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FINAL REPORT

DUAL TURBOPUMP TESTING IN TEST CELL C

NERVA Program, Contract SNP-1

June 1970

MASTER

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DUAL TURBOPUMP TESTING IN TEST CELL C

NERVA Program

Contract SNP-1

June 1970

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I. INTRODUCTION

The high reliability requirement of the NERVA engine indicates the need for a redundant propellant feed system (PFS). As a result of the hot-bleed PFS Trade Study (Reference 1), a PFS with multiple parallel components (i.e., turbopumps and valves) was recommended. This configuration included two turbopumps (TPA) operating in parallel and a turbine feed system with two control valves, four block valves, and an intertie. This study identified possible problems and operating regimes in which there was no current experience. As a result, early testing of a redundant feed system was desirable and was accomplished.

The configuration of the PFS utilized in the Test Cell C Dual Turbopump Test Program approximated the selected six-valve hot-bleed-cycle system (Reference 2). Since the steady-state and dynamic characteristics of the pumps dominate the behavior of the TPA's, the data acquired during this test program was directly applicable to the PFS for the full-flow engine. The Test Cell C system provided demonstration of the ability of the TPA's to survive the abrupt change in conditions (i.e., speed, flow rate, and pressure) required to maintain rated engine thrust in the event of a failure occurring within the PFS.

II. SUMMARY AND CONCLUSIONS

The Dual Turbopump Test Program was conducted at Test Cell C during the second quarter of Contract Year 1970. The following objectives of the program were successfully accomplished in the four experimental plans (EP's):

1. Provision of performance and operating characteristics data for the engine analysis activity to upgrade steady-state and transient models.
2. Provision of performance and operating characteristics data for component design (including pump, turbine, valve, and line hydro-aerodynamics), component fluid and mechanical interactions, and malfunction and transient response. These data support design and reliability analyses and provide early evaluation of preliminary malfunction detection and control systems.

During the test program the following was demonstrated:

1. Centrifugal pumps will provide the flow range necessary for dual-TPA engine operation.
2. Stable operation can be achieved with the ΔP vs $\dot{W}_p$ slopes which are practical for centrifugal pumps.
3. Stable operation can be accomplished with pump flow rate differences (asymmetry) of 10 lb/sec ($12\frac{1}{2}\%$).
4. Individual turbine control is not required based upon the performance scatter of a system randomly built within the tolerances of a specific set of fabrication drawings.

5. Control of the system during normal operation and malfunction transients can be achieved without any significant problems (speed and common pump-discharge pressure controllers were utilized).

6. Malfunctions in the turbine drive control valves can be survived.*

7. A turbopump malfunction or failure can be survived (simulated by opening a pump discharge bypass valve).*

8. Shutting down one TPA by closing the turbine block valve (TBV) results in a transient which can be survived.*

A summary of the operating time which was accumulated during the test program is shown in Table 1.

The data acquired included:

1. Steady-state performance data at various power levels.
2. Steady-state system impedance values, including valve characteristics and line drops.
3. Performance data during start and shutdown transients.
4. Transient response data resulting from simulated malfunctions, system disturbances, and control system demands.
5. Frequency response and transfer functions of the mechanical and control system.
6. General operational data for a dual-TPA/PFS.

* "Survived" denotes no significant degradation of thrust or unacceptable change in reactor or nozzle pressures or temperatures, based upon XE requirements.

TABLE 1

OPERATING TIME ACCUMULATED
DURING TEST PROGRAM

	PUMP No. 1	PUMP No. 2	DUAL-MODE
No. of Starts	26	24	22
Total Spin Time (Min)	143	123	118
Total Time Above 18,000 rpm (min)	86	70	67

III. PROGRAM OBJECTIVES

The dual-TPA test program had two overall objectives:

1. To provide performance and operating characteristics data for the engine analysis activity to upgrade steady-state and transient models.
2. To provide performance and operating characteristics data for component design (including pump, turbine, valve, and line hydro-aerodynamics) component fluid and mechanical interactions, and malfunction and transient response. These data support design and reliability analyses and provide early evaluation of preliminary malfunction detection and control systems.

Two classes of data were desired from the test program:

1. Feed-system performance at high or full power, including flow-rate ratios, system stability, and malfunction and transient behavior.
2. Feed-system performance at low power levels, including start and shutdown transients and bootstrap thresholds.

The former data significantly affect the overall design of the PFS (particularly reliability) whereas the latter affect the more subtle component design features.

The most important initial information appeared to be that involving high or full power operation. Because it does involve operation at severe conditions, it was desirable to start with a simple system and add complexity as the behavior became understood, provided the simple system produced useful data. The analysis performed in the PFS trade study (Reference 1) indicated that the major questions concerning operation of a dual-pump system involve the pump rather than the turbine. As a result, the test

plan concentrated on the liquid hydrogen (pump) system and accepted the minor discrepancy introduced by cold-gas drive of the turbine. The data acquired are directly applicable to the full-flow cycle since the steady-state and transient dynamics of the pumps dominate the TPA

IV. FLOW SYSTEM

The control room flow schematic for EP-1, EP-2, and EP-3 is shown in Figure 1.

Liquid hydrogen was provided to the pumps through a common inlet line from Dewar 2. The individual legs of the suction line had provisions to use a Frantz screen or orifice in either or both legs for suction pressure (NPSP) throttling.

The two pumps discharge into a common line. Each leg of the discharge line had a turbine type flowmeter (HF-850, HF-950) and an XE-type check valve upstream of the junction. Bypass valves (L-119, L-219) made it possible to flow from upstream of the check valves in each leg directly to the flare line. Another flow meter (LF-29) was located in the common section of line after the two discharge legs were joined. Pump impedance was controlled by an analog valve (L-30). Downstream of the impedance valve the flow could be directed either to the dewar through L-32 or to the flare header through L-31.

Turbine drive gas was provided either by the tank farm or from the turbine energy source (TES), a hot-water heat exchanger supplied with liquid hydrogen from the pump discharge flow through H-9. A calibrated orifice (HF-62) was used to measure the total gas flow rate in the system. Control of the turbine drive was provided by XE-type turbine power control valves (TPCV). The turbine inlet line had provisions for six valves. Two TPCV's (H-65, H-68) and two TBV's were used. They were either located at H-64 or at H-66 and H-69 locations, depending upon the individual test requirements. An intertie was provided between the inlet line legs downstream of the control valves. Orifices (HF-860, HF-960) were located in each leg to measure the flow rate into each turbine.

Figure 1 - NERVA Dual Pump Control Room Flow Schematic, LASL Drawing J5-SK-289, Revision 3

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V. TURBOPUMP

A. DESCRIPTION

The two TPA's utilized in the test program were modified XE-type TPA's (Reference 2). The TPA consists of a single-stage, backswept (35° nominal discharge angle, measured from tangential direction) centrifugal pump with an integral inducer directly driven by a two-stage, axial-flow impulse turbine. Shaft support was provided by propellant-cooled rolling-element bearings inboard of the overhung impeller and rotors. Thrust balance to the capability of the tandem ball thrust bearings was accomplished by impeller back vanes. Internal instrumentation was provided for assessment of performance and mechanical integrity.

The backswept impeller was designed to provide a negative slope $\Delta H/N^2$ vs Q/N curve required for stable operation of a dual-TPA system. The data acquired with the reduced discharge pressure of these TPA's can be correlated with the NERVA operating range.

B. PUMP DESIGN PHILOSOPHY AND METHOD

1. Operating Specification

The operating specification based upon dual pumps operating in a simulated malfunction mode was established at 80 lb/sec system flow rate of hydrogen at 22,000 rpm. In such a system, the pumps would operate in parallel in the normal mode with each pump supplying 40 lb/sec of hydrogen at 19,500 rpm. In the malfunction mode, however, only one pump would operate, but at the total system flow rate (i.e., twice the normal flow rate of 40 lb/sec) and at an increased speed of 22,000 rpm. The design pressure rise for both modes was 445 psi which is approximately one-half the pressure rise of the XE pump. Since the primary objective of the program was to

verify the concept of the dual pump with a minimum modification of existing hardware, the pressure rise obtainable with existing hardware was judged adequate. Additional problem of increased axial thrust would also be created by the higher pressures.* Operating specifications are summarized in Table 2 and the predicted head-flow curve is shown in Figure 3. For comparison, the operating specifications for the hot-bleed backswept pump with a 28° discharge blade angle (dual, two spool feed system) is presented in Table 3. Pump design allowed for upgrading to a twin-spool configuration for the planned Phase IB

2. Impeller

a. Discharge Geometry

To match the staging for a simulated twin-spool operation (so the low-speed inducer would operate at the flow coefficients for which two-phase hydrogen pumping capability has been demonstrated; see reference 3) the inducer flow parameter vs main-stage flow parameter was plotted for values of main-stage shaft horsepower and turbine exhaust system flow impedance. This information was provided by a computer transient program and is presented in Figures 4, 5, and 6. Figure 5 (i.e., intermediate turbine exhaust system impedance) indicates that main-shaft horsepower for the one-pump mode should be 3900 in order to use the existing low-speed turbine when the main-stage pump is operating at the desired operating point of 22,000 rpm and a 80 lb/sec flow rate. The impeller discharge tip diameter and port width were sized to provide this horsepower.

* Unlike the NERVA engine design, the XE TPA does not have a self-compensating thrust balance system.

TABLE 2

BACKSWEPT IMPELLER MODIFIED MK III, MOD 4 PUMP OPERATING

MODE	SPEED rpm	FLOW RATE lbs/sec	PRESSURE RISE psi	SHP	EFFICIENCY	$\Delta p - W$ SLOPE psi/lb/sec	SPECIFIC SPEED $\frac{(\text{rpm})(\text{gpm})^{1/2}}{\text{ft}^{3/4}}$	SIMULATED ENGINE CONDITION
One Pump	22,000	80	445	3900	.55	-4.1	1407	Full Thrust Nom T_c
Two Pumps	19,500	40	445	1750	.60	-1.7	863	Full Thrust Nom T_c
Two Pumps -Stall	15,400	25	278	720	.58	0	842	Throttled - Nom T_c 62.5% Thrust

Figure 3 - Predicted $\Delta H/N^2$ vs Q/N

TABLE 3

NERVA HOT-BLEED BACKSWEPT PUMP OPERATING SPECS.
DUAL, TWO-SPOOL TURBOPUMP FEED SYSTEM

	MODE	SPEED rpm	FLOW RATE lbs/sec	PRESSURE RISE psi	SHP	EFFICIENCY	$\Delta p - W$ SLOPE psi/lb/sec	SPECIFIC SPEED	SIMULATED ENGINE CONDITION
								$\frac{(\text{rpm})(\text{gpm})^{1/2}}{\text{ft}^{3/4}}$	
	One Pump	30,000	91	902	7117	.65	-9.1	1340	Full Thrust Nom T_c
51	Two Pumps	26,500	45.5	902	3531	.67	-4.0	831	Full Thrust Nom T_c
	Two Pumps -Stall	12,450	11.8	230	307	.53	0	535	Throttled- Nom T_c 25.7% Thrust

INDUCER FLOW PARAMETER VS MAINSTAGE FLOW PARAMETER

TURBINE BACK PRESSURE
 LOSS COEFFICIENT - .005

22000 rpm

Figure 4 - Inducer Flow Parameter vs Main Stage Flow Parameter
 (Turbine Exhaust System Flow Impedance equal 0.005)

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INDUCER FLOW PARAMETER vs MAINSTAGE FLOW PARAMETER

TURBINE BACK PRESSURE
 LOSS COEFFICIENT - .010

22000 rpm

Figure 5 - Inducer Flow Parameter vs Main Stage Flow Parameter
 (Turbine Exhaust System Flow Impedance equal 0.010)

INDUCER FLOW PARAMETER
vs

MAINSTAGE FLOW PARAMETER

TURBINE BACK PRESSURE
LOSS COEFFICIENT - .020

22000 rpm

Figure 6 - Inducer Flow Parameter vs Main Stage Flow Parameter
(Turbine Exhaust System Flow Impedance equal 0.020)

b. Blade Angle and Number of Blades

A nominal 35° discharge blade angle was selected to furnish a negative slope characteristic to the head-flow curve for simulation of single-and dual-pump engine operation. The negative slope was introduced in because of the possible flow stability problem with positive or zero slope predicted by the engine stability analysis.

A total of 12 blades, consisting of three full blades, three long-partial blades, and six short-partial blades were selected for this design. This is consistent with the general rule that the number of blades should be approximately equal to $1/3$ of the discharge blade angle.

c. Vane Generation

The M-1 oxidizer pump vane generation (mean camber line), P/N 297510, was selected primarily because performance data were available and because this geometry is similar to the XE impeller for matching with the housing. A comparison of the meridional profile using 96.5% of the M-1 oxidizer dimensions with the NERVA XE impeller is shown in Figure 7. This ratio was used to maintain the same eye diameter as the XE impeller.

d. Blade Contour

The same impeller blade tip contour as that of the existing XE impeller was maintained so the existing XE housing could be used. The hub contour was 96.5% of the M-1 dimension. Table 4 compares the new backswept design with the existing XE impeller.

DASH LINE PROFILE SHOWN IS
FOR DIMENSIONS WHICH ARE
96.5% OF 297510 DIMENSIONS
TO GIVE 287730 EYE DIMENSION

Figure 7 - Comparison of Meridional Profile Using 96.5% of Dimension of M-1 Oxidizer Blade with XE Blade

TABLE 4

COMPARISON OF MODIFIED BACKSWEPT IMPELLER WITH XE IMPELLER

<u>PARAMETER</u>	<u>BACKSWEPT IMPELLER (P/N 1136607)</u>	<u>XE IMPELLER (P/N 287730)</u>
Discharge Dia., in.	10.75	12.25
Discharge Blade Angle, Degrees	35	90
Inlet Tip Diameter, in.	6.95	6.95
Inlet Hub Diameter, in.	2.30	1.85
Inlet Tip Blade Angle, Degrees	7.55	7.0
Number of Blades		
Inlet	3	3
Discharge	12	48
Blade Height (Discharge), in.	0.672	0.485

The blade inlet tip angle, β_{1T} , of 7.55° resulted from the use of the scaled down M-1 oxidizer blade generation. Blade tip thickness at the inlet was established at 0.149 in. which is equal to 1/2 of the inlet blade hub thickness. The blade hub thickness at the inlet was set at 80% of the theoretical hub cavity height.

To simplify fabrication, the blades were designed to be machined with fixed cutter offsets, permitting the use of the same cams for both high- and low-pressure surfaces. The impeller blade thickness distribution resulting from this method is shown in Figure 8. A 3/8-in. cutter was specified on the basis of the minimum blade clearances at the beginning of the short partial blades.

The leading edge trim for the full blades resulted in a sweep-back of 78.2° which is similar to the M-1 oxidizer impeller.* Fairing on the low-pressure side is similar to the XE impeller with a constant 0.02-in. leading edge radius fairing into the normal blade thickness. The long-partial blade is trimmed back 25° while the short-partial blade is trimmed 20° .

Aluminum 7075-T73 was used to fabricate the initial back-swept impeller for the single-spool TPA. For incorporation into the twin-spool design, Titanium Al10-AT ELI will be used.

3. Analysis

a. Blade Loading

The hydraulic blade loading for the structural analysis

* Angular dimension is identical: the linear dimension is 96.5% of M-1 subscale impeller.

Figure 8 - Test Cell C Impeller Blade Thickness Distribution

of the inducer portion of the Test Cell C impeller was obtained from a computer program (Job 10041) based on the free streamline wake theory of a flat plate (Reference 4). The load analysis was performed for the following condition:

Speed	22,000 rpm
Flow Rate	45.13 lb/sec
NPSP	50 psi
Fluid Density	4.23 lb/ft ³

Results are plotted in Figure 9 as lines of constant pressure superimposed on the blade leading edge.

b. Axial Thrust

Backvanes were incorporated to balance the thrust for both single- and dual-pump operating modes. The vanes were designed to provide a thrust-trim capability during development because of the difficulty of accurately predicting thrust in a system with a multitude of variables.

Predicted thrusts for both single and twin-spool TPA's at the operating points are summarized below. The positive sign denotes thrust directed toward the pump suction, while the negative sign denotes thrust toward the turbine.

Single Spool - Thrust (lb)

<u>Speed</u> <u>(rpm)</u>	<u>Flow Rate</u> <u>(lb/sec)</u>	<u>Pump</u>	<u>Power</u> <u>Transmission</u>	<u>Turbine</u>	<u>Net</u>
22,000	80	2293	1936	-7441	-3212
19,500	40	4102	1424	-3727	+1799

Figure 9 - Blade Loading

Twin Spool - Thrust (lb)

<u>Speed</u> <u>(rpm)</u>	<u>Flow Rate</u> <u>(lb/sec)</u>	<u>Pump</u>	<u>Power</u> <u>Transmission</u>	<u>Turbine</u>	<u>Net</u>
22,000	80	1140	2126	-6665	-3399
19,500	40	3444	1508	-2888	+2064

c. Design and Off-Design Performance

Because of the relatively large space between the impeller discharge and the housing diffuser vanes, conservative values of efficiency and head coefficient were used. Tests of the two-spool demonstration pump with a radial blade impeller indicated that such a large clearance had an adverse effect upon efficiency and head coefficient.

Off-design torque characteristics were derived using data from M-1 oxidizer sacle-pump water tests. Housing off-design head loss characteristics at off-design conditions were estimated using loss coefficients derived from NERVA Mark III, Mod 3 pump water tests.

VI. PUMP PACKAGE

A. DESCRIPTION

The decision to conduct dual-TPA testing in Test Cell C brought about the concept of a pump package (Reference 5) with ANSC providing a complete package containing TPA's, piping, valves, and instrumentation with a defined interface with the test facility.

The basic structure of the pump package was the pump mounting frame; secured to the pump room floor in the opposite end of the room from the Rocketdyne pump package.

The pump package consisted of four systems: pump inlet; pump discharge; turbine inlet; and turbine exhaust.

The pump inlet system consisted of a "Y" section from a common interface flange to two inlet legs which contained expansion joints. The inlet legs were 10-in. schedule-10 pipe. Each leg reduced to 8 in. and then to the 7-in. pump inlet flange. Within each inlet leg provisions were allowed in a standard flange for either an orifice or a Franz screen. The restriction device was to control suction conditions to one or both pumps.

The pump discharge system consisted basically of 5- and 6-in. schedule-80 pipe. The system had two independent legs from the TPA's, each with a turbine-type flow meter, bypass line and valve, and a 5-in. XE-type check valve. The independent legs came together in a "Y" section then traverse through an 8-in. common turbine-type flow meter. The 8-in. line then joined the facility interface.

The turbine inlet system was a six-valve system with two configurations. The system used in EP-1, EP-2, and EP-3 consisted of two drive

legs (3.5-in. diameter pipe), each with a TBV and a TPCV. Downstream of each TPCV was an intertie line providing the capability of driving both TPA's with a single TPCV. For EP-4, the system was modified to incorporate a common line downstream of the TPCV's to eliminate the impedance difference in the drive lines. An operational TBV and a blocked-open TBV were also added to the system at this time. Both systems also contained individual flow measuring orifices with the necessary monitoring instrumentation.

The turbine exhaust system began at the TPA's and collected to a common line at the facility's 12-in. diameter exhaust header. Each TPA had two 6-in. tangential discharge lines. One line from each TPA was collected into a common 8-in. diameter leg. The two 8-in. legs then joined at the 12-in. interface.

The ANSC-supplied valves in the package were operated with a pneumatic supply from a supply console located near the pump package. This console was the valve checkout console initially used for XE valve checkout. The console was supplied from a 500-psig facility helium header. The console supplied a 10-micron filtered, 200-psig supply to the TPCV's and 500 psig to the TBV's. A secondary function of the console was to supply a helium purge to the pump package. The helium purge could be heated with the use of a facility heater for the dehydration purge on the TPA bearings. Figures 10 through 21 show the several stages of construction of the pump package.

B. OPERATIONAL HISTORY

The pump package was built and maintained utilizing ANSC-furnished procedures (References 6 through 20). During the package assembly, three modifications to the prefabricated parts were made to complete the assembly. The turbine inlet line intertie was shortened 0.25 in. to furnish approximately 0.05 in. compression in the bellows. The support frame cross braces were modified to provide adequate clearances of the turbine inlet lines and

Figure 10 - Turbopumps

Figure 11 - Turbine Exhaust Line Installed

Figure 12 - Pump Inlet Line Installed

Figure 13 - Turbine Inlet Line Installed

Figure 14 - Pump Discharge Line Common Section

Figure 15 - Pump Discharge System

Figure 16 - Valve Supply Console Installed

Figure 17 - Modified Turbine Exhaust Lines

Figure 18 - Modified Turbine Inlet Line

Figure 19 - Turbine Drive Valves

Figure 20 - Modified Turbine Inlet and Exhaust Lines

Figure 21 - Complete Pump Package Assembly

pump housings. The bolt holes on the upstream flange of the interface elbow assembly in the discharge line were modified to interface with the misaligned flange of the 8-in. commercial flowmeter. The bolt holes in the flange were elongated 0.75 in. to allow for the mismatch.

During the initial system leak tests, a failure was experienced in the supports of the turbine exhaust lines. The anchor bolts holding the supports of the flexible exhaust lines were inadequate. The anchors separated from the concrete floor allowing the flexible exhaust lines to extend beyond the allowable stretch of the bellows. This caused permanent distortion of the bellows. Six of the eight bellows required replacement. In addition to replacing the bellows, a wire braid was installed over each bellows to support the pressure load (see Figure 17). With this modification, the original supports were not required.

Only one significant leak developed in the entire pump package during cryogenic operations: a body flange seal on one pump discharge check valve leaked. The valve was disassembled between EP-1 and EP-2 to replace the seal. At the same time, the body flange retaining bolts were changed from the relatively low-strength bolts to high-strength A-236 bolts.* The cause of the leakage was determined to be yielding of the body flange retaining bolts as a result of the higher line stresses in the Test Cell C installation which, in turn, caused the flange of the valve body to separate.

During EP-1 TPCV S/N 880025 failed to fully close. Posttest removal and subsequent inspection of the valve revealed a fractured disk seal ring which had broken in two pieces at a ring retaining pin hole allowing unrestricted expansion of the ring. The unrestrained ring segment became jammed and bent over the edge of the seal disc. This caused a wedging action between the disc and the valve body and prevented full closure. The valve assembly was returned to the Sacramento Facility for repair. A new disc

*The later model check valves used on the XE system utilized high-strength bolts.

seal ring assembly was installed and the valve was returned to NRDS and re-installed in the test cell.

During EP-2, a similar failure occurred on TPCV S/N 880026. Upon completion of this test series both TPCV's were removed from the test facility and returned to Sacramento.

Disassembly of the S/N 880026 valve revealed a nearly identical mode of failure to that experienced on the S/N 880025 unit after EP-1. In addition, the torque required to rotate the pneumatic actuator was excessive and erratic. Consequently, actuator S/N 019 was replaced.

Disassembly of the S/N 880025 valve revealed a cracked seal ring in the new disc seal ring assembly installed prior to EP-2. The imminent mode of failure on the cracked ring was identical to the two previous failures.

A decision was made to reassemble both TPCV's without disc seal rings. Since the function of the TPCV is to control flow, the removal of the rings was not deleterious to system operation.*

A review of the TPCV position traces for EP-1, EP-2, and EP-3 indicate unprogrammed valve movement of approximately $\pm 0.1^\circ$ at approximately 15-30 cps about the set point of 38° open. This motion was evident at and above nominal turbine flow rates.

The seal ring failures were attributed to fatigue failure at the ring adjacent to the retaining pin hole and caused by the excessive cycles to which the seal rings were subjected.

*The shutoff function of the turbine inlet system was performed by the TBV.

After disassembly of the Model NT-D2 S/N 019 actuator from TPCV S/N 880025, it was noted that the breakaway torque of the actuator output was somewhat higher than normal.

The actuator was then subjected to the same acceptance tests to which it had been subjected prior to shipment to Test Cell C. A comparison of test data with the original acceptance data revealed the actuator to be incapable of meeting the performance requirements. Evaluation of the TPCV actuator performance was made from a study of EP-2 data and it was determined that the degraded actuator performance had no deleterious affect upon EP-2 testing. A decision was made to rebuild the S/N 880025 valve, using backup actuator S/N 023, and to disassemble the S/N 19 actuator to determine cause of increased torque. Disassembly of the actuator revealed that the input shaft bearings were contaminated by wear particles of bearing cage material. The actuator was rebuilt with new bearings as a spare unit for the test program.

A valve log was maintained during the test program to document the number of cycles and the actual "working" time on the valves. Tables 5 through 9 contain data from the valve logs. After EP-3, the TBV's were returned to ANSC for preventive maintenance which consisted of replacing the input shaft to the disk connecting pin.

Also prior to EP-4, another TBV was installed in the turbine drive line with a nonworking (i.e., blocked open) TBV to accomplish both turbine drive failure and simulated pump failure tests without re-entry.

During assembly, flow measuring orifices of 2.635 and 2.632-in. diameter were installed in turbine drive legs 1 and 2, respectively. For EP-3, a 3.676-in. diameter orifice was installed in the inlet leg of Pump 1 to unbalance the pump inlet lines. On a re-entry during EP-3, the turbine drive orifice in side 1 was changed to a 2.495-in. diameter orifice to give further unbalance of the TPA's. For EP-4, the inlet side orifice of pump 1 was removed and the turbine drive orifice in side 1 was restored to the original 2.635-in. diameter orifice.

TABLE 5

VALVE HISTORY LOG, TPCV S/N 880025

TPCV P/N 1116909-69
S/N 880025
BFV S/N 880033
Actuator S/N 0019

	Date	Actuations		Time		Remarks
		100 psig	200 psig	100 psig	200 psig	
	1-20-70	10		1.0 Hr		H-65 1st Checkout
	1-21-70		*		2.0 Hr	H-65 Freq. Response
	2-13-70	5		0.5 Hr		H-65 Final Check
	2-18-70	2		2.0 Hr	.5 Hr	H-65 Dry Run EP-1
	2-19-70		5		12.0 Hr	H-65 R-Day Ep-1
	2-20-70	Valve Removed, Broken Seal Ring Replaced				
	Total	17	5	3.5 Hr	14.5 Hr	
	2-27-70	4	3	0.5 Hr	0.5 Hr	H-65 Post Repair Check
	3-4-70	2		2.0 Hr	0.5 Hr	H-65 Dry Run EP-2
	3-5-70		5		8.0 Hr	H-65 R-Day EP-2
	3-6-70	Valve Removed, Seal Ring Removal				
	Total	6	8	2.5 Hr	9.0 Hr	
Replacement Actuator S/N 0023	3-12-70	2	4	0.5 Hr	0.5 Hr	H-68 Post Repair Check
	3-17-70	4		0.66 Hr		H-68 Check V _{tn} Data
	3-18-70	2		2.0 Hr		H-68 Dry Run EP-3
	3-19-70		6		6.0 Hr	H-68 R-Day EP-3
	4-8-70	2	2	0.5 Hr	0.5 Hr	H-68 Valve Check
	4-15-70	2		2.0 Hr		H-68 Dry Run EP-4
	4-16-70		21		8.0 Hr	H-68 R-Day EP-4
	4-21-70		*		2.0 Hr	H-68 Freq. Response
	Total	12	33	5.66 Hr	17.0 Hr	

* Cycles or actuations were not counted during the frequency response measurements. Only the time duration of pneumatic pressure on the TPCV actuator was recorded.

TABLE 6

VALVE HISTORY LOG, TPCV S/N 880026

TPCV P/N 1116909-69

S/N 880026

BFV S/N 880036

Actuator S/N 0022

Date	Actuations		Time		Remarks
	100 psig	200 psig	100 psig	200 psig	
1-20-70	10		1.0 Hr		H-68 1st Checkout
1-21-70		*		2.0 Hr	H-68 Freq. Response
2-13-70	5		0.5 Hr		H-68 Final Check
2-18-70	2	4	2.0 Hr	0.5 Hr	H-68 Dry Run EP-1
2-19-70		7		12.0 Hr	H-68 R-Day EP-1
2-20-70		6		0.66 Hr	H-68 Adjust Loop Gain
2-27-70	2	2	0.5 Hr	0.5 Hr	H-68 Checkout
3-4-70	2	9	2.0 Hr	0.5 Hr	H-68 Dry Run EP-2
3-5-70		8		8.0 Hr	H-68 R-Day EP-2
3-6-70	Valve Removed, Broken Seal Ring				
Total	21	36	6.0 Hr	24.16 Hr	
3-12-70	2	5	0.5 Hr	0.5 Hr	H-65 Post Repair Check
3-17-70	4		0.66 Hr		H-65 Check V _{tn} Data
3-18-70	2		2.0 Hr		H-65 Dry Run EP-3
3-19-70		6		6.0 Hr	H-65 R-Day EP-3
4-8-70	3	2	0.5 Hr	0.5 Hr	H-65 Valve Check
4-15-70	2		2.0 Hr		H-65 Dry Run EP-4
4-16-70		16		8.0 Hr	H-65 R-Day EP-4
4-21-70		*		2.0 Hr	H-65 Freq. Response
Total	13	29	5.66 Hr	17.0 Hr	

* Cycles or actuations were not counted during the frequency response measurements. Only the time duration of pneumatic pressure on the TPCV actuator was recorded.

TABLE 7

VALVE HISTORY LOG, TBV S/N 880000

TBV P/N 1117188-89
 S/N 880000
 BFV S/N 880034
 Actuator S/N 880000

Date	Actuations		Location	Remarks
	50 psig	500 psig		
1-20-70	10		H-66	Potentiometer Adjustment
1-21-70		4	H-66	Initial Checkout
2-13-70	6		H-66	Checkout
2-18-70	2		H-66	Dry Run EP-1
2-19-70		6	H-66	R-Day EP-1
2-27-70	9		H-64	Valve Check
3-4-70	2		H-64	Dry Run EP-2
3-5-70		4	H-64	R-Day EP-2
3-12-70	2		H-66	Valve Check
3-18-70	2		H-66	Dry Run EP-3
3-19-70		5	H-66	R-Day EP-3
3-20-70	Valve Removed, Preventative Maintenance			
Total	33	19		
4-8-70	2		H-66	Valve Check
4-15-70	2		H-66	Dry Run EP-4
4-16-70		18	H-66	R-Day EP-4
Total	4	18		

TABLE 8

VALVE HISTORY LOG, TBV S/N 880001

TBV P/N 1117188-89
 S/N 880001
 BFV S/N 880035
 Actuator S/N 880001

Date	Actuations		Location	Remarks
	50 psig	500 psig		
1-20-70	10		H-69	Potentiometer Adjustment
1-21-70		4	H-69	Initial Checkout
2-13-70	6		H-69	Checkout
2-18-70	2		H-69	Dry Run EP-1
2-19-70		5	H-69	R-Day EP-1
2-27-70	7		H-67	Valve Check
3-4-70	2		H-67	Dry Run EP-2
3-5-70		5	H-67	R-Day EP-2
3-12-70	2		H-69	Checkout
3-18-70	2		H-69	Dry Run EP-3
3-19-70		5	H-69	R-Day EP-3
3-20-70	Valve Removed, Preventative Maintenance			
Total	31	19		
4-8-70	2		H-69	Valve Check
4-15-70	2		H-69	Dry Run EP-4
4-16-70		15	H-69	R-Day EP-4
Total	4	15		

TABLE 9

VALVE HISTORY LOG TBV S/N 880028

TBV P/N 1117188-89
S/N 880028
BFV S/N 880025
Actuator S/N 880025

Date	Actuations		Location	Remarks
	50 psig	500 psig		
3-31-70	5	2	H-67	Initial Checkout
4-8-70	2		H-67	Valve Check
4-15-70	2		H-67	Dry Run EP-4
4-16-70		17	H-67	R-Day EP-4
Total	9	19		

Prior to EP-4, it was also deemed necessary to modify the turbine drive line. The unequal impedance in the intertie system with one TPCV controlling caused a separation in the operating points of the pumps which was greater than desired. The turbine drive system was modified to allow for a single, common drive line downstream of the TPCV's to achieve an equal impedance path in the drive lines to the TPA's.

Component stress analysis of the pump support frame and the pump package piping was conducted by ANSC and LASL. Upon completion of the test series, the pump package was secured by establishing a nitrogen pad purge on the TPA's, piping, and valve actuators. The intent was to maintain the package intact pending the possibility of further testing.

VII. FACILITY DESCRIPTION

To conduct dual-TPA testing in Test Cell C, extensive facility modifications had to be performed (References 21 through 24). The original intent was to provide an independent test position to preclude extensive effort or time in converting to other testing configurations. Strategic valves and line blinds were to be used to isolate the systems.

The ANSC pump package was supplied liquid hydrogen from Dewar 2 and recirculated to Dewar 1. An additional inlet line section from outside the pump room was required which traversed the roof of the room and entered directly above the pump package. By "swinging" an elbow and "blanking" a line, the Dewar supply line could feed either the ANSC pump package or the Rocketdyne package.

The pump discharge system from the ANSC package was isolated from the facility by valves. Piping and valves were installed as part of the facility to either duct the pump discharge flow to Dewar 1 or directly to the flare system. Also included in the pump discharge system were the bypass lines to the flare system. To handle additional flare system requirements, the 30-in. vent header was extended and a 12-in. diameter section was installed.

The 8-in. facility turbine drive header was modified to extend to the interface point on the ANSC package. This system was isolated from the Rocketdyne package by the use of a line blind. The existing gaseous hydrogen tank farm and TES were used to supply turbine drive gas. The TES liquid hydrogen was supplied from a new facility line installed from a point upstream of the impedance valve to the TES supply line in the pump room. This system was isolated from the facility by repositioning a line section.

The ANSC package also required a turbine exhaust manifold installed in the pump room to transfer the exhaust to the flare system.

All facility modifications were designed with the intent to permit a "turnaround" of two weeks between testing the Rocketdyne and ANSC systems.

VIII. CONTROL SYSTEM

The control system for dual-TPA testing was designed by the Los Alamos Scientific Laboratory (LASL) to the requirements specified by ANSC. The dual-TPCV driver chassis was designed and fabricated by ANSC. The fabrication of the control system was subcontracted by LASL to Edgerton, Geimeshausen and Grier (EG&G). The existing LASL control system was utilized whenever possible or appropriate.

The control system had the following operational capabilities.

1. The signals required to open and close the four TBV's (H-64, H-66, H-67 and H-69) in position control and to close them as a result of the shutdown chains.
2. Two TPCV's (H-65 and H-68) with parallel or individual position and turbine speed controls. A single-pump discharge pressure control could be used to control one or both TPCV's in parallel. The position mode was individually selectable from the other modes. This permitted operation of one valve in position control while the other valve was in turbine speed or pump discharge control. There was a position trim on TPCV 2 which could be used in pressure control to unbalance the TPCV's. The pump control operated by using SLP-29. The turbine speed control operated by use of the highest speed signal (SHQ-850, SHQ-850A, SHQ-950, and SHQ-950A).
3. Common pump discharge impedance was provided by L-30 which had position control.
4. The individual pump discharge bypass valves had individual position and parametric modes of control.
5. The primary shutdown chain terminated the test if any one of a number of predetermined limits was exceeded.

6. Two "mini" shutdown chains were provided. One was used during malfunction simulation tests. When a predetermined limit was exceeded, the chain initiated the corrective action required for the system to survive the simulated malfunction. These chains, however, generally do not terminate the test.

A. SPEED LOOP

A speed response was run during EP-1 at 18,000 rpm at a Q/N of 0.3. Table 10 shows the results of this response. A Nichols* plot of the closed-loop gain is shown in Figure 22. The 3-db bandwidth of the closed loop is seen to be 2 Hz, gain margin 14 db, and phase margin 60°. A response was run on pump 2 at the same operating point, and Figure 23 shows bandwidth of 2 Hz, gain margin of 14 db, and a phase margin of 60°. Response to the steps shows approximately a 0.2-sec rise time with some nonlinearity in evidence. Response of both pumps is seen to be the same. A Bode plot of speed to turbine power control valve position is shown in Figure 24. The transfer function of the rpm controller for this run was as follows:

$$\frac{\delta X_{tv}}{\delta N_e} = \frac{.0067 (S + 1)}{S \left(\frac{S}{10} + 1 \right)} \frac{\% - \text{sec}}{\text{rpm}}$$

The speed controller was modified for EP-2. However, the TPA's were not operated in speed control during this experimental plan.

The speed controller compensation for EP-2 was:

$$\frac{\delta X_{tv}}{\delta N_e} = \frac{0.025 \left(\frac{S}{7.14} + 1 \right)}{S} \frac{\% - \text{sec}}{\text{rpm}}$$

*All Nichols charts are plotted using data from the Solatron automatic transfer function analyzer.

TABLE 10

EP-1 SPEED RESPONSE 1, SINGLE PUMP (NO 1), SINGLE TPCV

Gains All Peak-to-Peak

Frequency (Hz)	OSC N DEM		HR-65		N ₁		HF-850		LP-29	
	G	θ	G	θ	G	θ	G	θ	G	θ
	<u>rpm</u>	<u>deg</u>	<u>%</u>	<u>deg</u>	<u>rpm</u>	<u>deg</u>	<u>#/sec</u>	<u>deg</u>	<u>psi</u>	<u>deg</u>
0.04	588	0	5.00	+78	628	0	1.60	0	22	0
0.10	588	0	2.00	+45	684	-19.8	2.50	+3.6	22	-18
0.40	588	0	1.75	-22	468	-36.0	2.40	-21.6	12	-36
0.63	588	0	1.40	0	448	-18.0	2.20	-22.0	12	-27
1.00	588	0	2.00	+14	592	-50.0	2.90	-50.0	18	-57
1.60	588	0	3.20	-6	600	-81.0	4.10	-87.0	16	-128
2.50	588	0	2.60	-81	360	-144.0	3.60	-189.0	8	-207
4.00	588	0	.50	-115	49	-230.0	.27	-288.0	--	--

State Point: Time 25339

N - 18,000 rpm	$\dot{w}_p$ - 51 lbs/sec
Q/N - .3	HP-60 - 330 psi
HR-65 - 37%	HP-865 - 132 psi

Figure 22 - Speed Response, Pump #1, EP-1, Single TPCV - Nichols Plot

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Figure 24 - Speed Response, Pump #1, EP-1, Single TPCV - Bode Plot

B. PRESSURE LOOP

A pressure-loop response test was run on pump 1 at 18,000 rpm at a Q/N of 0.3 using both a single TPCV and two TPCV's. Tables 11 and 12 show the results of these tests. Closed-loop 3-db bandwidth with a TPCV is seen from the Nichols chart of Figure 25 to be 0.5 Hz with a gain margin of 12 db and a phase margin of 180°. A pressure response run at the same operating point with TPCV's is plotted on the same Nichols chart. Closed-loop response results show 3-db bandwidth of 1.5 Hz, a gain margin of 6 db, and a phase margin of 50°. Evidence of closed-loop peaking at one cycle can be seen on the Nichols chart. This was confirmed by the response to the pressure steps. Gains of the discharge pressure with respect to TPCV position are plotted on the Bode chart of Figure 26.

The compensation of the pressure-control loop for EP-2 was modified to eliminate the underdamped pressure response experienced in EP-1 when using two TPCV's and one pump at high pump discharge pressures.

The pressure controller compensation for EP-2 was:

$$\frac{\delta X_{tv}}{\delta P_e} = \frac{0.25 \left(\frac{S}{7.14} + 1 \right)}{S} \frac{\% \text{-sec}}{\text{psi}}$$

C. DUAL-MODE PRESSURE CONTROLS

A response test was made in dual-mode pressure control during EP-1 at a speed of 20,000 rpm with a Q/N of 0.21 $\frac{\text{gpm}}{\text{rpm}}$ with both TPCV's operating. Results of this response are shown in Table 13. The data are plotted in Figure 27 and show closed-loop gain and phase. Discharge pressure to TPCV position gain and phase, as well as speed to TPCV position gain and phase Bode plots, are plotted in Figures 28 and 29. Bandwidth of the dual-mode pressure loop was 0.4 Hz, gain margin was 18 db, and phase margin 70°.

TABLE 11

EP-1 SINGLE-MODE PRESSURE RESPONSE, SINGLE PUMP (NO. 1), SINGLE TPCV

Gains All Peak-to-Peak

Frequency (Hz)	OSC		HR-65		N ₁		HF-850		LP-29	
	PRESS	DEM	G	θ	G	θ	G	θ	G	θ
	<u>psi</u>	<u>deg</u>	<u>%</u>	<u>deg</u>	<u>rpm</u>	<u>deg</u>	<u>#/sec</u>	<u>deg</u>	<u>psi</u>	<u>deg</u>
.04	20.5	0	1.0	+60	640	0	1.6	0	23	0
.10	20.5	0	2.2	+47	720	-14	3.0	-10.8	27	-14
.40	20.5	0	1.6	-43	432	-50	2.0	-28.8	12	-29
.63	20.5	0	1.4	-49	448	-81	2.4	-85.5	12	-81
1.00	20.5	0	2.1	-54	468	-81	2.2	-81.0	14	-90

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State Point: Time 25520

N - 18,000 rpm	$\dot{w}_p$ - 51 lbs/sec
Q/N - .3	HP-60 - 330 psi
HR-65 - 57%	HP-850 - 132 psi

TABLE 12

EP-1 SINGLE-MODE PRESSURE RESPONSE, SINGLE PUMP (NO. 1), DUAL TPCV

Gains All Peak-To-Peak

Frequency (Hz)	OSC		HR-65		N ₁		HF-850		HR-68		LP-29	
	PRESS	DEM	G	θ	G	θ	G	θ	G	θ	G	θ
	psi	deg	%	deg	%	deg	#/sec	deg	%	deg	psi	deg
.04	19	0	.8	+92.0	576	0	1.7	+16	.8	+92.0	21.0	-3
.10	19	0	1.4	+35.0	720	0	2.7	0	1.4	+36.0	23.0	0
.40	19	0	1.2	+14.4	540	-29	2.7	-29	1.2	-14.4	13.5	-36
.63	19	0	1.2	-13.5	648	-40	3.0	-45	1.2	0	18.9	-49
1.00	19	0	2.0	-36.0	864	-86	4.0	-86	2.2	-29.0	27.0	-101
1.60	19	0	.6	-127.0	200	-174	1.7	-195	.9	-104.0	6.0	-215

State Point: Time 25680

N - 18,000 rpm $\dot{w}_p$ - 51 lbs/sec
 Q/N - .3 HP-60 - 330 psi
 HR-65, HR-68 - 28% HP-850 - 132 psi

Figure 26 - Pressure Response, Pump #1, EP-1, Single TPCV - Bode Plot

TABLE 13

EP-1 DUAL-MODE PRESSURE RESPONSE, DUAL PUMP, DUAL TPCV

Gains All Peak-To-Peak

Frequency (Hz)	OSC		HR-65		N ₁		HF-850		HR-68		N ₂		HF-950		LP-29	
	PRESS	DEM	G	θ	G	θ	G	θ	G	θ	G	θ	G	θ	G	θ
	psi	deg	%	deg	rpm	deg	#/sec	deg	%	deg	rpm	deg	#/sec	deg	psi	deg
.04	19.8	0	.45	+49	480	7.2	.94	+14	.9	+90.0	465	0	1.1	+17	20.7	+2.9
.10	19.8	0	1.10	+50	610	0	1.70	+29	1.4	+86.0	590	-3	1.7	+36	25.2	-22.0
.40	19.8	0	1.20	-22	360	-58.0	2.00	-58	1.6	-7.2	360	-50	2.0	-50	13.5	-50.0
.63	19.8	0	1.10	-54	400	-67.5	1.90	-135	1.7	-31.5	400	-81	2.0	-85	13.5	-81.0
1.00	19.8	0	.76	-94	280	-122.0	.72	-122	1.5	-58.0	280	-108	1.5	-158	10.0	-122.0
1.60	19.8	0	.45	-116	200	-168.0	.50	-32	.8	-95.0	120	-168	---	---	4.0	-172.0

State Point: Time 33300

N - 20,000 rpm HF-850 - 40.5 lbs/sec

Q/N - .21 HF-960 - 43 lbs/sec

HR-65 - 35.5% HR-68 - 34.5%

Figure 27 - Dual Mode Pressure Response, EP-1, Dual TPCV - Nichols Plot

Q/N = .22

Figure 28 - Dual Mode Pressure Response, EP-1 - Bode Plot

Figure 29 - Dual Mode Speed Response, EP-1 - Bode Plot

Response to the steps indicated a 0.4-sec rise time on a negative going step and 0.2-sec rise time on a positive step. The transfer function for the pressure controller used in EP-1 was:

$$\frac{\delta X_{tv}}{\delta P_e} = \frac{.124 (S + 1)}{S (\frac{S}{4} + 1)} \frac{\% - \text{sec}}{\text{psi}}$$

Speed, specific speed, and ΔP pressure controllers used for EP-2, EP-3, and EP-4 were the same. Transfer functions of these controllers were:

$$\text{Speed: } \frac{\delta X_{tv}}{\delta N_e} = \frac{0.025 (\frac{S}{7.14} + 1)}{S} \frac{\% - \text{sec}}{\text{rpm}}$$

$$\text{Pressure: } \frac{\delta X_{tv}}{\delta P_e} = \frac{0.25 (\frac{S}{7.14} + 1)}{S} \frac{\% - \text{sec}}{\text{psi}}$$

$$\text{Specific Speed: } \frac{\delta X_{bv}}{\delta (KN - w_p)} = \frac{0.5 (\frac{S}{16} + 1)}{S (\frac{S}{100} + 1)} \frac{\% - \text{sec}}{\text{lb-sec}}$$

$$\Delta P: \frac{\delta X_{hex}}{\delta \Delta P_e} = \frac{0.047 (\frac{S}{0.63} + 1)}{S (\frac{S}{10} + 1)} \frac{\% - \text{sec}}{\text{psi}}$$

Additional controller cards were provided for increased pressure controller gain (+6 db) in the event discharged pressure errors were intolerably large during simulated valve and pump failures. This backup controller, however, was not used.

During EP-2, clamps were installed on the speed controller cards to prevent a negative valve command resulting from a positive speed error.

An additional shutdown input was designed to take the logical high-speed signals from pump 1. Normally, the highest primary speed signal from each pump and the highest backup speed signal go to two separate shutdown comparators.

A modification was made in the Q/N control potentiometer calibrator so the loop would permit operation at Q/N values as low as 0.05 gpm/rpm. A frequency response was run during EP-4 on the pressure loop at 20,000 rpm. Table 14 and Figure 30 show the results of this response.

The control loop and automatic shutdown circuitry performed as planned. Possibly slightly improved performance could have been obtained from the pressure controller had the increased gain controller been used, but, to maintain consistency of the data with regard to the feed system piping changes, this was not done.

TABLE 14

EP-4 DUAL-MODE PRESSURE RESPONSE, DUAL PUMP, DUAL TPCV

Gains All Peak-To-Peak

Frequency (Hz)	OSC		HR-65		N ₁		HF-850		HR-68		N ₂		HF-950		LP-29	
	PRESS	DEM	G	θ	G	θ	G	θ	G	θ	G	θ	G	θ	G	θ
	psi	deg	%	deg	rpm	deg	#/sec	deg	%	deg	rpm	deg	#/sec	deg	psi	deg
.04	19.7	0	1.20	+5.8	480	+5.8	1.10	+23	--	--	488	+4.3	.99	+22.0	20.4	0
.10	19.7	0	1.62	+104.0	580	+7.2	1.70	+29	1.98	+90.0	616	+21.6	1.85	+32.4	25.1	0
.40	19.6	0	1.62	-43.0	310	-86.0	1.44	-101	1.71	-43.2	308	-86.4	1.49	-86.4	12.6	-86.
.63	19.6	0	1.22	-45.0	220	-109.0	.86	-109	1.31	-54.4	216	-108.8	.95	-108.8	9.6	-100.
1.00	19.7	0	.95	-54.0	140	-115.0	.79	-144	1.04	-64.8	128	-129.6	.81	-144.0	4.5	-123.
1.60	19.6	0	.59	-47.0	56	-141.0	--	--	.65	-70.4	56	-140.8	--	--	3.0	-156.

State Point: Time 23220

N - 19,800 rpm HF-850 - 42.5 #/sec

Q/N - .222 HF-960 - 45.0 #/sec

HR-65 - 33.8% HR-68 - 33.2%

IX. INSTRUMENTATION

A. GENERAL

Measurements made during the test program are shown in Table 15 which is applicable to all the EP's with the following exceptions:

1. HS-888 (TPA 1 thrust) was cancelled after EP-1 because of thrust ring failure.
2. HT-970 (turbine inlet temperature) was cancelled after EP-2 because of probe failure.
3. HA-849 and HA-850 (pump 1 flowmeter horizontal and vertical acceleration measurement) was added to the flowmeter flange after EP-2.
4. HA-808, HA-809, and HA-810 (H-65 actuator, x, y, and z coordinates, acceleration measurements) were added after EP-3.
5. HP-858, HP-859, and HP-958 (turbine inlet line pressure measurements) were added after EP-3.
6. HP-878, HP-882, HP-878D, and HP-882D (turbine exhaust pressures and differential pressures) were cancelled after EP-3.
7. HT-878 and HT-882 (turbine exhaust temperatures) were cancelled after EP-3.

The locations of measurements within the pump package are shown in Reference 25. Reference 26 shows the location of measurements within the modified turbine inlet section utilized during EP-4.

TABLE 15

INSTRUMENTATION, TEST CELL C

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo-graph</u>	<u>Sanborn</u>	<u>Meter</u>
		HA-811.-C	+250g;0-2KHZ	TPA 1, Radial Acceleration, X-axis			
		HA-812.-C	+250g;0-2KHZ	TPA 1, Axial Acceleration, Y-axis			
		HA-813.-C	+250g;0-2KHZ	TPA 1, Radial Acceleration, Z-axis			
		HA-851.-C	+100g;0-2KHZ	TPA 1, Pump discharge check valve acceleration			
		HA-911.-C	+250g;0-2KHZ	TPA 2, Radial Acceleration, X-axis			
		HA-912.-C	+250g;0-2KHZ	TPA 2, Axial Acceleration, Y-axis			
		HA-913.-C	+250g; 0-2KHZ	TPA 2, Radial Acceleration, Z-axis			
		HA-951.-C	+100g;0-2KHZ	TPA 2, Pump discharge check valve acceleration			
72 SHF-850U-C	0-100 P/S	HF-850U-C	0-500 pps	TPA 1, Pump discharge flow rate (same transducer)	(2)	X	X
SHF-950U-C	0-100 P/S	HF-950U-C	0-500 pps	TPA 2, Pump discharge flow rate (same transducer)	(2)	X	X
HP-064.-C	0-500 psig	HP-064W-C	0-500 psig; 0-500 HZ	Common, Turbine Inlet Pressure		X	
HP-800.-C	0-100 psig			TPA 1, Pump system inlet pressure			
HP-805.-C	0-100 psig			TPA 1, Pump franz screen downstream pressure			
SHP-811.-C	0-100 psig			TPA 1, Pump inlet pressure		X	X
		HP-811W-C	0-100 psig; 0-500 HZ	TPA 1, Pump inlet pressure, wide band	X		
HP-820.-C	0-1000 psig			TPA 1, Bearing housing pressure		X	
HP-820D-C	0-500 psid			TPA 1, Bearing housing differential pressure		X	
HP-841-C	0-1000 psig	HP-841W-C	0-1000 psig; 0-500 HZ	TPA 1, Pump discharge pressure (same transducer)	X	X	X

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo-graph</u>	<u>Sanborn</u>	<u>Meter</u>
		HP-841C-C	0-1000 psig; 0-10KHZ	TPA 1, Pump discharge pressure (Kistler)			
SHP-851.-C	0-1000 psig			TPA 1, Pump discharge check valve upstream pressure		X	
		HP-852W-C	0-1000 psid, 0-500 HZ	TPA 1, Pump discharge check valve differential pressure	X		
SHP-855.-C	0-1000 psig			TPA 1, Pump discharge check valve downstream pressure		X	
HP-860.-C	0-500 psig			TPA 1, Turbine inlet orifice upstream pressure		(2)	
HP-860D-C	0-200 psid			TPA 1, Turbine inlet orifice differential pressure		(2)	
HP-865-C	0-500 psig			TPA 1, Turbine inlet orifice downstream pressure			
SHP-870-C	0-500 psig			TPA 1, Turbine inlet static pressure			
HP-870A-C	0-500 psig	HP-870W-C	0-500 psig; 0-500 HZ	TPA 1, Turbine inlet total pressure (same transducer)	X	X	X
HP-873-C	0-100 psig			TPA 1, Turbine 2nd stage rotor, discharge pressure		X	X
HP-873A-C	0-100 psig			TPA 1, Turbine 2nd stage rotor discharge pressure; backup			
HP-875.-C	0-500 psig			TPA 1, Turbine 1st stage rotor cavity pressure			
HP-876-C	0-100 psig	HP-876W-C	0-100 psig; 0-500 HZ	TPA 1, Exhaust leg 2 collector pressure (same transducer)		(2)	
HP-878-C	0-100 psig			Turbine Leg 2 line pressure		(2)	
HP-878D-C	0-50 psid			Turbine Leg 2 exhaust line orifice differential pressure.		(2)	
HP-880.-C	0-100 psig	HP-880W-C	0-100 psig; 0-500 HZ	Turbine 1, Exhaust Leg 1, collector pressure (same transducer)		(2)	

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo-graph</u>	<u>Sanborn</u>	<u>Meter</u>
HP-882.-C	0-100 psig			Turbine Leg 1, exhaust line pressure		(2)	
HP-882D-C	0-50 psid			Turbine Leg 1, exhaust line orifice differential pressure		(2)	
HP-900.-C	0-100 psig			TPA 2, Pump system inlet pressure			
HP-905.-C	0-100 psig			TPA 2, Pump franz screen downstream pressure			
SHP-911.-C	0-100 psig			TPA 2, Pump inlet pressure		X	X
		HP-911W-C	0-100 psig; 0-500 HZ	TPA 2, Pump inlet pressure	X		
HP-920.-C	0-1000 psig			TPA 2, Bearing housing pressure		X	
HP-920D-C	0-500 psid			TPA 2, Bearing housing differential pressure		X	
HP-941-C	0-1000 psig	HP-941W-C	0-1000 psig; 0-500 HZ	TPA 2, Pump discharge pressure (same transducer)	X	X	X
		HP-941C-C	0-1000 psig; 0-10KHZ	TPA 2, Pump discharge pressure (Kistler)			
SHP-951-C				TPA 2, Pump discharge check valve upstream pressure		X	
		HP-952W-C	0-1000 psid; 0-500 HZ	TPA 2, Pump discharge check valve differential pressure	X		
SHP-955-C	0-1000 psig			TPA 2, Pump discharge check valve downstream pressure		X	
HP-960-C	0-500 psig			TPA 2, Turbine inlet orifice upstream pressure		(2)	
HP-960D-C	0-200 psid			TPA 2, Turbine inlet orifice differential pressure		(2)	
HP-965-C	0-500 psig			TPA 2, Turbine inlet orifice downstream pressure			

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo-graph</u>	<u>Sanborn</u>	<u>Meter</u>
SHP-970-C	0-500 psig			TPA 2, Turbine inlet static pressure			
HP-970A-C	0-500 psig	HP-970W-C	0-1000 psig; 0-500 HZ	TPA 2, Turbine inlet total pressure (same transducer)	X	X	X
HP-973-C	0-100 psig			TPA 2, Turbine 2nd stage rotor discharge pressure		X	X
HP-973A-C	0-100 psig			TPA 2, Turbine 2nd stage rotor discharge pressure, backup			
HP-975-C	0-500 psig			TPA 2, Turbine 1st stage rotor cavity pressure			
HP-976-C	0-100 psig	HP-976W-C	0-100 psig; 0-500 HZ	TPA 2, Exhaust Leg 2, collector pressure (same transducer)		(2)	
HP-980-C	0-100 psig	HP-980W-C	0-100 psig; 0-500 HZ	TPA 2, Exhaust Leg 1, collector pressure (same transducer)		(2)	
SHQ-850-C	0-40K rpm			TPA 1, Shaft speed		X	X
SHQ-850A-C	0-40K rpm			TPA 1, Shaft speed; backup			
SHQ-950-C	0-40K rpm			TPA 2, Shaft speed		X	X
SHQ-950A-C	0-40K rpm			TPA 2, Shaft speed; backup			
HR-064A-C	0-100%	HR-064W-C	0-100%; 0-100 HZ	Turbine 1, TBV position (H-64)	(2)	X	X
HR-065A-CP	0-100%	HR-065W-C	0-100%; 0-100 HZ	Turbine 1, TPCV position (H-65)	X	X	X
HR-066A-C	0-100%	HR-066W-C	0-100%; 0-100 HZ	Turbine 1, TBV position (H-66)	X	X	X
HR-067A-C	0-100%	HR-067W-C	0-100%; 0-100 HZ	Turbine 2, TBV position (H-67)	(2)	X	X
HR-068A-CP	0-100%	HR-068W-C	0-100%; 0-100 HZ	Turbine 2, TPCV position (H-68)	X	X	X
HR-069A-C	0-100%	HR-069W-C	0-100%; 0-100 HZ	Turbine 2, TBV position (H-69)	X	X	X
HS-888.-C	$\pm$ 10K LBF			TPA 1, Thrust, bearing load		X	X
HS-988.-C	$\pm$ 10K LBF			TPA 2, Thrust, bearing load		X	X

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo- graph</u>	<u>Sanborn</u>	<u>Meter</u>
HT-800-C	35-54°R			TPA 1, Pump system inlet (RTT) temperature			
HT-805-C	35-590°R			TPA 1, Franz screen downstream (RTT) temperature			
HT-805N-C	35-112.6 R			TPA 1, Franz screen downstream temp. narrow range			
SHT-811.-C	35-54°R			TPA 1, Pump inlet temperature (RTT)		X	
HT-820-C	35-653.4°R			TPA 1, Bearing housing temp. (C/C)		X	X
HT-821-C	35-649°R			TPA 1, Upper roller bearing (C/A) temperature		X	
HT-821A-C	35-649°R			TPA 1, Upper roller bearing (C/A) temperature, backup			
HT-822-C	35-649°R			TPA 1, Upper thrust bearing (C/A) temperature			
HT-823-C	35-649°R			TPA 1, Lower thrust bearing (C/A) temperature			
HT-824-C	35-649°R			TPA 1, Lower roller bearing (C/A) temperature		X	
HT-824A-C	35-649°R			TPA 1, Lower roller bearing (C/A) temperature			
HT-824B-C	35-649°R			TPA 1, Lower roller bearing (C/A) temperature, backup		X	
HT-824C-C	35-649°R			TPA 1, Lower roller bearing (C/A) temperature, backup		X	
HT-841-C	35-65°R			TPA 1, Pump discharge temp. (RTT)		X	
HT-860.-C	250-726.3°R			TPA 1, Turbine inlet orifice (C/C) upstream temperature			
HT-865-C	250-726.3°R			TPA 1, Turbine inlet orifice (C/C) downstream temperature		(2)	
HT-870-C	150-660°R			TPA 1, Turbine inlet temp. (RTT)		X	
HT-876-C	250-726.3°R			Turbine 1, exhaust Leg 2, (C/C) collector temperature			

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo- graph</u>	<u>Sanborn</u>	<u>Meter</u>
HT-878-C	250-726.3°R			Turbine exhaust Leg 2, line temperature	(C/C)	(2)	
HT-880-C	250-726.3°R			Turbine 1 exhaust Leg 1 collector temperature	(C/C)		
HT-882-C	250-726.3°R			Turbine exhaust Leg 1, line temperature	(C/C)	(2)	
HT-900.-C	35-54°R			TPA 2, Pump system inlet temp. (RTT)			
HT-905-C	35-590°R			TPA 2, Franz screen downstream temperature	(RTT)		
HT-905N-C	35-112.6°R			TPA 2, Franz screen downstream temperature, narrow range			
SHT-911.-C	35.54°R			TPA 2, Pump inlet temperature	(RTT)	X	
HT-920-C	35-653.4°R			TPA 2, Bearing housing temp.	(C/C)	X	X
HT-921-C	35-649°R			TPA 2, Upper roller bearing temperature	(C/A)	X	
HT-921A-C	35-649°R			TPA 2, Upper roller bearing temperature, backup	(C/A)		
HT-922-C	35-649°R			TPA 2, Upper thrust bearing temperature	(C/A)	X	
HT-922A-C	35-649°R			TPA 2, Upper thrust bearing temperature, backup	(C/A)		
HT-923-C	35-649°R			TPA 2, Lower thrust bearing temperature	(C/A)	X	
HT-923A-C	35-649°R			TPA 2, Lower thrust bearing temperature, backup	(C/A)		
HT-924-C	35-649°R			TPA 2, Lower roller bearing temperature	(C/A)	X	
HT-924A-C	35-649°R			TPA 2, Lower roller bearing temperature	(C/A)		
HT-941.-C	35-65°R			TPA 2, Pump discharge temp.	(RTT)	X	

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo-graph</u>	<u>Sanborn</u>	<u>Meter</u>
HT-960.-C	250-726.3°R			TPA 2, Turbine inlet orifice upstream temperature (C/C)			
HT-965.-C	250-726.3°R			TPA 2, Turbine inlet orifice downstream temperature (C/C)		(2)	
HT-970-C	150-660°R			TPA 2, Turbine inlet temp. (RTT)		X	
HT-976-C	250-726.3°R			Turbine 2 exhaust Leg 2 collector temperature (C/C)			
HT-980-C	250-726.3°R			Turbine 2 exhaust Leg 1 collector temperature (C/C)			
LF-029U-C	0-150 P/S	LF-029W-C	0-2000 pps	Common, Pump discharge flow rate	(2)	X	X
SLP-029-C	0-1000 psig			LF-029 upstream pressure	X		
LP-029A-C	0-1000 psig	LP-029W-C	0-1000 psig; 0-500 HZ	LF-029 upstream pressure, backup (same transducer)	X	X	X
		OP-029C-C	0-1000 psig; 0-10KHZ	LF-029 upstream pressure (Kistler)			
LT-029-C	35-65°R			LF-029 upstream temperature (RTT)		X	
HT-064-C	150-660°R			AGC turbine system inlet temp (RTT)			
(1)HP-062.-C	0-500 psig			AGC turbine supply orifice upstream pressure		X	
(1)HP-062D-C	0-50 psid			AGC turbine supply orifice differential pressure		X	
(1)HP-069-C	0-100 psig			AGC turbine system exhaust pressure			
(1)HP-070-C	0-100 psig			AGC turbine system flare line press.			
(1)HT-062-C	150-660°R			AGC turbine supply orifice upstream temperature (RTT)		X	
(1)HT-069-C	150-660°R			AGC turbine system exhaust temperature (RTT)			
(1)HT-070-C	150-660°R			AGC turbine system flare line temperature (RTT)			
(1)LP-005-C	0-100 psig			AGC LH ₂ supply line pressure		X	

TABLE 15 (cont.)

<u>Narrow Band Channel</u>	<u>Range Narrow Band</u>	<u>Wide Band Channel</u>	<u>Range Wide Band</u>	<u>Description</u>	<u>Oscillo- graph</u>	<u>Sanborn</u>	<u>Meter</u>
(1)LP-030-C	0-1000 psig			L-30 downstream line pressure		X	
(1)LP-119-C	0-1000 psig			Pump 1 bypass; L-119 downstream pressure		X	
(1)LP-219-C	0-1000 psig			Pump 2 bypass; L-219 downstream pressure		X	
(1)LR-030A-C	0-100%	LR-030W-C	0-100% 0-100 HZ	Impedance Valve, L-30 stem position	X	X	
(1)LR-119A-CH	0-100%	LR-119W-C	0-100% 0-100 HZ	Pump 1 bypass; L-119 stem position	X	X	
(1)LR-219A-CH	0-100%	LR-219W-C	0-100% 0-100 HZ	Pump 2 bypass; L-219 stem position	X	X	
(1)LT-005-C	35-54°R			AGC LH ₂ supply line temp. (RTT)		X	
(1)LT-030-C	35-65°R			Impedance Valve, L-30 down-stream temperature (RTT)		X	
(1)LT-119-C	35-590°R			Pump 1 bypass, L-119 down-stream temperature (RTT)		X	
(1)LT-219-C	35-590°R			Pump 2 bypass, L-219 down-stream temperature (RTT)		X	

(1) Requested Parameters in Facility Package

(2) Parameters when requested shall be available within 15 minutes

X To be recorded during test

B. TURBOPUMP INTERNAL INSTRUMENTATION

1. Bearing Thermocouples

Chromel-alumel thermocouples were provided on each of the four main shaft bearings on TPA S/N 88016 (pump 1) and TPA S/N 88017 (pump 2). Pump 1 had two thermocouples on the upper roller bearing, one on the upper thrust bearing, one on the lower thrust bearing, and four on the lower roller bearings (two of which were specially mounted to determine if a more meaningful bearing temperature could be achieved). The location of the bearing thermocouple is shown in Figure 31. The specially mounted bearing thermocouple on the lower roller bearing were located approximately 0.01 in. from the inner surface of the outer race as shown in Figure 31.

Turbopump S/N 88017, pump 2, was provided with two standard-mounted thermocouples on each of the four bearings.

The evaluation of the special thermocouples during the initial chilldown (EP-1) indicated essentially no difference in the measurements in respect to the standard mounted thermocouple as depicted in Figure 32. However, as shown in Figure 33, the specially mounted thermocouple registered a higher temperature during the TPA operational phase than the standard-mounted thermocouples. This higher temperature would indicate a more valid indication of the heat generated in the bearing since it is closer to the bearing contact surface.

2. Thrust Measurement

Thrust rings were installed on the two TPA's to measure the axial load on the bearings. The thrust rings were located between the upper roller bearings and the upper thrust bearings. The thrust rings are thin-wall cylindrical sleeves with a full-bridge strain gage circuit attached.

Figure 31 - Bearing Thermocouple Location

Figure 32 - Bearing Thermocouple Performance - Initial Chilldown

Figure 33 - Bearing Thermocouple Performance

The calibration of the thrust ring was performed at ambient temperature and liquid nitrogen conditions and the results of the calibration are shown in Figures 34 and Figure 35. During the liquid nitrogen calibration, a zero offset of a negative (i.e., toward the turbine) 14.002 mv was experienced on the S/N 016 thrust ring and a negative 0.630 mv was experienced on the S/N 017 thrust ring. By "zeroing" the offsets, the difference in ambient and liquid nitrogen data was approximately 0.5% in 10 mv.

The S/N 016 thrust ring was mounted in TPA 1 and the S/N 017 thrust ring was mounted in TPA 2. The S/N 016 thrust ring measurement (HS-888) upon initial chilldown during EP-1 registered readings in excess of full-scale and could not be corrected. The S/N 017 thrust ring measurement (HS-988) had an initial offset of approximately 750 lbf toward the turbine because of the temperature shift. This measurement functioned throughout the test program. A comparison of the calculated and measured thrust in respect to TPA parameters is shown in Figure 36. The comparison shows that the measured thrust and the calculated values follow the same trend; however, the magnitudes are different.

3. Speed Probes

Each of the TPA's contains two speed probes. The probes each contain two coils, one approximately of four ohms and the other of approximately 40 ohms. The speed measurement was taken from the high resistance coil which has an output of 35 mv at 100 rpm and is linear to 40,000 rpm. No difficulties were encountered during the test with speed measurements.

C. FLOW MEASUREMENTS

Two flow-measuring orifices were used within the pump package. The orifices were in the turbine inlet line for the purpose of measuring

Figure 34 - NERVA Load Ring Calibration - S/N 016

Figure 35 - NERVA Load Ring Calibration - S/N 017

DUAL TURBOPUMP TESTS THRUST RING (HS-988) PERFORMANCE

Figure 36 - Thrust Ring Performance

flow rates into turbines 1 and 2. The orifices were identical in dimension on all EP's (except for the unequal turbine impedance test in EP-3) and were designed per ASME criteria for a square-edge orifice. The throat diameter used was 2.632 in. For EP-3 only, the throat diameter was reduced to 2.497 in. on the pump 1 side.

A comparison of the sum of the individually measured flow rates with the total measured turbine flow rate (facility orifice in the common turbine line) is shown in Figure 37.

Three turbine-type flowmeters were used to measure pump discharge flow rates, one on each of the individual pump discharge line and one on the common discharge line.

A comparison of the measured sum of the individual flow rates with the measured total flow rate was done and is shown in Figure 38.

*DUAL TURBOPUMP TESTS
COMPARISON OF INDIVIDUAL TURBINE FLOWRATE WITH
TOTAL TURBINE FLOWRATE*

Figure 37 - Comparison of Individual Turbine Flow Rate with Total Turbine Flow Rate

Figure 38 - Comparison of Individual Pump Flow Rates with Total Pump Flow Rate

X. DATA PROCESSING

The measured parameters used for data analysis were recorded on narrow-band tape, wideband tape, oscillograph (CEC), strip chart (Sanborn), and real-time computer PDP-116. The flow of the data is expressed in graphic form in Figure 39 and the mode of recording of each measurement channels is shown in Table 15. Figure 39 shows that a steady-state computer program was used to evaluate the data recorded on the narrow-band tape. This program was utilized to evaluate TPA performance and is a modification of ANSC Program 341. Only the "Visa Playback" option was utilized for the processing of wideband data.

Figure 39 - Data Reduction

XI. TEST PROGRAM

The analytical representation of the PFS used during the selection of the dual-pump system included predicted component characteristics (i.e., efficiencies, characteristic curve shapes, pressure drops, and inertias) and such system interaction effects as detection times, response rates, fluid inertias, thermal lags and system symmetry. The more critical analytical assumptions were:

1. Component performance predictions and tolerance (i.e., pump pressure rise, pump efficiency, turbine efficiency, pressure drops, and inertias) were achievable.
2. Pump pressure rise vs flow rate characteristic curve slope, as specified, would result in stable system operation and was achievable.
3. Pump stall margin was as predicted.
4. The TPA could withstand predicted shutdown profiles.
5. Check valve responses were adequate.
6. Control system and valve response times were achievable.
7. A malfunction detection system with adequate response time would be available from measurements of pressure, shaft speed, temperature, valve position or differentials between branches together with other parameters. Incipient failure detection systems incorporated in the TPA would be available as a backup or alternate system.

8. System pressure dynamics resulting from malfunctions were acceptable.

9. System leg symmetry tolerances (i.e., differential values of pressure rise or drop, turbopump efficiency, and flow profile) were achievable.

10. Predicted component and system reliability values were achievable and would be established as a part of the component and engine development programs.

11. Chillo down requirements remained to be established during the feed system design phase.

An essential supplement to the analytical study was a test program that verified critical component and system characteristics and assumptions or provided revised or refined data to permit upgrading of the analytical model. The data acquired from such a program served four basic purposes:

1. Established the validity of PFS selection, as described above
2. Provided component and subsystem design criteria through the system engineering activity, including the requirements for malfunction detection and control systems
3. Provided early component and subsystem performance, behavioral, and environmental data to support the early design reliability analysis
4. Provided component and subsystem performance and behavioral data to support early engine system steady-state and transient analysis and a continuous upgrading of this analysis.

The following test program outlines the testing sequence which was run to validate or adjust the assumptions made in the analytical representation.

A. EXPERIMENTAL PLAN 1

The first EP, conducted 19 February 1970, consisted of initial system checkout, TPA mapping in both the single- and dual-pump mode, and determination of single-TPA damping characteristics.

1. Turbopump 1 Green Run (Checkout)

A shaft speed of 5000 rpm was established using H-65 in position control to verify the presence of a speed feedback signal. Speed control was selected and the shaft speed was increased to 18,000 rpm. The test was terminated by demanding zero speed.

2. Turbopump 2 Green Run (Checkout)

This run was a duplication of the TPA 1 Green Run except that H-68 was used.

3. Turbopump 1 LHBV Calibration and Frequency Response Measurement:

Using H-65 in speed control, a TPA 1 shaft speed of 18,000 rpm at a pump Q/N of 0.30 gal/rev was established. Frequency response measurements were made in speed and pressure control with one TPCV. The other TPCV (H-68) was opened in position until its position matched H-65 and then switched to pressure control. Frequency response measurements were performed with both TPCV's in pressure control. The pump bypass valve (L-119) was mapped with the TPA at a discharge pressure of 530 psig and a Q/N of 0.35 gal/rev. The test was terminated by demanding zero pressure.

4. Turbopump 2 Frequency Response Measurements

Using H-68 in speed control, a TPA 2 shaft speed of 18,000 rpm at a pump Q/N of 0.30 gal/rev was established. Frequency response measurements were performed on the speed loop. The test was terminated by demanding zero speed.

5. Dual-Turbopump Mapping and Frequency Response Measurements

During this run phase, the steady-state performance of the dual TPA system was mapped with both TPCV's in speed control. Speed lines of 10,000, 14,000, 18,000, and 22,000 rpm were established. The stability threshold was also established for the low flow rate region of the pump map.

A frequency response measurement was performed on the pressure loop at a pump discharge pressure of 520 psig and a total flow rate of 80 lb/sec (i.e., 40 lb/sec per pump).

The high flow rate portion of the 10,000 and 14,000-rpm speed lines outside the limits of the TES were mapped using the tank farm to provide turbine drive gas. The test was terminated by demanding zero speed.

When zero speed was demanded, it was noted that one TPCV (H-65) did not close and remained approximately 15% open. The valve was held in this position during the remainder of EP-1. Later examination of the valve showed one of the seal rings surrounding the butterfly to be broken and bent, preventing the valve from fully closing.

In dual mode, a pump discharge pressure of 410 psia and a pump Q/N of 0.30 gal/rev were established. The test was terminated from this operating point by initiating the primary shutdown chain to observe TPA "coastdown" time.

f. Turbopump 1 Damping Characteristics

Turbopump 1 was operated using H-68 (with H-65 at 15%), at a pump discharge pressure of 520 psig. The damping characteristics of the TPA were investigated at flow rates of 40, 60, and 80 lb/sec by measuring the response of the system to steps in the system impedance valve (L-30). The test was terminated by the overspeed 1 input to the primary shutdown chain.

B. EXPERIMENTAL PLAN 2

The second EP, conducted 5 March 1970, evaluated the possible instability of a dual-pump system and the effect of some simulated turbine drive failures with an intertie configuration.

1. Dual-Turbopump System Stability Test

In dual-mode (with H-65 and H-68 in pressure control) a pressure of 410 psig and a pump Q/N of 0.30 gal/rev were established. Using position trim, H-68 was opened to investigate the effect upon pump flow rate symmetry. After the trim was returned to zero, the test was terminated by demanding zero pressure.

Both TPA's were then operated using both TPCV's in pressure control at a pump discharge pressure of 520 psig. System stability was investigated at total flow rates of 80 lb/sec (i.e., 40 lb/sec per pump) and 120 lb/sec (i.e., 60 lb/sec per pump) by measuring the response of the system to steps in the system impedance valve (L-30), the TPCV's, and one pump bypass valve (L-219). These steps were also repeated at a pump discharge pressure of 620 psig and flow rate of 90 lb/sec (i.e., 45 lb/sec per pump) and at a pump discharge pressure of 350 psig and a flow rate of 64 lb/sec (i.e., 32 lb/sec per pump). The test was terminated by demanding zero pressure.

2. Simulated Turbine Drive Failures with Intertie

Both TPA's were operated using both TPCV's in pressure control at a pump discharge pressure of 520 psig. Steps to 6% in the open and closed direction were made with H-68 which was then ramped closed at input rates of 10%/sec, and 40%/sec (the signal from the pressure controller reduces the rate of the resulting ramp) and then reopened. This test was terminated by a pump 2 Q/N input to the primary shutdown chain.

Following shutdown, it was noted that one TPCV (H-68) did not close fully. Later examination of the valve showed a failure of the seal ring surrounding the butterfly. Both TPCV's were returned to Sacramento to remove the seal rings prior to EP-3.

3. Experimental Plan 3

The third EP, conducted 19 March 1970, evaluated the effect of asymmetry in turbine efficiencies, pump efficiencies, and pump head rise.

1. Unequal Pump Inlet Impedance Test

An orifice was installed in the suction line of pump 1. Using both TPCV's in speed control, the 18,000- and 22,000-rpm speed lines were mapped in the dual-pump mode. Speed response measurements were made on the speed loop at a pump Q/N of 0.30 gal/rev at 18,000 rpm and a pump Q/N of 0.21 gal/rev at 20,000 and 22,000 rpm. The test was terminated by demanding zero speed.

2. Dual-Pump Stability with Unbalanced Turbine Drive

The flow measuring orifice in the turbine inlet line of pump 1 was replaced by a smaller orifice. This caused a larger difference in pump flow rate.

Both TPCV's were used in pressure control to operate both TPA's. Step response measurements were made on the pressure loop at a pump Q/N of 0.30 gal/rev at 18,000 rpm and a total flow rate of 80 lb/sec at 520-psig discharge pressure.

The system stability was investigated at total flow rates of 80 and 120 lb/sec by measuring the response of the system to steps in the system impedance valve (L-30), the TPCV's, and one pump bypass valve (L-219). The test was terminated by demanding zero pressure.

D. EXPERIMENTAL PLAN 4

The fourth EP, conducted 16 April 1970, evaluated the effect of simulated turbine drive failures with the modified turbine inlet system. Turbine block valve H-69 closure and simulated TPA failures were also evaluated.

1. Simulated Turbine Drive Failures with Modified Turbine Inlet System

Both TPA's were operated using both TPCV's in pressure control at a pump discharge pressure of 520 psig. Steps to 6% in the open and closed direction were made with H-68. H-68 was then ramped closed at the input rates of 20, 40, 60, and 200%/sec (the signal from the pressure controller reduces the rate of the resulting ramp) and then reopened. H-67 was then stepped closed. This test was terminated by demanding zero pressure.

The "mini" shutdown chain was then activated to close H-67 when the TPCV positions separated by 5%. Following each closure of H-67, the test was terminated by demanding zero pressure. The system was then restarted.

H-68 was ramped closed at the input rates of 20, 60, and 200%/sec. H-68 was then ramped open at the input rates of 20, 60, and 200%/sec. H-68 was then stepped open. During the last test (i.e., H-68 stepped open), the primary shutdown chain was tripped by a pump 2 Q/N input during the H-67 closure.

2. Pump Stall Mapping Test

Turbopump 1 was operated using H-65 in speed control. The pump flow rate was reduced while operating at a speed of 16,000 rpm to a pump Q/N of 0.12 gal/rev. The pump flow rate was increased to a Q/N of 0.25 gal/rev and the test terminated by demanding zero speed.

3. Dual-Pump Instability Test

Both TPA's were operated using both TPCV's in pressure control. A pump Q/N of 0.25 and a speed of 21,000 rpm were established and a frequency response measurement of the pressure loop conducted.

The TPCV's were switched to speed control and a speed of 16,000 rpm established. The pump Q/N was decreased to investigate instability. The pumps were returned to a Q/N of 0.25 and the test was terminated by demanding zero speed.

4. TBV (H-69) Closure

Both TPA's were operated using both TPCV's in pressure control. A pump discharge pressure of 350 psig and a total flow rate of 64 lb/sec (i.e., 32 lb/sec per pump) were established. H-69 was closed which shut down Pump 2. After completion of the flow "swing", pump 1 was shut down by demanding zero pressure. This was repeated at a pump discharge pressure of 520 psig and at a total flow rate of 80 lb/sec (i.e., 40 lb/sec per pump).

5. Simulated Pump Failure

Both TPA's were operated using both TPCV's in pressure control. The "mini" shutdown chain was activated to close H-69 when the pressure drop across the pump discharge check valve on the pump 2 side exceeded 50 psi in the negative direction.

A pump discharge pressure of 350 psig and a total flow rate of 64 lb/sec (32 lb/sec per pump) were established. The bypass valve on the pump 2 discharge (L-219) was stepped open to 35%. After the flow "swing" by pump 1 was completed and pump 2 shutdown, pump 1 was shutdown by demanding zero pressure.

This was repeated at a pump discharge pressure of 520 psig and a total flow rate of 80 lb/sec (i.e., 40 lb/sec per pump).

During each of the EP's outlined above, the effect of TPA chillover was investigated. The pumps were started at the beginning of each EP with the pumps at various thermal conditions.

Table 16 shows the operating time accumulated during each EP.

The detailed chronologies for the Experimental Plans are included as Appendices A, B, C, and D.

TABLE 16

OPERATING TIME ACCUMULATED
DURING EACH EXPERIMENTAL PLAN

EXPERIMENTAL PLAN 1

RUN	PUMP #1		PUMP #2		DUAL MODE	
	TOTAL (min)	Above 18000 RPM (min)	TOTAL (min)	Above 18000 RPM (min)	TOTAL (min)	Above 18000 RPM (min)
1	2.8	.4	—	—	—	—
2	—	—	2.0	.3	—	—
3	13.0	12.3'	—	—	—	—
4	—	—	3.5	2.3	—	—
5	21.9	7.3	21.9	7.3	21.9	7.3
6	1.9	.8	1.9	.8	1.9	.8
7	5.5	3.8	—	—	—	—
	45.1	24.6	29.3	10.7	23.8	8.1

EXPERIMENTAL PLAN 2

1	1.6	—	1.6	—	1.6	—
2	3.7	2.4	3.7	2.4	3.7	2.4
3	21.5	18.3	21.5	18.3	21.5	18.3
4	3.3	2.7	3.3	2.7	3.3	2.7
	30.1	23.4	30.1	23.4	30.1	23.4

EXPERIMENTAL PLAN 3

1	3.0	—	3.0	—	3.0	—
2	10.5	8.4	10.5	8.4	10.5	8.4
3	22.1	12.6	22.1	12.6	22.1	12.6
	35.6	21.0	35.6	21.0	35.6	21.0

TABLE 16 (cont.)

EXPERIMENTAL PLAN 4

RUN	PUMP #1		PUMP #2		DUAL MODE	
	TOTAL (min)	18000 RPM (min)	TOTAL (min)	18000 RPM (min)	TOTAL (min)	18000 RPM (min)
1	4.5	3.7	4.5	3.7	4.5	3.7
2	1.8	1.1	1.8	1.1	1.8	1.1
3	3.0	2.4	3.0	2.4	3.0	2.4
4	1.2	.7	1.2	.7	1.2	.7
5	1.4	.7	1.4	.7	1.4	.7
6	1.4	.6	1.4	.6	1.4	.6
7	1.4	.7	1.4	.7	1.4	.7
8	1.0	.5	1.0	.5	1.0	.5
9	2.3	—	—	—	—	—
10	5.3	3.0	5.3	3.0	5.3	3.0
11	2.0	.3	1.5	—	1.5	—
12	1.7	1.1	1.4	.9	1.4	.9
13	2.1	—	1.9	—	1.9	—
14	3.1	2.4	2.7	.5	2.7	.5
	32.2	17.2	28.5	14.8	28.5	14.8

XII. RESULTS

The test program consisted of four EP's as described in Section XI. During the program a large amount of operational data was acquired. This section discusses the significant results of the tests conducted. However, no attempt has been made to present all data acquired (more than 9500 "Cal Comp" plots alone made during testing).

The predicted pump performance is shown in Figure 40 in terms of pump normalized parameters, head rise divided by shaft speed squared ($\Delta H/N^2$), pump efficiency (η_p), and volumetric flow divided by shaft speed (Q/N). Figure 41 shows the pump performance verified by test results. Comparison of the predicted and the actual pump performance shows the stall point to be further to the left, the slope of the head curve to be greater, and the efficiency to be greater than what was predicted. The stall hysteresis is also shown in Figure 41.

The slope of the normalized head rise curve as a function of Q/N is shown in Figure 42. The polynomial equation shown was derived by using a polynomial curve fit program, "POLFIT," in the G.E. Time Share Library. The slope of the curve was solved by taking the first derivative of the polynomial equation.

The performance of the turbines of both TPA's is shown in terms of flow parameter $\frac{W_t}{P_{ttI}} \sqrt{T_{ttI}}$, as a function of pressure ratio (PR), and efficiency (η_t) as a function of velocity ratio (μ/Co), in Figures 43 and Figure 44. The difference in turbine performance characteristics shown in Figures 43 and 44 resulted in a small mismatch in operating points (pump flowrate) during dual-pump operation.

PUMP NORMALIZED HEAD
RISE, $\Delta H/N^2 \sim \text{FT/RPM}^2$

PREDICTED PUMP NORMALIZED PERFORMANCE TEST CELL 'C' PUMP

PUMP EFFICIENCY
 $\eta_p \sim \text{PER CENT}$

Figure 40 - Predicted Pump Normalized Performance

1/18/70 TAD

ACTUAL PUMP NORMALIZED PERFORMANCE
TEST CELL 'C' PUMP

Figure 41 - Actual Pump Normalized Performance

TAD 1018

SLOPE OF THE HEAD CURVE

$$Q/N = .15 \text{ TO } .24$$

TEST CELL 'C' PUMP

$$\text{SLOPE} \sim \frac{d(AH/N^2)}{d(Q/N)} (10)^{-5} \sim \frac{FT/RPM^2}{GPM/RPM}$$

Figure 42 - Slope of the Head Curve

[6]

Figure 43 - Turbine Flow Parameter

TAD 150 787

Figure 44 - Turbine Efficiency

TRD. 50

Tests were conducted to determine the effect of asymmetry upon the performance characteristics of the dual-TPA system. The effect of a mismatch is to force the pumps to operate at different performance conditions to obtain equilibrium at the common discharge point. This was characterized by the flow rates of the two pumps not being equal. The tests conducted during EP-3 were made for this purpose. To cause a mismatch in the system, an orifice was installed in the suction line of pump 1. Figures 45, 46, and 47 show measured TPA and valve parameters as a function of control room time for the test conducted. For another test, an orifice of smaller diameter was installed in the inlet line of turbine 1. Figures 48, 49, 50 show measured TPA and valve parameters as a function of control room time for the test conducted.

The effect of orificing is to unbalance the parallel system by changing the impedance. This change in impedance alters the shaft horsepower balance of the TPA's which is reflected in flow differences between the pumps, since pump discharge pressure must be equal. The effect of orificing is depicted in terms of pump flow in Figure 51 and in terms of pump flow parameter (Q/N) in Figure 52. Inspection of the figures shows there was an initial mismatch of the two TPA's. The initial mismatch was caused by the difference in turbine performance as reflected in Figures 43 and 44. The results of orificing is reflected in Figure 52, where the ratio of Q/N does not equal 1. This illustrates that the two pumps, in order to maintain equilibrium conditions at the pump discharge, had to operate at different conditions of head rise and efficiency. There were no indications from the tests conducted that manufacturing tolerances or other sources of mismatches would cause any operational problems in the operation of a dual-TPA system.

The effect of orificing which caused greater flow separation also caused flow oscillations of higher magnitude. The magnitude at various conditions is shown in Figure 53. The magnitude of the oscillations, at a Q/N of approximately 0.24 gpm rpm, starts to increase rapidly as Q/N is lowered. This increase is caused by the effect of the head rise slope on the dual pump stability.

Figure 45 - Experimental Plan 3 Data - Pump Parameters - Suction Orifice Installed

Figure 46 - Experimental Plan 3 Data - Pump Discharge Pressures - Suction Orifice Installed

Figure 47 - Experimental Plan 3 Data - Turbine Parameters - Suction Orifice Installed

Figure 48 - Experimental Plan 3 Data - Pump Parameters - Turbine Orifice Installed

Figure 49 - Experimental Plan 3 Data - Pump Discharge Pressures - Turbine Orifice Installed

Figure 50 - Experimental Plan 3 Data - Turbine Parameters - Turbine Orifice Installed

EFFECT OF IMPEDENCE
ON
PUMP FLOWRATE
DUAL MODE

Figure 51 - Effect of Impedance on Pump Flowrate

TAD

*Q/N DIFFERENCE
DUE TO IMPEDENCE DIFFERENCE
DUAL MODE*

Figure 52 - Q/N Difference due to Impedance Difference

Tap.

DUAL PUMP OPERATION
EFFECT OF ORIFICE ON FLOW
OSCILLATIONS AT VARIOUS Q/N

Figure 53 - Effect of Orifice on Flow Oscillation

The frequency of the oscillations observed in the flow was approximately five Hz. It has been calculated that the resonance frequency of the suction line (taking the length of line from the dewar to the pump inlet) was 5.64 Hz. At a frequency of 5 Hz, the response of the flow measurement system is down 6 db. The data shown, have not been corrected for this error, however.

Three dual-pump stability threshold tests were conducted, two during EP-1 and one during EP-4. In the two EP-1 tests, the flow was reduced to a Q/N value of approximately 0.18 gpm/rpm where a slight instability occurred. During the EP-4, the Q/N was reduced to lower than 0.18 gpm/rpm. Investigation of the flow characteristics of the two pumps shows that, as instability occurs, the phase relationship between the two flows becomes 180° apart as depicted in Figure 54 in terms of Q/N vs time. The degree of instability can be partially determined by the magnitude of the oscillation. Figure 55 indicates that for this configuration pump in a parallel system, the magnitude of the oscillation increases rapidly after a Q/N value of approximately 0.24 gpm/rpm. The magnitude of the oscillation is related to the slope of the headrise curve as shown in Figure 56. As shown, the magnitude of the oscillation increases as the slope of the curve goes from a negative to a positive slope. Figure 54 shows that at a Q/N of 0.175 gpm/rpm and at a control room time of 23425.9 sec of EP-4, a fairly high degree of instability occurred with one pump going to a Q/N of 0.14 gpm/rpm. Further investigation during this period also revealed that one pump always stayed on the negative slope side of the headrise curve while the other pump made the excursion to the positive slope of the head rise curve into stall and then returned. It is estimated that from 23425.9 to 23429.1 sec, where a Q/N shutdown occurred, the controllability of the system was very marginal as Figures 57 and 58 show when comparing pump impedance valve position LR-30 with the three flow measurements of HF-850 and 950, LF-029, and with the shaft speed of HQ-850 and 950.

Figure 54 - Data from EP-4 Stability Test

DUAL PUMP OPERATION
EFFECT OF FLOW OSCILLATION
DUE TO
PUMP OPERATION AT VARIOUS Q/N

Figure 55 - Effect of Flow Oscillation due to Pump Operating at Various Q/N

DUAL PUMP OPERATIONS
EFFECT OF SLOPE ON
FLOW OSCILLATION

Figure 56 - Effect of Slope on Flow Oscillation

Figure 57 - Experimental Plan 4 Data - Pump Discharge Parameters - Stability Test

Figure 58 - Experimental Plan 4 Data - Valve Positions - Stability Test

Various valves steps were conducted during the test program with H-68 (TPCV), L-219 (pump discharge bypass valve), and L-30 (common pump discharge impedance valve). These steps caused some perturbation in the system; however, they were minor.

The difference in the effect of the turbine inlet system used for EP-1, EP-2, and EP-3 compared with the one used for EP-4 was exemplified by the 40%/sec ramp closing of E-68. Figure 59 shows the path taken by the two pumps during the simulated turbine drive failure conducted with the intertie during EP-2. The path shown has been plotted on a small segment of the pump map and the numbers along the path are the times from the 40%/sec initiation in milliseconds. Figure 59 also illustrates the divergence in pump flow rates which is a result of the turbine intertie flow impedance. The calculated loss in pressure through the intertie was approximately 2.5 times less than the test results indicated. Because of this flow impedance, the energy available to one turbine was much less than the other. Therefore to balance the system, the two pump flows diverged. The same simulated turbine drive malfunction was conducted with the modified turbine system used in EP-4 and the results are shown in Figure 60. The configuration of this system dictates that the energy level to the turbines be approximately equal. The initial pump flow rate separation as depicted is caused by the difference in turbine performance (see Figure 59). The paths taken by the pump flows are in parallel and do not diverge as was the case in EP-2. This comparison would indicate that the modified turbine system would be a better design configuration for a dual pumping system.

The "mini" shutdown chain was used to close H-67 for the simulated turbine drive failure when the TPCV positions were 5% apart during EP-4. The system effect was dominated by H-67 closure. To illustrate the effects of this malfunction upon the pumping system an open and close rate of 200%/sec was chosen for H-68. Figure 61 shows system effect (i.e., common discharge pressure and total pump flow rate) resulting from the 200%/sec input ramps with H-67 closure. The recovery time of 400 millisecc was the same for both ramps. The general paths for both ramps were the same except for the initial upswing for the H-68 open ramp. Figures 62 and 63 depict the paths of the individual pumps during these tests.

Figure 59 - Simulated Turbine Drive Failure with Intertie

SIMULATED TURBINE DRIVE FAILURE
WITH INLET SYSTEM MODIFICATION
H-68 RAMP INPUT - 40%/SEC CLOSED

Figure 60 - Simulated Turbine Drive Failure with System Modified (H-68 Ramp

SIMULATED TURBINE DRIVE FAILURE
WITH INLET SYSTEM MODIFICATION
H-68 INPUT RAMP - 200%/SEC WITH
H-67 CLOSURE

Figure 61 - Simulated Turbine Drive Failure with System Modified
(H-68 Ramp Input - 200%/sec with H-67 Closure)

Figure 62 - Simulated Turbine Drive Failure with System Modified
(H-68 Ramp Input - 200%/sec Closed with H-67 Closure)

Figure 63 - Simulated Turbine Drive Failure with System Modified
(H-68 Ramp Input - 200%/sec Open with H-67 Closure)

Simulated TPA failure was accomplished during EP-4 by opening the pump discharge bypass valve on the pump 2 side (L-219) to 37%. When the pressure drop across the pump discharge check valve on that leg exceeded 50 psi, the "mini" shutdown chain closed H-69. Figures 64, 65, 66 and 67 plot the measured TPA parameters as function of time taken from 40-sample-per-sec data. The recovery of the system as shown was very rapid. As shown in Figure 66, L-219 was opened initially to 13.5% prior to opening to 37%. The initial opening was accomplished to chill the bypass line and eliminate "flashing" in the line. The rapid opening of L-219 from 13.5 to 37% initially caused suction pressure to lower approximately 18 psi because of the increase in pump flow and caused a water-hammer effect which resulted in a pressure spike of approximately 150 psia. Figure 68 depicts the excursion during this simulated malfunction in terms of common discharge pressure and total pump flow rate. Figure 69 shows the excursion taken by the two pumps during the simulated malfunction test.

For a parallel-TPA system to meet NERVA engine requirements, the system must survive a TBV closure. This would be required to shut down one TPA. The test conducted resulted in a very fast transient with little effect on the system as shown in Figure 70. The measured TPA parameters as a function of time are shown in Figures 71, 72, 73, and 74. The water-hammer effect in the suction line was minor as compared with the hammer effect that occurred in the simulated TPA failure test (see Figure 72). Figure 75 shows the excursion that the two pumps underwent.

The results of the tests revealed that the backswept centrifugal impeller type pumps were very capable in the parallel pumping system and could survive various malfunction modes.

During testing, data were obtained concerning the characteristic of a backswept impeller to "windmill" during chillover. Figure 76 shows the rotational speed resulting from various flow rates through the pump.

Figure 64 - Experimental Plan 4 Data - Pump Pressures - Simulated TPA Failure

Figure 65 - Experimental Plan 4 Data - Pump Flowrates - Simulated TPA Failure

Figure 66 - Experimental Plan 4 Data - Turbine Parameters - Simulated TPA Failure

Figure 67 - Experimental Plan 4 Data - Valve Positions - Simulated TPA Failure

Figure 68 - Simulated Turbopump Failure - System Conditions

Figure 69 - Simulated Turbopump Failure - Individual Pump Conditions

Figure 70 - Turbine Block Valve Closure - System Conditions

Figure 71 - Experimental Plan 4 Data - Pump Pressures - TBV Closure

Figure 72 - Experimental Plan 4 Data - Pump Flowrates - TBV Closure

Figure 73 - Experimental Plan 4 Data - Turbine Parameters - TBV Closure

Figure 74 - Experimental Plan 4 Data - Valve Positions - TBV Closure

Figure 75 - Turbine Block Valve Closure - Individual Pump Conditions

Figure 76 - Windmilling Data

Accelerometers were provided on the pump system and the data recorded are presented for TBV closure and simulated TPA failure tests conducted during EP-4. The relative locations and the direction of measurement are shown in Figure 77. HA-849 and 850 were located at the flange of the pump discharge flowmeter. HA-851 and 951 were located on the gimbal approximately 1 ft downstream of the pump discharge check valve. The data obtained from the accelerometers indicated that the closure of the TBV did not affect the structural dynamics of the pump system. The dynamics of the system, however, were affected by two functions:

1. Closure of the pump discharge check valve.
2. TPA shaft speed.

Comparison of the results of the two malfunction shows that the simulated TPA failure malfunction was structurally more detrimental to the system than the TBV closure test. The relative magnitude difference in the two malfunction tests can be best seen in the measurements of accelerometer HA-951. Prior to start of each malfunction sequence, the accelerometer measured ± 5 g at a frequency of 1500-1900 Hz. After the start of the malfunction sequence for TBV closure, HA-951 initially registered a 60 g spike of a duration of less than one millisecond. For the simulated TPA failure, HA-951 initially registered an 80 g spike of a duration less than one millisecond.

For both malfunctions, since pump 2 was being shut down, the effects of the malfunction were greater on the pump 2 flow system.

Figure 77 - Accelerometer Location

XIII. ANALOG SIMULATION

The dual TPA system was modeled upon the digital and analog computers which were utilized to predict system performance and the control system designs. Appendix E documents the digital and analog models of the test configuration. These models were used to assist in the development of the test program by establishing the capability of the test system, to check testing methods, and to determine valve step sizes for pump stability tests. The results of these analyses are shown in Appendix F.

The digital model was recently updated to the EP-4 test configuration in anticipation of the posttest evaluation of simulation techniques. Since this evaluation has not been completed at this writing, the documented models reflect the status of the analog model as of 3 March 1970.

XIV. RECOMMENDATIONS

The data obtained during this test program should be utilized to improve the modeling techniques used to predict system operation with analog and digital computers. Since these are the only data which exist concerning the performance of a dual -TPA system during malfunctions which could occur in the NERVA engine, it is the only means available to calibrate analog predictions. Further studies should be made with the Test Cell C models to either demonstrate that the techniques used are adequate or to improve the technique.

The feasibility and advantages of fabricating and operating a PFS more exactly representing the valving and flow paths of the feed system selected for the NERVA engine should be investigated. For the results to be meaningful, the component characteristic would probably have to be so close to those of the actual NERVA components that real NERVA components may be required.

A PFS utilizing NERVA components should be tested as soon as the components become available to allow the behavioral data which would be obtained to influence the design and development of the components.

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5. AGC Drawing 1136800, Test Assembly - Test Cell C Dual Turbopump
6. NRO-TCC-001, Turbopump Assembly Installation
7. NRO-TCC-002, Installation, Line Assembly, Pump Inlet
8. NRO-TCC-003, Installation, Line Assembly, Pump Discharge
9. NRO-TCC-004, Installation, Line Assembly, Turbine Inlet
10. NRO-TCC-005, Installation, Line Assembly, Turbine Exhaust
11. NRO-TCC-006, AGC TPA Purge and Dehydration
12. NRO-TCC-007, TPCV and TBV Actuation Setup and Secure
13. NRO-TCC-008, TBV Potentiometer Adjustment
14. NRO-TCC-009, Test Operations Setup and Secure
15. NRO-TCC-010, TPCV Removal
16. NRO-TCC-011, Seal Replacement on 5 in. PDKV
17. NRO-TCC-012, PDKV Removal and Installation
18. NRO-TCC-013, TBV Relocation
19. NRO-TCC-014, Installation, Line Assembly, Turbine Inlet P/N 1136803-14
20. NRO-TCC-015, Suction Line Orifice Installation and Removal

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21. LASL Drawing, J5-SK-285, NERVA Dual Pump Piping Isometrics
22. LASL Drawing, 3222-PD-220, NERVA Dual Pump Installation Plan
23. LASL Drawing, 3222-PD-221, NERVA Dual Pump Elevation and Sections
24. LASL Drawing, 3222-PD-204, NERVA Dual Pump Piping Details
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26. ANSC Sketch In-Drw-002, Revised Instrumentation - Turbine Inlet Line

APPENDIX A

CHRONOLOGY FOR EXPERIMENTAL PLAN 1

CHRONOLOGY FOR AGC PUMP TEST

EXPERIMENTAL PLAN 1

February 19, 1970

I. PRE-OPERATIONAL PHASE

- A. Setup Checklists Received and Approved; Status Board Cleared.
- B. Check the Control Room Net.
- C. Required Systems Switched to CP Control.
- D. Exercise the Valves.
- E. Check the Shutdown Chain.
- F. Inerting the Test Cell.

04356 Turn off the fans.
04361 Close Q-113.
04370 Pressurize the room inerting header (Bottles 13, 14, 15, and 16). Report QP-50 is 2450 psig.
04444 Begin inerting the test cell.
04448 Close L-403; open L-103; open G-451/G-452; and close L-103.

- G. Voltage Calibration.

05841-05941 Calibration Interval.

- H. Clear the Test Cell Area.

II. PRESSURIZATION, CHILLDOWN, AND OVERSPEED TRIP CHECK

- A. Pressurize the Headers.

07549 Report on room inerting.
07555 Open L-153, L-50, L-251, and H-50.
07586 Open G-50.
07591 Open W-50.
07598 Close Q-150.
07604 Close all the bottle purge valves.
07624 Pressurize the helium header (Bottle #1). QP-20 is 2550 psig.
07682 Pressurize the hydrogen header (Bottle #6). QP-30 is 2760 psig.
07769 Pressurize the nitrogen header (Bottle #11). QP-40 is 1790 psig.

- B. The Chillydown.

07962 Close L-261, L-262, L-153, and L-491.
07990 Open L-62.
07995 Select Dewar 2 Pressure Feedback.
08000 Open L-105.

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08007	Open L-2.
08010	Data tapes ON.
08023	Open L-3.
08081	Open L-91.
08090	Open L-32.
08097	Open L-30.
08116	Open H-9.
08130	In L-53 Pressure Control, establish 50 psig in Dewar 2.
08275	LT-5 is chilled; close L-105.
08309	Use L-119 to chill pump #1.
08525	The pump is chilled; close L-119.
08530	Use L-219 to chill pump #2.
08613	The pump is chilled; close L-219.
08653	Use H-101 to chill HT-101.
08716	Use L-191 to chill LT-191.
08899	LT-191 is 100°R. Close L-191; open L-92.
08963	Data tapes off.
08991	LT-91 is chilled; close L-92.
08946	Switch L-53 to Position Control and close.
08948	Close L-62.
08958	Open L-153.
08300-11870	Hold for re-entry to repair LH ₂ leak at L-105.
12341	Pressurize the hydrogen header (Bottle #6). QP-30 is 2280 psig.
12195	Open I-91.
12203	Open I-105.
12230	Open L-2.
12250	Close L-403.
12271	Open I-3 slowly.
12195	Open I-91.
12386	Open L-62.
12617	In L-53 Pressure Control, establish 50 psig in Dewar 2.
12635	LT-5 is chilled; close L-105.
12638	Use L-119 to chill pump #1.
12698	When the pump is chilled, close L-119.
12811	Use L-219 to chill pump #2.
12901	When the pump is chilled, close L-219.
12910	Use H-101 to chill HT-101.
12946	Use L-191 to chill LT-191.
12956	LT-191 is 100°R. Close L-191; open L-92.
13094	LT-91 is chilled; close L-92.
13119	Switch L-53 to Position Control and close.
13128	Close L-62.
13163	Open L-153.

C. Setup of Water System.

13218	Close W-153.
13223	Open W-1, W-211, W-221, W-231, W-11, W-31, W-45, W-49, and W-100.
13317	Use W-53 to establish 50 psig at WP-1.
13321	Turn on the water flow meter power.
13386	Close W-11, W-31, W-211, W-221, and W-231.

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D. Check the Speed Inputs to the Shutdown Chain and the Calibration of L-119 and L-219.

13508 Set the overspeed trip pot to 65 divisions.
 13526 Bypass all the inputs to the shutdown chain.
 13530 Switch the shutdown valves to override.
 13586 Use L-119 to trip overspeed #1 and overspeed #2.
 13643 Pump #1 is chilled; close L-119.
 13646 Use L-219 to trip overspeed #1 and overspeed #2.
 13720 When pump #2 is chilled, close L-219.
 13728 Close H-9.
 13730 DDP tape on.
 13736 Open L-119 to the following stem positions. Steady state conditions are at:

<u>TIME</u>	<u>POSITION</u>
13794	100%
13813	80%
13830	60%
13844	40%
13856	30%
13866	25%
13877	20%
13888	15%
13896	10%

13901 Close L-119.
 13903 Open L-219 to the following stem positions. Steady state conditions are at:

<u>TIME</u>	<u>POSITION</u>
13955	100%
13972	80%
13986	60%
14001	40%
14012	30%
14025	25%
14036	20%
14052	15%

14057 Close L-219.
 14066 Open H-9.
 14070 DDP tape off.

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14074

Report the following data:

<u>Dewar Level:</u>	<u>1</u>	<u>2</u>
Reflectometer	49,000 lbs	280,000 lbs
Staircase	43,500 lbs	261,000 lbs
0% Temperature	39.5°R	37.5°R
10% Temperature	39.6°R	37.8°R

QF-20 is 2540 psig.
 QF-30 is 2090 psig.
 QF-40 is 1600 psig.
 QF-50 is 1630 psig.

Hot water tank level: 215,000 gallons.

14605

Set shutdown position for L-119 and L-219 to 22%.

III. GREEN RUN; PUMP #1

14911 Set the overspeed trip pot to 535 divisions (20,000 rpm).
 14920 Activate the H-68 Hold Close.
 14928 Select Dewar 2 pressure feedback.
 14932 Close L-153.
 14949 Open L-62.
 14957 In L-53 Pressure Control, establish 50 psig in Dewar 2.
 14967 Set the Pump #1 Q/N pot to 170 divisions (Q/N = 0.20).
 14973 Activate HP-870, HP-811, LP-61, Overspeed #1, Overspeed #2, JP-101/JP-201, and Loss of Critical Power to the shutdown chain.
 15003 Switch L-119, H-11, H-65, H-66, H-180/H-53, H-101, and H-142 to Normal.
 15031 Close H-163.
 15035 Data tapes on.
 15051 Use L-119 to chill pump #1.
 15131 In L-119 Q/N Control, set the pot to 275 divisions (Q/N = 0.25).
 15141 Use H-101 to chill HT-101.
 15157 Use L-191 to chill LT-191.
 15232 Set L-30 to 64% (Q/N = 0.3).
 15242 Use L-219 to windmill pump #2 at 1,000 rpm.
 15260 Open the water bypass valves.
 15290 Switch H-11 to ΔP Control.
 15294 Open W-11.
 15313 Adjust WP-1 to establish 800 gpm at WF-12.

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15321	Open L-161.
15346	Open L-92.
15368	Open H-66.
15381	Close H-180.
15394	In H-53 Pressure Control, establish 130 psig at HP-60.
15409	Close H-101.
15415	In H-65 Position Control, establish 5,000 rpm.
15452	5,000 rpm set.
15455	Switch H-65 to Speed Control. Maintain H-68 in Position Control and close.
15466	In H-65 Speed Control, establish 13,000 rpm.
15482	Activate HT-811; Q/N pump #1.
15543	18,000 rpm set.
15548	HP-60 exceeds 300 psig; close L-251 and H-53.
15566	Demand zero speed.
15577	Switch H-65 to Position Control and close.
15590	Begin the following normal shutdown procedures.
15593	Bypass HT-811 and Q/N Pump #1.
15598	Close L-92.
15622	Open H-180.
15626	Data tapes OFF.
15629	Close H-66.
15633	Set H-101 to minimum setting.
15637	Close L-161.
15647	Close W-11.
15653	Switch H-11 to Position Control and close.
15662	Close W-211, W-221, and W-231.
15665	Switch L-119 to Position Control and close.
15676	Close L-219.
15680	Switch L-53 to Position Control and close.
15694	Close L-62.
15699	Open L-153.
15736	Open L-251.
15743	Bypass all the inputs to the shutdown chain.
15754	Switch the shutdown valves to Override.
15762	Bypass H-68 Hold Close.

IV. GREEN RUN; PUMP #2

15802	Set the overspeed trip pot to 535 divisions (20,000 rpm).
15815	Activate the H-65 Hold Close.
15819	Select Dewar 2 Pressure Feedback.
15822	Close L-153.
15841	Open L-62.
15845	In L-53 Pressure Control, establish 70 psig in Dewar 2.
15851	Set the Pump #2 Q/N pot to 170 divisions (Q/N - 0.20).
15856	Activate the inputs to the shutdown chain.

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15889	Switch the shutdown valves to Normal.
15912	Use L-219 to chill Pump #2.
15941	In L-219 Q/N Control, set the pot to 275 divisions (Q/N = 0.25).
15948	Use H-101 to chill HT-101.
15954	Use L-191 to chill LT-191.
15988	Set L-30 to 65% (Q/N = 0.30).
15992	Use L-119 to windmill Pump #1 at 500 rpm.
16003	Open the water bypass valves.
16048	Switch H-11 to ΔP Control.
16051	Open W-11.
16056	Adjust WP-1 to establish 800 gpm at WF-12.
16059	Open L-161.
16083	Open L-92.
16096	Open H-69.
16100	Close H-180.
16101	Data tapes ON.
16108	In H-53 Pressure Control, establish 130 psig at HP-60.
16117	Activate HT-911 and Q/N Pump #1.
16127	Close H-101.
16133	In H-68 Position Control, establish 5,000 rpm.
16172	5,000 rpm set.
16177	Switch H-68 to Speed Control. Maintain H-65 in Position Control and close.
16193	In H-68 Speed Control, establish 18,000 rpm.
16233	18,000 rpm set.
16238	HP-60 exceeds 300 psig. Close L-251 and H-53.
16250	On TC command, demand zero speed.
16270	Switch H-68 to Position Control and close.
16277	Begin normal shutdown procedure (see page 5).
16315	Data tapes OFF.
16552	Begin secure for a re-entry to check on LH ₂ leaks.
23959	Begin re-chilling the cryogenic lines.

V. L-119 CALIBRATION AND PUMP #1 FREQUENCY RESPONSE MEASUREMENTS

24888	Set the overspeed trip pot to 635 divisions (24,000 rpm).
24899	Close L-153.
24918	Open L-62.
24925	In L-53 Pressure Control, establish 70 psig in Dewar 2.
24938	Set the Pump #1 Q/N pot to 170 divisions (Q/N = 0.2).
24944	Activate the inputs to the shutdown chain.
24972	Switch the shutdown valves to Normal.
25007	Patch the oscillator to the H-65 Speed Loop.
25055	Set the oscillator amplitude to 0.75 volt.
25060	Set the step to +0.75 volt.
25071	Patch the step.
25078	Use L-119 to chill Pump #1.

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25117	Set L-30 to 65% ($Q/N = 0.30$).
25125	In L-119 Q/N Control, set the pot to 275 divisions ($Q/N = 0.25$).
25136	Use H-101 to chill HT-101.
25138	Use L-191 to chill IT-191.
25179	Use L-219 to windmill Pump #2 at 1,000 rpm.
25189	Open the water bypass valves.
25201	Open L-92.
25213	Open W-11.
25219	Adjust WP-1 to establish 800 gpm at WF-12.
25222	Open L-161.
25252	Open H-66.
25255	Data tapes ON.
25256	Close H-180.
25260	Switch H-11 to ΔP Control.
25265	In H-53 Pressure Control, establish 130 psig at HP-60.
25275	Activate HT-811 and Q/N Pump #1.
25281	Close H-101.
25290	In H-65 Speed Control, establish 18,000 rpm. Maintain H-68 in Position Control and close.
25330	18,000 rpm set.
25335	HP-60 exceeds 300 psig. Close L-251 and H-53.
25339	Proceed with the frequency response measurements on the H-65 Speed Loop.
25463	Unpatch the oscillator from the H-65 Speed Loop.
25470	Patch the oscillator to the Pressure Loop.
25482	Set the oscillator amplitude to 1.0 volt.
25486	Set the step to +1.0 volt.
25512	Switch H-65 to Pressure Control.
25518	Proceed with the frequency response measurement on the Pressure Loop.
25625	In H-68 Position Control, slowly open H-68 until the H-68 and H-65 stem positions are equal.
25678	Switch H-68 to Pressure Control.
25683	Proceed with the frequency response measurement on the Pressure Loop.
25785	In Pressure Control, establish 530 psig at HP-841.
25818	Using the L-119 Q/N pot, increase the Q/N to 0.35.
25887	Slowly close L-30.
25941	L-30 indicates 48%.
25985	L-30 indicates 45%.
26011	L-30 indicates 62%.
26017	Demand zero pressure.
26069	Switch H-65 and H-68 to Position Control and close.
26077	Begin normal shutdown procedures.
26100	Data tapes OFF.
26387	Data Hold.

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VI. PUMP #2 FREQUENCY RESPONSE MEASUREMENT

28100	Set the overspeed trip pot to 535 divisions (20,000 rpm).
28108	Close L-153.
28112	Open L-62.
28119	In L-53 Pressure Control, establish 70 psig in Dewar 2.
28171	Set the Pump #2 Q/N pot to 170 divisions (Q/N = 0.2).
28175	Activate the inputs to the shutdown chain.
28224	Bottle #7 added to hydrogen header.
28309	Switch the shutdown valves to Normal. QP-30 = 2950 psig.
28337	In L-53 Pressure Control, establish 70 psig in Dewar 2.
28369	Patch the oscillator to the H-68 Speed Loop.
28374	Set the oscillator amplitude to 0.75 volt.
28384	Set the step to +0.75 volt.
28389	Patch the step.
28395	Activate the H-65 Hold Close.
28400	Use L-219 to chill Pump #2.
28498	In L-219 Q/N Control, set the pot to 275 divisions (Q/N = 0.25).
28512	Use H-101 to chill HT-101.
28524	Use L-191 to chill LT-191.
28555	Set L-30 to 64% (Q/N = 0.3).
28562	Use L-119 to windmill Pump #1 at 1,000 rpm.
28604	Open the water bypass valves.
28628	Open W-11.
28647	Adjust WP-1 to establish 800 gpm at WF-12.
28660	Open L-161.
28684	Open L-92.
28700	Open H-69.
28710	Data Tapes ON.
28710	Close H-180.
28727	Switch H-11 to ΔP Control.
28734	In H-53 Pressure Control, establish 130 psig at HP-60.
28743	Activate HT-911 and Q/N Pump #2.
28747	Close H-101.
28756	In H-68 Speed Control, establish 18,000 rpm. Maintain H-65 in Position Control and close.
28805	When HP-60 exceeds 300 psig, close L-251 and H-53.
28809	18,000 rpm set.
28818	Proceed with the frequency response measurements.
28935	Demand zero speed.
28975	Switch H-68 to Position Control and close.
28978	Begin normal shutdown procedure.
29000	Data tapes OFF.

APPENDIX A

VII. DUAL PUMP MAPPING AND FREQUENCY RESPONSE MEASUREMENTS

32064	Set the overspeed trip pot to 635 divisions (24,000 rpm).
32081	Open L-62.
32090	In L-53 Pressure Control, establish 70 psig in Dewar 2.
32098	Set the Q/N pots to 65 divisions ($Q/N = 0.15$).
32114	Activate the inputs to the shutdown chain.
32144	Switch the shutdown valves to Normal.
32178	Patch the oscillator to the Pressure Loop.
32188	Set the oscillator amplitude to 1.0 volt.
32192	Set the step to +1.0 volt.
32197	Patch the step.
32203	Use L-119 to chill Pump #1.
32247	Use L-219 to chill Pump #2.
32276	Use E-101 to chill HT-101.
32279	The pumps are chilled; set the Q/N pots to 85 divisions ($Q/N = 0.16$).
32282	Use I-191 to chill LIT-191.
32316	Open the water bypass valves.
32319	Set L-30 to 90% ($Q/N = 0.35$).
32345	Open W-11 and W-31.
32353	Adjust WP-1 to establish 1700 gpm at WF-512.
32363	Open L-161.
32379	Open L-92.
32392	Switch H-11 and H-31 to ΔP Control.
32400	Data tapes ON.
32401	In H-53 Pressure Control, establish 130 psig at HP-60.
32405	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
32410	Close H-101.
32414	In Speed Control, establish 18,000 rpm.
32489	18,000 rpm set.
32493	Use L-30 to establish $Q/N = 0.35$.
32500	Decrease speed to 10,000 rpm.
32518	10,000 rpm set. Start a 10-second timer.
32532	Use L-30 to establish $Q/N = 0.35$.
32558	$Q/N = 0.35$. Start a 10-second timer.
32573	Using L-30, decrease Q/N to 0.25.
32615	$Q/N = 0.25$. Start a 10-second timer.
32635	Using L-30, slowly decrease Q/N to indication of instability or minimum $Q/N = 0.16$.
32683	Q/N unstable. $Q/N = .185$.
32689	Using L-30, increase Q/N to 0.35.
32734	In Speed Control, establish 14,500 rpm.
32781	14,500 rpm set. Start a 10-second timer.
32789	Close L-251.
32810	Using L-30, decrease Q/N to 0.25.

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32849 Q/N = 0.25. Start a 10-second timer.
 32868 Using L-30, slowly decrease Q/N to indication of
 instability or minimum Q/N = 0.16.
 32916 Q/N unstable. Q/N = .180.
 32920 Using L-30, increase Q/N to 0.35.
 32950 In Speed Control, establish 18,000 rpm at a Q/N = 0.35.
 32980 18,000 rpm set. Readjust Q/N to 0.35.
 32998 Start a 10-second timer.
 33016 Using L-30, decrease Q/N to 0.25.
 33054 Q/N = 0.25. Start a 10-second timer.
 33068 Using L-30, slowly decrease Q/N to 0.2.
 33100 Q/N = 0.20. Start a 10-second timer.
 33115 Using L-30, slowly increase Q/N to 0.25.
 33134 In Speed Control, establish 22,000 rpm at Q/N = 0.25.
 33164 22,000 rpm set. Start a 10-second timer.
 33179 Using L-30, slowly decrease Q/N to 0.2.
 33215 Q/N = 0.20. Start a 10-second timer.
 33233 Using L-30, increase Q/N to 0.25.
 33253 Select Pressure Control.
 33265 In Pressure Control, establish 520 psig pump discharge
 pressure.
 33300 Using L-30, decrease flow rate to 40 lbs/sec (Pump #1).
 33329 Proceed with the frequency response measurement.
 33333 Step in.
 33393 Add Bottle #7 to hydrogen header.
 33440 Switch to Speed Control.
 33447 Using L-30, increase Q/N to 0.3.
 33478 Decrease speed to 14,500 rpm.
 33497 14,500 rpm set. Hold until additional GH_2 Bottle is on
 line.
 33562 In H-53 Pressure Control, establish 300 psig at HP-60.
 33582 Switch H-11 and H-31 to Position Control and close.
 33586 Close H-9.
 33592 Open H-101.
 33597 Using L-30, increase Q/N to 0.45.
 33629 L-30 is 100% open. Q/N = 0.385.
 33667 Decrease speed to 10,000 rpm.
 33683 10,000 rpm set.
 33707 Demand zero speed.
 33718 Switch H-65 and H-68 to Position Control and close.
 33721 Begin normal shutdown procedure.
 33750 H-65 has remained open.
 33751 Data tapes OFF.
 34000 Begin secure for re-entry.
 37572 Begin LH_2 transfer from Dewar 1 to Dewar 2.
 39880 LH_2 transfer complete.

APPENDIX A

VIII. SECOND PORTION OF THE DUAL PUMP EXPERIMENTS (H-65 NOT USABLE)

40081	Activate H-65 Hold Closed.
40094	Set the overspeed trip pot to 535 divisions (20,000 rpm).
40113	Open L-62.
40128	In L-53 Pressure Control, establish 70 psig in Dewar 2.
40137	Set the Q/N pots to 170 divisions (Q/N = 0.20).
40150	Activate the inputs to the shutdown chain.
40178	Switch the shutdown valves to Normal.
40214	Use I-119 to chill Pump #1.
40268	Use I-219 to chill Pump #2.
40313	The pumps are chilled; set the Q/N pots to 275 divisions (Q/N = 0.25).
40315	Use H-101 to chill HT-101.
40318	Use I-191 to chill LT-191.
40351	Open the water bypass valves.
40381	Set I-30 to 85% (Q/N = 0.30).
40388	Open W-11 and W-31.
40393	Adjust WP-1 to establish 1700 gpm at WF-512.
40407	Open L-161.
40423	Open L-92.
40434	Open H-66 and H-69.
40445	Close H-180.
40450	Data tapes ON.
40455	Switch H-11 and H-31 to ΔP Control.
40465	Close H-101.
40480	In H-53 Pressure Control, establish 130 psig at HP-60.
40523	In H-68 Pressure Control, establish 410 psig at HP-841 and IP-941.
40569	Activate HT-811, HT-911, and Q/N Pumps 1 and 2.
40594	HP-841 and HP-941 indicate 410 psig.
40605	Adjust Q/N to 0.3.
40611	Q/N = 0.3.
40636	Push the Emergency Shutdown Button.
40638	Begin Emergency Shutdown Procedure.
40639	Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
40648	Reset the Emergency Shutdown Chain.
40652	Set H-101 to a minimum setting.
40654	Switch H-11 and H-31 to Position Control and close.
40658	Close H-142.
40667	Close L-92.
40670	Data tapes OFF.
40691	Close L-161.
40720	Close W-11, W-31, W-211, W-221, and W-231.
40737	Switch L-53 to Position Control and close.
40743	Close L-62.

APPENDIX A

41345	Set the step to +1.2 volts.
41350	Computer out of order.
41364	Proceed with the step (-2.5 Cv).
41375	Using L-30, increase HF-850 to 60 lbs/sec.
41381	Set the step to -1.7 volts.
41391	60 lbs/sec set.
41398	Proceed with the step (+5 Cv).
41404	Set the step to +1.4 volts.
41419	Proceed with the step (-2.5 Cv).
41426	Set the step to +2.5 volts.
41437	Proceed with the step (-5 Cv).
41446	Using L-30, increase HF-850 to 80 lbs/sec.
41452	Set the step to +1.7 volts.
41466	80 lbs/sec set.
41477	Proceed with the step (-5 Cv).
41483	Set the step to -1.7 volts.
41497	Proceed with the step (+5 Cv).
41501	Shutdown trip on Overspeed #1.
41503	Begin Emergency Shutdown procedures.
41530	Data tapes OFF.
42143	Begin startup for continuation of run phase.
42210	HOLD - LH ₂ Leak at L-31.
42686	Begin secure phase.

X. SHUTDOWN PHASE

APPENDIX B

CHRONOLOGY FOR EXPERIMENTAL PLAN 2

APPENDIX B

CHRONOLOGY

AGC DUAL MODE PUMP TEST SERIES

EXPERIMENTAL PLAN 2

MARCH 5, 1970

I. PRE-OPERATIONAL PHASE

- A. Setup Checklists Received and Approved; Status Board Cleared.
- B. Report on Test Cell Personnel.
- C. Check the Control Room Net.
- D. Required Systems Switched to CP Control.
- E. Exercise the Valves in the Inerted Areas.
- F. Check the Shutdown Chain.
- G. Check Mini-Chain #2.
- H. Inerting the Test Cell.

04243	Turn off the fans.
04248	Close Q-113.
04254	Pressurize the room inerting header (Bottles #13, 14, 15, and 16). QP-50 is 2250 psig.
04324	Begin inerting the test cell. Open G-451/G-452.

I. Exercise the Remaining Valves.

J. Voltage Calibration.

05391-05491 Calibration interval.

K. Clear the Remote Team from the Test Cell Area.

II. PRESSURIZATION AND WATER SYSTEM SETUP

A. Pressurize the Headers.

06561	Open L-153, L-50, L-251, and H-50.
06589	Open G-50.
06593	Open W-50.
06601	Close Q-150.
06607	Close all the bottle purge valves.
06620	Pressurize the helium header (Bottles #1 and #2). QP-20 is 3000 psig.
06658	Pressurize the hydrogen header (Bottles #3, 4, 5, 6, 7, and 8). QP-30 is 3240 psig.

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06734 Pressurize the nitrogen header (Bottles #9, 10, 11, or 12). QP-40 is 1830 psig.

B. Set Up the Water System.

06947 Close W-153.
 06952 Open W-1, W-211, W-221, W-231, W-11, W-31, W-45, W-49, and W-100.
 07065 Use W-53 to establish 50 psig at WP-1.
 07138 Turn on the water flow meter power.
 07153 Close W-11, W-31, W-211, W-221, and W-231.
 07178 Report the following data:

<u>Dewar Level:</u>	<u>1</u>	<u>2</u>
Reflectometer	55 k	297 k
Staircase	101.5 k	290 k
0% Temperature	36.5°R	37.5°R
10% Temperature	36.5°R	37.5°R

QP-20 is 3000 psig.
 QP-30 is 3240 psig.
 QP-40 is 1670 psig.
 QP-50 is 1750 psig.

Hot Water Tank Level: 215 k gallons.

III. CHILLDOWN, SPEED INPUT CHECKS, AND WARM LINE STARTUP

07561 Set the overspeed trip pot to 65 divisions.
 07567 Bypass all the inputs to the shutdown chain.
 07571 Switch the shutdown valves to override.
 07575 Open H-101.
 07579 Close L-491.
 07586 Open L-191.
 07601 Close L-261, L-262, and L-153.
 07631 Open L-62.
 07637 Select Dewar 2 pressure feedback.
 07640 Close L-403.
 07645 Open L-2.
 07657 Open L-3.
 07679 Open L-31.
 07681 Data tapes on.
 07689 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 07753 The pump is chilled; use L-119 to trip overspeed #1 and overspeed #2.
 07849 The pump is chilled; use L-219 to trip overspeed #1 and overspeed #2.

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07861 Set the overspeed trip pot to 455 divisions (17,000 rpm).

07865 Set the Q/N pots to 170 divisions (Q/N = 0.20).

07877 Activate HP-811, HP-870, HP-970, HP-911, Overspeed #1, Overspeed #2, JP-101/JP-201, and Loss of Critical Power to the shutdown chain.

07908 Switch L-119, L-219, H-65, H-180/H-53, H-64, H-67, H-68, and L-2 to Normal.

07935 Open the water bypass valves.

07938 Close H-163.

07962 Open L-105.

08039 Open L-119 and L-219 to 15%.

08050 LT-5 is chilled; close L-105.

08076 Use L-30 to chill LF-29 and set to minimum setting.

08263 Close L-119 and L-219.

08271 In Q/N Control, set the Q/N pots to 215 divisions (Q/N = 0.22).

08293 Open H-64 and H-67.

08300 Close H-180.

08308 In H-53 Pressure Control, establish 200 psig at HP-60.

08391 Activate HT-811, HT-911, Q/N #1, and Q/N #2.

08329 Set L-30 to 72% (Q/N = 0.25).

08381 In Pressure Control, establish 15,000 rpm.

08436 15,000 rpm set.

08450 Demand zero pressure.

08465 Switch H-65 and H-68 to Position Control and close. (Begin normal shutdown procedure.)

08468 Bypass HT-811, HT-911, Q/N #1, and Q/N #2.

08471 Let L-30 to a minimum.

08475 Switch H-53 to Position Control and close.

08478 Open H-180.

08484 Close H-64 and H-67.

08488 Close the water bypass valves.

08495 Switch L-119 and L-219 to Position Control and close.

08501 Bypass all the inputs to the shutdown chain.

08509 Switch the shutdown valves to override.

08648 Open H-9.

08657 Use H-101 to chill HT-101.

08662 Close L-31.

08675 Open L-30.

08695 Open L-32.

08722 Open L-91.

08730 Use L-191 to chill LT-191.

08844 LT-191 is 100°R. Close L-191; open L-92.

08918 LT-91 is chilled; close L-92.

08943 Start a 600-second timer.

08946 Switch L-53 to Position Control and close.

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08952	Close L-62.
08959	Open L-153.
08990	Data tapes OFF.

IV. DUAL PUMP STABILITY TEST

A. Dual Pump Stability Test (Shutdown Due to LH₂ Leak).

09755	Set the overspeed trip pot to 657 divisions (25,000 rpm).
09764	Close L-153.
09780	Open L-62.
09786	In L-53 Pressure Control, establish 70 psig in Dewar 2.
09796	Set the Q/N pot to 107 divisions (Q/N = 0.17).
09807	Activate the inputs to the shutdown chain.
09855	Switch the shutdown valves to normal.
09895	Set the step to -0.46 volt.
09900	Patch the step to L-30.
09917	Use L-119 to chill pump #1.
09919	Use L-219 to chill pump #2.
10051	The pumps are chilled; set the Q/N pot to 150 divisions (Q/N = 0.19).
10055	Use H-101 to chill HT-101.
10059	Use L-191 to chill HT-191.
10170	Set L-30 to 78% (Q/N = 0.25).
10180	Open the water bypass valves.
10223	Hold for computer problem.
10368	Open W-11 and W-31.
10388	Adjust WP-1 to establish 1700 gpm at WF-512.
10392	Open L-161.
10409	Open L-92.
10425	Open H-64 and H-67.
10439	Close H-180.
10440	Switch H-11 and H-31 to ΔP Control (ΔP = 30 psid).
10441	Data tapes ON.
10442	In H-53 Pressure Control, establish 130 psig at HP-60.
10498	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
10464	In Pressure Control, establish a pump discharge pressure of 520 psig.
10524	When HP-60 exceeds 300 psig, close L-251 and H-53.
10538	Using Position Trim, slowly close H-68.
10654	Demand zero speed.
10692	Close H-65 and H-68.
10695	Begin normal shutdown procedure.
10900	Hold for re-entry.

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B. Dual Pump Stability Test.

13909	Set the Q/N pot to 107 divisions ($Q/N = 0.17$).
13927	Activate the inputs to the shutdown chain.
13951	Switch the shutdown valves to normal.
13985	Set the step to -0.46 volt.
13990	Patch the step to L-30.
13998	Use L-119 to chill pump #1.
14000	Use L-219 to chill pump #2.
14137	The pumps are chilled; set the Q/N pot to 150 divisions ($Q/N = 0.19$).
14146	Use H-101 to chill HT-101.
14148	Use L-191 to chill LT-191.
14233	Set L-30 to 85% ($Q/N = 0.30$).
14240	Open the water bypass valves.
14264	Open W-11 and W-31.
14291	Adjust WP-1 to establish 1700 gpm at WF-512.
14293	Open L-161.
14311	Open L-92.
14326	Open H-64 and H-67.
14333	Close H-180.
14340	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
14346	In H-53 Pressure Control, establish 130 psig at HP-60.
14350	Data tapes ON.
14360	Close H-101.
14365	In Pressure Control, establish a pump discharge pressure of 520 psig.
14384	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
14414	When HP-60 exceeds 300 psig, close L-251 and H-53.
14449	520 psig set.
14461	Using L-30, decrease HF-850 and HF-750 to 40 lbs/sec.
14497	40 lbs/sec set.
14504	Proceed with the step (+2.5 Cv).
14511	Set the step to -0.93 volt.
14521	Proceed with the step (+5 Cv).
14526	Set the step to +0.46 volt.
14535	Proceed with the step (-2.5 Cv).
14542	Unpatch the step from L-30.
14547	Patch the compensator to L-219.
14554	Switch L-219 to Position Control.
14561	Open L-219 to 10%.
14566	Set the step to -0.45 volt.
14581	Proceed with the momentary step (0.5 in^2).
14586	Set the step to -0.75 volt.
14633	Proceed with the momentary step (1.0 in^2).
14645	Switch L-219 to Q/N Control.
14655	Set the L-219 Q/N pot to 150 divisions ($Q/N = 0.19$).
14664	Using L-30, increase Q/N to 0.25.

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14686 In Pressure Control, decrease pump discharge pressure to 350 psig.
 14726 350 psig set.
 14734 Using L-30, decrease HF-850 and HF-950 to 32 lbs/sec.
 14738 Set the step to -0.75 volt.
 14753 32 lbs/sec set.
 14761 Switch L-219 to Position Control.
 14771 Open L-219 to 10%.
 14788 Proceed with the momentary step (1 in^2).
 14793 Switch L-219 to Q/N Control.
 14805 Set the L-219 Q/N pot to 150 divisions ($Q/N = 0.19$).
 14813 Unpatch the compensator from L-219.
 14820 Patch the step to L-30.
 14828 Set the step to -0.93 volt.
 14836 Proceed with the step ($+5 \text{ Cv}$).
 14841 Set the step to $+0.46$ volt.
 14851 Proceed with the step (-2.5 Cv).
 14856 Using L-30, increase Q/N to 0.25.
 14874 In Pressure Control, establish 620 psig pump discharge pressure.
 14879 Set the step to -0.93 volt.
 14923 Using L-30, decrease HF-850 and HF-950 to 45 lbs/sec.
 14942 45 lbs/sec set.
 14947 Proceed with the step ($+5 \text{ Cv}$).
 14953 Set the step to $+0.46$ volt.
 14961 Proceed with the step (-2.5 Cv).
 14966 Unpatch the step from L-30.
 14972 Patch the compensator to L-219.
 14979 Switch L-219 to Position Control.
 14983 Open L-219 to 10%.
 14991 Set the step to -0.75 volt.
 15001 Proceed with the momentary step (1 in^2).
 15005 Switch L-219 to Q/N Control.
 15013 Set the L-219 Q/N pot to 150 divisions ($Q/N = 0.19$).
 15021 Using L-30, increase Q/N to 0.25.
 15033 Unpatch the compensator from L-219.
 15038 In Pressure Control, establish 520 psig pump discharge pressure.
 15043 Set the step to $+0.46$ volt.
 15059 520 psig set.
 15061 Patch the step to L-30.
 15069 Using L-30, increase HF-850 and HF-950 to 60 lbs/sec.
 15084 60 lbs/sec set.
 15090 Proceed with the step (-2.5 Cv).
 15095 Set the step to $+0.93$ volt.
 15103 Proceed with the step (-5 Cv).
 15108 Set the step to -0.46 volt.
 15116 Proceed with the step ($+2.5 \text{ Cv}$).
 15120 Unpatch the step from L-30.
 15124 Patch the compensator to L-219.
 15128 Switch L-219 to Position Control.

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15135	Open L-219 to 10%.
15138	Set the step to -0.75 volt.
15148	Proceed with the momentary step (1 in^2).
15151	Unpatch the compensator.
15155	Switch L-219 to Q/N Control.
15162	Set the L-219 pot to 150 divisions ($Q/N = 0.19$).
15173	Switch H-53 to Pressure Control.
15178	Switch H-11 and H-31 to Position Control and close.
15190	Close H-9.
15196	Open H-101.
15202	In H-53 Pressure Control, maintain 400 psig at HP-60.
15205	Open W-311 to 50%.
15210	Set the step to $+0.05$ volt.
15218	Close W-11 and W-31.
15225	Use W-311 to maintain 35 psig at WF-45.
15237	Patch the step to the H-65 and H-68 Position inputs.
15248	Using L-30, establish 60 lbs/sec at HF-850 and HF-950.
15259	Switch H-65 and H-68 Position Control.
15269	Proceed with the step (-0.5%).
15275	Set the step to $+0.1$ volt.
15282	Proceed with the step (-1%).
15287	Set the step to -0.05 volt.
15293	Proceed with the step ($+0.5\%$).
15335	Set the step to $+0.1$ volt.
15345	Proceed with the step.
15350	Set the step to $+0.2$ volt.
15359	Proceed with the step.
15365	Set the step to -0.1 volt.
15374	Proceed with the step.
15382	Switch to Pressure Control.
15387	Using L-30, establish 40 lbs/sec at HF-850 and HF-950.
15405	Set the step to -0.1 volt.
15419	Switch H-65 and H-68 to Position Control.
15425	Proceed with the step ($+1.0\%$).
15430	Set the step to -0.2 volt.
15436	Proceed with the step ($+2\%$).
15441	Set the step to $+0.1$ volt.
15446	Proceed with the step (-1.0%).
15451	Switch to Pressure Control.
15455	Using L-30, establish $Q/N = 0.25$.
15476	In Pressure Control, establish 620 psig pump discharge pressure.
15496	Using L-30, establish 45 lbs/sec at HF-850 and HF-950.
15506	Set the step to -0.2 volt.
15512	Switch H-65 and H-68 to Position Control.
15521	Proceed with the step ($+2\%$).
15526	Set the step to $+0.1$ volt.

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15537	Proceed with the step (-1.0%).
15536	Switch to Pressure Control.
15543	Using L-30, establish a Q/N = 0.25.
15552	In Pressure Control, decrease pump discharge pressure to 350 psig.
15577	350 psig set.
15579	Using L-30, establish 32 lbs/sec at HF-850 and HF-950.
15584	Set the step to -0.2 volt.
15593	Switch H-65 and H-68 to Position Control.
15599	Proceed with the step (+2%).
15604	Set the step to +0.1 volt.
15610	Proceed with the step (-1.0%).
15615	Switch to Pressure Control.
15620	Using L-30, establish a Q/N = 0.25.
15632	Demand zero pressure.
15648	Switch H-65 and H-68 to Position Control and Close.
15652	Begin normal shutdown procedure.
15680	Data tapes OFF.

V. SIMULATED TURBINE DRIVE FAILURE TEST

19300	Set the overspeed trip pot to 608 divisions (23,000 rpm).
19306	Close L-153.
19321	Open H-62.
19326	In L-53 Pressure Control, establish 70 psig in Dewar 2.
19332	Set the Q/N pots to 107 divisions (Q/N = 0.17).
19336	Activate the inputs to the shutdown chain.
19365	Switch the shutdown valves to Normal.
19396	Set the step to +0.2 volt.
19405	Patch the step.
19414	Patch the positive H-68 ramp.
19429	Set the H-68 ramp rate to 10%/sec.
19435	Patch the step to H-68 Position input.
19440	Use L-119 to chill pump #1.
19442	Use L-219 to chill pump #2.
19507	The pumps are chilled; set the Q/N pots to 150 divisions (Q/N = 0.19).
19510	Use H-101 to chill HT-101.
19512	Use L-191 to chill IT-191.
19518	Set L-30 to 78% (Q/N = 0.25).
19573	Open the water bypass valves.
19596	Open W-11 and W-31.
19600	Adjust WP-1 to establish 1700 gpm at WF-512.
19617	Open L-161.
19635	Open L-92.
19648	Open H-64 and H-67.

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19653	Close H-180.
19658	Switch H-11 and H-31 to ΔP Control.
19664	In H-53 Pressure Control, establish 130 psig at HP-60.
19675	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
19679	130 psig set.
19682	Close H-101.
19689	In Pressure Control, establish 520 psig at HP-841 and HP-941.
19738	HP-60 exceeds 300 psig; close L-251 and H-53.
19756	Using L-30, establish 40 lbs/sec at HF-850 and HF-950.
19783	Proceed with the step (-2%).
19788	Set the step to +0.4 volt.
19794	Proceed with the step (-4%).
19799	Set the step to +0.6 volt.
19806	Proceed with the step (-5%).
19811	Set the step to -0.6 volt.
19820	Proceed with the step (+6%).
19832	Using H-68 ramp, proceed with the 10%/sec H-68 closed ramp.
19838	Ramp out.
19849	H-65 and H-68 stem positions are equal.
19852	Set the H-68 ramp rate to 20%/sec.
19866	Using H-68 ramp, proceed with the 20%/sec H-68 closed ramp.
19869	Ramp out.
19876	H-65 and H-68 stem positions are equal.
19879	Set the H-68 ramp rate to 40%/sec.
19896	Using H-68 ramp, proceed with the 40%/sec H-68 closed ramp.
19898	Shutdown trip on Q/N #2.
19900	Begin emergency shutdown procedures.
19940	Data tapes OFF.

VI. SHUTDOWN PHASE

APPENDIX C

CHRONOLOGY FOR EXPERIMENTAL PLAN 3

CHRONOLOGY FOR AGC DUAL MODE PUMP TEST SERIES

EXPERIMENTAL PLAN 3

March 19, 1970

I. PRE-OPERATIONAL PHASE

- A. Setup Checklists Received and Approved; Status Board Cleared from the Test Cell.
- B. Report on Test Cell Personnel.
- C. Check the Control Room Net.
- D. Required Systems Switched to CP Control.
- E. Exercise the Valves in the Inerted Areas.
- F. Check the Shutdown Chain.
- G. Inerting the Test Cell.

04328 Turn off the fans.
04370 Close Q-113.
04377 Pressurize the room inerting header (Bottle 13).
QP-50 indicates 1940 psig.
04438 Begin inerting the test cell. Open G-451/G-452.

- H. Exercise the Remaining Valves.

- I. Perform a Voltage Calibration.

05500-05600 Calibration interval.

- J. Clear the Remote Team From the Test Cell Area.

II. PRESSURIZATION AND WATER SYSTEM SETUP

- A. Pressurize the Headers.

06312 Open L-153, L-50, L-251, and H-50.
06335 Open G-50.
06340 Open W-50.
06347 Close Q-150.
06359 Close all the bottle purge valves.
06370 Pressurize the helium header (Bottles 1 and 2).
QP-20 indicates 1830 psig.
06410 Pressurize the hydrogen header (Bottles 3, 4, 5, 6,
7, and 8). QP-30 indicates 3100 psig.
06680 Pressurize the nitrogen header (Bottle 11). QP-40
indicates 3050 psig.

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B. Setup of the Water System.

06743 Close W-153.
 06748 Open W-1, W-211, W-221, W-231, W-11, W-31, W-45, W-49,
 and W-100.
 06835 Use W-53 to establish 50 psig at WP-1.
 06880 Turn on the water flow meter power.
 06886 Close W-11, W-31, W-211, W-221, and W-231.
 06910 Report the following data:

<u>Dewar Level</u>	<u>1</u>	<u>2</u>
Reflectometer	55K	300K
Staircase	43.5K	300K
0% Temperature	36.5°R	37.0°R
10% Temperature	36.5°R	37.1°R

QP-20 indicates 1830 psig.
 QP-30 indicates 3100 psig.
 QP-40 indicates 2800 psig.
 QP-50 indicates 1480 psig.

Hot Water Tank Level: 215 K gallons.

III. CHILLDOWN, SPEED INPUT CHECKS, AND UNEQUAL DENSITY STARTUP

07078 Set the overspeed trip pot to 65 divisions.
 07085 Bypass all the inputs to the shutdown chain.
 07090 Switch the shutdown valves to override.
 07094 Open H-101.
 07099 Close L-491.
 07103 Open L-191 and L-91.
 07125 Close L-261, L-262, and L-153.
 07150 Open L-62.
 07155 Select Dewar 2 pressure feedback.
 07160 Close L-403.
 07165 Open L-2.
 07170 Data Tapes ON.
 07176 Open L-3.
 07194 Open L-31.
 07200 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 07234 Use L-119 to trip Overspeed #1 and Overspeed #2.
 07333 Use L-219 to trip Overspeed #1 and Overspeed #2.
 07419 Set the overspeed trip pot to 455 divisions (17,000 rpm).
 07426 Set the Q/N pots to 170 divisions (Q/N = 0.20).
 07442 Activate HP-811, HP-870, HP-970, HP-911, Overspeed #1,
 Overspeed #2, JP-101/JP-201, and Loss of Critical Power
 to the Shutdown Chain.
 07468 Switch L-119, L-219, H-65, H-180/H-53, H-66, H-69, H-68,
 and L-2 to Normal.

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07490	Open the water bypass valves.
07514	Close H-163.
07533	Open L-105.
07649	Close L-105.
07655	Use L-219 to chill Pump #2.
08141	Open L-119 to 15%.
08187	Use L-30 to chill Pump #1 and LF-29 and set to minimum setting.
08275	Close I-119.
08285	In Q/N Control, set the Q/N pots to 215 divisions (Q/N = 0.22).
08301	Open H-66 and H-69.
08308	Close H-180.
08322	Set L-30 to 75% (Q/N = 0.25).
08338	In H-53 Pressure Control, establish 200 psig at HP-60.
08373	In Speed Control, establish 15,000 rpm.
08380	Activate HT-811, HT-911, Q/N #1, and Q/N #2.
08460	Demand zero speed.
08487	Switch H-65 and H-68 to Position Control and close.
08411	15,000 rpm set.
08490	Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
08494	Switch H-53 to Position Control and close.
08498	Open H-180.
08502	Set L-30 to a minimum.
08511	Close H-66 and H-69.
08518	Close the water bypass valves.
08520	Data Tapes OFF.
08525	Switch L-119 and L-219 to Position Control and close.
08530	Bypass all the inputs to the shutdown chain.
08538	Switch the shutdown valves to Override.
08545	Open H-9.
08551	Use H-101 to chill HT-101.
08559	Close I-31.
08564	Open L-30.
08575	Open L-32.
08581	Use L-191 to chill LT-191.
08684	When LT-191 is 100°R, close L-191 and open L-92.
08874	Start a 600-second timer.
08878	Switch L-53 to Position Control and close.
08882	Close L-62.
08892	Open L-153.

IV. UNEQUAL PUMP INLET IMPEDANCE TEST

A. Unequal Pump Inlet Impedance Test.

09695	Set the overspeed trip pot to 635 divisions (24,000 rpm).
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09713 Close L-153.
 09728 Open L-62.
 09734 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 09749 Set the Q/N pots to 107 divisions ($Q/N = 0.17$).
 09758 Activate HP-870, HP-970, HP-811, HP-911, Overspeed #1, Overspeed #2, JP-101/JP-201, Loss of Critical Power, and LP-61 to the Shutdown Chain.
 09787 Switch L-119, L-219, H-65, H-66, H-68, H-69, H-11, H-31, H-142, H-180/H-53, H-101, and L-2 to Normal.
 09819 Set the step to +0.75 volt.
 09829 Patch the step.
 09836 Patch the step to H-65 Speed Loop.
 09841 Use L-119 to chill Pump #1.
 09947 Use L-219 to chill Pump #2.
 09988 Set the Q/N pot to 150 divisions ($Q/N = 0.19$).
 10004 Use H-101 to chill HT-101.
 10014 Use L-191 to chill LT-191.
 10136 Set L-30 to 82% ($Q/N = 0.3$).
 10152 Open the water bypass valves.
 10175 Open W-11 and W-31.
 10192 Adjust WP-1 to establish 1700 gpm at WF-512.
 10201 Open L-161.
 10221 Open L-92.
 10235 Open F-66 and H-69.
 10248 Close H-180.
 10250 Data Tapes ON.
 10253 Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
 10257 Close H-101.
 10263 In H-53 Pressure Control, establish 130 psig at HP-60.
 10282 In Speed Control, establish 18,000 rpm.
 10304 Activate HT-811, HT-911, Q/N #1, and Q/N #2.
 10318 18,000 rpm set.
 10324 HP-60 exceeds 300 psig; close L-251 and H-53.
 10353 Using L-30, establish a $Q/N = 0.3$.
 10360 Proceed with the Speed Loop step response measurement.
 10399 Using L-30, increase Q/N to 0.35.
 10420 Using L-30, slowly increase Q/N to maximum which the TES will allow.
 10448 Using L-30, decrease Q/N to 0.25.
 10486 Using L-30, increase Q/N to 0.20.
 10518 Using L-30, increase Q/N to 0.25.
 10528 In Speed Control, establish 20,000 rpm.
 10544 20,000 rpm set.
 10564 Using L-30, decrease Q/N to 0.21.
 10573 Proceed with the step response measurement on the speed loop.
 10593 Using L-30, increase Q/N to 0.25.

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10598 In Speed Control, establish 22,000 rpm.
 10614 22,000 rpm set.
 10635 Using L-30, decrease Q/N to 0.21.
 10643 Proceed with the step response measurement on the
 Speed Loop.
 10664 Using L-30, decrease Q/N to 0.2.
 10701 Using L-30, increase Q/N to 0.25.
 10718 Using L-30, slowly increase Q/N to maximum which the
 TES will allow.
 10790 Using L-30, decrease Q/N to 0.3.
 10800 Demand zero speed.
 10851 Push the Emergency Shutdown Button.
 10855 Bypass HT-811, HT-911, HP-811, HP-911, Q/N Pump #1,
 and Q/N Pump #2.
 10867 Reset the Emergency Shutdown Chain.
 10875 Set H-101 to a minimum setting.
 10880 Switch H-11 and H-31 to Position Control and close.
 10887 Close H-142.
 10900 Data Tapes OFF.
 10909 Close L-92.
 10944 Close L-161.
 10953 Close W-11, W-31, W-211, W-221, and W-231.
 10987 Switch L-53 to Position Control and close.
 10990 Close L-62.
 10996 Open L-153 and L-251.
 11013 Slowly open L-2.
 11016 Bypass all the inputs to the shutdown chain.
 11019 Switch the shutdown valves to Override.

V DUAL PUMP STABILITY TEST WITH UNBALANCED TURBINE DRIVE

16940 Set the overspeed trip pot to 657 divisions (25,000 rpm).
 16945 Close L-153.
 16950 Open L-62.
 16957 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 16965 Set the Q/N pot to 107 divisions (Q/N = 0.17).
 16970 Activate HP-870, HP-970, HP-811, HP-911, Overspeed #1,
 Overspeed #2, JP-101/JP-201, Loss of Critical Power, and
 IP-61 to the shutdown chain.
 16998 Switch L-119, L-219, H-65, H-66, H-68, H-69, H-11, H-31,
 H-142, H-180/H-53, and H-101 to Normal.
 17032 Set the step to +1.0 volt.
 17051 Patch the step to the Pressure loop.
 17062 Use L-119 to chill Pump #1.
 17148 Use L-219 to chill Pump #2.
 17185 When the pumps are chilled, set the Q/N pot to 150
 divisions (Q/N = 0.19).

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17199	Use H-101 to chill HT-101.
17203	Use L-191 to chill LT-191.
17260	Set L-30 to 82% ($Q/N = 0.30$).
17264	Open the water bypass valves.
17288	Open W-11 and W-31.
17305	Adjust WP-1 to establish 2400 gpm at WF-512.
17314	Open I-161.
17333	Open I-92.
17359	Open H-66 and H-69.
17384	Close H-180.
17389	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
17390	Data Tapes ON.
17396	Close H-101.
17426	In H-53 Pressure Control, establish 130 psig at HP-60.
17448	In Pressure Control, establish 18,000 rpm at a $Q/N = 0.3$.
17464	Activate HT-811, HT-911, Q/N #1, and Q/N #2.
17500	HP-60 exceeds 300 psig; close L-251 and H-53.
17532	18,000 rpm set.
17544	Proceed with the step response measurement on the Pressure Loop.
17555	In Pressure Control, establish a pump discharge pressure of 520 psig.
17664	Using L-30, decrease HF-850 and HF-950 until HF-850 indicates 40 lbs/sec.
17675	Proceed with the step response measurement on the Pressure Loop.
17685	Set the step to -0.93 volt.
17691	Unpatch the step from the Pressure Loop.
17695	Patch the step to L-30.
17706	Proceed with the step (+5 Cv).
17718	Set the step to +0.46 volt.
17723	Proceed with the step (-2.5 Cv).
17731	Unpatch the step from L-30.
17734	Patch the compensator to L-219.
17747	Switch L-219 to Position Control.
17777	Open L-219 to 10%.
17786	Set the step to -0.75 volt.
17793	Proceed with the momentary step (1.0 in^2).
17800	Switch L-219 to Q/N Control.
17808	Set the L-219 Q/N pot to 150 divisions ($Q/N = 0.19$).
17826	Unpatch the compensator from L-219.
17832	Patch the step to L-30.
17840	Set the step to +0.93 volt.
17865	Using L-30, increase HF-850 and HF-950 until HF-850 indicates 60 lbs/sec.
17894	Proceed with the step (-5 Cv).
17904	Set the step to -0.46 volt.

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17914	Proceed with the step (+2.5 Cv).
17922	Unpatch the step from L-30.
17926	Patch the compensator to L-219.
17933	Switch L-219 to Position Control.
17951	Set the step to -0.75 volt.
17974	Open L-219 to 10%.
17980	Proceed with the momentary step (1.0 in ²).
17987	Unpatch the compensator.
17997	Switch L-219 to Q/N Control.
18013	Set the L-219 pot to 150 divisions (Q/N = 0.19).
18018	Switch H-53 to Pressure Control.
18021	Switch H-11 and H-31 to Position Control and close.
18028	Close T-9.
18032	Open H-101.
18040	In H-53 Pressure Control, maintain 400 psig at HP-60.
18046	Open W-311 to 50%.
18049	Set the step to +0.2 volt.
18052	Close W-11 and W-31.
18060	Use W-311 to maintain 35 psig at WP-45.
18074	Patch the step to the H-65 and H-68 position inputs.
18089	Using L-30, establish 60 lbs/sec at HF-850 and HF-950.
18119	Switch H-65 and H-68 to Position Control.
18126	Proceed with the step (-2%).
18133	Set the step to -0.1 volt.
18139	Proceed with the step (+1%).
18146	Switch to Pressure Control.
18156	Set the step to -0.2 volt.
18173	Using L-30, decrease HF-850 and HF-950 until HF-850 indicates 40 lbs/sec.
18180	Switch H-65 and H-68 to Position Control.
18189	Proceed with the step (+2%).
18196	Set the step to +0.1 volt.
18201	Proceed with the step (-1%).
18209	Switch to Pressure Control.
18228	Using L-30, establish Q/N = 0.25.
18233	On TC command, demand zero pressure.
18260	At zero pressure demand, push the Emergency Shutdown Button.
18263	Bypass HT-811, HT-911, HP-811, HP-911, Q/N Pump #1, and Q/N Pump #2.
18273	Reset the Emergency Shutdown Chain.
18280	Set H-101 to a minimum setting.
18286	Open H-9.
18288	Close H-142.
18300	Data Tapes OFF.
18301	Close L-92.
18325	Close L-161.

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18361	Close W-311, W-211, W-221, and W-231.
18376	Switch L-53 to Position Control and close.
18385	Close L-62.
18394	Open L-153 and L-251.
18407	Bypass all the inputs to the shutdown chain.
18410	Switch the shutdown valves to Override.
18420	Unpatch the step.

VI. SHUTDOWN PHASE

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CHRONOLOGY FOR EXPERIMENTAL PLAN 4.

APPENDIX D

CHRONOLOGY FOR AGC DUAL MODE PUMP TEST SERIES

EXPERIMENTAL PLAN 4

APRIL 16, 1970

I. PREOPERATIONAL PHASE

- A. Setup Checklists Received and Approved. Status Board Cleared From the Test Cell.
- B. Report on Test Cell Personnel.
- C. Check the Control Room Net.
- D. Required Systems Switched to CP Control.
- E. Exercise the Valves in the Inerted Areas.
- F. Check the Shutdown Chain.
- G. Check Mini-Chain #2.
- H. Begin Inerting the Test Cell.
 - 04124 Turn off the fans.
 - 04130 Close Q-113.
 - 04140 Pressurize the room inerting header (Bottles #13, 14, 15, and 16). QP-50 indicates 830 psig.
 - 04185 Begin inerting the test cell. Open G-451/G-452.
- I. Exercise the Remaining Valves.
- J. Voltage Calibration.
 - 05161-05260 Calibration interval.
- K. Clear the Remote Team from the Test Cell Area.

II. PRESSURIZATION AND WATER SYSTEM SETUP

- A. Pressurize the Headers.
 - 07196 Open L-153, L-50, L-251, and H-50.
 - 07219 Open G-50.
 - 07224 Open W-50.
 - 07232 Close Q-150.
 - 07237 Close all the bottle purge valves.
 - 07252 Pressurize the helium header (Bottle #1). QP-20 indicates 2360 psig.

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07299 Pressurize the hydrogen header (Bottles 3 and 4).
QP-30 indicates 3050 psig.
07369 Pressurize the nitrogen header (Bottle 11). QP-40
indicates 2950 psig.

B. The Setup of the Water System.

07544 Close W-153.
07550 Open W-1, W-211, W-221, W-231, W-11, W-31, W-45, W-49,
and W-100.
07670 Use W-53 to establish 50 psig at WP-1.
07705 Turn on the water flow meter power.
07723 Close W-11, W-31, W-211, W-221, and W-231.
07750 Report the following data:

<u>Dewar Level:</u>	<u>1</u>	<u>2</u>
Reflectometer	50 k	248 k
Staircase	43.5 k	232 k
0% Temperature	38.0°R	37.2°R
10% Temperature	38.0°R	37.3°R

QP-20 indicates 2360 psig.
QP-30 indicates 3070 psig.
QP-40 indicates 2740 psig.
QP-50 indicates 440 psig.

Hot water tank level: 215 k gallons.

III. CHILLDOWN AND SPEED INPUT CHECKS

A. Chillumdown.

08443 Set the overspeed trip pot to 80 divisions.
08448 Bypass the inputs to the shutdown chain.
08452 Switch the shutdown valves to Override.
08456 Open H-101.
08460 Close L-491.
08465 Open L-191 and L-91.
08480 Close L-262 and L-153.
08505 Open L-62.
08512 Select Dewar 2 Pressure Feedback.
08515 Close L-403.
08520 Open L-2.
08525 Data Tapes ON.
08531 Open L-3.
08545 Open L-31.

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08599	In L-53 Pressure Control, establish 70 psig in Dewar 2.
08605	Use L-119 to trip Overspeed #1, Overspeed #2, and N ₁ .
08686	Use L-219 to trip Overspeed #1 and Overspeed #2.
08875	Set the overspeed trip pot to 460 divisions (17,000 rpm).
08880	Set the Q/N pots to 275 divisions (Q/N = 0.20).
08896	Activate HP-811, HP-870, HP-970, HP-911, Overspeed #1, Overspeed #2, JP-101/JP-201, and Loss of Critical Power to the shutdown chain.
08918	Switch L-119, L-219, H-65, H-180/H-53, H-66, H-69, and H-68 to Normal.
08940	Open the water bypass valves.
08957	Close H-163.
09237	Use L-219 to chill Pump #2.
09351	Use L-30 to chill Pump #1 and LF-29 and set to minimum setting.
09356	In Q/N Control, set the Q/N pots to 310 divisions (Q/N = .22).
09392	Open H-66, H-67, and H-69.
09400	Close H-180.
09405	H-66, H-67, and H-69 went closed.
09630	Begin secure for re-entry.
09700	Data tapes OFF.

B. Recovery to Continue Chill.

14167	Close L-153.
14186	Open L-62.
14190	Select Dewar 2 Pressure Feedback.
14195	Open L-105.
14212	Slowly open L-3.
14247	In L-53 Pressure Control, establish 70 psig in Dewar 2.
14255	Close L-105.
14305	Use L-119 to chill Pump #1.
14401	Use L-219 to chill Pump #2.
14443	Use H-101 to chill HT-101.
14447	Verify L-91 is open.
14450	Open L-30.
14585	LT-191 is chilled; close L-191; and open L-92.
14637	Close L-92.
14754	Start a 600-second timer.
14758	Switch L-53 to Position Control and close.
14763	Close L-62.
14767	Open L-153.

IV. SIMULATED TURBINE DRIVE FAILURE TEST #1

15473	Set the overspeed trip pot to 604 divisions (23,000 rpm).
15478	Close L-153.
15493	Open L-62.

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15511 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 15506 Set the Q/N pots to 220 divisions ($Q/N = 0.17$).
 15521 Activate LP-61, HP-811, HP-870, HP-970, HP-911, Overspeed #1, Overspeed #2, JP-101/JP-201, and Loss of Critical Power to the shutdown chain.
 15547 Switch L-119, L-219, H-11, H-31, H-65, H-142, H-180/H-53, H-66, H-69, H-101, and H-68 to Normal.
 15579 Set the step to +0.2 volt.
 15587 Patch the step.
 15594 Patch the positive H-68 ramp.
 15601 Set the H-68 ramp rate to 20%/sec.
 15608 Patch the step to H-68 Position input.
 15614 Use L-119 to chill Pump #1.
 15655 Use L-219 to chill Pump #2.
 15690 Set the Q/N pots to 255 divisions ($Q/N = 0.19$).
 15694 Use H-101 to chill HT-101.
 15696 Use L-191 to chill LT-191.
 15703 Set L-30 to 75% ($Q/N = 0.25$).
 15722 Open the water bypass valves.
 15758 Open W-11 and W-31.
 15776 Adjust WF-1 to establish 1700 gpm at WF-512.
 15783 Open L-161.
 15801 Open L-92.
 15816 Open H-57, H-66, and H-69.
 15830 Close H-180.
 15840 Close H-163.
 15858 Switch H-11 and H-31 to ΔP Control.
 15860 Close H-101.
 15866 In H-53 Pressure Control, establish 130 psig at HP-60.
 15870 Data Tapes ON.
 15874 Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
 15884 In Pressure Control, establish 520 psig at HP-841 and HP-941.
 15928 HP-60 exceeds 300 psig; close L-251 and H-53.
 15935 520 psig set.
 15940 Using L-30, establish 40 lbs/sec at HF-850 and HF-950.
 15955 Pump average at 40 lbs/sec.
 15964 Proceed with the step (-2%).
 15969 Set the step to +0.4 volt.
 15978 Proceed with the step (-4%).
 15984 Set the step to +0.6 volt.
 15989 Proceed with the step (-6%).
 15997 Set the step to -0.6 volt.
 16005 Proceed with the step (+6%).
 16021 Using H-68 ramp, proceed with the 20%/sec H-68 closed ramp.
 16033 Set the H-68 ramp rate to 40%/sec.
 16047 Using H-68 ramp, proceed with the 40%/sec H-68 closed ramp.

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16060	Set the H-68 ramp rate to 60%/sec.
16078	Using H-68 ramp, proceed with the 60%/sec H-68 closed ramp.
16086	Set the H-68 ramp rate to 200%/sec.
16108	Using H-68 ramp, proceed with the 200% H-68 closed ramp.
16130	Close H-67.
16138	Demand zero pressure.
16159	Zero pressure demand; push the shutdown button.
16161	Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
16166	Reset the shutdown chain.
16169	Set H-101 to a minimum setting.
16174	Switch A-11 and H-31 to Position Control and close.
16177	Close H-142.
16183	Close L-92.
16200	Data tapes OFF.
16206	Close L-161.
16240	Close W-11, W-31, W-211, W-221, and W-231.
16272	Switch L-53 to Position Control and close.
16281	Open L-251.
16296	Bypass all the inputs to the shutdown chain.
16305	Switch the shutdown valves to Override.
16316	Unpatch the step.
16321	Unpatch the H-68 ramp.

V. SIMULATED TURBINE CONTROL VALVE FAILURE TESTS

A. Test #2.

16374	Set the overspeed trip pot to 604 divisions (23,000 rpm).
16389	In L-53 Pressure Control, establish 70 psig in Dewar 2.
16394	Set the Q/N pots to 220 divisions (Q/N = 0.17).
16409	Activate HP-870, HP-970, HP-811, HP-911, Overspeed #1, Overspeed #2, JP-101/JP-201, Loss of Critical Power, and LP-61 to the Shutdown Chain.
16434	Switch L-119, L-219, H-66, H-65, H-68, H-69, H-11, H-31, H-142, H-180/H-53, and H-101 to Normal.
16470	Activate H-68 Low to the Mini-Chain #2.
16482	Patch the Positive H-68 Ramp.
16490	Set the H-68 ramp rate to 20%/sec.
16494	Patch the step to H-68 Position Input.
16500	Use L-119 to chill Pump #1.
16550	Use L-219 to chill Pump #2.
16568	The pumps are chilled; set the Q/N pots to 255 divisions (Q/N = 0.19).
16580	Use H-101 to chill HT-101.
16583	Use L-191 to chill LT-191.
16586	Set L-30 to 75% (Q/N = 0.25).
16591	Open the water bypass valves.

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16631	Open W-11 and W-31.
16637	Adjust WP-1 to establish 1700 gpm at WF-512.
16650	Open L-161.
16658	Open L-92.
16679	Open H-66, H-67, and H-69.
16686	Close H-180.
16693	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
16695	Close H-101.
16700	Data tapes ON.
16701	In H-53 Pressure Control, establish 130 psig at HP-60.
16708	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
16716	In Pressure Control, establish a pump discharge pressure of 520 psig.
16750	HP-60 exceeds 300 psig; close L-251 and H-53.
16774	520 psig set.
16780	Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.
16786	40 lbs/sec set on Pump #1.
16798	Using H-68 ramp, proceed with the 20%/sec ramp closed on H-68.
16805	Demand zero pressure.
16826	Begin preparations for Test 3.
16865	Data tapes OFF.

B. Test #3.

16904	In L-53 Pressure Control, establish 70 psig in Dewar 2.
16910	Activate H-68 Low to Mini-Chain #2.
16920	Patch the Positive H-68 Ramp.
16930	Set the H-68 ramp rate to 60%/sec.
16937	Use L-119 to chill Pump #1.
16942	Use L-219 to chill Pump #2.
16965	The pumps are chilled; set the Q/N pcts to 255 divisions (Q/N = 0.19).
16973	Use H-101 to chill HT-101.
16978	Use L-191 to chill LT-191.
17028	Open L-92.
17040	Open H-67.
17046	Close H-180.
17051	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
17055	Data Tapes ON.
17056	Close H-101.
17060	In H-53 Pressure Control, establish 130 psig at HP-60.
17064	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
17074	In Pressure Control, establish a pump discharge pressure of 520 psig.
17108	HP-60 exceeds 300 psig; close L-251; close H-53.
17115	520 psig set.
17120	Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.

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17126 40 lbs/sec set.
 17136 Using H-68 ramp, proceed with the 60%/sec ramp closed on H-68.
 17142 Demand zero pressure.
 17161 Begin preparations for Test #4.
 17190 Data Tapes OFF.

C. Test #4.

17226 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 17236 Activate H-68 Low to Mini-Chain #2.
 17244 Patch the Positive H-68 Ramp.
 17253 Set the H-68 ramp rate to 200%/sec.
 17262 Use L-119 to chill Pump #1.
 17266 Use L-219 to chill Pump #2.
 17285 The pumps are chilled; set the Q/N pots to 255 divisions (Q/N = 0.19).
 17292 Use H-101 to chill HT-101.
 17295 Use L-191 to chill HT-191.
 17331 Open L-92.
 17335 Open H-67.
 17340 Close H-180.
 17345 Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
 17348 Close H-101.
 17350 Data Tapes ON.
 17354 In H-53 Pressure Control, establish 130 psig at HP-60.
 17360 Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
 17366 In Pressure Control, establish a pump discharge pressure of 520 psig.
 17394 HP-60 exceeds 300 psig; close L-251 and H-53.
 17404 520 psig set.
 17409 Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.
 17415 40 lbs/sec set.
 17425 Using H-68 ramp, proceed with the 200%/sec ramp closed on H-68.
 17433 Demand zero pressure.
 17446 Begin preparations for Test #5.
 17460 Data Tapes OFF.

D. Test #5.

17492 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 17496 Activate H-68 High to Mini-Chain #2.
 17500 Bypass any other inputs.
 17508 Patch the Negative H-68 Ramp.
 17518 Set the H-68 ramp rate to 20%/sec.
 17528 The pumps are chilled; set the Q/N pots to 255 divisions (Q/N = 0.19).

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17533 Use H-101 to chill HT-101.
 17543 Open H-67.
 17548 Close H-180.
 17553 Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
 17557 Close H-101.
 17560 Data Tapes ON.
 17562 In H-53 Pressure Control, establish 130 psig at HP-60.
 17570 Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
 17576 In Pressure Control, establish a pump discharge pressure of 520 psig.
 17604 HP-60 exceeds 300 psig; close L-251 and H-53.
 17615 520 psig set.
 17620 Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.
 17626 40 lbs/sec set.
 17638 Using H-68 ramp, proceed with the 20%/sec ramp open on H-68.
 17647 Demand zero pressure.
 17664 Begin preparations for Test #6.
 17690 Data Tapes OFF.

E. Test #6.

17700 In L-53 Pressure Control, establish 70 psig in Dewar 2.
 17710 Activate H-68 High to Mini-Chain #2.
 17715 Patch the Negative H-68 Ramp.
 17720 Set the H-68 ramp rate to 60%/sec.
 17730 The pumps are chilled; set the Q/N pcts to 255 divisions (Q/N = 0.19).
 17733 Use H-101 to chill HT-101.
 17739 Open H-67.
 17743 Close H-180.
 17747 Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
 17750 Data Tapes ON.
 17751 Close H-101.
 17754 In H-53 Pressure Control, establish 130 psig at HP-60.
 17760 Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
 17766 In Pressure Control, establish a pump discharge pressure of 520 psig.
 17800 HP-60 exceeds 300 psig; close L-251 and H-53.
 17812 520 psig set.
 17817 Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.
 17820 40 lbs/sec set.
 17832 Using H-68 ramp, proceed with the 60%/sec ramp open on H-68.
 17837 Demand zero pressure.
 17850 Begin preparations for Test #7.
 17880 Data Tapes OFF.

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F. Test #7.

17890	In L-53 Pressure Control, establish 70 psig in Dewar 2.
17895	Activate H-68 High to Mini-Chain #2.
17900	Patch the Negative H-68 Ramp.
17905	Set the H-68 ramp rate to 200%/sec.
17918	When the pumps are chilled, set the Q/N pots to 255 divisions (Q/N = 0.19).
17923	Use H-101 to chill HT-101.
17927	Open H-67.
17930	Close H-180.
17934	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
17937	Close H-101.
17942	In H-53 Pressure Control, establish 130 psig at HP-60.
17948	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
17957	In Pressure Control, establish a pump discharge pressure of 520 psig.
17992	HP-60 exceeds 300 psig; close L-251 and H-53.
18004	520 psig set.
18009	Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.
18015	40 lbs/sec set.
18028	Using H-68 ramp, proceed with the 200%/sec ramp open on H-68.
18035	Demand zero pressure.
18050	Begin preparations for Test #8.
18075	Data Tapes OFF.

G. Test #8.

18084	In L-53 Pressure Control, establish 70 psig in Dewar 2.
18089	Activate H-68 High to Mini-Chain #2.
18094	Set the step to -10.0 volts.
18109	Patch the step.
18117	Set the overspeed trip pot to 652 divisions (25,000 rpm).
18129	When the pumps are chilled, set the Q/N pots to 255 divisions (Q/N = 0.19).
18134	Use H-101 to chill HT-101.
18137	Open H-67.
18140	Close H-180.
18143	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
18145	Data Tapes ON.
18146	Close H-101.
18149	In H-53 Pressure Control, establish 130 psig at HP-60.
18155	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
18162	In Pressure Control, establish a pump discharge pressure of 520 psig.
18196	HP-60 exceeds 300 psig; close L-251 and H-53.

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18210	520 psig set.
18215	Using L-30, decrease HF-850 and HF-950 to 40 lbs/sec.
18220	40 lbs/sec set.
18229	Proceed with the H-68 step open.
18230	Q/N #2 Shutdown Trip.
18238	Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
18246	Reset the shutdown chain.
18249	Set H-101 to a minimum setting.
18254	Reset Mini-Chain #2.
18256	Switch H-11 and H-31 to Position Control and close.
18259	Close H-142.
18262	Close L-92.
18270	Data Tapes OFF.
18288	Close L-161.
18326	Close W-11, W-31, W-211, W-221, and W-231.
18350	Switch L-53 to Position Control and close.
18356	Close L-62.
18363	Open L-153 and L-251.
18377	Bypass all the inputs to the shutdown and Mini-Chain #2.
18390	Switch the shutdown valves to Override.
18395	Switch the valves on Mini-Chain #2 to Override.
18419	Unpatch the step.
18423	Unpatch the H-68 ramp.
18429	Select common speed controllers.

VI. PUMP #1 STALL MAPPING TEST

21730	Pressurize GH ₂ Header with Bottles 5 and 6. QP-30 indicates 3300 psig.
21890	Switch to GN ₂ header for inerting.
21973	Set the overspeed trip pot to 486 divisions (18,000 rpm).
21981	Close L-153.
21995	Open L-62.
22004	In L-53 Pressure Control, establish 70 psig in Dewar 2.
22014	Set the Q/N pot to 020 divisions (Q/N = 0.06).
22036	Activate HP-870, HP-811, Overspeed #1, Overspeed #2, JP-101/JP-201, Loss of Critical Power, and LP-61 to the shutdown chain.
22059	Switch L-119, H-65, H-66, H-11, H-142, H-180/H-53, and H-101 to normal.
22079	Use L-119 to chill Pump #1.
22110	Use L-219 to windmill Pump #2 at 500 rpm.
22139	The pumps are chilled; set the L-119 Q/N pot to 020 divisions (Q/N = 0.06).
22146	Use H-101 to chill HT-101.
22150	Use L-191 to chill IT-191.
22153	Set L-30 to 57% (Q/N = 0.25).

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22161 Open the water bypass valves.
22182 Open W-11.
22191 Adjust WP-1 to establish 1000 rpm at WF-512.
22198 Open L-161.
22214 Open L-92.
22227 Open H-66.
22237 Activate the H-68 Hold Close.
22244 Close H-180.
22245 Data Tapes ON.
22248 Switch I-11 to ΔP Control ($\Delta P = 30$ psid).
22251 Close H-101.
22259 In H-53 Pressure Control, establish 130 psig at HP-60.
22266 Activate HT-811 and Q/N Pump #1.
22273 In Speed Control, establish 16,000 rpm at a Q/N = 0.25.
22306 16,000 rpm set.
22310 HP-60 exceeds 300 psig; close L-251 and H-53.
22320 Using L-30, slowly decrease Q/N to indication of instability or minimum Q/N = 0.06.
22350 Q/N = 0.18.
22362 Q/N = 0.16.
22389 Using L-30, establish Q/N = 0.25.
22400 Demand zero speed.
22416 Push the shutdown button.
22419 Bypass HT-811 and Q/N Pump #1.
22423 Reset the shutdown chain.
22426 Set H-101 to a minimum setting.
22429 Switch I-11 to Position Control and close.
22432 Close H-142.
22436 Close L-92.
22440 Data Tapes OFF.
22443 Close L-219.
22463 Close L-161.
22499 Close W-11, W-211, W-221, and W-231.
22520 Switch L-53 to Position Control and close.
22525 Close L-62.
22531 Open L-153 and L-251.
22562 Bypass the H-68 Hold Close.
22567 Bypass all the inputs to the shutdown chain.
22575 Switch the shutdown valves to Override.

VII. DUAL PUMP INSTABILITY TEST

22731 Set the overspeed trip pot to 486 divisions (18,000 rpm).
22741 Close L-153.
22757 Open L-62.
22772 Set the Q/N pots to 165 divisions (Q/N = 0.14).
22776 Activate HP-870, HP-970, HP-811, HP-911, Overspeed #1, Overspeed #2, JP-101/JP-201, Loss of Critical Power, and LP-61 to the shutdown chain.

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22816 Switch L-119, L-219, H-65, H-66, H-68, H-69, H-11, H-31, H-142, H-180/H-53, and H-101 to normal.

22848 Patch the oscillator to the Pressure Loop.

22856 Set the oscillator amplitude to 1.0 volt.

22860 Set the step to +1.0 volt.

22874 Patch the step.

22880 Use L-119 to chill Pump #1.

22883 Use L-219 to chill Pump #2.

22930 The pumps are chilled; set the Q/N pot to 200 divisions (Q/N = 0.16).

22936 Use H-101 to chill HT-101.

22940 Use L-191 to chill LT-191.

22944 Set L-30 to 75% (Q/N = 0.25).

22949 Open the water bypass valves.

22975 Open W-11 and W-31.

22994 Adjust WP-1 to establish 1700 gpm at WF-512.

22996 Open L-161.

23016 Open L-92.

23028 Open H-66, H-67, and H-69.

23038 Close H-180.

23043 Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).

23047 Close H-101.

23050 Data Tapes ON.

23055 In H-53 Pressure Control, establish 130 psig at HP-60.

23061 In L-53 Pressure Control, establish 70 psig in Dewar 2.

23067 Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.

23110 Establish 200 psig at HP-60.

23128 In Pressure Control, establish 21,000 rpm at a Q/N = 0.25.

23167 HP-60 exceeds 300 psig; close L-251 and H-53.

23178 21,000 rpm set.

23186 Using L-30, decrease Q/N to 0.22 at 20,000 rpm.

23220 Proceed with the frequency response measurement on the pressure loop.

23319 Switch to Speed Control.

23326 Using L-30, increase the Q/N to 0.25.

23341 In Speed Control, establish 16,000 rpm.

23355 16,000 rpm set.

23380 Using L-30, slowly decrease Q/N to indication of instability or minimum Q/N = 0.16 on Pump #1.

23425 Q/N = 0.18.

23430 Shutdown trip on Q/N #2.

23436 Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.

23439 Reset the shutdown chain.

23441 Set H-101 to a minimum setting.

23444 Switch H-11 and H-31 to Position Control and close.

23447 Close H-142.

23450 Close L-92.

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23470	Data Tapes OFF.
23475	Close L-161.
23509	Close W-11, W-31, W-211, W-221, and W-231.
23537	Switch L-53 to Position Control and close.
23540	Close L-62.
23545	Open L-153.
23563	Bypass all the inputs to the shutdown chain.
23571	Switch the shutdown valves to override.
23579	Unpatch the oscillator.
23582	Unpatch the step.
23590	Select individual controllers.

VIII. SIMULATED PUMP FAILURE TEST #1

23690	Set the overspeed trip pot to 535 divisions (20,000 rpm).
23701	Close L-153.
23740	Open L-52.
23750	Set the Q/N pot to 220 divisions ($Q/N = 0.17$).
23762	Activate HP-870, HP-970, HP-811, Overspeed #1, Overspeed #2, JP-101/JP-201, Loss of Critical Power, and N_1 to the shutdown chain.
23788	Switch L-119, L-219, H-65, H-66, H-68, H-69, H-11, H-31, H-142, H-180/H-53, and H-101 to normal.
23814	Use L-119 to chill Pump #1.
23817	Use L-219 to chill Pump #2.
23854	Use H-101 to chill HT-101.
23856	Use L-191 to chill HT-191.
23860	Set L-30 to 75% ($Q/N = 0.25$).
23864	Open the water bypass valves.
23888	Open W-11 and W-31.
23896	Adjust EP-1 to establish 1700 gpm at WF-512.
23905	Open L-161.
23920	Open L-92.
23932	Open H-66 and H-69.
23940	Close H-180.
23947	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
23950	Data Tapes ON.
23951	Close H-101.
23958	In H-53 Pressure Control, establish 200 psig at HP-60.
23964	In L-53 Pressure Control, establish 70 psig in Dewar 2.
23975	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
23984	In Pressure Control, establish 350 psig at a $Q/N = 0.25$.
24020	350 psig set.
24024	When HP-60 exceeds 300 psig, close L-251 and H-53.
24034	Using L-30, establish 32 lbs/sec at HF-850 and HF-950.
24042	32 lbs/sec set.
24054	Bypass HP-811, HP-911, HT-911, Overspeed #1, Overspeed #2, and Q/N Pump #2.

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24082	Close H-69.
24094	Demand zero pressure.
24105	Push the shutdown button.
24107	Bypass HT-811 and Q/N Pump #1.
24111	Reset the shutdown chain.
24119	Set H-101 to a minimum setting.
24122	Switch H-11 and H-31 to Position Control and close.
24125	Close H-142.
24128	Close I-92.
24130	Data Tapes OFF.
24160	Close L-161.
24191	Switch L-53 to Position Control and close.
24206	Bypass all the inputs to the shutdown chain.
24212	Switch the shutdown valves to Override.
24342	Set L-30 to 75% (Q/N = 0.25).
24359	Open L-161.
24392	Open L-92.
24394	Open H-56 and H-69.
24404	Close H-180.
24409	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
24412	Close H-101.
24415	Data Tapes ON.
24417	In H-53 Pressure Control, establish 200 psig at HP-60.
24422	In L-53 Pressure Control, establish 70 psig in Dewar 2.
24437	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
24441	In Pressure Control, establish 520 psig at HP-60.
24473	HP-60 exceeds 300 psig; close L-251 and H-53.
24480	520 psig set.
24487	Using L-30, establish 40 lbs/sec at HF-850 and HF-950.
24495	40 lbs/sec set.
24503	Bypass HP-811, HP-911, HT-911, Overspeed #1, Overspeed #2, and Q/N Pump #2.
24526	Close H-69.
24532	Demand zero pressure.
24545	At zero pressure demand, push the shutdown button.
24548	Bypass HT-811 and Q/N Pump #1.
24553	Reset the shutdown chain.
24555	Set H-101 to a minimum setting.
24557	Switch H-11 and H-31 to Position Control and close.
24562	Close H-142.
24564	Close L-92.
24570	Data Tape OFF.
24590	Close L-161.
24598	Switch L-53 to Position Control and close.
24625	Close W-11, W-31, W-211, W-221, and W-231.
24633	Close L-62.
24638	Open L-153 and L-251.

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24659 Bypass all the inputs to the shutdown chain.
24666 Switch the shutdown valves to Override.

IX. SIMULATED PUMP FAILURE TEST #3

24712 Set the overspeed trip pot to 535 divisions (20,000 rpm).
24717 Close L-153.
24734 Open L-62.
24742 In L-53 Pressure Control, establish 70 psig in Dewar 2.
24748 Set the Q/N pot to 220 divisions ($Q/N = 0.17$).
24754 Activate the inputs to the shutdown chain.
24780 Switch the shutdown valves to normal.
24813 On Mini-Chain #2, switch H-69 to normal.
24819 Set the step to -2.2 volts (35%).
24830 Patch the compensator to L-219.
24844 Patch the step.
24850 Use L-219 to chill Pump #1.
24854 Use L-219 to chill Pump #2.
24883 Use H-101 to chill HT-101.
24886 Use L-191 to chill LT-191.
24890 Set L-30 to 75% ($Q/N = 0.25$).
24894 Open the water bypass valves.
24919 Open W-11 and W-31.
24923 Adjust WP-1 to establish 1700 gpm at WF-512.
24936 Open L-161.
24944 Open H-66 and H-69.
24955 Open L-92.
24965 Close I-180.
24971 Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
24974 Close I-101.
24980 In H-53 Pressure Control, establish 130 psig at HP-60.
24986 Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
24993 In Pressure Control, establish 350 psig at a $Q/N = 0.25$.
25033 When HP-60 exceeds 300 psig, close L-251 and H-53.
25039 Using L-30, establish 32 lbs/sec at HF-850 and HF-950.
25053 Use L-219 to chill the vent line and set to 13%.
25082 Switch L-219 to override.
25088 On Mini-Chain #2, activate the Pump #2 ΔP input.
25093 Re-establish 32 lbs/sec.
25109 Proceed with the step.
25123 Demand zero pressure.
25129 Shutdown trip on Q/N #2.
25134 Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
25137 Reset the shutdown chain.
25142 Set H-101 to a minimum setting.
25146 Reset Mini-Chain #2.
25150 Switch H-11 and H-31 to Position Control and close.

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25152	Close H-142.
25159	Close L-219.
25160	Data Tapes OFF.
25165	Close L-92.
25195	Close L-161.
25221	Switch L-53 to Position Control and close.
25242	Open L-251.
25252	Bypass all the inputs to the shutdown chain and Mini-Chain #2.

X. SIMULATED PUMP FAILURE TEST #4

25273	Set the overspeed trip pot to 652 divisions (25,000 rpm).
25291	In L-53 Pressure Control, establish 70 psig in Dewar 2.
25296	Set the Q/N pot to 220 divisions ($Q/N = 0.17$).
25350	Switch H-69 on Mini-Chain #2 to Normal.
25354	Set the step to -2.2 volts (35%).
25361	Patch the compensator to L-219.
25367	Patch the step.
25374	Use L-119 to chill Pump #1.
25376	Use L-219 to chill Pump #2.
25386	Open L-161.
25410	Use H-101 to chill HT-101.
25414	Use L-191 to chill LT-191.
25417	Set L-30 to 75% ($Q/N = 0.25$).
25447	Open I-92.
25456	Open H-66 and H-69.
25464	Close H-180.
25469	Switch H-11 and H-31 to ΔP Control ($\Delta P = 30$ psid).
25470	Data Tapes ON.
25473	Close H-101.
25477	In H-13 Pressure Control, establish 130 psig at HP-60.
25484	Activate HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
25489	In Pressure Control, establish 520 psig at a $Q/N = 0.25$.
25525	HP-60 exceeds 300 psig; close L-251 and H-53.
25542	Using L-30, establish 40 lbs/sec at HF-850 and HF-950.
25550	Use L-219 to chill the vent line and set to 13%.
25568	Re-establish 40 lbs/sec.
25578	Switch L-219 to Override.
25584	On Mini-Chain #2, activate the Pump #2 ΔP input.
25595	Proceed with the step.
25605	Demand zero pressure.
25619	Push the shutdown button.
25622	Bypass HT-811, HT-911, Q/N Pump #1, and Q/N Pump #2.
25628	Reset the shutdown chain.
25631	Set H-101 to a minimum setting.
25634	Reset Mini-Chain #2.

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25638	Switch H-11 and H-31 to Position Control and close.
25641	Close H-142.
25644	Close L-219.
25646	Close L-92.
25656	Data Tapes OFF.
25666	Close L-161.
25678	Switch L-53 to Position Control and close.
25682	Close L-62.
25689	Open L-153 and L-251.
25701	Bypass all the inputs to the shutdown chain and Mini-Chain #2.
25704	Close W-11, W-31, W-211, W-221, and W-231.
25720	Switch the shutdown chain and Mini-Chain #2 valves to Override.
25734	Unpatch the compensator.

XI. SHUTDOWN PHASE

APPENDIX E

TEST CELL C DIGITAL (TAF) AND
ANALOG MODEL EQUATIONS

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I A-1 PUMP SUCTION

$$1. \quad \text{PLP62} = 75.$$

$$2. \quad \frac{d\text{PLP6}}{dt} = 23.437 (\text{WL2} - \text{WPA} - \text{WPB}(\text{PUMP-1.}))$$

$$3. \quad \text{PHP811} = \text{PLP6} - \frac{\text{C811}}{4.23}(\text{WPA})^2$$

$$4. \quad \text{PHP911} = \text{PLP6} - \frac{\text{C911}}{4.23}(\text{WPB})^2$$

$$5. \quad \frac{d\text{WL2}}{dt} = 27.766(\text{PLP62} - \text{PLP6} - .27784 \times 10^{-3}(\text{WL2})^2)$$

$$6. \quad \text{WPA} = \text{WL119} + \text{WH850}$$

$$7. \quad \text{WPA} = \text{WL219} + \text{WH950}$$

$$\text{C811} = 0$$

$$\text{C911} = 0$$

I A-2 PUMPS

NO STALL:

$$WPA,B/NTA,B > .0017$$

$$1. \quad MPA,B = .4383 \times 10^{-6} (NTA,B)^2 + .3995 \times 10^{-3} (NTA,B)(WPA,B) - .02718 (WPA,B)^2$$

$$WPA,B/NTA,B < .0017$$

$$2. \quad MPA,B = .4452 \times 10^{-7} (NTA,B)^2 + .1517 \times 10^{-3} (NTA,B)(WPA,B) + .4374 (WPA,B)^2$$

STALL:

$$WPA,B/NTA,B > .0017$$

$$3. \quad MPA,B = .01244 \times 10^{-5} (NTA,B)^2 + 61.5 \times 10^{-5} (NTA,B)(WPA,B) - .03288 (WPA,B)^2$$

$$WPA,B/NTA,B < .0017$$

$$4. \quad MPA,B = .05663 \times 10^{-5} (NTA,B)^2 + 4563 \times 10^{-5} (NTA,B)(WPA,B) - .08305 (WPA,B)^2$$

$$5. \quad \frac{dNTA}{dt} = 97.32(MTA-MPA)$$

$$6. \quad \frac{dNTB}{dt} = 97.32(MTB-MPB)$$

I A-3 PUMP DISCHARGE

1. $\Delta P = .1281 \times 10^{-5} \text{RPM}^2 + .1410 \times 10^{-4} \text{RPM} \times \text{WP} - .03677 \text{WP}^2$ $\text{WP}/\text{RPM} \geq .0017$
2. $\Delta P = .4158 \times 10^{-7} \text{RPM}^2 + .3044 \times 10^{-3} \text{RPM} \times \text{WP} + .3058 \text{WP}^2$ $\text{WP}/\text{RPM} < .0017$
 $\text{RPM} = \text{RPMA}, \text{RPMB}$ For no stall use equation 1 only
3. $\text{PHP841} = \text{PHP811} + \Delta P$
4. $\text{PHP941} = \text{PHP911} + \Delta P$
5. $\text{A119} = f(\text{TH119})$
6. $\text{WL119} = 96.26 * \text{A119} * \sqrt{4.4 * (\text{PHP841} - \text{PA})}$
7. $\text{A219} = f(\text{TH219})$
8. $\text{WL219} = 96.26 * \text{A219} * \sqrt{4.4 * (\text{PHP941} - \text{PA})}$
9. $\text{WBCA} = 1.41 * 10^{-3} * \text{PHP841} - .78 * 10^{-6} * (\text{PHP841})^2$
10. $\text{WBCB} = 1.41 * 10^{-3} * \text{PHP941} - .78 * 10^{-6} * (\text{PHP941})^2$
11. $\frac{d\text{WH850}}{dt} = 41.89 \left((\text{PHP841} - \text{PLP29}) - 3.272 * 10^{-3} (\text{WH850})^2 \right)$
12. $\frac{d\text{WH950}}{dt} = 41.89 \left((\text{PHP941} - \text{PLP29}) - 3.272 * 10^{-3} (\text{WH950})^2 \right)$
13. $\frac{d\text{PLP29}}{dt} = (410.4 + .17 \text{PLP29}) * \left((\text{WH850} + \text{WH950}) - (\text{WL30} + \text{WH9}) \right)$
14. $\frac{d\text{PLP30}}{dt} = (56.73 + .02350 * \text{PLP30}) (\text{WL30} - \text{WLCT})$
15. $\text{CVL30} = f(\text{TH30})$

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$$16. \quad WL30 = .01760 * CVL30 * \sqrt{4.4 * (PLP29 - PLP30)}$$

$$17. \quad \frac{dWLCT}{dt} = 13.44 * \left((PLP30 - PA) - 2.15 * 10^{-3} (WLCT)^2 \right)$$

$$PA = 12.9$$

I A-3 PUMP DISCHARGE

TABLE I A-3-1

TH119, TH219(deg)	A119, A219 (in ²)
0.	0.
12.	0.
20.	.56
35.	1.8
39.	2.54
46.3	4.2
49.	5.0
59.3	10.0
63.3	11.2
68.5	12.28
80.	13.6
98.	15.15
100.	15.15

I A-3 PUMP DISCHARGE

TABLE I A-3-2

TH30 (deg)	CVL30
0	0
10	3.5
20	9.2
30	17.
40	28.5
50	44.
60	64.5
70	94.
80	126.
90	160.5
100	195.

I B-1 TES FEEDSYSTEM

$$1. \quad \frac{dWH9}{dt} = 7.027 * \left((PLP29 - PHP20) - 6.25 * 10^{-3} * (WH9)^2 \right)$$

$$2. \quad \frac{dPHP20}{dt} = (334.6 + .1386 * PHP20) (WH9 - WH21)$$

$$3. \quad \frac{dRHP21}{dt} = 9.097 * 10^{-3} (WH21 - WH)$$

$$4. \quad PHP21 = 5.32 * THT63 * RHP21$$

$$5. \quad CV21 = f(TH21)$$

$$6. \quad WH21 = .0176 * CV21 * \sqrt{4.4 * (PIP20 - PHP21)}$$

I B-1 TES FEEDSYSTEM

TABLE I B-1-1

TH21 (deg)	CV21
0	0
50.	114.
100.	228.

I B-2 TES

$$1. \quad \frac{dWH}{dt} = 3.244 \left(PHP21 - PHP63 \right) - \frac{77.24 \times 10^{-3}}{RHP63} (WH)^2$$

$$2. \quad PHP63 = 5.32 \text{ THT63} \times RHP63$$

$$3. \quad \frac{dRHP63}{dt} = .03533 (WH + WH53 - WH63)$$

$$THT63 = 620^{\circ}R$$

I B-3 TURBINE INLET

1. $PHP64 = 5.32THT63 \times RHP64$
2. $\frac{dRHP64}{dt} = 1.234(WH63 - WH68 - WH65)$
3. $\frac{dWH63}{dt} = 13.10 \left(PHP63 - PHP64 - \frac{.03466 + .02095}{RHP63} (WH63)^2 \right)$
4. $P285 = 5.32 * THT63 * R285$
5. $P285A = P285$
6. $P285B = P285$
7. $A65 = f(TH65)$
8. $P65R = 1 - \frac{P285A}{PHP64}$
9. $SN65 = f(P65R)$
10. $WH65 = \frac{.1402 * A65 * PHP64 * SN65}{\sqrt{THT63}}$
11. $A68 = f(TH68)$
12. $P68R = 1 - \frac{P285B}{PHP64}$
13. $SN68 = f(P68R)$
14. $WH68 = \frac{.1402 * A68 * PHP64 * SN68}{\sqrt{THT63}}$
15. $PHP870 = P285A - \frac{.126576}{R285} (WH860)^2$
16. $PHP970 = P285B - \frac{.126576}{R285} (WH960)^2$

$$17. \quad \frac{dR285}{dt} = .5938 * ((WH68 + WH65) - (WH860 + WH960))$$

$$18. \quad FP285 = f\left(\frac{PHP69}{PHP870, 970}\right)$$

$$19. \quad WH860 = \frac{PHP870}{\sqrt{THT63}} (FP285 - (THT63 - 500.) * 7.6 * 10^{-5})$$

$$20. \quad WH960 = \frac{PHP970}{\sqrt{THT63}} (FP285 - (THT63 - 500) * 7.6 * 10^{-5})$$

I B-3 TURBINE INLET

TABLE I B-3-1

TH65, TH68 (deg)	A65, A68 (in ²)
0	.023
10	.097
20	.2116
25	.4265
30	.7091
35	1.106
40	1.60
45	2.263
50	3.065
55	3.909
60	4.862
65	5.827
70	6.7
75	7.437
80	7.928
85	8.294
90	8.531

I B-3 TURBINE INLET

TABLE I B-3-2

PHP69/PHP870, 970	FP285
0.	.59
.3	.59
.375	.583
.45	.57
.55	.545
.75	.475
.85	.42
.89	.383
.925	.325
.97	.2
1.0	0.

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I B-3 TURBINE INLET

TABLE I B-3-3

P65R, P68R	SN65, SN68
0.	0.
.01	.2055
.04	.4007
.08	.5625
.1	.6159
.15	.7355
.2	.8154
.25	.8815
.3	.9309
.4717	1.0
.5	1.0

I B-4 TURBINE

PTMA

$$1. \quad MTA = 10.993 * WH360 \left[\sqrt{THT63} \left(1. - \left(\frac{PHP69}{PHP870} \right)^{.286 \frac{1}{2}} \right) - 1.491 * 10^{-4} RPMA \right] TNTA$$

$$2. \quad MTB = 10.993 * WH960 \left[\sqrt{THT63} \left(1. - \left(\frac{PHP69}{PHP970} \right)^{.286 \frac{1}{2}} \right) - 1.491 * 10^{-4} RPMB \right]$$

$$3. \quad TNTA = .31 + 3.75 * 10^{-4} * RPMA \leq 1.0$$

$$4. \quad TNTB = .31 + 3.75 * 10^{-4} * RPMB \leq 1.0$$

I B-5 TURBINE EXHAUST

1. $PHP69 = 5.32 \text{ RHP69}^* \text{THT69}$
2. $\frac{dRHP69}{dt} = .0182(WH860 + WH960 + WBCA + WBCB - WFS)$
3. $\frac{dTHT69}{dt} = .5328 \left((WH860 + WH960) (.74THT63 - THT69) - (WBCA + WBCB)^* \right. \\ \left. (THT69 - TLT29) \right)$
4. $\frac{dWFS}{dt} = 33.06 \left(PHP69 - PA - \frac{.002685}{RHP69} (WFS)^2 \right)$

$$PA = 12.9$$

$$TLT29 = 40$$

I C-1 TURBINE POWER CONTROLS

1. $PLP29E = PLP29D - PLP29$
2. $\frac{TH65D,68D}{PLP29E} = \frac{.224\left(\frac{S}{7.7} + 1\right)}{S}$
3. $RPMEA,B = RPMD - RPMA,B$
4. $\frac{TH65D,68D}{RPMEA,B} = \frac{.0224\left(\frac{S}{7.7} + 1\right)}{S}$
5. $\frac{TH65,68}{TH65D,68D} = \frac{1}{\frac{S^2}{(94.247)^2} + \frac{2(.6)S}{94.247} + 1}$

I C-2 Q/N FLOW BYPASS CONTROL

$$1. \quad QEA, B = WPA, B - (Q/RPM)_D \times RPMA, B$$

$$2. \quad \frac{TH119D, 219D}{QEA, B} = \frac{K_1}{S} \frac{\left(\frac{S}{W1} + 1\right)}{\left(\frac{S}{W2} + 1\right)}$$

$$3. \quad \frac{TH119, 219}{TH119D, 219D} = \frac{1}{\frac{s^2}{(50.256)^2} + \frac{2(.6)S}{50.256} + 1}$$

K_1, W_1 not determined

I C-3 TES FEED FLOW CONTROL

$$1. \quad \text{DLP21E} = \text{DLP21D} - (\text{PHP20} - \text{PHP21})$$

$$2. \quad \frac{\text{TH21D}}{\text{DLP21E}} = \frac{.047}{s} \frac{\left(\frac{s}{.63} + 1\right)}{\left(\frac{s}{10} + 1\right)}$$

$$3. \quad \frac{\text{TH21}}{\text{TH21D}} = \frac{1}{\frac{s^2}{(75.36)^2} + \frac{2(.6)s}{75.36} + 1}$$

II BASIC EQUATIONS

1. Hydraulic line resistive pressure drop

$$\Delta P = c \frac{w^2}{\rho}$$

$$c = 3.6278 \sum_{n=1}^m \frac{f \left(\frac{L}{D_n} + k_n \right)}{d_n^4}$$

ΔP = pressure drop (psi)

c = hydraulic resistance ($\text{sec}^2/\text{ft}^3 \text{ in}^2$)

w = flow rate (lb/sec)

ρ = fluid density (lb/ft^3)

f = friction factor

L = line length (ft)

D = line diameter (ft)

d = line diameter (in)

K = loss coefficient for entrance exit, bends, fittings

m, n = pipe section indices

2. Hydraulic line fluid inertia pressure change

$$\frac{dP}{dt} = \frac{L}{gA} \frac{dW}{dt}$$

P = pressure (psi)

W = flow rate (lb/sec)

L = line length (ft)

A = line flow crosssectional area (in^2)

g = $32.2 \text{ ft}/\text{sec}^2$

3. Valve flowrate

$$W = .0176 * cv * \sqrt{\rho * \Delta P}$$

W = flow rate (lb/sec)

cv = valve flow coefficient

ρ = fluid density (lb/ft³)

ΔP = pressure drop (psi)

4 Fluid compressibility pressure change

$$\frac{dP}{dt} = \frac{\beta}{V} (W_{in} - W_{out})$$

P = pressure at a node (psia)

β = compressibility (lbf-ft³/lbm-in²)

V = volume defined for P (ft³)

W_{in} = flow rate into the node (lb/sec)

W_{out} = flow rate out at the node (lb/sec)

5. Gas line flow rate change

$$\frac{dW}{dt} = \frac{gA}{L} \left[(P_{in} - P_d) - \frac{c * W^2}{\rho} \right]$$

W = flow rate (lb/sec)

A = line flow area (in²)

L = line length (ft)

P_{in} = line inlet pressure (psia)

P_d = line discharge pressure (psia)

c = flow resistance (sec²/ft³ in²)

ρ = fluid density (lb/ft³)

g = 32.2 ft/sec²)

6. Gas density change

$$\frac{d\rho}{dt} = \frac{1}{V} (W_{in} - W_{out})$$

ρ = density at a node (lb/ft³)

V = volume defined at a node (ft³)

W_{in} = flow rate into a node (lb/sec)

W_{out} = flow rate out of a node (lb/sec)

7. Equation of state - gas

$$P = \frac{\rho RT}{144}$$

P = pressure (psia)

ρ = gas density (lb/ft³)

T = gas temperature (°R)

R = parahydrogen gas constant (ft/°R) = 766.08

8. Valve flow rate - gas

$$W = \frac{.1402 * A * P_{in} * SN}{\sqrt{T}}$$

$$SN = f\left(1 - \frac{P_{out}}{P_{in}}\right)$$

W = flow rate (lb/sec)

A = valve flow area (in²)

P_{in} = valve inlet pressure (psia)

P_{out} = valve outlet pressure (psia)

T_{in} = valve inlet temperature (°R)

SN = Mach number function

9. Pump pressure rise

$$\Delta P = C_1 * RPM^2 + C_2 * RPM * W + C_3 * W^2$$

ΔP = pump pressure rise (psi)

RPM = pump speed (rpm)

W = pump flow rate (lb/sec)

C_1, C_2, C_3 = pump coefficients obtained from pump performance data

10. Pump torque

$$MP = K_1 * RPM^2 + K_2 * RPM * W + K_3 * W^2$$

MP = pump torque (ft-lb)

RPM = pump speed (rpm)

W = flow rate

K_1, K_2, K_3 = pump torque coefficients obtained from pump performance data

11. Turbine torque

$$MT = \left\{ C_1 * W * \sqrt{T_{in}} \left[1 - \left(\frac{P_{out}}{P_{in}} \right)^{.286} \right] - C_2 * RPM \right\} * TNT$$

$$TNT = C_3 + C_4 * RPM$$

MT = turbine torque (ft-lb)

W = turbine flow rate (lb/sec)

T_{in} = turbine gas flow inlet temperature ($^{\circ}R$)

P_{in} = turbine gas flow inlet pressure (psia)

P_{out} = turbine gas flow outlet pressure (psia)

RPM = turbine speed (rpm)

TNT = turbine efficiency factor

C_1, C_2, C_3, C_4 = coefficients obtained from turbine performance data

12. Turbine speed

$$\frac{dRPM}{dt} = \frac{60}{2\pi I} (MT - MP)$$

RPM = turbine speed (rpm)

MT = turbine torque (ft-lb)

MP = pump torque (ft-lb)

I = polar moment of inertia (ft-lb-sec²)

13. Turbine flow rate

$$W = \frac{P_{in}}{\sqrt{T_{in}}} \left[f\left(\frac{P_{out}}{P_{in}}\right) - 7.6 \times 10^{-5} * (T_{in} - 500.) \right]$$

W = turbine flow rate (lb/sec)

P_{in} = turbine inlet pressure (psia)

T_{in} = turbine inlet temperature (°R)

P_{out} = turbine outlet pressure (psia)

P_{in} = turbine inlet pressure (psia)

f(P_{out}/P_{in}) = Mach number function

14. Turbine exhaust density

$$\frac{d\rho}{dt} = \frac{1}{V} (W_{in} - W_{out})$$

ρ = turbine exhaust gas density (lb/ft³)

W_{in} = turbine exhaust node flow rate in (lb/sec)

W_{out} = turbine exhaust node flow rate out (lb/sec)

V = turbine exhaust node volume (ft³)

15. Turbine exit temperature

$$\frac{dT}{dt} = \frac{1}{CP \cdot M} (W \cdot (.74 \cdot T_{in} - T) - W_b (T - T_p))$$

T = turbine exit temperature

CP = specific heat of hydrogen in turbine exit line (BTU/lbm^oR)

M = mass of gas in turbine exit line (lbm)

W = turbine flow rate (lb/sec)

T_{in} = turbine inlet temperature (°R)

W_b = bearing coolant flow rate (lb/sec)

T_p = pump discharge temperature (°R)

III A MODEL CHECKS - STEADY STATE

<u>NAME</u>	<u>ANALOG</u>	<u>DIGITAL</u>	<u>NAME</u>	<u>ANALOG</u>	<u>DIGITAL</u>
MPA	477.3	476.5	WFS	6.357	6.68
MPB	474.8	476.5	WH	6.725	6.68
MTA	478.3	476.5	WH9	6.658	6.68
MTB	475.9	476.5	WH21	6.655	6.68
P285	168.5	170.5	WH53	0.	0.0
P285B	168.5	170.5	WH63	6.625	6.68
P285A	168.5	170.5	WH65	3.350	3.34
PA	12.9	12.9	WH68	3.350	3.34
PHP20	423.5	423.1	WH850	53.88	53.26
PHP21	389.9	389.3	WH860	3.336	3.34
PHP63	357.9	357.6	WH950	53.88	53.26
PHP64	335.4	334.7	WH960	3.308	3.34
PHP841	432.9	432.7	WL2	105.9	106.5
PHP870	141.1	143.2	WL30	99.70	99.84
PHP941	431.2	432.7	WL119	0.	0.0
PHP970	140.8	143.2	WL219	0.	0.0
PHP69	23.05	23.31	WLCT	99.70	99.84
PLP6	71.9	71.35	WPA	53.35	53.26
PLP29	423.6	423.4	WPB	53.32	53.26
PLP30	34.3	34.33	WBCA	.4644	.4641
PLP62	75.	75.	WBCB	.4644	.4641
R285	.0511	.05169	TH65	41.51	41.3
RHP21	.1182	.118	TH68	41.51	41.3
RHP63	.1085	.1084			
RHP64	.1017	.1015			
RHP69	.0107	.01098			
THT69	407.4	407.7			
TNTA	1.0	1.			
TNTB	1.0	1.			
THT63	620.	620.			
TLT29	40.1	40.			
NTA	18770.	18760.			
NTB	18770.	18760			

Analog Run Dated 3 March 1970

Digital Run (TAF) Dated 26 May 1970

III B MODEL CHECKS - FREQUENCY RESPONSE

<u>Frequency (Hz)</u>	PLP29/TPCVD			
	Analog		Digital	
	<u>DB</u>	<u>Phase</u>	<u>DB</u>	<u>Phase</u>
10.	3.9	-115.	3.9	-125.
6.3	8.1	-100.	7.6	-104.
4.	5.9	-123.	4.8	-119.
2.5	17.6	-85.	16.1	-83.
1.6	20.0	-64.	18.4	-65.
1.	21.5	-50.	20.1	-53.5
.63	22.5	-43.	21.5	-43.4
.4	23.5	-43.	23.	-49.
.25	25.1	-48.	25.2	-51.5
.16	27.3	-52.	27.9	-52.6
.1	30.0	-53.	30.8	-49.
.063	33.	-49.	33.3	-42.
.04	35.6	-42.	35.1	-31.6
.025	37.4	-33.	36.1	-21.9
.016	38.2	-24.	36.6	-14.5
.01	38.6	-17.	36.8	-9.3

Analog Run Dated 3 March 1970

Digital Run (TAF) Dated 26 May 1970

Appendix E

<u>Frequency (Hz)</u>	RPMA/TPCVD			
	Analog		Digital	
	<u>DB</u>	<u>Phase</u>	<u>DB</u>	<u>Phase</u>
10.	34.3	-113.	33.4	-123.
6.3	39.4	-99.7	38.3	-103.
4.	43.6	-89.1	42.6	-88.8
2.5	47.3	-71.3	45.6	-69.6
1.6	49.6	-55.7	47.7	-56.9
1.	50.9	-43.9	49.4	-47.7
.63	51.8	-38.4	50.7	-43.3
.4	52.6	-38.9	52.1	-43.9
.25	54.1	-43.6	53.9	-47.2
.16	56.2	-48.8	56.4	-49.2
.1	58.8	-50.4	59.2	-47.0
.063	61.7	-46.9	61.7	-49.1
.04	64.1	-40.4	63.5	-30.6
.025	65.5	-31.7	64.5	-21.2
.016	66.2	-23.4	64.9	-14.1
.01	66.6	-16.7	65.2	-9.1

Analog Run Dated 3 March 1970

Digital Run (TAF) Dated 26 May 1970

IV NOMENCLATURE

<u>NAME</u>	<u>DEFINITION</u>	<u>UNITS</u>
MPA	Pump torque A side	ft-lbs
MPB	Pump torque B side	ft-lbs
MTA	Turbine torque A side	ft-lbs
MTB	Turbine torque B side	ft-lbs
P285A,B	Turbine valve discharge pressure, A,B side	psia
P285	Turbine valve discharge pressure, common	psia
PA	Atmospheric pressure	psia
PHP20	H21 inlet pressure	psia
PHP21	Heater inlet pressure	psia
PHP63	Heater discharge pressure	psia
PHP64	TPCV inlet pressure	psia
PHP841	Pump discharge pressure A side	psia
PHP870	Turbine inlet pressure A side	psia
PHP941	Pump discharge pressure B side	psia
PHP970	Turbine inlet pressure B side	psia
PHP69	Turbine exhaust pressure	psia
PLP6	Propellant feed line pressure	psia
PLP29	L30 inlet pressure	psia
PLP30	L30 discharge pressure	psia
PLP62	Propellant tank pressure	psia
PHP811	Pump suction pressure A side	psia
PHP911	Pump suction pressure B side	psia
PQP30	CH ₂ gas farm pressure	psia
R285	Turbine inlet density	lbs-ft ³

Appendix E

<u>NAME</u>	<u>DEFINITION</u>	<u>UNITS</u>
RHP21	Heater inlet density	lbs/ft ³
RHP63	Heater discharge density	lbs/ft ³
RHP64	TPCV inlet density	lbs/ft ³
RHP69	Turbine discharge density	lbs/ft ³
THT69	Turbine discharge temperature	°R
TNTA	Turbine torque constant A side	-
TNTB	Turbine torque constant B side	-
THT63	Heater discharge temperature	°R
TLT29	Propellant feed line temperature	°R
NTA, RPMA	Turbine speed A side	RPM
NTB, RPMB	Turbine speed B side	RPM
VFS	Total turbine discharge flow	lbs/sec
WH	Heater flow	lbs/sec
WH9	Turbine drive flow	lbs/sec
WH21	H21 flow	lbs/sec
WH53	GH ₂ gas farm flow	lbs/sec
WH63	H63 flow	lbs/sec
WH65	TPCV flow A side	lbs/sec
WH68	TPCV flow B side	lbs/sec
WH850	Pump discharge flow A side	lbs/sec
WH950	Pump discharge flow B side	lbs/sec
WH860	Turbine flow A side	lbs/sec
WH960	Turbine flow B side	lbs/sec
WL2	Propellant feed line flow	lbs/sec
WL3	Propellant feed line flow	lbs/sec
WL30	L30 flow	lbs/sec

Appendix E

<u>NAME</u>	<u>DEFINITION</u>	<u>UNITS</u>
WL119	Pump bypass flow A side	lbs/sec
WL219	Pump bypass flow B side	lbs/sec
WLCT	Catch tank flow	lbs/sec
WPA	Pump suction flow A side	lbs/sec
WPB	Pump suction flow B side	lbs/sec
WBCA	Bearing coolant flow A side	lbs/sec
WBCB	Bearing coolant flow B side	lbs/sec
A65	Turbine control valve flow area A side	in ²
A68	Turbine control valve flow area B side	in ²
A119	Q/N control valve flow area A side	in ²
A219	Q/N control valve flow area B side	in ²
CV21	H21 valve flow coefficient	-
CVL30	L30 valve flow coefficient	-
TH21	H21 valve position	degrees
TH30	L30 valve position	degrees
TH65, TPCVD	Turbine control valve position A side	degrees
TH68, TPCVD	Turbine control valve position B side	degrees
TH119	Q/N control valve position A side	degrees
TH219	Q/N control valve position B side	degrees

TEST CELL C SYSTEM FLOW DIAGRAM

APPENDIX F

TEST CELL C TEST SIMULATION

Subject: Test Cell "C" Test Simulation

Introduction

A series of runs were made on the hybrid computer to determine the capability of the dual pump system under test at Test Cell "C". The results of this effort were used to check the testing methods and to determine such things as valve step sizes for pump stability tests. The runs made were as close to actual test conditions as could be programmed.

A check on the designed control system was made concurrently by observing the response of the system to all perturbations made.

The test simulations made are discussed and a listing of all data points taken is shown in Table 1.

Summary

The system as simulated and tested gave no unexpected results and proved useful in preparing the test plan for EP-1.

The control system for PLP2⁰ and turbine speed operated well in the region it was designed for. However it was somewhat oscillatory at low flow conditions.

The dual pump instability was observed and occurred where expected. A diagram of the system is shown in Figure 1 and a list of nomenclature in Table 2.

Discussion of Runs

1. Pump #1 Green Run (1-8-70-301, 302)

The first test to be simulated was to start one pump with one TPCV in open loop control (closed loop on position), then change control mode to turbine speed control at a speed of 5000 RPM. A manual change in set point is then made to 18,000 RPM. The valve L30 is initially set to provide 52 lbs/sec flow at 18,000 RPM. When the system stabilizes another change in control mode to LP29 control (pump discharge pressure) is made.

These conditions were imposed on the model to observe system effects. An offset between the 5000 RPM initial turbine speed and the control system set point of 5500 was purposely made to observe the transient when changing from open loop control to RPM control. The system is well behaved as the overshoot is only 25 RPM and the transient settles out in less than a second. The manual set point increase is somewhat more oscillatory as it is in part a function of how smoothly the set point potentiometer is changed.

The switch from RPM control to LP29 control was done with a 20 psi offset to again observe system response. The system settled out in one to two seconds.

Zero LP29 set point pressure was then demanded which closed the TPCV and shut the system down.

No unusual system conditions were observed for these system perturbations.

2. Pump #1 LHBV Calibration (1-8-70-303, 304)

During this second test simulation, the second TPCV was brought on line in position control with only one TPA and then sequenced to closed loop pressure control. This was done at a system condition of 18,500 RPM and a flow of 52 lbs/sec. The LP29 set point pressure is then increased to produce a speed of 21,000 RPM and a flow of 62 lbs/sec.

The valve L30 was then moved toward the closed position until the stall point was reached at a flow of 37.0 lbs/sec and a speed of 20,800 RPM. Again the system behaved as expected.

3. Dual Pump Mapping (1-8-70-305, 306, 307, 308)

The simulation runs 1-8-70-305 to 308 were dual pump mapping runs to determine the point at which the dual pump instability occurs. These were run in RPM control for speeds of 10,000, 14,000, 18,000 and 22,000 RPM, (Figure 2).

At the low speed of 10,000 RPM it was possible to drive one pump into stall completely if the flow was lowered sufficiently. However at an average pump flow of 20 lbs/sec the system did oscillate. Listed below are the amplitudes of the oscillations for the various pump speeds and the flows for which they occur.

<u>Avg RPM</u>	<u>Avg Pump Flow</u>	<u>$\Delta W H 850$</u>	<u>$\Delta P H P 841$</u>	<u>$\Delta R P M$</u>
10,000	20	± 10	± 10	± 1000
14,000	27	± 15	± 20	± 1500
18,000	35	± 30	± 50	± 2000
22,000	42	± 35	± 80	± 2500

Run 1-8-70-309 showed that any perturbation near the region of instability can cause the system to go unstable. The RPM set point was lowered from a condition of 19,400 RPM and a pump flow of 40 lbs/sec to 17,500 and a flow of 36 lbs/sec where the system went unstable. At this point L30 was increased to produce a flow of 44 lb/sec before the oscillation was stopped.

4. HP53 Determination for Low Speed Mapping (1-9-70-301 thru 306)

Energy source and HP53 pressure supplied from the gas farm with the system in RPM control. This was simulated by holding PHP63 constant. Pressures

from 200 to 400 were investigated by stepping L30 to produce an approximate positive 10 lbs/sec change in individual pump flow and observing the response. The initial system condition for this was 18,000 RPM and pump flow of 30 lbs/sec.

Runs 1-9-70-305 and 306 illustrate the operation of the system at different conditions using the gas farm. With PHP63 equal to a constant 300 psia, the flow was increased from 30 to 60 lbs/sec and back to 30 lbs/sec. The RPM set point was then set to zero and the system shut down.

5. TPCV Unbalance Investigation (1-9-70-308)

The effect of unbalanced TPCV positions was investigated by putting one TPCV into position control. The initial system conditions were RPM = 18,000 and a pump flow of 52 lbs/sec and two TPA's and two TPCV's in pressure control. One TPCV was then sequenced to position control and moved open then closed. The only effect is that the other TPCV in closed loop pressure control keeps the system at the proper set point by appropriately opening or closing until it is either closed or loses control at the TES limit.

6. Pump #1 Damping Characteristics (1-9-70-309 to 314)

A simulated test was run to determine the effect of stepping the valve L30 (pump discharge valve) on a system of two TPCV's and one TPA. This was done with the system in closed loop control on PLP29 with a set point pressure of 520 psia. Valve L30 was set to three initial positions to produce flows of 40, 60, 80 lbs/sec. From these points, L30 was then sequenced a relative C_v value of ± 2.5 , ± 5 , ± 10 , ± 20 from the nominal. For the low flow case of 40 lbs/sec all negative steps produced stall except the -2.5 step. All other steps appeared normal. A nominal change of $C_v = 1$ gives approximately 1 lb/sec flow change (Figure 1).

Runs 1-9-70 315 and 316 operate at points of the system other than 520 psia. First the system was sequenced to RPM control to 22,000 RPM and the flow set to 86 lbs/sec with L30. Then the RPM set point was changed to 18,000 RPM at which point the flow was increased from 70 to 73 lbs/sec which is very close to the TES limit.

Run 1-10-70-301 is a repeat of runs 1-9-70-303 to 314 but includes digital print out information. (See Appendix Table 3).

7. Pump #1 Damping Characteristics continued) (1-10-70-302, 304)

A series of runs was made using the gas farm in place of the TES and operating the system with position controlled TPCV's for one TPA. Run 1-10-70-302 showed that operating in open loop control with the TES was impractical as the response time due to the TES was inordinately long in the order of 5 to 10 seconds.

Nominal conditions were PLP29 = 520 psia and flow rates of 40 lbs/sec and 80 lbs/sec. The size steps investigated were $\pm 1^{\circ}$ to $\pm 10^{\circ}$. The flow step experienced was a function of the nominal condition and the higher positive steps for the 80 lbs/sec case came close to the energy source limitation of 400 psia.

8. Dual Pump System Stability Test

A. TPCV Steps (1-10-70-305, 306, 311, 312)

These runs are similar to those in (7) with the exception that they are run with two TPA's. Again the initial PLP29 pressure set was 520 for initial flows of 40 lbs/sec and 60 lbs/sec. Also in this case the energy system limited the positive going steps for the 60 lbs/sec case.

A negative going TPCV step of 3° for the 40 lbs/sec case caused the system to go to its unstable condition.

Another series of runs was made for a lower initial PLP29 pressure of 620 psia and individual pump flow of 44.5 lbs/sec. This was repeated for another condition of 320 psia and a flow of 30 lbs/sec. The range of TPCV valve motion was $\pm 10^{\circ}$ from the nominal, with the high flow and pressure case going unstable at -6° step.

B. L30 Steps (1-10-70-307, 310)

Another check on the stability of the system was made by stepping the valve L30 positive and negative. This was done in PLP29 control at a set point of 520 psia and two initial flows of 40 lbs/sec and 60 lbs/sec. Various steps ranging from an effective C_v of +20 to -40 were used. The low flow case went unstable at a value of -7.5 while the higher steps for the high flow case brought the system close to the TES limits.

C. Bypass Valve Pulse (1-10-70-308, 309)

A third test of the stability of the dual pump system was a perturbation by pulsing and stepping one of the pump bypass valves, in this case L119. The conditions were PLP29 set point of 520 psia and two initial flows of 40 lbs/sec and 60 lbs/sec. The valve L119 was then pulsed to values of effective area openings from 2 in^2 to its full open position of 10 in^2 . For all values of area tested, the side pulsed increases in flow while the other sides flow is reduced to a point where it is in stall except for a value of 10 in^2 which caused the system to go unstable and an area of 15 in^2 and 20 in^2 caused the system to shut down.

A pulse of less than one second duration does not allow the system to stabilize at the peak of the pulse and therefore is always in a transient during the pulse.

9. TES Limit (1-10-70-313 thru 320)

A series of runs was made to determine the TES limits for speeds of 10,000, 14,000, 18,000, 22,000 in speed control. Response in the region near the limits would at best be quite slow.

The limits were defined by increasing L30 position until the TPCV's lost control. However, any type of control after the TPCV's have reached 50. degrees is very difficult as the system gain rapidly approaches zero.

Runs 1-10-70-313 to 316 are for one TPA and two valves while 1-10-70-317 thru 320 are for two TPA's and two TPCV's. (Figure 3).

10. TBV Closure (1-10-70-321)

An instantaneous TBV closure was simulated and a TPA taken off line. Flow from the malfunctioned pump steps in 50 millisecc while the other pump pick up speed to maintain pressure as the system is in PLP29 control at a set point of 520 psia. Both TPCV's are still in operation and a new operating point is found to provide the proper pressure. An 8 to 10 cps oscillation is observed on PLP29 after TBV closure and damps out in about one second. This is a function of the line configuration downstream of the pumps and upstream of the valve L30.

Appendix F

TABLE I
TEST SIMULATION DATA POINTS

<u>1-8-70 301</u>								
	<u>RPMA</u>	<u>WH350</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
1. Initial	750	9	.1	55	120	13	13	4
2.	5000	19	.45	80	120	15	13	22.5
3.	5500	20	.50	85	120	15	13	23.5
4.	18000	52	3.3	420	375	175	16.5	32.0
<u>1-8-70 302</u>								
1. PLP29 cont	18500	53	3.4	460	400	180	16.5	31.5
2. RPM cont	18000	52	3.3	440	390	170	16	31.5
3. PLP29 cont	18500	53	3.4	460	400	180	16.5	31.5
<u>1-8-70 303</u>								
1. TH65 in cont	18500	52	3.35	440	390	180	16.5	32
2. TH68 open	18500	52	1.5	445	390	180	16.5	24.5
3. TH68 in cont	18500	52	1.7	445	390	180	16.5	25.5
4. Increase op. pt.	21000	62	2.35	595	520	240	19.0	25.5
<u>1-8-70 304</u>								
1. Initial	21000	62	2.35	595	525	240	20	25.5
2. Stall	20800	37	1.6	590	540	160	16	21
3. Out of stall	20900	52	2.0	585	530	205	18	23.5
4. High point	22900	78	3.0	600	515	320	22.5	30
5. Low point	20900	51	2.0	585	535	200	18	23.5
6. High point	22500	75	2.9	600	520	300	22	28.5
<u>1-8-70 305</u>								
1. Initial	18000	62	4.15	400	250	210	28	52.5
	10000	38	1.45	205	120	80	16	47
	10000	24	1.1	220	155	60	14	39
<u>1-8-70 306</u>								
1.	10000	34	1.4	180	120	75	16	36.5
2.	14000	44	2.4	290	205	125	20	38
3.	14000	34	2.05	310	250	105	18	30.5
4.	14000	27	1.7	320	260	90	17	28
<u>1-8-70 307</u>								
1.	14000	47	2.5.5	280	190	135	20	42
2.	18000	58	4.0	420	285	200	27	43.5
3.	18000	43	3.2	460	380	140	23	31.5
4.	18000	37	2.9	465	395	120	22	30
5.	1800	36	2.8	470	395	120	22	29

Appendix F

1-8-70 308

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
1.	18000	43	3.2	460	380	165	23	31.5
2.	22000	52	4.75	650	535	240	30	32
3.	22000	46	4.35	660	550	220	28	30
4.	22000	42	4.0	660	560	200	27	29
5.	22000	53	4.8	650	530	245	30.5	32

1-8-70 309

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
1.	19400	40	3.25	520	440	170	23.5	30
2.	17500	36	2.4	430	360	130	20	28
3.	16400	44	2.9	380	300	150	21.5	33.5
4.	16400	36	2.5	400	325	130	20	30
5.	14000	31	1.9	310	260	100	18	29.5

Appendix F

1-9-70 301

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
1	14000	31	1.85	310	190	100	17	35
2	14000	41.5	2.3	295	180	120	19	41.5

1-9-70 302

1	14000	30	1.8	310	240	80	17.5	
2	14000	42	2.3	300	235	100	19	

1-9-70 303

1	14000	30	1.8	310	285	100	16.5	28
2	14000	41	2.3	300	280	120	18.5	31

1-9-70 304

1	14000	30	1.8	310	340	100	17	26
2	14000	40	2.25	300	330	120	18.5	28.5

1-9-70 305

1	14000	30	1.8	310	380	100	17	25
2	14000	40.5	2.2	300	390	120	19	28

1-9-70 306

1	14000	30	1.8	310	285	100	16.5	28
2	14000	60	2.9	210	270	155	22	37.5

1-9-70 307

1	14000	60	2.9	210	270	150	22	37.5
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1-9-70 308

1	18000	53	3.6	440	330	190	25	37
2	18000	53	0.5	440	330	190	25	18.5
3	18000	53	0	440	330	190	25	0

1-9-70 309

	<u>RPMA</u>	<u>WH350</u>	<u>WH65</u>	<u>PHF841</u>	<u>PHP69</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
1	19700	50	1.8	530	490	190	16.5	24
2	19500	41	1.5	530	490	160	16.0	22
3	20250	32	1.4	530	490	155	15.5	21.5
4	20200	59	2.05	530	490	220	22	26
5	19500	41	1.5	530	490	160	16	22
6	20200	24	1.25	530	490	140	14	21

1-9-70 310

1	19500	39	1.6	530	490	170	16	23
2	19500	41	1.5	530	490	160	16	22.5
3	19500	43.5	1.45	530	490	155	16	22
4	19500	45.5	1.65	530	490	175	16	23.5
5	19500	41	1.5	530	490	160	16	22.5
6	20000	37	1.4	530	490	150	16	21.5

1-9-70 311

1	20500	63	2.2	540	490			26.5
2	20300	60.5	2.15	540	490			26
3	20100	58	2.05	540	490			25.5
4	20300	65	2.3	540	490			27
5	20300	60.5	2.15	540	490			26
6	20000	56	1.95	540	490			25.5

1-9-70 312

1	21000	70	2.65	540	470	260	20	28
2	20300	60.5	2.15	540	480	220	18	26
3	19800	52	1.8	540	480	195	17	24
4	22000	78.5	2.8	540	460	300	21.5	31
5	20300	60.5	2.15	540	480	220	18	26
6	19500	42.5	1.6	540	490	165	16	22

Appendix F

1-9-70 313

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
1	25000	89	3.35	550	450	350	24	33
2	22200	80.5	2.95	550	460	310	22	32
3	20500	72	2.55	540	470	270	20	31
4	23200	100	3.85	570	440	410	26	39
5	22200	80.5	2.95	550	460	310	22	32
6	21300	62.5	2.2	540	480	230	18	30

1-9-70 314

1	22400	82.5	3.0	550	460	320	22	33
2	22200	80.5	2.95	550	460	310	22	32
3	22000	78.5	2.8	550	460	300	22	31
4	22600	85	3.15	550	460	330	23	34
5	22200	80.5	2.95	550	460	310	22	32
6	21700	76	2.75	550	460	290	21	30

1-9-70 315

1	22000	80.5	2.95	540	460	310	22	32
2	22000	86	3.05	510	415	320	20.5	36.5

1-9-70 316

1	22000	86	3.05	510	415	320	23	37.5
2	18000	70	2.0	360	290	215	18	35
3	18000	73	2.05	340	270	220	18	42

Appendix F

1-10-70 303

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
PCV = initial 24°	19500	40	1.55	530	400	160	16	24
+1°	20100	42.5	1.65	560	400	175	16	25
+5°	23000	52	2.25	700	400	235	18.5	29
-5°	15600	23	0.85	340	400	95	19	19
-3°	18000	29	1.20	440	400	120	14.5	21
-1°	19000	36.5	1.40	500	400	195	15	23

1-10-70 304

PCV = initial 38°	22100	80	3.0	540	390	300	22	38
+5	23100	84	3.2	580	390	340	23.5	43
+10	23600	86	3.4	600	390	350	24	48
-10	19000	63.5	2.05	440	390	215	18	28

1-10-70 305

PCV = initial 42°	20400	60	4.8	535	400	290	30	42
+5	21400	63.5	5.25	580	400	270	33	47
+10	21800	64.5	5.45	595	400	280	34	52
-10	17600	48.5	3.4	430	400	180	24	32

1-10-70 306

PCV = initial 32°	21100	40	3.25	520	385	175	24	32
+5	22600	44.5	4.05	610	380	210	27	37
+10	19000	49	4.75	680	375	290	30	42
-1	18500	48	3.2	505	380	165	23	31
-2	18000	47	3	480	380	160	22	30
-3	-	-	-	-	-	-	-	29

1-10-70 307

VL30=initial 89.3	19500	40	3.35	525	445	180	24	30.5
+2	19500	41	4.0	520	445	180	24	31
+10	19500	44	3.6	530	440	190	25	32
+20	19700	48	3.85	530	430	200	26	33
-2.5	19500	38.5	3.3	525	445	180	24	30.25
-5	19500	38	3.2	525	445	180	24	30
-7.5	19000	36.5	3.15	525	440	180	23	29.5

Appendix F

1-10-70 308

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P235</u>	<u>PHP69</u>	<u>TH65</u>
19 = initial	19500	40	3.25	520	440	175	24	30
+2 pulse	19500	44	3.6	520	430	190	25	32
+2 pulse	19500	44	3.6	520	430	190	25	32
+3 pulse	19500	44	3.6	520	425	185	25	32.5
+4 pulse	19500	47.5	3.8	520	415	180	26	35.5
+10 pulse	19500	46	4.4	420	375	225	28.5	39
+10 step	20100	58	4.6	535	400	240	30	39
+20 step	-	-	-	-	-	-	-	-
+15 pulse	-	-	-	-	-	-	-	-
+10 pulse	-	-	-	-	-	-	-	-
+4 pulse	19500	44	3.7	520	415	180	26	32.5

1-10-70 309

19 = initial	20400	60	4.8	535	390	245	30.5	40
+10 pulse	20000	83	5.15	400	345	280	31.5	50
+10 pulse	20000	83	5.15	400	345	280	31.5	50
+10 step	-	-	-	-	-	-	-	-
+5	20200	64	5.05	500	370	260	32	44
+6	20200	67.5	5.15	490	350	270	32.5	46

1-10-70 310

1930=initial 138.5	20100	60	4.8	535	395	250	31	40
+10	20800	64	5.15	535	375	265	32	49
+20	21000	68	5.5	535	350	285	34.5	52
+5	20500	62	5.0	535	380	260	32	42
+15	20900	66	5.3	540	360	280	33.5	47.5
-10	20000	56	4.45	535	405	235	29.5	38
-20	19900	52	4.2	535	420	220	28	35
-30	19600	48	3.8	530	430	200	26	33
-40	19500	43.5	3.6	530	440	190	25	31.5

Appendix F

1-10-70 311

	<u>RPMA</u>	<u>WH850</u>	<u>WH65</u>	<u>PHP841</u>	<u>PHP64</u>	<u>P285</u>	<u>PHP69</u>	<u>TH65</u>
PCV = initial 37°	21500	44	4.15	620	380	210	27.5	37
+5	23000	48	4.8	705	370	245	30.5	42
+10	24100	50.5	5.3	765	365	275	27.5	42
-1	21200	43.5	4.0	610	380	205	26.5	36
-2	21000	42	3.8	595	380	200	26	35
-3	20500	41	3.6	570	380	190	25	34
-5	19500	38.5	3.3	525	380	175	23.5	32
-6	-	-	-	-	-	-	-	-

1-10-70 312

PCV = initial 36°	14500	30	2	325	390	105	17.5	36
+5	17800	36.5	2.85	4.55	380	150	21.5	41
+10	19900	44.5	3.75	540	380	195	26	46
-1	13600	28.5	1.8	300	390	95	17	35
-2	13000	27.5	1.6	280	390	90	16	34
-3	12500	26.5	1.5	260	390	80	16	33
-4	11500	25	1.35	235	390	75	15	32
-5	10000	22.5	1.1	195	390	60	14	31
-10	7500	19.5	0.75	140	390	40	13.5	26

TABLE 2 - DEFINITION OF TERMS

NAME	DEFINITION	UNITS
MPA	Pump torque A side	ft/lbs
MPB	Pump torque B side	ft/lbs
MTA	Turbine torque A side	ft/lbs
MTB	Turbine torque B side	ft/lbs
P285B	Turbine inlet pressure B side	psia
P285A	Turbine inlet pressure A side	psia
P1	Atmospheric pressure	psia
PHP20	H21 inlet pressure	psia
PHP21	Heater inlet pressure	psia
PHP63	Heater discharge pressure	psia
PHP64	TPCV inlet pressure	psia
PHP341	Pump discharge pressure A side	psia
PHP941	Pump discharge pressure B side	psia
PHP69	Turbine exhaust pressure	psia
PLP5	Propellant feed line pressure	psia
PLP29	L30 inlet pressure	psia
PLP30	L30 discharge pressure	psia
PLP61	Propellant tank pressure	psia
PLPS	Pump suction pressure	psia
PQP30	CH ₂ gas farm pressure	psia
R285	Turbine inlet density	lbs/ft ²
RHP21	Heater inlet density	lbs/ft ²
RHP63	Heater discharge density	lbs/ft ²
RHP64	TPCV inlet density	lbs/ft ²
RHP69	Turbine discharge density	lbs/ft ²

Appendix F

NAME	DEFINITION	UNITS
THT69	Turbine discharge temperature	$^{\circ}\text{R}$
TNTA	Turbine torque constant A side	-
TNTB	Turbine torque constant B side	-
THT63	Heater discharge temperature	$^{\circ}\text{R}$
TLT29	Propellant feed line temperature	$^{\circ}\text{R}$
NTA	Turbine speed A side	RPM
NTB	Turbine speed B side	RPM
WFS	Total turbine discharge flow	lbs/sec
WH	Heater flow	lbs/sec
WH9	Turbine drive flow	lbs/sec
WH21	H21 flow	lbs/sec
WH53	GH ₂ gas farm flow	lbs/sec
WH63	H63 flow	lbs/sec
WH55	TPCV flow A side	lbs/sec
WH58	TPCV flow B side	lbs/sec
WH350	Pump discharge flow A side	lbs/sec
WH350	Pump discharge flow B side	lbs/sec
WH360	Turbine flow A side	lbs/sec
WH960	Turbine flow B side	lbs/sec
WL2	Propellant feed line flow	lbs/sec
WL3	Propellant feed line flow	lbs/sec
WL30	L30 flow	lbs/sec
WL119	Pump bypass flow A side	lbs/sec
WL219	Pump bypass flow B side	lbs/sec

Appendix F

NAME	DEFINITION	UNITS
WLCT	Catch tank flow	lbs/sec
WPA	Pump suction flow A side	lbs/sec
WPB	Pump suction flow B side	lbs/sec
WBCA	Bearing coolant flow A side	lbs/sec
WBCB	Bearing coolant flow B side	lbs/sec
TH55	TPCV position A side	degrees
TH58	TPCV, position B side	degrees
A21	H21 area	in. ²
CVL30	L30 flow coefficient	

Appendix F
TABLE III
FURTHER DUMPING CHARACTERISTIC DATA POINTS

19477.50	461.20	1.52	520.20	520.80	43.10	22.71
0.00	0.00	1.56	75.30	520.60	43.10	22.72
19477.50	462.20	1.5	520.20	520.50	43.10	23.10
0.00	0.00	1.57	75.30	520.50	43.60	23.10
19495.00	503.00	1.65	520.30	520.60	48.10	23.70
0.00	0.00	1.66	75.30	520.30	48.10	23.70
19477.50	467.50	1.61	533.10	507.70	40.60	21.43
2.50	0.20	1.65	67.40	507.70	40.30	21.31
19477.50	433.20	1.59	500.10	520.30	45.60	23.10
0.00	0.00	1.62	75.10	520.50	45.60	23.30
19500.00	526.00	1.72	521.30	520.50	50.60	24.13
0.00	0.00	1.75	75.70	520.50	50.60	24.13
20200.00	441.40	1.70	524.20	520.40	35.60	22.28
0.00	0.00	1.70	71.70	520.40	35.60	22.10
19477.50	463.00	1.59	520.10	520.30	45.60	23.10
2.50	0.00	1.67	75.50	520.50	45.60	23.30
19402.50	570.60	1.60	528.70	520.70	55.60	25.17
0.00	0.20	1.60	75.30	520.70	55.60	25.17
20215.00	337.00	1.35	522.00	520.40	25.50	21.85
0.00	0.20	1.38	75.70	520.40	25.50	21.86
19477.50	483.00	1.59	520.00	520.50	45.60	23.10
0.00	0.20	1.61	75.30	520.30	45.60	23.10
20110.00	608.00	2.11	522.20	520.60	65.60	26.68
2.50	0.20	2.17	75.10	520.60	65.60	26.78
20160.00	602.20	2.13	531.80	520.70	65.10	26.78
0.00	0.00	2.15	75.00	520.70	65.10	26.78
20317.50	638.30	2.22	532.00	520.60	67.60	27.23
0.00	0.00	2.24	74.60	520.60	67.60	27.23
20477.50	715.00	2.30	533.30	520.70	70.10	27.10
0.00	0.20	2.32	75.00	520.70	70.10	27.17
20012.50	638.20	2.00	531.00	521.70	62.60	26.35
0.00	0.00	2.06	75.00	520.70	62.60	26.35
20317.50	630.00	2.22	532.30	520.70	67.60	27.24
0.00	0.20	2.24	74.60	520.70	67.60	27.23
20070.00	741.00	2.30	531.30	520.30	72.60	28.43
2.50	0.20	2.40	74.70	520.30	72.60	28.40
20020.00	570.20	1.71	524.00	520.70	57.70	25.53
2.50	0.00	1.74	75.10	520.70	57.70	25.53
20120.00	645.00	2.22	532.10	520.80	57.60	27.24
0.00	0.00	2.23	74.60	520.80	57.60	27.24

A	21005.00	797.50	1.50	530.50	67.57	520.80	77.60	21.61
B	2.50	0.00	2.57	74.50	0.02	520.80	77.60	21.61
A	19495.00	500.80	1.05	527.10	42.11	520.70	47.60	21.61
B	2.50	0.00	1.67	75.10	0.02	520.70	47.60	21.62
A	20320.00	688.40	2.22	532.80	60.07	520.80	67.60	27.23
B	2.50	0.00	2.23	75.00	0.02	520.80	67.60	27.23
A	21952.50	918.60	2.95	540.80	77.90	520.90	87.70	32.53
B	0.00	0.00	2.95	74.50	0.02	520.90	87.70	32.53
A	21950.00	918.60	2.94	540.70	77.88	520.80	87.70	32.53
B	0.00	0.00	2.96	74.50	0.01	520.80	87.70	32.52
A	22190.00	948.40	3.04	541.90	79.90	520.90	90.20	33.38
B	0.00	0.00	3.05	74.40	0.03	520.90	90.20	33.38
A	22430.00	979.80	3.14	543.10	82.08	520.90	92.70	34.40
B	0.00	0.00	3.14	74.20	0.02	520.90	92.70	34.40
A	21725.00	888.40	2.84	539.70	75.71	520.90	85.20	31.70
B	0.00	0.20	2.85	74.40	0.02	520.90	85.20	31.70
A	22195.00	948.60	3.04	542.00	80.00	520.80	90.20	33.38
B	0.00	0.00	3.05	74.10	0.02	520.80	90.20	33.38
A	22660.00	1011.40	3.24	544.50	84.21	521.00	95.20	35.56
B	2.50	0.00	3.24	74.50	0.02	521.00	95.20	35.55
A	21795.00	828.40	2.65	537.80	71.36	520.80	80.20	30.40
B	0.00	0.00	2.66	74.40	0.03	520.80	80.20	30.40
A	22190.00	948.40	3.04	541.60	80.00	521.00	90.20	33.38
B	0.00	0.00	3.04	74.50	0.02	521.00	90.20	33.38
A	23170.00	1076.50	3.44	546.70	88.54	521.00	100.20	38.92
B	0.00	0.00	3.43	73.90	0.02	521.00	100.20	38.91
A	20467.50	715.00	2.50	533.70	62.54	520.90	70.10	27.76
B	2.50	0.20	2.51	74.20	0.03	520.90	70.10	27.76
A	22192.50	948.40	3.04	542.00	79.77	520.90	90.20	33.38
B	0.00	0.00	3.05	74.10	0.02	520.90	90.20	33.38
A	24112.50	1210.20	3.85	550.50	97.13	520.20	110.20	52.64
B	0.00	0.00	3.85	73.50	0.01	520.20	110.20	52.63

SYSTEM CONFIGURATIONS

FIGURE 2
DUAL PUMP STABILITY REGION

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FIGURE 3
TURBINE ENERGY SOURCE LIMITS (TES)

TURBOPUMP PERFORMANCE MAP
TEST CELL 'C'

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