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## ABSTRACT

Experience in the design and development of liquid hydrogen feed systems utilizing two turbopumps operating in parallel is described. The pumps are supplied with liquid hydrogen from a common inlet and discharge into a common duct; the turbines also are supplied with turbodrive gases from a common inlet. Two system configurations were designed, developed, and delivered to NRDS: one having dual Mark 9 turbopumps and one having dual Mark 25 turbopumps. The systems deliver flows up to 330 lb/sec and pressures up to 2000 psi. They were developed for use in Phoebus reactor testing performed by the Los Alamos Scientific Laboratory.

Component and system performance, and dynamic characteristics of the systems are described. Development tests have proved the practicality of parallel dual, liquid hydrogen turbopump operation. The two units operate with complete hydrodynamic stability, sharing the hydraulic load equally, and no detrimental mechanical interactions have been found.

Dual turbopumps offer the potential of emergency, single pump operation. The current feed system (Rocketdyne Model NFS-3B) has a check valve in each pump discharge prior to the common header, and the potential for such emergency operation is being evaluated.

## PHOEBUS FEED SYSTEM

In 1961, the Los Alamos Scientific Laboratory and the Space Nuclear Propulsion Office began planning for a new series of nuclear rocket reactor tests to be designated the Phoebus reactor test series. The Phoebus reactors were to be larger, more powerful versions of the Kiwi B Reactors, and a power level range between 3000 and 4000 megawatts was targeted for the new reactors.

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The pump performance level requirements established for the Phoebus Feed System were:

| | |
|---|---|
| Developed Head, feet | 50,000 |
| Delivered Flow, gpm | 21,200 |
| NPSH, feet | 350 |

In addition, the performance range requirement was specified to encompass an operating envelope bounded by a continuously variable, delivered discharge pressure ranging from 100 to 1600 psia, and a continuously variable, delivered flowrate ranging to approximately 200 lb/sec.

System Definition A survey was made of various methods for meeting the liquid hydrogen pumping requirements associated with the higher powered reactors, and it was concluded that manifolding (in parallel) multiple Mark 9 turbopumps was feasible, that liquid hydrogen bypass capability would provide the flexibility of very low delivered flowrate at full system discharge pressure, and that this approach offered significant schedule and cost advantages. Accordingly, in late 1961, a comparative study was conducted by Rocketdyne of alternate configurations for coupling two Mark 9 turbopumps to a common hydraulic load and a selection made of a preferred configuration. The resulting Nuclear Feed System (NFS-3) is shown schematically in Fig. 1. This system has a dual turbopump speed control subsystem and a pump specific speed limit control subsystem. Dual, parallel turbopump speed control loops are used to control both turbopump speeds from a common supplied reference. Shaft speed is sensed on each turbopump, by means of proximity-type inductance pickups, and compared to the speed reference signal. The resulting error signal is supplied to an integrating-type controller, which, through an internal-position loop adjusts the turbine valve to vary turbine power and speed. The NFS-3 turbopump speed control system is integrated into the facility flow control system, which supplies the reference speed-change signal upon comparing measured reactor flow to commanded reactor flow.

Pump specific speed limiting is accomplished by controlled actuation of the liquid hydrogen bypass valve. Both the pump discharge volume flowrate and the turbopump shaft speed are measured, and the ratio of flowrate-to-pump speed (Q/N) is related to the preselected minimum value for Q/N. If the measured Q/N is less than the desired minimum Q/N, an error signal is generated, which causes a proportional integral plus lead-lag-type controller to command the bypass valve to open, thereby diverting liquid hydrogen out the bypass line, and increasing total pump flow until the minimum desired Q/N value is satisfied.

The servocontrol logic diagram for NFS-3 is shown in Fig. 2. Alternate control systems configurations analyzed in the study included: (1) single vs dual turbine control valves, i.e., one for each turbine; and (2) single vs dual liquid hydrogen bypass valves (LHBV). Dynamic analyses conducted included; startup, full power, and shutdown operations; tolerance studies (turbopump mismatch effects between the No. 1 and No. 2 units and valve characteristic effects); and malfunction analyses. As a result of the studies, a single turbine control valve and a single liquid hydrogen bypass valve were found to provide stable operation over the operating regime of the dual turbopumps, and on the basis of simplicity were selected for utilization in the system.

Figure 3 indicates the dynamic characteristics of the dual turbopump system as exhibited in the initial analog studies. Primary system parameters are indicated, but only the output from turbopump unit No. 1 is included because on the indicated scale, the behavior of the two units appear the same. Figure 3a presents a fast startup and shutdown operation with speed ramp rates of 34,000 rpm/sec. This condition represents an order of magnitude faster speed change than anticipated to be demanded in reactor testing. The model indicated very good characteristics for this rapid startup. Due to turbopump and fluid inertias, the shutdown operation exhibited desirable exponential decay characteristics, since the reduction in reactor power is determined by the fission product decay, and normally eliminates the need for rapid shutdown of the liquid hydrogen feed system.

The systems response to small (400 rpm) speed demand steps at 34,000 rpm is indicated in Fig. 3b with a 100 rpm speed overshoot and approximately 1 lb/sec flow overshoot at 210 lb/sec delivered flow. The indicated system speed and specific speed control responses were approximately 3 to 4 cps (90-degree phase shift point) over the operating range.

The results of the investigations of general pump/system load stability analyses are shown in Fig. 4. The load line use for the analysis is indicated, with the relative slope of possible pump curves along the planned operating specific speed indicated for slope comparison. This figure illustrates several interesting characteristics. Hydrodynamically, the Mark 9 pump would be very stable along the planned Phoebus operating load line because the slope of the Mark 9 head/flow characteristic is approximately -10psi/lb/sec for two pumps operating in parallel. For this application, changes in fluid flow are stable and overdamped for all pump H/Q slopes more negative than -7; stable, though underdamped, for pump H/Q slopes up to +1; and unstable for slopes greater than +1. Relatively steep negative pump curves are desirable for systems in which the pumps are operated in parallel, which in effect reduces the equivalent system pump H/Q curve slope by a factor of 2.

Upon completion of the design and associated analyses of the NFS-3 system in the late spring of 1962, the system configuration shown in Fig. 5 and described below was accepted by SNPO-Washington and LASL, and fabrication of the hardware was initiated.

Design Features The two Mark 9 pumps and turbines are mounted vertically, side by side, in an alignment collor, which is supported by a tripod structure. Liquid hydrogen is supplied to the system inlet from a 10-inch facility duct. The initial horizontal system inlet duct splits and turns 90 degrees downward; two vertical 8-inch ducts, 6 feet long, then carry the hydrogen into the pump inlets. The high-pressure hydrogen is discharged horizontally from the single-exit volutes of each pump into two adapter duct sections containing turbine-type, 4-inch liquid hydrogen flowmeters.

The two 6-inch discharge ducts then turn 90 degrees upward, rise 7 feet, and turn 90 degrees outward, joining into a common 8-inch duct, which mates with the facility discharge duct. A 3-1/2-inch liquid hydrogen bypass valve, located just upstream of the system discharge flange, provides the capability for bypassing controlled amounts of hydrogen, thereby limiting the hydraulic impedence that the facility discharge ducting and test reactor may impose on the feed system.

The supply of turbodrive gases for the NFS-3 system was originally specified to be high-pressure, ambient-temperature hydrogen gas, stored in facility bottles. A 6-inch, combination shutoff and throttle valve is utilized to control the flow of hydrogen gas to the turbine, in response to the demands of the turbopump speed control system; this flow is conducted to both turbine inlet flanges by means of an adapter and two 3-inch turbine inlet ducts, which are approximately 6 feet in length. The two turbine exhaust flows are carried to the facility flare-stack line by 8-inch exhaust ducts, which turn 90 degrees outward and extend 9 feet horizontally and 13 feet vertically to the 30-inch facility flare-stack header.

The design of the NFS-3 system permitted ready conversion to single-turbopump operation, termed single mode, by (1) removal of one each of the pump vertical inlet ducts, pump discharge ducts, and turbine inlet ducts; (2) capping of the unused inlet flange of the pump discharge "Y" duct and the exit flange of the turbine inlet "Y" duct; (3) blanking of the unused turbine exhaust connect flange in the facility flare-stack header; (4) substitution of a single, horizontal system inlet duct for the split inlet duct; and (5) appropriate deactivation of the nonoperative turbopump speed control and specific speed sensing circuits.

Development Program

Single Mode The development test program of the NFS-3 system was initiated in December 1963, and completed in April 1965. The first series of 12 tests was conducted in single mode, and was concerned with (1) demonstration of the performance potential of the turbopump to full speed and power, (2) limited pump performance mapping and stall definition testing, and (3) verification of the operational capability of the turbopump speed and pump specific speed control systems.

A second series of 24 tests was conducted with the following objectives: (1) demonstration of mechanical integrity of the turbopump to 34,000 rpm, (2) measurement, by means of special proximity instrumentation, of the pump rotor radial and axial displacements as a function of turbopump speed and pump specific speed, and (3) turbopump speed control loop frequency response tests. The pump rotor displacement measurements obtained from this series of tests revealed for the first time the existence of subsynchronous rotor whirl over certain operating regions of the pump map.

The third and final series of eight single-mode tests of the NFS-3 development program was initiated in February and completed in April 1965. The objectives of the test series were exploratory evaluations of several potential hydrodynamic forcing functions, and of effective bearing spring rates (with and without bearing carrier dampening) upon the subsynchronous whirl tendencies of the Mark 9 pump rotor.

Dual Mode The first dual mode tests were initiated in February 1964. Three low-power exploratory tests were conducted, and some limited dual-turbopump speed control response data was obtained. In general, the feasibility of dual-turbopump operation, with common sources of turbodrive gases, pump inlet, and system discharge ducting, was indicated. A second series of 14 dual-mode tests was conducted during the period of November 1964 through January 1965. The first 4 tests were concerned with evaluating the mechanical and hydrodynamic performance of the dual-turbopump operations, while the last 10 tests were directed toward the determination of the capabilities of the dual-turbopump speed and specific speed-limiting control systems. NFS-3 dual-mode test experience is indicated in Table I.

Response of the NFS-3 system to a step demand in turbopump speed of 4000 rpm is shown in Fig. 6. The acceleration of the turbopump approached 50,000 rpm/sec$^2$, the overshoot was less than 1000 rpm, and the speed differential between the two turbopumps was only a few hundred rpm. The behavior of the system was substantially as predicted in Fig. 3b, although the amplitude of the speed step in this test was 10 times that used in the analog model study.

Response of the NFS-3 system, operating in dual mode, to a programmed increase in the impedance exhibited by the facility discharge system (created by commanding the facility throttle valve toward the closed position) caused the flow through each pump to decrease at a maximum rate of 45 lb/sec/sec as shown in Fig. 7. The LHBV opened at a maximum rate of 110 percent/sec to limit the measured flow error to 4.5 lb/sec. (The flow error would have been appreciably less if the LHBV had been modulating flow at the time of the perturbations; but because of the deadband created by the LHBV seal, 12 percent of full stroke occurred before any appreciable bypass flow developed.)

This series of tests clearly demonstrated the feasibility and practicality of dual-turbopump operation. The two units operated with complete hydrodynamic stability, sharing the hydraulic load equally, and no detrimental mechanical interactions were found.

A duplicate NFS-3 system was shipped to Nuclear Rocket Development Station in March 1965 for installation in Test Cell C.

Phoebus 1 and Pheobus 2 Test Requirements Meanwhile, in 1964, LASL's planning for the Phoebus reactor tests had advanced to the point where two reactor configurations and their test requirements had been identified. The first configuration, Phoebus 1, based on the Kiwi B4 reactors, would also feature a 35-inch reactor, and would be uprated in power sufficiently to generate fuel element power densities equivalent to those planned for the second configuration. The latter unit, Phoebus 2, would feature a 55-inch reactor, and a planned power level to 5000 megawatts. The required feed system performance levels, identified with the two planned Phoebus reactor configurations are listed below:

|  | Phoebus 1 | Phoebus 2 |
|---|---|---|
| Target Power Level, megawatts | 2000 | 5000 |
| Hydrogen Flowrate, lb/sec | 115 | 290 |
| Pump Discharge Pressure, psia | 1950 | 1450 |

About the same time, Rocketdyne had undertaken a company-sponsored project to design and fabricate a more powerful and improved axial-flow hydrogen pump, based on the same physical size as the Mark 9, and utilizing some of its elements. This test pump was designated the E-bladed, Mark 9 pump. The E-blading hydrodynamic changes included the utilization of symmetrical blading; increasing the flow and head coefficients, while maintaining approximately the same diffusion and retardation factor as were employed in the Mark 9 stators; and increasing the solidity, but decreasing the blade height slightly. These changes resulted in a test pump featuring an inducer plus four high-pressure-rise axial stages within the same envelope as the inducer, plus six axial stages Mark 9 pump (Fig. 8); and with predicted hydrodynamic performance increases of approximately 50 percent in flow, 26 percent in total head rise, and 89 percent in fluid horsepower. The predicted performance map of the E-bladed Mark 9 pump, as compared to the original Mark 9 pump, is presented in Fig. 9.

In view of the potential of the E-bladed pump to satisfy, in single mode, the pumping requirements of the Phoebus 1 reactor and, in dual mode, the Phoebus 2 reactor, SNPO-Washington authorized a series of electric drive tests to define the performance of the modified pump. A total of 40 tests were conducted during the period of December 1964 through April 1965, to determine the H/Q, stall, and cavitation characteristics of the pump up to 30,000 rpm. The results of these tests are shown in Fig. 10. The measured NPSH requirements were equivalent to one velocity head at the inducer inlet over the Q/N range tested. No measurement of quality was made at the inlet; however, the results indicate that mixed phase hydrogen might be pumped with this design and that testing with the pump mounted just below a vertical tank, in conjunction with tank emptying studies, would be profitable.

NFS-3A Design Features Possessing proved hydrodynamic performance of the E-bladed pump, SNPO-Washington authorized a new scope of work for the Phoebus Feed System program, in which modifications to components of the NFS-3 system to uprate the feed system performance to the new requirements of the Phoebus 1 and Phoebus 2 reactor test series would be accomplished and the system redesignated NFS-3A. In addition to incorporating the E-blading, the modified pump, hereafter referred to as the Mark 25 pump, was strengthened mechanically by the use of K-Monel in the rotor; the use of larger, duplex 55 mm bearings (loaded back to back) at each end of the pump; and other detail improvements.

The increased pump power requirements, coupled with a decision for NRDS operation to supply the turbodrive gases from liquid hydrogen bled from the pump discharge line and warmed to ambient temperature by a hot water heat exchanger, dictated modifications to the turbine. Because of the turbine inlet pressure limitations resulting from the use of a pump-bleed system, it was necessary to increase the effective turbine flow area.

This change was accomplished by removal of the first-stage inlet nozzles and rotor blades, making the previous second-stage stator and rotor the inlet stage of the modified turbine. In addition, the turbine was strengthened by the use of Inco 718 in the rotor, by increasing the blade sections in the last two rotor stages, and other detail improvements. With these modifications, the unit was redesignated as the Mark 25 turbine. Finally, a new, multiple-row, ball-spline coupling was designed to provide greater torque and speed capacity at the pump-turbine interface.

The increased flow requirements of the uprated Phoebus Feed System also dictated changes in the systems ducts (Fig. 11). The original pump inlet ducts had short adaptive exit sections below the second bellows to accommodate a reduction from an 8-inch-diameter duct down to the 7.25-inch-diameter Mark 9 pump inlet. The modification to the pump inlet duct involved replacing the short, adaptive, exit section with an exit section retaining the 8-inch diameter down to the Mark 25 pump inlet flange.

The original pump discharge ducts also had short adaptive inlet sections to accommodate the change in cross section from that of the 4-inch flowmeter to that of the 6-inch diameter, major portion of the pump discharge ducts. The 4- and 6-inch flowmeters are shown in Fig. 12. The 6-inch flowmeter utilized in the NFS-3A and 3B systems was scaled from the 4-inch NFS-3 version. To maintain flow measurement response, while retaining the same magnetic pickups to sense the passage of the blade tips, two more blades (totaling six) were added to the 6-inch rotor. The changes to the discharge ducts involved tapered sections from the 5-inch pump discharge flanges to the 6-inch flowmeter housings, the substitution of the larger liquid hydrogen flowmeters, and a larger bypass valve connect flange to accommodate a 5-1/2-inch liquid hydrogen bypass valve.

The turbine inlet ducts were redesigned to increase their diameter to 4 inches, and to utilize externally tied bellows. These changes increased the flow capacity of the turbine inlet ducts, without the penalty of excessive pressure drop.

NFS-3A Development Program A single-mode development test program of the NFS-3A system was initiated in May 1965, and continued through December 1966. Because of the lead time required to fabricate and modify the system hardware, the initial system tests were conducted with the E-bladed pump; a five-stage Mark 9 turbine (the blades were machined off the first-stage rotor, and the inlet nozzle block removed); and a modified NFS-3A type pump inlet duct. The remainder of the system components were NFS-3 hardware.

The first series of 35 tests were conducted between May and October 1965. The objectives of this test series were (1) to demonstrate the performance expected of the Mark 25 turbopump over the complete operating map specified for the uprated Phoebus Feed System, (2) to define the vibration characteristics (critical speeds, subsynchronous whirl regions, synchronous vibration levels, etc.) as a function of the turbomachinery operating point, (3) re-evaluation of the capabilities and response characteristics of the turbopump speed and pump specific speed limiting control systems, and (4) the pump stall-recovery capabilities of the NFS-3A system. Table II presents three typical test sequences employed in the system test series, the turbopump speed and pump specific speed are preselected and automatically time programmed.

The hydrodynamic performance of the E-bladed pump during the system test agreed closely with the performance exhibited during the earlier electric drive tests. Since the system tests ranged to 34,000 rpm, and the pump discharge pressures to 2000 psi, the compressibility effect upon the apparent head developed by the pump was more evident. By properly accounting for the enthalpy conditions existing at the inlet and exit of the pump, the true head rise across the pump could be determined, and the true head vs volume flowrate curve, obtained from the higher power tests, correlated well with the curves obtained from the lower power tests. In addition, the definition of the stall line, a constant value of $Q/N = 0.30$ over a range of speeds from 10,000 to 32,000 rpm, confirmed the results obtained from the earlier electric drive tests.

The vibration and rotordynamic characteristics exhibited by the interim NFS-3A system during the initial test series can be summarized as follows: (1) an apparent, bearing-stiffness-determined, pump rotor critical speed existed at approximately 26,500 rpm, (2) subsynchronous whirl of the pump rotor was in evidence when the pump operating specific speed was less than the design, and the shaft speeds were above 24,000 rpm, (3) the pump synchronous radial vibration levels, exhibited at the forward bearing housing, did not normally exceed 20 g, and (4) a supersynchronous, 700-cps vibration, possibly flow induced, was usually exhibited in the system mount, ducts, and turbomachinery housings when the system was operated at high power and high pump specific speeds. These vibration modes were not believed to be sufficiently strong to limit the operation of the system for the planned reactor tests.

The development of the turbopump speed and the pump specific speed limiting control systems resulted in dynamic control capabilities which exceeded the requirements of NRDS. Specifically, the bandwidth of the turbopump speed control system with adequate stability margin, was determined to be 2 cps at 30,000 rpm. The response of the specific speed limiting control system was optimized to limit the reduction in pump operating Q/N to less than 11 percent, when the system delivered flow was deliberately reduced at a rate as high as 1000 $lb/sec^2$. When conducting tests in which dynamic control operations occurred, no significant control interaction stability problems were evidenced.

The stall recovery capabilities of the NFS-3A system were demonstrated over a range in speeds from 10,000 to 25,000 rpm. By driving the facility throttle valve at maximum rate toward its closed position, with the pump operating initially at a Q/N of 0.33, it was possible to overwhelm momentarily the specific speed limiting control and drive the pump into stal Immediately, however, the liquid hydrogen bypass valve was commanded o reducing the hydraulic impedance seen by the pump, and stall recovery w effected with the system resuming steady-state operation at a Q/N of 0.33. The duration of the stall-transient varied from 0.10 second at 10,000 rpm to 0.23 second at 25,000 rpm. Figure 13 presents a time display of some of the pertinent system operating parameters from a typical stall-recovery test.

During December 1965 and January 1966, a second series of five tests was conducted with the interim NFS-3A system to evaluate the mechanical and rotordynamic behavior to be expected from the Mark 25 pump rotor. For these tests, a specially modified E-bladed pump, with duplex 45 mm bearing sets (loaded back to back) at each end of the pump rotor, was utilized. The results obtained demonstrated the improvements in rotor radial piloting and axial positioning to be expected from the 55 mm duplex bearing configuration, in that there was no evidence of rotor rubbing in close-clearance areas. Furthermore, subsynchronous whirl was not observed, even though the pump was operated at a specific speed of approximately 900 to 30,000 rpm.

By February 1965, the first Mark 25 turbopump, and one each of all of the modified system ducts, were available for converting the interim NFS-3A system to a single-mode NFS-3A system. The requisite components were installed and a series of 25 Mark 25 turbopump tests conducted. The objectives of this test series were (1) to verify the hydrodynamic performance of the Mark 25 turbopump over the complete operating map specified for the uprated Phoebus feed systems, (2) to determine the rotor dynamic and vibrations characteristics of the new turbomachinery in the NFS-3A system as a function of operation point, and (3) to demonstrate the mechanical integrity of the complete system by a series of six full-power, facility-duration tests. The data from this test series confirmed the performance, rotordynamic, and mechanical vibration characteristics of the earlier interim NFS-3A system test data, with the exception that the subsynchronous whirl region had moved up into the corner of the pump map.

With the completion of the aforementioned test series in May 1966, acceptance tests of two Mark 25 turbopumps were conducted, and the units delivered to NRDS. A new scope of development effort was then authorized in June 1966, to expand the available data on the nature and possible causes of the rotordynamic and vibration phenomena observed in the earlier development testing, and to accumulate additional test time on the Mark 25 turbopumps prior to entering the planned dual-mode test program. This additional, single-mode, test program continued through December 1966, during which time 30 controlled input ("shaker") vibration tests and 46 turbine-powered pumping tests of the NFS-3A system were carried out.

The purposes of the shaker tests were to determine to what extent the system's structural resonances were associated with the vibration phenomena noted on the turbomachinery housing and the system ducting, and to investigate the effect of several possible structural modifications upon the principle structural resonances. The results of the vibration testing indicated many natural frequencies, with a strong 710-cps resonance in the pump inlet duct. Also, it was noted that when the pump inlet duct was excited at 380 cps, it responded sharply at 760 cps. Additionally, the turbine inlet duct exhibited a strong resonance at 370 cps. Structural modifications performed during the shaker tests produced little change in the multiresonant characteristics of the system, although a reduction in amplitudes was noted when the turbopump support was stiffened.

During the conduct of the system pumping tests, particular attention was paid to the rotordynamic, hydrodynamic, and mechanical vibration characteristics exhibited by components of the system as a function of operating point on the pump map, as well as direction of change of the operating point. Subsynchronous whirl, at a frequency of approximately 0.62 times the rotor speed frequency, was noted to occur at pump specific speeds less than design and at speeds above 30,000 rpm; the edge of the whirl region seemed to correlate with a line, the slope of which is proportional to the ratio of head developed divided by speed, while the location of the whirl region on the map appears dependent on the bearing stiffness, i.e., at constant specific speed, the greater the bearing stiffness, the higher the threshold speed/pressure required to trigger the instability.

On occasion, usually correlating with a particular pump, 120-cps pressure oscillations were noted when the pump was operated in the vicinity of the design specific speed and above 32,000 rpm. The data indicate that the fluid oscillation is a standing longitudinal wave in the liquid hydrogen system, but the initiating source has not yet been identified. When the pump was operated at flowrates between 137 and 155 lb/sec, and at speeds above 31,000 rpm, a strong 700- to 780-cps vibration was noted in the turbopump housings and the major ducts. These characteristics, coupled with the pump inlet duct resonant frequencies determined from the shaker tests, suggest that this mode of vibration may be flow excited, and that an observed hysteresis effect may be due to nonlinearities or an energy threshold required to excite the vibration.

The causes of the pump rotordynamic and the system vibration phenomena discussed above have not been established; but no known hardware damage occurred from these operating conditions in the many system tests conducted to date. Insofar as synchronous vibrations are concerned, the acceleration levels sensed on the turbomachinery housings were typically less than 20 g peak to peak. There appears to be a bearing stiffness-determined critical speed at approximately 28,800 rpm; but the amplification realized is not sufficiently large to prejudice bearing reliability.

Three cases of inducer blade cracking were encountered during the test program. The cracks were very small, and only occurred at the trailing edges of the full blades. Previous vibration tests had not revealed a mode corresponding with the cracks at any wake excitation frequency, and the power-bending loads on these blades were quite reasonable; however, the trailing edges of the full blades overlapped the leading edges of the second partial blades, which suggested the possibility of a flow-induced flutter. Axial trimming of the blades, to reduce the overlap and increase the edge thickness to a minimum of 0.040 inch, seems to have eliminated this problem.

During the earlier (preacceptance) testing of the Mark 25 turbopump, strain gage measurements of the turbine bearing carriers had revealed axial thrust loads and oscillations ranging up to 6000 pounds and ±1500 pounds, respectively. A reduction in the clearance at the first labyrinth seal reduced the axial load to an acceptable value of less than 1500 pounds and eliminated the oscillations. In addition, the gas flow to the turbine was reduced by 9 percent.

The foregoing series of 75 single-mode NFS-3A system tests resulted in the accumulation of a large amount of Mark 25 turbopump performance data, much of it at high power (20,000 horsepower). This data provided the basis for the performance map shown in Fig. 14; also shown are the Phoebus 1 and Phoebus 2 feed system requirements, as defined earlier. The actual performance capabilities of the system extend beyond the contract-defined envelope, and are currently being explored at NRDS.

Late in the NFS-3A test program, SNPO-Washington authorized additional development effort to investigate the practicality and repeatability of high-speed balancing of the pump rotor, with attention to rotor element repositioning errors, and related rotordynamic behavior. The investigations were carried out in Rocketdyne's rotordynamic facility, which has a large vacuum-spin pit and high-speed electric drive, and has the capability of driving a fully instrumented pump rotor at full speed.

During December 1965 through February 1967, 29 vacuum-spin pit tests were conducted; the first 10 tests were concerned with checking out the facility and instrumentation, and establishing test procedures, while the second series of 19 tests was expended in evaluating the feasibility of high-speed balancing. The corrective balance adjustments made reduced the rotor radial displacements, particularly at the critical speed of approximately 28,000 rpm, where the displacements of the most sensitive plane were reduced by a factor of 5. It was therefore concluded that high-speed balancing of the Mark 25 pump rotor was practical, and resulted in a better-balanced rotor than can be achieved with low-speed balancing.

NFS-3B Design Features In earlier planning for the modifications to test cell C, NRDS, it had been decided to install a hot water-to-liquid hydrogen heat exchanger system (designated Turbine Energy Source) to provide the turbodrive and dewar pressurization gases, and a high-pressure liquid hydrogen dewar (designated Emergency Cooldown Dewar) to provide an auxiliary source of reactor coolant for test situations involving unexpected shutdown of the main liquid hydrogen supply system. The integration of these modifications into the test facility are indicated in Fig. 15, which also sets forth the full power operating conditions expected for the planned Phoebus 2A reactor test.

As a result of these decisions, the NRDS operational requirements for the uprated Phoebus feed system were further defined in the fall of 1965. Because of the premium placed on minimizing the turbine energy source-bootstrap loop pressure drop when testing at the Phoebus 2 operating point, the specification for the plug and seat of the turbine control valve was recommended to be changed from a CV of 195 to 350, thereby increasing the effective flow area by 80 percent. The incorporation of the Emergency Cooldown Dewar into the facility high-pressure hydrogen delivery line introduced the need for isolation of the pump inlet system from the discharge system under emergency shutdown conditions. Analog and digital simulation studies of the predicted dynamic behavior of the feed systems in this facility resulted in the recommendations that check valves be installed in each pump discharge duct, and larger liquid hydrogen bypass valves be located just upstream of each check valve with separate specific speed controllers for each liquid hydrogen bypass valve as indicated in Fig. 16.

The NFS-3B digital simulation model, with indicated computation points, is presented in Fig. 17. The model features completely variable pumped fluid (liquid hydrogen) physical properties, thermodynamics of variable turbopump efficiency, and spatially distributed hydrogen flows and pressures; and generated predicted speed transients which were in good agreement with test data. Response of the NFS-3B system to a step increase in the facility discharge impedance at 25,000 rpm, as determined by the digital model, is presented in Fig. 18. The input is a 2-millisecond ramp reduction in facility liquid hydrogen throttle valve (Valve No. 1, Fig. 17) position from 100 to 10 percent open. The delivered flow drops to 30 percent in 2 milliseconds, and to 15 percent in 28 milliseconds when the check valves (Valves No. 4 and 5) seat closed. The liquid hydrogen bypass valve begins opening on specific speed control at 8 milliseconds and is full open 85 milliseconds later. The transient is over and the system is operating essentially at steady state in 100 milliseconds with 10 percent flow being delivered and 90 percent bypassed. This transient is extremely severe compared to reality; however, when the model predicted behavior is compared to the pertinent single mode transients experienced in pumping tests of this type, the indications are that the system would accommodate satisfactorily the abrupt changes in flows, pressures, and implied loads. By far the most critical component is the pump inlet duct, which experiences pressure surges to 100 percent over the maximum operating level, for approximately 10 milliseconds.

The individual check valves and bypass valves for each pump also provide the potential for emergency, single pump operation when turbine shutoff valves are incorporated in each turbine inlet duct. These valves would be actuated by pressure difference across the check valve. This system is being evaluated for possible use at NRDS to provide additional assurances of adequate liquid hydrogen flow to the reactor under emergency test conditions.

With the acceptance of these recommendations, design of the new check valves, new liquid hydrogen bypass lines, and associated redesign of the pump discharge ducts was initiated in November 1966, and resulted in a new system configuration, designated NFS-3B (Fig. 19).

The redesign of the pump discharge ducts to accept the check valves involved cutting into the vertical sections between the tied bellows, and installing flange joints and chambers in each duct to contain the check valves. In addition, a tee and flange were installed in the horizontal section of each duct adjacent to the flowmeter to accommodate the larger 5-1/2-inch liquid hydrogen bypass valves. These bypass valves were connected to the facility flare-stack line by 6-inch ducts, 8 feet in length, which carried the bypass hydrogen to the facility interface flanges.

The 7-inch check valves (Fig. 20) were designed to exhibit a pressure drop of less than 50 psi at full Phoebus 2 flowrates, and to withstand the impact and pressure loads associated with closing in less than 20 milliseconds under 2000-psi reverse pressure. The new 5-1/2-inch liquid hydrogen bypass valve (Fig. 21) was designed to function under continuous servoduty as either a shutoff or throttle valve; operate with upstream pressures ranging up to 2250 psi, and yet withstand reverse pressures of 1000 psi; provide an effective unblocked area of approximately 20 sq in.; and have a gate slewrate of at least 1200 percent/sec. The gate is actually a ball incorporating stub shafts with those portions of the ball not required for sealing cutaway. A two-position, bell-crank-type actuator is employed so that the torque applied to the gate shaft would approximate a pure couple, thereby minimizing the radial loading on the gate shaft bearings.

NFS-3B Development Program Testing of the NFS-3B system has been conducted only at test cell C, NRDS. The initial tests, begun in September 1966, were conducted with the single-mode configuration for the purpose of qualifying the systems for the Phoebus 1B reactor test, as well as gaining experience with the operation of the new system in the modified test cell. A total of 17 turbine-powered tests were conducted between October and December 1966 (Table III), during which 2580 seconds were accumulated on one turbopump at speeds and power levels in excess of the requirements predicted for the Phoebus 1B full-power run. On 23 February 1967, the actual full-power test occurred, and the feed system functioned properly for the entire 44 minutes of turbine-powered operation.

In April 1967, the NFS-3B system was converted to the dual-mode configuration, and dual-mode testing was initiated. The first 11 tests were concerned in part with gaining operational experience with the system in dual mode, and the turbopump speeds were limited to 30,000 rpm. Then, beginning in May and continuing through June, an additional 13 dual-mode and 25 single-mode tests were conducted during which (1) the system was operated repeatedly, in dual mode, at or above the Phoebus 2 operating point, (2) one of the turbopumps accumulated approximately 25 minutes at or above the planned Phoebus 2A pumping power requirements, and (3) the same turbopump was taken to 36,000 rpm, developing 24,000 shaft horsepower, while delivering 185 lb/sec of liquid hydrogen at a delivery pressure of 1700 psia.

In addition, during the later portion of the test series, it was found possible to operate one of the turbopumps at any desired point on its operating map, while the other turbopump was allowed to motor slowly by bleeding a small amount of liquid hydrogen from its bypass valve. The source of turbodrive gases was isolated from the second turbine by installing a blanking flange on the corresponding leg of the turbine inlet duct. This mode of operation partially demonstrates the feasibility of turbopump-out capability for nuclear rocket engines employing multiple turbopumps.

Table III presents a summary of representative test data from a few of the 60 tests conducted with the NFS-3B system at Nuclear Rocket Development Station.

## SUMMARY

Rocketdyne has designed, fabricated, tested, and delivered two configurations of dual-mode liquid hydrogen feed systems for use in testing Phoebus reactors in the Rover Program. One system incorporates dual Mark 9 turbopumps and the other dual Mark 25 turbopumps. The characteristics of these two feed systems, NFS-3A and NFS-3B, are presented in Table IV. Approximately

1500 seconds of dual-mode NFS-3 and 4500 seconds of dual-mode NFS-3B testing to date have proved the practicality and flexibility of parallel operation of two liquid hydrogen turbopumps. The parallel units operate with complete hydrodynamic stability, sharing the hydraulic load equally at either steady state condition or through large speed transients involving turbopump accelerations up to 50,000 rpm/sec. In addition, the pumps responded smoothly and equally to programmed reductions in delivered flow.

The dual turbopump systems can be operated in single mode, i.e., one turbopump by installing blanking flanges in pertinent system ducts. and switching the control console to the single-mode operating condition. Together with the automatic liquid hydrogen discharge bypass capability the system provides for the operation at all delivered pressures to 2000 psia, and all delivered flows to 330 lb/sec. The utilization of multiple turbopumps has provided significant cost and schedule advantages to the Rover Program.

Multiple turbopumps offer the potential of pumpout feed system operation. The NFS-3B feed system incorporates a check valve in each pump discharge duct, upstream of the common header, and pumpout operation at NRDS is being evaluated.

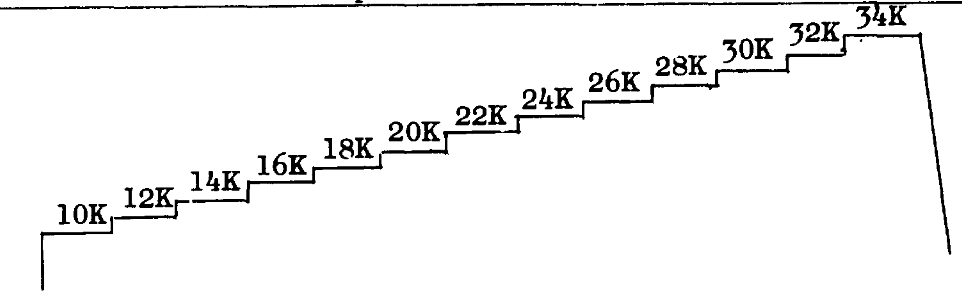
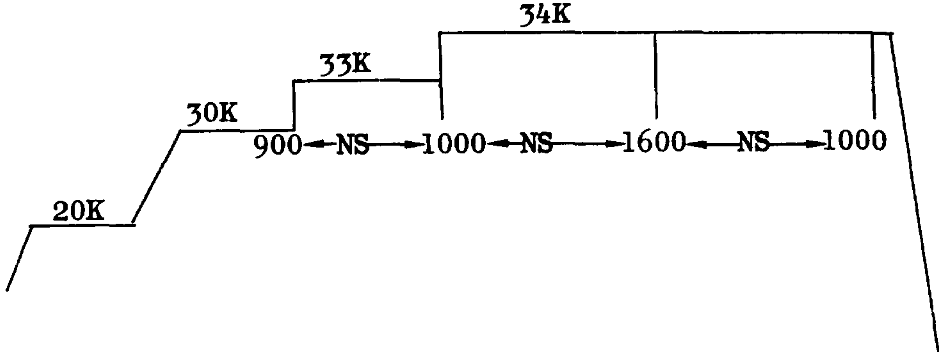
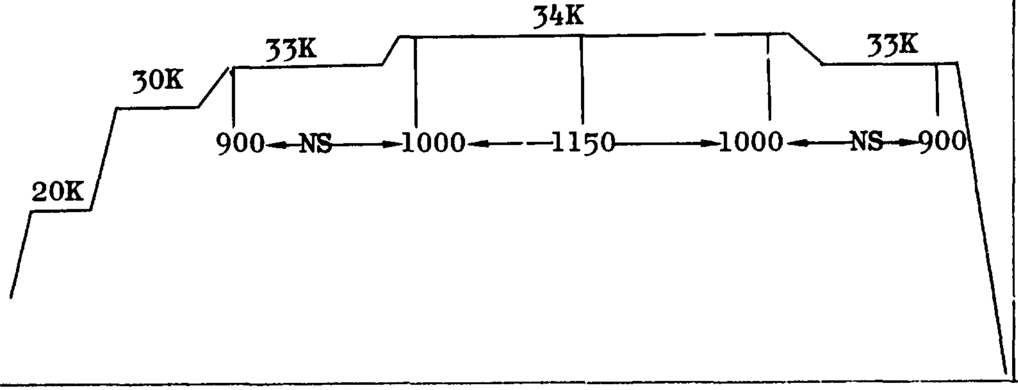
## PHOEBUS 1B FULL-POWER REACTOR TEST

On 23 February 1967, the Phoebus 1B was tested at full power. The 44-minute run was, in general, a resounding success, with the reactor operating in the power range of 1200 to 1450 megawatts for 30 minutes. Figure 22 is a system schematic of the major hydrogen supply and flow equipment as they functioned during the test. The pertinent test parameters, associated with the operation of this equipment at the beginning of the full-power portion of the run, are indicated on the schematic.

TABLE I. NFS-3 DUAL MODE TESTS

| Date | Duration, seconds | Flowrate, lb/sec | Pressure Rise, psi | Horse-power | Speed, rpm | Test Objectives |
|---|---|---|---|---|---|---|
| 2-26-64 | 34 | 110 | 450 | 3,600 | 18,300 | Check-out of overspeed trip and $N_s$ limit control |
| 2-26-64 | 48 | 140 | 750 | 7,400 | 23,600 | Obtain turbopump speed loop response and verify $N_s$ limit control |
| 2-28-64 | 10 | 145 | 800 | 8,400 | 24,500 | Obtain turbopump speed loop response |
| 11-25-64 | 48 | 88 | 290 | 1,900 | 15,000 | Evaluate system mechanical integrity to 15,000 rpm checkout program speed operation |
| 12-3-64 | 59 | 120 | 605 | 5,200 | 21,000 | Evaluate system mechanical integrity to 21,000 rpm |
| 12-8-64 | 68 | 140 | 850 | 8,600 | 24,600 | Evaluate system mechanical integrity to 25,000 rpm |
| 12-10-64 | 58 | 175 | 1180 | 14,600 | 29,600 | Evaluate system mechanical integrity to 30,000 rpm |
| 12-14-64 | 68 | 40 | 60 | 200 | 6,800 | Obtain low power turbopump speed loop response |
| 12-14-64 | 148 | 90 | 270 | 1,800 | 14,800 | Obtain low power turbopump speed loop response |
| 12-17-64 | 164 | 150 | 840 | 9,000 | 25,500 | Obtain medium power turbopump speed loop response |
| 12-31-64 | 125 | 150 | 880 | 9,800 | 26,200 | Obtain medium power turbopump speed loop response |
| 1-4-65 | 81 | 180 | 1220 | 15,600 | 30,000 | Obtain high power turbopump speed loop response |
| 1-8-65 | 36 | 80 | 250 | 1,400 | 13,600 | Obtain low power $N_s$ limit system response |
| 1-18-65 | 31 | 90 | 300 | 1,920 | 15,000 | Obtain low power $N_s$ limit system response |
| 1-19-65 | 147 | 180 | 1150 | 14,600 | 29.900 | Checkout $N_s$ limit system at high power |
| 1-21-65 | 87 | 180 | 1200 | 7,900 | 30,200 | Evaluate interaction of turbopump speed and pump $N_s$ limit control systems |
| 1-27-65 | 131 | 170 | 1230 | 15,000 | 29,600 | Obtain high power $N_s$ limit system response |
| Total | 1,343 | | | | | |

## TABLE II. TYPICAL TEST SEQUENCE

| Test | Speed Profile | Description of Objectives |
|---|---|---|
| F-1 |  | 34,000-rpm green run: 1000-rpm/sec up ramps, 3-second plateaus, 5000-rpm/sec down ramp. Turbine S/N 001 (all seal mods). Pump S/N 002 close inducer/stator space 600 pound bearing preload. |
| F-2 |  | Evaluate pump whirl and pressure oscillations, system vibration characteristics with tie straps; 2000-rpm/sec up ramps, 2-second plateaus at 20 and 30K; at 33,000 rpm, vary $N_s$ from 900 to 1000; at 34,000 rpm, vary $N_s$ from 1000 to 1600, to 1000; 5000-rpm/sec down ramp. Turbine S/N 001, pump S/N 002 |
| F-3 |  | Define effect of direction of $N_s$ transverse up upon location of regions of pump whirl and pressure oscillations with tie straps: 2000-rpm/sec up ramps, 2-second plateaus at each preselected operating point; at 33,000 rpm, vary $N_s$ from 900 to 1000, to 900; at 34,000 rpm, vary $N_s$ from 1000 to 1150, to 1000; 5000-rpm down ramp, turbine S/N 001, pump S/N 002 |

## TABLE III. NFS-3B TEST SUMMARY

| Date | Duration, seconds | Flowrate, lb/sec | Pressure Rise, psi | Horsepower | Speed, rpm | Mode |
|---|---|---|---|---|---|---|
| 10-6-66 | 1,000 | 110 | 1440 | 11,500 | 28,000 | Single |
| 12-7-66 | 1,000 | 110 | 1440 | 11,500 | 28,000 | Single |
| 12-9-66 | 2,000 | 110 | 1400 | 11,500 | 28,000 | Single |
| 12-15-66 | 1,700 | 120 | 1620 | 14,000 | 30,000 | Single |
| 2-23-67* | 1,800 | 110 | 1320 | 10,400 | 26,800 | Single |
| 4-20-67 | 400 | 250 | 865 | 16,200 | 25,000 | Dual |
| 4-26-67 | 1,500 | 260 | 830 | 16,400 | 25,500 | Dual |
| 5-10-67 | 1,400 | 155 | 1500 | 17,500 | 32,000 | Single |
| | | 185 | 1225 | 20,000 | 34,000 | Single |
| 5-25-67 | 400 | 185 | 1200 | 20,000 | 34,000 | Single |
| 5-26-67 | 200 | 250 | 2000 | 36,000 | 32,500 | Dual |
| 6-15-67 | 1,440 | 350 | 1500 | 40,000 | 34,000 | Dual |
| 6-16-67 | 50 | 185 | 1650 | 24,000 | 36,000 | Single |
| 7-12-67 | 480** | 85 | 200 | 1,400 | 14,000 | Single |
| | 270 | 165 | 1500 | 19,000 | 34,000 | Single |
| 7-19-67 | 960** | 165 | 200 | 2,600 | 13,500 | Dual |
| | 270 | 165 | 1500 | 19,000 | 34,000 | Single |
| Total | 14,870 | | | | | |

*Phoebus 1B
**Phoebus 2 Cold Flow

## TABLE IV. PHOEBUS FEED SYSTEM CHARACTERISTICS

| System | NFS-3 | | NFS-3B | |
|---|---|---|---|---|
| Delivery Date | 1965 | | 1966 | |
| Location | NRDS<br>Test Cell C | | NRDS<br>Test Cell C | |
| | Single | Dual | Single | Dual |
| PUMP | | | | |
| Designation | Mark 9 | Mark 9 | Mark 25 | Mark 25 |
| Flowrate, lb/sec | 90 | 180 | 130 | 330 |
| Discharge Press, psig | 1250 | 1250 | 2000 | 2000 |
| Speed, rpm | 31,000 | 31,000 | 33,000 | 33,400 |
| TURBINE | | | | |
| Designation | Mark 9 - Mod 1 | | Mark 25 | |
| Inlet Press, psia | 511 | 511 | 900 | 880 |
| Pressure Ratio | 12.3 | 12.3 | 10.0 | 10.0 |
| Flowrate, lb/sec | 9.0 | 18.0 | 18.0 | 38.0 |
| Shaft Horsepower | 8600 | 17,200 | 18,000 | 36,000 |

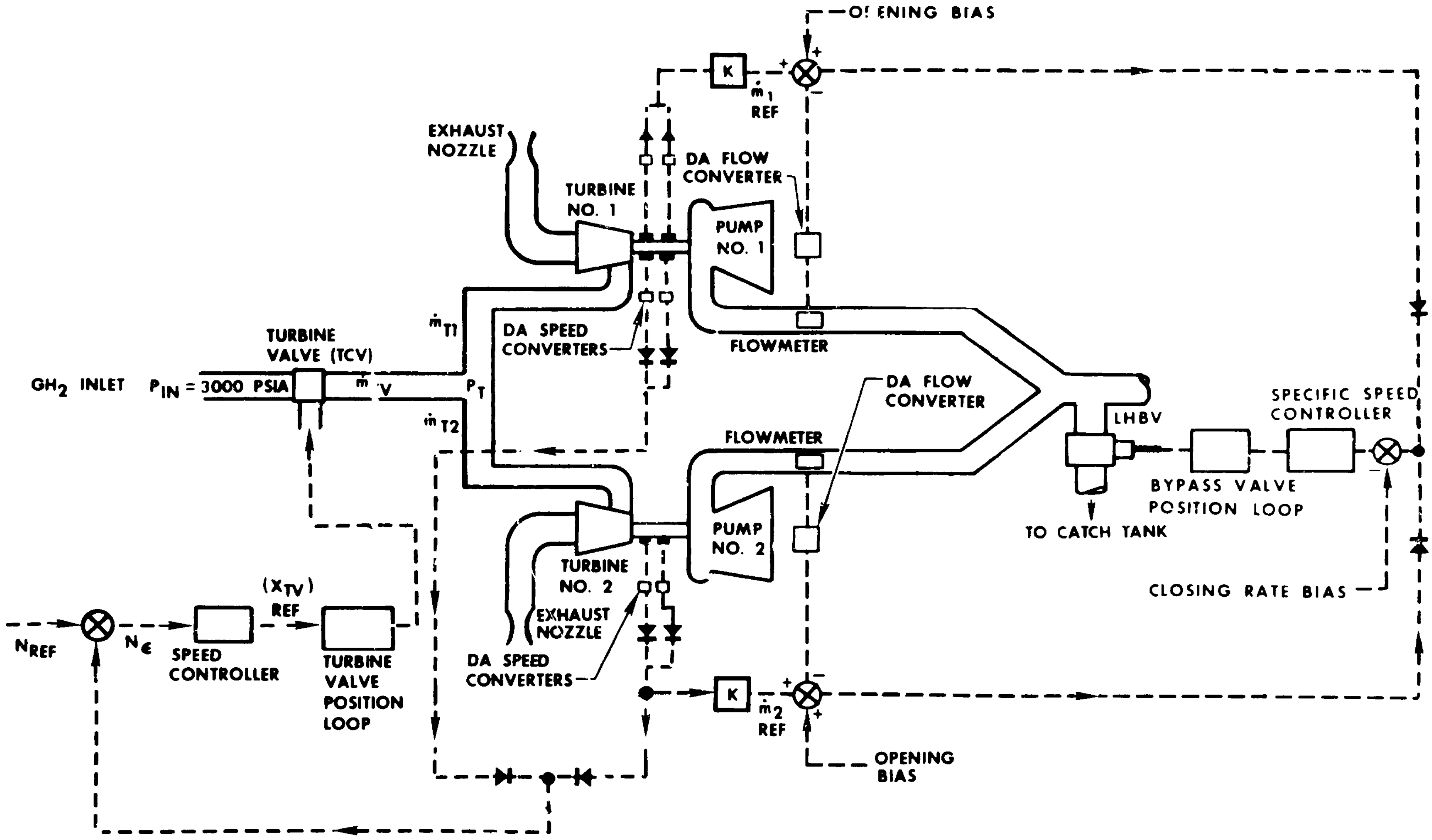


Figure 1. NFS-3 Feed System Schematic

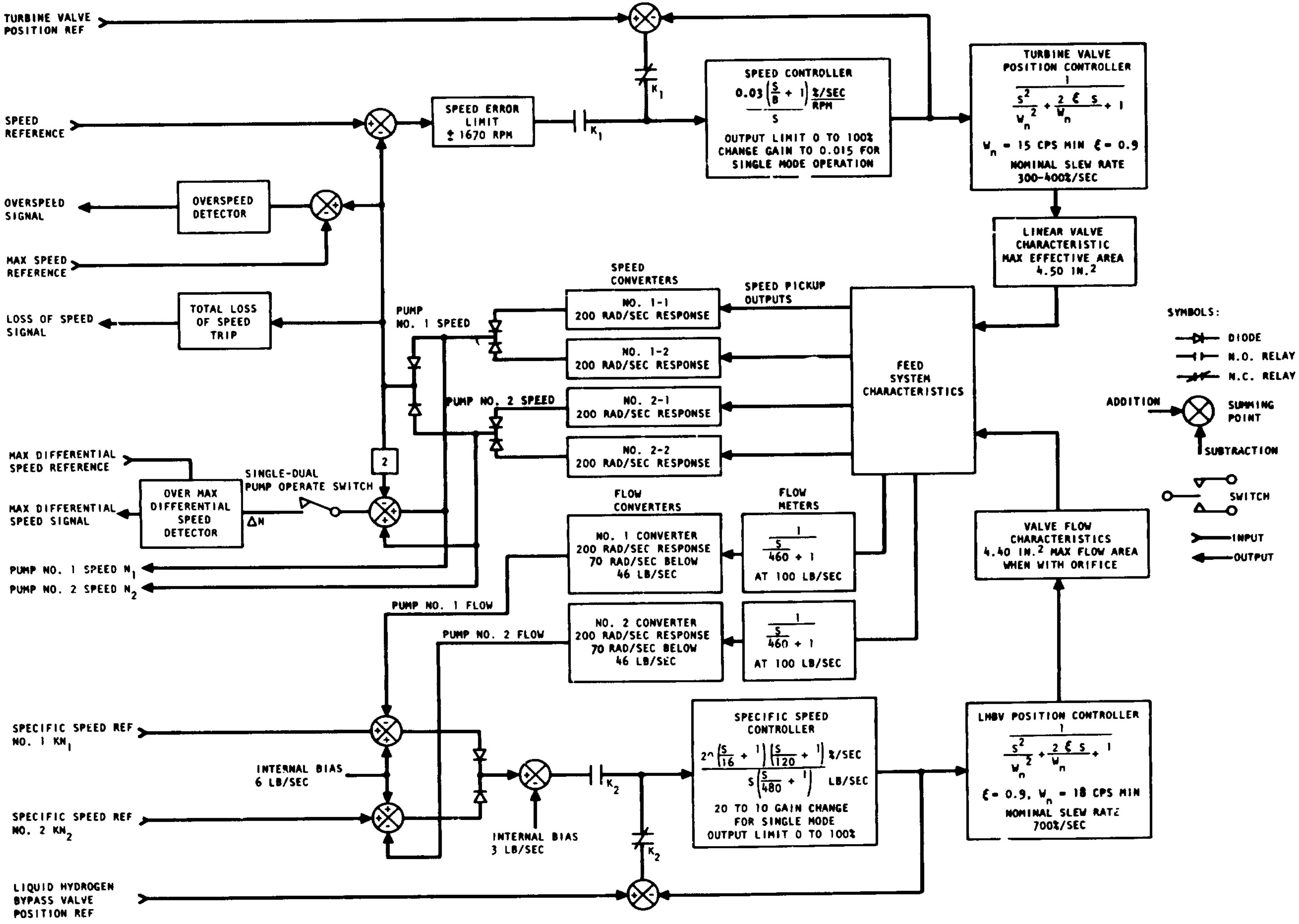
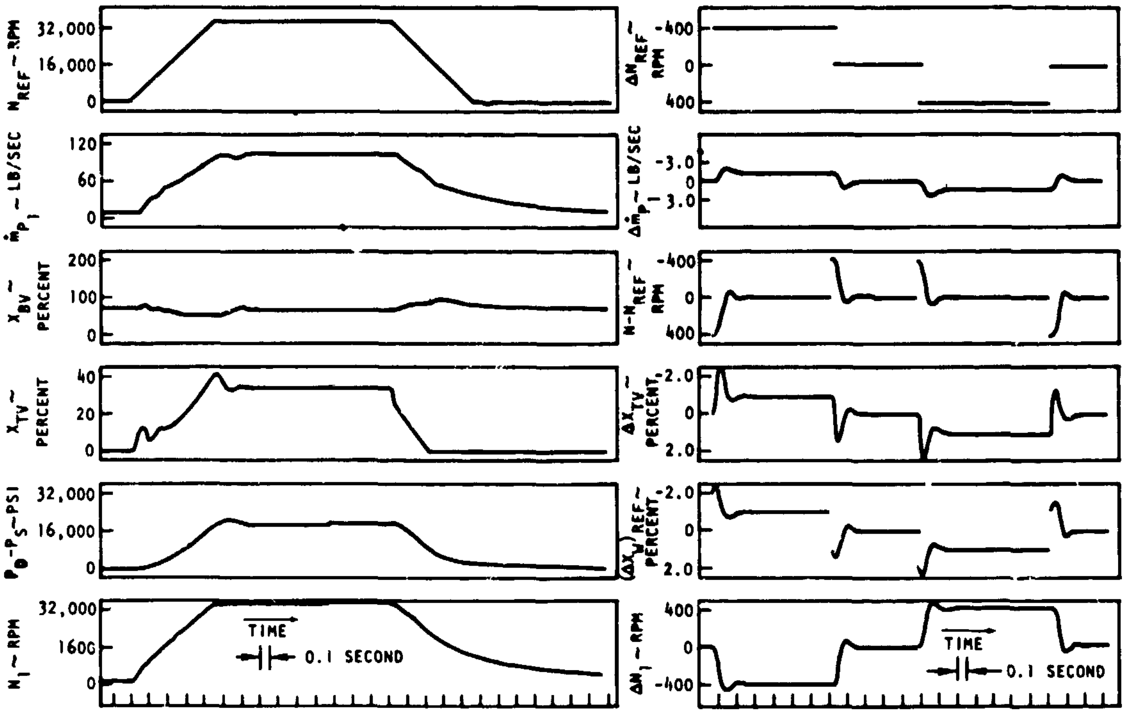


Figure 2. Servocontrol Logic Diagram for NFS-3



3a. Startup and Shutdown (34,000 rpm/sec Ramps)

3b. 400 rpm Steps at 34,000 rpm

Figure 3. NFS-3 Dynamic Speed Characteristics (Analog Data)

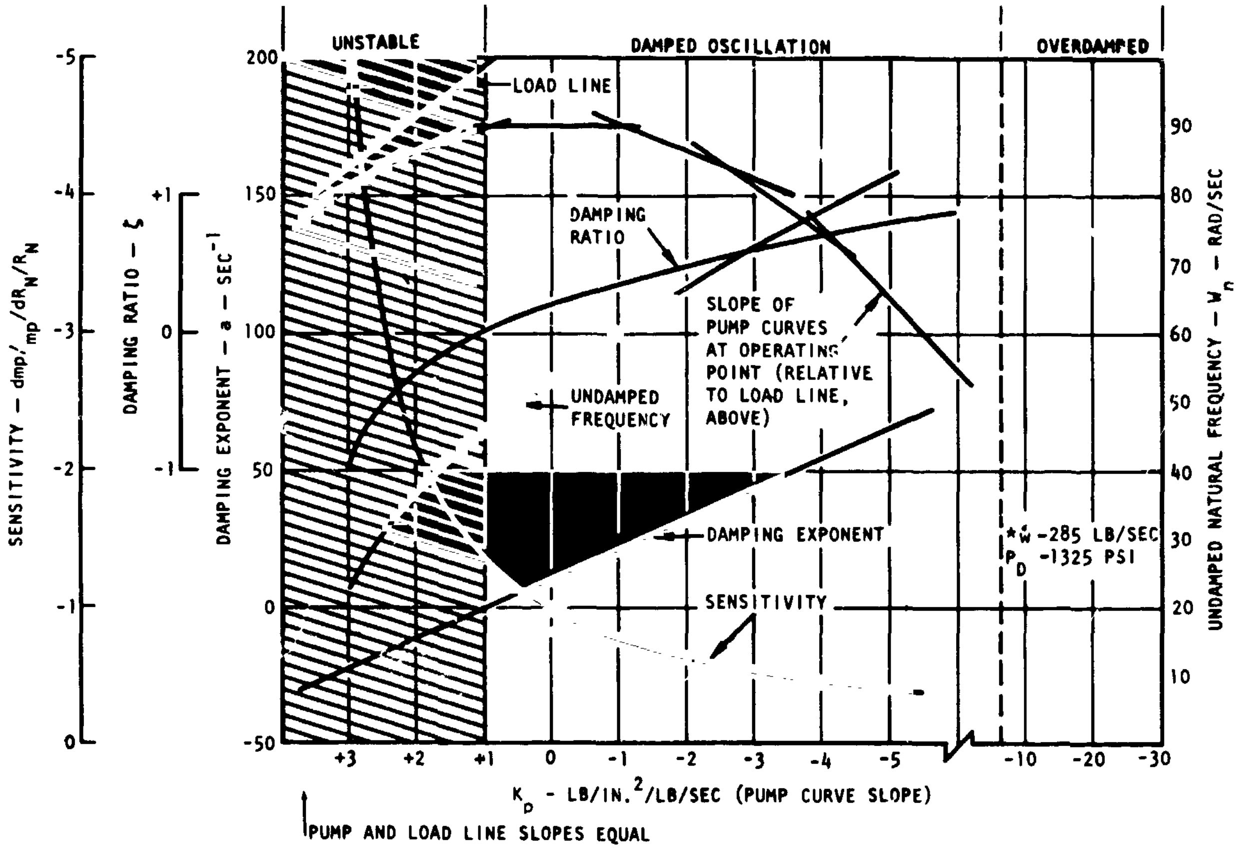


Figure 4. Typical Pump System Stability Characteristics (With Phoebus* Load Characteristics)

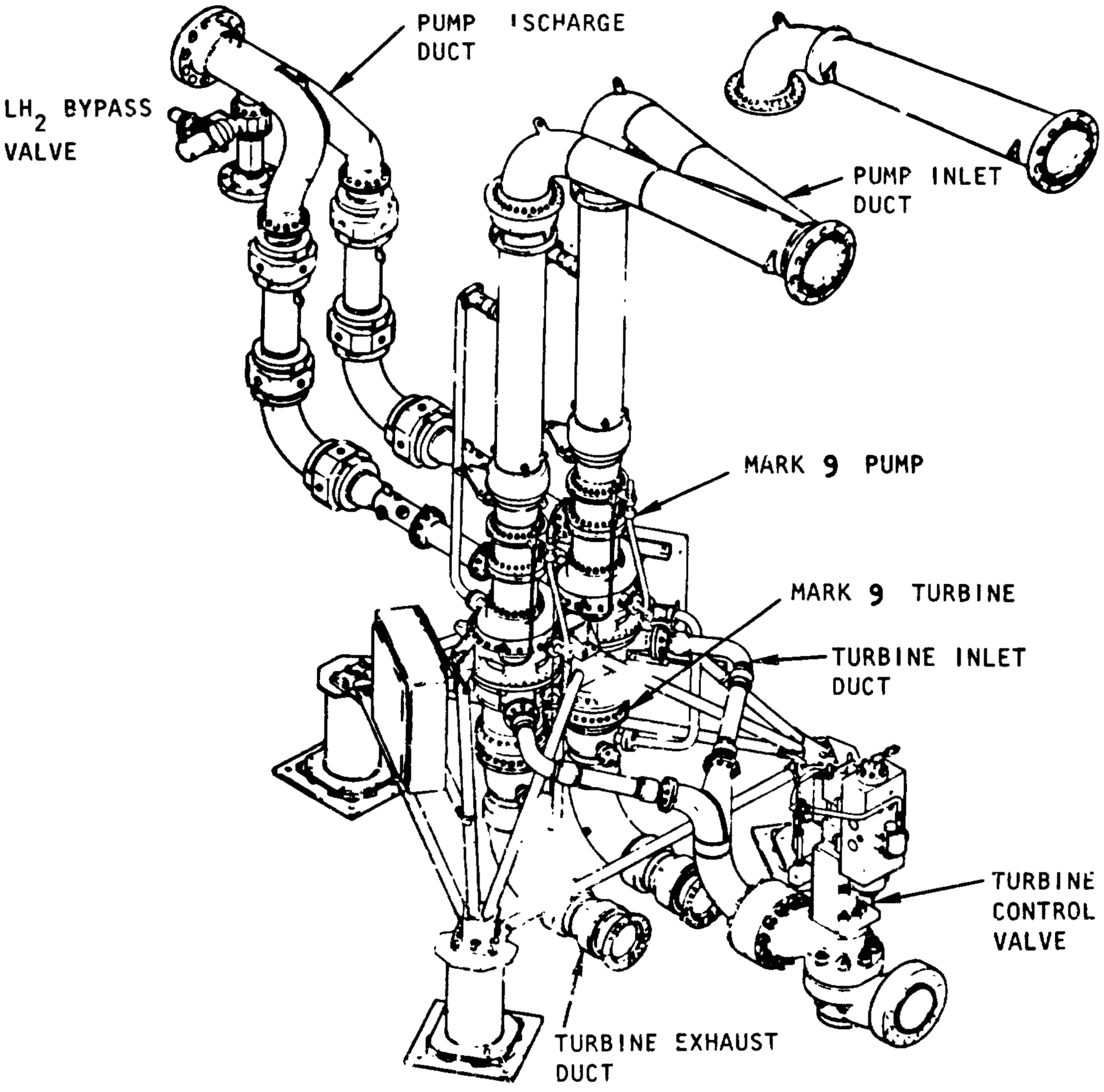


Figure 5. NFS-3 Feed System

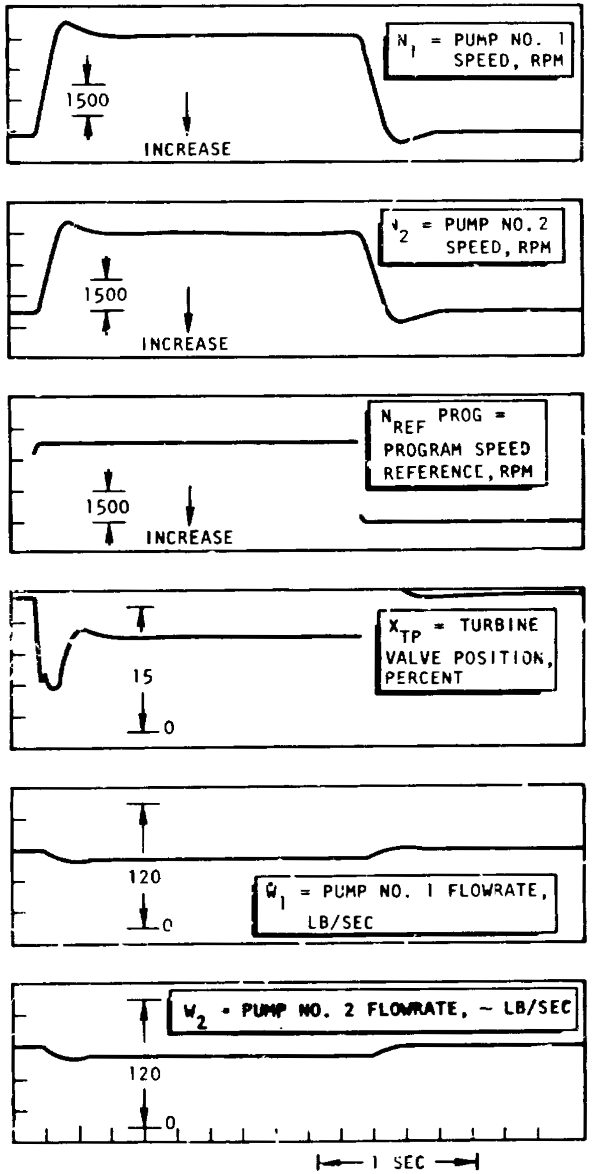


Figure 6. Test 050 Large Amplitude Step (4000 rpm) Transient at 25,000 rpm

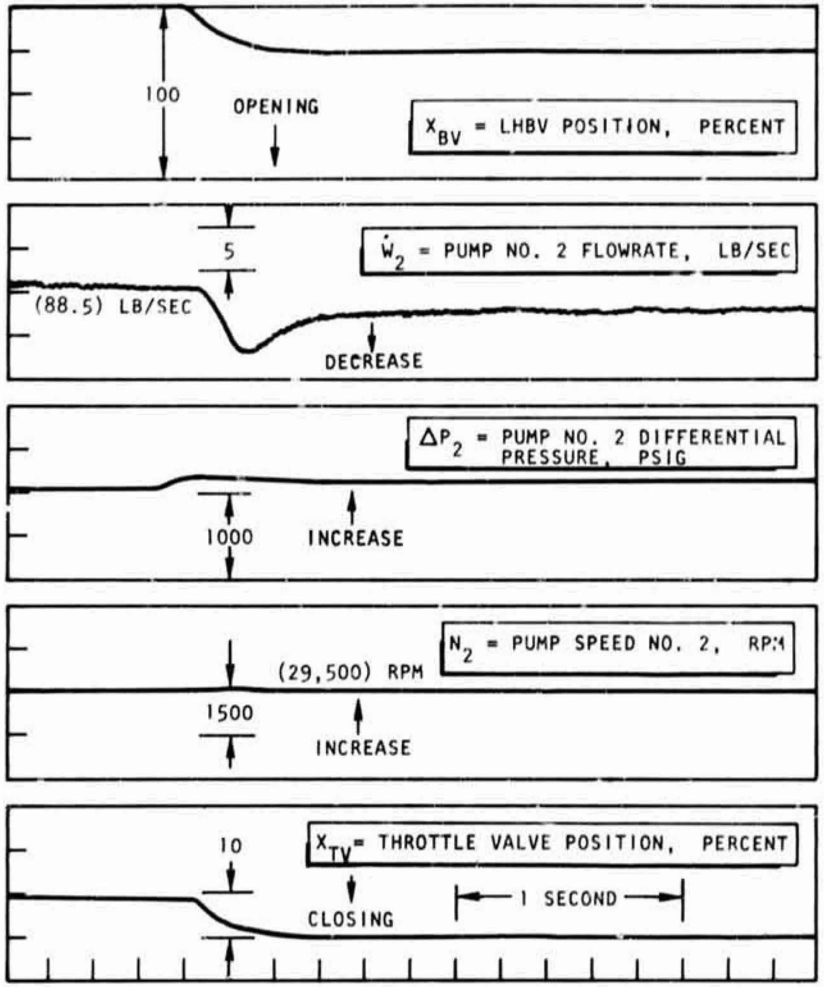
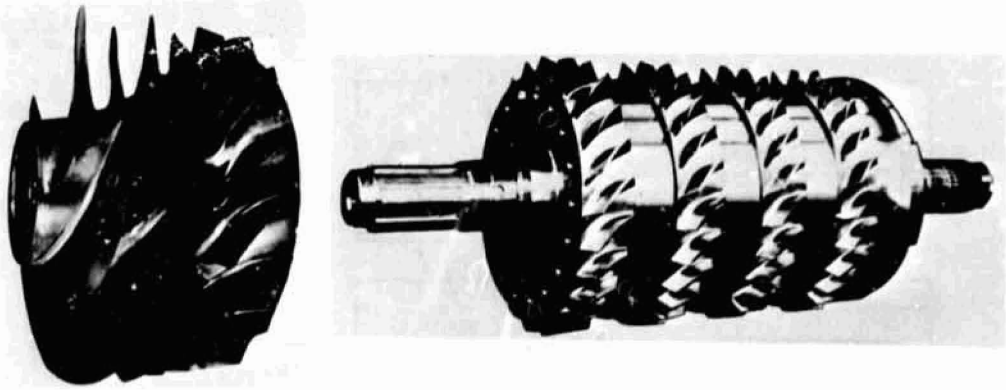


Figure 7. Test 004 Dual NFS-3 Feed System Response to Programmed Increase in System Impedance at 30,000 rpm

Mark 9



E-Bladed

Figure 8. Comparison of Pump Rotors

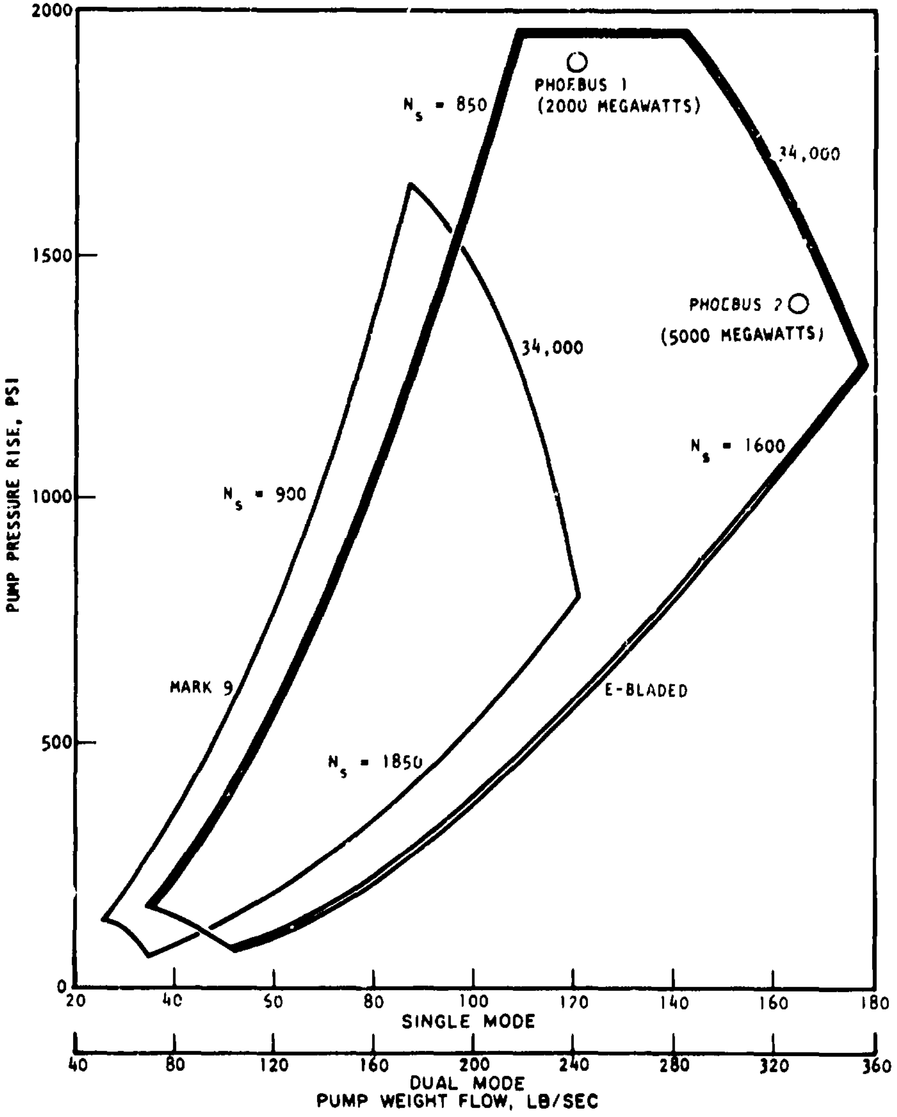
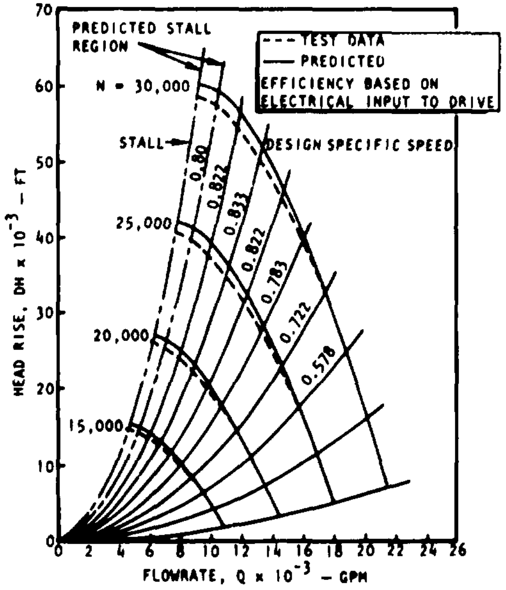
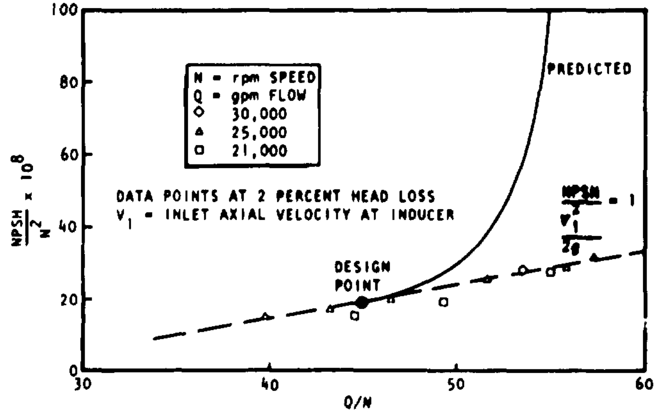


Figure 9. E-Bladed vs Mark 9 Pump H/Q Performance Comparison



10a. H/Q Performance of E-Bladed Pump



10b. NPSH Requirements of E-Bladed Pump

Figure 10. Predicted vs Test Performance of E-Bladed Pump

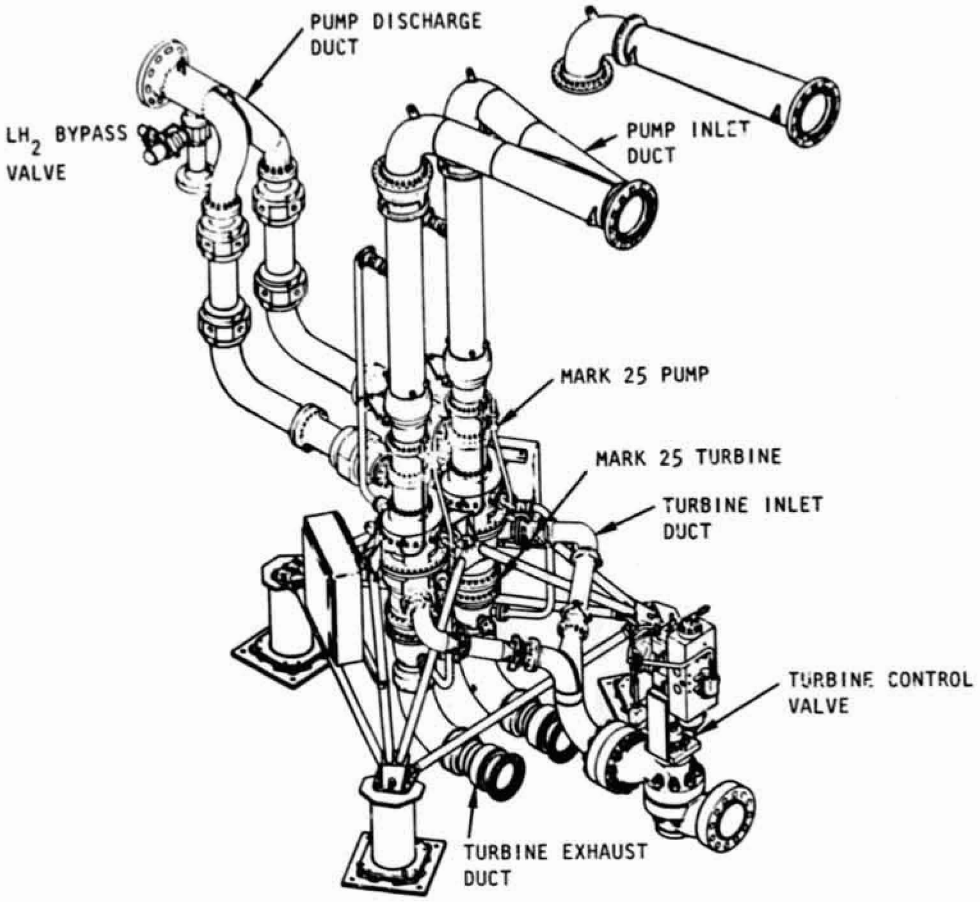


Figure 11. NFS-3A Feed System

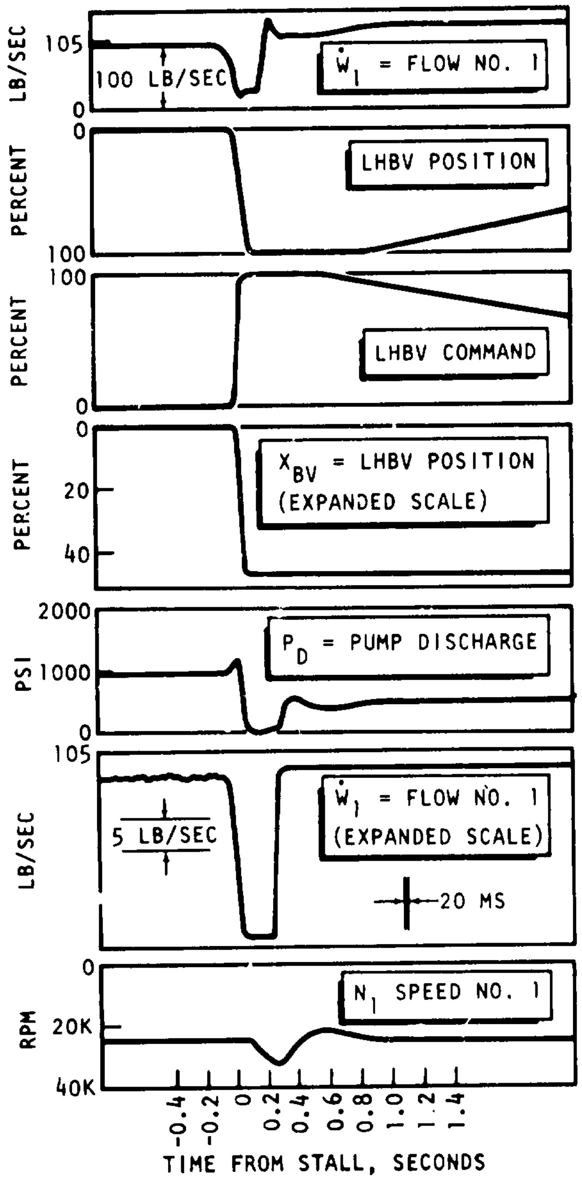


Figure 13. Single Pump Stall Recovery Test at 25,000 rpm (Run 352049)

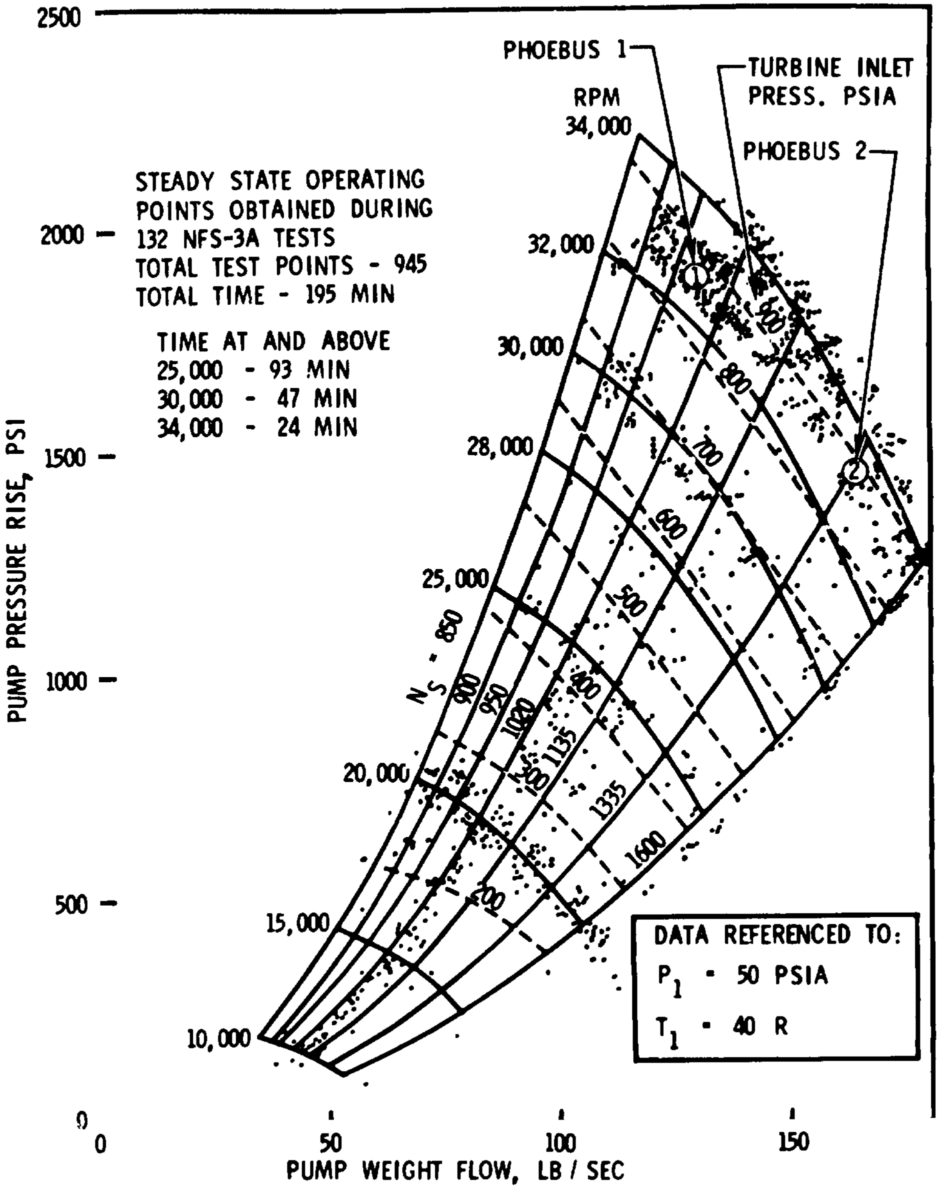


Figure 14. Mark 25 Turbopump Performance Map

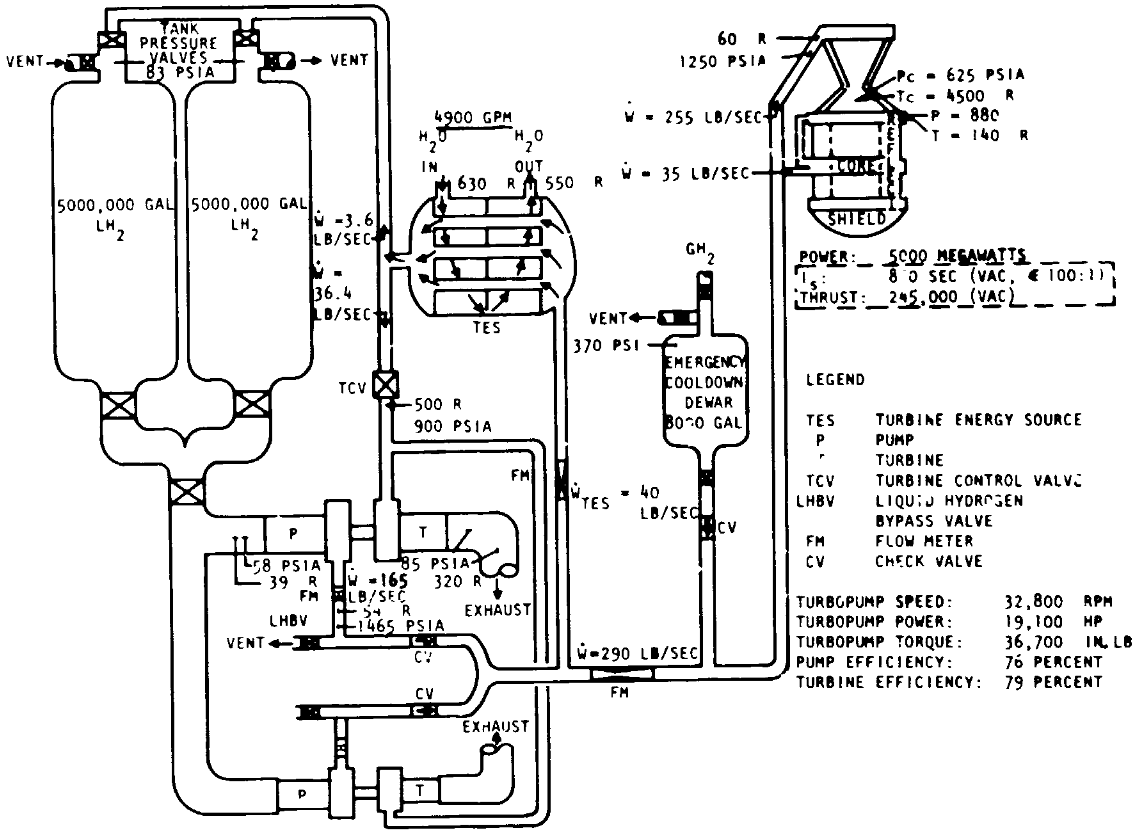


Figure 15. Full-Power Phoebus 2 Operating Conditions

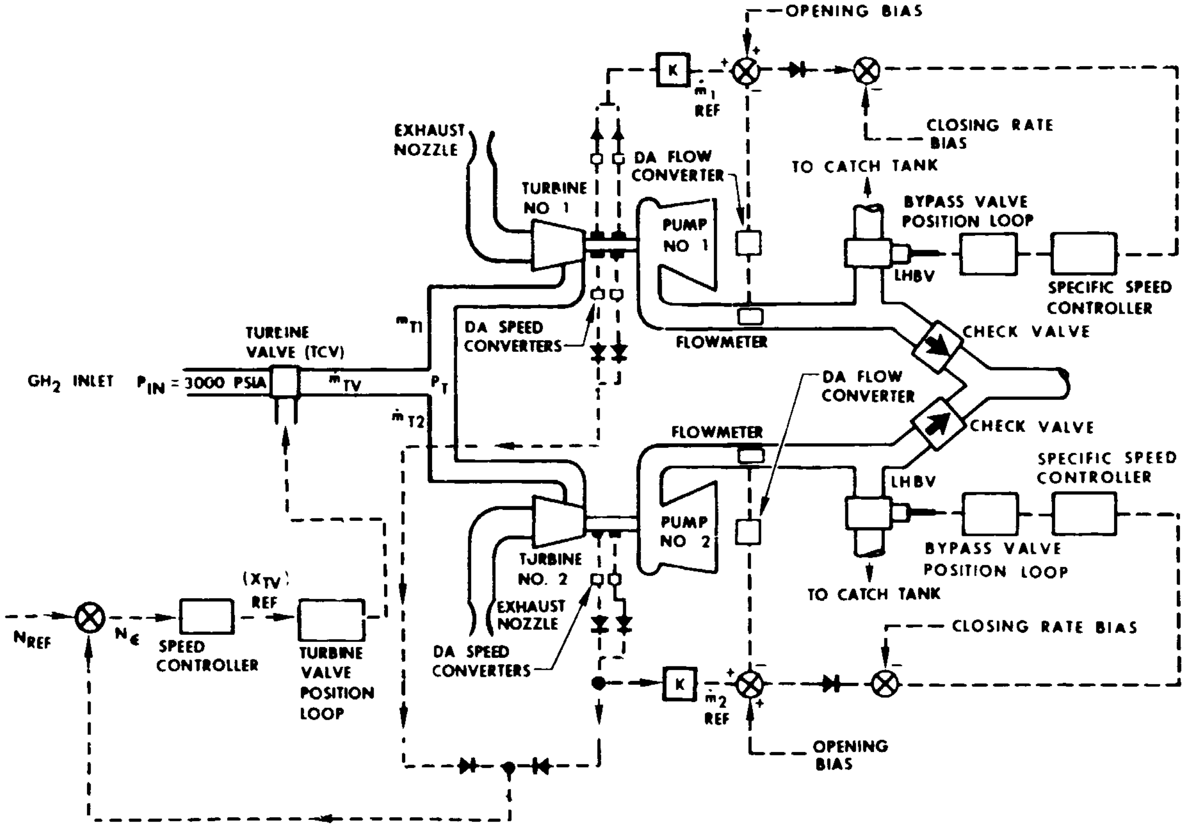


Figure 16. NFS-3B Feed System Schematic

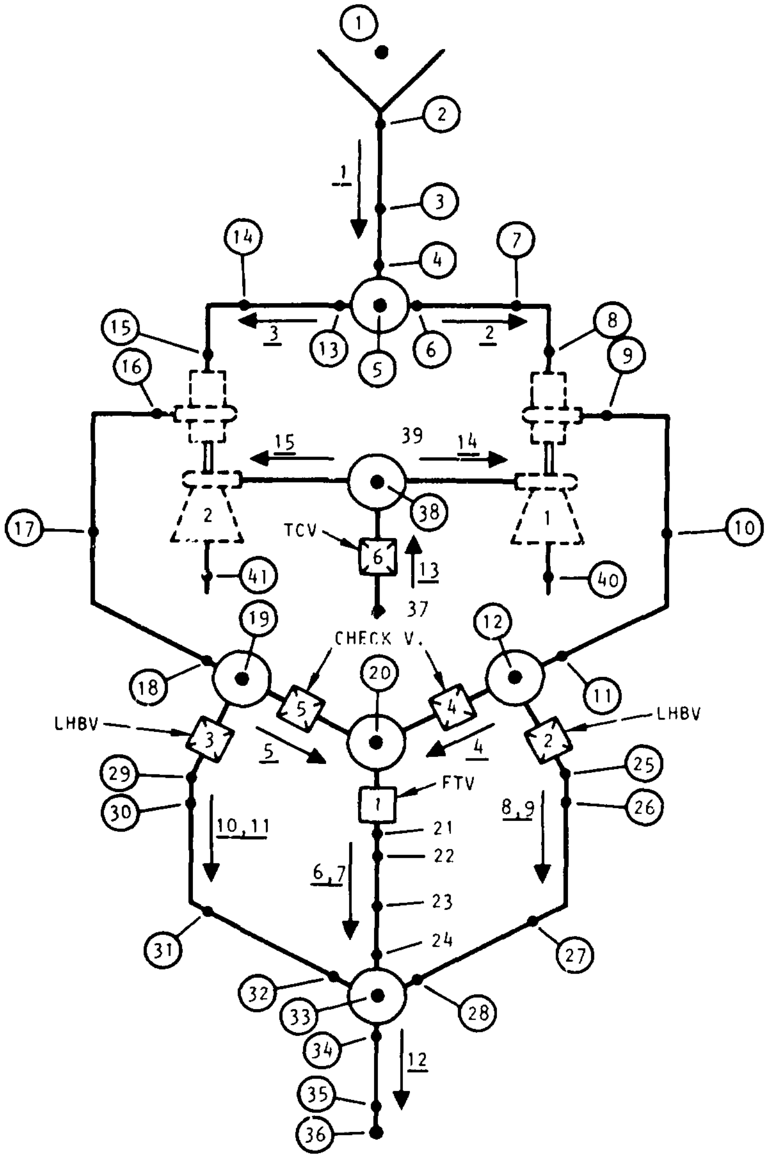


Figure 17. NFS-3B Digital Simulation Model

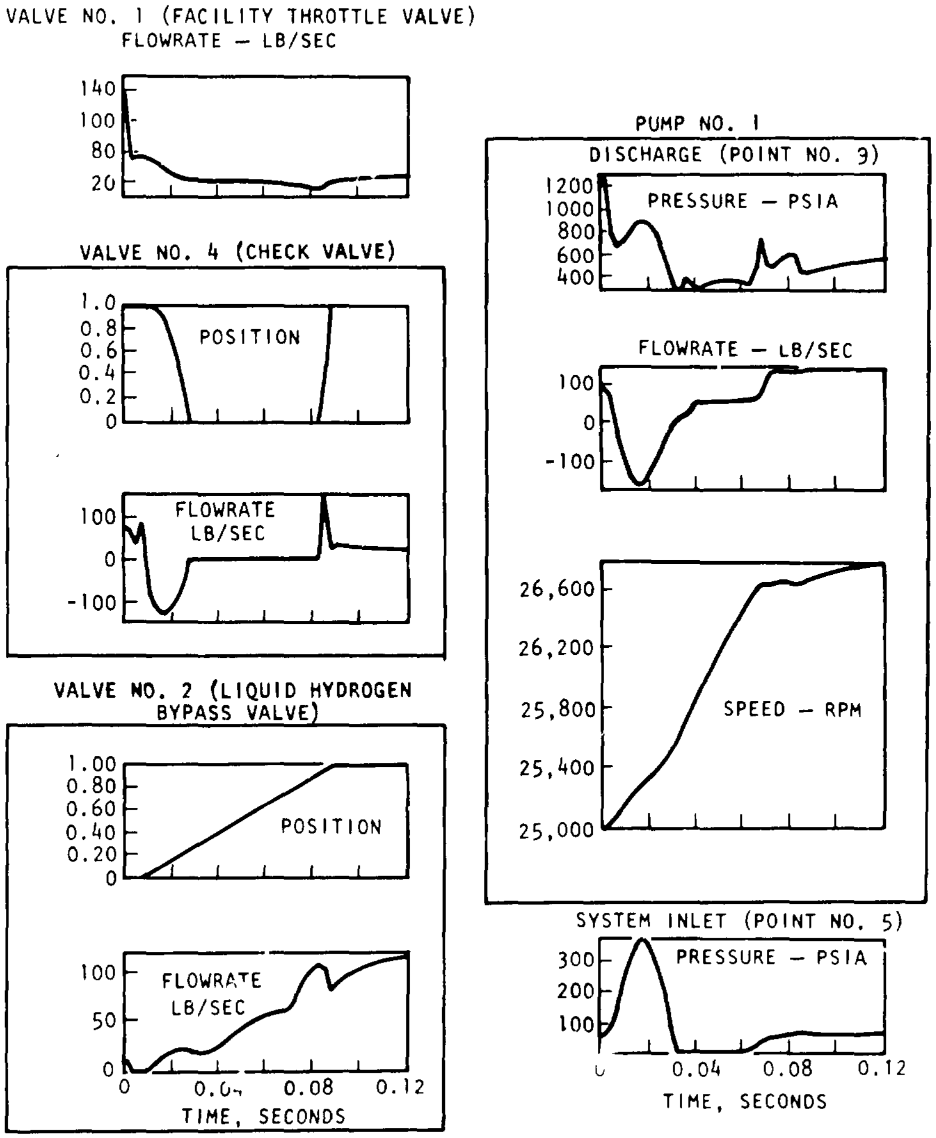


Figure 18. NFS-3B Response to Increase in System Impedance at 25,000 rpm (Facility Throttle Valve Stepped From 100 to 10 Percent in 2 Milliseconds)

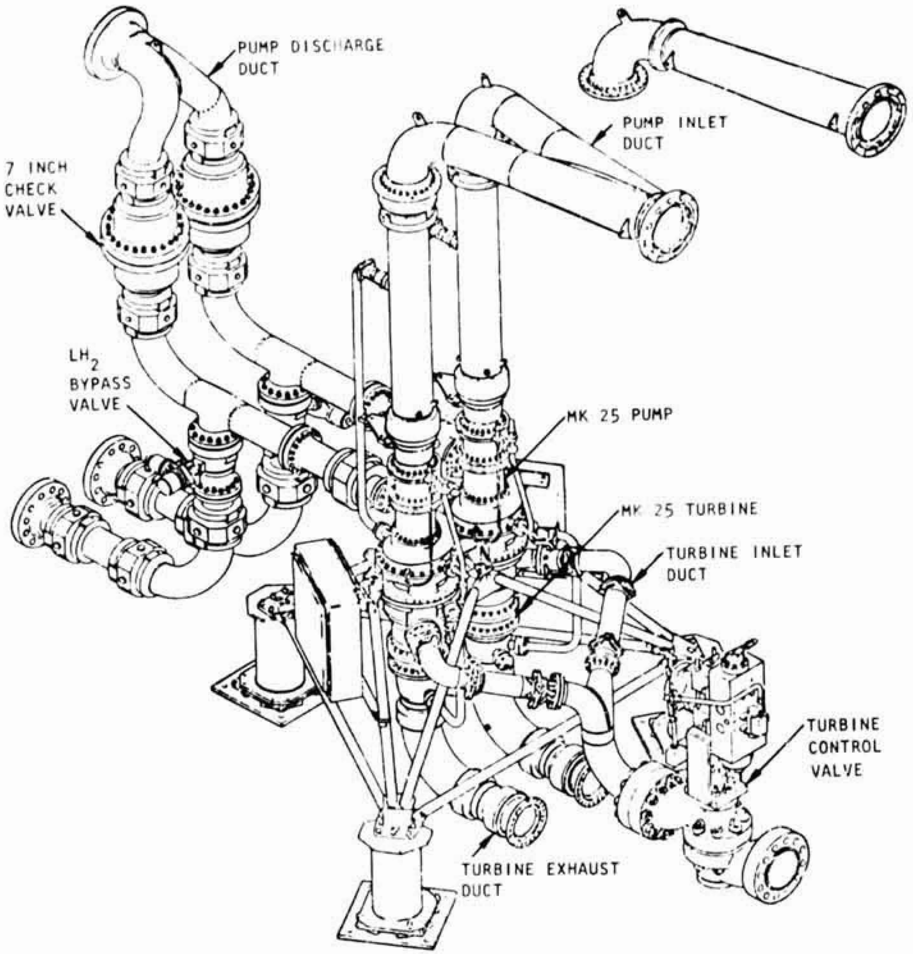


Figure 19. NFS-3B Feed System

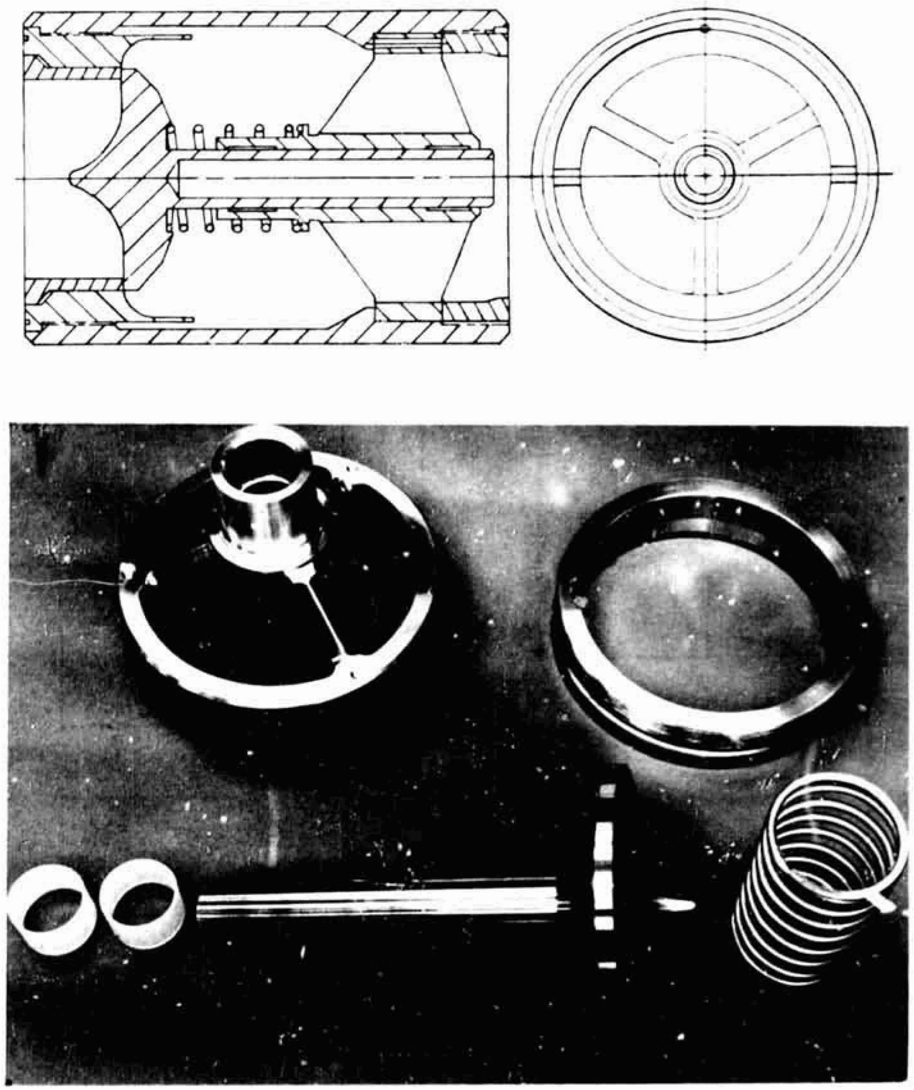


Figure 20. Liquid Hydrogen 7-Inch Check Valve

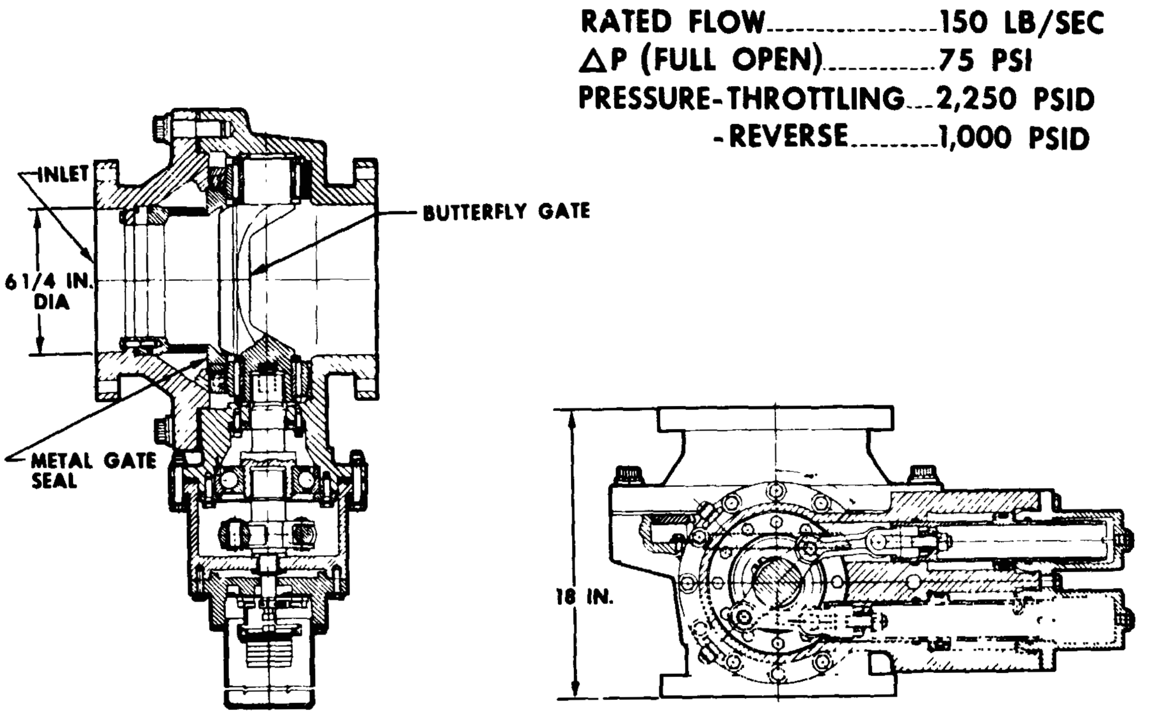


Figure 21. Liquid Hydrogen Bypass Valve

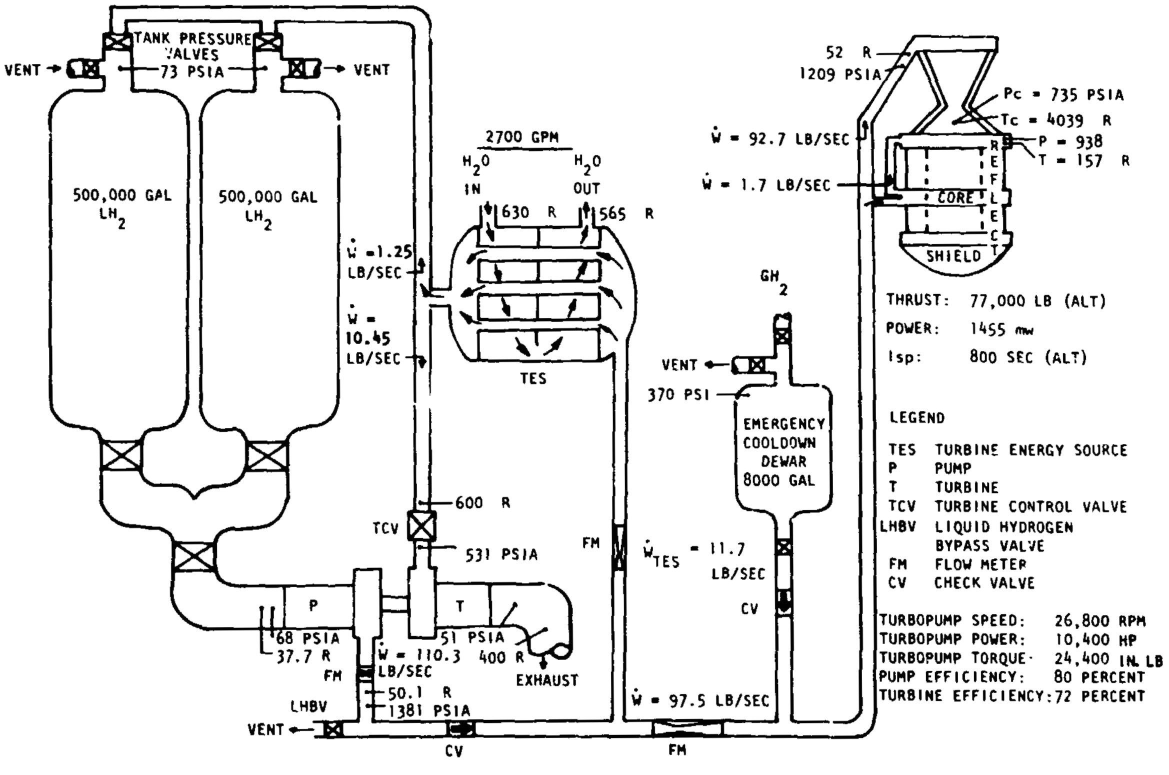


Figure 22. Full-Power Phoebus 1B Operating Parameters