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SOLID ROCKET BOOSTER THRUST VECTOR CONTROL SUBSYSTEM TEST REPORT (D-1)

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16. ABSTRACT

This report presents the results of the sequence of tests performed on the Space Shuttle Solid Rocket Booster thrust vector control subsystem by the Marshall Space Flight Center, Huntsville, Alabama. The tests were performed between July and December 1976.

The operational characteristics of the thrust vector control subsystem components, as determined from the tests, are discussed. Special analyses of fuel consumption, basic steady-state characteristics, GN_2 spin, and actuator displacement are presented which will aid in understanding the performance of the auxiliary power unit. The possibility of components malfunction is also discussed.

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TECHNICAL MEMORANDUM 78174

SOLID ROCKET BOOSTER THRUST VECTOR CONTROL SUBSYSTEM TEST REPORT (D-1)

INTRODUCTION

A thrust vector control (TVC) subsystem (Figs. 1 and 2) was installed in an MSFC test stand (Figs. 3 and 4) and tests run to determine the operational characteristics of the subsystem and its components. The tests were divided into groups or series according to the nature of the tests and the data to be obtained. Hot firings and GN_2 spins of the auxiliary power unit (APU) were performed with both unloaded actuators and load banks.

The TVC subsystem is composed of six principal parts: the APU (Fig. 5), hydraulic pump, a fuel supply module, a hydraulic reservoir, a fluid filter manifold assembly, and an actuator (Fig. 6). The APU main components are the APU turbine, fuel pump, primary and secondary valves, gas generator, and gearbox. Except for the APU, ground test hardware (not flight hardware) was used with the various components and fixtures either being manufactured by MSFC or procured from vendor sources.

The subsystem was subjected to 30 hot firings for a total of 2971 s of operation: 21 load bank tests (Table 1) lasting 1960.5 s and 9 unloaded actuator tests (Table 2) lasting 1010.5 s. In addition, there were 14 GN_2 spin tests (Table 3) for the load bank lasting 1559.5 s and 3 GN_2 spin tests (Table 4) for the unloaded actuator lasting 486.5 s. Of the 21 load bank tests, 12 were completed, 2 were terminated before completion, and 7 tests were terminated in the early stages. Of the 9 unloaded actuator tests, 6 were completed, 1 was terminated before completion, and 2 were immediately terminated.

Fifty-eight measurements were recorded in the load bank tests and 71 were recorded for the unloaded actuator test. In the 58 readings, there were 17 pressures, 15 temperatures, 8 signal positions, 8 flows, 4 accelerations and acoustics, 2 winds, 1 turbine speed, and 3 calculated values. In the 71 readings, there were 26 pressures, 19 temperatures, 8 signal positions, 8 flows, 3 actuator input currents, 2 winds, 1 turbine speed, 1 actuator piston position, and 3 calculated values. It is important to note that some of these parameters were active during testing, but did not register any significant readings.

In summary, the results obtained from the tests were not considered completely satisfactory because of the questionable operation of the APU fuel pump. They should be better, however, when an improved pump is installed in the subsystem.

It should also be noted that the majority of the load bank tests performed on the subsystem were severe compared to the actual flight conditions. (This action explains for example the high hydraulic fluid temperatures and varying hydraulic pressures obtained from these tests.)

II. HISTORY OF HOT FIRINGS[1]

A. Load Bank Tests

Test P037-005 (Hot Firing 1) was conducted successfully on July 15, 1976. The purpose of this test was to verify the hardware and software and their functioning. The test duration was 4.4 s. No anomalies occurred during testing.

Test P037-007 (Hot Firing 2) was conducted successfully on July 21, 1976. Again, the purpose of this test was to verify the hardware and software and their functioning, although on a more extensive basis than Test P037-005. Beginning with this test, the fuel tank was subjected to a pressure decay (the change for this test was 12 psi). The test duration was 20.3 s. No anomalies occurred during testing.

Test P037-009 (Hot Firing 3) was conducted successfully on July 23, 1976. The purpose of this test was to subject the APU to a nominal mission profile to verify the subsystem's control. The test duration was 146 s. This was the first complete test performed during the firing sequence. No anomalies occurred during testing.

Test P037-010 (Hot Firing 4) was conducted on July 27, 1976. This test consisted of a series of firings to establish a pattern of steady-state data by programming constant flow steps (i.e., the hydraulic flowrate would be constant for a period of 10 s before a change would be conducted. This would be done on several flowrates during testing). The following steady flows were achieved during testing: 3.7, 7.2, 23.2, 45.7, and 59.1 gpm. The test duration was 146 s. No difficulties were encountered during testing.

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[1] Appendix B contains additional data on hot firing hydraulic flowrates.

Test P037-011 (Hot Firing 5), conducted on July 29, 1976, was the second test in the series of steady-state performance tests and was the first attempt to reach maximum APU horsepower. The maximum hydraulic flowrate was 59.4 gpm, and the maximum APU horsepower encountered was 124. The fuel consumed during this test was 1.55 gal and the time duration of the firing was 146 s. No difficulties were found during testing.

Test P037-012 (Hot Firing 6) was conducted on July 30, 1976. This test was part of a series of test firings to obtain steady-state data and maximum horsepower. The maximum hydraulic flowrate achieved was 45.2 gpm and the maximum APU horsepower was 94. Fuel pump discharge and gas generator pressures reached maximum values (1390 psi and 1200 psi, respectively) for all the 100 percent turbine speed tests made. The amount of fuel consumed during this test was 1.61 gal, and the duration of testing was 146 s. The data showed no indication of problems during firing.

Test P037-013 (Hot Firing 7) was conducted on August 4, 1976. The purpose of this test was to attain steady-state performance and maximum APU horsepower. However, the test was terminated after 4.3 s because of low lube oil pressure. At cut-off time, the maximum pressure reached was 9 psig; the minimum cut-off value was 10 psig.

Test P037-014 (Hot Firing 8) was also conducted on August 4, 1976. The purpose of this test was to achieve steady-state performance and maximum APU horsepower. The test was terminated after 4.3 s because of low lube oil pressure (9 psi).

Test P037-015 (Hot Firing 9) was also conducted on August 4, 1976, becoming the third firing performed on the same data. The purpose of the test was the same as for previous tests (to attain steady-state performance and maximum APU horsepower). This time, the test was successful. The maximum hydraulic flowrate attained was 55.9 gpm and the maximum APU horsepower was 113. Fuel consumed for this test was 1.94 gal. The increase in temperature for the hydraulic reservoir was unusually high with a 46°F change. The duration of testing was 146 s. There were no major problems encountered during firing.

Test P037-016 (Hot Firing 10) was conducted on August 11, 1976. The intent was to run a steady-state performance data test which would attain maximum APU horsepower, but the test was terminated after 62.9 s because of low hydraulic load bank flowrate.

Test P037-020 (Hot Firing 11) was conducted on September 9, 1976, as part of the sequence of steady-state data and maximum APU horsepower firings. It was terminated after 4.3 s of run time because of low lube oil pressure. The pressure reading at cut-off time was 7 psig (below the minimum of 10 psig).

Test P037-021 (Hot Firing 12) was conducted on September 9, 1976. This test is also part of the same sequence of steady-state data and maximum APU horsepower firings. It was run for 128 s and was terminated because the fluid level in the hydraulic reservoir was too low. The reservoir pressure change during testing was too high (12.5 psi), presenting a maximum value of 77 psig and a minimum value of 64.5 psig. However, the test was conducted with enough time to record sufficient data of constant flow conditions. The maximum hydraulic flow was 69.9 gpm and the maximum APU horsepower recorded was 141. Fuel consumed during the test was 2.12 gal. The only other problem during the test was the interference "noise" recorded by the flowmeter.

Test P037-023 (Hot Firing 13) was conducted successfully on September 4, 1976. The test had the same objectives as the previously mentioned tests. This time, the data indicated that the behavior of the system was good throughout the entire test. The only problems noted were the excessive time for the primary valve to open (3.277 s) and the minor noise recorded by the flowmeter. Hydraulic reservoir pressure was low at high flowrate (63.5 psig). The maximum hydraulic flow was 68.1 gpm and the maximum APU horsepower was 137. The fuel consumed during this test was 2.13 gal, and the time duration of the firing was 146 s.

Test P037-024 (Hot Firing 14), conducted successfully on September 17, 1976, was the first and only test which executed the backup mission for the entire (110 percent turbine speed) firing. It was also the last steady-state performance and maximum APU horsepower test performed. All components appeared to perform satisfactorily. The data showed the effect of the test, mainly in the pressure readings. The maximum hydraulic flow was 72.8 gpm and the maximum APU horsepower registered was 150. The fuel consumed during run time was 2.23 gal, and the time duration was 146 s. Again, the only problem encountered was the noise recorded by the flowmeter.

Test P037-026 (Hot Firing 15) was conducted on September 23, 1976. The purpose was to expose the APU to a nominal mission profile for an extended duration of 300 s. The test was cut off after 239 s of run time because of high lube oil pressure (40 psi, the upper limit for cut-off purposes). Although the main objective of the test was not accomplished, sufficient data were recorded on which other analyses could be based. The temperature readings were high on most of the components because of the long duration of the test. Again, as in Test P037-024, the flowmeter recorded significant noise. The fuel consumed during the firing was 3.05 gal.

Test P037-032 (Hot Firing 16) was conducted on September 29, 1976. The purpose of this test was to observe the operation of the TVC subsystem on a backup mission profile. However, the test was terminated because of low lube oil pressure (approximately 10 psi at cut-off). The data also showed degradation in the performance of the APU fuel pump. The turbine speed experienced a very low rpm value (59 000) before cut-off and the test duration was 10 s.

Test P037-033 (Hot Firing 17) was conducted on October 1, 1976. The purpose of this test was to evaluate the APU fuel pump performance. No problems were experienced during testing, but the data showed low performance of the APU fuel pump. The fuel pump valve remained open too long (4.414 s). The maximum fuel pump discharge pressure was low, achieving a high value of only 1275 psig. The gas generator temperature reached a maximum value (1312°F) for all testing. The fuel consumed in this test was 2.29 gal, and the test duration was 147 s. Table 5 shows overall APU system performance during the test.

Test P037-036 (Hot Firing 18), conducted on September 6, 1976, was run with a low hydraulic reservoir level and a constant fuel supply module pressure (approximately 400 psig). Smaller increases were observed in the hydraulic reservoir, hydraulic load bank return, and hydraulic pump discharge temperatures because of the reservoir level. The fuel consumed was 1.2 gal. After the test, some hydrazine leakage from the FSM was noted. The data indicated only minor problems during the firing.

Test P037-037 (Hot Firing 19) was conducted on September 8, 1976. This test was conducted with the hydraulic pump case drain line blocked. The firing was terminated after 11 s of run time because of low lube oil pressure. (The pressure reading was barely 10 psig, the minimum cut-off value.)

Test P037-038 (Hot Firing 20) was conducted on September 8, 1976, again with the hydraulic pump case drain line blocked. The firing was terminated after 11 s of run time because of low lube oil pressure. (The pressure reading was 10 psig, the minimum cut-off value.)

Test P037-039 (Hot Firing 21) was conducted on September 8, 1976. Again, this test was conducted with the hydraulic pump case drain line blocked. This time, the firing was completed with few problems. The hydraulic pump case drain temperature remained constant throughout the entire test and the hydraulic reservoir, hydraulic load bank, and hydraulic pump discharge temperatures were again smaller in this firing than in previous ones. The fuel consumed was 1.2 gal, and the time duration was 146 s.

B. Unloaded Actuator Tests

Test P037-041 (Hot Firing 22) was conducted on November 2, 1976. The purpose of this test was to observe the subsystem's response to sine wave inputs. However, the test was terminated after 11 s of run time because of the low hydraulic reservoir level.

Test P037-042 (Hot Firing 23) was conducted on November 2, 1976. Again, the purpose of this test was to observe the subsystem's response to sine wave inputs. The test was terminated after 12.5 s of run time because of the low hydraulic reservoir level.

Test P037-044 (Hot Firing 24) was conducted on November 4, 1976. Again, the purpose of this test was to observe the subsystem's response to sine wave inputs. The data gathered from this successfully completed test showed signs of good system behavior. The actuator inlet and outlet pressures showed some variations, but they were very few. Some hydraulic temperature increases (pump case drain, pump discharge) were smaller than usual. The test duration was 146 s.

Test P037-046 (Hot Firing 25) was conducted on November 11, 1976. The purpose of this test was to observe the subsystem's response to square wave inputs. The actuator's inlet and outlet pressure readings showed some variation. The total actuator movement was 79.9 in., the fuel consumed was 1.05 gal, and the time duration of the test was 146 s. No major problems were encountered during testing.

Test P037-047 (Hot Firing 26) was conducted on November 17, 1976. The purpose of this test was to observe the subsystem's response to triangular wave inputs. The triangular wave inputs caused some of the hydraulic temperatures (pump discharge, load bank return, and reservoir) to increase more than usual. The actuator measurements revealed increased variations both in the inlet and outlet pressures, and the temperature increase of the actuator was greater than usual. The time duration for this test was 146 s, and the data gathered indicated no major difficulties occurred during testing.

Test P037-048 (Hot Firing 27) was conducted on November 19, 1976. The purpose of this test was to observe the subsystem's response to sine wave inputs. Some temperature increases were unusually higher (i.e., gas generator and lube oil temperatures, and in the hydraulic system: pump discharge, pump case drain, load bank, and reservoir temperatures). The data indicated significant variations in the actuator inlet and outlet pressures (the most significant recorded in all the unloaded actuator tests). The increase in temperature in the actuator was also greater than in any other test. The test duration was 146 s. No major problem occurred during testing.

Test P037-049 (Hot Firing 28) was conducted on November 24, 1976. Again, the purpose of this test was to observe the subsystem's response to sine wave inputs. The readings obtained were favorable (Table 6). The actuator inlet and outlet pressures showed some variation although not as significant as in Tests P037-047 and P037-048. The total actuator movement during the test was 56.86 in., the fuel consumed was 1.1 gal, and the time duration was 146.5 s. No anomalies occurred during testing.

Test P037-050 (Hot Firing 29) was conducted on December 1, 1976. The purpose of this test was to observe the subsystem's response to sine wave inputs, however, this time with a hydraulic accumulator added. The readings indicated favorable operation of the subsystem during firing. The actuator inlet and outlet pressures decreased more in magnitude of variation than in Test P037-049. This decrease is attributed to the accumulator. The total actuator movement was 54.02 in., the fuel consumed was 1 gal, and the test duration was 146.5 s. No difficulties were encountered during testing.

Test P037-051 (Hot Firing 30) was conducted on December 1, 1976. The purpose of this test was to observe the subsystem's response to square wave input and the hydraulic accumulator added in Test P037-050. The test was terminated after 110 s of run time because of a malfunction in the actuator control tape. However, the duration was long enough to gather information on the behavior of the subsystem with the accumulator added. The readings showed good system operation, and because of the accumulator the actuator inlet and outlet pressure measurements showed a diminishing effect in magnitude of variation. The total actuator movement was 26.9 in., and the fuel consumed was 0.74 gal.

III. ANALYSIS AND DESCRIPTION OF OPERATING CONDITIONS ON THE APU SYSTEM COMPONENTS DURING TESTING

A. Turbine

There were few problems encountered during the APU turbine tests. However, it should be noted that the speed band (variation in speed) for the turbine was greater than the allowable value of ±5 percent at a normal duty cycle. This variation, noticeable in the last series of tests, was caused by a degraded fuel pump.

It was also observed that at low hydraulic horsepower, the turbine speed was high, but the speed band was small and as the horsepower increased, the turbine speed decreased while the speed band increased. This behavior was common to all tests.

During all the tests, the APU turbine speed had a characteristic acceleration time of 2.6 s for the period between startup and 72 000 rpm (100 percent speed).

Tables 7 and 8 give some of the more important measurements to be considered when comparing the turbine against given tolerances. Table 7 gives the maximum and minimum turbine speed obtained for all the tests, divided according to the nature of the firings: load bank (100 and 110 percent speed) and unloaded actuators, with their respective speed bands (deviation from the nominal value) and the condition at which these extremes occurred. Table 8 gives the maximum and minimum turbine speed at a normal mission for each test. This table includes the speed band for the speed given and the average horsepower for the program run.

B. Primary Fuel Valve

1. Valve Openings. Figure 7 shows how certain parameters vary before the valve is opened, while it is opening, and while it is closing during a typical test. This figure gives a pictorial representation of the behavior of fuel pump inlet and discharge pressures, fuel valve bypass pressure, and gas generator pressure. The following is a listing of values considered important and were derived from the tests when determining the effects of pressure on valve openings:

a. Maximum fuel pump discharge pressure — 1110 psig

b. Fuel pump inlet pressure

  1. Nominal — 385 psig
  2. Minimum — 295 psig
  3. Maximum — 540 psig

c. Fuel valve bypass pressure

  1. Nominal — 375 psig
  2. Minimum — 265 psig
  3. Maximum — 625 psig

d. Time duration of valve opening — 0.275 s.

2. Valve and Hydraulic Pump Outlet Pressure. Figure 8 shows the behavior of the hydraulic pump outlet pressure as the primary fuel valve opens and closes, comparing the pressure band and primary valve openings for different flowrates and time spans of the same test.

As can be seen from the figure, for early stages of the test, when the hydraulic flowrate is increasing, outlet pressure has a band form that shrinks when the valve opens and enlarges when it closes. During this test, a change in the previous pattern was noticed — the band enlarged as the valve opened and shrunk as it closed. This condition was common for all tests examined at decreasing hydraulic flowrates. There is no specific explanation for this behavior.

3. Valve Openings and Horsepower. Figure 9 is a curve showing the percent of time the valve is open at any hydraulic horsepower. The percentage of time the valve is open is taken by dividing the time the valve is open by the time between consecutive valve openings, for the same period of time. Figure 9 also shows a band of all those curves plus a line showing the average behavior of all tests. As can be seen from the figure, the relation is linear for most of the points (except for those points located at high hydraulic horsepower, where a variation is found). An interesting point to note is the values for this band become more variable with an increase in hydraulic flow (and, consequently, with an increase in hydraulic horsepower).

If the curve of Figure 10 is compared to the curve of Figure 9, it can be seen that for Test P037-024 the percentage of time openings is lower at the same hydraulic horsepower for all points, except at very low flows in which the curve comes within the boundaries of the drawn band.

During test operations, several unusual occurrences involving the operation of the valve were observed. For example, during Test P037-015, it appeared that the valve tried to prematurely open. This occurrence was also observed at low flowrates both at the beginning (few seconds after startup) and at the end (before shutdown) of the test program. No explanation for this anomaly can be given.

It was also noted that on all hot firings after Test P037-015 the valve stayed open too long when compared to previous tests. The reason for this was the inability of the fuel pump to carry the load (HP) required by the tests at those specific moments. Table 9 gives a comparison of valve opening times selected from steady flow data, and Table 10 gives the number of valve openings for the load bank and unloaded actuator.

C. Fuel Pump

The faulty operation of the fuel pump during this series of tests was the most serious problem encountered. It affected the pump discharge pressure and the other APU components such as the gas generator and the fuel valve as previously stated. It was also partly responsible for the failure (termination) of Test P037-032 and the results in the last tests of the load bank series.

Another important point to note was the decrease in pressure in the sequence of tests following Test P037-012, both on the highest and lowest values recorded on each test for the discharge (Table 11). The higher values are found at high flow regions and the low values are found on low hydraulic flows, usually at the end of the tests. A similar behavior was found in the pressure increase that occurred as the fuel (hydrazine) traveled through the pump. Beginning with Test P037-012, these values diminished throughout the remainder of the firings. It was also noted that the largest increases occurred at high flowrates after the test started. An exception was Test P037-024 (110 percent speed), which registered the highest recorded maximum discharge pressure (1450 psig) for all the tests. An average of the pressures obtained in Tests P037-021 and 026 (1312.5 psig) when compared to the value for Test P037-024, represents an increase of 10.4 percent. The temperature of the fuel pump increased only slightly (an average of 7°F) throughout all the tests. The biggest increase was recorded in Test P037-046 (unloaded actuator step wave input) with 12°F. The increase in temperature continued long after the test was finished.

From Figure 11, it can be seen that for later firings, the degradation of the fuel pump was less significant as the pressure changed. In Test P037-024 (110 percent turbine speed), the sequence did not repeat. In fact, the change in pressure was greater than for any previous test. However, for the remainder of the test series (Tests P037-026 and 033), the sequence did follow the normal pattern. The curves of Figure 11 also show the behavior of the change in pressure at different hydraulic flows for each test. (All values were taken at constant flowrate and each curve represents a single test.)

D. Gas Generator

The operation of the gas generator is related to the operation of the fuel pump. (The maximum pressure obtained during a test occurred at high flowrate, but diminished as the tests were put into sequence.) Table 12 gives the recording of the highest maximum pressure for the given tests. As can be seen from the table, all diminished in sequence except for Test P037-024 (110 percent turbine speed), which had an increase of 9.7 percent compared to an average obtained from Tests P037-023 and 026 (1132.5 psig). This increase compares favorably for the increase in turbine speed of 10 percent. The average increase in temperature for a load bank test was greater than for unloaded actuator tests. For load bank tests, the average increase was 1043°F, and for unloaded actuator, the average increase was 859°F. The highest temperature recorded occurred in Test P037-023 (1312°F). The largest increase in temperature (1106°F) was also recorded in this test. Figure 12 shows the relationship of gas generator temperature and time for Test P037-021.

E. Lube Oil and Gearbox

Low lube oil pressure was the cause of most of the cut-offs during the firing period. Six out of seven tests were terminated at the beginning for this reason. In all these firings, the pressure was below the minimum preprogrammed permissible value. One test was terminated after 239 s of run time because the pressure reached the highest permissible value in the program (40 psig). However, after 146 s of firing, the lube oil pressure showed a reading of 26 psig which could be considered normal. No unloaded actuator test was terminated because of the lube oil pressure.

The average pressure increase during testing was 24 psi for actuator tests and 25 psi for load bank tests. The normal pressure reading after 4 s of operation was 14 to 15 psig for the test completed.

Figure 13 shows a comparison between a complete test (P037-023) and a firing terminated by low lube oil pressure (P037-038). Test P037-038 shows the normal behavior in lube oil pressure for a test having early termination. Note the downward effect of the pressure in this graph because of low lube oil flow and that the pressure was not as high as a common complete test after 2 s of firing because of the inclined path of the curve. This was the normal pattern for most of the terminated tests; i.e., the pressure would increase over the lower permissible value, then start decreasing until it reached 10 psig and cut-off was performed.

In terms of temperature, the average increase for the load bank tests was 139°F and the greatest increase was 271°F (Test P037-026). The highest temperature achieved during testing was also recorded on Test P037-026 (343°F). The average change on the unloaded actuator test was 120°F. The starting temperature of the lube oil was ambient or near ambient conditions. Figure 14 shows the normal curve for lube oil temperature. Although Test P037-021 was terminated after 128 s of operations, the temperature measurement obtained was considered satisfactory.

The behavior of gearbox parameters are closely related to the behavior of the lube oil parameters. For example, the pressure increase during a typical test was 6 psig for the load bank program and 5 psig for the unloaded actuator program. Only Test P037-026 (extended duration test) showed a significant difference (i.e., an increase of 17 psig) which was probably due to the extended time duration. The pressure change was normal at the end of 146 s, but then suddenly increased.

F. Hydraulic Pump

The average hydraulic pump outlet pressure recorded at the beginning of testing was 3166 psig. The lowest pressures were registered at high flowrates where an average of 2984 psig was obtained. The lowest pressure for high flowrates was 2705 psig (Test P037-021) and the highest outlet pressure registered during testing at high flowrates was 3137 psig (Test P037-026). In fact, the high flowrate region was unstable in terms of steady-state because the pressure changed considerably. Although high pressures were obtained at the beginning, the highest recorded pressures were located at the end of the tests. For example, a value of 3210 was commonly recorded for low hydraulic flowrates, and the highest pressure for all tests under the same condition was 3235 psig.

The pump outlet pressure oscillograph reading had the form of a pressure band (this was due to the pumping effect), which showed variations in size during a regular valve opening. These variations have a direct relation to the two main steps that occur while a valve undergoes an opening (open and close phases) because the low ripple always appeared at the end of a valve opening. However, this only occurred during the interval when the hydraulic flowrate increased in steady-state steps. This process reversed when the flowrate started decreasing; that is, now the high ripple appeared at the beginning and the low ripple appeared at the end. Figure 8 illustrates this behavior by comparing the location of the ripple at different flowrates and time in a single test.

Table 13 presents the behavioral data of the ripple found in the oscillograph recording in terms of band pressure. This band had places where it enlarged and places where it shrank, indicating that its pattern of behavior was dependent on the hydraulic flowrate (Table 14). For example, small low ripples were found at the beginning and end of the tests at the low hydraulic flowrates, while large low ripples were characteristic of the highest or near highest flowrates [except for Test P037-024 (110 percent turbine speed)]. Also, small high ripples are a characteristic of low flowrate at the end of the tests, while large ripples are often found in the period where the hydraulic flowrate is increasing near the highest flowrates. In some cases, large ripples are found at the maximum flowrate of the test.

The hydraulic pump outlet pressure showed a direct relationship to the hydraulic flowrate variations. Figure 15 shows the general trend in this behavior. In almost all cases, the pressure increased as the hydraulic flowrate decreased. In Test P037-012, the pressure stayed approximately the same up to 32.5 gpm, then decreased slightly; after reaching 43.2 gpm the pressure increased again (this increase is not common). In Test P037-015, an increase in pressure occurred after 49.5 gpm of flow. In Test P037-024 (110 percent speed) an increase in pressure occurred after 6.4 gpm; however, the pressure decreased again when it reached a flowrate of 23.7 gpm. Also from Figure 15, sharp decreases can be seen at very high flowrates in Tests P037-021 and 023 (at flows over 67 gpm).

One point of interest was the strange behavior of the pump outlet pressure at high hydraulic flowrates. This behavior is graphically shown in Figure 16 where in the period between 65 and 105 s of operation, the pressure underwent sudden increases and decreases (up to 500 psi of change) that did not occur at any other interval in the same test. This unstable region appeared only at high hydraulic flows (marked in the figure). It is interesting to note the contrast in the behavior of the outlet pressure between this interval and other time intervals in the test and the tendency of the pressure to stay constant at low flows.

The variation in pressure in the hydraulic pump also affected the hydraulic reservoir pressure.

In the tests performed, the greatest increase in temperature occurred in the load bank tests with an average increase of 120° F through a regular 146 s mission. Test P037-026 registered the greatest increase in temperature (180° F) and the highest temperature recorded in any test (249°F). In the unloaded actuator tests, the average increase in temperature was approximately 25°F, the difference in the temperature increment being due to the nature of the tests. Only Test P037-048 recorded a significant change in temperature (an increase of 82°F); but, again, it was small compared to the average increase in the load bank set.

It is important to note that the high temperatures and large pressure variation were caused by the severe conditions under which the test was performed and does not indicate that the subsystem did not work properly. In fact, the high temperatures registered during testing served to prove the subsystem's capability to resist heat.

G. Hydraulic Reservoir

Pressure in the hydraulic reservoir varies with the hydraulic flow in the same manner as the hydraulic pump outlet pressure. The higher the flowrate, the lower the pump outlet and reservoir pressure. The highest registered pressure was 77 psig (Test P037-021) and the lowest registered pressure was 63.5 psig. The greatest drop in pressure at any constant flowrate was recorded in Test P037-021, which terminated because of low hydraulic reservoir level after 128 s of run time (Fig. 17).

The greatest change in temperature in the first series of tests was recorded in Test P037-015 (46°F load bank) and Test P037-026 (37°F extended duration). The highest temperature was registered in Test P037-015 (129°F). The high temperatures observed in the firings are a result of the severe load input in the system. In the unloaded actuator tests, the greatest change (85°F) and the highest temperature (144°F) was recorded in Test P037-048 (sine wave input). The high temperatures in this test were caused by the severe actuator program that was used.

Figure 18 shows the behavior of the temperature as time progresses for three different tests: Tests P037-015 and 021 (load bank tests) and Test P037-049 (unloaded actuator test). The curve representing Test P037-049 shows the average increase, and the curves representing Tests P037-015 and 021 show the extremes.

H. Fluid Manifold Assembly

The only measurement taken in the fluid manifold assembly was the hydraulic manifold return pressure which showed variations during testing caused by changes in hydraulic flowrates. These variations were more significant for tests where the flow was subjected to many abrupt changes, such as found in Test P037-033. However, an exception was Test P037-036. Generally speaking, for a load bank test the average pressure change was approximately 10 psi; however, it always returned to the baseline pressure (approximately 73 to 77 psig). Few changes were observed in Test P037-036 which recorded an almost constant pressure of approximately 74 psig.

I. Fuel Supply Module

Two categories of tests were performed using the fuel supply module as a basis. The first category included all the tests in which the fuel supply module was subject to pressure decay and the second category included all tests on which the fuel tank pressure was constant.

All hot firings from Test P037-007 to P037-033 inclusive were in the first category and the rest were in the second category. The change in pressure was directly related to the fuel consumed during the test and to the duration of the firing. The greatest pressure decay was registered in Test P037-026 (extended duration). The change in pressure in this test totaled 128 psi. The average initial pressure for the first category was approximately 390 psig and for the second category was approximately 400 psig. For all tests, the temperature stayed constant and near ambient.

J. Actuator

The actuator pressure readings show a short period (depending on the mission ordered) of constant nominal pressure, followed by a period (usually shorter than the first) of agitation where the pressure increased to a high value in an abrupt manner, very similar to a pulse. This occurred every time the actuator moved, and the magnitude of it depended more on the length of the movement performed and the length of the interval depended on the type of signal movement ordered in the test. This pulse appeared in all the pressure measurements in the actuator, with the magnitude of the increase having a greater effect on the outlet pressure than on the inlet pressure.

The fluid accumulator was added in Tests P037-050 and P037-051 to reduce the effect of the actuator movement on the actuator pressures. The fluid accumulation reduced the magnitude of the pulses that formed as a result of this movement and in some cases eliminated or almost eliminated this undesirable behavior.

Three types of signals were used on the actuator and each test was programmed with only one signal. The signal inputs used were square wave, sine wave, and triangular wave. The following listing gives a correlation of the test performed to its corresponding signal input:

Test No.	Signal Used
P037-044	Sine wave
P037-046	Square wave
P037-047	Triangular wave
P037-048	Sine wave
P037-049	Sine wave
P037-050	Sine wave (with hydraulic accumulator)
P037-051	Square wave (with hydraulic accumulator)

The average nominal interface inlet pressure of the actuator for all tests was approximately 3194 psig. Throughout all the tests, the previously mentioned variations in pressure were recorded, both positive (increasing pressure) and negative (decreasing pressure). These positive and negative actuator movements depended on the frequency and amplitude of the actuator displacement. These variations were much lower in magnitude and in some instances disappeared during Tests P037-050 and 051 (the fluid accumulator was added in both tests). Variations showing a greater magnitude were observed in Test P037-048 as a result of the severe actuator movement to which the system was subjected. This test also showed an unusually low pressure recording (2129 psig) due to the severity of the mission run. Only one test deviated significantly from the average nominal interface inlet pressure (Test P037-044). The nominal pressure value for this test was 3206 psi or 12 psi greater than the average nominal pressure.

The behavior of the interface outlet pressure is directly related to that of the inlet pressure. Every change in the inlet pressure is also reflected in the outlet pressure. The nominal pressure during testing varied from 72 to

77 psig (an average of approximately 75 psig). The greatest variation in pressure occurred during Test P037-047, but the test with the longest agitation period was Test P037-048. This was due to the mission program (the actuator's movement is accentuated by sine wave inputs). The last tests (P037-050 and 051) showed less variation in the nominal value, although the variation in the agitation periods was approximately the same and the calm periods were more constant.

The average nominal actuator inlet pressure was approximately 3156 psig. All of the tests recorded pressures near this value except Test P037-048, which had an average pressure of 3100 psig. The variations in this test were greater in magnitude but the same in length when compared to similar readings (e.g., interface inlet pressures). The lowest pressure recorded for Test P037-048 was 2029 psig, and the data showed large periods of agitation for this measurement (even where not expected). Tests P037-046, 047, and 049 showed variations, but they were not as significant as those of 048. In Tests P037-050 and 051 these variations still occurred, although to a lesser extent than in previous tests but showing more agitation than in similar readings (e.g., interface inlet pressures).

The behavior of the inlet and outlet temperature in the interface showed a direct relationship. Temperature changes (increases) occurred in the incoming fluid but these increases were not related to actuator movement. That is, there was no significant change in temperature as the fluid went through the actuator. In fact, this change was almost null. The average change (for all tests) of the fluid temperature entering the actuator was 32°F (which is not a big difference), and the only test where there was a significant increase in temperature was Test P037-048 where the temperature change was 86°F. (In this test, the final inlet temperature was 148°F — the highest in the testing sequence.)

K. Environmental Conditions

During testing, the TVC subsystem was exposed to changes in ambient conditions (i.e., changes in temperature, wind speed and direction, as well as weather conditions). Among these changes; the most significant was ambient temperature. The lowest temperature recorded for any firing was 43°F while the highest recorded was 96°F. It should be noted that the subsystem was never exposed to what could be called flight environment conditions, but only current ambient conditions.

A brief test plan is given in Table 15 and lists typical steps in the test process.

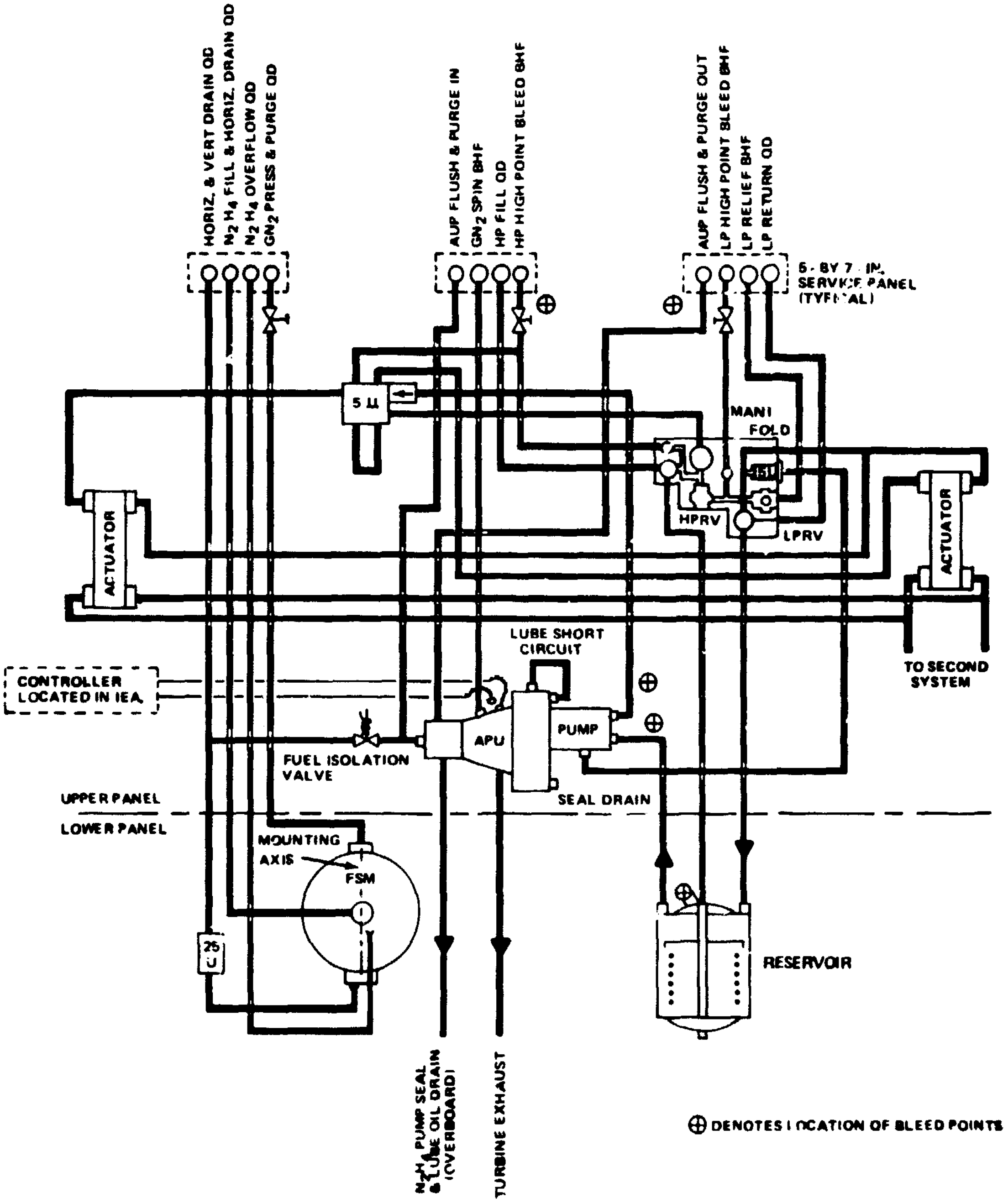

Figure 1. Thrust vector control (TVC) schematic.

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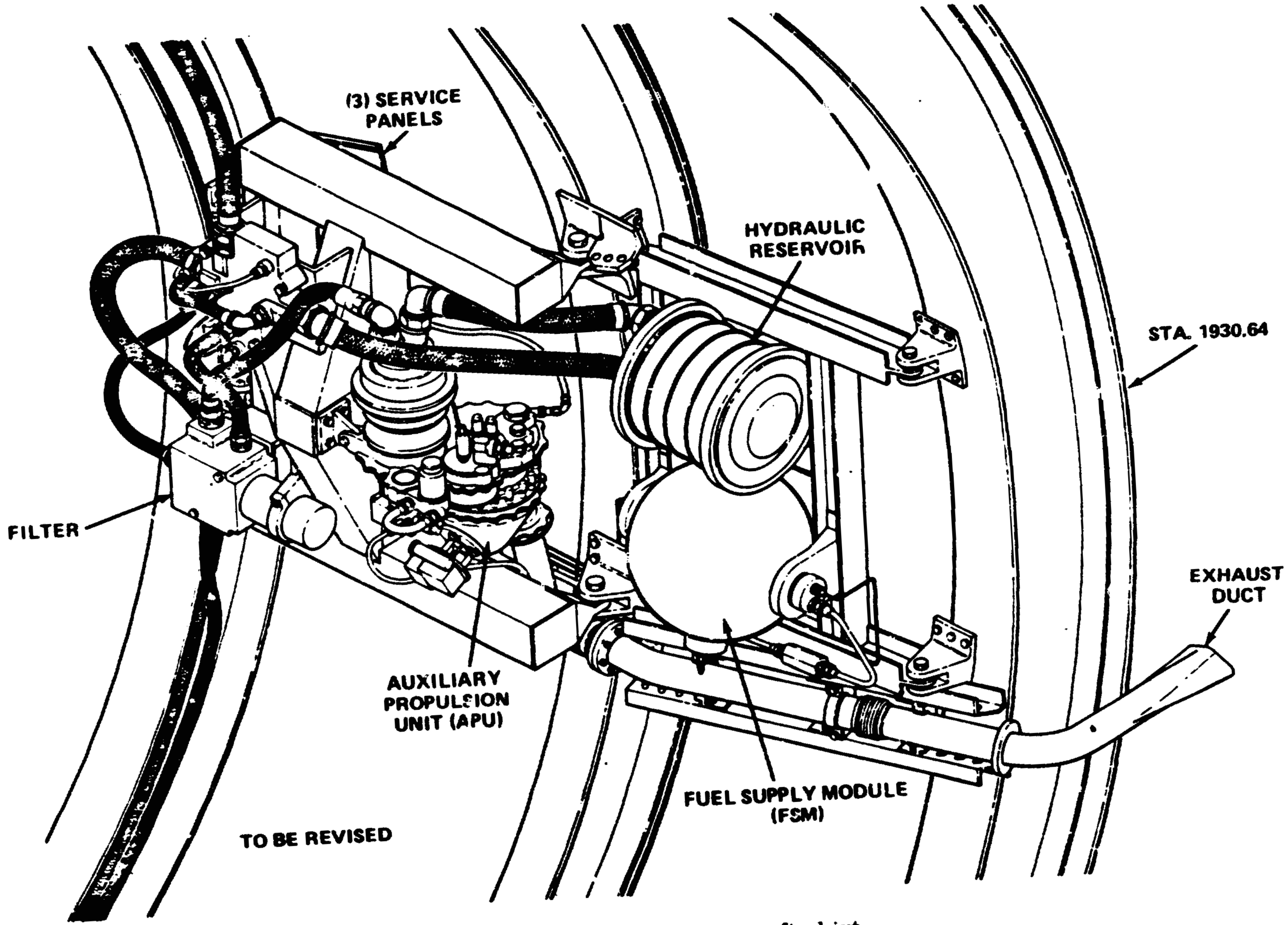

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Figure 2. TVC subsystem aft skirt.

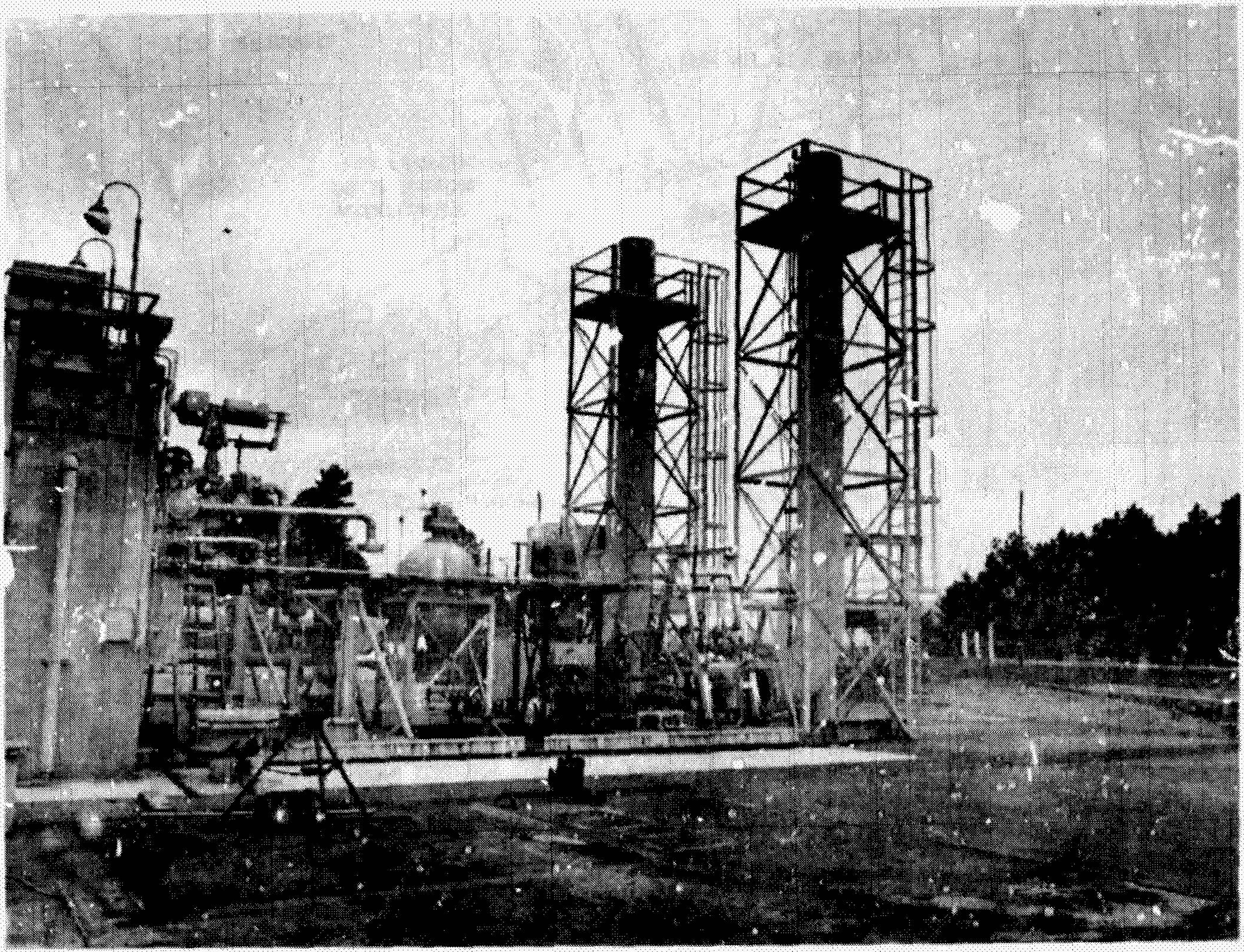

Figure 3. Photograph of the TVC subsystem stand before installation.

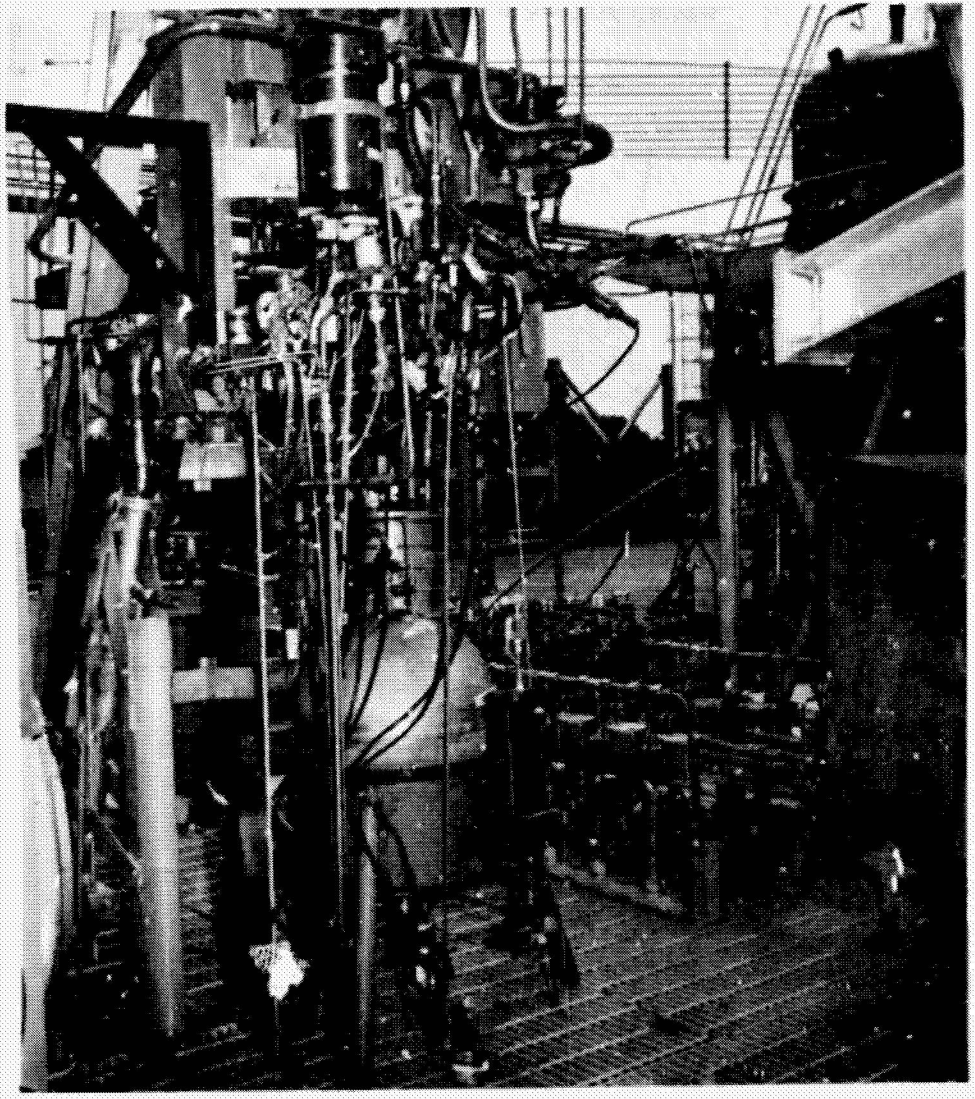

Figure 4. Photograph of the TVC subsystem in test stand.

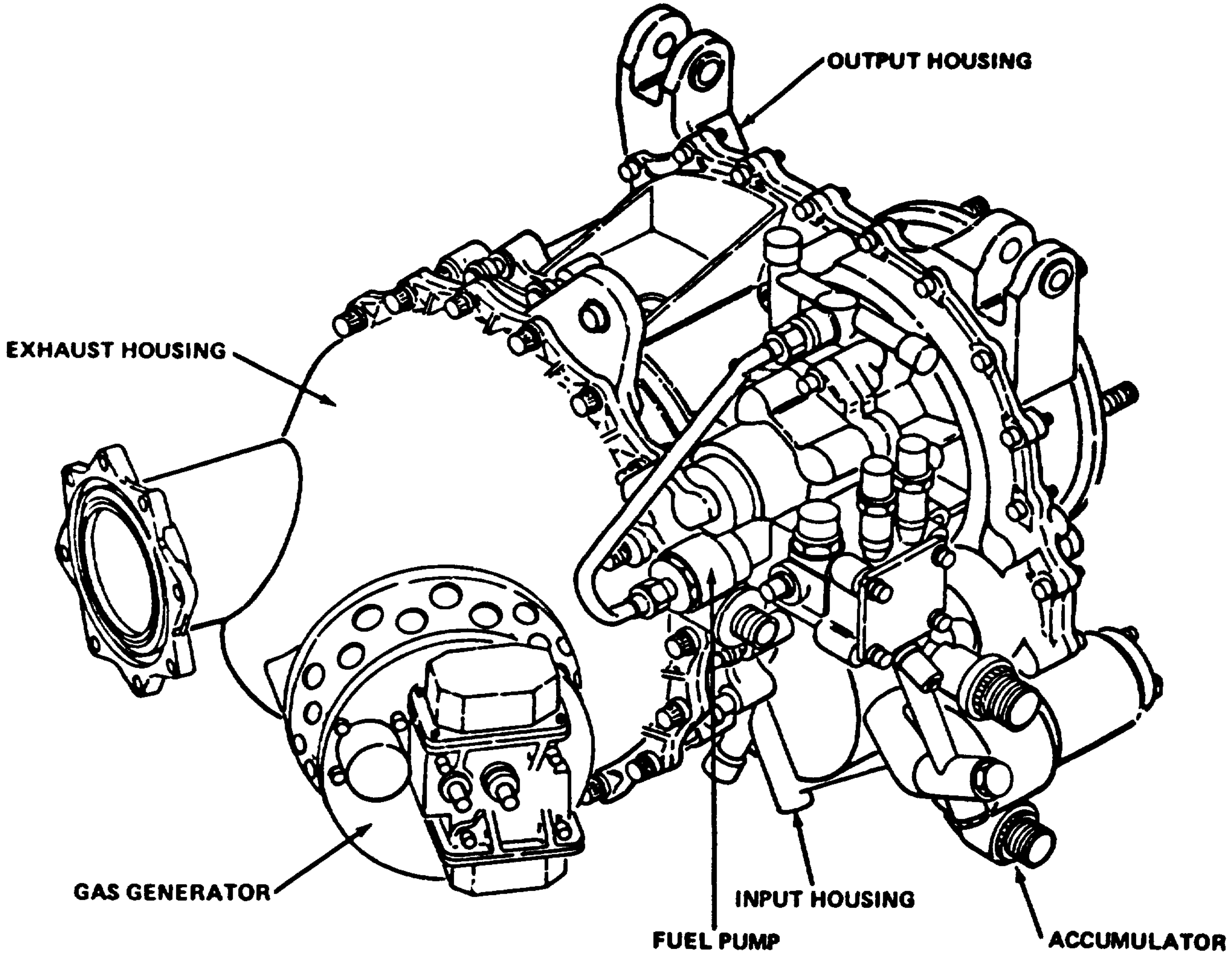

Figure 5. Auxiliary power unit (APU).

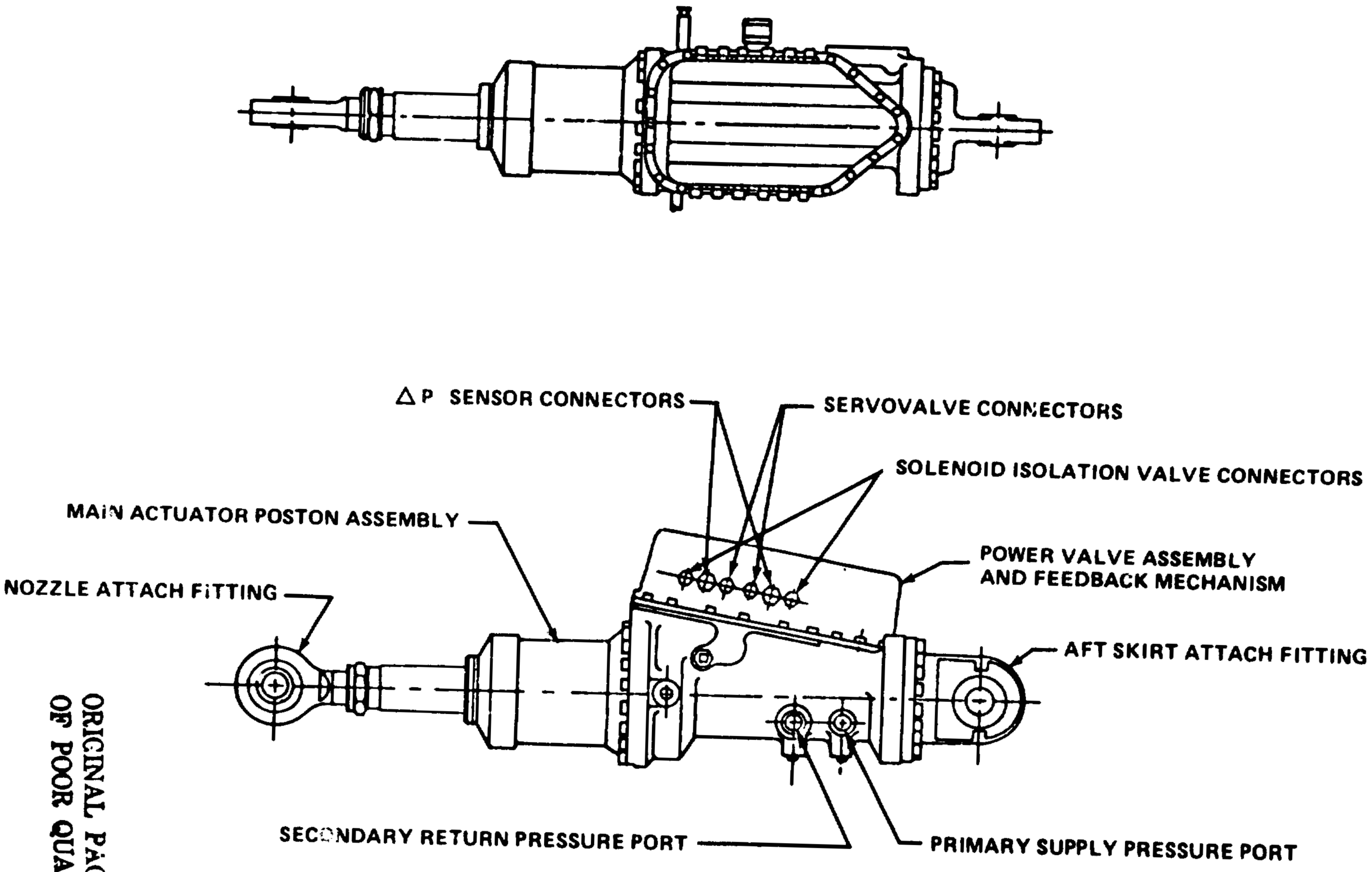

Figure 6. Actuator.

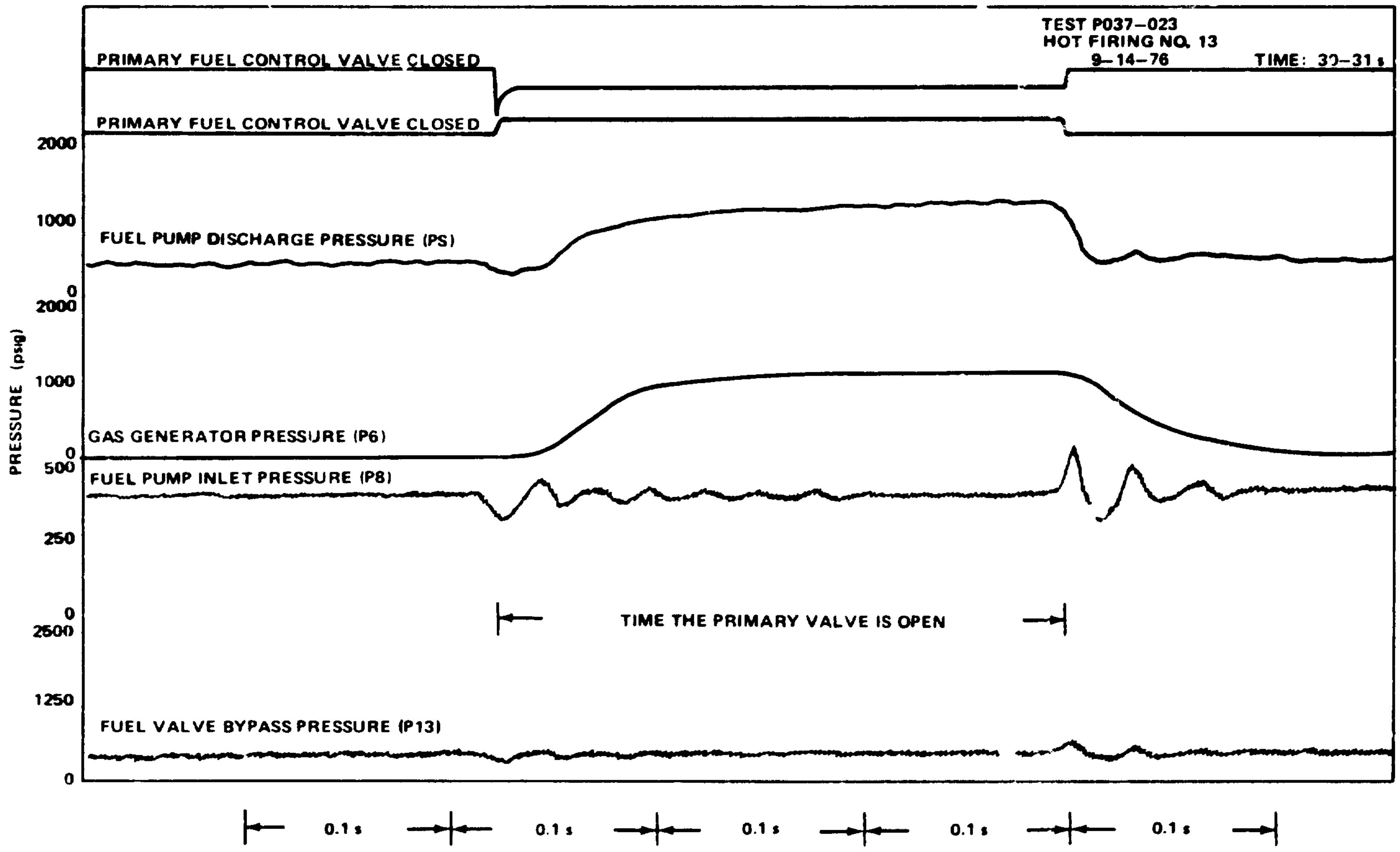

Figure 7. Typical pressure behavior at a point where the primary valve is open.

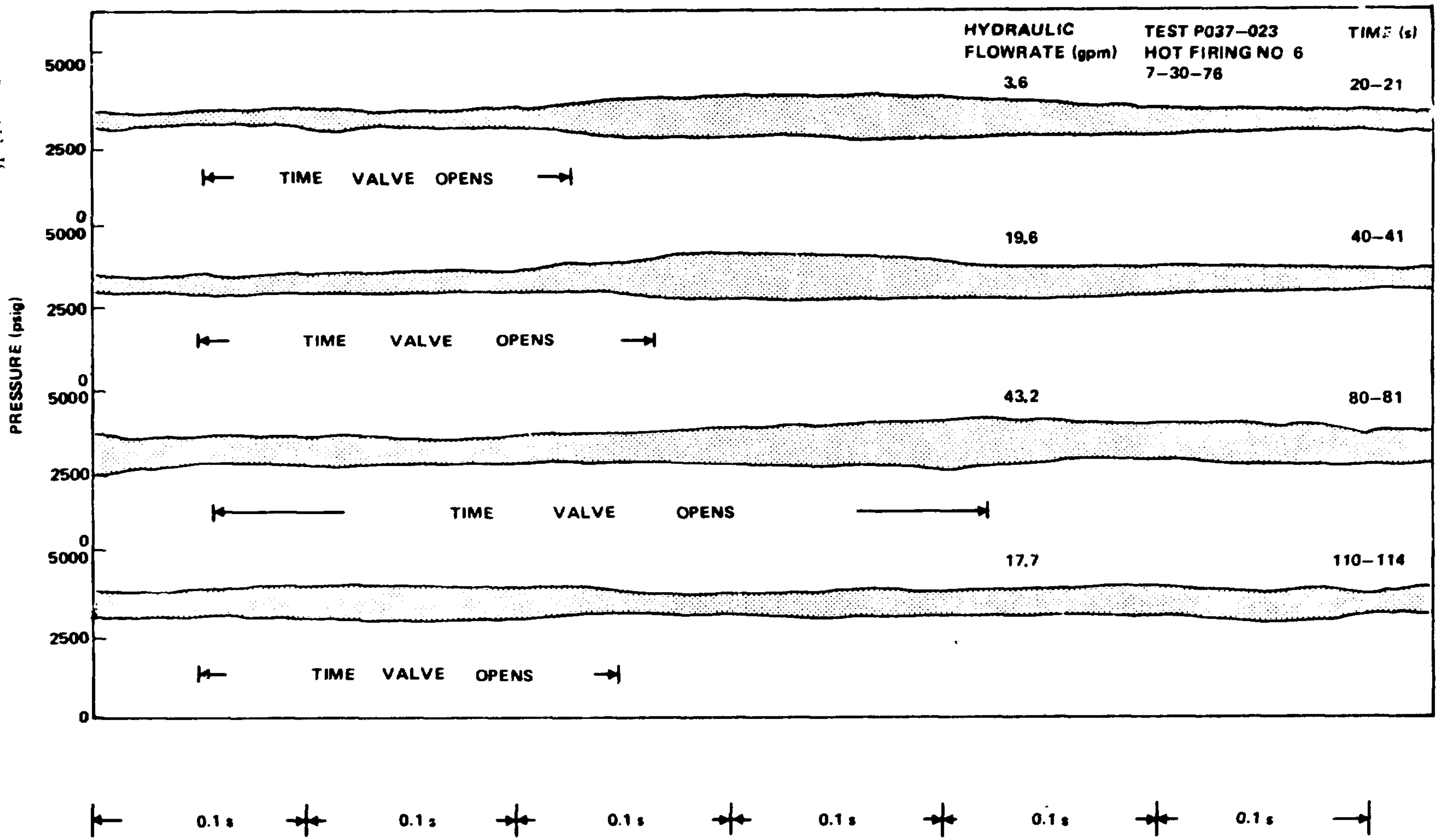

Figure 8. Hydraulic pump outlet pressure band matched with primary valve openings for different flowrates of the same test.

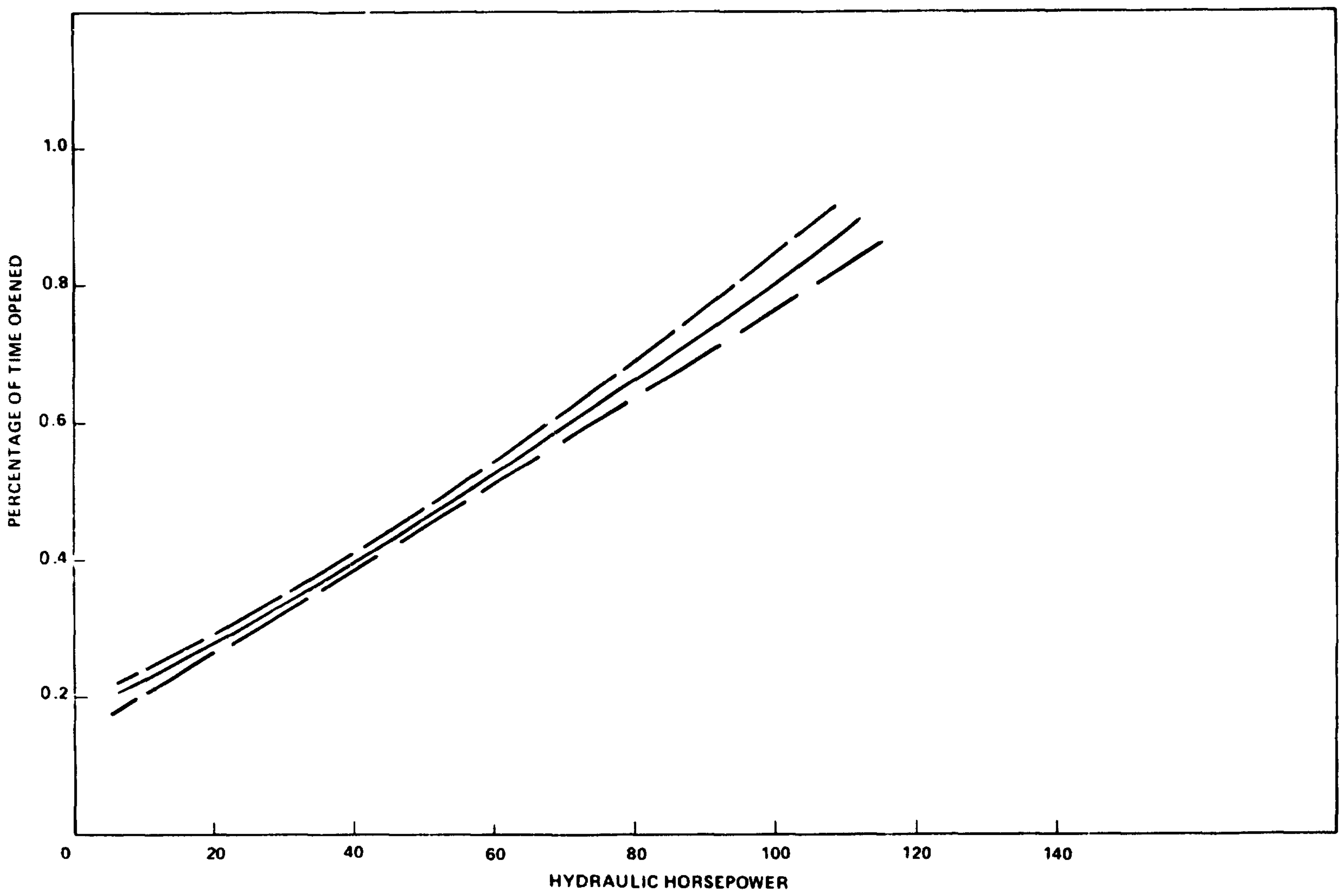

Figure 9. Percent of time the valve is open at any hydraulic horsepower.

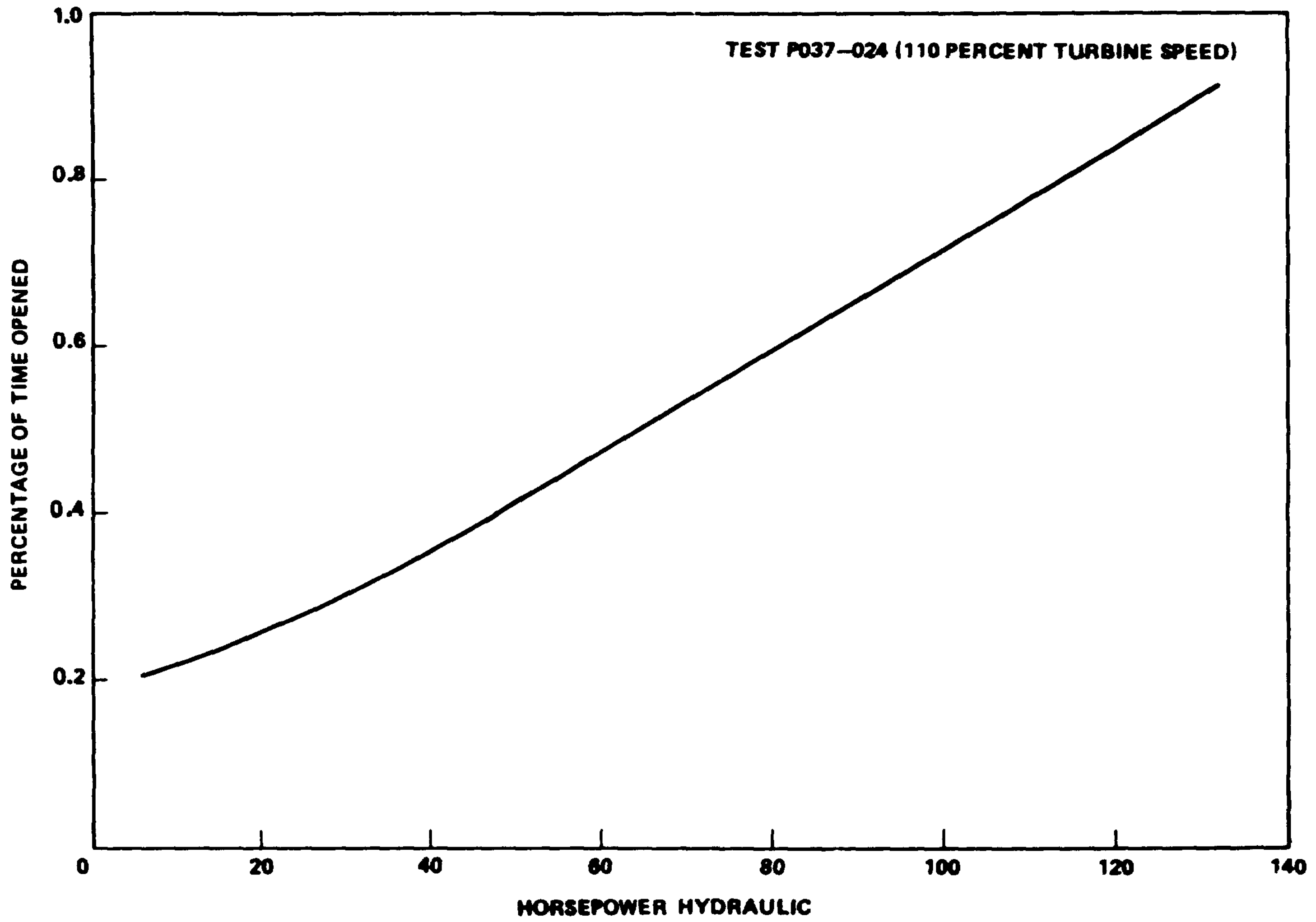

Figure 10. Percent of time valve opens versus hydraulic horsepower.

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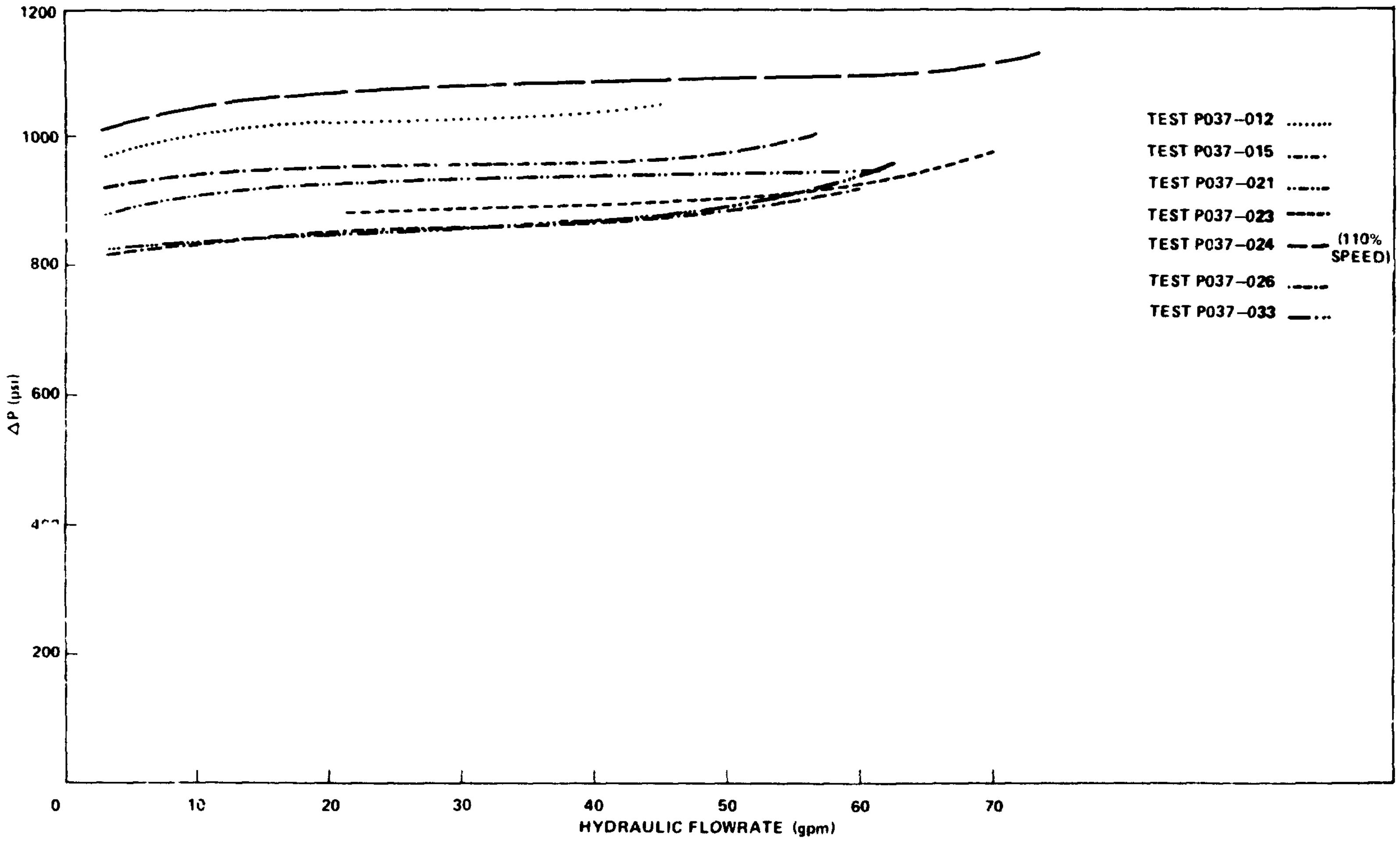


Figure 11. Pressure difference between the inlet and outlet pressure of the fuel pump and hydraulic flowrate.

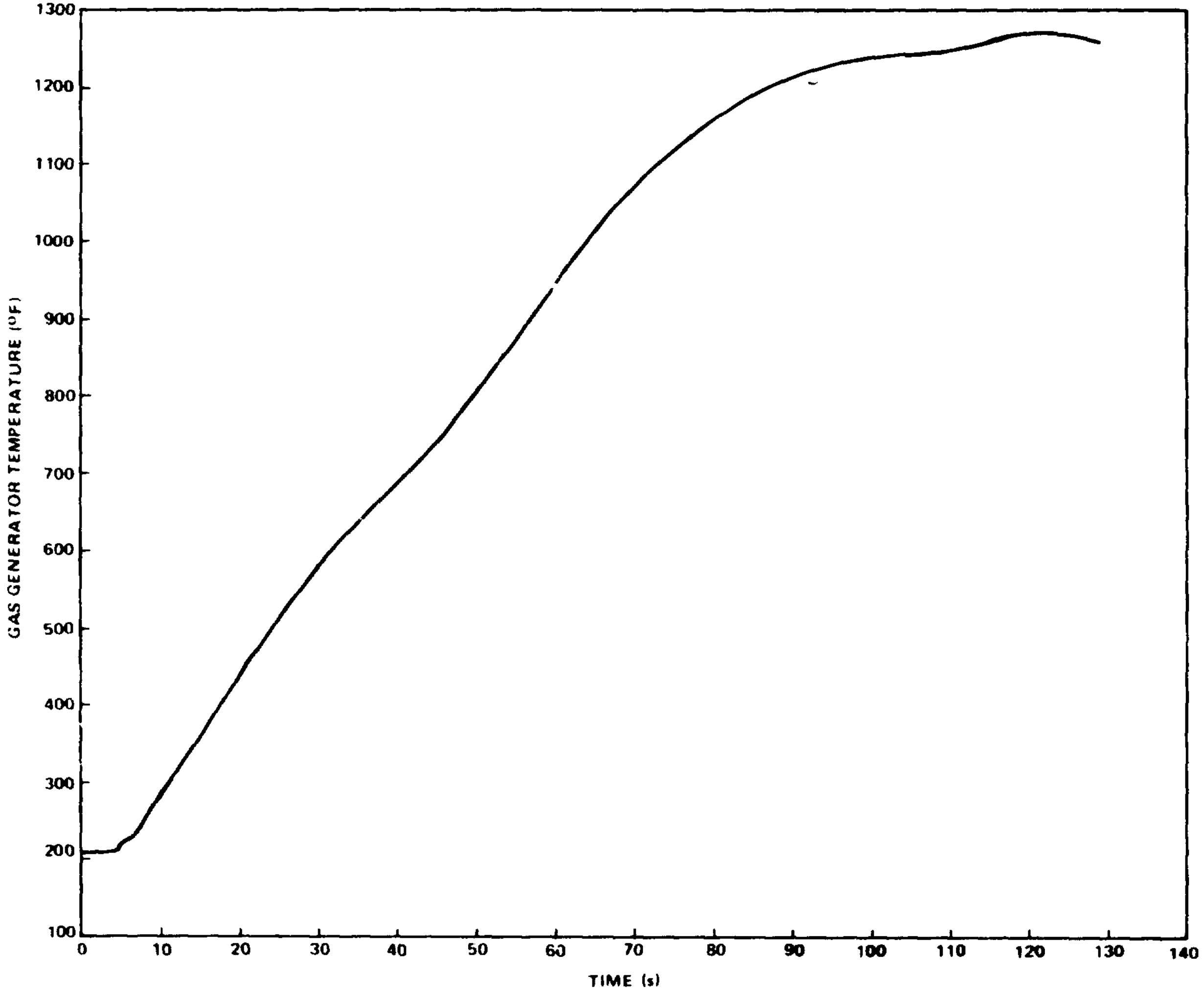


Figure 12. Gas generator temperature versus time for Test P037-021.

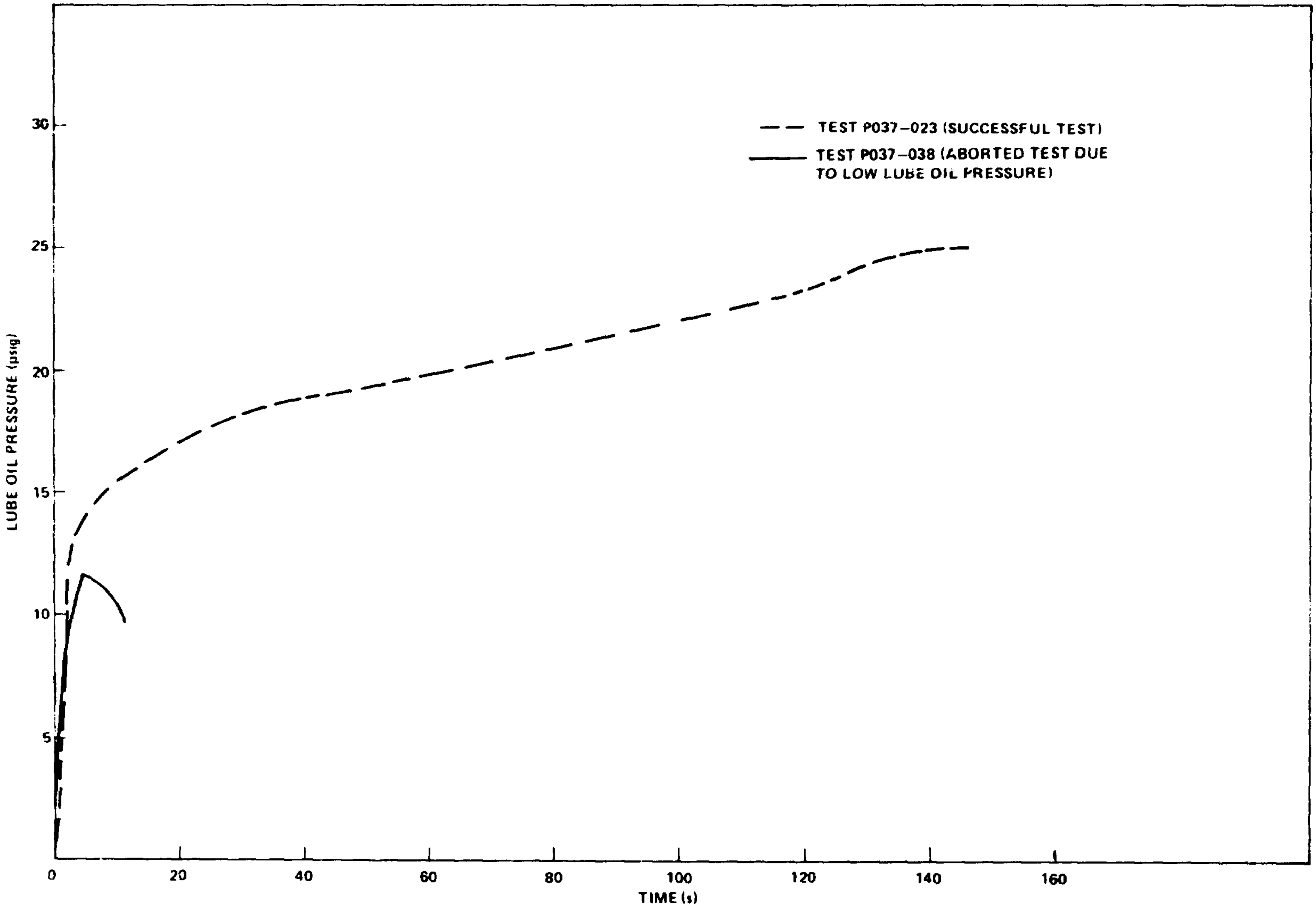


Figure 13. Lube oil pressure versus time for Tests P037-023 and 038.

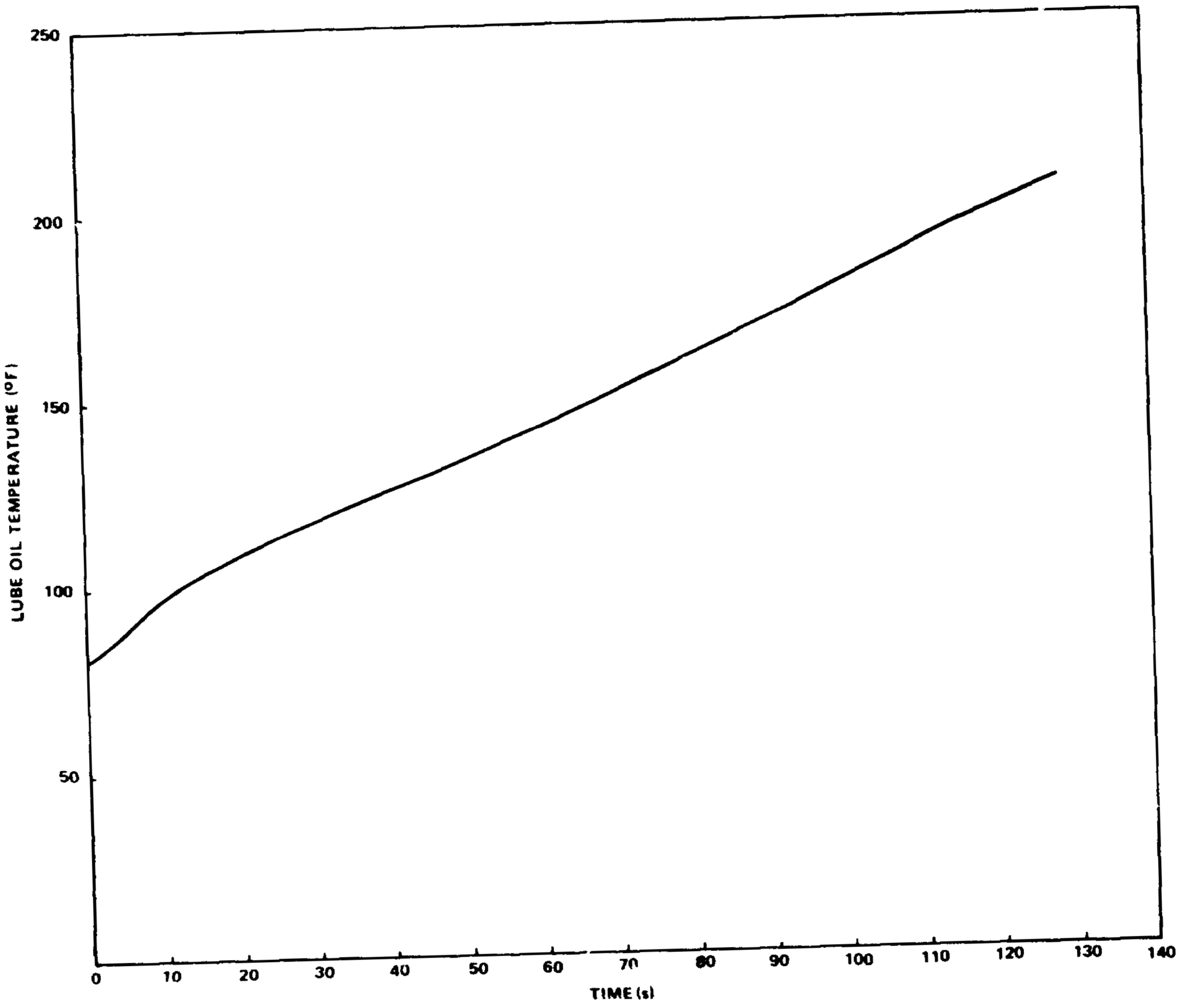


Figure 14. Lube oil temperature versus time for Test P037-021.

TEST	HYDRAULIC FLOW RATE (gpm)	HYDRAULIC PUMP OUTLET PRESSURE (psig)
P037–012	3.6	3169
	17.6	3159
	32.5	3153
	39.7	3145
	43.2	3134
	45.2	3133
P037–015	3.7	3167
	18.2	3152
	32.2	3145
	45.2	3134
	49.5	3134
	52.2	3132
	55.9	3122
P037-021	3.4	3166
	27.1	3149
	6[illegible].9	3129
	67.9	3042
	68.7	2882
	69.9	2705
P037–23	3.4	3162
	23	3146
	46.7	3137
	58.7	3124
	61.6	3119
	64.6	3076
	67.3	2765
	68.1	2815

TEST	HYDRAULIC FLOW RATE	HYDRAULIC PUMP OUTLET PRESSURE (psig)
P037-024	3.4	3159
	6.4	3163
	23.7	3153
	47.1	3137
	59.1	3133
	62.1	3123
	65.2	3122
	68.2	3128
	70.9	3102
	72.8	2967
P037-026	3.3	3166
	6.7	3170
	23.7	3157
	47.1	3137
	59.3	3137

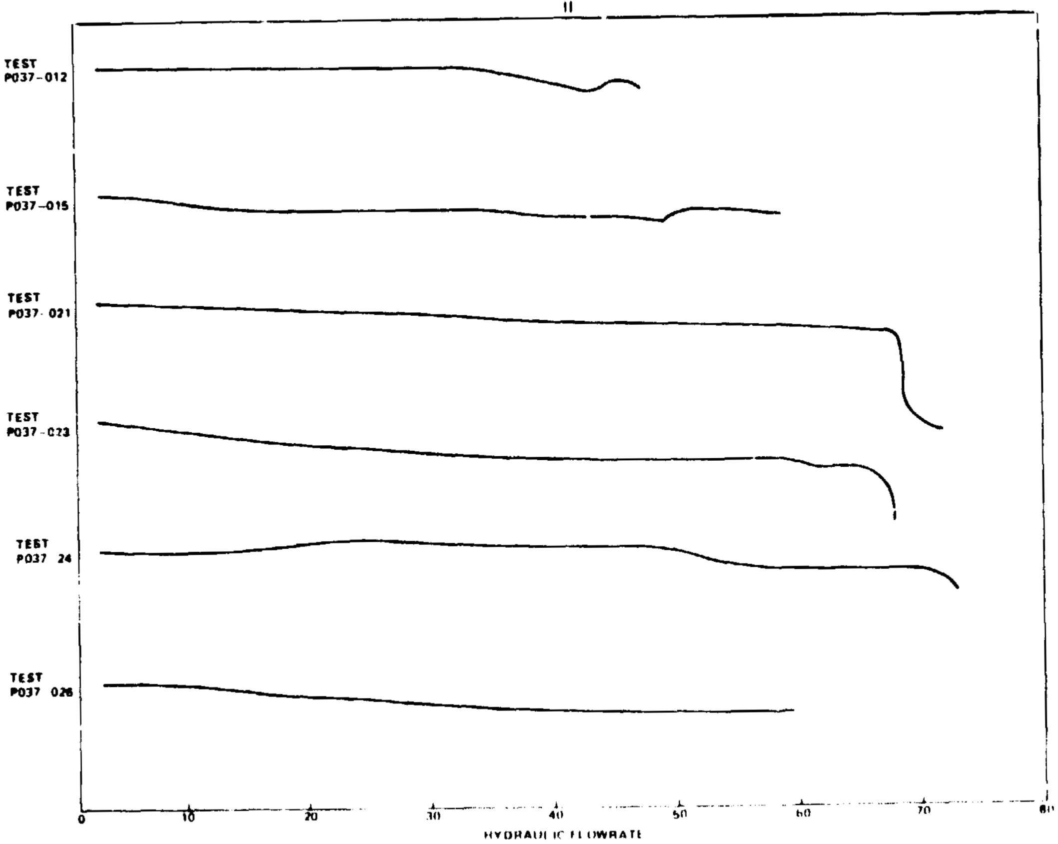
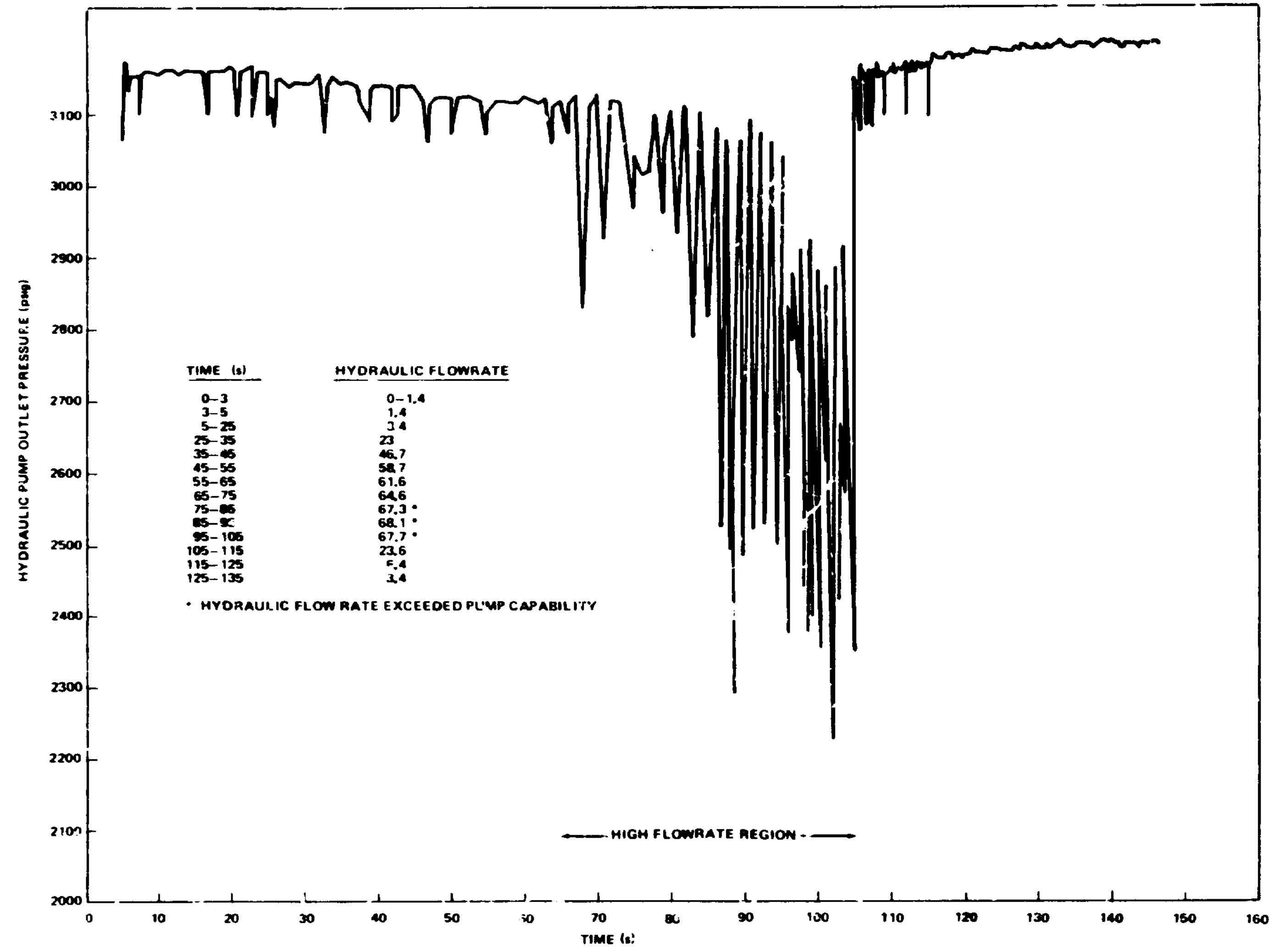


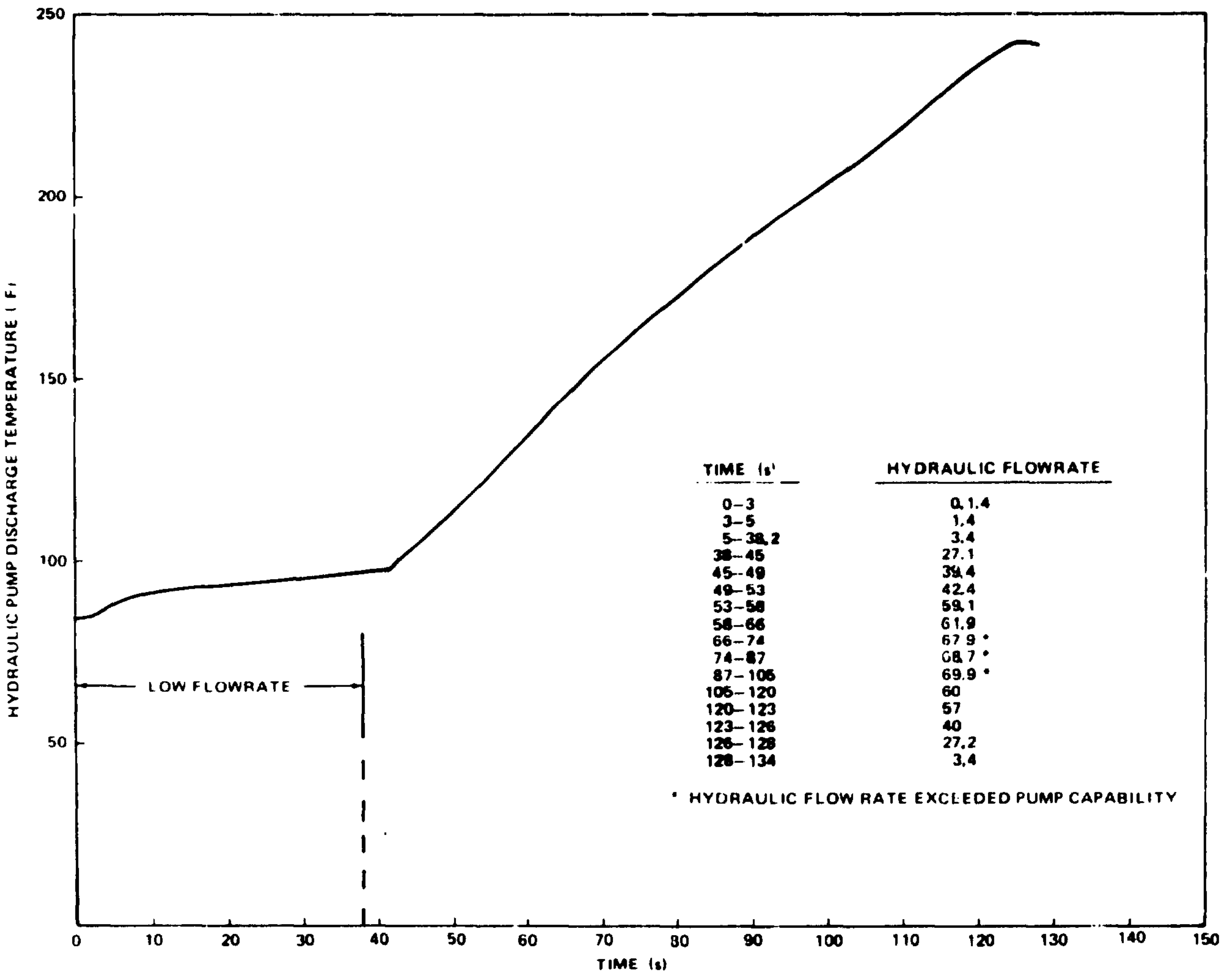
Figure 15. Relation between hydraulic pump outlet pressure and hydraulic flowrate as a comparison for several tests.



TIME (s)	HYDRAULIC FLOWRATE
0–3	0–1.4
3–5	1.4
5–25	3.4
25–35	23
35–45	46.7
45–55	58.7
55–65	61.6
65–75	64.6
75–85	67.3 *
85–95	68.1 *
95–105	67.7 *
105–115	23.6
115–125	5.4
125–135	3.4

* HYDRAULIC FLOW RATE EXCEEDED PUMP CAPABILITY

Figure 10 Hydraulic pump outlet pressure behavior versus flowrate for Test P037-023.



TIME (s)	HYDRAULIC FLOWRATE
0–3	0.1.4
3–5	1.4
5–38.2	3.4
38–45	27.1
45–49	39.4
49–53	42.4
53–58	59.1
58–66	61.9
66–74	67.9 *
74–87	68.7 *
87–106	69.9 *
106–120	60
120–123	57
123–126	40
126–128	27.2
128–134	3.4

* HYDRAULIC FLOW RATE EXCEEDED PUMP CAPABILITY

Figure 17. Hydraulic pump discharge temperature versus time for Test P037-021.

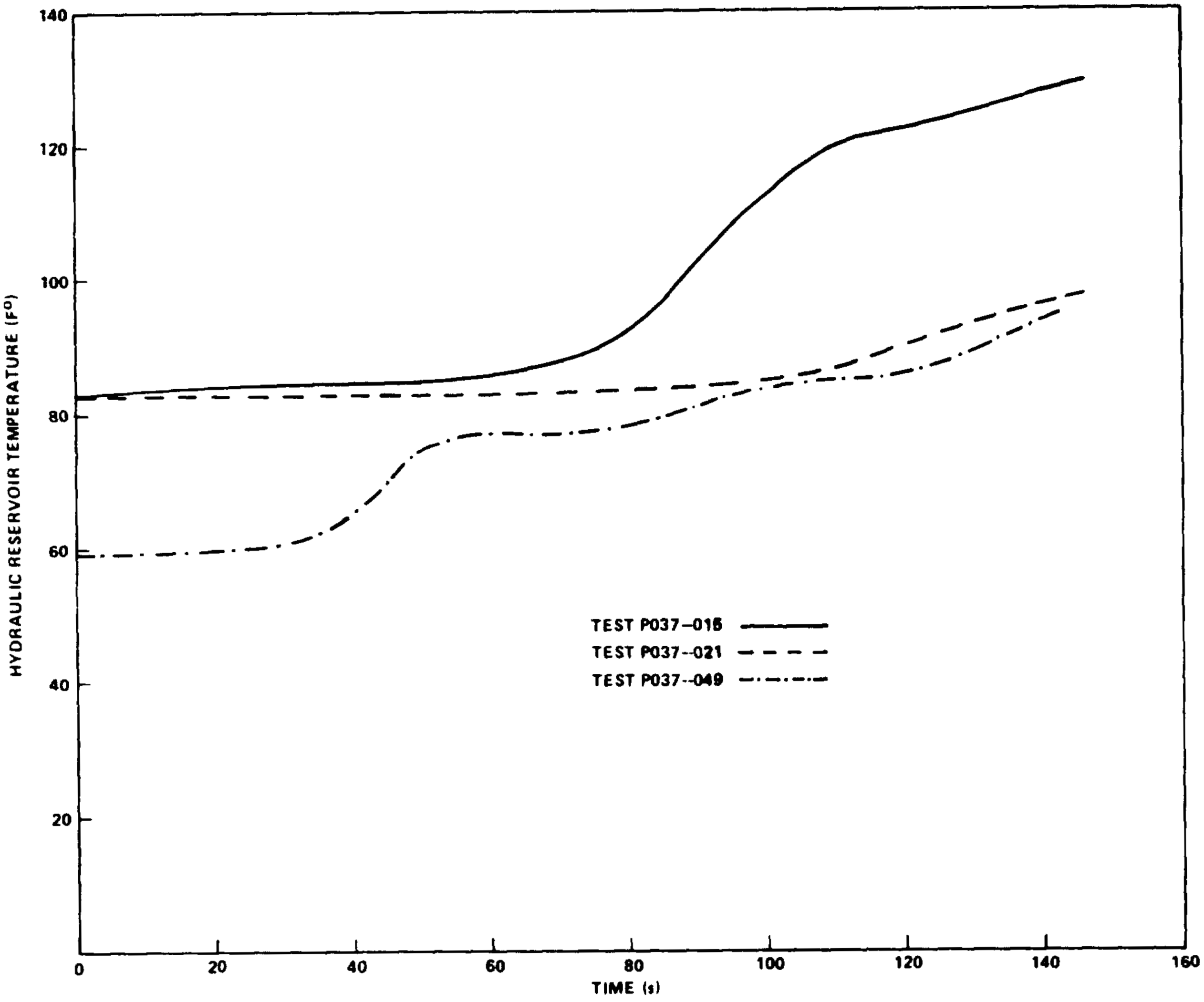


Figure 18. Hydraulic reservoir temperature versus time for Tests P037-015, 021, and 049.

TABLE 1. HOT FIRING TESTS (LOAD BANK)

Firing No.	Test No.	Date	Firing Duration (s)	Remarks
1	P037-005	7-15-76	4.4	Hardware and software verification
2	P037-007	7-21-76	20.3	Hardware and software verification
3	P037-009	7-23-76	146	Nominal mission profile
4	P037-010	7-27-76	146	Steady-state performance data
5	P037-011	7-29-76	146	Steady-state data and maximum APU horsepower
6	P037-012	7-30-76	146	Steady-state data and maximum APU horsepower
7	P037-013	8-4-76	4.3	Test terminated (aborted)
8	P037-014	8-4-76	4.3	Test terminated
9	P037-015	8-4-76	146	Steady-state data and maximum APU horsepower
10	P037-016	8-11-76	62.9	Test terminated
11	P037-020	9-9-76	4.3	Test terminated
12	P037-021	9-9-76	128	Test terminated
13	P037-023	9-14-76	146	Steady-state data and maximum APU horsepower
14	P037-024	9-17-76	146	Steady-state data and maximum APU horsepower (110 percent speed)
15	P037-026	9-23-76	239	Nominal mission profile (extended duration) — terminated
16	P037-032	9-29-76	10	Test terminated
17	P037-033	10-1-76	147	Evaluate APU fuel pump performance
18	P037-036	10-6-76	146	Low reservoir level and constant FSM pressure
19	P037-037	10-8-76	11	Test terminated
20	P037-038	10-8-76	11	Test terminated
21	P037-039	10-8-76	146	Blocked hydraulic pump case drain line
21 tests			1960.5	

TABLE 2. HOT FIRING TESTS (UNLOADED ACTUATOR)

Firing No.	Test No.	Date	Firing Duration (s)	Remarks
1	P037-041	11-2-76	11	Test terminated
2	P037-042	11-2-76	12.5	Test terminated
3	P037-044	11-4-76	146	System response (sine wave inputs)
4	P037-046	11-11-76	146	System response (square wave inputs)
5	P037-047	11-17-76	146	System response (triangular wave inputs)
6	P037-048	11-19-76	146	System response (sine wave inputs)
7	P037-049	11-24-76	146.5	System response (sine wave inputs)
8	P037-050	12-1-76	146.5	Sine wave inputs, evaluate hydraulic accumulator
9	P037-051	12-1-76	110	Square wave inputs, evaluate hydraulic accumulator
9 tests			1010.5	

TABLE 3. GN_2 SPIN TESTS (LOAD BANK)

Firing No.	Test No.	Date	Run Duration (s)
1	P037-002	7-9-76	34
2	P037-004	7-15-76	60.5
3	P037-006	7-20-76	73.5
4	P037-008	7-23-76	138
5	P037-019	9-9-76	153
6	P037-022	9-14-76	154.5
7	P037-025	9-22-76	179.5
8	P037-027	9-28-76	193
9	P037-028	9-28-76	17
10	P037-029	9-28-76	73.5
11	P037-030	9-29-76	9
12	P037-031	9-29-76	174
13	P037-034	10-1-76	151
14	P037-035	10-6-76	149
14 tests			1559.5

TABLE 4. GN_2 SPIN TESTS (UNLOADED ACTUATOR)

Firing No.	Test No.	Date	Run Duration (s)
1	P037-040	11-2-76	159
2	P037-043	11-4-76	174
3	P037-045	11-11-76	153.5
3 tests			486.5

TABLE 5. OVERALL APU SYSTEM PERFORMANCE DURING TEST P037-033

Time (s)	Hydraulic Flow (gpm)	Hydraulic Horsepower
0-2.5	0-1.2	0-0.37
2.5-5.0	1.2	0.45
5-10	3.4	6.14
10-20	6.7	12.61
20-30	23.3	43.17
30-40	47.0	85.76
40-50	53.0	95.18
50-60	56.1	100.74
60-70	58.8	104.77
70-80	60.8	108.81
80-90	62.1	110.69
90-100	65.2	117.07
100-105	23.8	42.91
105-110	3.4	6.18
110-113	23.8	43.09
113-116	59.4	106.08
116-121	3.4	6.20
121-124	47.7	86.30
124-127	59.8	108.16
127-132	3.4	6.21
132-135	59.1	103.89
135-152	3.4	6.21

TABLE 6. APU SYSTEM RESPONSE TO SINE WAVE INPUTS (TEST P037-049)

Amplitude (in.)	Frequency (cps)	Piston Displacement		Time (s)
		Cycles	Slew Rate (in./s)	
0.2	0.2	1	0.08	12-18
0.2	0.5	2	0.2	23-27
0.2	1	4	0.4	29-33
0.2	2	4	0.8	34-37
0.16	4	4	1.28	38-40
0.11	6	6	1.32	41-42
0.1	8	8	1.6	44-45
0.08	10	10	1.6	47-48
0.07	12	12	1.68	50-51
0.06	14	14	1.68	53-54
0.4	0.2	1	0.16	56-61
0.4	0.5	2	0.4	68-72
0.38	1	4	0.76	75-79
0.35	2	4	1.4	81-84
0.3	4	4	2.4	85-86
0.2	6	6	2.4	88-89
0.14	8	8	2.24	91-92
0.10	10	10	2	94-95
0.95	0.2	1	0.38	100-105
0.95	0.5	2	0.95	109-113
0.95	1	4	1.9	116-120
0.85	2	4	3.4	122-125
0.59	4	4	4.72	126-127
0.3	(period — 4 s)	1	2.0	130-134
0.3	(period — 4 s)	1	2.0	139-144

Note: Total actuator movement is 56.86 in.

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TABLE 7. MAXIMUM AND MINIMUM TURBINE SPEED AT NORMAL OPERATION CONDITIONS

Speed (K rpm)		Speed Band (percent)			Average Hydraulic Horsepower
Maximum	Minimum	Maximum	Minimum	Test No.	
Load Bank Tests					
76.43	69.15	6.2	-4	P037-009	
76.80	68.84	6.7	-4.4	P037-010	
76.57	68.15	6.3	-5.3	P037-011	42.19
76.78	69.2	6.6	-3.9	P037-012	44.17
76.73	68.89	6.6	-4.3	P037-015	55.13
75.94	69.31	5.5	-3.7	P037-021	69.62
76.14	68.79	5.75	-4.5	P037-023	66.03
82.64	76.24	4.8	-4.1	P037-024 (110 percent speed)	71.29
75.40	68.98	4.7	-4.2	P037-026	53.02
76.04	67.23	5.6	-6.6	P037-033	72.37
76.66	67.45	6.5	-6.3	P037-036	30.3
76.19	67.66	5.8	-6.0	P037-039	27
Unloaded Actuator Tests					
76.43	69.87	6.2	-3.0	P037-044	
76.21	68.39	5.8	-5	P037-046	
76.11	68.30	5.7	-5.1	P037-047	
76.37	68.94	6.1	-4.25	P037-048	
76.28	69.70	5.9	-3.2	P037-049	
76.51	70.1	6.3	-2.6	P037-050	
76.65	70.05	6.5	-2.7	P037-051	

TABLE 8. MAXIMUM AND MINIMUM TURBINE SPEED FOR LOAD BANK AND UNLOADED ACTUATOR (72 000 rpm ± PERCENT)

Type of Test	Speed (rpm)	Speed Band (percent)	Test No.	Condition
Load Bank (100 percent speed)				
Maximum Speed Registered	77 410	75.5	P037-009	Low Hydraulic Flow Rate
Minimum Speed Registered	60 100	-16.5	P037-026	Very High Hydraulic Flow Rate
Load Bank (110 percent speed: 79 200 rpm ± 5 percent)				
Maximum Speed Registered	83 920	6	P037-024	Low Hydraulic Flow Rate
Minimum Speed Registered	71 750	- 9.4	P037-024	Very High Hydraulic Flow Rate
Unloaded Actuator				
Maximum Speed Registered	77 660	7.9	P037-051	Mild Actuator Movement
Minimum Speed Registered	62 620	-13.0	P037-048	Severe Actuator Movement

TABLE 9. COMPARISON OF VALVE OPENING TIMES SELECTED FROM STEADY FLOW DATA

Test No.	Time Valve Is Open (s)	Hydraulic Flowrate (gpm)	Time (s)
P037-012	0.427	45.2	90-94
P037-015	0.462	55.9	80-84
P037-021	1.687	67.9	69-73
P037-023	3.093	61.6	60-64
P037-024	1.805	72.8	100-104
P037-026	1.243	59.3	50-54
P037-033	4.414	65.2	88-93

TABLE 10. NUMBER OF VALVE OPENINGS FOR LOAD BANK AND UNLOADED ACTUATOR

APU Hot Firings with Load Bank		
Test Number	Number of Valve Openings	Test Duration (s)
P037-005	3	4.4
P037-007	32	20.3
P037-009	157	146
P037-010	205	146
P037-011	218	146
P037-012	236	146
P037-013	2	4.3
P037-014	2	4.3
P037-015	214	146
P037-016	79	62.9
P037-020	2	4.3
P037-021	117	128
P037-023	132	146
P037-024	149	146
P037-026	238	239
P037-032	6	10
P037-033	128	147
P037-036	135	146
P037-037	3	11
P037-038	10	11
P037-039	151	146
Total	2246	1960.5

TABLE 10. (Concluded)

APU Hot Firings with Actuator		
Test Number	**Number of Valve Openings**	**Test Duration (s)**
P037-041	9	11
P037-042	11	12.5
P037-044	127	146
P037-046	130	146
P037-047	143	146
P037-048	191	146
P037-049	136	146.5
P047-050	137	146.5
P047-051	93	110
Total	987	1010.5

Test	Number of Valve Openings	Duration of Test (s)
Load Bank Tests	2246	1960.5
Tests with Actuator	987	1010.5
Total	3233	2971

Ratio: No Valve Openings/s = 3233/2971 = 1.088

TABLE 11. CHARACTERISTIC PARAMETERS OF OPERATION FOR THE FUEL PUMP

Test No.	Highest Recorded Maximum Fuel Pump Discharge Pressure (psig)	Time (s)	Hydraulic Flow (gpm)	Lowest Recorded Maximum Fuel Pump Discharge Pressure (psig)	Time (s)	Hydraulic Flow (gpm)	Largest Increase in Pressure as Fuel Goes Through the Fuel Pump (psi)	Time (s)	Hydraulic Flow (gpm)	Smallest Increase in Pressure as Fuel Goes Through the Fuel Pump (psi)	Time (s)	Hydraulic Flow (gpm)
P037-012	1390	50-54	32.5	1345	136-140	3.6 (End)	1055	110-114	17.7	975	20-24	3.6 (Start)
P037-015	1330	40-44	32.2	1290	121-125	3.6 (End)	992.5	80-84	55.9	920	20-24	3.7 (Start)
P037-021	1320	61-65	61.9	1280	32-36	3.4 (Start)	975	112-116	60	880	32-36	3.4 (Start)
P037-023	1325	20-24	3.4	1230	130-134	3.4 (End)	967.5	100-104	67.7	882.5	30-34	23
P037-024	1450	40-44	47.1	1400	140-144	3.4 (End)	1115	100-104	72.8	1010	100-104	3.4 (Start)
P037-026	1300	50-54	59.3	1230	146-150	3.4 (End)	945	110-114	23	820	10-14	3.3 (Start)
P037-033	1275	45-49	53	1215	15-19	6.7 (Start)	947.5	85-89	62.1	927.5	15-19	6.7 (Start)

TABLE 12. HIGHEST MAXIMUM PRESSURE RECORDINGS

Test No.	Highest Maximum Pressure (psig)
P037-012	1200
P037-015	1180
P037-021	1140
P037-023	1125
P037-024	1242.5 (110 percent speed)
P037-026	1140
P037-033	1120

TABLE 13. RIPPLE BEHAVIOR

Test No.	Small Low Ripple (psi)	Hydraulic Flowrate (gpm)	Large Low Ripple (psi)	Hydraulic Flowrate (gpm)	Small High Ripple (psi)	Hydraulic Flowrate (gpm)	Large High Ripple (psi)	Hydraulic Flowrate (gpm)
P037-012	500	3.6 (B)	900	45.2 (h)	1000	3.6 (B)	1500	32.5 (R)
P037-015	475	3.6 (e)	900	55.9 (h)	850	3.6 (e)	1475	32.2; 45.2 (R)
P037-021	500	3.4 (B)	800	61.9 (n)	1075	69.9 (h)	1550	67.9 (R)
P037-023	500	3.4 (B)	850	64.6 (n)	1000	67.7; 6.4; 3.4 (e)	1450	58.7; 64.6 (R)
P037-024	450	6.4; 3.4 (e)	950	59.1	825	3.4 (e)	1500	47.1 (R)
P037-026	450	3.3 (B)	700	59.3 (h)	1050	6.7	1317.5	59.3 (h)
P037-033	450	6.7 (B)	875	62.1 (n)	1000	6.7 (B)	1550	65.2 (h)

Note:

R = Rising
e = End
h = Highest
B = Beginning
n = Near Highest

TABLE 14. BEHAVIOR OR NOMINAL HYDRAULIC PUMP OUTLET PRESSURE VERSUS HYDRAULIC FLOWRATE

Test No.	Pressure at Beginning of Tests (psig)	Hydraulic Flowrate (gpm)	Lowest Nominal Pressure (psig)	Hydraulic Flowrate (gpm)	Highest Nominal Pressure (psig)	Hydraulic Flowrate (gpm)
P037-012	3170	3.6	3133	45.2	3194	3.6 (End)
P037-015	3167	3.7	3122	49.5	3192	3.6 (End)
P037-021	3167	3.4	2705	69.9	3183	27.2 (End)
P037-023	3162	3.4	2765	67.7	3199	6.4; 3.4 (End)
P037-024	3159	3.4	2967	72.8	3235	3.4 (End)
P037-026	3166	3.3	3137	47.1; 59.3	3218	6.7 (End)
P037-033	3169	6.7	3059	65.2	3210	6.7 (End)

TABLE 15. BRIEF TYPICAL TEST PLAN

1. **Prefiring sequence — Time: 8:00 a.m. to 10:30 a.m.**
    - a. **Set up facilities**
    - b. **Record fuel level**
    - c. **Service hydraulic system (as required)**
    - d. **Checkout of valves and switches**
    - e. **Transfer hydrazine into fuel supply module**
    - f. **Check gearbox lube oil level**
    - g. **Check transducers for a possible malfunction**
2. **Firing**
3. **Post firing procedure —**
    - a. **Check level of contamination in the air (look for hydrazine content)**
    - b. **Check hydrazine leakage**
    - c. **Check hydraulic leakage**
    - d. **Record fuel level**
    - e. **Record lube oil level**
    - f. **Service facilities (the required)**

APPENDIX A

ADDITIONAL ANALYSES

A. Fuel Consumption Analysis

An analysis of fuel consumption was performed for predicting the fuel consumed under certain loads applied to the TVC subsystem. These loads consisted of specific flows (gpm) of hydraulic fluid from which certain amounts of power (hydraulic horsepower) were obtained. Under each load, the quantity of fuel consumed at a steady flow point was measured and combined with the flowrate to obtain the fuel consumption rate.

Different values and curves representing the fuel consumption rate (FCR) were obtained for each test. From these curves, a band of curves was constructed showing values for every test on which calculations were performed.

The values obtained for the band of curves were always taken with steady hydraulic fluid flow and constant hydraulic outlet pressure. For this reason, other tests mentioned in the analysis (P037-036 and P037-039) were not included in the band. Similarly, certain high flowrates were never used because the hydraulic pump outlet pressure was never constant.

Although a steady flow and constant pressure values were recorded for Test P037-015, the FCR curve for this test was too large for the band constructed. Also, some of the values recorded were not precise readings. Consequently, this curve was omitted from the band.

Table A-1 lists the tests analyzed and presents the results of the analysis. Table A-2 presents a summary of all the FCR tests, and Table A-3 lists the maximum and minimum points for FCR at certain values of hydraulic horsepower.

Figure A-1 shows a band of graphs representing FCR versus hydraulic horsepower for the tests listed in Table A-1, and Figure A-2 shows the FCR curve for a sample test (P037-024).

As a means of predicting the fuel consumed in a period of time of a given test, a curve showing how the consumption of fuel varied with fuel tank pressure was constructed (Fig. A-3). By knowing the initial pressure and the change in pressure in the tank, it is possible to determine the fuel consumed for the firing.

To aid the reader, a table of previous tests is included as an inset to Figure A-3. In this table the fuel consumed is compared to the corresponding change in pressure.

Figures A-4 and A-5 aid in the interpretation of Figure A-3. Figure A-4 presents a relation of pressure change (with time) and gallons per seconds for that change. The curve is divided into two parts: increasing and decreasing hydraulic flow. If it is known on which side of the curve the point is located, it is possible to determine the fuel flow at that instant. Figure A-5 presents a band of curves showing how the change in pressure (per gallon of fuel) acts at certain periods of time for all the tests on which Figure A-2 is based.

The data used were taken only from tests that had pressure decay in the tank. Table A-4 presents a correlation of pressure decay with the tests used in the construction of Figures A-3, A-4, and A-5.

B. GN_2 Spin Pressure and Turbine Speed Relations

A series of curves (Fig. A-6) was constructed to show the relationship between spin pressure and turbine speed for the purpose of finding the point where spin pressure begins to decrease with a corresponding increase in turbine speed. Three sets of curves were drawn for three different flowrates: 3.3, 6.6, and 9.5 gpm. Each set of curves shows the point for which differences exist according to each flowrate.

One curve of the set corresponds to an average curve constructed from a group of pretest curves, and the other is a curve obtained from one of the tests and considered to be the best representation of all the curves at the given flow.

The following listing gives approximate values where these points are matched with their corresponding flowrates:

Hydraulic Flowrate (gpm)	Turbine Speed (K rpm)	Spin Pressure (psig)
3.3	30	440
6.6	29	555
9.5	26	675

The listed data were taken from the GN_2 spin tests performed during the sequence presented in this report. However, only those curves from which good data could be obtained were used to construct the curves shown in Figure A-6.

C. Constant Flow Conditions

Constant flow condition measurements were taken from oscillographs to match up the values obtained in different tests at similar flowrates, to determine behavior of certain parameters at different flows and time, and to aid in search for possible causes of aborted tests. Table A-5 presents a sample listing of the readings arranged according to time and flowrate for a typical test.

Two sets of curves showing the relation between hydraulic horsepower and hydraulic flowrate are included in this appendix (Figs. A-7 and A-8). In Figure A-7, curves are presented showing the behavior of hydraulic flowrate versus hydraulic horsepower for Tests P037-012, 015, 021, 023, 024, 026, and 033. Figure A-8 shows a band of the curves with an average line of values included (a constructed line from which the value of one parameter is obtained by knowing the other). Both sets were obtained from data of several tests at constant flow. In Figure 15 of this report, a set of curves is presented which shows the variation of the hydraulic pump outlet pressure at different flowrates (each was taken at a constant flowrate). Table A-5 presents typical behavioral data for a test at constant flow conditions (Test P037-026).

D. Actuator Displacement Analysis

Agitation in both interface pressures [inlet (P17) and outlet (P18)] occurs everytime the actuator piston position is subjected to a change. In a case of sine wave, this agitation has the form of an oscillatory curve where the maximum points for the curve occur at the same time as the maximum and minimum points in the movement of the piston. In a case of the step function, agitation takes the form of a single perturbation or pulsar that takes place everytime the piston moves, with the maximum point of the perturbation taking place just before the piston stops. These variations in pressure occur three or four times in every step signal (depending on the number of movements ordered for the same signal).

Table A-6 presents generalized actuator data from Tests P037-046, 049, 050, and 051 (hot firings with actuator, unloaded), and Tables A-7, A-8, A-9, and A-10 present detailed data from Tests P037-046, 049, 050, and 051, respectively.

For the tests with an accumulator added, it was discovered that the agitation in the inlet pressure diminished. The variation between the maximum and minimum pressure was very small compared to the previous tests without the accumulator.

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In the step function tests, the interface outlet pressure in the tests with the accumulator at times was larger or smaller compared to the value obtained in the test without the accumulator. The variations in pressure again were small, however, and considered negligible.

For the sine wave tests, the interface outlet pressure was higher after the accumulator was added; this increase was significant in some cases. Another point to note is that in some of these readings, a sharp increase in the pressure band (difference in high and low points of the pulsar) could be seen, and in others, where the previously mentioned increase was slight, they were almost similar bands (and in some cases even smaller).

Agitation in pressure is present in the sine wave in almost all frequencies and amplitude for the wave indicated. The only cases where this did not occur were at low frequencies: 0.2, 0.5, and 1.0 cps. However, as the amplitude increased, perturbations appeared; first at 1.0 cps, then (last increase) at 0.5 cps. Perturbations never appeared for 0.2 cps and for the square wave which was added at the end of the sine wave program.

The worst cases of agitation in pressure occurred always at 4 cps and 6 cps. As the amplitude of the wave increased, agitation increased (for the same frequency).

In the case of the step wave, agitation occurred in all the waves imposed and as previously mentioned, perturbation took the form of a pulsar, appearing everytime there was movement by the piston.

The place of worst agitation in this program was at an amplitude of 0.85 in. (±0.425 in. moved) in a test without accumulator.

When the accumulator was added, a definite pattern of new initial pressure points could not be detected because they did not appear at one specific place (frequency or amplitude) and were scattered throughout the entire tests. But, these new critical points were never as critical as they were in the tests performed without the accumulator because the pressure band was very small in the first (with accumulator) compared to that in the latter test.

The effect of the fluid accumulator in the previously mentioned tests is shown graphically in Figures A-9 through A-13. Figures A-9 and A-10 show a comparison between Tests P037-046 and 051. The pressure pulses occur at a similar interval of time. Because the velocity in the oscillograph machine during testing was different for both tests, a difference in time span is observed.

However, the range is the same in both and is the only coordinate needed when studying the effect mentioned. Figures A-11, A-12, and A-13 make the same comparison for Tests P037-049 and 050; however, in these figures both coordinates have the same proportion, so the difference here is null.

During the step wave test, the amount of time the inlet interface pressure (P17) exceeded 3750 psig in each pressure agitation ran between 0.027 and 0.030 s, and the outlet interface pressure (P18) time exceeded 375 psig from 0.006 to 0.007 s. Both were in a test performed without fluid accumulator. For the test with fluid accumulator, the inlet interface pressure never exceeded 3750 psig and the outlet pressure exceeded 375 psig for 0.007 s.

In the sine wave tests, the time that both the inlet and outlet interface pressures exceeded 3750 psig and 375 psig, respectively, varied according to the frequency and amplitude to which the actuator was exposed. The usual time that the inlet pressure exceeded 3750 psig was approximately 0.02 to 0.03 s for each pressure pulse, and the outlet pressure exceeded 375 psig for 0 to 0.004 s, both for the test with and without fluid accumulator. The longest time period (0.5 s) that the inlet pressure was over 3750 psig occurred both at high frequency and large amplitude. The worst case also occurred at these conditions (on Test P037-049 at 123 to 124 s after startup). In the tests with a fluid accumulator, the inlet pressure never exceeded the 3750 psig barrier and the outlet pressure only exceeded the 375 psig barrier for 0.002 to 0.007 s.

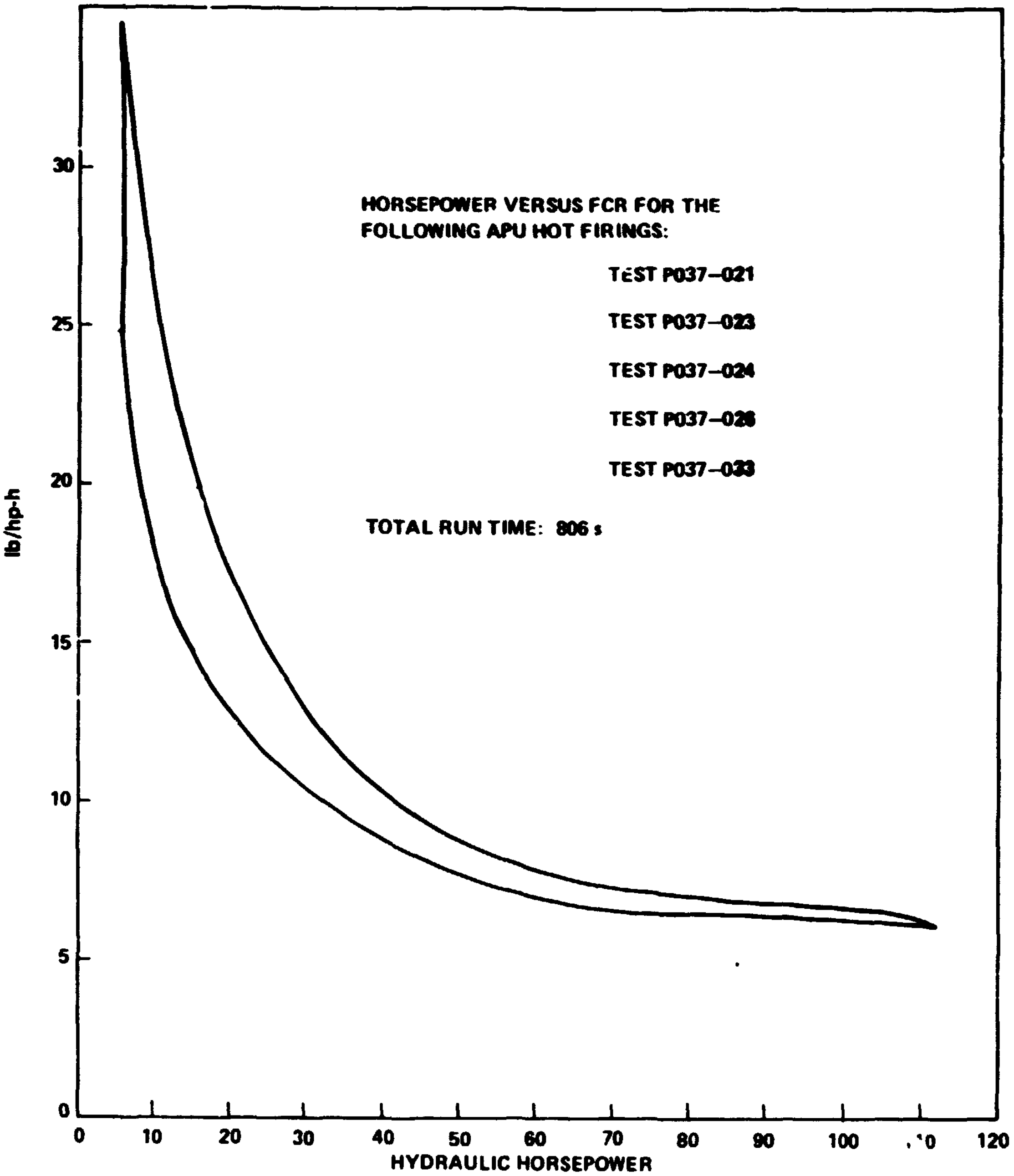

Figure A-1. Band of graphs for FCR versus hydraulic horsepower.

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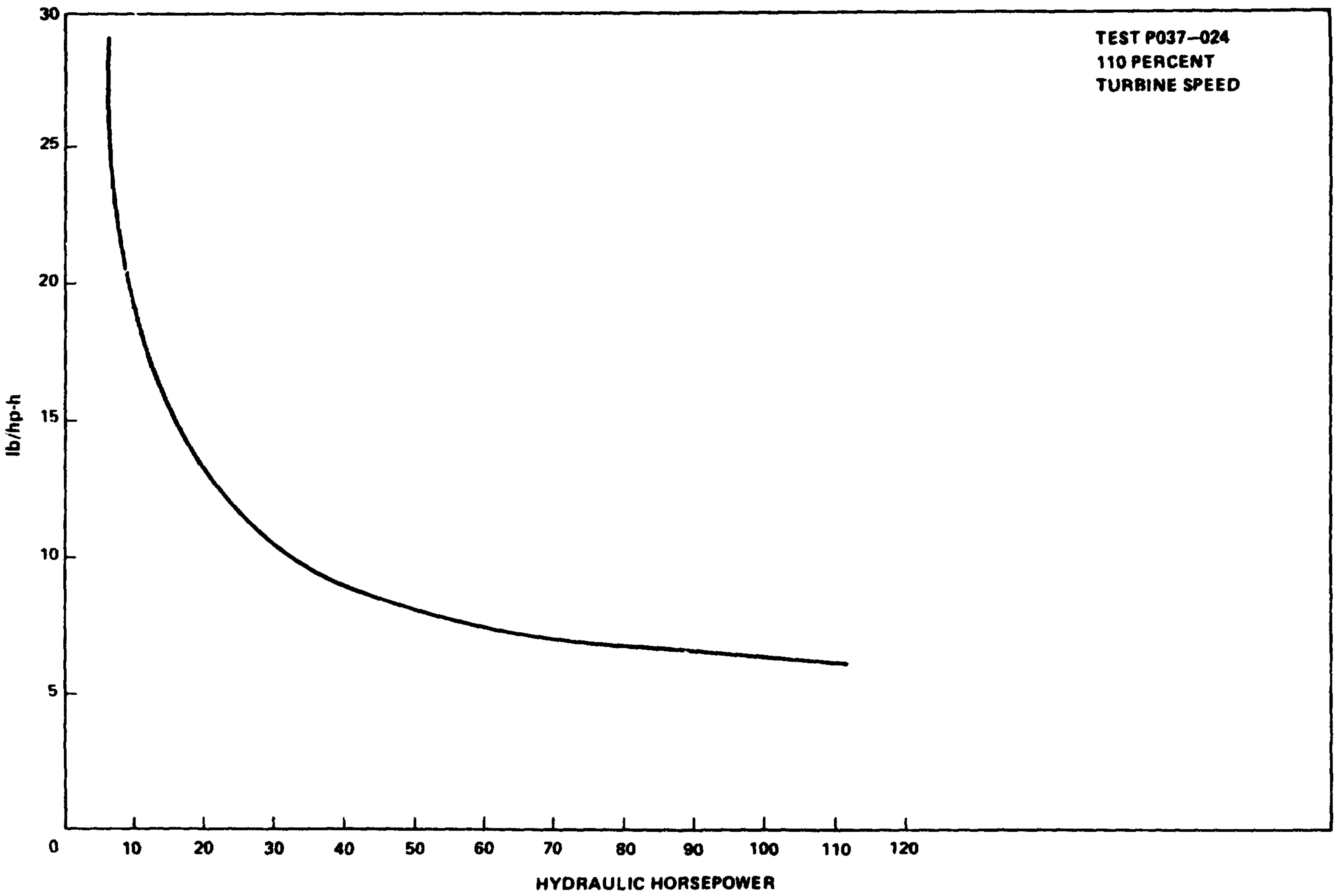
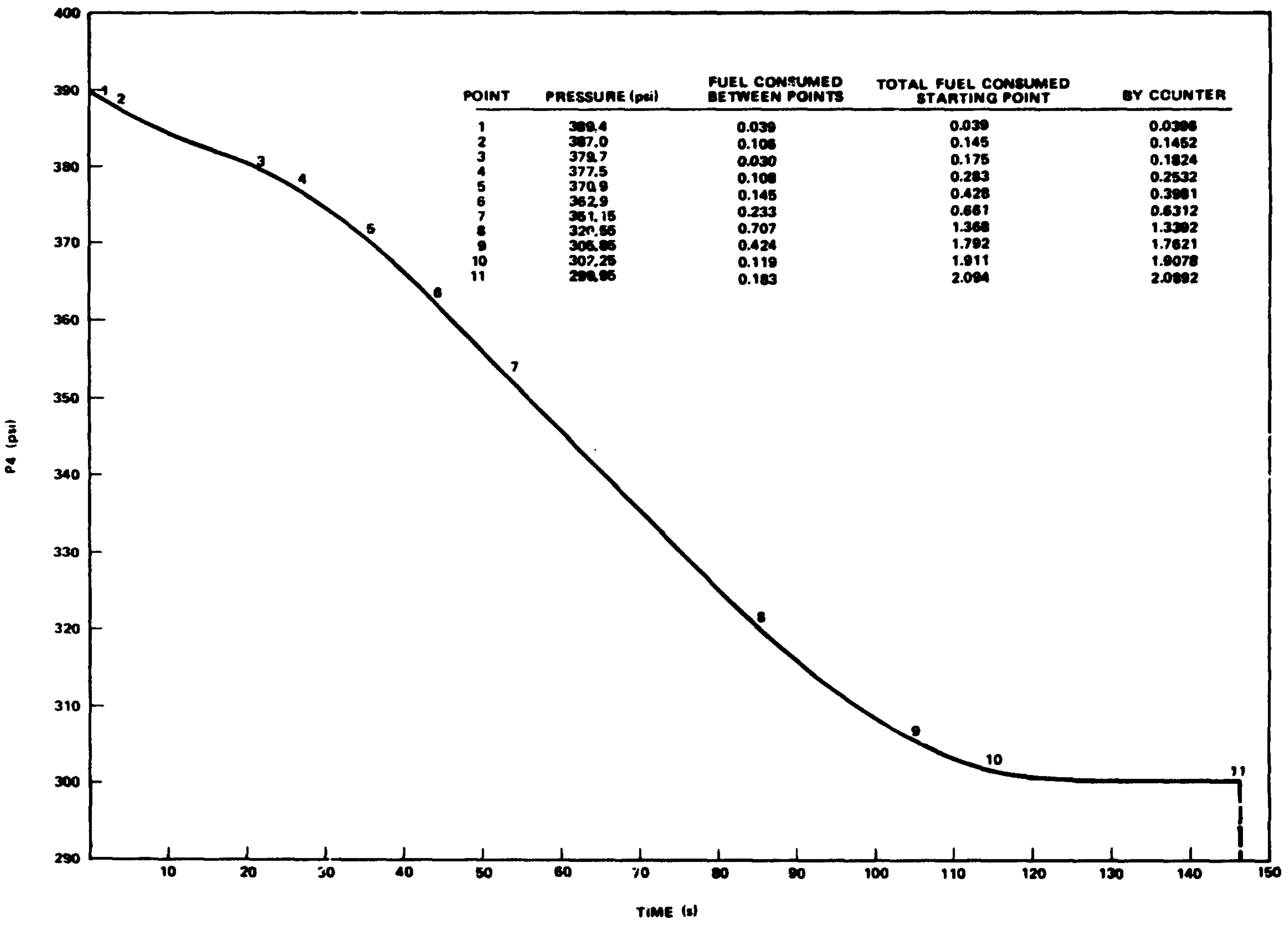


Figure A-2. Graph of FCR versus hydraulic horsepower.



POINT	PRESSURE (psi)	FUEL CONSUMED BETWEEN POINTS	TOTAL FUEL CONSUMED STARTING POINT	BY COUNTER
1	389.4	0.039	0.039	0.0396
2	387.0	0.106	0.145	0.1452
3	379.7	0.030	0.175	0.1824
4	377.5	0.108	0.283	0.2532
5	370.9	0.145	0.428	0.3981
6	362.9	0.233	0.661	0.6312
7	361.15	0.707	1.368	1.3392
8	320.55	0.424	1.792	1.7621
9	306.85	0.119	1.911	1.9078
10	307.25	0.183	2.094	2.0892
11	298.95			

Figure A-3. Relation between pressure and fuel consumed.

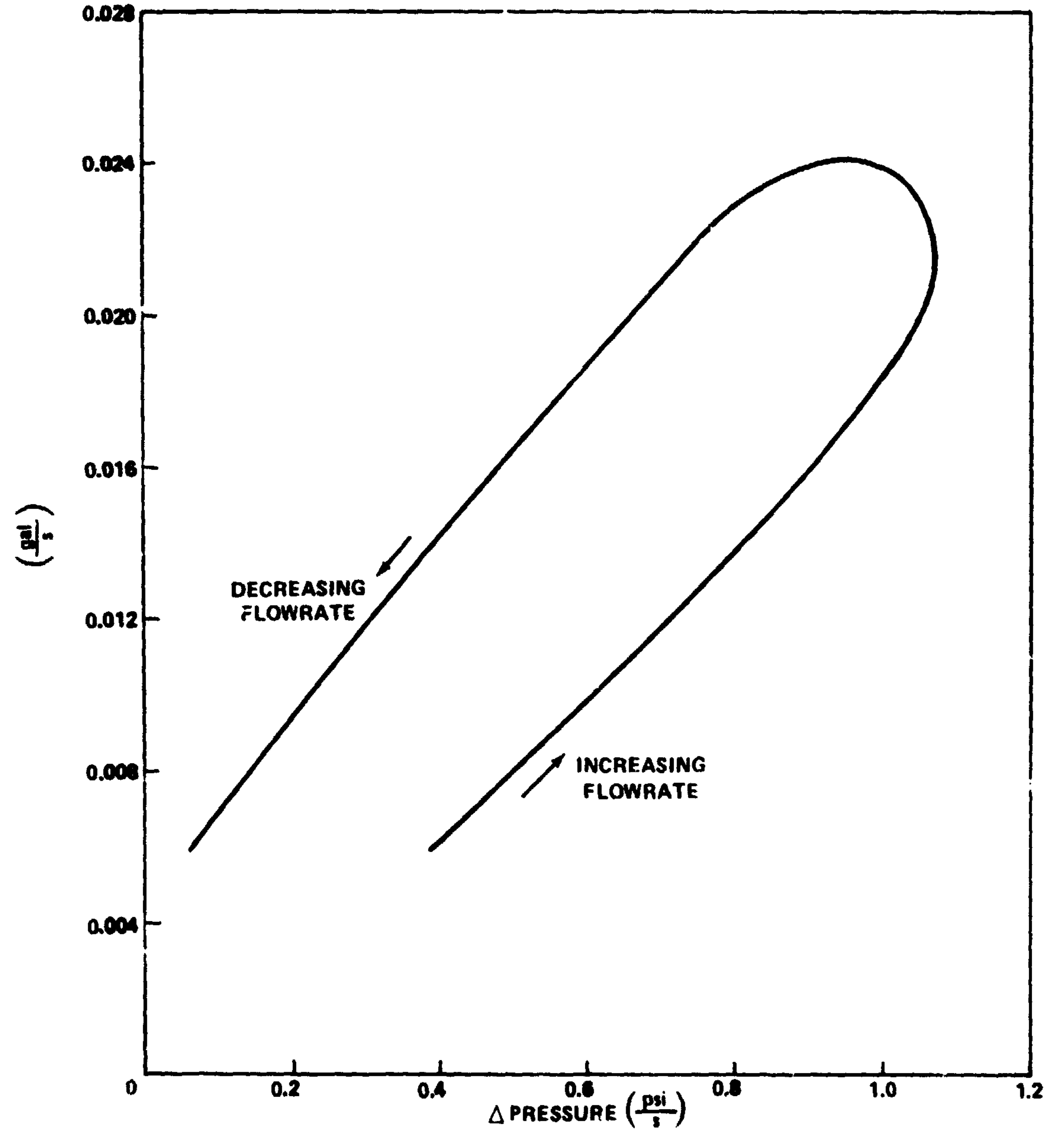


Figure A-4. Curves of gallons of fuel consumed per second versus pressure change per second.

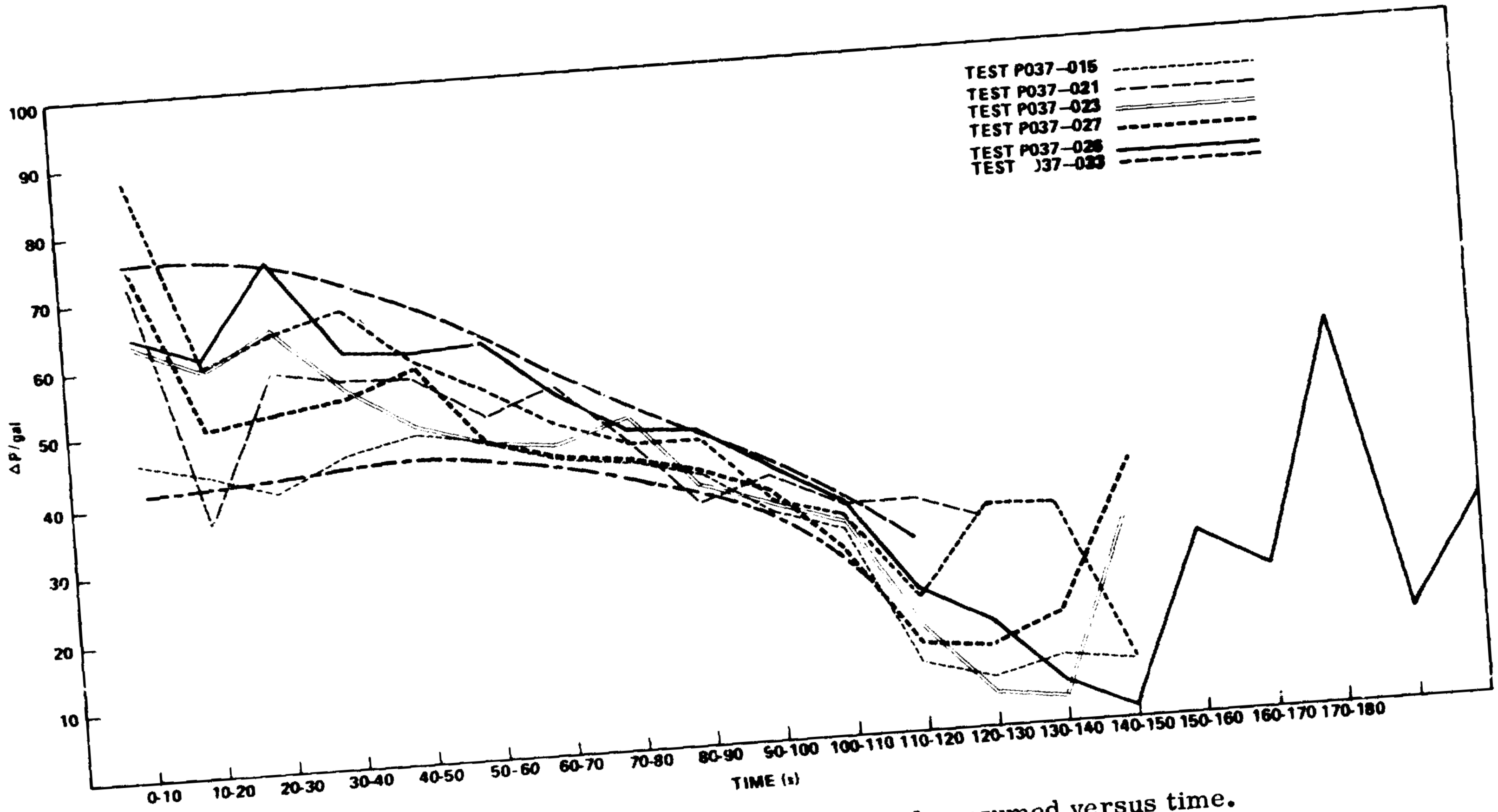


Figure A-5. Change in pressure per gallon of fuel consumed versus time.

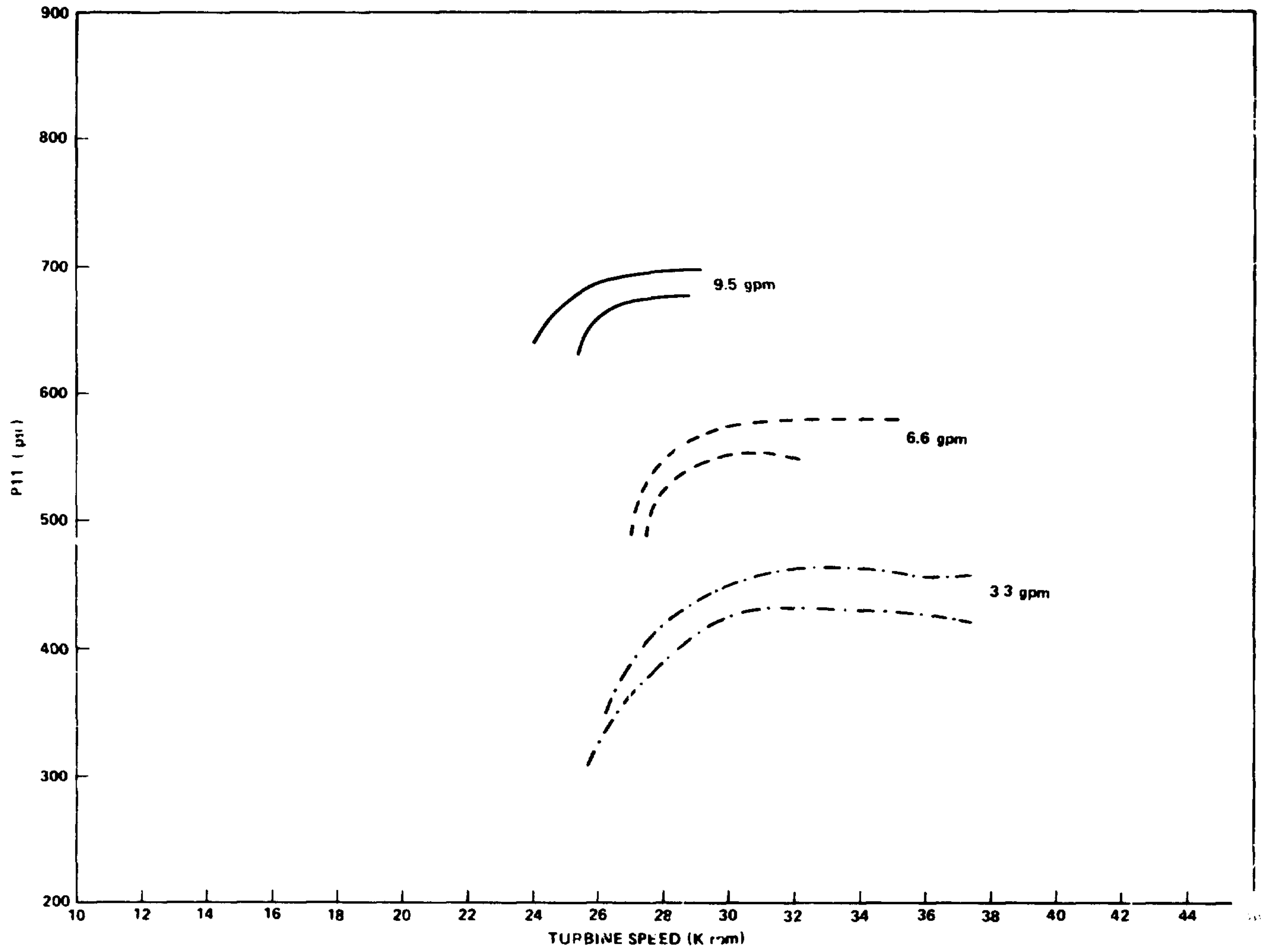


Figure A-6. The relationship between spin pressure and turbine speed for three flowrates.

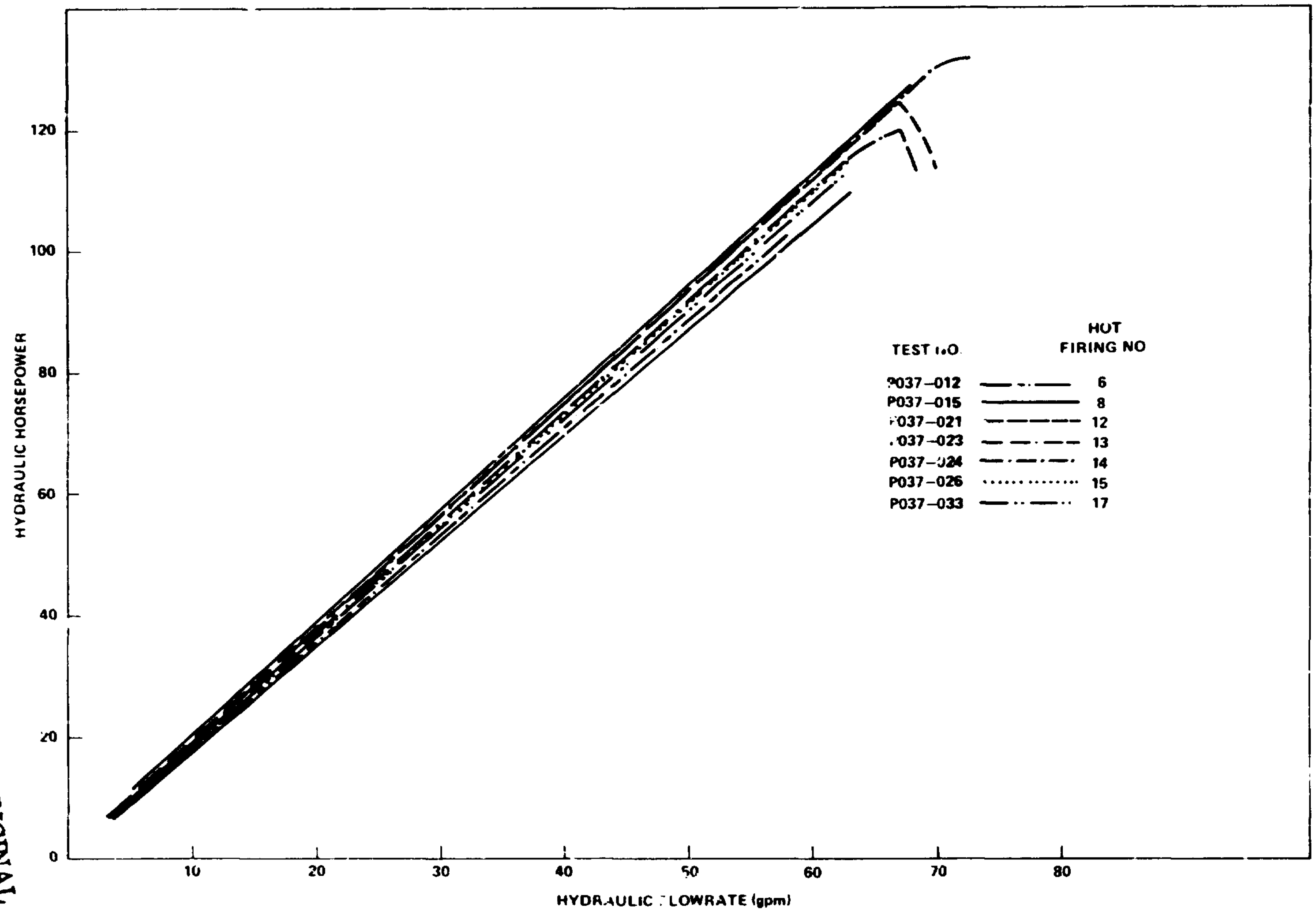


Figure A-7. Hydraulic flowrate versus hydraulic horsepower.

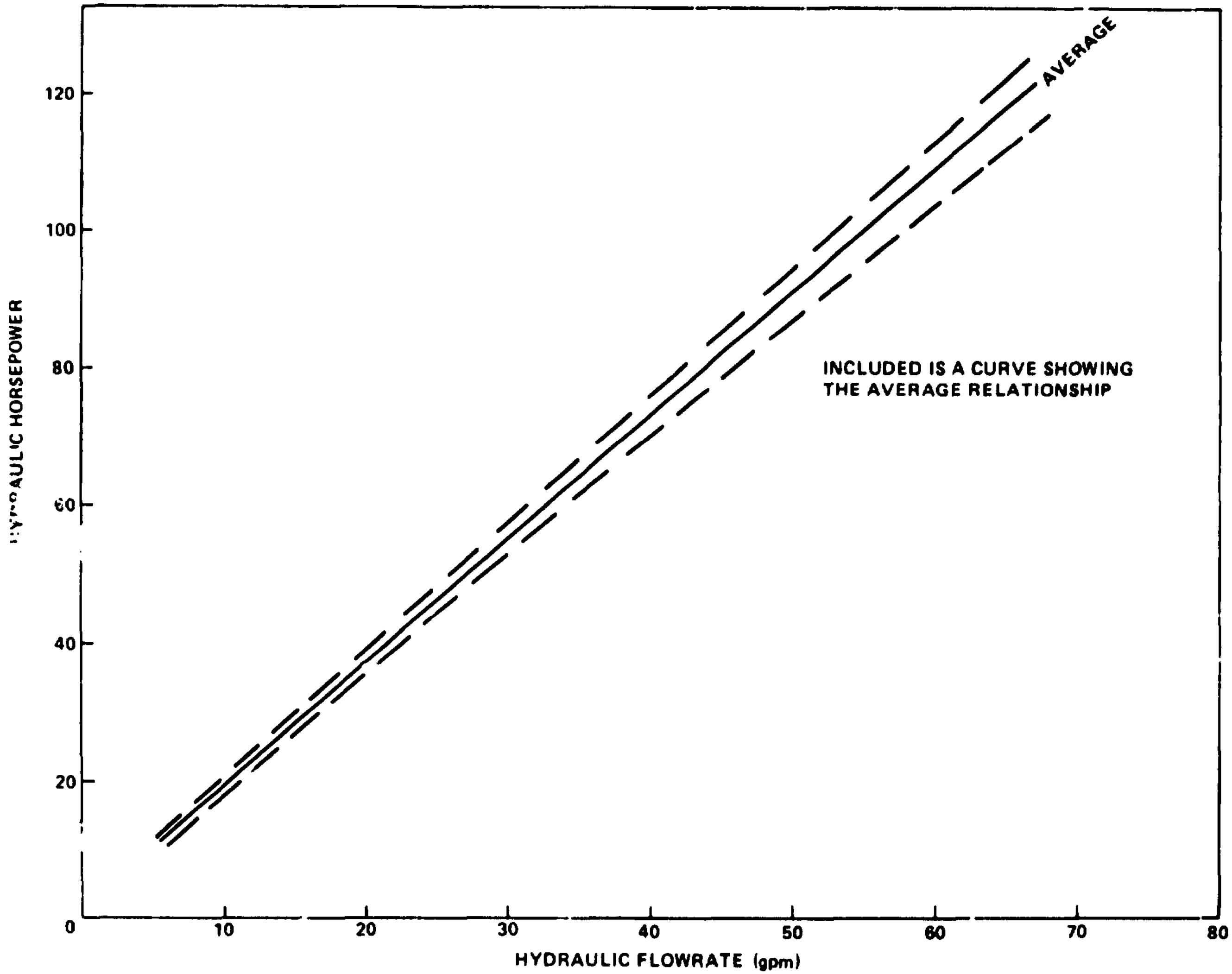


Figure A-8. Band of curves of hydraulic flowrate versus hydraulic horsepower (for curves shown in Fig. A-7).

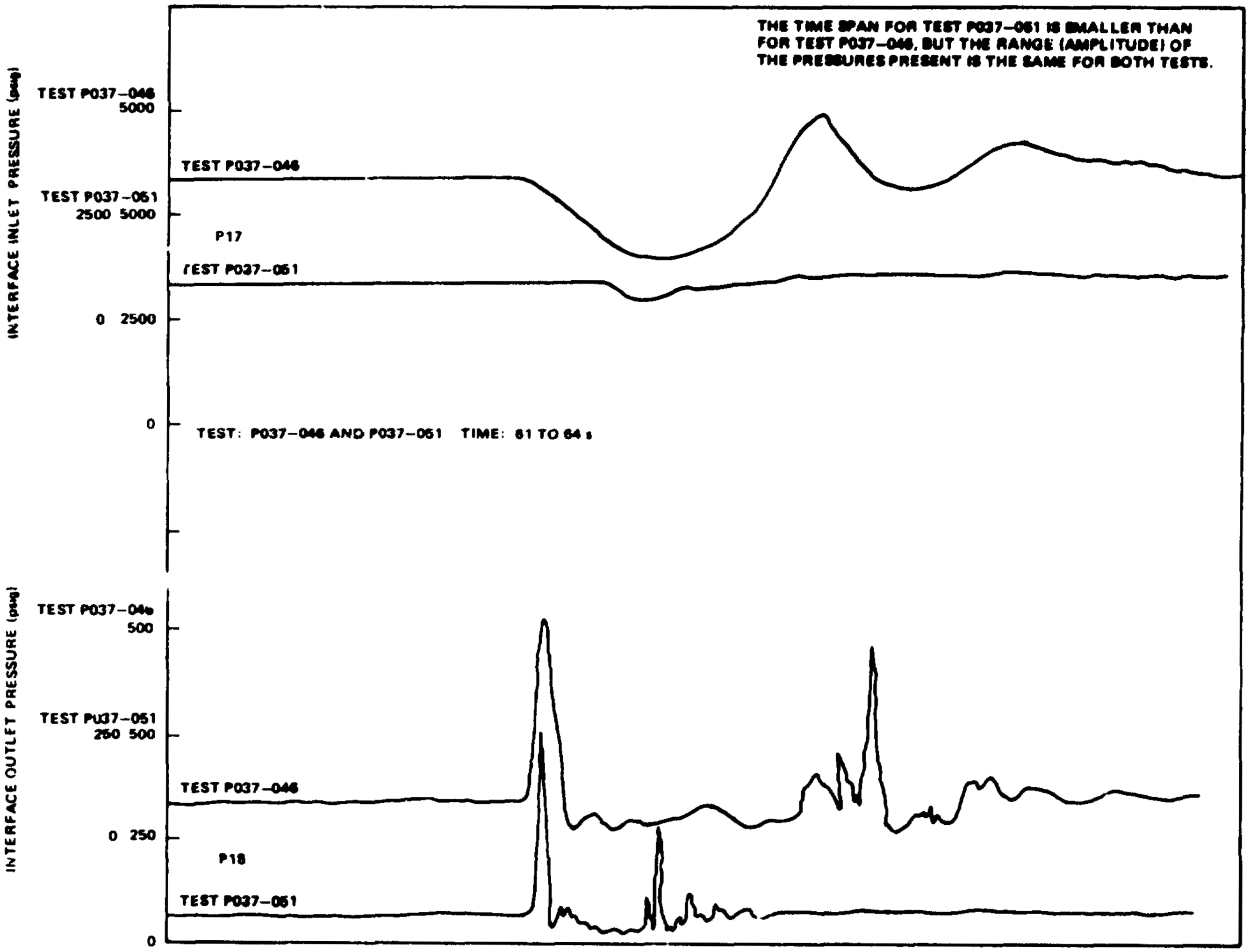


Figure A-9. A comparison of interface inlet and outlet pressures for Tests P037-046 and 051.

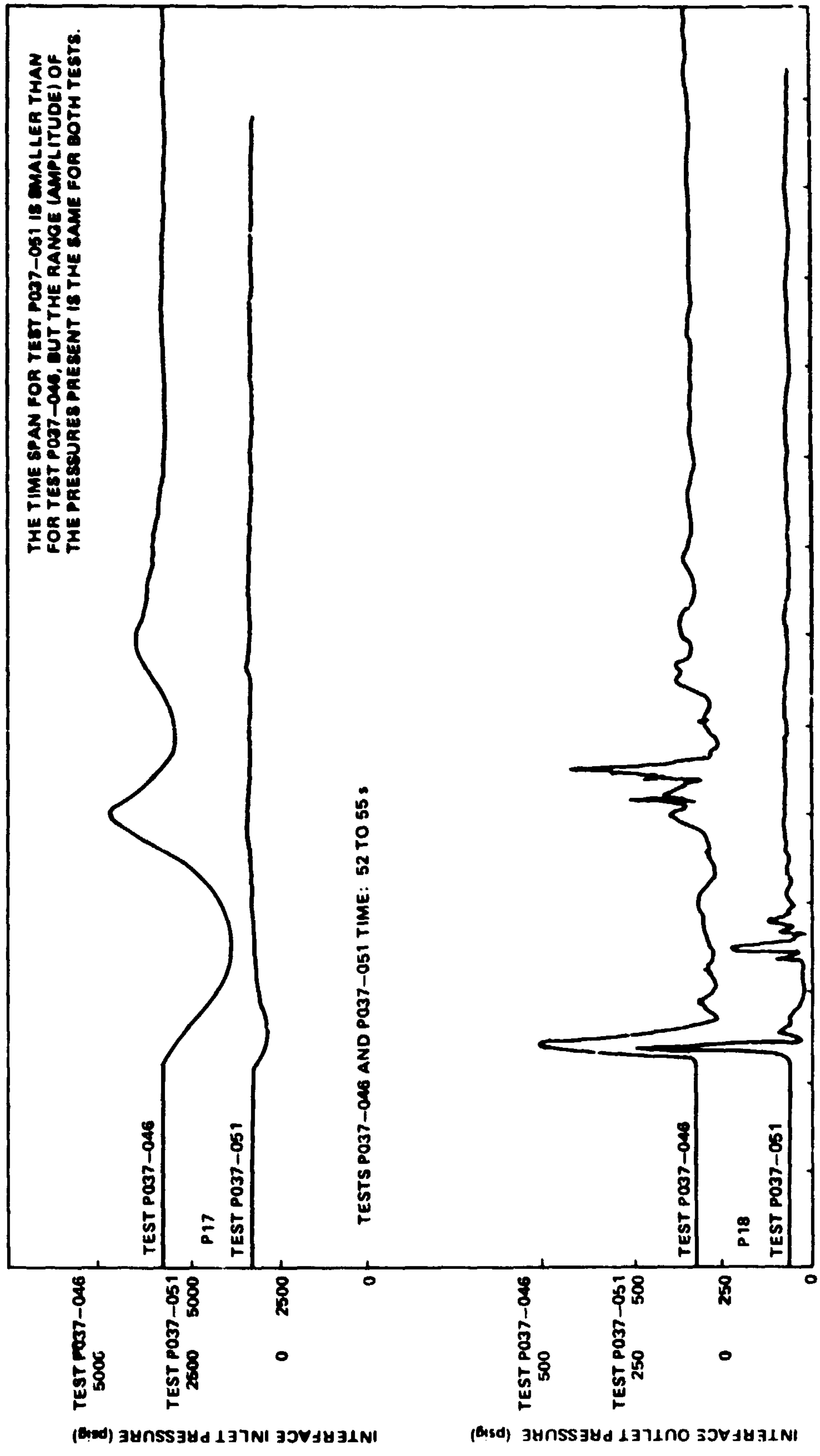


Figure A-10. Comparison of interface inlet and outlet pressures for Tests P037-046 and 051.

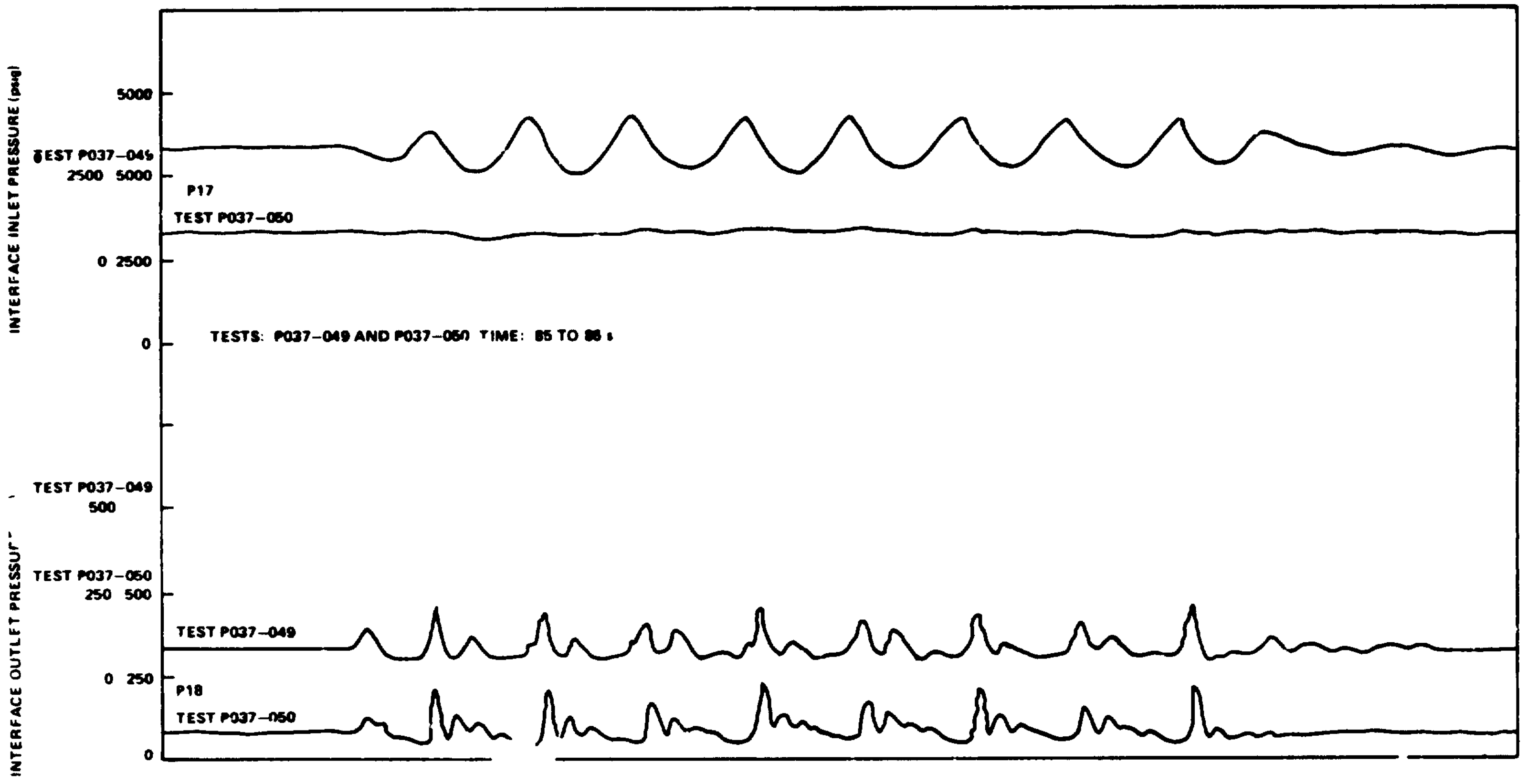


Figure A-11. Comparison of interface inlet and outlet pressures for Test P037-049 and 050.

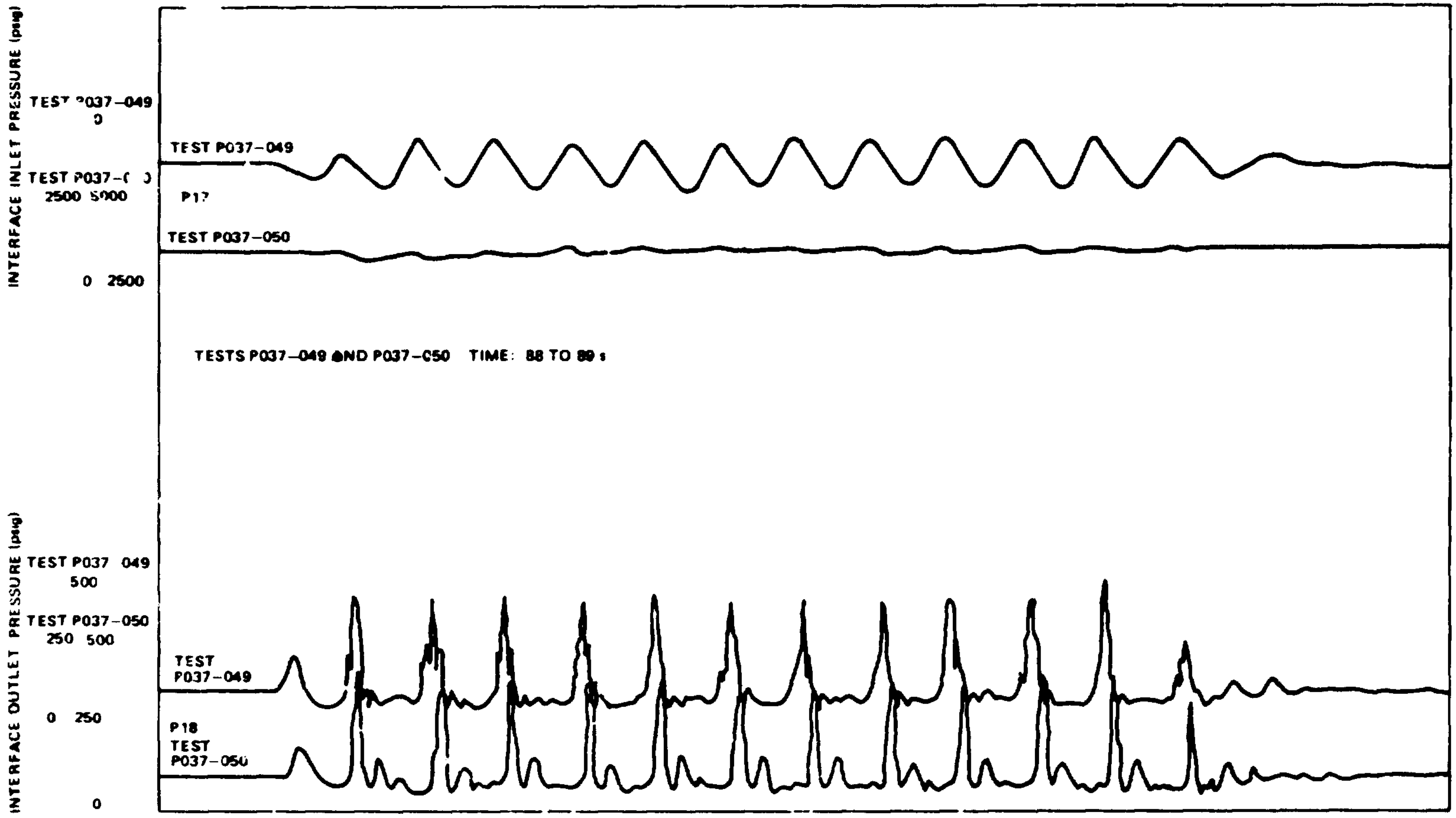


Figure A-12. Comparison of interface inlet and outlet pressures for Test P037-049 and 050.

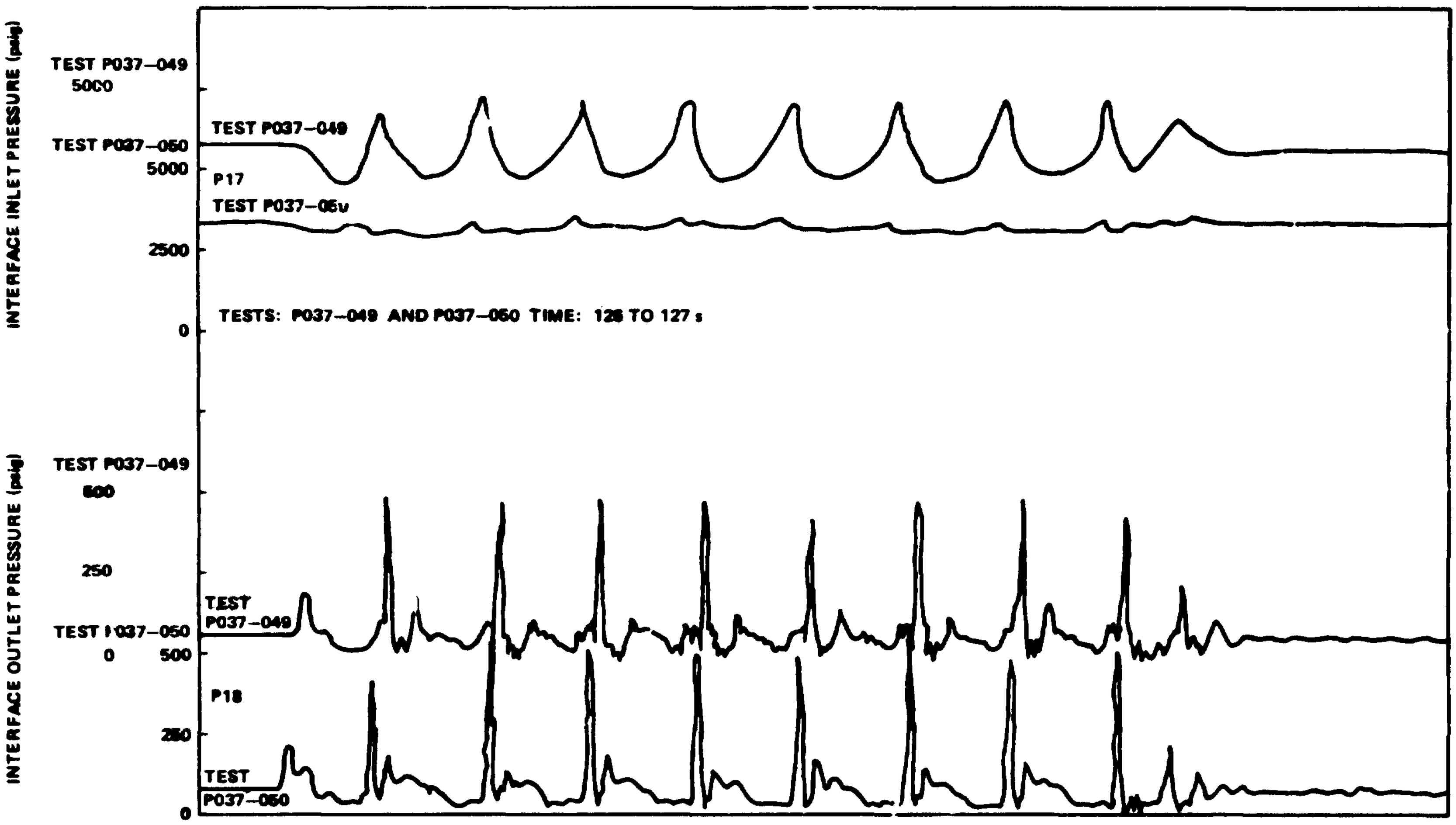


Figure A-13. Comparison of interface inlet and outlet pressures for Test P037-049 and 050.

TABLE A-1. RESULTS OF FUEL CONSUMPTION ANALYSIS

Test No.	gpm	Hydraulic Horsepower	hp-s	Fuel Consumption Rate (lb/hp-h)
P037-021	3.4	6.12	30.58	25.66
	27.1	48.29	193.16	8.10
	60.0	107.71	538.56	6.20
P037-023	3.4	6.08	30.41	34.74
	23.0	40.94	204.72	8.70
	46.7	82.34	411.70	6.82
	58.7	103.97	519.83	6.33
	61.6	110.61	553.06	6.11
	6.4	11.97	59.84	18.16
	3.4	6.20	30.98	27.28
P037-024	3.4	6.03	30.13	29.16
	6.4	11.55	57.73	16.80
	47.1	84.03	420.15	6.70
	59.1	106.84	534.20	6.30
	62.1	112.19	560.95	6.05
	6.4	12.04	60.19	18.63
	3.4	6.31	31.54	28.82
P037-026	3.3	6.20	30.98	28.47
	6.7	12.67	63.36	15.83
	23.7	43.48	217.40	8.53
	23.0	43.76	218.80	8.34
	6.7	11.90	59.48	18.40
	3.4	6.00	59.98	26.35
P037-033	6.7	12.0	59.98	16.23
	23.3	42.24	211.2	8.64
	62.1	108.81	544.0	6.20

TABLE A-2. SUMMARY OF ALL TESTS

Test No.	hp-s	Fuel Consumed (gal)	Average Fuel Consumption Rate (Entire Test)
P037-015	7 082.80	1.94	8.28
P037-021	7 841.68	2.12	8.17
P037-023	8 483.90	2.13	7.59
P037-024	9 159.88	2.23	7.35
P037-026	11 151.78	3.05	8.27
P037-033	9 362.36	2.29	7.40
P037-036	3 892.84	1.20	9.32
P037-039	3 469.03	1.18	10.28

TABLE A-3. MAXIMUM AND MINIMUM POINTS FOR FCR AT A CERTAIN VALUE OF HYDRAULIC HORSEPOWER

Hydraulic Horsepower	Maximum FCR	Minimum FCR
6 (Starting point)	34.74	25.66
10	27.3	18.4
20	17.6	13.0
30	12.9	10.6
40	10.4	8.9
50	8.8	7.7
60	7.7	7.0
70	7.3	6.6
80	7.0	6.4
90	6.7	6.3
100	6.6	6.2
110	6.2	6.1
112 (Final point)	6.0	6.0

TABLE A-4. PRESSURE DECAY (IN THE FUEL TANK)

Test With Pressure Decay	Correlated Test Curve
P037-007	P037-015
P037-009	P037-021
P037-010	P037-023
P037-011	P037-024
P037-012	P037-026
P037-013	P037-033
P037-014	
P037-015	
P037-016	
P037-020	
P037-021	
P037-023	
P037-024	
P037-026	
P037-032	
P037-033	

TABLE A-5. TYPICAL BEHAVIOR AT CONSTANT FLOW CONDITIONS (TEST P037-026)

Time (s)	Hydraulic Flow (gpm)	Hydraulic Horsepower (hp)	Hydraulic Pump Outlet Pressure (psig)			Hydraulic Reservoir Pressure (psig)	Time APU Control Valve Is Open (s)	Time Between APU Control Valve Openings (s)	Maximum Gas Generator Pressure (psig)	Maximum Fuel Pump Discharge Pressure (psig)	Fuel Pump Inlet Pressure (psig)		Pulsations		Fuel Valve Bypass Pressure (psig)		
			Nominal	Low Ripple	High Ripple						Nominal	Ripple	Minimum	Maximum	Nominal	Minimum	Maximum
10-14	3.3	6.21	3166	450	1050	74	0.193	1.008	1100	1230	430	12.5	342.5	595	400	287.5	650
20-24	6.7	12.61	3170	500	1100	75	0.199	0.899	1100	1250	425	12.5	335	592.5	400	280	625
30-34	23.7	43.92	3157	500	1100	74	0.273	0.645	1125	1275	420	12.5	330	545	375	275	625
40-44	47.1	85.93	3137	625	1150	73	0.549	0.782	1140	1250	405	12.5	314	570	375	250	612.5
50-54	59.3	108.20	3137	700	1317.5	72.5	1.243	1.437	1140	1300	392.5	12.5	305	555	350	225	590
110-114	23	44.63	3174	550	1200	74	0.278	0.648	1125	1280	335	12.5	262.5	495	300	187.5	560
120-124	6.7	13.10	3192	300	1050	74	0.200	0.903	1110	1250	335	12.5	265	480	300	187.5	545
146-150	3.4	6.63	3209	500	1130	74.5	0.191	1.015	1080	1230	330	10	260	475	300	187.5	532.5
156-160	6.7	13.19	3208	500	1110	75	0.203	0.866	1100	1240	330	10	255	470	300	187.5	540

TABLE A-6. ACTUATOR DISPLACEMENT ANALYSIS — HOT FIRINGS WITH ACTUATOR (UNLOADED)

Test No.	Duration (s)	Signal	Accumulator	Fuel Consumed (gal)
P037-046	146	Step	Without	1.05
P037-049	146.5	Sine	Without	1.10
P037-050	146.5	Sine	With	1.00
P037-051	110	Step	With	0.74
Total	549			3.89

TABLE A-7. ACTUATOR TEST P037-046

Starting Points — P17 = 0 and P18 = 0 | Total Actuator Movement — 79.9 in.

P17		P18		Piston Displacement			
Maximum	Minimum	Maximum	Minimum	Amplitude (in.)	Period (s)	Slew Rate (in./s)	Time (s)
				0.1	4	0.727	13-18
3575	3150	115	60				13-14
4000	2800	200	45				15-16
3550	3125	115	65				17-18
				0.1	4	0.727	23-27
3925	2850	190	45				24-25
3550	3150	115	70				26-27
				0.2	4	1.333	32-36
4175	2800	240	35				32-33
*4450	1750	380	20				34-35
*4450	2250	365	5				35-36
				0.2	4	1.333	41-45
4150	2750	235	25				41-42
4425	1700	380	15				43-44
*4450	2250	365	5				45-46
				0.8	4	3.2	50-55
4425	1875	385	10				50-51
4200	1200	560	0				52-53
*4800	1375	515	0				54-55
				0.8	4	3.2	59-64
*4450	1825	400	5				59-60
4200	1075	570	5				61-62
*4800	1350	525	5				63-64
				1.9	4	5.429	68-73
4350	1175	585	0				68-69
4300	1075	660	0				70-71
4300	1150	650	0				72-73
				1.9	4	5.429	77-82
4325	1125	570	0				77-78
4300	1050	655	-10				79-80
4300	1175	650	0				81-82
				3.775	4	6.292	86-91
4325	1075	655	-10				86-87
4300	1075	655	-10				88-89
4250	1100	655	-10				90-91
				3.775	4	6.292	95-100
4350	1075	655	-10				95-96
4300	1075	655	- 5				97-98
4200	1150	660	-10				99-100
				5.6	6	6.222	104-111
4350	1000	660	- 5				104-105
4300	1075	655	-10				106-107
4325	1100	660	- 5				108-109
4325	1175	655	-10				110-111
				5.6	6	6.222	112-119
4350	1150	655	- 5				112-113
4300	1075	655	- 5				114-115
4325	1150	660	- 5				116-117
4325	1150	655	- 5				118-119
				7.6	6	6.333	120-127
*4450	1175	660	-10				120-121
4325	1150	655	- 5				122-123
4350	1175	660	- 5				124-125
4325	1175	655	- 5				126-127
				7.6	6	6.333	128-135
4350	1150	660	-10				128-129
4300	1150	655	- 5				130-131
4425	1175	660	-10				132-133
4300	1250	660	- 5				134-135

Note: One cycle used for each signal

* Points of interest

TABLE A-8. ACTUATOR TEST P037-049

Starting Points — P17 = 0 and P18 = 0					Total Actuator Movement — 56.86 in.			
P17		P18		Piston Displacement				Time (s)
Maximum	Minimum	Maximum	Minimum	Amplitude (in.)	Frequency (cps)	Cycles	Slew Rate (in./s)	
—	—	—	—	0.2	0.2	1	0.08	12-18
—	—	—	—	0.2	0.5	2	0.2	23-27
—	—	—	—	0.2	1	4	0.4	29-33
3425	3050	70	50	0.2	2	4	0.8	34-37
•3750	2950	120	50	0.16	4	4	1.28	38-40
•3675	2900	185	30	0.11	6	6	1.32	41-42
3450	3050	320	10	0.1	8	8	1.6	44-45
3500	3000	215	25	0.08	10	10	1.6	47-48
3350	3150	165	10	0.07	12	12	1.68	50-51
3350	3200	175	25	0.06	14	14	1.68	53-54
—	—	—	—	0.4	0.2	1	0.16	56-61
—	—	—	—	0.4	0.5	2	0.4	68-72
3425	3300	80	70	0.38	1	4	0.76	75-79
3500	3050	95	70	0.35	2	4	1.4	81-84
•4325	2500	210	55	0.3	4	4	2.4	85-86
•3950	2575	340	25	0.2	6	6	2.4	88-89
•3675	2950	415	15	0.14	8	8	2.24	91-92
•3700	2950	325	20	0.10	10	10	2	94-95
—	—	—	—	0.95	0.2	1	0.38	100-105
3300	3200	80	70	0.95	0.5	2	0.95	109-113
3425	3150	80	60	0.95	0.1	4	1.9	116-120
•3700	2675	135	40	0.85	2	4	3.4	122-125
4700	2250	400	30	0.59	4	4	4.72	126-127
—	—	—	—	0.3	(Period 4 s)	1	2.0	130-134
—	—	—	—	0.3	(Period 4 s)	1	2.0	139-144

* Points of interest

TABLE A-9. ACTUATOR TEST P037-050

Starting Points — P17 = 0 and P18 = 0						Total Actuator Movement — 54.02 in.		
P17		P18		Piston Displacement				Time (s)
Maximum	Minimum	Maximum	Minimum	Amplitude (in.)	Frequency (cps)	Cycles	Slew Rate (in./s)	
—	—	—	—	0.2	0.2	1	0.08	11-16
—	—	—	—	0.21	0.5	2	0.21	23-27
—	—	—	—	0.2	1	4	0.4	29-33
3350	3250	85	70	0.2	2	4	0.8	34-36
3375	3250	125	55	0.14	4	4	1.12	38-39
3300	3200	195	50	0.11	6	6	1.32	41-42
3375	3250	225	45	0.09	8	8	1.44	44-45
3300	3200	335	55	0.06	10	10	1.2	47-48
3375	3250	275	20	0.05	12	12	1.2	50-51
3400	3200	255	20	0.05	14	14	1.4	53-54
—	—	—	—	0.35	0.2	1	0.14	56-62
—	—	—	—	0.38	0.5	2	0.38	68-72
3350	3250	85	75	0.36	1	4	0.72	74-79
3400	3250	85	60	0.33	2	4	1.32	81-83
3300	3200	225	45	0.27	4	4	2.16	85-86
3375	3250	375	40	0.20	6	6	2.4	88-89
3325	3125	500	10	0.15	8	8	2.4	91-92
3400	3050	435	10	0.12	10	10	2.4	94-95
—	—	—	—	0.92	0.2	1	0.368	98-103
3325	3250	90	80	0.92	0.5	2	0.92	109-113
3500	3125	95	75	0.88	1	4	1.76	115-120
*3325	3175	235	50	0.82	2	4	3.28	122-125
*3425	3200	580	35	0.57	4	4	4.56	126-127
—	—	—	—	0.28	(4 s)	1	1.87	130-134
—	—	—	—	0.33	(4 s)	1	1.87	139-143

* Point of Interest

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TABLE A-10. ACTUATOR TEST P037-051

Starting Points — P17 = 0 and P18 = 5				Total Movement Actuator — 26.9 in.			
P17		P18		Piston Displacement			Time (s)
Maximum	Minimum	Maximum	Minimum	Amplitude (in.)	Period (s)	Slew Rate (in./s)	
				0.2	4	1.2308	13-18
3400	3200	135	60				13-14
3400	3175	220	50				15-16
3400	3200	130	60				17-18
				0.2	4	1.2308	24-27
3400	3150	205	45				24-25
3350	3200	120	55				26-27
				0.4	4	2.1333	29-34
3350	3125	225	20				29-30
•3350	2950	360	25				31-32
•3350	3050	360	5				33-34
				0.4	4	2.2857	40-45
3350	3150	220	20				40-41
3350	2950	370	30				42-43
•3350	3050	360	10				44-45
				0.85	4	3.7778	47-52
3350	3000	365	15				47-48
3500	2750	555	15				49-50
•3425	2850	510	10				51-52
				0.9	4	4	58-63
3350	3000	370	15				58-59
3500	2750	560	10				60-61
•3425	2900	515	5				62-63
				1.75	4	5.3846	67-72
3500	2800	550	15				67-68
3550	2750	650	- 5				69-70
3500	2750	650	- 5				71-72
				1.75	4	5.3846	76-81
3500	2800	555	5				76-77
3550	2750	650	-10				78-79
3500	2800	650	0				80-81
				3.5	4	6.3636	85-90
3500	2700	650	-20				85-86
3550	[illegible]	650	-10				88-89
3500	2750	650	-10				89-90
				3.5	4	6.3636	94-99
3500	2750	650	-25				94-95
3525	2750	650	-20				97-98
3500	2750	650	-20				98-99

Note: One cycle used for each signal

• Points of interest

APPENDIX B

ADDITIONAL HOT FIRING FLOWRATE DATA

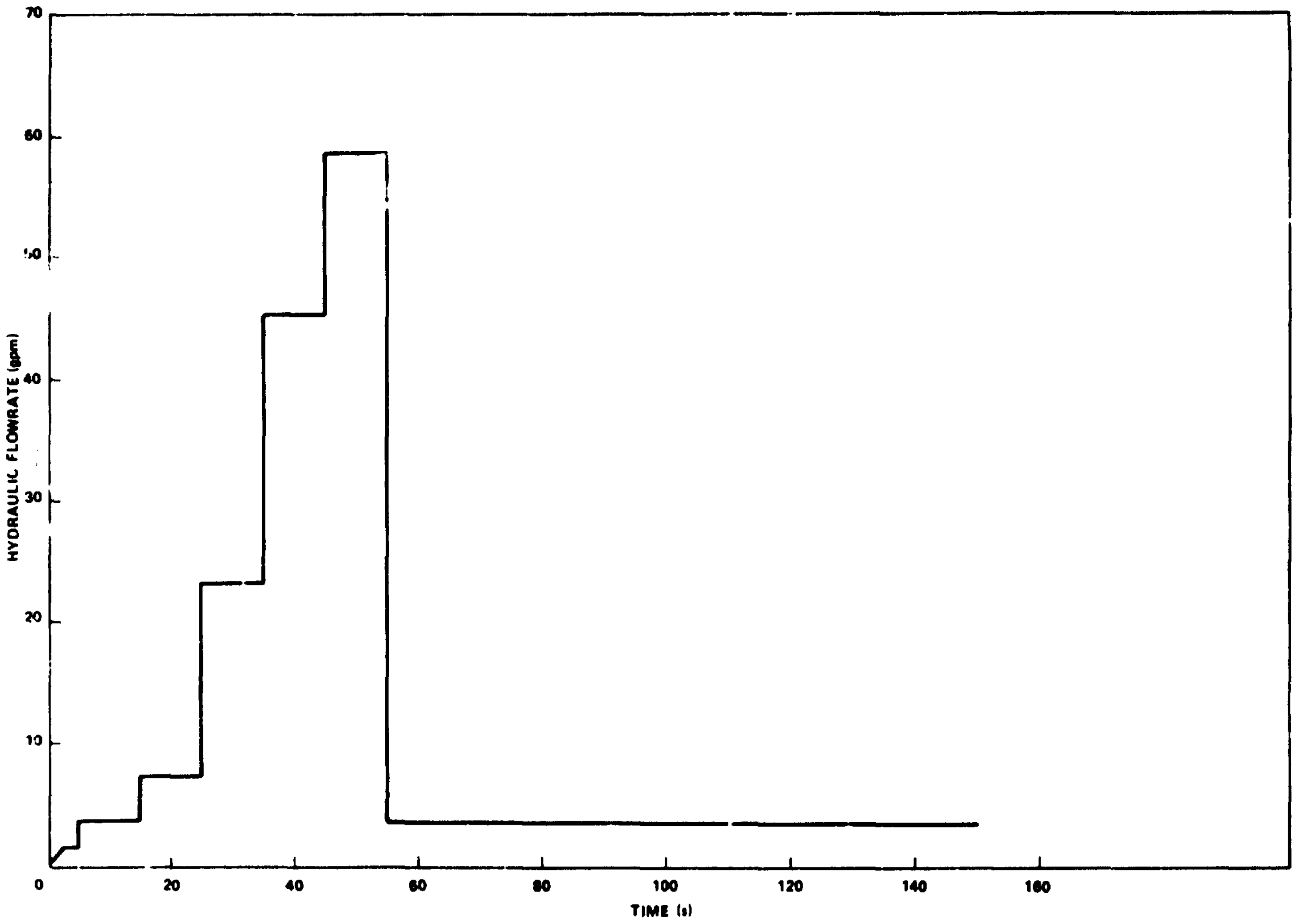

Figure B-1. Hydraulic flowrate for Test P037-010 (APU hot firing No. 4, July 27, 1976).

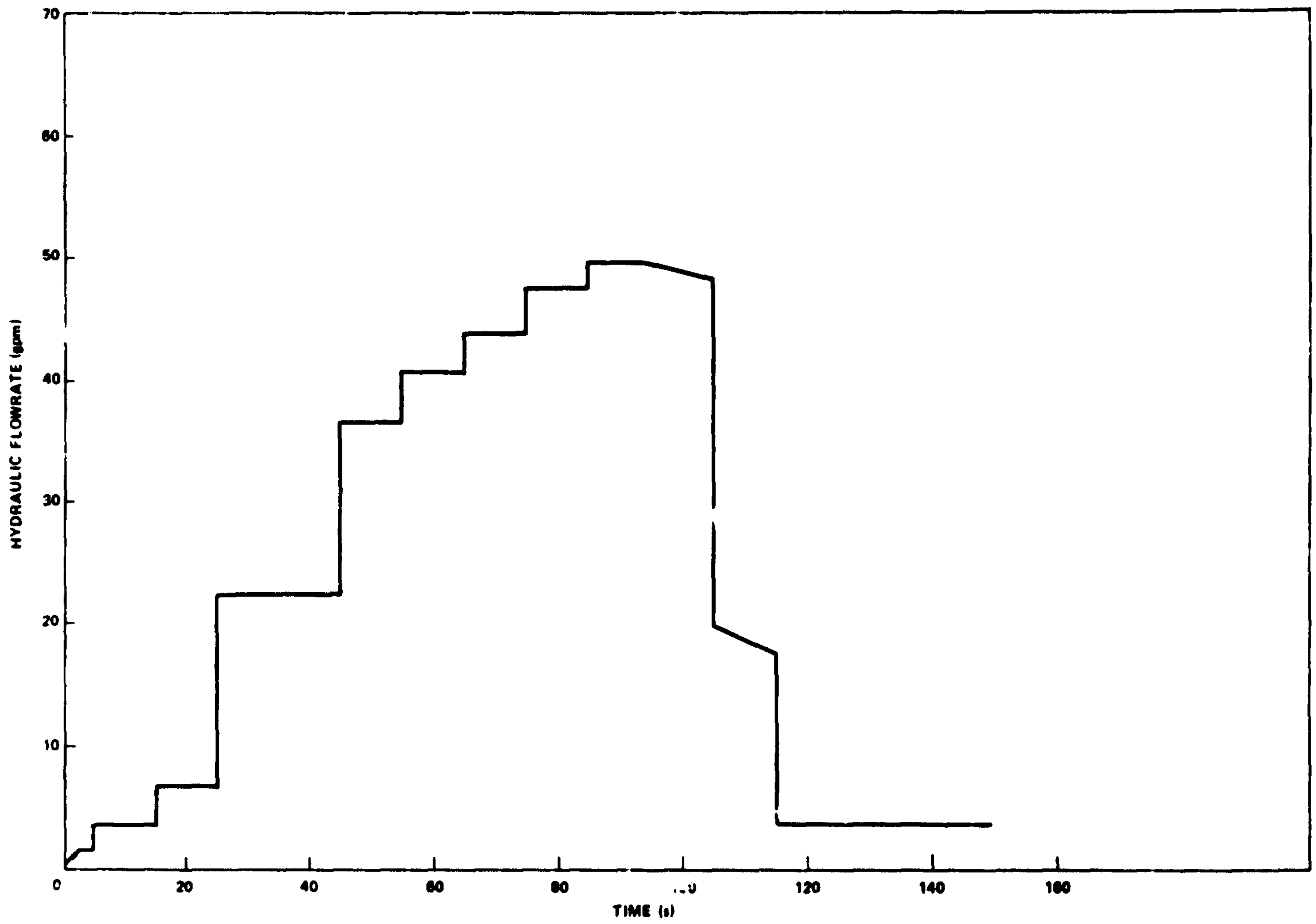

Figure B-2. Hydraulic flowrate for Test P037-011 (APU hot firing No. 5, July 29, 1976).

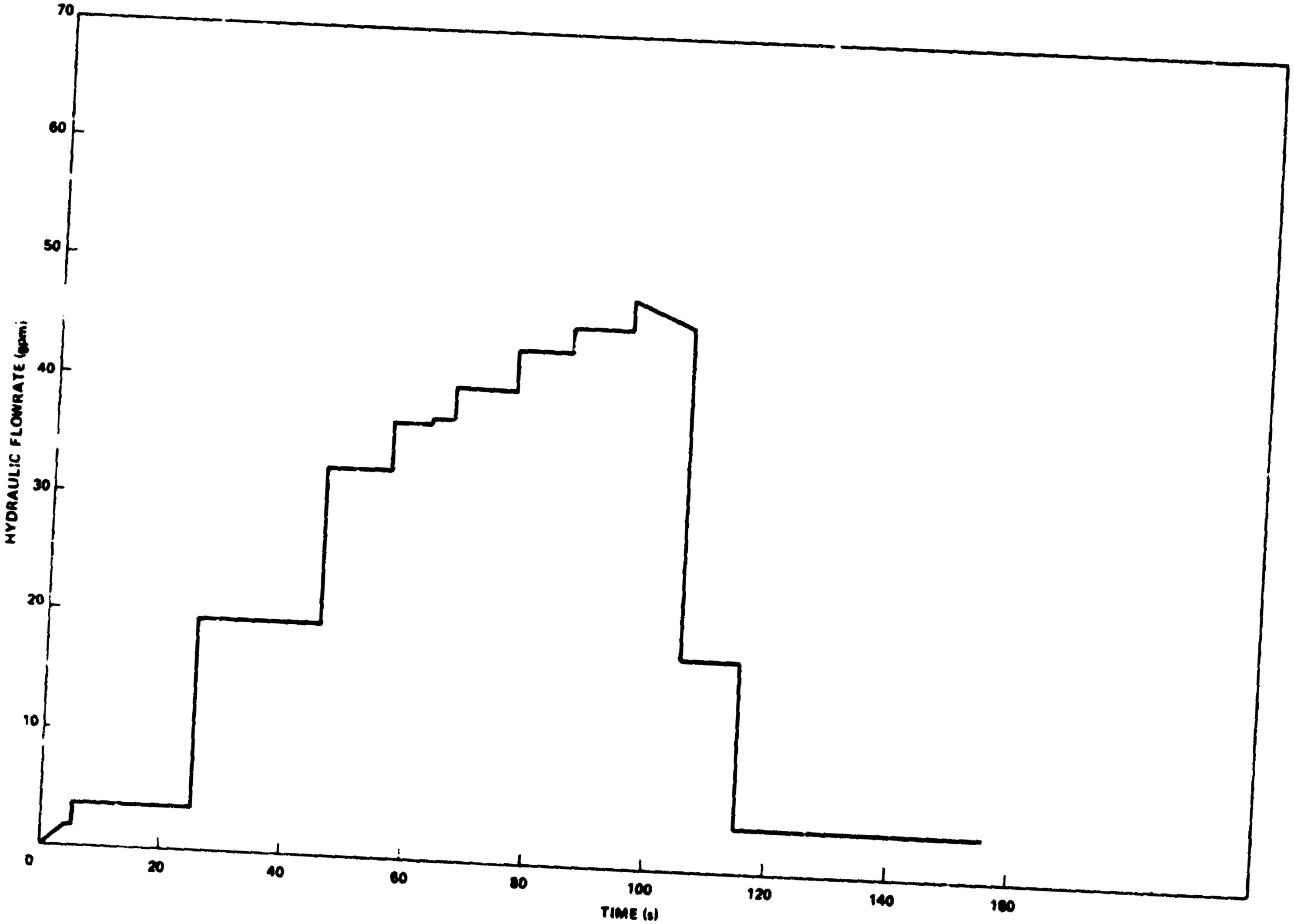

Figure B-3. Hydraulic flowrate for Test P037-012 (APU hot firing No. 6, July 30, 1976).

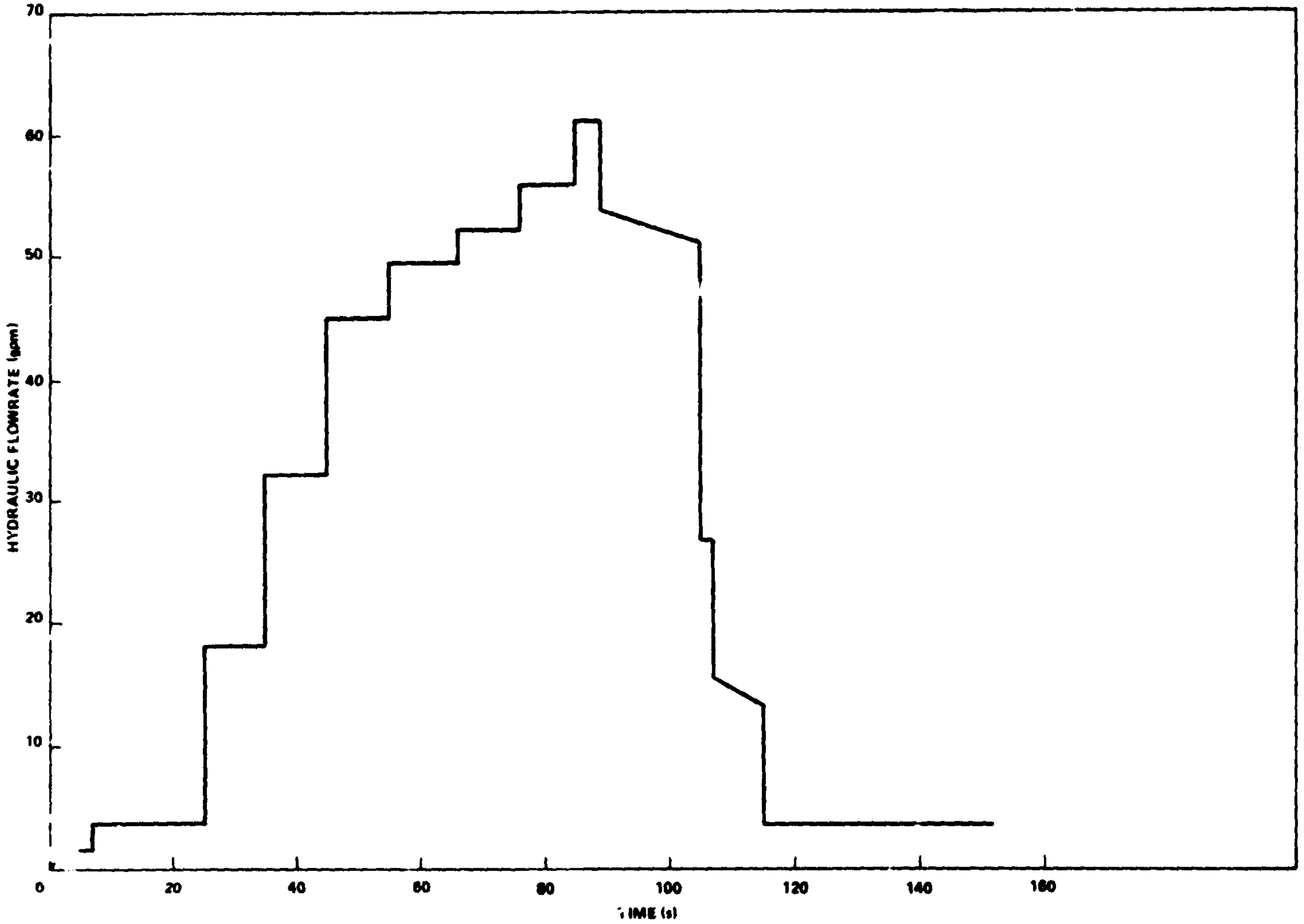

Figure B-4. Hydraulic flowrate for Test P037-015 (APU hot firing No. 8, August 4, 1976).

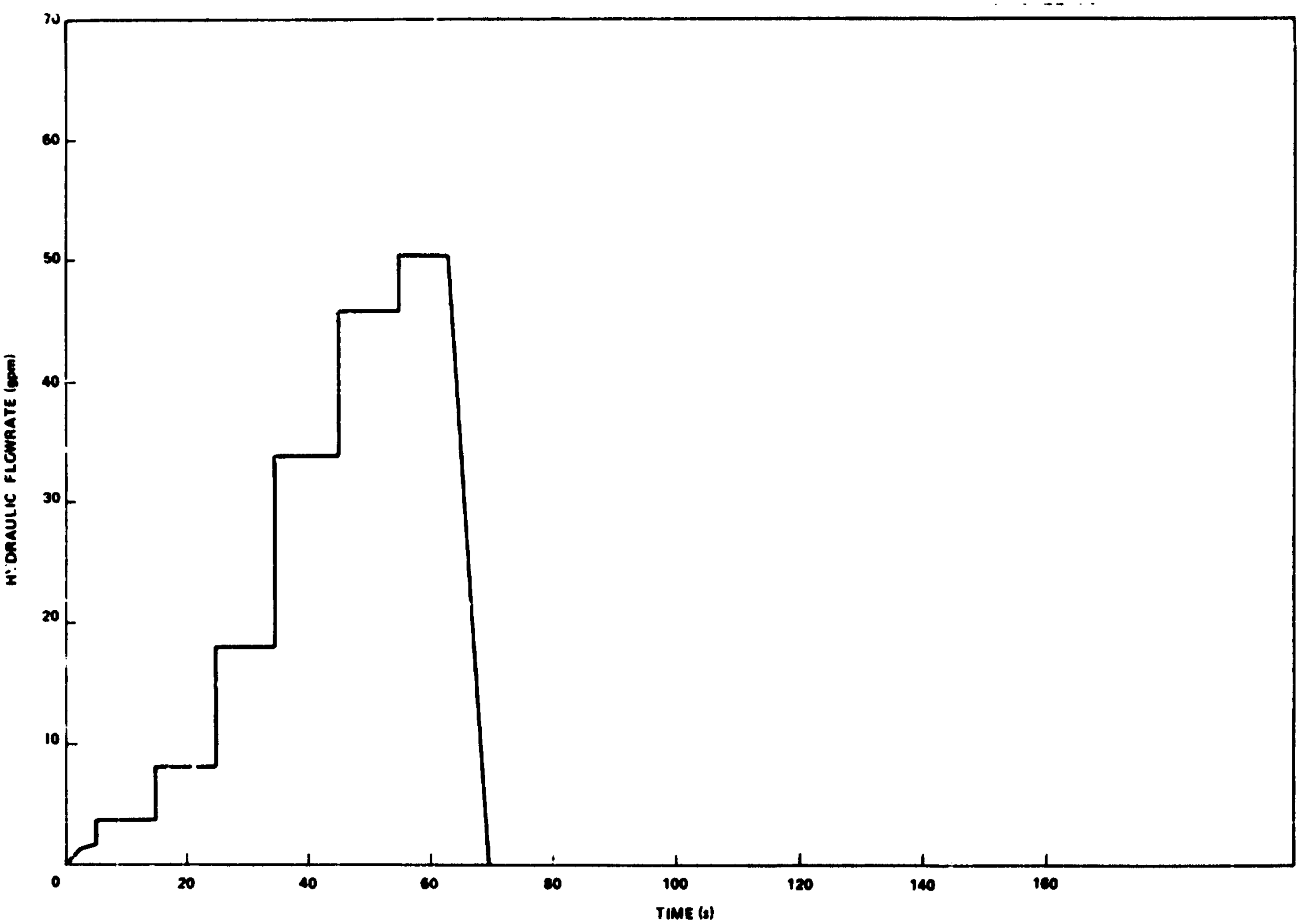

Figure B-5. Hydraulic flowrate for Test P037-016 (APU hot firing No. 10, August 11, 1976).

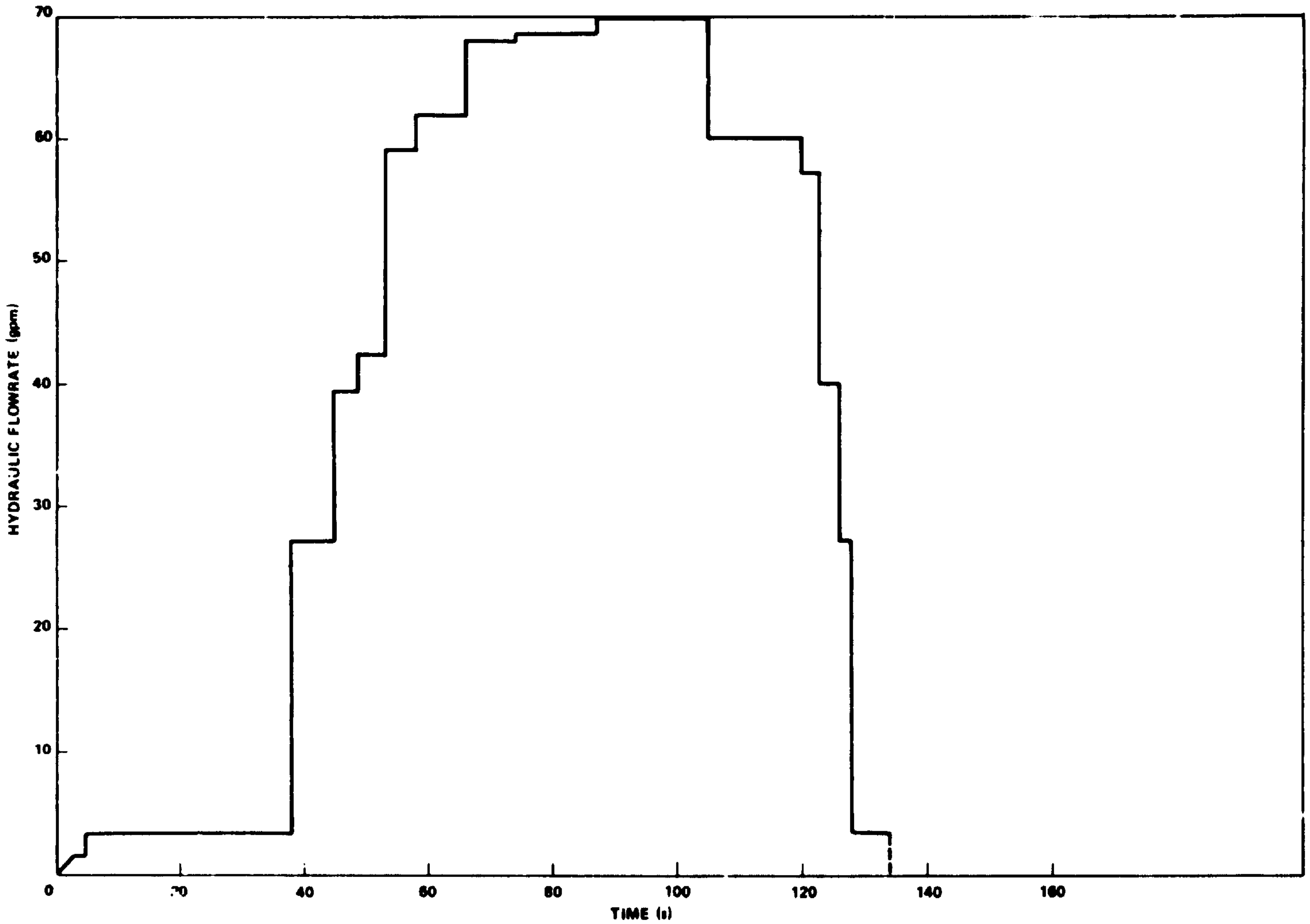

Figure B-6. Hydraulic flowrate for Test P037-021 (APU hot firing No. 12, September 9, 1976).

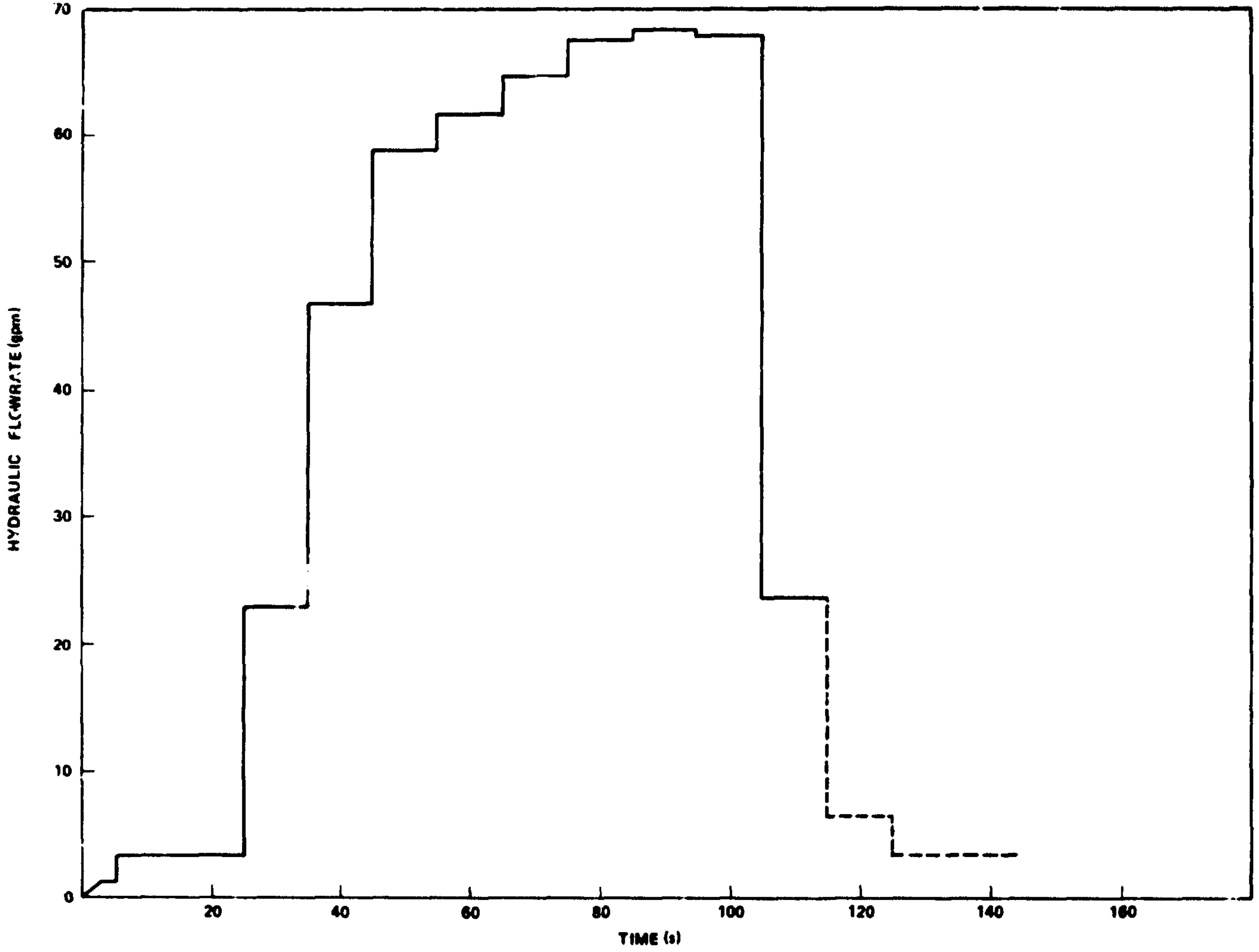

Figure B-7. Hydraulic flowrate for Test P037-023 (APU hot firing No. 13, September 14, 1976).

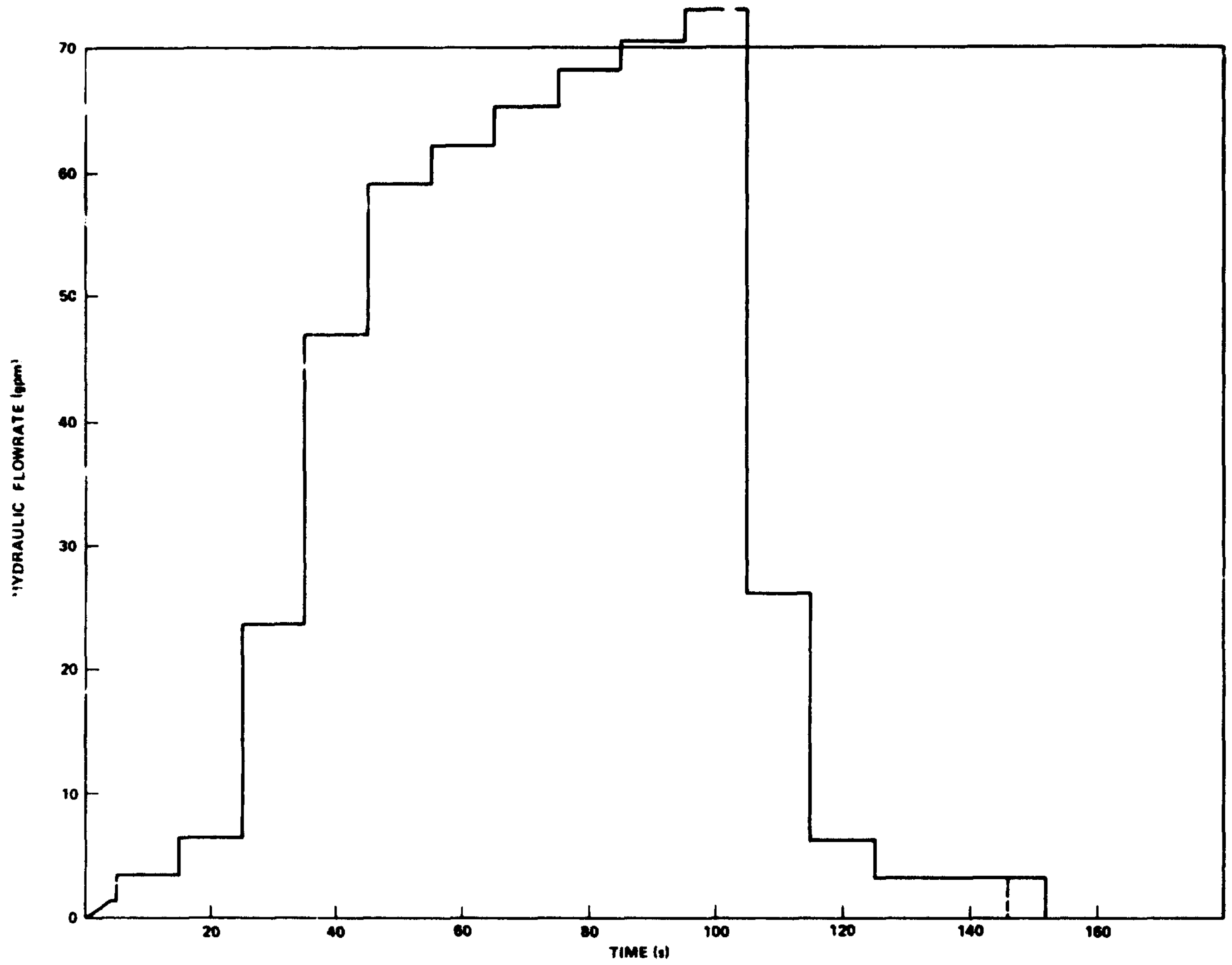

Figure B-8. Hydraulic flowrate for Test P037-024 (APU hot firing No. 14, September 17, 1976).

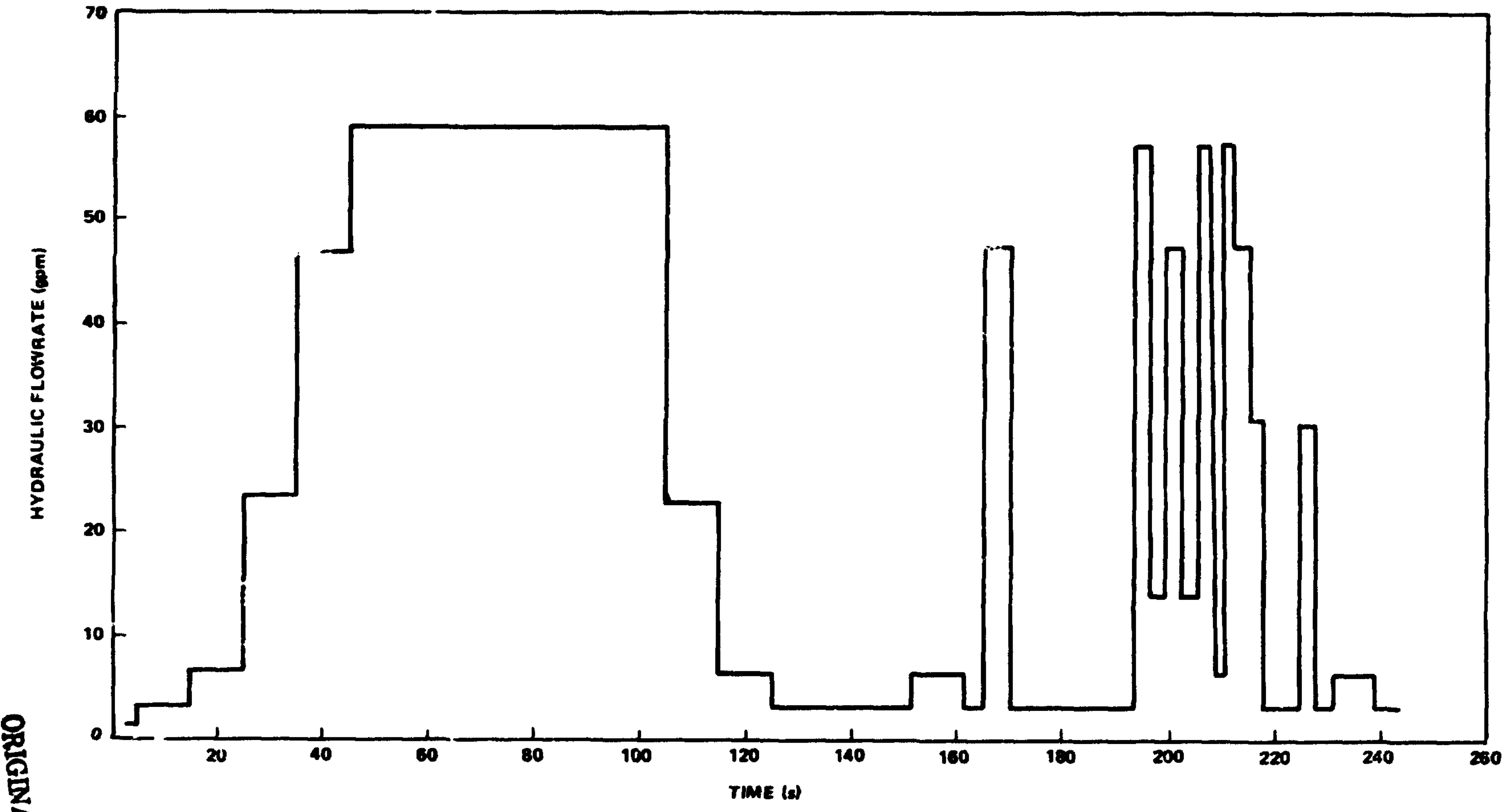

Figure B-9. Hydraulic flowrate for Test P037-026 (APU hot firing No. 15, September 23, 1976).

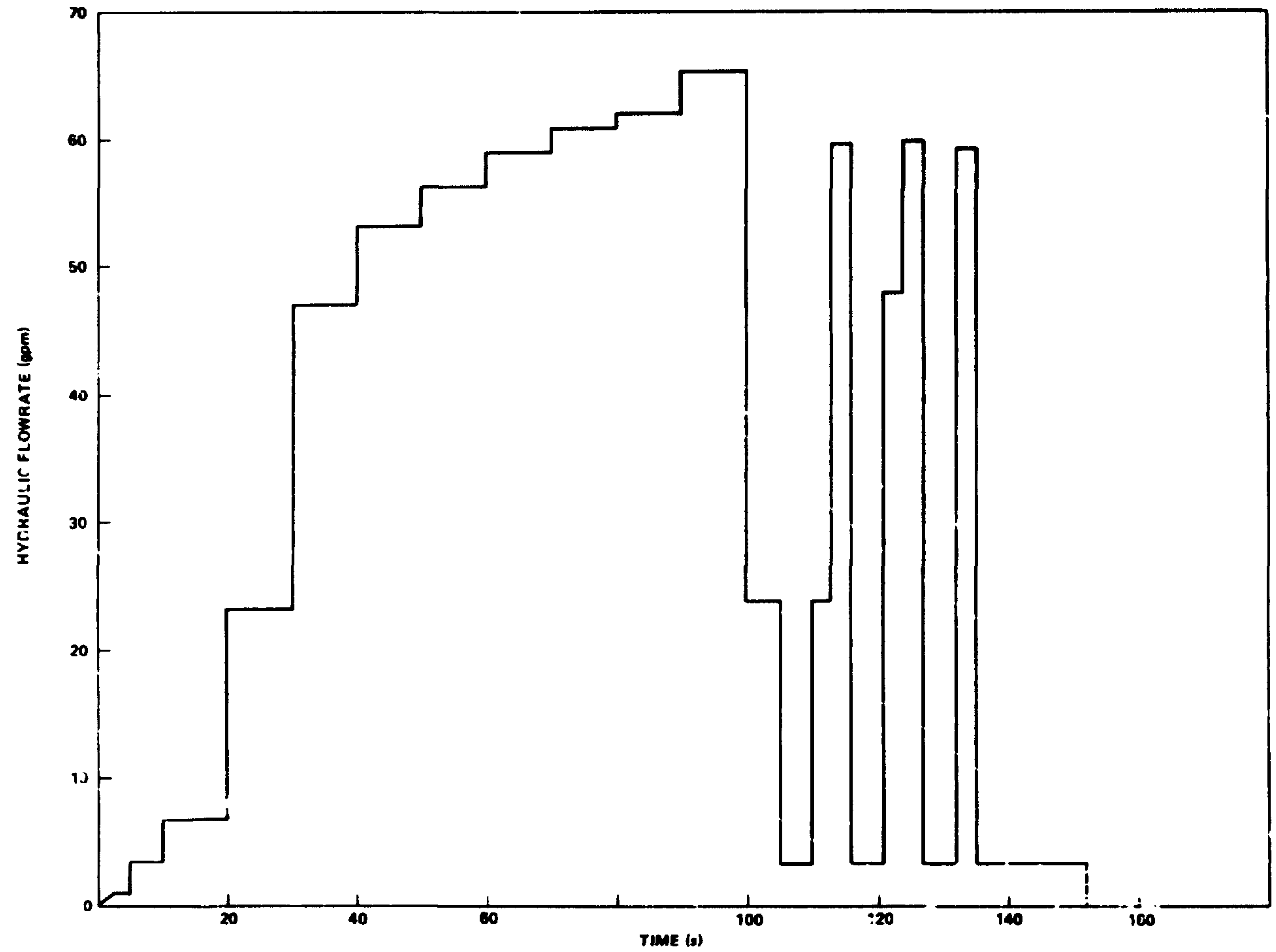

Figure B-10. Hydraulic flowrate for Test P037-033 (APU hot firing No. 17, October 1, 1976).

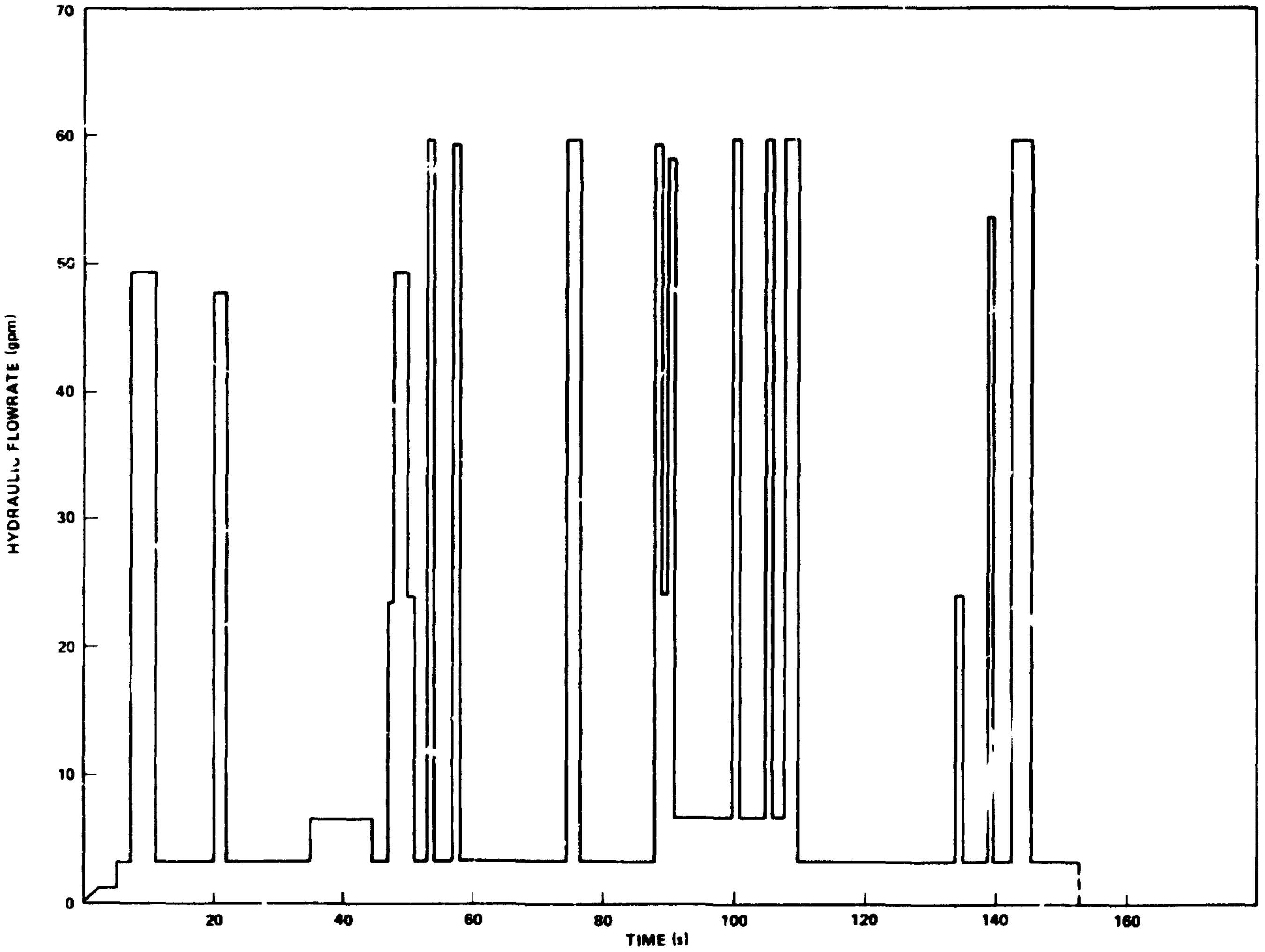

Figure B-11. Hydraulic flowrate for Test P037-036 (APU hot firing No. 18, October 6, 1976).

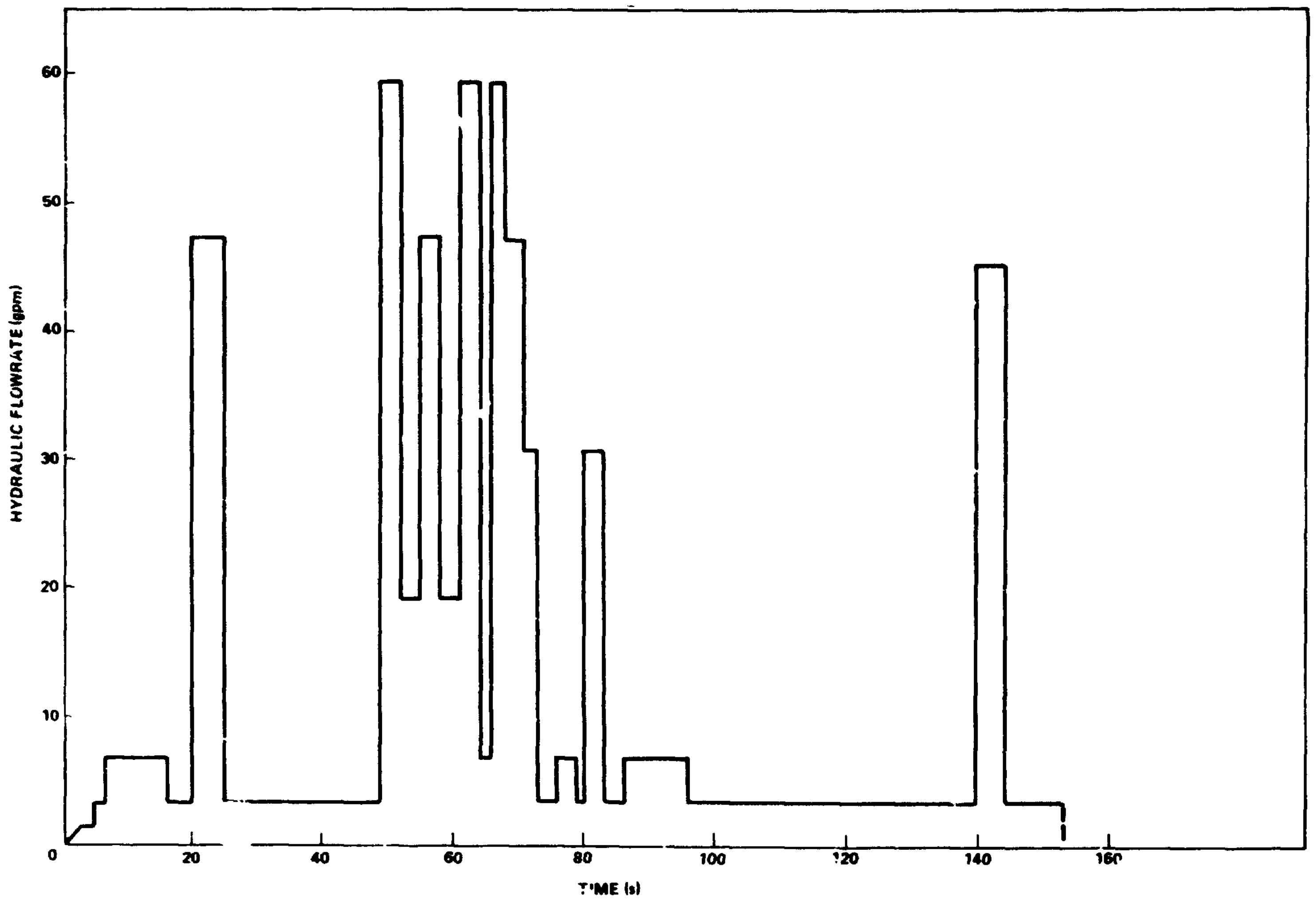

Figure B-12. Hydraulic flowrate for Test P037-039 (APU hot firing No. 19, October 8, 1976).

APPROVAL

SOLID ROCKET BOOSTER THRUST VECTOR CONTROL SUBSYSTEM TEST REPORT (D-1)

By Boris Pagan

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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