CFDTS test program. Run 001 was a chilldown test in which the turbine power control valve was not opened and the turbopump was locked to prevent rotation. The run was made with a tank pressure of 70 psia and a nozzle and turbine back pressure of 14 psia. Runs 019, 020, 021 and 022 were run at the ETS-1 back pressure conditions of 7.5 psia. During the first three, run at a tank pressure of 35 psia, the TPCV was programmed to open at different times relative to the opening of the propellant shutoff valve to evaluate the effect of delayed opening of the TPCV on the bootstrap characteristics. Run 022 was run at a tank pressure of 50 psia. The final dry pump test was run with a tank pressure of 70 psia and a back pressure of 13 psia. The TPCV was controlled during this test by the automatic pressure control system with the chamber pressure demand set at 35 psia.

1. Comparison of Wet Pump and Dry Pump Bootstrap Characteristics

The unique feature of the dry pump bootstrap runs was the occurrence of oscillations in the pump performance (speed, flow and head rise). The oscillations began about 1/3 to 1/2 way through the run following a steady gradual increase in pump speed. They continue with increasing magnitude to a point at which the pump accelerates to its peak performance. A discussion of the causes of these oscillations is presented in Section V.c.2. Except for the oscillations, the general pattern of the runs was similar to the wet pump runs.

The peak pump speed, flow, and discharge pressure and the time to peak pump performance data for the dry pump runs is also shown in Figures 12, 13, 14 and 15 with the data from the wet pump runs. The data are limited but it appears that the variation of the peak pump parameters with tank pressure follows a similar "S" shape curve as established by the wet pump data.

The test data showed that under similar tank and back pressure conditions the pump attained a lower peak speed and discharge pressure but a higher peak flow rate during a run with a dry pump condition at start than with a wet pump at start indicating that the wet pump was operating at a lower ratio of capacity to speed, (Q/N), at the time of peak performance. With a tank pressure of 35 psia and a back pressure of about 7.5 psia the wet pump peak speed and discharge pressure on Run 015 were 8200 rpm and 158 psia while Run 021 at similar conditions resulted in a peak discharge pressure of 144 psia. However, the peak pump flow rate of Run 021 was 29.4 lb/sec while the peak flow in Run 015 was only 27.7 lb/sec. At the time of peak performance the pump was operating at Q/N of about 0.345 and 0.395 gpm/rpm, respectively, in the wet and dry pump runs. The run time when measured from TPCV opening to peak pump speed was considerably longer with the dry pump. On wet pump Run 015 the time to peak speed was about 30 seconds while on Run 021 the time was approximately 70 seconds.

An investigation disclosed that the lower Q/N during the time of peak performance on the wet pump Test No. 015 resulted from a greater restriction to flow from the pump caused by warmer gas temperatures between the nozzle tube outlet and the nozzle chamber. The density of the warmer fluid was lower, resulting in higher pressure drops across the shield and core. A comparison of the temperatures on the wet and dry pump runs 015 and 021 is shown in Figure 16 while comparisons of the pump performance parameters, system flow rates, turbine inlet pressure and pressure drops across major flow paths within the system during the time of peak performance are given in Figures 17 and 18. The data disclose that during Run 015 the pressure drop across the dome and shield was about 5 psi (28%) higher at the peak conditions than on Run 021, while across the core the pressure drop was 11.5 psi (20%) higher. The pressure drops in the pump discharge line and

Figure 17

Comparison of Pump Operation
Wet and Dry Pump Bootstrap Runs

Figure 18

Comparison of System Pressures, Flows and Pressure Drops
at Peak Operation with Wet and Dry Pump Tests

nozzle manifold and tubes were approximately the same in both cases. This means that during the wet pump run the pump was operating against a higher resistance to flow during the peak performance phase. With the higher resistance, the pump was operating at a lower Q/N , tending to produce a greater head rise, but a lower flow rate and a probable higher pump speed.

The test data disclosed that the turbine inlet temperature was approximately 9% higher during the wet pump run (420°R vs 384°R) while the turbine flow rate and inlet pressures were about equal to the dry pump run. This means more energy was available to the wet pump turbine which would tend to create greater pump performance or greater speed, flow, and pressure. The combination of the lower Q/N and the additional energy to the turbine then resulted in higher peak pump speed and discharge pressure, but a lower peak flow rate during the wet pump run No. 015 than during the similar dry pump run No. 021. These results are probably typical for a comparison between wet and dry pump bootstrap performance (i.e., the wet pump will produce a higher peak speed and discharge pressure but a lower flow); however, a general conclusion should not be made until a comparison at other tank pressures and back pressure conditions is made.

The data in Figure 18 also indicate that even though the peak pump flow during the dry pump start is higher than during the wet pump start, the nozzle, diluent and turbine flows during the peak conditions are approximately the same. This is explained by the fluid storage characteristics of the system. As indicated in Figure 16, the system was cooler during the time period when the pump was accelerating to peak speed during the dry pump start than during the wet pump start. The storage within the system during the dry pump start would then be at a higher density and require a greater mass storage rate.

2. Analysis of Dry Pump Start

The bootstrap runs with a dry pump condition at start were characterized by oscillations in the pump speed and the system pressures, temperatures and flow rates. The oscillations began at a point about $1/3$ to $1/2$ way through the runs. They started as small fluctuations and continued with increased amplitude up to the point where the pump reaches its peak. The period of the oscillations increased from an initial value of 1 to 2 seconds to a final value of 2.5 to 5.5 seconds. The oscillation characteristics from the CFDTIS runs made with a dry pump at start are summarized in Table IV.

A detailed analysis was made of Run 030 in an effort to determine and understand the causes and effects of the oscillations. Run 030 was considered because it was run with a combination of a high tank pressure of 70 psia and back pressures of 12.7 psia which resulted in a relatively short run in which the oscillation effects were well defined; however, the characteristics demonstrated during this test were typical and representative of the performance oscillations that occurred in the other dry pump bootstrap runs. Plots of the pump parameters and the system temperatures, pressures and pressure drop data, measured during the test are presented in Figures 19, 20, 21, 22 and 23.

Run 030 was run with a closed pressure loop control made on the turbine power control valve (TPCV) with the chamber pressure demand set at 35 psia. This resulted in a "slow ramp" opening of the TPCV to a maximum open position of 82 degrees. Also, just prior to the occurrence of the peak operating point, the pressure control system caused the TPCV to start to close. The controller would have had a negligible effect on the characteristics of the oscillations.

The basic pattern of the oscillations revolves around the pump operation. The pump operation is alternating between periods of high efficiency "pumping" with liquid and periods of low performance with warm fluid. This produces oscillations in the pump discharge pressure and flow rate which reflect throughout the system. Oscillations also occur in the temperatures throughout the system because of the effect of the variation in pressure and flow rate on the

TABLE IV

SUMMARY OF DRY PUMP BOOTSTRAP
OSCILLATION CHARACTERISTICS

<u>Run No.</u>	<u>001</u>	<u>019</u>	<u>020</u>	<u>021</u>	<u>022</u>	<u>027</u>	<u>030</u>
Tank Pressure psia		35.4	34.5	34.4	49.5	19.7	69.4
Back Pressure psia		7.4	7.3	7.3	7.4	0.3*	12.7
Time to Initiation of Oscillations sec	No Oscillations	32	30	30.5	11.5		10
Duration of Oscillations sec		26.3	29	34.5	14.5		9
Time to Peak Pump Speed sec		59	64.3	65.4	71.0	30.1	23
Number of Cycles	No Oscillations	11	11	14	8		5
Initial Period of Oscillations sec			1.8	2.0	1.5	1.25	1.4
Final Period of Oscillations sec			4.0	4.5	5.5	2.5	2.6

*Nozzle Back Pressure went to approximately 13.5 psia at $F_{s1} + 44$ sec.

Figure 19

Profile of Pump Performance Parameters During

Dry Pump Bootstrap Run No 030

Figure 21

Profile of System Fluid Temperatures Performance Parameters During
Dry Pump Bootstrap Run No. 030

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Figure 23

heat transfer to the fluid, the vaporization rate and the fluid phase condition and the continuing chilldown of the system hardware.

The data presented in Figure 20 show that the pressures from the pump discharge through the system to the nozzle chamber and turbine inlet were in phase. The pressure oscillations also coincided with the system flow rates represented by the nozzle flow rate in Figure 19. Correlation of the pump discharge pressure and the pressure difference across the pump with speed discloses that the pressure was out of phase with the speed, i.e., the highest pump head and discharge pressure were developed at the low pump speeds and the lowest head and pressure when the speed was high. Correlation with the pump inlet temperature, however, shows that the pump is receiving warm fluid or gas with little or no net positive suction pressure at the inlet during the peak portions of the speed oscillations. Under this condition the pump was not producing any work to absorb the power from the turbine and the turbopump assembly had accelerated under a "no load" condition. Since the gas driving the turbine is bled from the shield end dome and nozzle chamber oscillations are created in the turbine inlet pressure, flow rate, (and the turbine power), in phase with the other system pressures and flows. This means the power input to the pump from the turbine was affected by the pump performance itself. As a result, the pump speed obtained during the "no load" acceleration phase of the oscillations was limited. Figure 19 shows that there was also an oscillation in the pump inlet pressure and a correlation of this oscillation with the pump discharge pressure oscillation shows that it was in phase with the discharge pressure. It would normally be expected to be out of phase with the pump discharge pressure and the possible causes of this unique correlation will be discussed later in this section. This oscillation in the pump inlet pressure would have transferred through the pump to the pump discharge pressure and was thus superimposed on the pressure oscillations that occurred in the system downstream of the pump.

Analysis of the data from Run 030 resulted in the theory that the oscillations that occur during the bootstrap runs from a dry pump start condition are triggered by a sudden drop in pump performance during that phase of pump chilldown in which the fluid is liquid at the pump inlet but two-phase at the pump exit.

Figure 22 shows temperatures measured at different locations in the system during Run 030. Also, shown with each temperature is a plot of the temperature for two-phase hydrogen at the pressures measured at the same location. These data indicate that the fluid at the pump inlet became liquid at a time of about 49 seconds and remained liquid throughout the remainder of the run, except for brief warm periods during the oscillations. The fluid at the pump discharge became two-phase at about 52 seconds and remained two-phase, with brief warm periods, until a time of 64 seconds at which time the data disclose that it becomes liquid. It is also seen that the fluid in the pump discharge line to the nozzle manifold became two-phase at about 54 seconds and became liquid at about 66 seconds. The oscillations occurred during a time period from 56 seconds to 64 seconds which was during the time that the flow was two-phase at the pump exit with the termination of the oscillations at the time the flow at the pump discharge changed from two-phase to liquid.

The pump performance shown in Figure 19 shows that the pump starts developing head at a time of about 54 seconds. The oscillations start at about 56 seconds. Correlation of the pressure difference across the pump, the pump speed and the fluid conditions at the pump inlet shows that when the speed was at a minimum and the pump began accelerating, it was receiving liquid and the performance was increasing. Part-way through the acceleration phase, the head rise across the pump (ΔP plot in Figure 19) and the pump discharge pressure peaked sharply and began decreasing. It is theorized that as the pump is accelerating the pump performance approaches a low speed cavitation condition, defined by a low ratio of flow to speed in which vapor forms on the low pressure side of the vanes. When the pump encounters this region (at the point where the discharge pressure peaks) there is a loss in flow-head developed across the point allowing the warm two-phase flow, in which the vaporization has been suppressed by the head developed by the pump, to begin boiling or flashing off. Once the boiling begins it causes a further restriction to flow through the pump and continuing decay in the pump performance. The fluid in the pump and pump inlet boils off or is allowed to warm up because of the decrease in flow rate and begins to vaporize resulting in a gaseous fluid condition within the pump and the pump inlet. A loss in NPSP and pump performance results. With the pump not developing any work to absorb the power supplied by the turbine, the turbopump assembly continues accelerating.

An indication that the pump Q/N is depressed into the critical region where cavitation occurs is provided by the plot of the ratio of nozzle flow to pump speed (W_N/N_T) shown in Figure 19. During the oscillations the flow measurements from the flow meters upstream of the pump became very erratic and were considered useless. However, the nozzle flow rate is considered representative of what the pump flow rate was during this time, at least as far as phasing and direction of change, and was used to provide a flow-to-speed ratio. The ratio of W_N/N_T is seen to begin decreasing as the pump begins accelerating, indicating the pump Q/N is being depressed. The depression of the Q/N apparently results from the creation of an excessive restriction to flow by the two-phase fluid. It is indicated that this restriction may be occurring primarily within the pump housing, as the pump is able to operate without cavitating once liquid hydrogen is indicated at the pump discharge.

Liquid hydrogen gradually flushes the warm and gaseous fluid through the pump inlet as the pressure downstream of the pump decays and liquid returns to the pump. The pump again begins developing head and producing flow. It decelerates from the overspeed condition to a minimum level and then begins accelerating. As the pump accelerates, the Q/N is again depressed to a critical value, cavitation occurs and the cycle repeats. When the fluid at the pump discharge becomes liquid, the pump is then apparently able to accelerate to its peak operating condition without the Q/N being depressed to the cavitation region.

As mentioned previously, the pump inlet oscillations were in phase with the pressures downstream of the pump. If they were just caused by variations in the pressure drops, from the flow resistances in the flow circuit from the run tank to the pump, with flow rate they should be out of phase. The pressures at various locations and the pressure drops across the different segments of the run tank propellant line and pump inlet line were evaluated in an effort to explain the unusual phasing of the pressure. Figure 24 shows the run tank outlet, run tank propellant line, pump inlet and pump discharge pressures during the period of oscillations from run no. 030, while Figure 25 shows the pressure drops between: (1) the tank outlet and a location upstream of the flow meters, (2) locations upstream and downstream of the flow meters and (3) a location downstream of the flow meters and the pump inlet.

Figure 24

Profile of Pressure Between Run Tank and Pump During Oscillations

DRY PUMP RUN NO. 030

Figure 25

Profile of Pressure Drops Between Run Tank and Pump During Oscillations

The pressure drop data presented in Figure 25 show that the magnitude of the fluctuations in the pressure drop across the section of line including the flow meters was much greater than across the other sections of lines. Negative pressure drops are also indicated by the data. The pressure drop across the section of line from the run tank outlet to the flow meters follows a similar pattern, but with less magnitude. This means that the oscillations in the pump inlet pressure and the phasing of the oscillations resulted primarily from these fluctuations in pressure difference across the flow meters and in the run tank propellant line above the flow meters. A precise correlation of these fluctuations with physical conditions within the flow circuit could not be established, but it is concluded that they resulted from the reaction of the flow meters to a pattern of varying flow rates, and fluid properties in the propellant line from the tank to the pump, resulting from the oscillations in pump performance.

Figure 24 shows there were also some fluctuations in the pressure measured at the run tank outlet which are reflected in the pump inlet pressure oscillations. Portions of the cycle can be correlated with probable variations in flow rate. However, the larger decreases in pressure are not understood. Additional analysis and possibly more data would be necessary to completely understand the pressure and pressure drop oscillations that occurred in the propellant feed circuit between the run tank and the pump inlet.

3. Effect of TPCV Opening Delay

Dry pump Run 019 was run with the opening of the TPCV, admitting power to the turbopump assembly, delayed for 18 seconds after the initiation of the test (with the opening of the propellant shutoff valve). This test was followed by similar runs, 020 and 021, in which there was a 13 second and a zero delay in the TPCV opening. Profiles of the pump speed during the runs are shown in Figure 26. The tests disclosed that no excessive pump acceleration or overspeeding occurs regardless of when the TPCV is opened. The oscillations, typical of the dry pump runs, were similar in all runs except that they terminate sooner, followed by the pump acceleration to peak operation, when the TPCV opening is

Figure 26

Effect of Delayed Opening of TPCV on Dry Pump Bootstrap Characteristics

delayed. There was no significant difference in the peak pump speed achieved during the tests, although delaying the TPCV opening did result in a slightly greater peak speed.

The data show that delaying the opening of the TPCV resulted in a shorter period of oscillations and earlier peak operation. This provides a technique for minimizing the time during which oscillations occur and the total flow through the system prior to achieving the peak performance. The delayed opening apparently resulted in a faster chilldown of the pump. The factors causing the faster chilldown have not been determined at present.

D. PERFORMANCE OF AUTOMATIC PRESSURE CONTROLLER

The test results indicated that the CFDTIS system operated satisfactorily with the pressure control loop closed at the initiation of the runs. The turbine power control was driven full open by the controller at the test stand and held full open during the early portion of the system acceleration. When the chamber pressure exceeded the pre-set demand value, the TPCV received a signal to close. Subsequent movement of the valve indicated proper performance of the pressure controller. After the system performance peaked and the chamber pressure was decreasing the controller again drove the valve full open in an attempt to maintain the chamber pressure. The reaction of the TPCV to chamber pressure and the controller during a typical run is shown in Figure 27.

E. HELIUM BLANKET ON TPA

Test No. 014 was run with the turbopump assembly blanketed in helium instead of nitrogen. The other test conditions were the same as Test No. 011. A comparison of pump speed during the runs is shown in Figure 28. The peak speed measured on Run 014 was slightly lower and occurred about 7 seconds later than on Run 011. However, because the measured differences were relatively small, and may be within the range of accuracy of the test conditions and the data measurements, it is concluded that any effects of blanketing the TPA in helium instead of nitrogen are insignificant.

Figure 27
Performance of TPCV with Automatic Pressure Controller

Figure 28

Comparison of Turbopump Speed with
Helium and Nitrogen Blanketing of TPA

F. REMOVAL OF DILUENT LINE ORIFICE

The flow measuring orifice in the diluent line was removed after Run 024. This reduced the line loss factor from 36.4 to 15.2. A comparison of Run 009, which was made under the same test conditions but with the orifice installed, and Run 025 (Figure 29) indicated an improvement of approximately 4% in peak pump speed resulting from an increase in the maximum flow to the turbine from 1.38 pounds per second to 1.47 pounds per second with the removal of the orifice. The test results mean that the turbine and system bootstrap performance is relatively insensitive to changes in the diluent line configuration as a 42.5% reduction in line loss factor only produced a 4% increase in peak pump speed.

G. PUMP INLET LINE CHILLDOWN

In the analysis of data from the first series of tests (Reference 3), a question was raised as to the mechanism of the chilldown of the pump inlet line. A sketch of the line is shown in Figure 30. Additional measurements were made in the second series of tests to obtain more information. Four additional thermocouples were installed at the side opposite of those used in the first series. The additional measurements are labeled TPII-5, -6, -7, and -8. Table V lists the temperatures at FS-1 and FS-2 for typical wet and dry pump starts.

The measurements indicate that the thin section of the inlet line chilled down faster than the thick section, as expected. In the previous analysis, the distinction between the two sections was not made because of the sparsity of data. Heat transfer coefficients obtained without that distinction indicated the possibility of an occurrence of film boiling in the inlet line during the chilldown. With the additional measurements, heat transfer coefficients may be estimated for the thin section alone.

Data from a dry pump start is used, since in wet pump starts the pump inlet line is already chilled when the run begins. The dry pump starts are complicated by flow, pressure, and temperature oscillations, but for purposes

Figure 29

Effect of Removal of Diluent Line Orifice on Bootstrap Performance

Figure 30

Sketch of Pump Inlet Line and Structure

TABLE V

PUMP INLET LINE TEMPERATURES

Wet Pump	TPIL-1	TPIL-2	TPIL-3	TPIL-4	TPIL-5	TPIL-6	TPIL-7	TPIL-8
Run 007								
FS-1	296	43	55	257	314	48	50	274
FS-2	262	50	46	195	283	46	44	232
Run 008								
FS-1	192	44	40	138	220	40	-	137
FS-2	164	44	45	126	187	-	-	116
Run 009								
FS-1	150	53	43	117	159	35	38	106
FS-2	135	55	38	114	140	-	-	101
Run 010								
FS-1	204	47	46	131	208	38	36	110
FS-2	155	50	44	110	165	-	-	100
Dry Pump								
Run 019								
FS-1	529	527	528	526	528	525	528	530
FS-2	468	212	177	454	472	222	173	456
Run 020								
FS-1	512	508	510	520	516	503	509	513
FS-2	451	202	126	440	455	207	156	440

of obtaining "rough estimates" of heat transfer coefficients, the oscillations are ignored. Taking the temperature measurements from Run 019, an average heat transfer coefficient for the thin section of the line is estimated from the expression:

$$h = \frac{C_{Ps} \rho_s l}{\Delta t} \ln \frac{(T_{W1} - T_b)}{(T_{W2} - T_b)}$$

where:

- $\bar{h}$ = average heat transfer coefficient
- C_{Ps} = heat capacity of wall
- ρ_s = density of wall
- l = wall thickness
- T_b = fluid temperature (assumed constant)
- T_{W1} = wall temperature at beginning of run
- T_{W2} = wall temperature at end of run
- Δt = duration of run

The following values are applicable to Run 019:

- C_{Ps} = 0.11 BTU/16°R
- ρ_s = 0.29 lb/in.³
- l = 0.25 in.
- T_b = 45°R
- T_{W1} = 520°R
- T_{W2} = 196°R
- Δt = 75 sec

The value of the heat transfer coefficient is obtained as:

$$\bar{h} = 1.22 \times 10^{-4} \text{ BTU/in.}^2 \text{ sec}^\circ\text{R}$$

A heat transfer coefficient was calculated using the liquid correlation of Thompson and Geery (Reference 5) in the "B" region:

$$N_u = .0217 R_e^{.8} P_r^{.4} (T_w/T_b)^{-.34}$$

where: N_u = Nusselt number evaluated at bulk fluid temperature

R_e = Reynolds number evaluated at bulk fluid temperature

P_r = Prandtl number evaluated at bulk fluid temperature

T_w = wall temperature

T_b = bulk fluid temperature

For Run 019, the average wall temperature over the duration of the run is about 358°R and the average flow rate is approximately 15 lb/sec. The heat transfer coefficient is obtained as:

$$h (\text{liquid}) \approx 4.12 \times 10^{-4} \text{ BTU/in.}^2 \text{ sec}^\circ\text{R}$$

Using the two-phase correlation of Hendricks, Graham, Hsu, and Medeiros (Reference 6), using a quality of 0.5, the value of the heat transfer coefficient obtained was:

$$h (\text{two-phase}) = 1.24 \times 10^{-4} \text{ BTU/in.}^2 \text{ sec}^\circ\text{R}$$

For film boiling, the heat transfer coefficient as calculated using the correlation of Reference 7 is:

$$h (\text{film boiling}) = 0.31 \times 10^{-4} \text{ BTU/in.}^2 \text{ sec}^\circ\text{R}$$

Thus, comparing the heat transfer coefficients reveals that the heat transfer situation in the pump inlet line is most closely described by a two-phase characterization.

H. TEMPERATURE DISTRIBUTIONS IN PLENUMS DURING CFDTS TESTS

1. Introduction

Cold flow bootstrap operations during the CFDTS tests were accomplished from wet pump as well as dry pump starts. The pump was sufficiently pre-chilled during the wet pump start by flowing liquid hydrogen from the tank through the pump and venting at the pump discharge, while the pump was not pre-chilled during the dry pump start. The system pressures remained below the critical pressure of hydrogen, 188 psia, for all tests over the duration of the run or a major portion of the run. Therefore, two-phase flow conditions could have existed in the system during all of these tests. Two-phase flow did initially appear in the feed line and later moved into the nozzle coolant tubes and the reflector as the feed line and the nozzle, initially at ambient temperature, were chilled down with flowing hydrogen. However, the reflector section was never sufficiently chilled so that a two-phase flow condition never appeared in the shield dome-end plenum.

Angular asymmetrical temperature distributions in the reflector inlet (or nozzle tube outlet) and outlet plenums were observed during the NRX-A2 test series (Reference 8) when two-phase flow conditions existed in the nozzle coolant tubes. An investigation was then conducted to determine the extent of temperature asymmetry and its effect on system performance during the CFDTS.

2. Measured Temperatures in Plenums

Three runs, including two wet pump starts and one dry pump start, were selected for this investigation. In Table VI the major operating conditions of these runs are summarized.

TABLE VI
MAJOR OPERATING CONDITIONS OF TYPICAL CFDTS TESTS

Test No.	<u>008</u>	<u>010</u>	<u>022</u>
Tank Pressure, psia	69.4	49.4	49.5
Turbine Back Pressure, psia	14.2	12.7	7.4
Chilldown Condition	Wet Pump Start	Wet Pump Start	Dry Pump Start
Peak Pump Speed, rpm	7440	6880	8700
Pump Discharge Pressure, psia*	173	137	191
Pump Discharge Flow Rate, lb/sec*	28.5	25.3	31.8

* At peak pump speed.

a. Test No. 008 Data

In Figure 31 the time history of fluid properties in the nozzle manifold is traced on the temperature-entropy diagram of hydrogen. The bootstrap operation commenced at run time of 371 seconds when the pump discharge valve and the turbine power control valve were opened. A two-phase flow interface was moving through the pump discharge line until run time of 372.5. At this time flow into the nozzle manifold became two-phase. Beyond this time two-phase flow moved into the nozzle coolant tubes and then into the reflector. At a run time of 373.7 the flow into the nozzle manifold became liquid.

Figure 32 presents composite plots of the temperature measurements in the nozzle manifold, the nozzle coolant tube outlet, the reflector outlet and the shield dome end plenum at different angular locations (or theta). Temperature asymmetry seemed to have existed in the nozzle manifold from the start of the run to run time of 373.2 seconds. This was not a true temperature asymmetry but was caused by inability of the resistance temperature transducer (RTT) at theta of 295 degrees to respond to rapidly changing fluid temperature. During this period, feed to the nozzle manifold was gaseous hydrogen, and the feed temperature was rapidly dropping at a rate greater than 200°R per second. Response of a temperature probe to rapidly changing fluid temperature depends greatly upon the local mass velocity of flowing fluid. In the nozzle manifold fluid mass velocity is not constant, but decreases rapidly from the inlet side of theta of 120 degrees to the opposite side at theta of 300 degrees. It can be observed in Figure 32 that the temperature probe, THNM-1, at theta of 295 degrees was indicating a higher temperature than the other probes, THNM-2 and 3, while the fluid temperature was rapidly dropping in the nozzle manifold. Calculations indicated that the observed temperature difference was indeed related to a lag in the response of THNM-1 at theta of 295 degrees by approximately 0.6 seconds time constant. However, a maximum of 10°R difference in fluid temperatures could exist during this period from the inlet side to the opposite side in the nozzle manifold because of heat transfer from the manifold, initially at ambient temperature, to the flowing fluid. After the fluid in the nozzle manifold became liquid, all three temperature probes began to measure the same temperature.

Figure 31

Temperature, Pressure and Phase Characteristics of
Fluid in Nozzle Manifold

Figure 32

Beyond run time of 372.5 seconds, two-phase conditions existed in the nozzle tube manifold and were spreading through the nozzle tubes towards the reflector inlet plenum. During this period, temperature asymmetry existed in the nozzle coolant tube outlet and was carried into the reflector outlet plenum. Beyond run time of 383.5 seconds, two-phase flow moved into the reflector, causing more pronounced temperature asymmetry in the reflector outlet plenum.

Temperature asymmetry seemed to have existed in the shield dome end plenum beyond run time of 380 seconds as the fluid temperature gradually dropped. The observed temperature asymmetry was at most 30°R. Since uncertainty of copper-constantan thermocouples, which were installed in this plenum, becomes increasingly large below 400°R (uncertainty of about $\pm 10^{\circ}\text{R}$ at 400°R), the observed temperature asymmetry is largely attributed to uncertainty of the measurements. Therefore, it was concluded that no significant temperature asymmetry existed in the shield dome end plenum. A similar conclusion was made in the earlier investigation (Reference 7).

Figure 33 presents the measured nozzle chamber temperatures. The nozzle chamber temperature remained approximately at ambient temperature until the system components began to be cooled at more rapid rates with increasing mass flow in the system. After a run time of 10 seconds after FS-1, the nozzle chamber temperature began to drop and a temperature asymmetry was observed from measured temperatures in the nozzle chamber. Three of the four measured temperatures were obtained from resistance-temperature transducers (RTT's), while one was obtained from a chromel-alumel thermocouple. Since response and uncertainty characteristics of the chromel-alumel thermocouples are different from those of the RTT's, investigation of the observed temperature asymmetry was made with the RTT's (THNC-1, 2, and 3) only.

The measured temperature from THNC-1 and 3 lagged THNC-2 during the period of rapid decrease in the nozzle chamber temperature. The following conditions were considered to be capable of causing the observed

Figure 33

temperature asymmetry in the nozzle chamber: (1) non-uniform cooling of the core, (2) asymmetrical temperature distribution in the core inlet plenum, and (3) difference in response of the temperature probes to changing fluid temperature because of the difference in local mass velocities of fluid, as was previously discussed in Section IV.B, above.

Non-uniform cooling in the circumference of the core, together with streaming of the jets exiting from the core, could produce asymmetrical temperature distribution in the nozzle chamber. However, the total of six thermocouples installed in the core were insufficient to determine any indication of non-uniform cooling in the circumference of the core. Asymmetrical temperature distribution in the core inlet plenum could be carried into the nozzle chamber. Figure 34 presents measured fluid temperatures in the core inlet plenum at run times of 384 and 390 seconds. These data did not show any clear-cut indication of temperature asymmetry in the core inlet plenum. Therefore it is concluded that the observed temperature asymmetry in the nozzle chamber was largely caused by lag in response of THNC-1 and 3 coupled with some uncertainties in the temperature measurements.

b. Test No. 010

This run was a wet pump start with the tank pressure of 49.4 psia and the turbine back pressure of 12.7 psia. Figure 35 presents a time-history trace of the fluid properties in the nozzle manifold on the temperature-entropy diagram of hydrogen. The run was started at approximately 191.4 seconds. Two-phase flow existed in the pump discharge line until a run time of 193.4 seconds. Beyond this time, two-phase flow moved into the nozzle coolant tubes and the reflector.

Figure 36 presents composite plots of fluid temperatures in the nozzle manifold, the nozzle tube outlet, the reflector outlet, and the shield dome end plenum. Temperature asymmetries in these plenums are similar to the conditions of test No. 008; (1) the observed temperature asymmetry in

Figure 34
Fluid Temperature in Core Inlet Plenum

Figure 35

Temperature, Pressure and Phase Characteristics of
in Nozzle Manifold

Figure 36

the nozzle manifold during the initial few seconds was caused by the inability of the temperature probe at theta of 295 degrees to respond to rapidly decreasing fluid temperature because of low mass velocity at that location, and (2) temperature asymmetry in the nozzle tube outlet, which was caused by two-phase flow in the nozzle coolant tubes, was carried into the reflector outlet plenum but not into the shield dome end plenum.

c. Test No. 022

This run was a dry pump start with the tank pressure of 49.5 psia and the turbine back pressure of 7.4 psia. The run was started at run time of 71.7 seconds. Figure 37 presents time-history trace of fluid properties in the nozzle manifold on the temperature-entropy diagram of hydrogen. Two-phase flow was observed in the nozzle manifold from run time of 85.5 seconds to 96.9 seconds.

Figure 38 presents composite plots of fluid temperatures in the nozzle manifold, the nozzle tube outlet, the reflector outlet, and the shield dome end plenum. Characteristic oscillations of the dry pump start appeared concurrently with two-phase flow in the nozzle manifold at run time of 85.5 seconds. Thereafter, fluid in the nozzle manifold cycled from two-phase, to gaseous phase until run time of 86.9 seconds when the feed to the nozzle manifold became liquid. During this period, temperature oscillations were coupled with temperature asymmetries in the nozzle coolant tube outlet and the reflector outlet plenum. Temperature oscillation was still observable in the shield dome end plenum but not in the core inlet plenum.

Figure 39 presents fluid temperature at turbine inlet. Temperature oscillation was not observed at turbine inlet. The peak pump speed of 8700 rpm was achieved 29 seconds after the bootstrap operation was initiated. The turbine inlet temperature decreased from 525°R to 455°R during this period.

Figure 37

Temperature, Pressure and Phase Characteristics in
in Nozzle Manifold

FLUID TEMPERATURES IN NOZZLE MANIFOLD, NOZZLE TUBE OUTLET,
REFLECTOR OUTLET, AND SHIELD DOME END PLENUM
(CFDTS TEST NO. 022)

Figure 38

Fluid Temperatures in System Plenums - Run 022

Figure 39
Fluid Temperature at Turbine Inlet

3. Conclusions

The system pressures during the CFDTs cold flow bootstrap operations mostly remained below the critical pressure (188 psia) of hydrogen. Therefore, two-phase flow condition could and did exist during a large portion of the run, initially appearing in the feed system, then moving into the nozzle coolant tubes and the reflector. Two-phase flow caused temperature asymmetries in the nozzle coolant tube outlet and the reflector outlet plenum, but not in the shield dome end plenum. The temperature asymmetries did not have any effect on the system operation or performance, however.

During the dry pump starts, temperature asymmetries were coupled with temperature oscillations in the nozzle coolant tube outlet and the reflector outlet plenum over the time periods when fluid in the nozzle manifold was cycling from two-phase to gaseous phase. Temperature oscillations were also observable in the shield dome end plenum, but not in the core inlet plenum. Temperature oscillation was not observed at the turbine inlet.

BLANK

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