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COLD-FLOW STARTUP TEST SUMMARY OF A FULL-SCALE NUCLEAR ROCKET ENGINE USING A RADIAL TURBOPUMP

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16. Abstract

Results are presented from an unfueled nuclear rocket simulator test conducted to determine if enough heat energy from the engine components is available to the turbine to start pumping propellant. The investigation was conducted with the pump at ambient and liquid-hydrogen temperatures and at tank pressures of 25 and 35 psia (17.2 and 24.1 N/cm^2) for both pump conditions. Data show a flow surge existed several seconds after power was applied to the turbine. Analysis indicates the flow surge experienced can be minimized either by flushing the system prior to applying power to the turbine or by programmed throttling at the pump discharge.

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SUMMARY

This report presents results from an unfueled nuclear rocket simulator test conducted to determine if enough driving energy is available to a turbine to start pumping propellant at time of flow initiation. The energy is obtained from the temperature difference between the vaporizing liquid-hydrogen propellant and the engine materials, which are at ambient temperature. The experimental investigation was conducted both with the pump prechilled to liquid-hydrogen temperature and at ambient temperature. The tank pressures were 25 and 35 psia (17.2 and 24.1 N/cm^2) for both pump conditions.

Plots of pump pressure rise as a function of pump inlet flow were obtained from the experimental data for each test condition. These plots show a flow surge existed several seconds after power was applied to the turbine.

In an attempt to reduce or eliminate the flow surge, special tests were conducted. In one test, power was applied to the turbine 10 seconds after flow initiation. Another test had a programmed load value at the pump discharge. To illustrate the reduction of the flow surge, a plot of pump inlet flow against time is presented.

The data indicate that the propellant entering the pump increased in temperature approximately 1.5° R (0.83 K) and that the radial pump is sensitive to fluid conditions. In addition, a comparison between the radial and axial pump maps shows that the system damping is a function of the slope of the constant speed lines of the pump.

Other tests were conducted to determine the severity of pressure and temperature oscillations and to determine the time history of the component and fluid temperatures without applying power to the turbine. The results were used to determine a schedule for applying power to the turbine.

INTRODUCTION

In the development of the nuclear rocket propulsion system, as in other propulsion systems, it is important to understand all phases of operation. Typically, most attention is given to design point operation where the significant long-term use occurs. However, startup and shutdown modes cannot be neglected. The component characteristics operating off-design may lack system compatibility or require operational restraints. This is more significant for nuclear rockets than for other propulsion systems because of the longer startup and shutdown time increments.

Startup of the nuclear rocket flow system uses the "bootstrap" technique, where a portion of the flow is bled off to power the turbopump. The feasibility of such a start depends on the ability to extract enough energy from the bleed gas to permit excess turbine torque to accelerate the pump, increasing flow. So the question to be answered is - will the system bootstrap? And will it do so in a well-behaved controllable manner?

Analytical determination of "bootstrap" characteristics is extremely difficult since the individual components are operating far off their design values and the hydrogen propellant is boiling within some of the components. Therefore, an experimental evaluation program was conducted at Lewis to determine bootstrap startup feasibility.

The first reported startup of an unfueled nuclear engine system (ref. 1) occurred in an earlier test series. An axial pump was used. No significant operational problems existed in that test. The system dynamic startup performance using the axial pump is reported in references 1 to 3. Component evaluation of experimental data on heat transfer and pressure drop for single-phase and two-phase hydrogen flow is reported in references 4 to 7. The investigation of the low-speed, or off-design, characteristics of the axial turbopump is reported in references 8 and 9.

A mathematical model predicting quasi-static startup performance of the axial pump nuclear engine system is reported in reference 10. The model was generated by using component test data and showed good agreement with those data.

An effort to study in more detail, and extend, the mathematical model dynamic performance resulted in an additional experimental investigation. This investigation used the same unfueled nuclear engine system simulator, except that the axial pump was replaced by a radial pump. This turbopump is similar to the prototype turbopump of the Nuclear Experimental Engine which was hot fired at the Nuclear Rocket Development Station (NRDS) in Nevada.

The purpose of this report is to summarize the experimental investigation and to obtain further insight into operation of the cold-flow unfueled nuclear engine during startup transients. This is done by an examination of significant parameters measured during the tests. The following section of this report, on the experimental program, outlines the scope and types of tests most recently performed using the unfueled nuclear engine simulator with a radial pump.

EXPERIMENTAL PROGRAM

Seventeen tests were conducted with the nuclear rocket simulator using a radial flow pump in the propellant feed system. The radial pump was operated at either of two conditions: (1) wet pump (i.e., the pump was prechilled to liquid-hydrogen temperature prior to test) or (2) dry pump (i.e., the pump was at ambient temperature prior to test).

The advantage of using a dry pump start is that it makes possible the elimination of two valves from the engine system. This simplifies the control system and reduces the engine weight. The disadvantage of a dry pump start is that care must be taken not to apply power to the turbine until liquid hydrogen is observed at the pump discharge. This is necessary to avoid pump overspeed, which could damage the pump.

The first series of tests included both wet and dry pump cooldown tests (i.e., power was not applied to the turbine). The initiation of system flow results from tank pressure alone. The cooldown tests were conducted to investigate the system flow dynamics independent of the turbopump dynamics. In addition, the dry pump cooldown tests were used to estimate the time at which power could be applied to the turbine.

The next series of tests was similar to the cooldown tests, except that power was applied to the turbine. The turbine gas flow was obtained from a bleed port in the nozzle chamber (fig. 1). The energy was obtained from the temperature difference between the vaporizing liquid-hydrogen propellant and the engine materials, which are at ambient temperature. Therefore, a portion of the main system flow was used to power the turbine in a bootstrap technique. If enough energy was available to power the turbine, such that a buildup of system flow and pressure resulted, the system bootstrapped.

The bootstrap tests were conducted with a wet or dry pump condition. Power was applied to the turbine simultaneously with the start of propellant flow in the wet pump bootstrap tests. In the dry pump bootstrap tests, power to the turbine was delayed, as determined by the cooldown test data, to allow liquid hydrogen to cool the pump. During the wet and dry pump bootstrap tests, a large flow surge was observed. Subsequent radial pump bootstrap tests were conducted for the specific purpose of reducing or eliminating this flow surge. In addition, two special tests were conducted to obtain data for an analog computer system dynamics simulation, as is reported in reference 11.

Nominal tank pressures of 25 and 35 psia (17.2 and 24.1 N/cm^2) were used for both wet and dry pump cooldown tests and wet and dry bootstrap tests. To simulate altitude conditions, the nozzle exit pressure was maintained at less than 1 psia (0.69 N/cm^2) for the duration of the test.

SYSTEM DESCRIPTION

Unfueled nuclear rocket startup simulator tests using a radial flow turbopump were conducted at the Plum Brook Station of the Lewis Research Center. The test facility consisted primarily of a test stand, a propellant supply system, and an altitude exhaust system. A schematic of the research hardware and its piping configuration is shown in figure 1. The facility and research hardware are described in detail in reference 12. The research hardware consisted of the run tank and associated pressurization controls, turbine and pump assembly, flow control valves, reactor assembly, regeneratively cooled nozzle, and connecting propellant feedlines.

An illustration of the turbopump assembly used in these tests is shown in figure 2. The pump was a radial flow, centrifugal type with an integral three-blade helical inducer. The turbine was a two-stage axial flow type coupled to the pump with a common shaft supported by hydrogen-cooled bearings. Hydrogen was supplied from the tank to the pump through the pump inlet line. The turbine effluent exited from two ports of the exhaust manifold to the altitude exhaust system of the test facility.

The reactor assembly was basically a KIWI-B1-B type. Aluminum was substituted for beryllium in the reflector system and unloaded graphite fuel elements were used. No control rod actuators were installed, and various parts, such as bearings, were replaced by solid pieces of metal to simulate heat capacity and coolant flow path. The control rods were set in a fixed position representative of that required during the initial part of the bootstrap startup. Calculations were performed which indicated that these modifications did not compromise the research data.

The regeneratively cooled nozzle used was designed for the KIWI reactor. It was modified to include a turbine bleed port, an instrumentation port, and a port for illuminating and photographing the discharge face of the reactor core. The liquid-hydrogen propellant from the pump discharge entered the nozzle assembly, as shown in figure 3, through a torous inlet manifold at the exit end of the nozzle.

The research hardware components were arranged in a close-coupled configuration to simulate a flight engine as closely as possible. To minimize external heat transfer, insulation was used for the entire length of the pump inlet and discharge lines. The pump was insulated similarly. Thus, the heat transfer, flow, and dynamic interaction effects of the various components closely simulated a nuclear rocket engine system during the early part of the startup transient.

TEST PROCEDURE

A general description of the test procedure used during each test is included in this section of the report. A more detailed test procedure is contained in reference 12.

Four types of tests were conducted: (1) wet pump cooldown tests, (2) dry pump cooldown tests, (3) wet pump bootstrap tests, and (4) dry pump bootstrap tests.

A time-history of events produced by an automatic test sequencer for typical examples of these tests is shown in figure 4. Time zero (t = 0) for all tests corresponds to the time when the valve controlling propellant flow through the system began opening.

Cooldown Tests

The valves mentioned in the following test sequences appear schematically in figure 1.

Wet pump sequence. - The pump is chilled by flowing liquid hydrogen from the storage tank through the pump, including its associated piping, to the pump main discharge valve (PMDV). Liquid hydrogen is discharged through a liquid-hydrogen bypass valve (LHBV) and out the burnoff stack. The LHBV remains open until just before the test starts.

After pump chilldown is completed (i.e., the pump case temperature stabilizes at or near liquid-hydrogen temperature), the altitude exhaust system is activated. This evacuates the nozzle, the reactor, and the facility exhaust system. When the nozzle exit pressure at the exhaust duct reaches 1 psia (0.69 N/cm^2), the test run is initiated by starting the run programmer. This occurs 40 seconds before the propellant starts flowing through the system, or at t = -40 seconds, as shown in figure 4.

Tank pressure is ramped to its set point; the digital data acquisition system and various recorders, including the FM magnetic tape recorder, are switched on. At t = 0, liquid-hydrogen flow is started through the system by controlled opening of the pump main discharge valve (PMDV). At this point in time, exhaust duct pressure has been reduced to 0.8 psia (0.55 N/cm^2). The test run is terminated by the test operator when the hydrogen liquid-gas interface, as indicated by on-line monitoring, has reached the desired position in the research test apparatus configuration.

Dry pump sequence. - This series of tests was made without prechilling the pump. The research hardware is in the following condition prior to flow initiation: the pump inlet flowmeters are prechilled with the propellant shutoff valve (PSOV) in the closed position. The pump main discharge valve (PMDV) remains open, while the turbine power control valve (TPCV) remains closed for the duration of the run.

An identical procedure to that used on the wet pump tests is followed except that at t = 0 liquid-hydrogen flow is started through the system by controlled opening of the propellant shutoff valve (PSOV). The test run is terminated by the test operator, as in the wet pump sequence.

Bootstrap Tests

The bootstrap test procedures are basically the same as those for the corresponding wet and dry pump cooldown tests. However, control is obtained from a turbine power control valve (TPCV) located in the nozzle bleed line, which is opened at the start of, or during, the run (see fig. 4 including dashed lines). Shutdown is generally initiated after the internal heat of the system has produced maximum speed of the turbopump.

TEST RESULTS

Five cooldown tests and 12 bootstrap tests were conducted with the unfueled nuclear rocket simulator. The most significant result of the bootstrap tests was that the engine system could be successfully bootstrapped with a buildup of pump speed and system flow and pressure. The only operational problem encountered was the occurrence of a large flow surge during the initial period of bootstrapping.

Detailed measurements of engine system pressures, temperatures, flows, vibrations, and valve positions were taken during each test and listed in digital printouts and plots. For purposes of presenting a summary of test results, significant parameters have been selected for discussion.

The test conditions for the 17 tests are summarized in table I. The first five tests were cooldown tests, during which the TPCV remained closed. The remaining tests were bootstrap tests, during which the TPCV was opened at various times and rates. Two special bootstrap tests were conducted to obtain data for the analog computer system simulation. In these tests the TPCV was programmed such that the turbopump speed stepped ±500 rpm about 5000 rpm.

The peak values of the significant system performance parameters for each of the 17 tests are summarized in table II.

Wet and Dry Pump Cooldown Tests

From an examination of the cooldown data, it appears that in the wet pump tests the heat energy was extracted from the system at a faster rate than in the dry pump tests. This enabled the start of bootstrap earlier and from a higher pressure and flow rate level.

The rate at which latent heat is extracted from the system depends upon the propellant flow rate. During the dry pump test, a sufficient amount of liquid hydrogen had vaporized in the pump to increase the flow resistance. This reduced the initial liquid-hydrogen flow through the system.

This is shown in figure 5, which is a detailed plot of the first 25 seconds of pump inlet flow for both the wet and dry pump cooldown tests. The tests under consideration had a nominal tank pressure of 35 psia (24.1 N/cm^2). Flow oscillations occurred for both tests, but for the wet pump test the oscillations were of smaller amplitude and at a higher flow rate level. In addition, the amplitude of oscillations appears to decay sooner in the wet pump test. For comparison, an arbitrary amplitude of the oscillations of 1.0 pound per second (0.45 kg/sec) was chosen. Thus, the amplitude of the oscillations was less than 1.0 pound per second (0.45 kg/sec) after approximately 5 seconds for the wet pump test and after approximately 24 seconds for the dry pump test.

As a result of the reduced flow through the system during the initial phases of the dry pump cooldown test, heat energy was extracted from the system at a slower rate. For example, the nozzle chamber temperature decreased more slowly and the nozzle chamber pressure peaked lower and later in the dry pump test than in the wet pump test. This is shown in figure 6, which is a time profile of the nozzle chamber fluid temperature and pressure for both the wet and dry pump cooldown tests. From an examination of these curves, it appears that it takes approximately 68 seconds to reach 200° R (111 K) for the dry pump test and approximately 43 seconds to reach 200° R (111 K) for the wet pump test. In addition, the pressure peak was 13.5 psia (9.3 N/cm^2) at approximately 58 seconds for the dry pump test, whereas the pressure peak was 15.8 psia (10.9 N/cm^2) at approximately 33 seconds for the wet pump test.

System Bootstrap Tests

Plots of pump pressure rise against pump inlet flow with constant speed lines superimposed for the 35- and 25-psia (24.1- and 17.2-N/cm^2) wet pump bootstrap tests are shown in figures 7(a) and (b). These plots indicate that the engine system successfully bootstrapped since the pump speed, pump pressure rise, and system flow increased in magnitude to a peak value. After the available heat energy in the system was exhausted, the pump speed and pressure fell. Meanwhile, the system flow remained fairly constant before subsiding.

A turbopump requirement that liquid hydrogen be at the pump discharge before power is applied to the turbine was used to determine the time delay in opening the TPCV for the dry pump bootstrap tests. When a pressure-enthalpy diagram and the pump discharge pressure and temperature obtained from a prior 25-psia (17.2-N/cm^2) nominal-tank-pressure dry pump cooldown test were used, the data indicated that liquid hydrogen was observed at the pump discharge at approximately 30 seconds. Thus, a 30-second delay would be sufficient for both the 25- and 35-psia (17.2- and 24.1-N/cm^2) nominal-tank-pressure dry pump bootstrap tests.

However, the system did not bootstrap for the 25-psia (17.2-N/cm^2) nominal-tank-pressure bootstrap test. It appears that the liquid-hydrogen interface near the pump discharge coupled with flow oscillations results in the interface moving in and out of the pump. As a result, the condition of the propellant in the pump was alternately liquid or vapor, thus loading and unloading the pump.

A successful dry pump bootstrap test was achieved for the 35-psia (24.1-N/cm^2) nominal tank pressure. A plot of pump pressure rise against pump inlet flow for this test is shown in figure 7(c).

An important feature of figure 7 is the large flow surge (as indicated) that occurs during the initial period of bootstrapping. The flow surge is preceded by flow oscillations with increasing amplitude. Typically, this surge lasted less than 5 seconds after initiation of bootstrap with a nominal tank pressure of 35 psia (24.1 N/cm^2) and less than 8 seconds with a nominal tank pressure of 25 psia (17.2 N/cm^2).

To summarize the three radial pump bootstrap tests shown in figure 7, table III lists the maximum flow rate, maximum pump pressure rise, maximum pump speed, and the time after opening TPCV to reach maximum speed.

The effects of tank pressure on bootstrapping are shown in table III. For the wet pump tests, it took a shorter period of time to reach peak speed with a higher tank pressure. The higher tank pressure caused a greater initial driving force across the system. This resulted in a higher initial propellant flow rate, which chilled the system faster and reduced the flow resistance so that pumping of liquid hydrogen could begin earlier. Also, the higher tank pressure resulted in a higher peak speed since more energy was available in the system at the time the pumping began.

Flow profile. - The flow rate for both the 35-psia (24.1-N/cm^2) and 25-psia (17.2-N/cm^2) wet pump bootstrap tests oscillated with increasing amplitude. There was one final oscillation or flow surge before the flow rate increased smoothly to its final peak value. In the dry pump bootstrap test which had a nominal tank pressure of 35 psia (24.1 N/cm^2) and an approximate 30-second time delay before TPCV opening, there was just one flow oscillation before the large flow surge. These flow oscillations are shown in figure 8, which is a detailed plot of the flow-rate time history after opening of the TPCV. The flow surge did represent the true variation in flow rate, except where flow reversal was noted but not calibrated, as shown in figures 8(b) and (c).

The dry pump test reached peak flow sooner after opening of the TPCV, as shown in figure 8(c). However, the system had been cooling down for approximately 30 seconds prior to TPCV opening. As a result, flow had already reached 4 pounds per second (1.81 kg/sec) at the time the TPCV opened. This higher propellant flow rate, along with a reduction in system resistance before the start of bootstrap, enabled pumping of liquid hydrogen to begin earlier, with respect to opening the TPCV. This also enabled the flow rate to reach a higher level.

Turbopump performance. - Pump speed rose smoothly without oscillations during the initial period of bootstrapping. However, there was a change in speed, actually a deceleration, before reaching peak speed. This is shown in figure 9, which is a plot of speed against time after TPCV opening for both the 35-psia (24.1-N/cm^2) and 25-psia (17.2-N/cm^2) wet pump bootstrap tests and the 35-psia (24.1-N/cm^2) dry pump bootstrap test.

A comparison of figures 8 and 9 shows that the deceleration occurred during the large flow excursion. Thus, the pump appears to be unloaded before the excursion. As the flow builds up, the pump becomes loaded enough to actually reduce its speed. At some point later in time, there is again enough power available to accelerate the pump until it reaches some peak speed.

Another important feature of figure 9 shows that the peak speed varied for the three bootstrap tests from about 8800 to 9050 rpm. However, there is only a difference of approximately 50 rpm when the nominal tank pressure for the wet pump test is increased from 25 psia (17.2 N/cm^2) to 35 psia (24.1 N/cm^2). During these tests, the nozzle exit pressure was held below 1 psia (0.69 N/cm^2). A peak speed of 8800 rpm was attained in the dry pump bootstrap test. This was within 2 percent of the peak speed of the 35-psia (24.1-N/cm^2) wet pump test, although the pump accelerated on different pump load lines. The load line was different in the dry pump test because liquid hydrogen flowed through the system for approximately 30 seconds prior to opening the TPCV. As a result the system resistance was reduced, changing the load on the pump.

Pump rotation prior to bootstrapping is also shown in figure 9. For example, the wet pump test had a speed of approximately 500 rpm and the dry pump test a speed of approximately 250 rpm prior to bootstrapping. Because the turbine discharge valves were open prior to bootstrapping, the altitude exhaust system pulled a vacuum of approximately 1.0 psia (0.69 N/cm^2) at the turbine exit. As a result, liquid hydrogen used to cool the pump bearings was able to flow through the bearing cavity into the turbine inlet and power the turbine even though the TPCV was closed.

The acceleration rates before and after pump loading, along with the time interval used to determine the acceleration rates, are presented in table IV. An examination of the table indicates that the wet pump bootstrap acceleration rate was 1700 and 2000 rpm per second for nominal tank pressures of 25 and 35 psia (17.2 and 24.1 N/cm^2), respectively. This was lower than for the dry pump test at 35-psia (24.1-N/cm^2) nominal tank pressure, in which an acceleration rate of 3200 rpm per second was achieved. However, once the pump was loaded, the acceleration rate varied from 2100 to 2300 rpm per second for the three bootstrap tests, or approximately ±4.5 percent difference. The difference in acceleration rates before the pump was fully loaded was attributed to the quality of the fluid entering the pump.

Typical temperature and pressure profiles. - A typical profile of fluid temperature through the engine system against time for the wet pump bootstrap test with a 35-psia (24.1-N/cm^2) nominal tank pressure is shown in figure 10. The pump inlet and pump discharge fluid temperatures are at liquid-hydrogen temperature since the test was a wet pump test. The initial fluid temperature of the turbine inlet and turbine exit was lower than ambient temperature (approx 430° R (239 K) and 100° R (55.6 K), respectively). The temperature was lower because flow from the pump through the bearing coolant passages during the pump cooldown period entered the turbine. These temperatures rose as soon as flow through the turbine was introduced from the nozzle chamber. The average nozzle chamber temperature held fairly level (within 5 percent of initial temperature) for about 6.5 seconds since the bulk of the system mass was in the reactor. This time corresponds to the time at which the pump speed accelerated to its peak value. After 6.5 seconds, the nozzle chamber temperature began to fall at a uniform rate.

The relative pressure profile through the system for the wet pump bootstrap test with the 35-psia (24.1-N/cm^2) nominal tank pressure is shown in figure 11. After the first 4 to 4.5 seconds, the pressure oscillations were no longer observed, and the pressures rose to a maximum and decayed smoothly. The pump inlet pressure decreased to approximately 32 psia (22.1 N/cm^2) at 6.5 seconds. This loss is attributed not only to the frictional pressure loss of the pipe but to the much greater pressure drop across the volumetric-type flowmeter. At approximately 6.5 seconds, the time at which the pump reached maximum speed, the pump discharge pressure was approximately 187 psia (129 N/cm^2).

Axial Pump Comparison

Prior to the radial pump bootstrap tests, a series of tests was conducted using an axial pump with the nuclear rocket simulator. The results from the wet axial pump test having a 35-psia (24.1-N/cm^2) nominal tank pressure with a zero TPCV delay are presented in this section to show the system operating parameter differences during startup.

A plot of pump pressure rise against pump inlet flow with constant speed lines superimposed for the axial pump bootstrap test is shown in figure 12. This plot indicates the engine system successfully bootstrapped without the occurrence of a flow surge. In addition, it appears that the pump acceleration was limited by the pump stall region.

The flow rate for the axial pump bootstrap tests oscillated before increasing smoothly to its peak value. These flow oscillations are shown in figure 13, which is a detailed plot of the flow-rate time history after opening of the TPCV.

A plot of pump speed against time after TPCV opening (fig. 14) shows that pump speed accelerated smoothly without oscillations during bootstrapping. As a result, the pump reached a peak speed of 9700 rpm. This was approximately 37 percent of design speed for the axial pump. The acceleration rate was probably limited by the pump stall region to 1100 rpm per second.

The fluid temperature profile through the engine against time for the axial pump bootstrap test is shown in figure 15. The nozzle chamber temperature is approximately equal to its initial temperature at 6.5 seconds. At 12.3 seconds, the time at which the axial pump produced the maximum pressure rise, the temperature is down to approximately 136° R (75.5 K).

The pressure profile through the system for the axial pump bootstrap test is shown in figure 16. After approximately the first 3 seconds, pressure oscillations were no longer observed, and the system pressures rose to a maximum. The maximum pump discharge pressure of approximately 142 psia (91 N/cm^2) occurred at 12.3 seconds. This is almost twice the time that the wet radial pump with the 35-psia (24.1-N/cm^2) tank pressure and zero TPCV conditions used to reach peak speed. The difference in system pressure can be attributed to the temperature differences or loads at various points in the system at the time of equal pump discharge pressure.

Flow Surge Tests

As previously mentioned, subsequent radial pump bootstrap tests were conducted for the specific purpose of reducing or eliminating the flow surge frequently noted. These tests were shown in figure 7. In particular, two tests are discussed in this section. These tests were of the wet pump, at a nominal tank pressure of 35 psia (24.1 N/cm^2). However, one test had a 10-second delay in opening the TPCV. The other test had a zero delay in opening the TPCV but had a programmed PMDV. The PMDV program is shown in figure 17.

A plot of flow rate against time for the two flow surge tests is shown in figure 18. For comparison, figure 8(a) is also plotted in figure 18. The figure shows that the two special tests minimized the flow surge. In addition, the test with the programmed PMDV opening is more desirable because it reduces not only the flow surge but also the flow oscillations without sacrificing time to bootstrap. To summarize the three tests shown in figure 18, the maximum flow rate, pump pressure rise, speed, and time to reach maximum speed are presented in table V.

Flow Surge Analysis

During test sequence the liquid-hydrogen bypass valve (LHBV) which is used to prechill the pump was closed approximately 10 seconds prior to opening the PMDV. An analysis of the test data revealed that the temperature of the liquid hydrogen in the pump inlet line increased due to heat leak of several components. After the PMDV is opened, this warmer fluid is flushed through the pump.

A plot of pump inlet temperature against time for three wet radial pump tests and the axial pump test is shown in figure 19. The test conditions for the three radial pump tests were 35-psia (24.1-N/cm^2) nominal tank pressure with (1) zero delay in opening the TPCV, (2) 10-second delay in opening the TPCV, or (3) zero delay in opening the TPCV and programmed opening of the PMDV. The axial pump test conditions, 35-psia (24.1-N/cm^2) tank pressure with zero delay in opening TPCV, were described in the section Axial Pump Comparison. In addition, a liquid-hydrogen saturation temperature reference at 35 psia (24.1 N/cm^2) is shown as a dashed line in figure 19.

Figure 19 shows the temperature of the fluid as it passes the pump inlet station. The fluid entering the pump has increased in temperature approximately 1.5° R (0.83 K) before decreasing to a constant value. Under these operating conditions, an increase of this magnitude in liquid-hydrogen temperature in the line could lower the net positive suction head (NPSH) at the pump inlet. As a result, the possibility of pump cavitation would be increased.

In figure 19, the time at which the flow surge ended for the wet pump test with zero TPCV delay is indicated. Thus, the flow surge occurred during the time the pump inlet line was being flushed. For the 10-second TPCV delay test, the pump inlet line was flushed before the start of bootstrap. In addition, both the test with the programmed PMDV opening and the axial pump test bootstrapped without a flow surge during the flush time. It appears that the radial pump test with zero TPCV delay was the only test sensitive to the fluid conditions entering the pump.

To explain why there was no flow surge in either the wet radial pump tests with the programmed PMDV opening or the axial pump test, the radial and axial pump maps are examined. The pump maps (refs. 9 and 13) are shown in figure 20. These maps are plots of head rise against pump inlet flow with lines of constant speed shown. The most significant difference in these maps is the slope of the speed lines. For the axial pump, the slopes of the speed lines are always negative, whereas the slopes of the speed lines for the radial pump are slightly positive or zero.

A study (ref. 11) shows that the damping factor for the system is a function of the slope of the speed lines. In particular, the system is underdamped if the slopes of the speed lines are positive and highly damped if the speed lines are negative. Therefore, the system was highly damped for the axial pump system test since the speed lines are negative. This accounts for the absence of a flow surge.

When the PMDV was programmed open, it effectively changed the characteristics of the pump. If the characteristics of the partly open valve are combined with the pump characteristics, the system load downstream of the PMDV would remain the same. The effective pump characteristics would change to reflect both the radial pump and the valve.

Data of pressure drop across the PMDV against flow of the programmed PMDV opening were used to combine the valve characteristics with the pump characteristics. As a result, a new pump map was obtained, as shown by the dashed lines of figure 21. This clearly shows that the slope of the speed lines changed from a nearly zero slope to a negative slope. Therefore, the system was highly damped, and a flow surge did not occur for the radial pump system tests when the PMDV was programmed open.

CONCLUDING REMARKS

For the range of test conditions investigated, the experimental data suggest the following conclusions:

1. There is an adequate amount of heat stored in the system components to provide sufficient energy to bootstrap under altitude conditions.

2. For the wet pump tests, successful bootstraps were made at both nominal tank pressures, 25 and 35 psia (17.2 and 24.1 N/cm^2). With approximately 30 seconds cooldown time for the dry pump tests, successful bootstrapping was achieved with nominal tank pressures of 35 psia (24.1 N/cm^2), but not with 25 psia (17.2 N/cm^2).

3. A successful bootstrap depends on adequate conditioning of the liquid-hydrogen propellant entering the pump. This is accomplished either by prechilling the pump and its related inlet lines (wet pump) or by cooling down the system, utilizing tank head flow while not applying power to the turbine.

4. Although flow and pressure oscillations occurred during some of the startups, bootstraps were achieved without detrimental effects on the system components. The large flow surge experienced by the radial pump can be minimized by providing damping either by flushing the system prior to applying power to the turbine or by programmed throttling at the pump discharge.

Lewis Research Center,
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TABLE I. - SUMMARY OF TEST CONDITIONS

[Altitude exhaust pressure maintained at ~0.8 psia (0.55 N/cm^2).]

Test	Nominal tank pressure		Pump condition at start	Initial temperature of pressure vessel		Turbine power control valve (TPCV) program (includes pump main discharge valve (PMDV) program when used)
	psia	N/cm^2		^oR	K	
1	35	24.1	Wet	512	284	Cooldown test (TPCV closed)
2	25	17.2	Wet	502	278	Cooldown test (TPCV closed); PMDV stepped during test
3	25	17.2	Dry	520	289	Cooldown tests (TPCV closed)
4	35	24.1	Dry	539	300	
5	35	24.1	Wet	515	286	
6	35	24.1	Wet	542	301	Step open at start
7	25	17.2	Wet	530	295	
8	25	17.2	Wet	527	293	
9	25	17.2	Dry	482	268	Step open 29 seconds after propellant shutoff servovalve (PSOV) opening
10	35	24.1	Dry	530	295	Step open 33 seconds after PSOV opening
11	35	24.1	Wet	488	271	Step open 10 seconds after PMDV opening
12	35	24.1	Dry	527	293	Step open 41 seconds after PSOV opening
13	35	24.1	Wet	512	284	Step open at start; PMDV programmed to 100 percent open in 6 seconds
14	35	24.1	Wet	518	288	Ramp speed to 5000 rpm followed by speed steps of ±500 rpm about 5000 rpm
15	35	24.1	Dry	506	281	Ramp speed at 1000 rpm per second after 15 seconds delay; PMDV stepped to 39 percent open
16	25	17.2	Wet	505	281	Same as test 14
17	25	17.2	Wet	506	281	Step open at start; PMDV programmed to 100 percent open in 10 seconds

TABLE II. - SUMMARY OF SELECTED TEST RESULTS

Test	Time reflector inlet fluid temperature is at 80° R (40 K), sec	Maximum pump speed, rpm	Maximum pump inlet flow		Maximum pump pressure rise		Maximum pump pressure rise		Nozzle chamber				Maximum turbine inlet flow		Remarks
									Maximum pressure		Corresponding temperature				
			lb/sec	kg/sec	psi	N/cm^2	psia	N/cm^2	psia	N/cm^2	^{o}R	K	lb/sec	kg/sec	
1	20.6	0	12.5	5.7	-9.1	-6.3	27	18.6	15.8	10.9	355	197	0	0	TPCV closed
2	40	0	3	1.4	-.5	-.4	29.3	16.8	7.4	5.1	445	247			TPCV closed
3	81.1	0	5.7	2.6	-2.6	-1.8	32.3	22.3	9.1	6.3	451	250			TPCV closed
4	47.2	270	10.6	4.8	-6.7	-4.6	28.1	19.4	13.4	9.3	380	211			Incomplete tank pressure
5	26	0	11.2	5.1	-7.5	-5.2	24.1	16.6	15.3	10.6	350	195			TPCV closed
6	5.9	9000	32.5	14.8	158	109	198	136.5	70.4	48.6	510	284	1.4	0.64	----------------------
7	7	8800	30	13.7	(a)	(a)	(a)	(a)	64	44.1	435	242	1.3	0.59	PMDV leaked
8	8.7	9000	28.5	13.0	151	104	173	119.4	64.4	44.4	483	268	1.3	.59	----------------------
9	38.5	(a)	(a)	(a)	41	28.3	63	43.5	22	15.2	448	249	.5	.23	----------------------
10	36	8800	34.5	15.7	147	101.5	177	122	70.8	48.8	388	216	1.5	.68	----------------------
11	11.4	8400	31.4	14.3	137	94.5	168	116	64.5	44.5	413	230	1.3	.59	----------------------
12	42.3	7950	34	15.5	121	83.5	150	103.5	62	42.8	335	186	1.4	.64	PSOV leaked
13	4.8	8650	31.3	14.2	144	99.4	178	122.5	65.5	45.2	403	224	1.3	0.59	----------------------
14	6.7	6200	22.9	10.4	74	51	109	73.5	40.8	28.2	349	194	.7	.32	----------------------
15	32.7	9500	(b)	(b)	96	66.2	127	87.6	37	25.5	475	264	.6	.27	PSOV leaked
16	10.7	5700	22	10	64	44.1	89	61.4	37.6	25.9	388	216	.7	.32	----------------------
17	8.8	8600	29	13.2	142	98	163	112.5	62	42.8	449	250	1.3	.59	----------------------

[a]Exceeds transducer limit.

[b]Limited.

TABLE III. - EFFECTS OF TANK PRESSURE ON BOOTSTRAPPING, RADIAL PUMP TESTS

Pump condition	Nominal tank pressure		Maximum flow rate		Maximum pressure rise		Maximum speed, rpm	Time from turbine power control valve (TPCV) open to maximum speed, sec	TPCV time delay, sec	Total time, sec
	psia	N/cm^2	lb/sec	kg/sec	psi	N/cm^2				
Wet	35	24.1	32.6	14.8	164	113	9050	6.5	0	6.5
Wet	25	17.2	30.4	13.8	153	105.5	9000	10.3	0	10.3
Dry	35	24.1	35	15.9	148	102	8800	5.4	33	38.4

TABLE IV. - ACCELERATION RATES

Pump condition	Nominal tank pressure		Before loading		After loading	
	psia	N/cm^2	Acceleration rate, rpm/sec	Time after TPCV opens, sec	Acceleration rate, rpm/sec	Time, sec
Wet	35	24.1	2000	2 to 3	2200	5 to 6
Wet	25	17.2	1700	4.3 to 5.3	2100	8 to 9
Dry	35	24.1	3200	0 to 1	2300	3 to 4

TABLE V. - WET PUMP BOOTSTRAP TESTS AT 35-PSIA

(24.1-N/cm^2) NOMINAL TANK PRESSURE

Test condition	Maximum flow		Maximum pressure rise		Maximum speed, rpm	Time to attain maximum speed, sec
	lb/sec	kg/sec	psi	N/cm^2		
Zero turbine-power-control-valve (TPCV) delay	32.6	14.8	164	113	9050	6.5
Ten-second TPCV delay	31.4	14.3	138	95.2	8400	13.25
Programmed pump-main-discharge-valve (PMDV) opening	31.4	14.3	146	101	8650	6.25

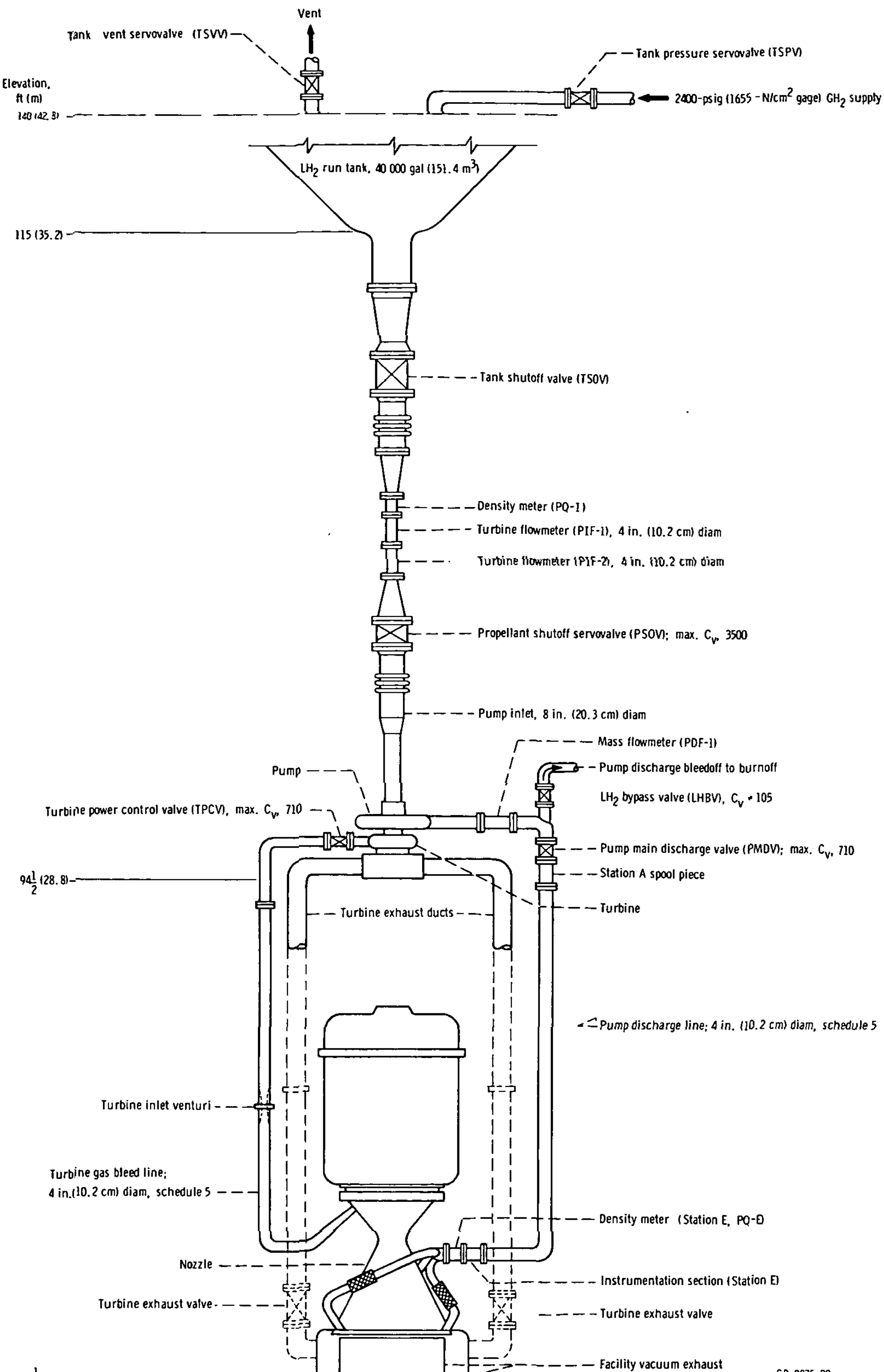


Figure 1. - Full-scale nuclear rocket cold-flow experiment in B-3 facility.

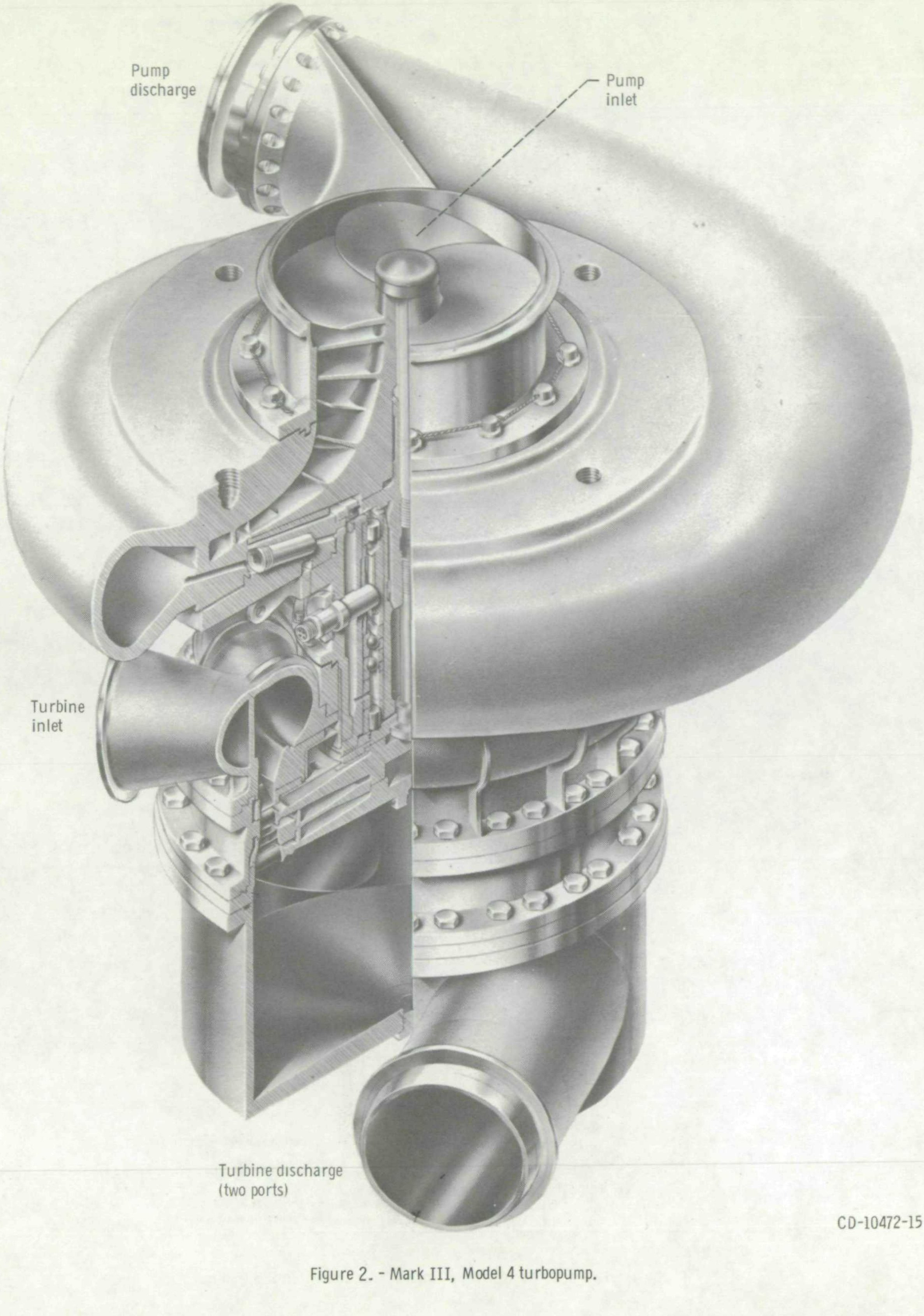


Figure 2. - Mark III, Model 4 turbopump.

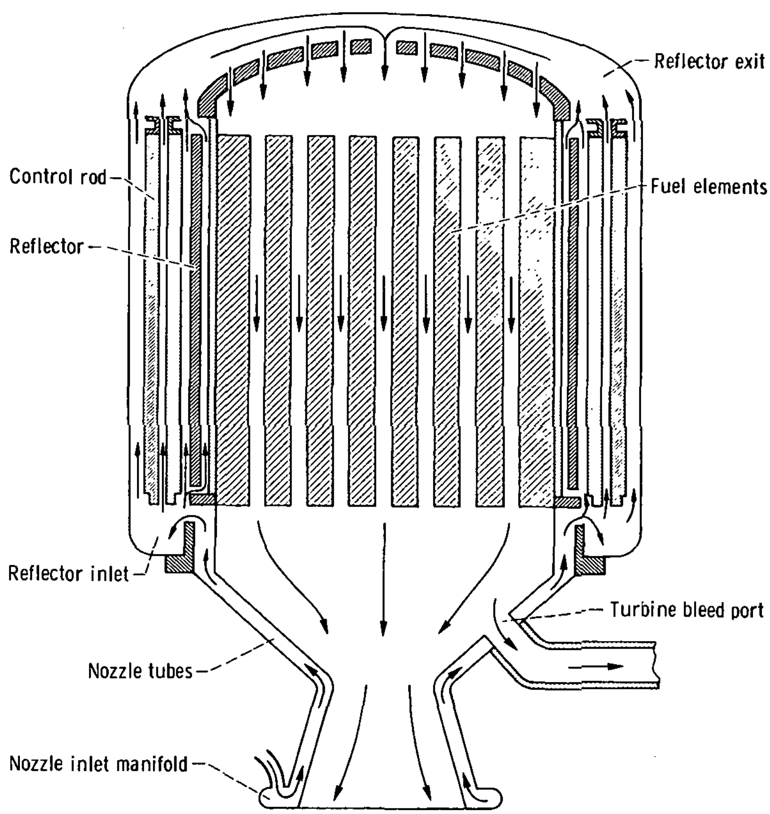


Figure 3. - Reactor assembly and nozzle.

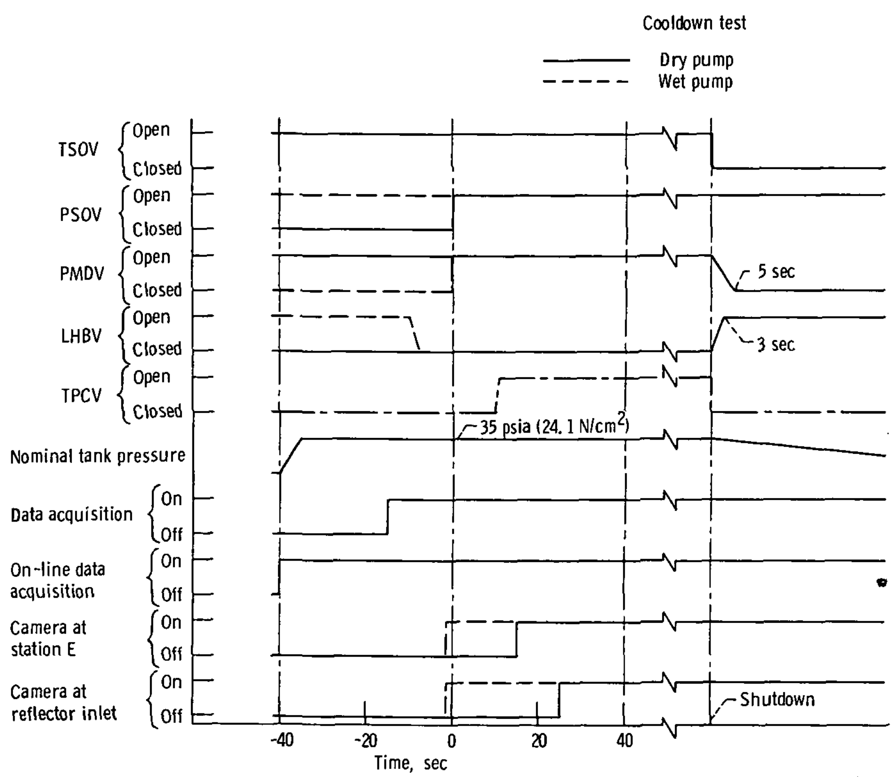


Figure 4. - Time history of events produced by an automatic test sequencer. TPCV open for bootstrap tests only.

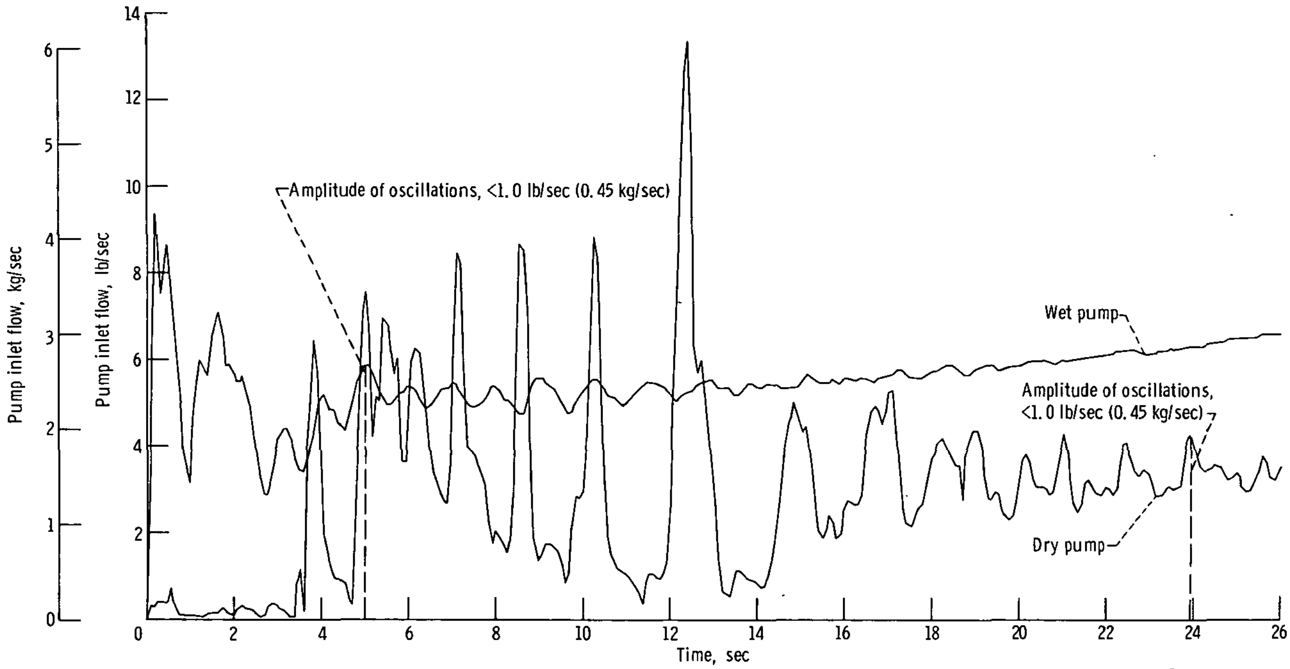


Figure 5. - Pump inlet flow against time for wet and dry pump cooldown tests. Nominal tank pressure, 35 psia (24. 1 N/cm^2).

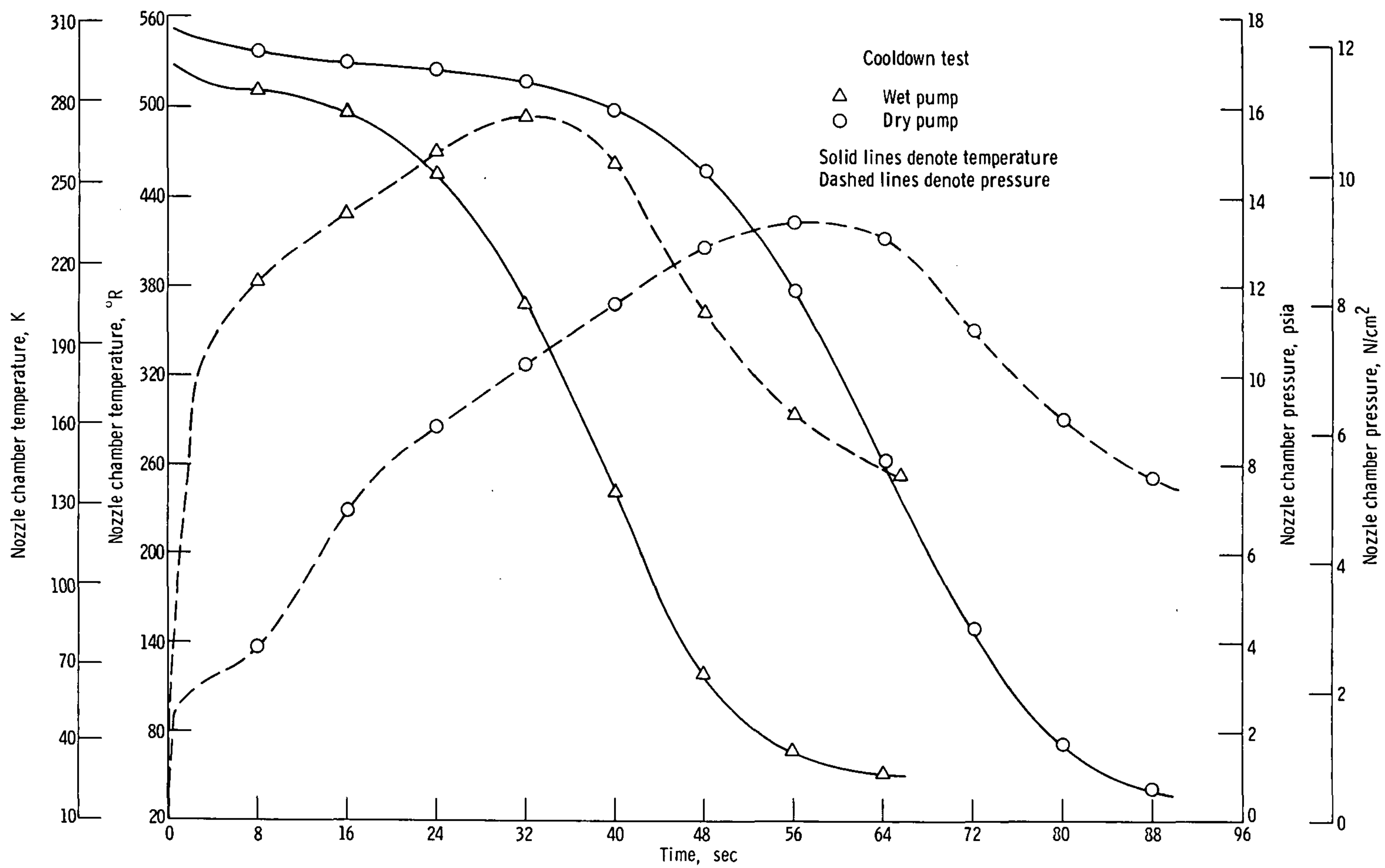
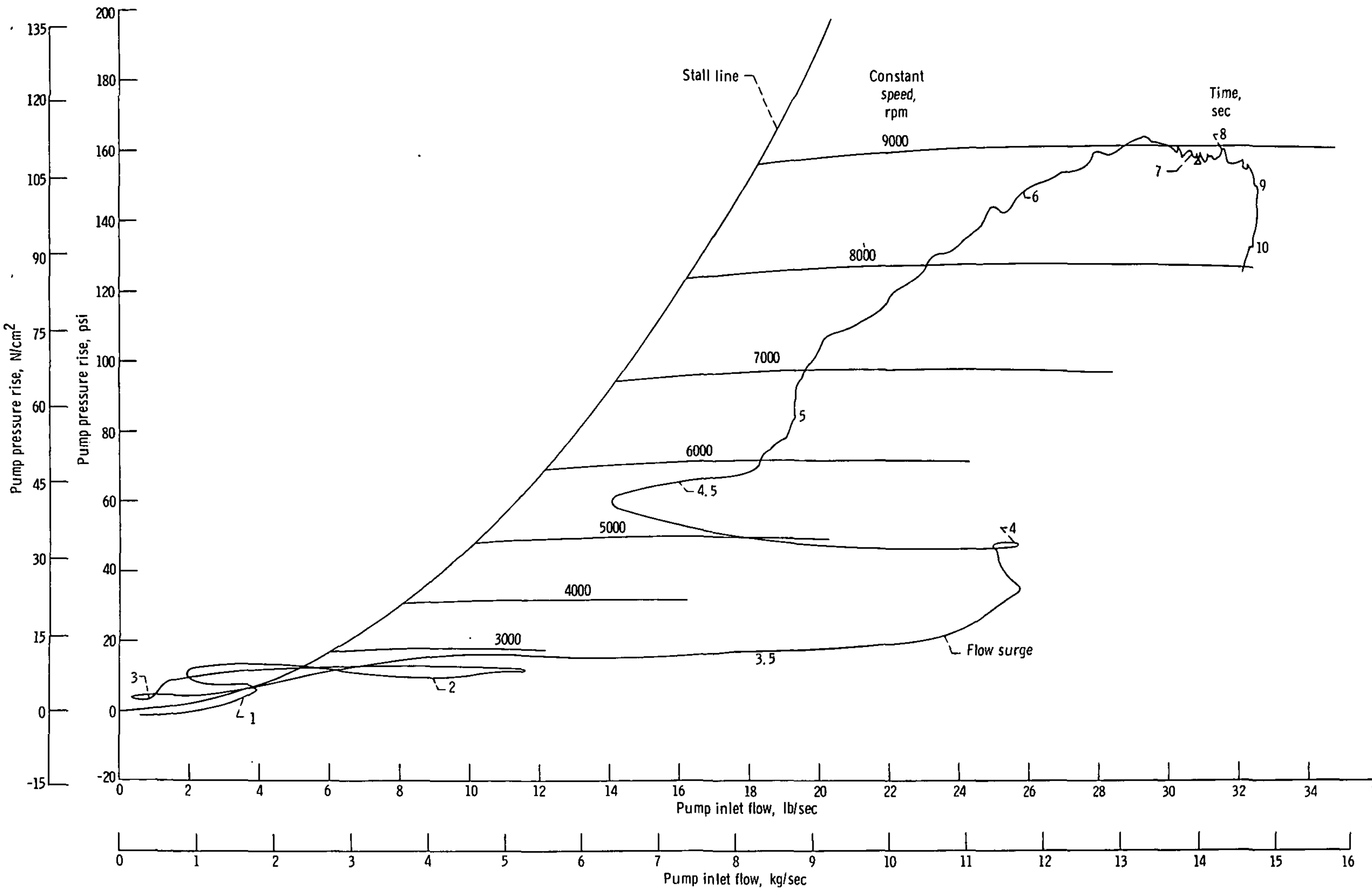
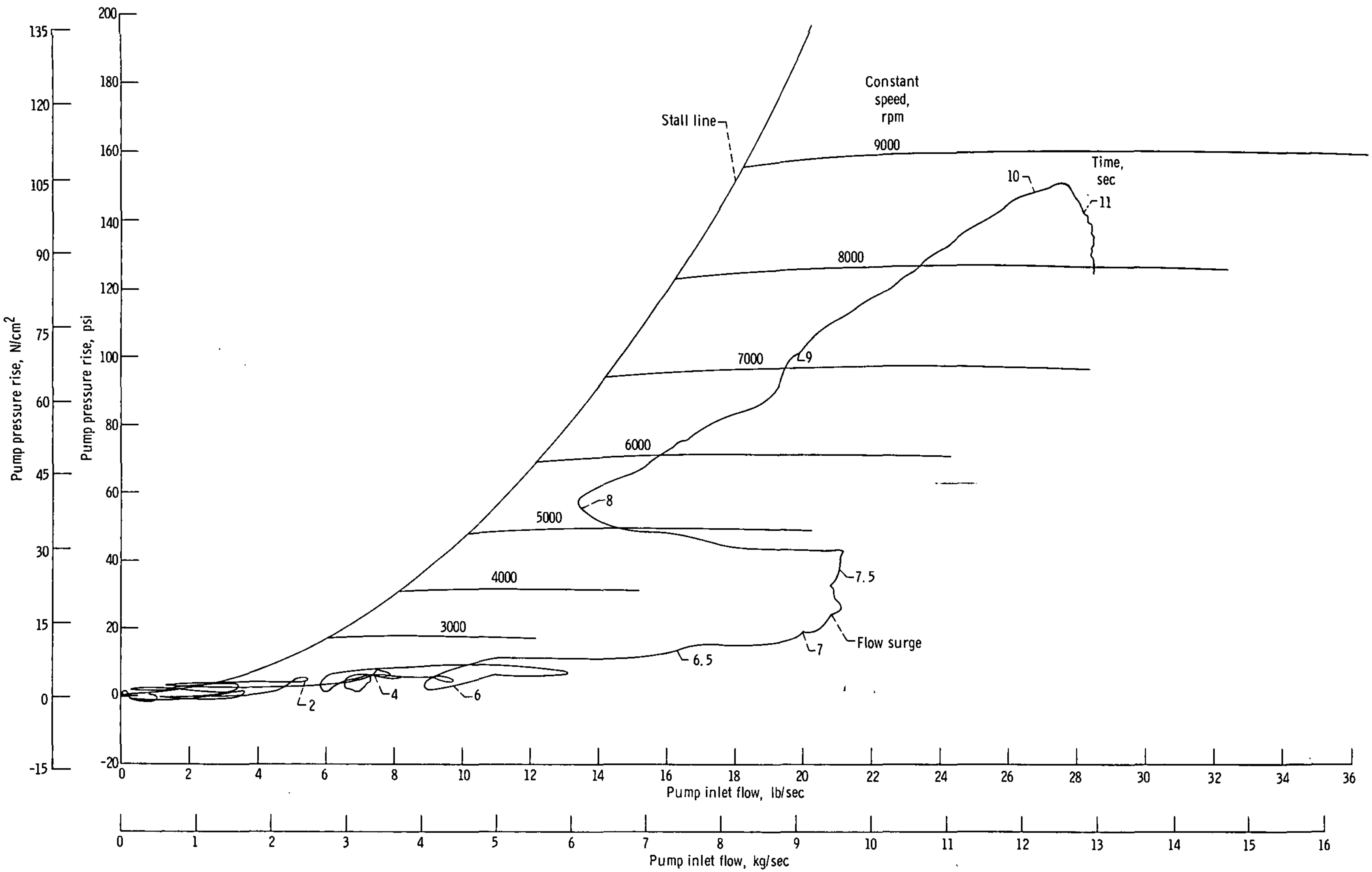


Figure 6. - Nozzle chamber fluid pressure and temperature against time for wet and dry pump cooldown tests. Nominal tank pressure, 35 psia (24.1 N/cm^2).



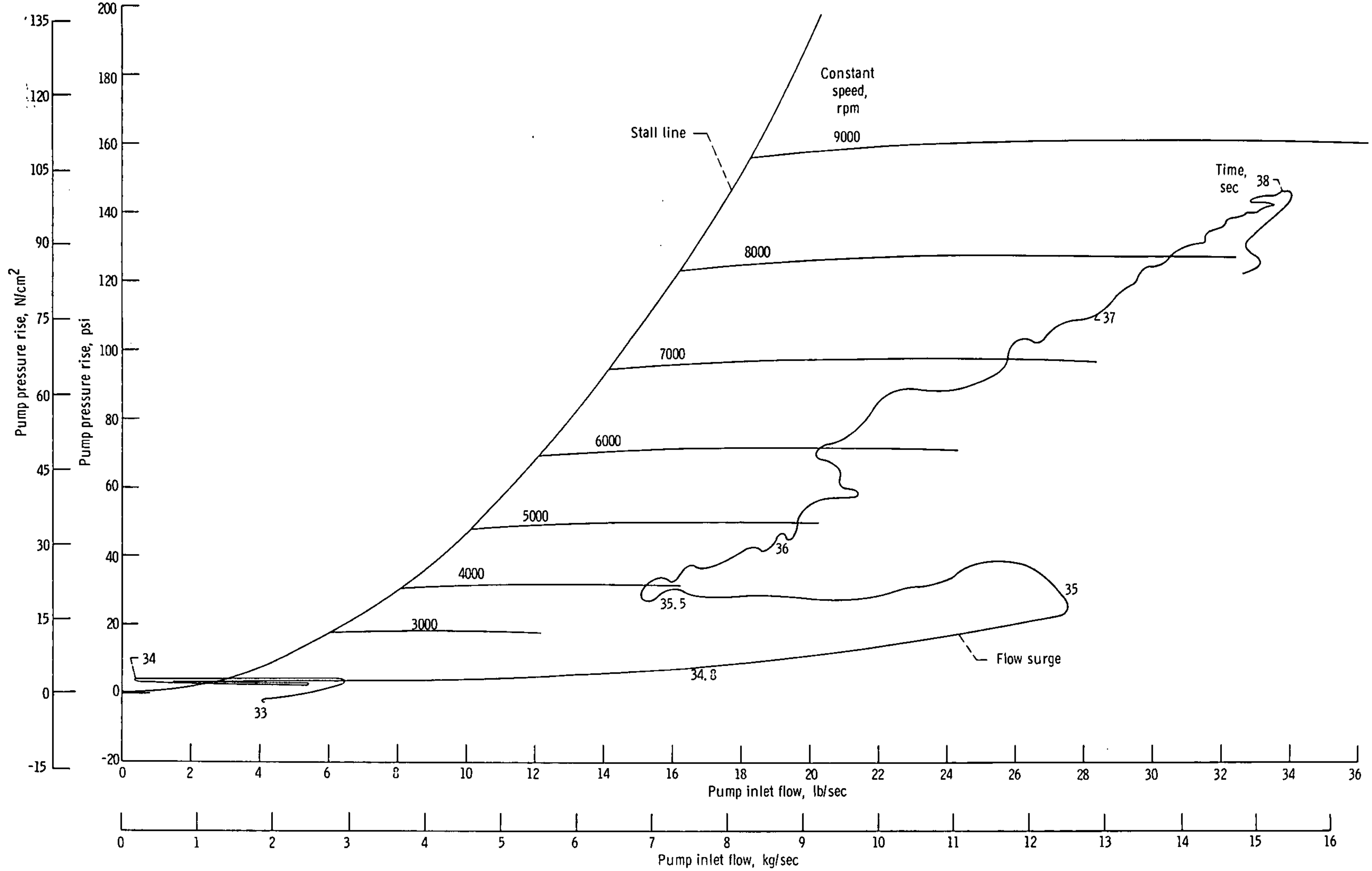
(a) Wet pump test; nominal tank pressure, 35 psia (24.1 N/cm^2).

Figure 7. - Pump pressure rise against pump inlet flow for three bootstrap tests.



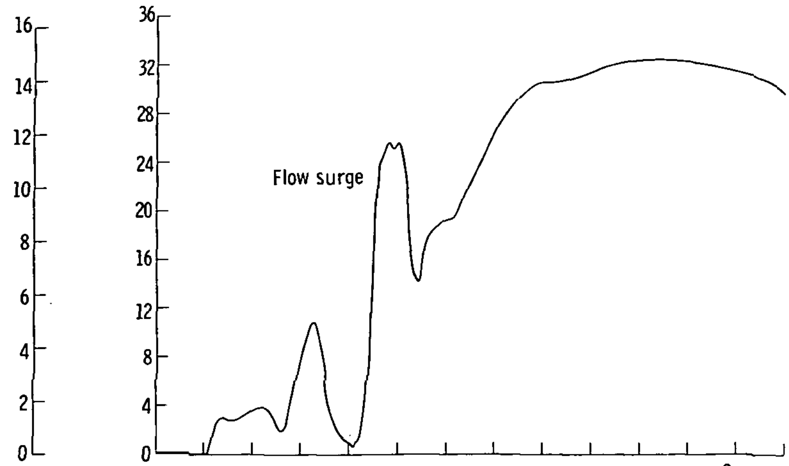
(b) Wet pump test; nominal tank pressure, 25 psia (17.2 N/cm^2).

Figure 7. - Continued.

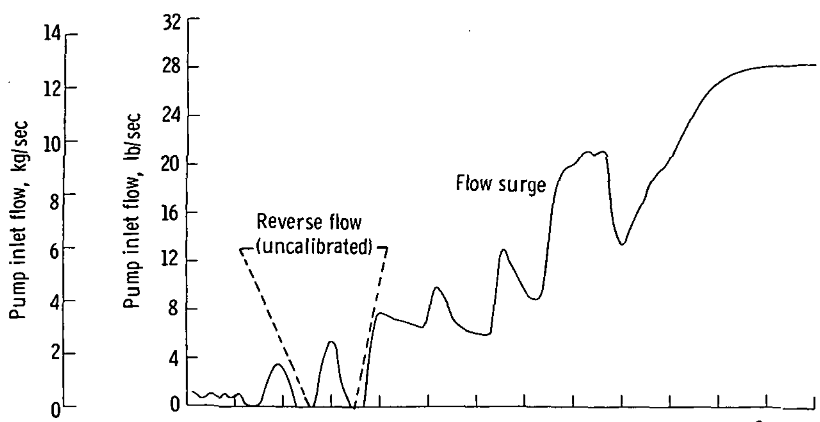


(c) Dry pump test; nominal tank pressure, 35 psia (24.1 N/cm^2); TPCV delay, 3.3 seconds.

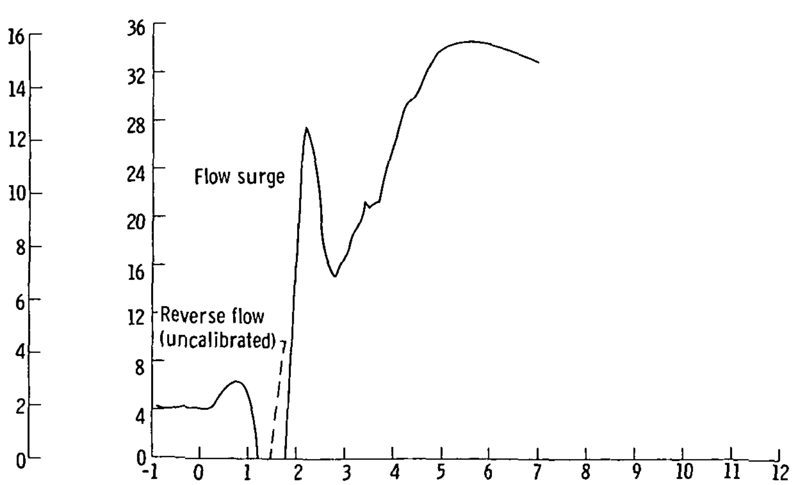
Figure 7. - Concluded.



(a) Wet pump test; nominal tank pressure, 35 psia (24.1 N/cm²).

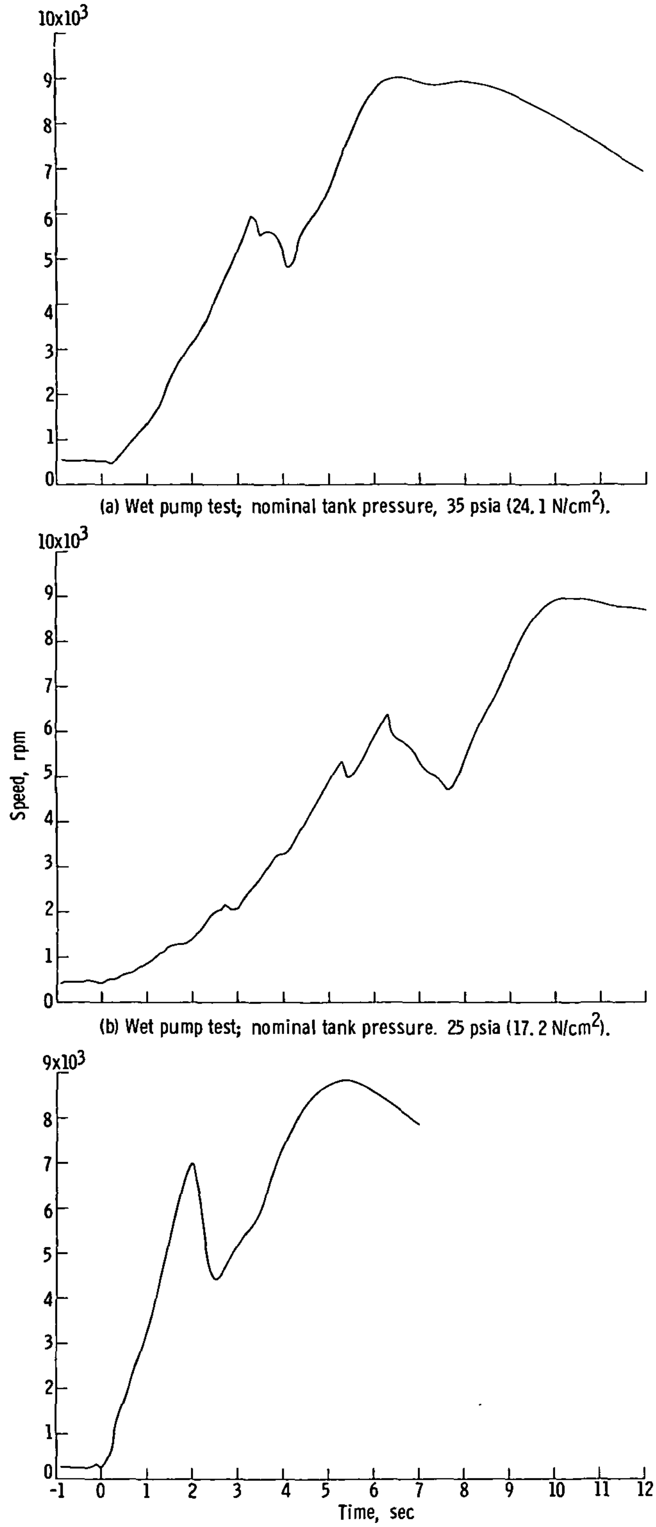


(b) Wet pump test; nominal tank pressure, 25 psia (17.2 N/cm²).



(c) Dry pump test; nominal tank pressure, 35 psia (24.1 N/cm²); TPCV delay, 33 seconds.

Figure 8. - Pump inlet flow against time after opening of turbine power control valve (TPCV) for four bootstrap tests.



(c) Dry pump test; nominal tank pressure, 35 psia (24.1 N/cm²); TPCV delay, 33 seconds.

Figure 9. - Pump speed against time after opening of turbine power control valve (TPCV) for four bootstrap tests.

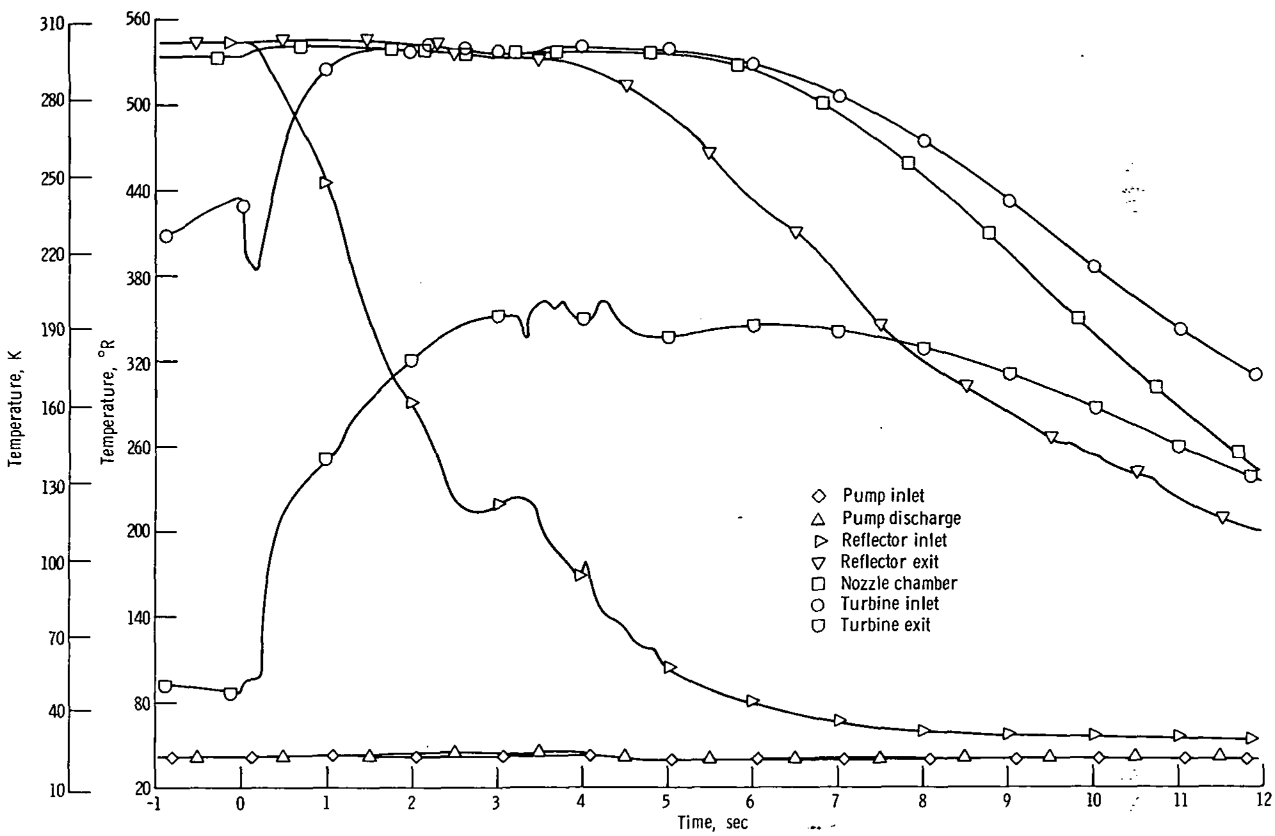


Figure 10. - Temperature profile for wet pump bootstrap test. Nominal tank pressure, 35 psia (24.1 N/cm²).

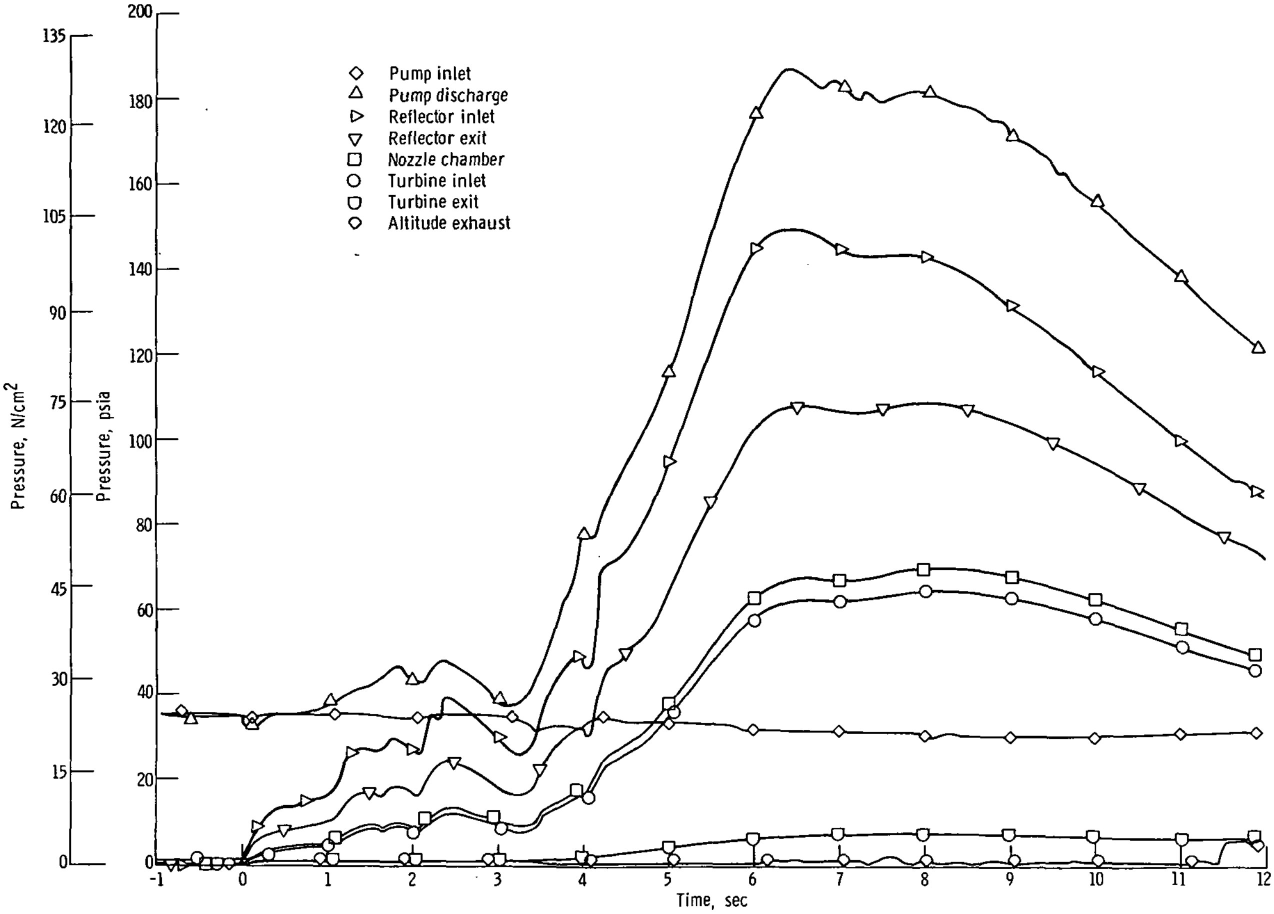


Figure 11. - Pressure profile for wet pump bootstrap test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

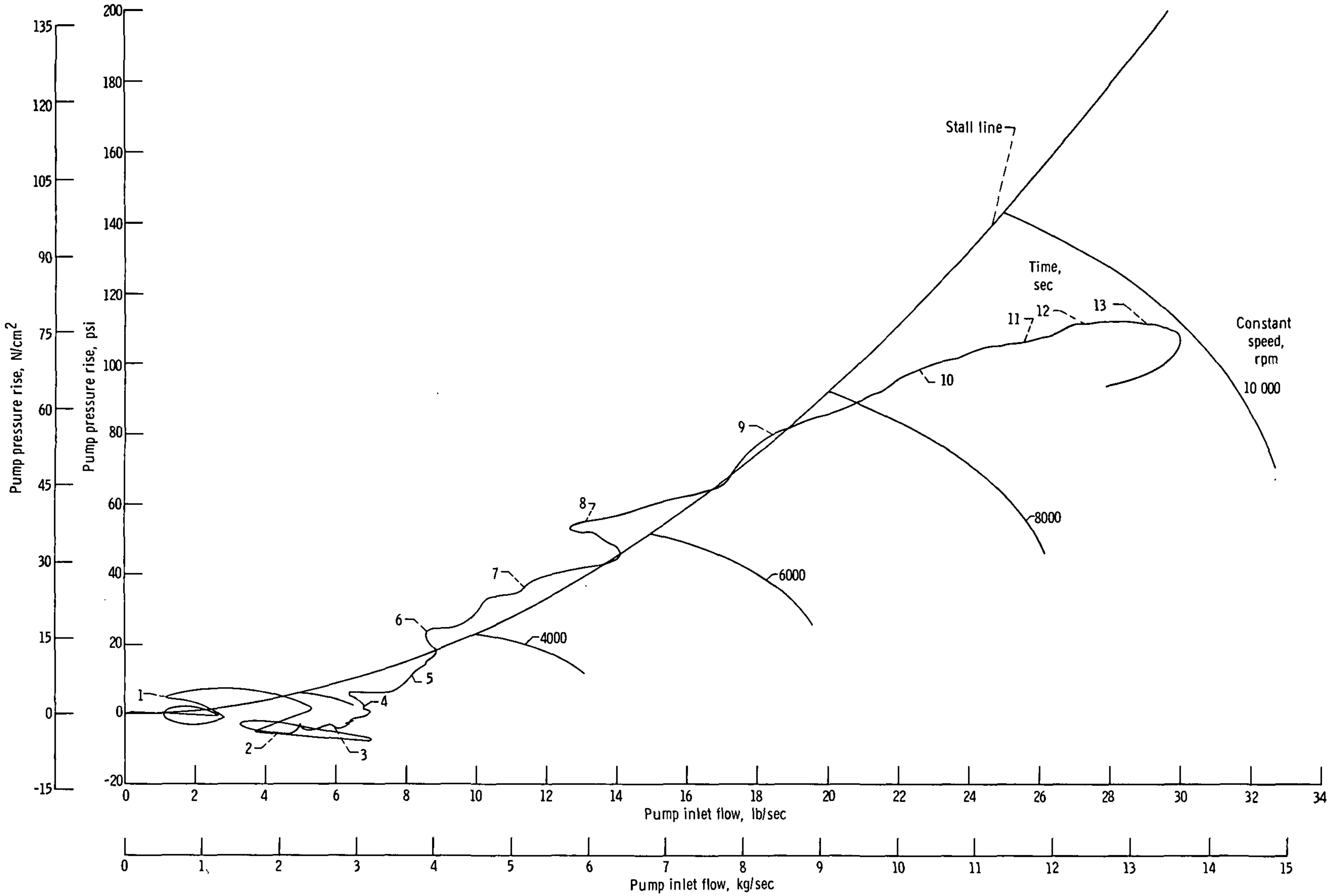


Figure 12. - Pressure rise against inlet flow for wet axial pump test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

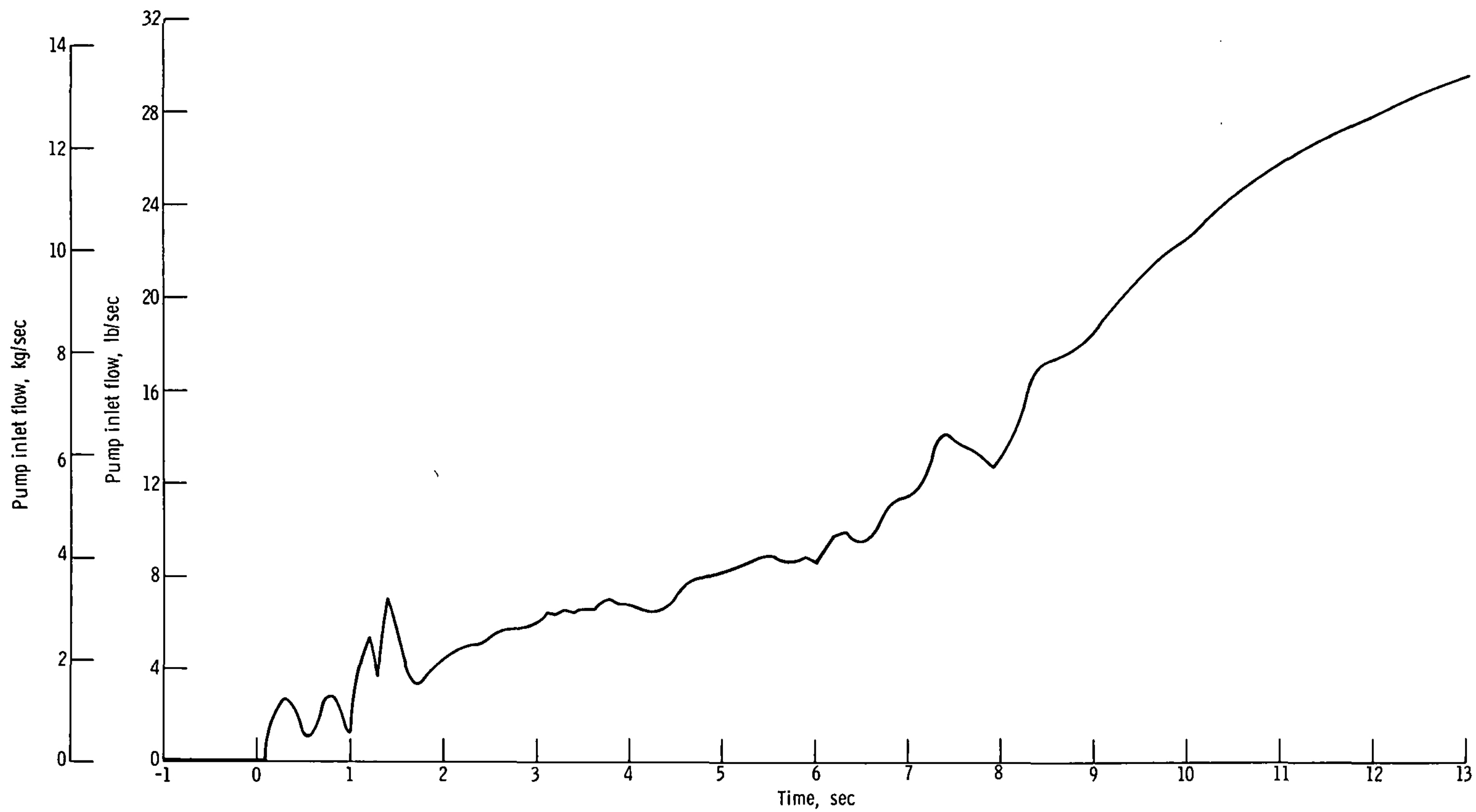


Figure 13. - Inlet flow against time for wet axial pump test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

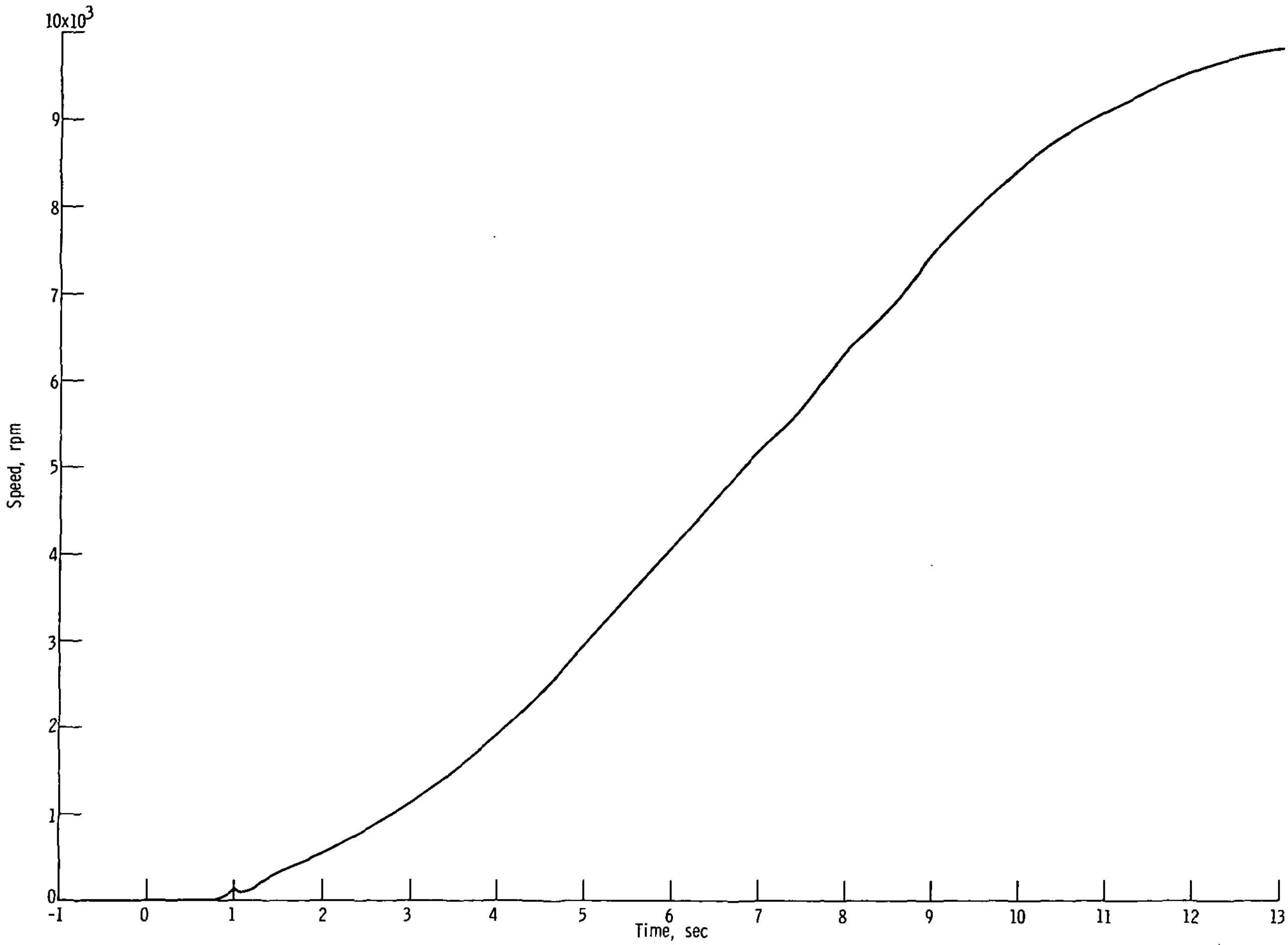


Figure 14. - Speed against time for wet axial pump test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

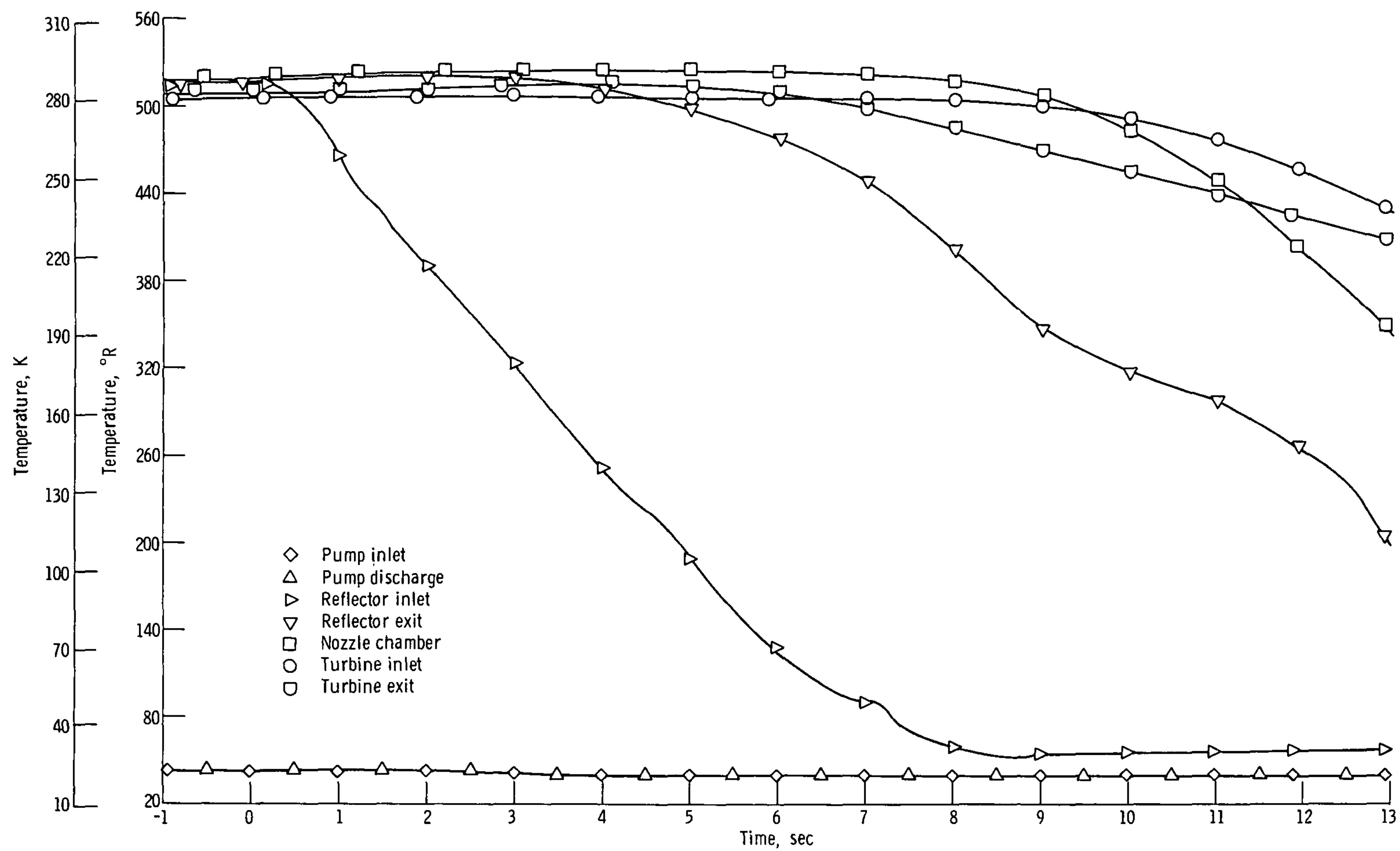


Figure 15. - Temperature profile for axial pump bootstrap test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

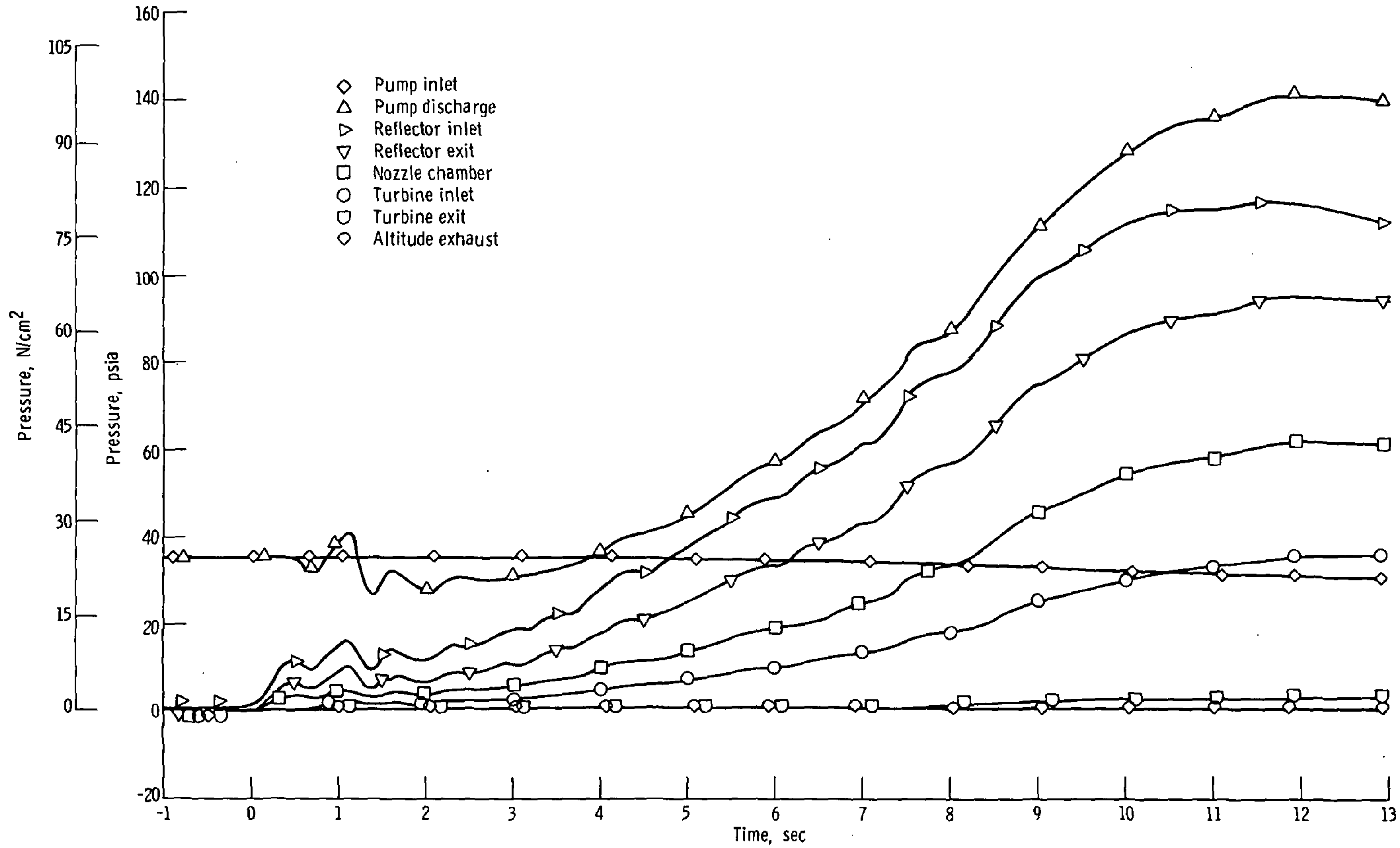


Figure 16. - Pressure profile for axial pump bootstrap test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

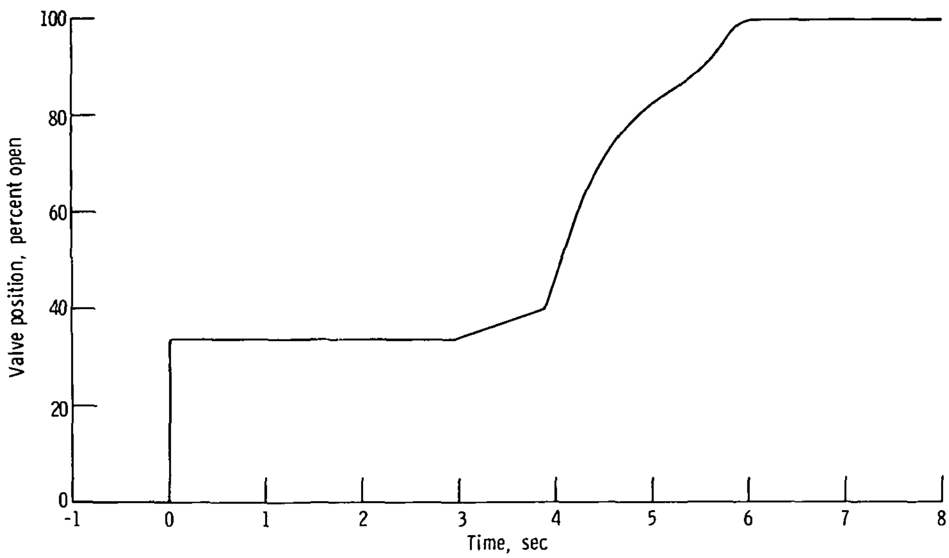


Figure 17. - Programmed opening of pump main discharge valve (PMDV) for wet pump bootstrap test. Nominal tank pressure, 35 psia (24.1 N/cm^2).

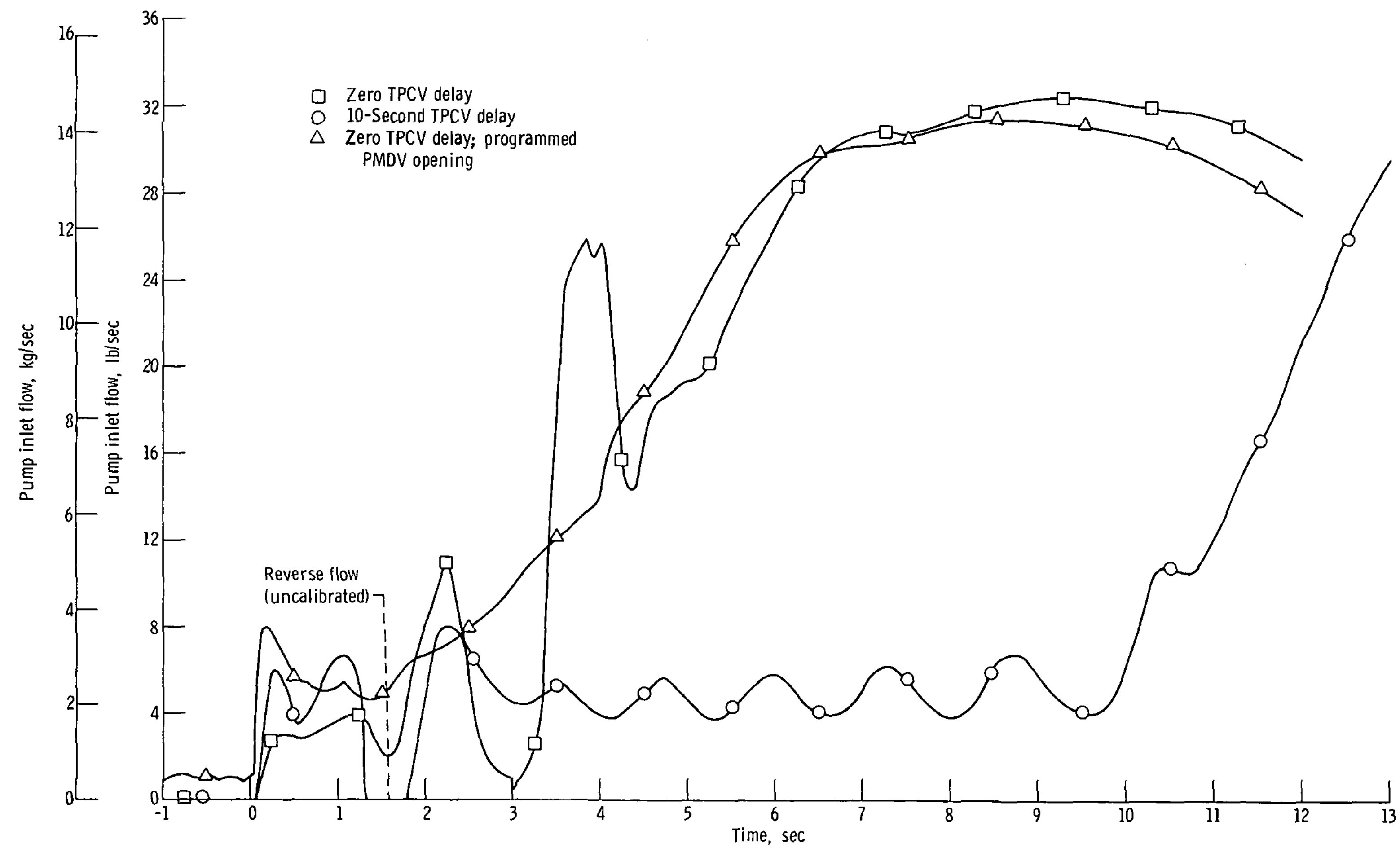


Figure 18. - Pump inlet flow against time for wet pump bootstrap tests. Nominal tank pressure, 35 psia (24.1 N/cm^2).

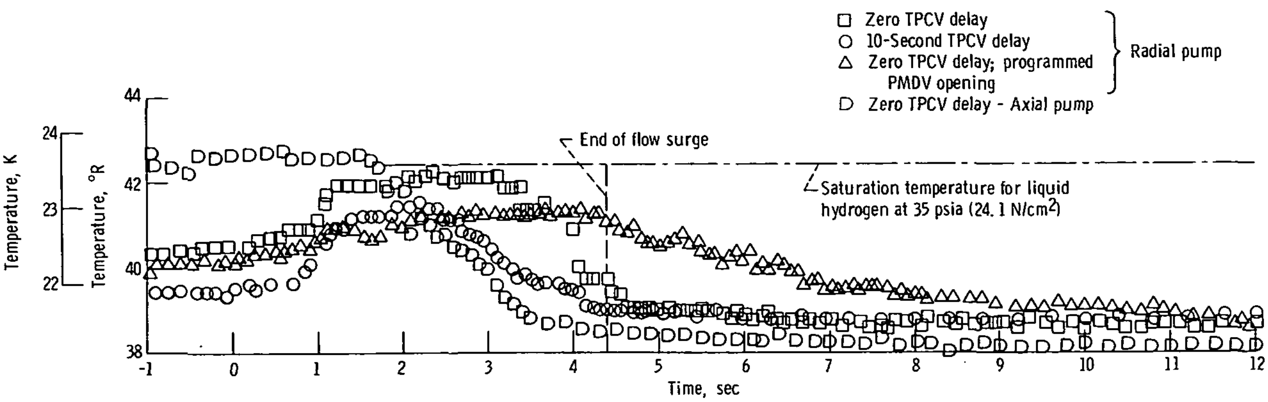


Figure 19. - Pump inlet temperature against time for wet pump bootstrap tests with 35-psia (24.1-N/cm^2) nominal tank pressure.

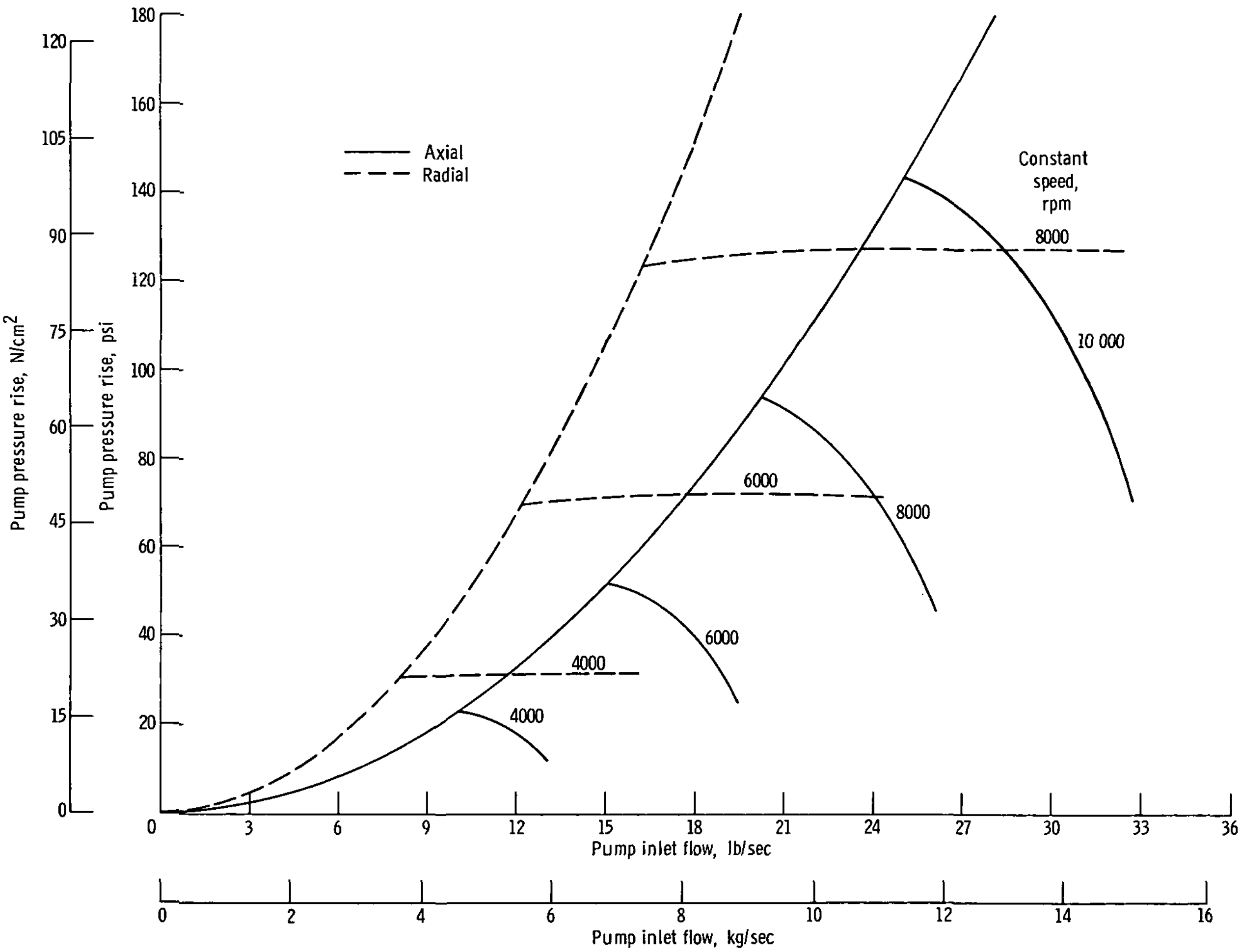


Figure 20. - Axial and radial characteristics of pump used in bootstrap tests.

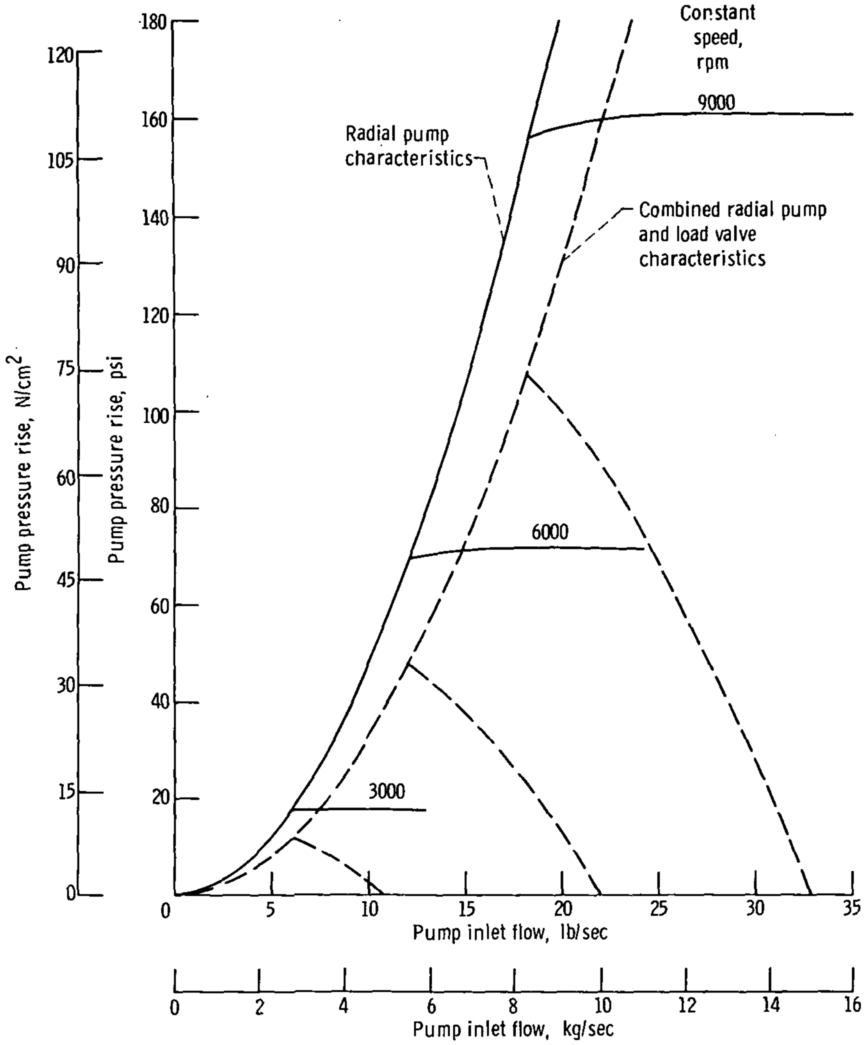


Figure 21. - Pump pressure rise against pump inlet flow for radial pump.

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