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PROPELLANT MANAGEMENT REPORT FOR THE TITAN/CENTAUR TC-5 EXTENDED MISSION

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16. Abstract

The Titan/Centaur vehicle, with the Helios B spacecraft, was launched on January 15, 1976. After the spacecraft was placed into its desired heliocentric trajectory, the Centaur vehicle continued into an extended mission to perform experiments demonstrating increased operational capabilities. Three of the major objectives of the extended mission were: (1) to evaluate the Centaur propellant behavior, (2) to evaluate the effects of reduced tank pressurization levels and (3) to evaluate a propellant duct prechill technique. All of these objectives were successfully accomplished. The major flight data results show that (1) the propellants can be controlled with short collection times, even with a simulated H202 engine failure, (2) extensive tank ventings can be safely performed, (3) the Centaur boost pumps can perform adequately with no LH2 tank pressurization, and with low LO2 tank pressurization levels, (4) the duct prechill technique is an effective way to reduce boost pump cavitation and improve engine childown, and (5) the Centaur boost pumps should be completely stopped prior to an engine start sequence.

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SUMMARY

The Titan/Centaur vehicle, with the Helios B spacecraft, was launched on January 15, 1976. After the spacecraft was placed into its desired heliocentric trajectory, the Centaur vehicle continued into an extended mission to perform experiments demonstrating increased operational capabilities. Three of the major objectives of the extended mission were: (1) to evaluate the Centaur propellant behavior, (2) to evaluate the effects of reduced tank pressurization levels and (3) to evaluate a propellant duct prechill technique. All of these objectives were successfully accomplished.

The major flight data results show that (1) the propellants can be controlled with short collection times, even with a simulated H2O2 engine failure, (2) extensive tank ventings can be safely performed, (3) the Centaur boost pumps can perform adequately with no LH2 tank pressurization, and with low LO2 tank pressurization levels, (4) the duct prechill technique is an effective way to reduce boost pump cavitation and improve engine chilldown, and (5) the Centaur boost pumps should be completely stopped prior to an engine start sequence.

INTRODUCTION

The Titan/Centaur vehicle TC-5, with the Helios B spacecraft was launched from the Eastern Test Range on January 15, 1976. The primary mission included a Centaur first main engine firing to place the vehicle in a 90 n.mi. parking orbit. After a 28 minute low gravity coast with settled propellants, the Centaur engines were fired for a second time in order to place the spacecraft into its desired heliocentric trajectory.

After spacecraft separation, the Centaur vehicle continued into an extended mission in order to perform a series of experiments with the Centaur stage. This extended mission started with a 5¼ hour zero gravity coast to demonstrate the Centaur synchronous orbit coast capability. This coast was followed by five engine start experiments each one separated by coast periods of from 5 to 120 minutes. The total duration of the extended mission was 8 hours 22 minutes.

Three of the major objectives of the extended mission, designed to evaluate Centaur operational margins, were (1) to evaluate the propellant behavior during coast and main engine start sequencing, (2) to evaluate the effects of reduced levels of tank pressurization and reduced liquid levels on boost pump performance, and (3) to evaluate a duct prechill technique prior to engine cooldown.

The flight results and data relevant to these objectives are presented in this report. This report is an extension to the TC-5 Helios B Flight Data Report NASA TMX-73435 which presented the Centaur systems data from liftoff through spacecraft separation. This report is also a supplement to the Thermodynamic Data Report for the TC-5 extended mission NASA TMX-73605.

EXTENDED MISSION DESCRIPTION

The planned TC-5 extended mission consisted primarily of five Centaur main engine restart experiments. The first engine start experiment was designed to occur after a 5.25 hour zero gravity coast in order to simulate the time for a synchronous injection mission. For this engine start the selected Centaur tank pressurization levels (3.2 PSID LO2 Tank, 2.7 PSID LH2 Tank), propellant collection and settling time (300 sec.), and engine chilldown time (20 sec.) were sufficiently conservative to insure a successful demonstration of Centaur synchronous mission capability. For the remaining engine restart experiments, the Centaur operational parameters were selected to evaluate the Centaur engine restart capability under imposed adverse conditions. These conditions, together with the objectives of each engine start experiment, are summarized in Table 1.

As shown in Table 1, tank pressurization levels as low as 0.24 PSID in the LO2 tank and zero PSID in the LH2 tank, engine cooldown times as short as five seconds, propellant collection times as short as 60 seconds, and propellant volumes as low as four percent were obtained. The detailed flight sequencing associated with each of the engine start experiments is listed in Table 2. In general, an engine start sequence is initiated with the activation of two six-pound thrust H2O2 engines for propellant settling. Once the propellants are settled, the tanks are vented, if required. After the tank venting the tanks are pressurized, the boost pumps are started, and then the engines are conditioned (cooled) for the main engine start. For the propellant settling prior to MES 4 a simulated H2O2 engine failure was planned as indicated in Table 2. After the 5 engine start experiments, an extended boost pump deadhead experiment was planned as indicated in Table 1

For the MES 5 and MES 7 engine start experiments, a new method of duct chilldown was planned in which the engine cooldown valves were opened for a short time prior to boost pump start in order to fill the ducts with liquid and to "prechill" the ducts and the engine turbopumps prior to boost pump start

The objectives of the various coast periods prior to the engine start experiments are summarized in Table 3. As shown in this table, the coast periods ranging from 5 minutes to 5.25 hours were planned. These coast periods were selected to evaluate Centaur coast phase extremes that can occur in operational missions.

The propellant residuals that existed in the Centaur tanks at the beginning of each coast period are listed in Table 4. These propellant volumes are significantly less than the 20 percent or more propellant residuals that normally exist in the Centaur tanks during a space coast for an operational mission. However, the propellant volumes for the extended mission were selected to be sufficient to provide meaningful propellant management and engine start experiment data.

FLIGHT INSTRUMENTATION

The LH2 tank was instrumented with 12 liquid-vapor sensors in order to monitor the position of the liquid during the coast periods. The location of these sensors is shown in Figure 1. All of the sensors performed normally throughout the flight. There were no liquid-vapor sensors in the LO2 tanks, so the location and behavior of the liquid in this tank had to be inferred from tank pressure behavior and boost pump performance data.

DISCUSSION OF RESULTS

LH_2 Behavior During Coast

The LH2 tank liquid-vapor sensor activations during the TC-5 extended mission are shown in Figures 2 and 3. An overview of this data shows that as the mission progressed from one engine start experiment to another the number of activations (wet indications) of the sensors greatly decreased. This decrease is the result of a reduction in propellant residuals from 14.5 percent at MECO 2 to 3.2 percent at MECO 7. The liquid level location at the end of each engine firing is shown in Figure 4. As shown in this figure, the liquid level at the start of the two hour zero gravity coast (MECO 6) was about 20 inches below the lowest liquid-vapor sensor.

During the first 200 seconds of the 5¼ hour coast (after MECO 2) the LH2 was scattered throughout the tank as shown by the liquid-vapor sensor activations in Figure 5. At MECO 2 the successive wet indications of CM254X, CM252X, CM243X, CM320X, CM242X and CM241X indicates that the LH2 had progressively flowed up the tank walls and had reached the top of tank by MECO +40 seconds. This flow probably resulted from the boost pump deadhead recirculation and volute bleed flows that occur during the boost pump spin down after MECO. At MECO +72 seconds the helium retrothrust was started (average negative thrust of 38 pounds for 18 seconds) and the two bottom sensors CM255X and CM256X went dry indicating that the retrothrust produced rapid LH2 flow away from the tank bottom and toward the top of the tank.

Within 30 minutes after MECO 2, the LH2 had achieved its steady state location. The four uppermost sensors had gone dry, the bottom sensors became wet again, and the sensors along the tank wall were wet. This LH2 location remained relatively constant throughout the coast until MECO 2 +186 minutes at the second H2O2 settling engine warming firing. Within a few seconds after this firing the bottom sensors CM255x and CM256X and the wall sensors CM247X and CM248X went dry and the sensor CM241X at the top of the tank went wet. These activations indicate that the short firing of the four H2O2 settling engines (25 pounds thrust for 10 seconds) had caused the liquid to flow down the tank walls and recirculate along the tank central axis to the top of the tank. This behavior also occurred after the third H2O2 settling engine warming firing 95 minutes later.

At the end of the 5.25 hour coast, at the start of the pre-MES 3 propellant collection at MES 3 420 seconds, the liquid was probably located in the positions shown by the dashed line in Figure 4. Within 20 seconds after the start of the two H2O2 settling engines, the LH2 had been collected at the tank bottom with the liquid level near the location of sensors CM255X and CM256X, as shown by the intermittent wet/dry activations of these sensors. The LH2 remained collected during the remainder of the MES 3 engine start sequencing.

After MECO 3, the LH2 liquid-vapor sensors activated in a manner similar to the post MECO 2 activations. By 30 seconds after MECO 3 the LH2 had flowed to the top of the tank and along the tank walls where it remained during the 30 minute zero g coast. Within 20 seconds after the start of the one H202 settling engine firing (instead of the normal two settling engines) at MECO -270 seconds the LH2 was collected at the tank bottom. This simulated settling engine failure had no apparent effect on the LH2 collection process.

After MECO 4 the LH2 level had been reduced to the extent that only the two bottom sensors, CM255X and CM256X, activated during the 20 minute zero g coast. All of the LH2 was probably retained in the LH2 tank crevice at the tank bottom. Drop tower tests at LeRC have shown that liquid stability forces in the LH2 tank crevice can retain large quantities of LH2, even under large negative accelerations. Within seven seconds after the start of the pre-MES 5 propellant collection (at MES 5 -270 seconds), these two bottom sensors went dry indicating that the LH2 was collected.

There were no liquid-vapor sensor activations during the five minute low gravity coast between MECO 5 and MES 6. The LH2 was continuously retained at the tank bottom by the firing of two six pound thrust H202 settling engines.

At MECO 6 the LH2 level was about two feet below the lowest sensors. During the two hour zero gravity coast between MECO 6 and MES 7, these two sensors were wetted intermittently as the LH2 surface flowed back and forth along the tank wall in response to vehicle motions. The probable LH2 location at the start of the pre-MES 7 propellant collection at MES 7 -150 seconds is shown in Figure 4. There were no liquid-vapor sensor activations during the zero gravity coast and boost pump experiment after MECO 7 which indicated that all of the liquid was retained at the tank bottom.

LO_2 Behavior During Coast

During the extended mission, the calculated LO2 residuals varied from 12.6 percent (volume) at MECO 2 to 2.8 percent at MECO 7, as listed in Table 4. The location of the resulting one-g equivalent liquid levels with respect to the LO2 tank thrust barrel are shown in Figure 6. As shown in this figure, the liquid residuals nearly covered the thrust barrel at MECO 2 and by MECO 6 had been reduced such that only about 50 percent of the thrust barrel was covered.

An estimate of the LO2 location during a zero gravity coast is presented in Figure 6 for the 20 minute zero gravity coast prior to MES 5. This estimated location was based on the steady state orientation of LO2 as determined by analyses and drop tower testing for the LO2 tank and thrust barrel configuration. The vapor in the thrust barrel assumes a spherical shape during zero gravity coasting because of the cylindrical configuration of the thrust barrel. Since almost all of the LO2 was contained at the tank bottom during the TC-5 extended mission, and the thrust barrel was never emptied, the LO2 was probably collected rapidly after the start of each propellant collection period. These collections were apparently accomplished well within the alloted time periods.

Propellant Tank Venting

The tank pressure histories during the ventings are shown in Figures 7 and 8 for the LH2 tank and LO2 tank respectively. The tank pressure decays were consistent with the decays expected if only gas was vented. There were no pressure spikes or oscillations observed in either tank during the propellant collection and venting periods.

There were two ventings of the LH2 tank and three ventings of the LO2 tank during the extended mission. The first significant tank venting occurred at MECO 6 +5620 seconds. This vent was initiated when the LH2 tank pressure had reached the vent initiation pressure of 27.6 PSIA. The onboard computer then started a venting sequence which consisted of 150 seconds of propellant collection (2 S engines on) followed by a 40 second vent (4 S engines on). During this vent period the LH2 tank pressure was reduced to the computer controlled vent termination pressure of 23.5 PSIA. Since the LO2 tank pressure was 2.6 PSID above its vent termination pressure of 35.0 PSI the LO2 was also vented at this time.

The second significant venting was programmed to start at 50 seconds after the start of the H2O2 depletion experiment (MECO 7 +300 seconds). The propellant tanks were programmed to vent sequentially at this time to permit an evaluation of individual venting disturbances on the vehicle. The tanks were permitted to vent down to the vent valve reseat pressures of 20.5 PSIA and 30.5 PSIA for the LH2 tank and LO2 tank respectively in order to "safe" the vehicle at the termination of the extended mission. No significant vehicle disturbances occurred during the sequential venting experiment.

The only other tank vent that occurred during the extended mission took place in the LO2 tank during the 24 second venting prior to MES 3. The LO2 tank was vented since it was 0.1 PSID above the vent termination pressure of 32.5 PSIA.

Liquid Hydrogen Vapor Ingestion

The liquid level in the hydrogen tank decreased from 57.8 inches to 32.8 inches above the tank bottom during the extended mission. As a result of this decrease, the liquid level at the start of the boost pump experiment after MECO 7 was only 6.8 inches above the vapor ingestion height for the Centaur LH2 tank. The determination of this distance is shown in Figure 9 which compares the liquid level at boost pump start with an analytical vapor ingestion height based on the boost pump outflow rate (Weber No.) and the vehicle acceleration (Bond No.). Because of the closeness of this comparison, and the uncertainties in the analysis and liquid levels, it is possible that some vapor ingestion occurred during the boost pump experiment.

Tank Pressurization

One of the objectives of the engine start experiments during the TC-5 extended mission was to investigate the effects of reduced tank pressurization levels on boost pump performance. The specified boost pump NPSP requirements are 0.1 PSID and 0.71 PSID for the LH2 and LO2 boost pumps respectively. The tank pressurization levels chose for operational engine starts after a space coast are 3.4 PSID for the LH2 tank and 3.5 PSID for the LO2 tank. These levels are well in excess of the specified NPSP requirements in order to provide operational margins. The tank pressurization levels obtained for each of the engine start experiments at pertinent times are listed in Table 5 along with the propellant saturation pressures at the boost pump inlet. No pressurization was provided for the LH2 tank for the pre-MES 4, 5, 6, and 7 pressurization. The resulting boost pump NPSP values are listed in Table 6.

Pre-MES 3 Pressurization: The pre-MES 3 tank ullage pressure histories are shown in Figure 10. The tank pressurization control levels were programmed for a 3.2 PSID and 2.7 PSID increase for the LOX tank and LH2 tank respectively. These levels were chosen to insure a successful engine start after the 5¼ zero gravity coast and to provide a baseline of proper boost pump performance for the other engine start experiments. As shown in Table 6, the resulting LO2 and LH2 boost pump NPSP levels were well above the required values by five seconds after boost pump start (BPS).

The increase in saturation pressure during the tank pressurization prior to BPS is attributed to the bubble collapse and condensation within the sump volume of the vapor generated during coast and/or propellant collection. After BPS, cool liquid is drawn in from the tank bulk by the boost pump deadhead operation. This cool liquid produces a decrease of the sump liquid temperature. In the LO2 tank, this temperature decrease begins immediately at BPS, but in the LH2 tank there is characteristically a four second delay (attributed to the temperature probe location).

The resulting LH2 and LO2 pre-MES 3 boost pump performances as shown by the headrise and speed curves were excellent and no cavitation was evident. The LH2 and LO2 boost pump headrise and speed curves are shown in Figures 11 and 12 respectively.

Pre-MES 4 Pressurization: The pre-MES 4 tank ullage pressure histories are shown in Figure 13. The pre-MES 4 pressurization was programmed to use the same initial tank pressures that existed for the pre-MES 3 pressurization. This technique was used to investigate the possibility of using the existing partial pressures of helium in order to reduce the amount of additional helium required. As shown in Figure 13, the desired tank pressure increases were 2.0 PSID and 1.5 PSID for the LO2 tank and LH2 tank respectively. Because of the pre-MES 3 initial tank pressure reference the desired pressure increases were achieved by the addition of only 0.24 PSID for the LO2 tank and no additional pressurization for the LH2 tank.

The resulting LH2 boost pump NPSP during the pre-MES 4 engine start sequence was constant and near zero, as indicated in Table 6. During the first minute of the zero gravity coast after MECO 3 the energy from the boost pump spin down (bearing coolant flow) increased the saturation pressure (temperature) of the LH2 in the sump to the tank ullage pressure level. This saturation pressure increase effectively removed the partial pressure advantage of the helium used for the pre-MES 3 pressurization and reduced the NPSP to zero. The LH2 boost pump performance under this severe NPSP condition was, surprisingly, near normal and indicated only very slight cavitation prior to prestart. This slight cavitation is shown in the headrise curve of Figure 14. After engine prestart the boost pump performance was normal. At prestart cool liquid is drawn into the sump volume which reduces the saturation pressure.

The resulting LO2 boost pump NPSP during the pre-MES 4 engine start sequence reached an indicated minimum of only 0.43 PSID at five seconds after prestart. This NPSP value was much lower than expected and is well below the 0.71 PSID minimum specification requirement. After MECO 3 the LO2 boost pump spin down which persisted for 7 minutes 12 seconds added sufficient energy to the sump fluid to raise the saturation pressure to the existing tank ullage pressure. As a result, the partial pressure advantage of the existing helium in the tank was lost. After prestart, when the LO2 sump temperature typically continues to increase as a result of the increased volute bleed flow, the NPSP began to decrease. By five seconds after prestart this NPSP decrease resulted in excessive boost pump cavitation as shown by the pump headrise curve in Figure 15. Even though the RL10 engines started successfully with this cavitating boost pump, such cavitation is definitely not desirable. The flight data showed the LO2 boost pump to be less tolerant of low NPSP values than the LH2 boost pump during the engine restarts.

The technique of relying on the partial pressure of helium, that exists prior to pressurization, to provide the required LO2 boost pump NPSP was not suitable for the pre-MES 4 application.

Pre-MES 5 Pressurization: The pre-MES 5 tank ullage pressure histories are shown in Figure 16. As shown in this figure, no pressurization was planned for the LH2 tank and a 2.0 PSID increase was planned for the LOX tank. The actual LOX tank pressure increase was 1.84 PSID.

A new technique of propellant feed system thermal conditioning (called "duct prechill") was investigated during the fifth engine start sequence. At MES 5 -60 seconds the engine inlet valves were opened (boost pumps not running) to permit the tank pressure to force fill the propellant ducts with liquid. At MES 5 -55 seconds the engine inlet valves were closed and the liquid residing in the ducts was given time to remove the sensible duct and main engine valve heat by percolation. This liquid also removed some of the engine turbo-pump heat by conduction. The system precooling associated with the duct prechill permitted a reduction in the engine prestart duration from 17 seconds to 7 seconds. The calculated total propellant quantity required for cooling using the 5 second prechill plus a 7 second pre-start is about 60 percent less than for the normal 17 second prestart alone.

The duct prechill technique was completely successful. As shown in Table 5, the duct prechill resulted in a LO2 boost pump NPSP of over 1.55 PSID. And, as shown in Figure 15, no cavitation was evident in the LO2 boost pump headrise. The LH2 boost pump again performed satisfactorily with no tank pressurization with only a slight cavitation prior to prestart, as shown in Figure 14. The duct prechill apparently serves to flush out the vapor and hot propellants that are produced during the coast prior to the start of tank pressurization.

P__MES 6 Pressurization: The pre-MES 6 tank ullage pressure histories are shown in Figure 17. No pressurization was planned for the LH2 tank and 2.0 PSID was planned for the LO2 tank. The same initial tank pressures that existed for the pre-MES 5 tank pressurization was used for the initial tank pressure reference for the pre-MES 6 tank pressurization. This is the same pressurization technique that was used for the pre-MES 4 tank pressurization. However, the pre-MES 6 engine start was preceeded by a 5 minute settled coast as compared with a 20 minute zero gravity coast prior to MES 4. The settled coast maintained propellants at the bottom of the tank which absorbed the heating from the boost pump spin down after MECO 5. As a result, the LO2 saturation temperature at MES 5 and MES 6 were nearly the same and the partial pressure advantage of the helium used for the pre-MES 5 pressurization was maintained through to the start of pressurization for MES 6.

The resulting LO2 boost pump NPSP is listed in Table 5. The NPSP values were well in excess of the 0.71 PSID specification requirement. The LH2 boost pump NPSP was again near zero since the LH2 tank was not pressurized.

The pre-MES 6 LH2 and LO2 boost pump headrise and speed curves are shown in Figures 11 and 12 respectively. The LH2 boost pump performance was similar to the pre-MES 4 behavior and indicated some cavitation prior to engine prestart resulting in above normal speed and reduced headrise. At prestart the boost pump headrise and speed recover to their normal values as a result of increased flow of cool liquid being drawn into the sump area from the tank bulk.

The LO2 boost pump performance, however, did not recover at prestart and instead showed extensive cavitation as the headrise plummeted to 7 PSID and the speed increased to 52,000 rpm. This cavitation occurred even at the high NPSP values that existed. This extensive cavitation was theorized to be the result of ullage entrainment in the LO2 thrust barrel liquid. Since the coast period was short (5 minutes), the LO2 boost pump did not have sufficient time to completely spin down after MECO 5 and was still spinning at 5000 rpm at boost pump start. During this coast the LO2 thrust barrel was only about 50 percent full (refer to Figure 6) and the gas and liquid in the thrust barrel was probably mixed by the boost pump spin down. Since the LO2 boost pump was spinning during the entire coast, the liquid was prevented from settling away from the ullage which resulted in a gas-liquid mix for the boost pump flow when the pumps were started. When the flow rate demand was increased at prestart, the dynamic gas-liquid conditions that existed in the thrust barrel probably resulted in large quantities of gas being ingested into the pump inflow.

The performance of the LO2 boost pump for the MES 6 engine start experiment demonstrated that an engine start should not be attempted after a very short coast with LO2 levels that are significantly below the top of the thrust barrel. Sufficient coast time should be provided to permit the LO2 boost pump to completely spin down and for the LO2 to achieve a reasonably quiescent condition.

Pre-MES 7 Pressurization: The pre-MES 7 tank ullage pressure histories are shown in Figure 18. No pressurization was planned for the LH2 tank and 2.0 PSID was planned for the LO2 tank. However, because of the low helium bottle supply pressure that existed prior to MES 7, the actual LO2 tank pressurization proceeded very slowly and the actual tank pressure increase was only 0.56 PSID.

The resulting LO2 pump NPSP values are listed in Table 5. As shown in this table, the actual NPSP was well in excess of the 0.56 PSID provided by the pressurization since the LO2 tank ullage gas became superheated about one PSID above the bulk liquid saturated pressure during the coast. This NPSP resulted in good boost pump performance for the MES 7 engine start sequence as shown in Figure 19. Because of the two hour coast preceeding MES 7, the LO2 boost pump had time to spin down and thus preclude the gas-liquid mix problem associated with the MES 6 engine start sequence.

The resulting LH2 boost pump NPSP was again near zero since the tank was not pressurized. Some cavitation was evident in the boost pump performance prior to prestart as shown in Figure 20. But the pump recovered quickly after prestart to the normal speed and headrise levels.

Prior to the start of the boost pumps for MES 7 another duct prechill experiment was performed. The engine prestart valves were opened for 10 seconds, from MES 7-70 seconds to MES 7-60 seconds, to fill the engine propellant supply ducts with liquid. An example of the effectiveness of the duct prechill technique is shown in Figure 21 for the LH2 duct and engine turbopump. As shown in this figure, the LH2 ducts were completely chilled, and the turbopump temperatures had decreased by 40°R, by the time of boost pump start. The LH2 duct temperatures for the MES 3 engine start sequence are also shown in Figure 21 for comparison. As shown by this data, the prechill operation had removed the duct sensible heat. This removal would greatly reduce the amount of vapor that would be generated during boost pump deadheading. This reduction in temperature enabled the seventh engine start to proceed smoothly with only five seconds of prestart and with very low tank pressurization levels. The duct pre-chill technique is recommended for long space coast missions that produce high propellant duct temperatures.

Boost Pump Experiment

The boost pump experiment (BPX) was started 320 seconds after MECO 7. The purpose of the BPX was to run the boost pump deadheaded for 20 seconds to observe the effects of the bearing coolant flow on boost pump cavitation, without tank pressurization, and at very low propellant levels. A similar experiment on the TC-2 extended mission had shown that the LH2 boost pump will cavitate after 14 seconds of deadheading as the result of the filling the sump with vapor (from the bearing coolant flow) and spilling over into the boost pump inlet.

The LH2 boost pump performance during the BPX is shown in Figure 20. As shown in this figure, the boost pump began to cavitate excessively after only five seconds of operation. The reason for the cavitation at this time is not clear. It is possible that LH2 vapor ingestion occurred, even though the liquid level based on the known propellant mass was about six inches above the calculated vapor ingestion height. The actual LH2 level may have been lower if the LH2 was not sufficiently collected, since only 20 seconds of propellant collection time was provided prior to the BPX. The boost pump spin down after MECO 7 may also have affected the LH2 level.

The LO2 boost pump performance during the BPX is shown in Figure 19. As shown in this figure, the LO2 boost pump was still rotating at about 10,000 rpm at the start of the experiment. This continuous spinning from MECO 7 to the BPX probably resulted in a gas-liquid mix in the thrust barrel. This mixing was more extensive than the mixing that occurred prior to MES 6 since the thrust barrel was only about 30 percent filled. When the pump flow rate increased sufficiently at BPX +8 seconds, this gas-liquid mix may have been sucked into the pump to reduce the pump headrise. This behavior again indicates that for low liquid levels the boost pump rotation should be completely stopped prior to the start of an engine start sequence. The time required to stop the rotation of the boost pumps may be considerable (about 10 minutes) for zero gravity coasts with low propellant residuals, since the pumps would not be loaded.

CONCLUSIONS

The major objectives of the TC-5 extended mission to (1) evaluate the Centaur propellant behavior, (2) evaluate the effects of reduced tank pressurization levels and liquid levels on boost pump performance and (3) evaluate a propellant duct prechill technique, were all successfully accomplished.

The flight data results show that (1) the propellants can be controlled with short collection times, even with a simulated H2O2 engine failure, (2) extensive tank ventings can be safely performed, (3) the Centaur boost pumps can perform adequately with no LH2 tank pressurization, and with low LO2 tank pressurization levels, (4) relying on the existing helium partial pressure in the propellant tanks may not be an acceptable substitute for tank pressurization, (5) the duct prechill technique is an effective way to reduce boost pump cavitation, improve engine chill-down, and reduce engine prestart times and (6) the Centaur boost pumps should be completely spun down prior to attempting another engine start sequence.

TABLE 1 Extended Mission Main Engine Start Objectives

Engine Start Sequence	Objective
MES 3	Demonstrate an engine restart after a long zero-G coast. Use nominal tank pressurization levels (3.2 PSID LOX, 2.7 PSID LH2), propellant settling time (300 sec) and cooldown time (20 sec).
MES 4	Obtain engine restart data with reduced tank pressurization levels (.25 PSID LOX, 0 PSID LH2), propellant settling time (150 sec), and cooldown time (17 sec). Obtain data on the effects of a simulated H2O2 engine failure.
MES 5	Obtain engine restart data using a prechill technique for duct cooldown and reduced pressurization levels (1.89 PSID LOX, 0 PSID LH2) and cooldown time (7 sec).
MES 6	Obtain data on an engine restart following a very short settled coast (causing cold start conditions), and with low tank pressurization levels (.56 PSID LOX, 0 PSID LH2) and low propellant levels (5.6 percent LOX, 5.7 percent LH2).
MES 7	Obtain engine restart data under adverse conditions of low tank pressurization levels (1.20 PSID LOX. 0 PSID LH2), short propellant settling time (60 sec), short cooldown time (5 sec), and low propellant levels (4.2 percent LOX, 3.8 percent LH2).
Boost Pump Experiment	Investigate maximum boost pump deadhead time before cavitation occurs.

TABLE 2 Extended Mission Engine Start Sequencing

Event	Time from Main Engine Start (MES), [illegible]				
	Burn 3	Burn 4	Burn 5	Burn 6	Burn 7
2 S H202 Engines ON	-420	-270	-270	-300	-150
1 S H202 Engines ON**	--	-267	--	--	--
4 S H202 Engines ON	-120	-120	- 50	--	--
3 S H202 Engines ON**	--	-117	--	--	--
Start Tank Vent	-120	-120	-120	--	- 90
End Tank Vent	- 96	- 96	- 96	--	- 66
Start Prechill	--	--	- 60	--	- 70
End Prechill	--	--	- 55	--	- 60
Start Tank Pressurization	- 43	- 43*	- 43*	- 43*	- 43*
Boost Pump Start	- 28	- 28	- 18	- 28	- 15
Prestart	- 20	- 17	- 7	- 17	- 5
MES	0	0	0	0	0
MECO	11.0	13.0	6.0	6.2	7.0

* No LH2 Tank Pressurization

** Simulated S H202 Engine Failure

TABLE 3 Extended Mission Coast Periods

Coast Period	Coast Duration	Propellant Control Mode	Objective
Prior to MES 3	5.25 hours	Zero G	Demonstrate synchronous equatorial coast capability.
Prior to MES 4	30 minutes	Zero G	Demonstrate short zero-G coast capability for MJS missions.
Prior to MES 5	20 minutes	Zero G	Demonstrate minimum zero-G coast capability.
Prior to MES 6	5 minutes	settled	Demonstrate minimum settled coast capability.
Prior to MES 7	2 hours	Zero G	Obtain data on component thermal behavior during prolonged periods with solar heating extremes.

TABLE 4 Propellant Residuals

	2nd MECO		3rd MECO		4th MECO		5th MECO		6th MECO		7th MECO	
	LO2	LH2	LO2	LH2	LO2	LH2	LO2	LH2	LO2	LH2	LO2	LH2
Propellant Volume (ft^3)	47.1	183.5	37.9	146.2	26.7	104.7	21.8	87.2	16.4	63.4	10.6	41.3
Propellant Mass (LB)	3252	811	2585	626	1819	450	1489	374	1115	273	721	177
Height above tank bottom (inches)	19.5	57.8	17.5	51.4	13.8	44.9	14.5	43.4	12.9	38.9	8.9	32.8
Propellant Percentage of Tank Volume	12.6	14.5	10.1	11.5	7.1	8.3	5.8	6.9	5.0	3.8	2.3	3.2

TABLE 5 TC-5 Extended Mission Tank Pressurization Levels

Engine Start Sequence	LO2 Tank Ullage Pressure, PSIA					LO2 Saturation Pressure, PSIA				
	Start Press'n	BPS	BPS +5 sec.	Prestart	MES	Start Press'n	BPS	BPS +5 sec.	Prestart	MES
MES 2	32.34	36.40	36.45	36.00	35.98	32.95	32.95	32.95	33.30	33.50
MES 3	32.23	34.30	34.90	35.30	35.34	32.70	33.90	32.70	33.00	33.50
MES 4	34.03	34.23	34.25	34.23	34.27	34.50	34.50	33.50	33.80	33.50
MES 5	34.11	35.60	35.95	36.00	35.95	34.25	33.90	33.90	34.25	34.40
MES 6	35.41	36.10	36.08	36.10	35.98	34.25	34.25	34.25	34.25	34.75
MES 7	35.70	36.45	36.70	36.80	36.90	35.30	36.50	34.95	35.30	35.65
BPX	---	36.80	36.80	---	---	---	34.00	34.45	---	---

Engine Start Sequence *	LH2 Tank Ullage Pressure, PSIA					LH2 Saturation Pressure, PSIA				
	Start Press'n	BPS	BPS +5 sec.	Prestart	MES	Start Press'n	BPS	BPS +5 sec.	Prestart	MES
MES 2	20.90	24.35	24.50	24.15	24.09	21.90	25.80	22.90	22.70	21.30
MES 3	22.38	24.70	25.15	25.30	25.18	23.45	25.80	23.45	23.45	23.45

* no LH2 tank pressurizations were performed after MES 3.

TABLE 6 TC-5 Extended Mission Boost Pump NPSP Values

Engine Start Sequence	LO2 Boost Pump NPSP (PSID).			Spec. Requirement = 0.71 PSID	
	Start Press'n	BPS	BPS +5 sec.	Prestart	MES
MES 2	- .61	3.45	3.50	2.70	2.48
MES 3	- .47	0.40	2.20	2.30	1.84
MES 4	- .47	- .27	0.75	0.43	0.77
MES 5	- .15	1.70	2.05	1.75	1.55
MES 6	1.16	1.85	1.83	1.85	1.23
MES 7	0.46	-0.05	1.75	1.50	1.25
BPX	---	2.80	2.35	---	---
	LH2 Boost Pump NPSP (PSID).*			Spec. Requirement = 0.10 PSID	
	Start Press'n	BPS	BPS +5 sec.	Prestart	MES
MES 2	-1.00	-1.45	1.60	1.45	2.79
MES 3	-1.07	-1.10	1.70	1.85	1.73
MES 4	-1.36	-1.36	-1.36	-1.36	-1.36
MES 5	-1.60	-1.60	-1.60	-1.60	-1.69
MES 6	-1.40	-1.40	-1.40	-1.40	-1.70
MES 7	-1.40	-1.40	-1.40	-1.40	-1.40

* NOTE: There is an unknown large error in the LH2 saturation temperature measurement. This error results in a corresponding large error in the LH2 saturation pressure value. The actual LH2 boost pump NPSP is near zero for MES 4 and on.

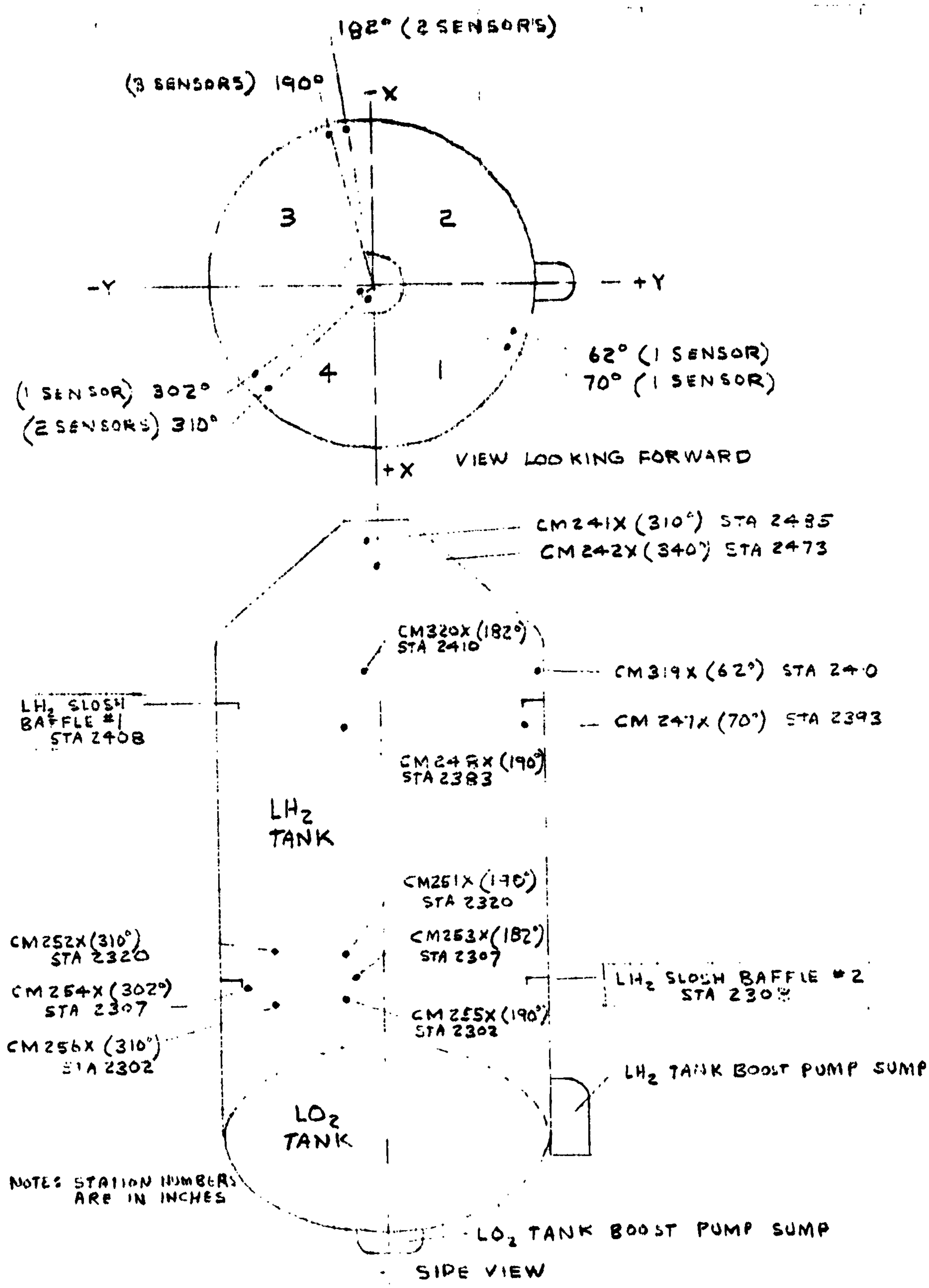


FIGURE 1. LOCATION OF LH_2 LIQUID-VAPOR SENSORS.

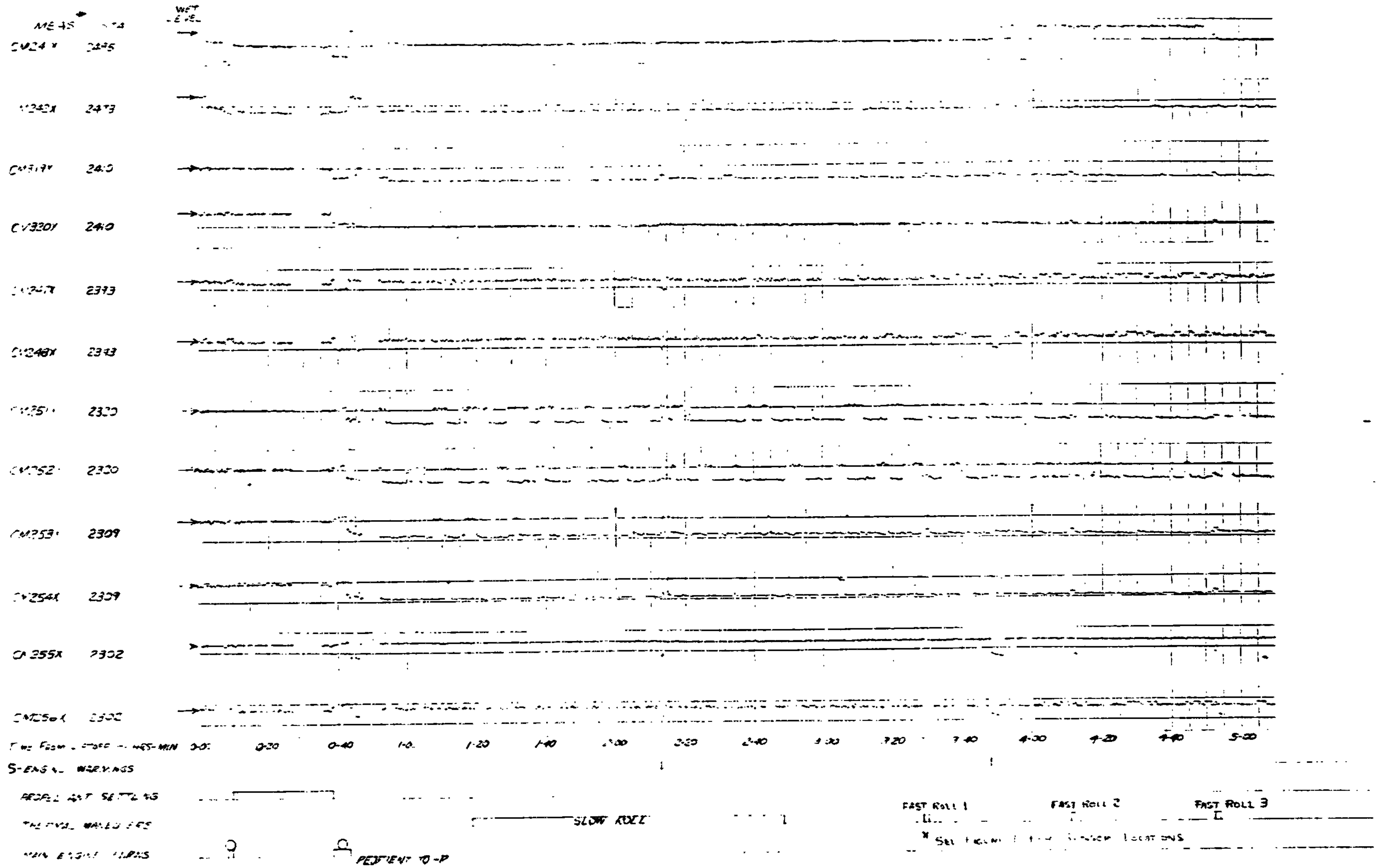


FIGURE 2. HYDROGEN TANK LIQUID/VAPOR SENSOR ACTIVATIONS

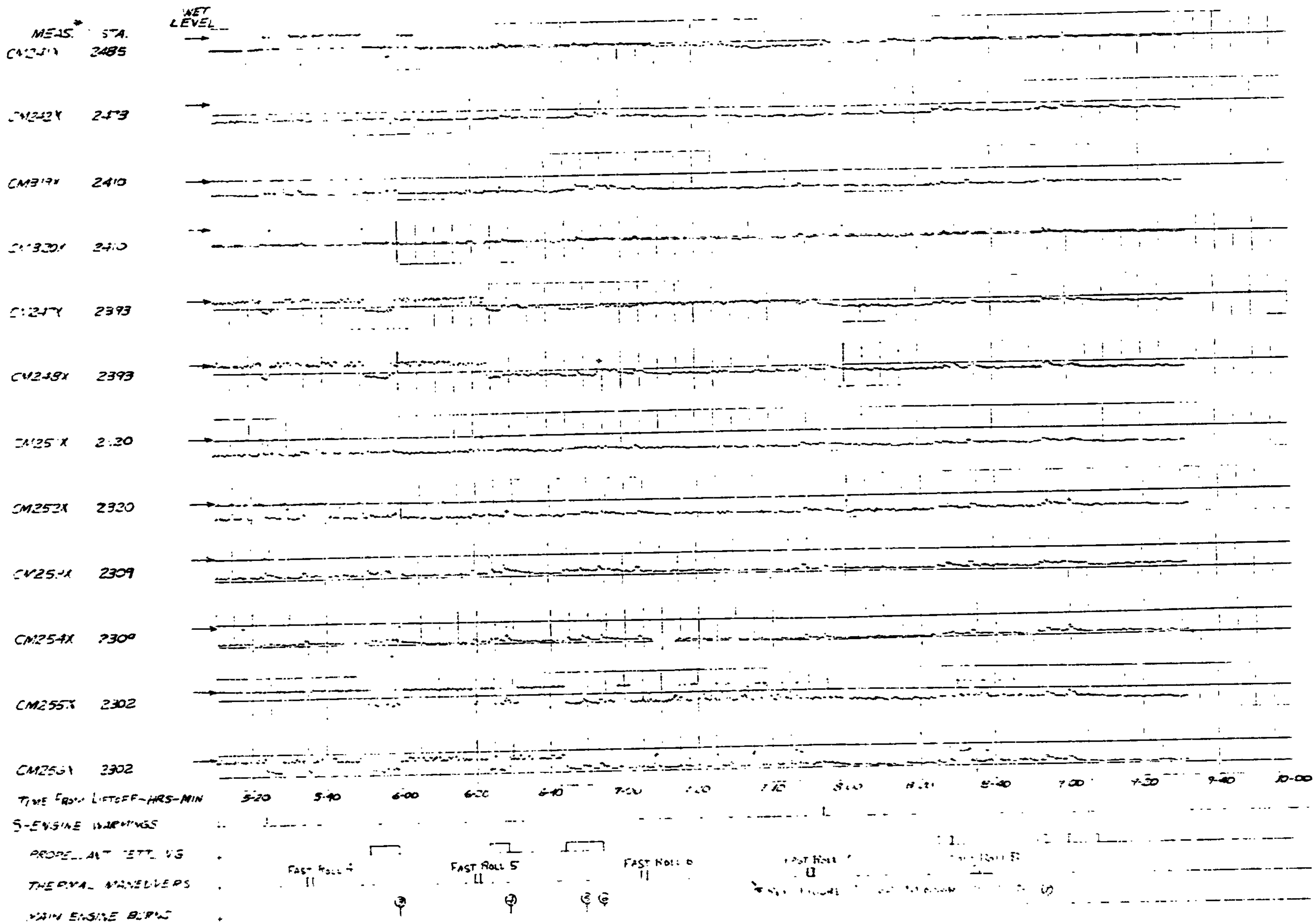


FIGURE 3. HYDROGEN TANK LIQUID VAPOR SENSOR ACTIVATIONS

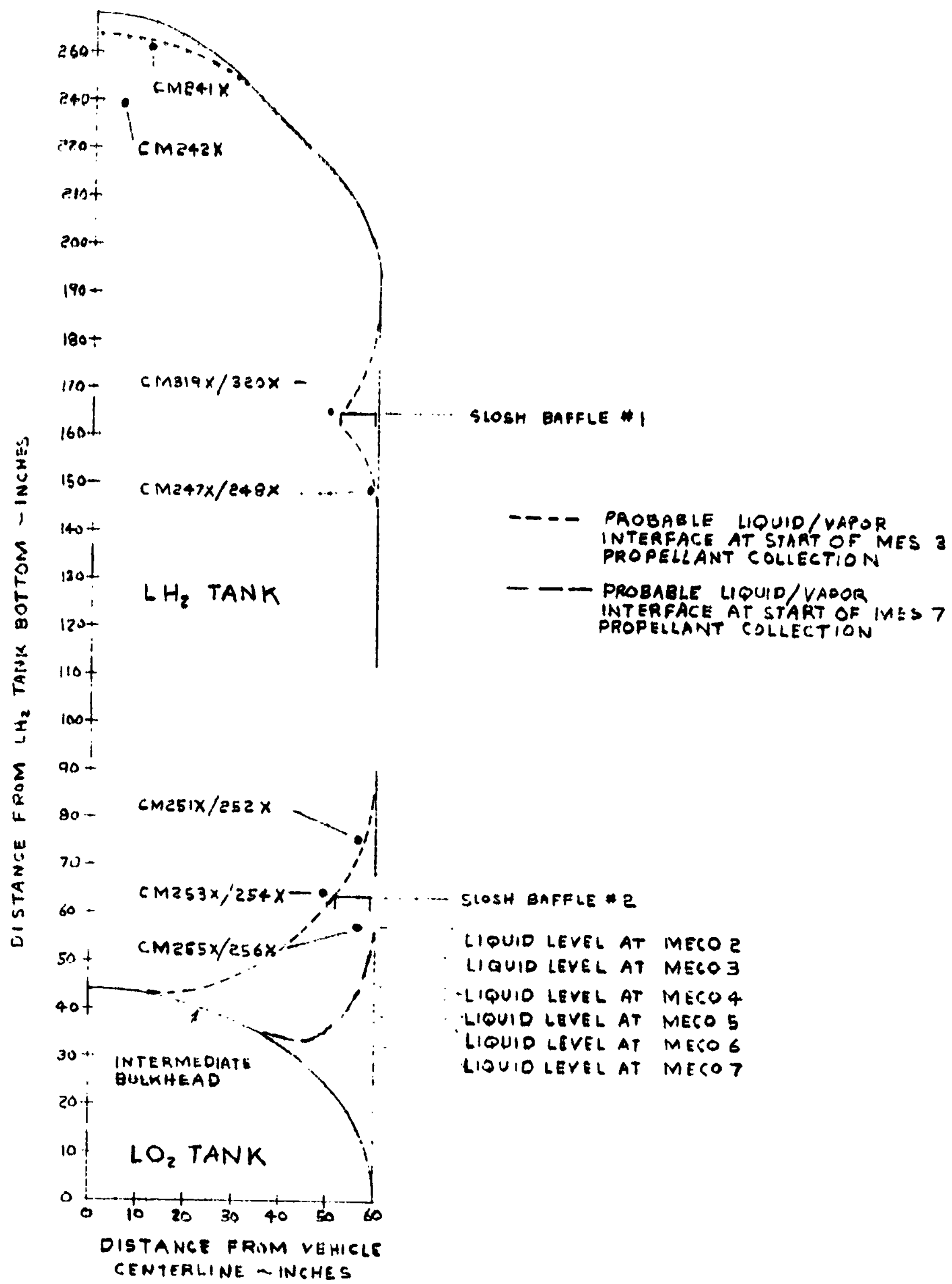


FIGURE 4. LH_2 LEVELS AND PRE MES 3 AND 7 LH_2 ORIENTATION DURING THE TC-5 EXTENDED MISSION.

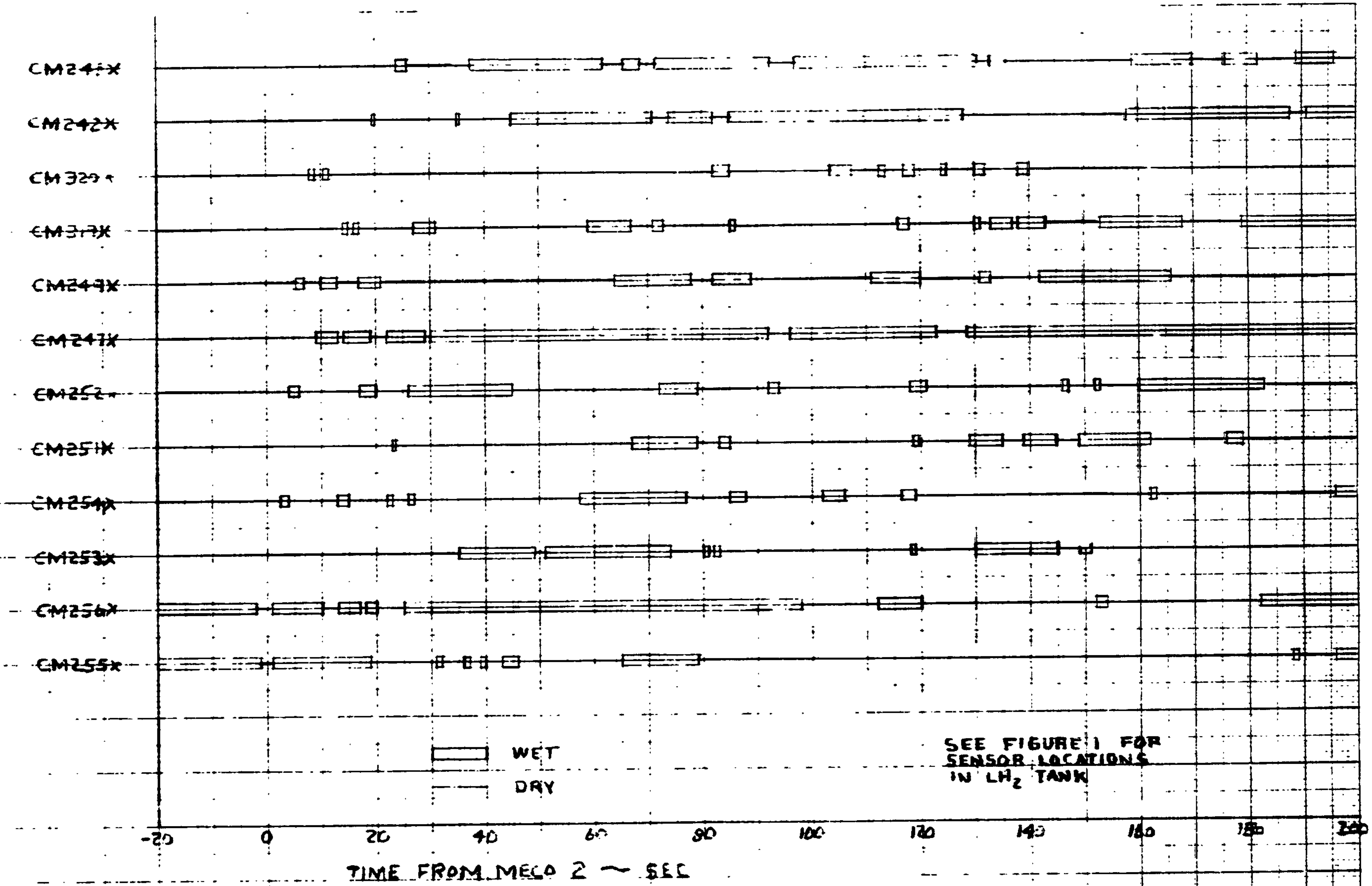


FIGURE 5. LIQUID-VAPOR SENSOR ACTIVATIONS AFTER MECO 2.

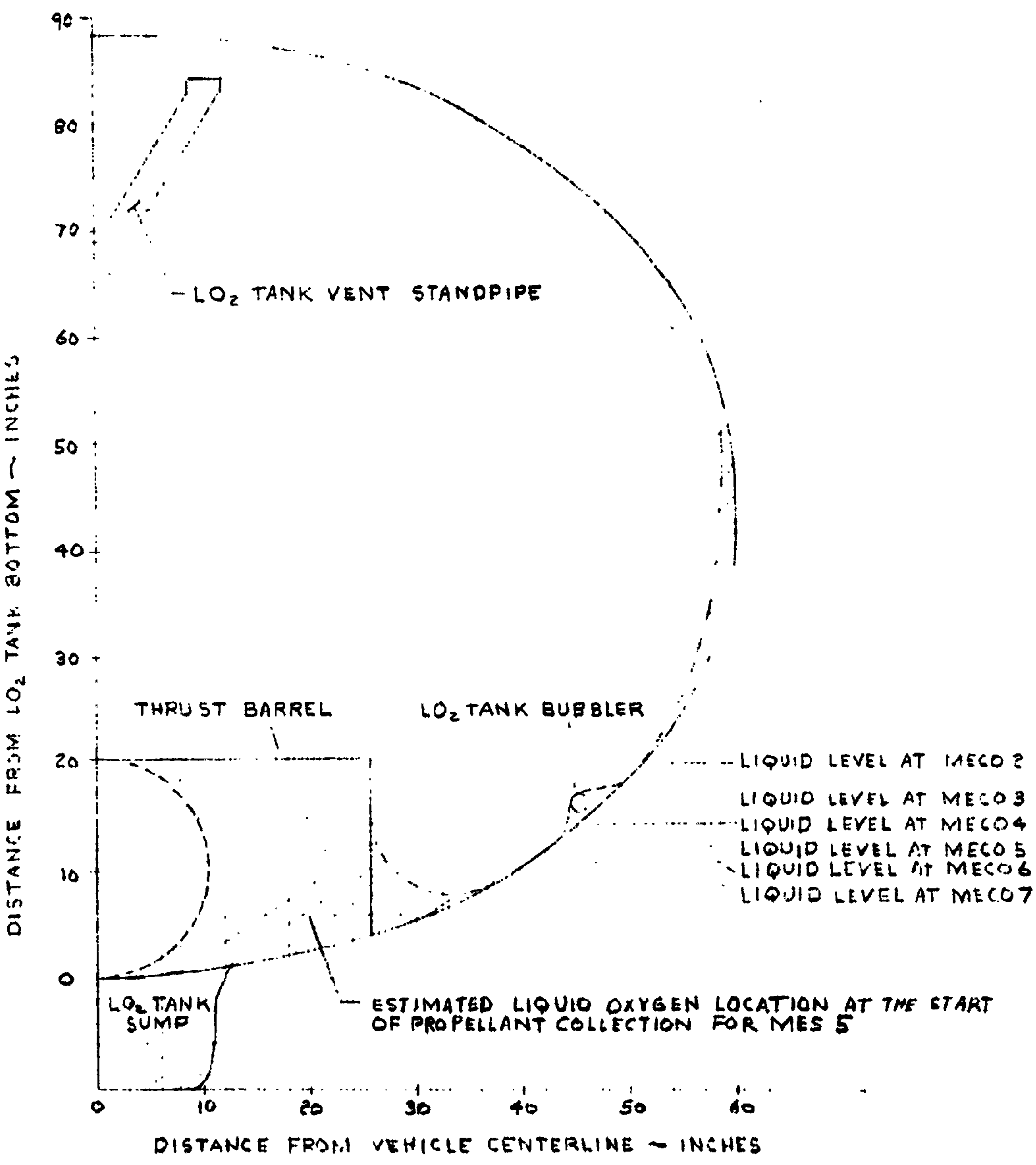


FIGURE 6. LIQUID OXYGEN LEVELS AND PRE MES 5 LO_2 ORIENTATION DURING THE TC-5 EXTENDED MISSION

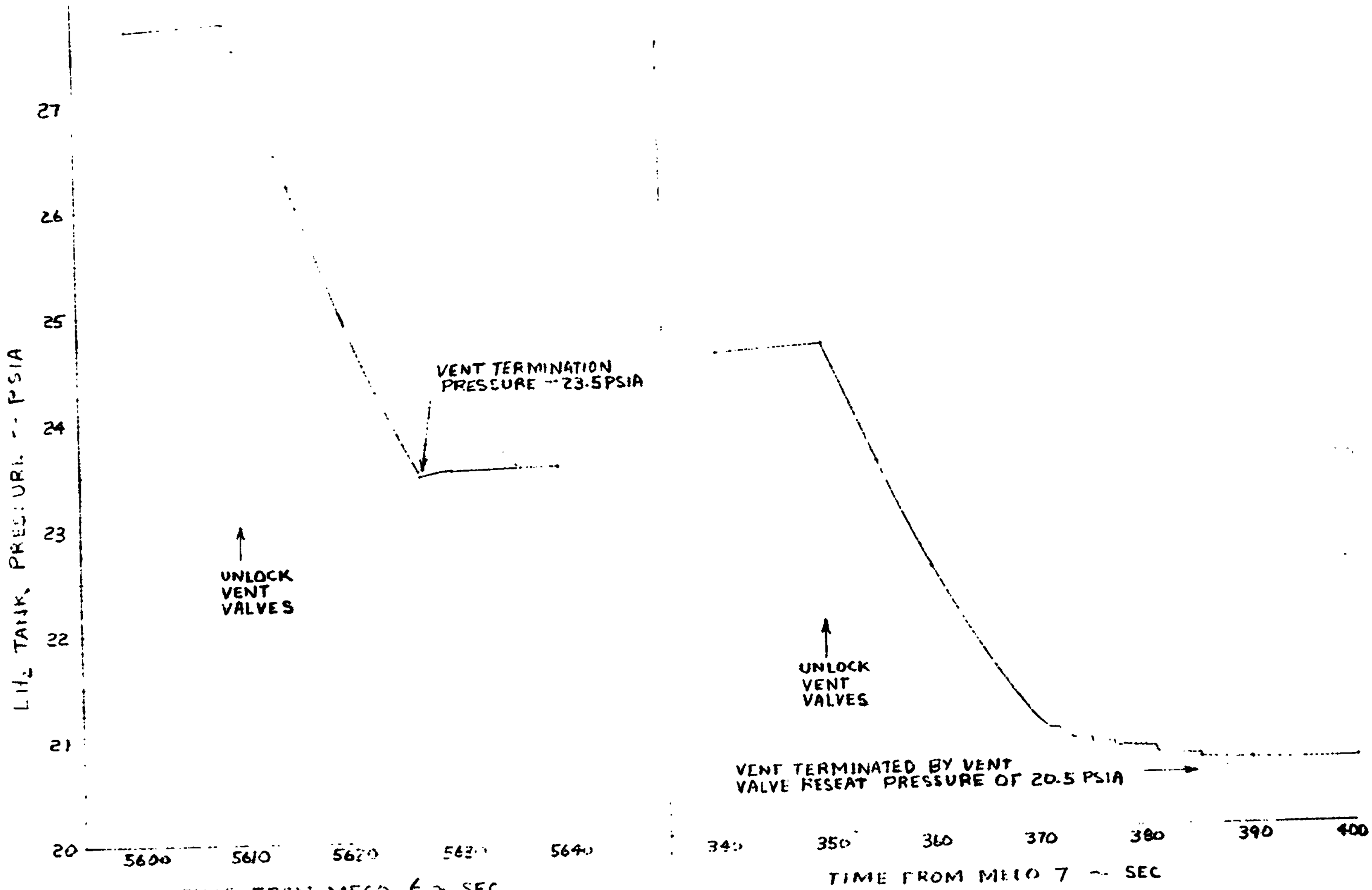


FIGURE 7. LIQUID HYDROGEN TANK VENTS DURING TC-5 EXTENDED MISSION

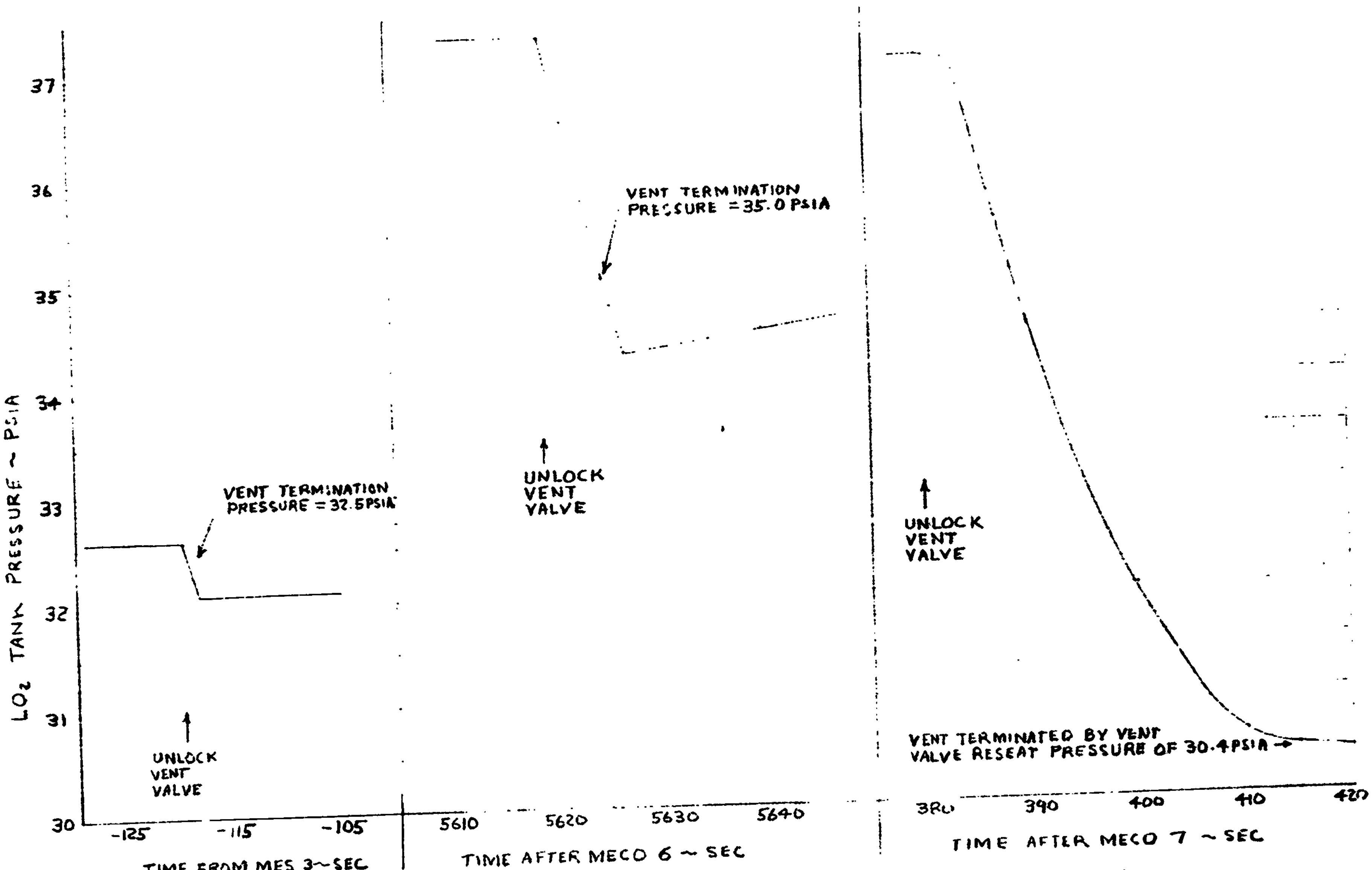


FIGURE 8. LIQUID OXYGEN TANK VENTS DURING TC-5 EXTENDED MISSION

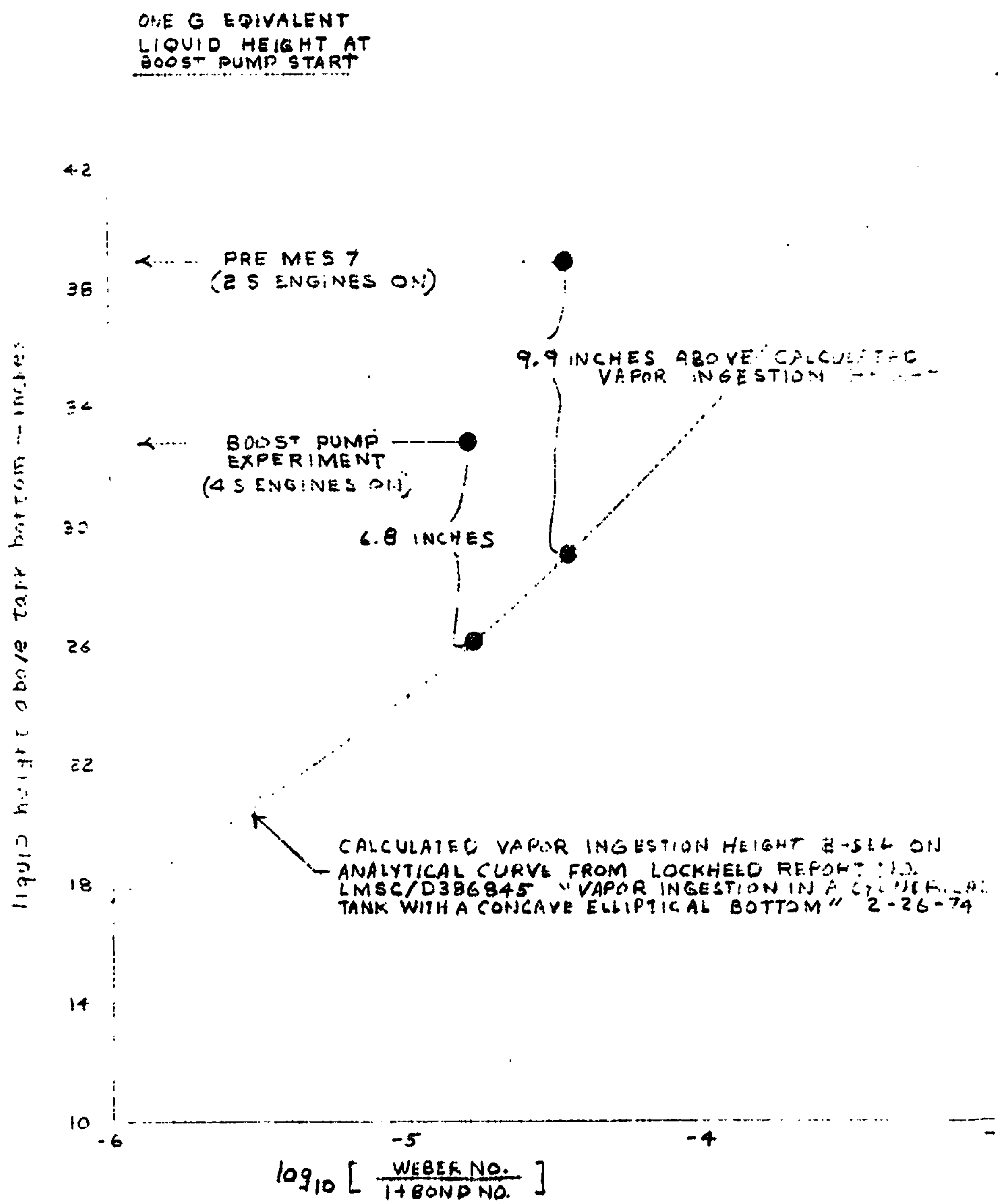


FIGURE 9. LH_2 VAPOR INGESTION HEIGHT DURING BOOST PUMP OPERATION FOR PRE MES 7 AND THE BOOST PUMP EXPERIMENT.

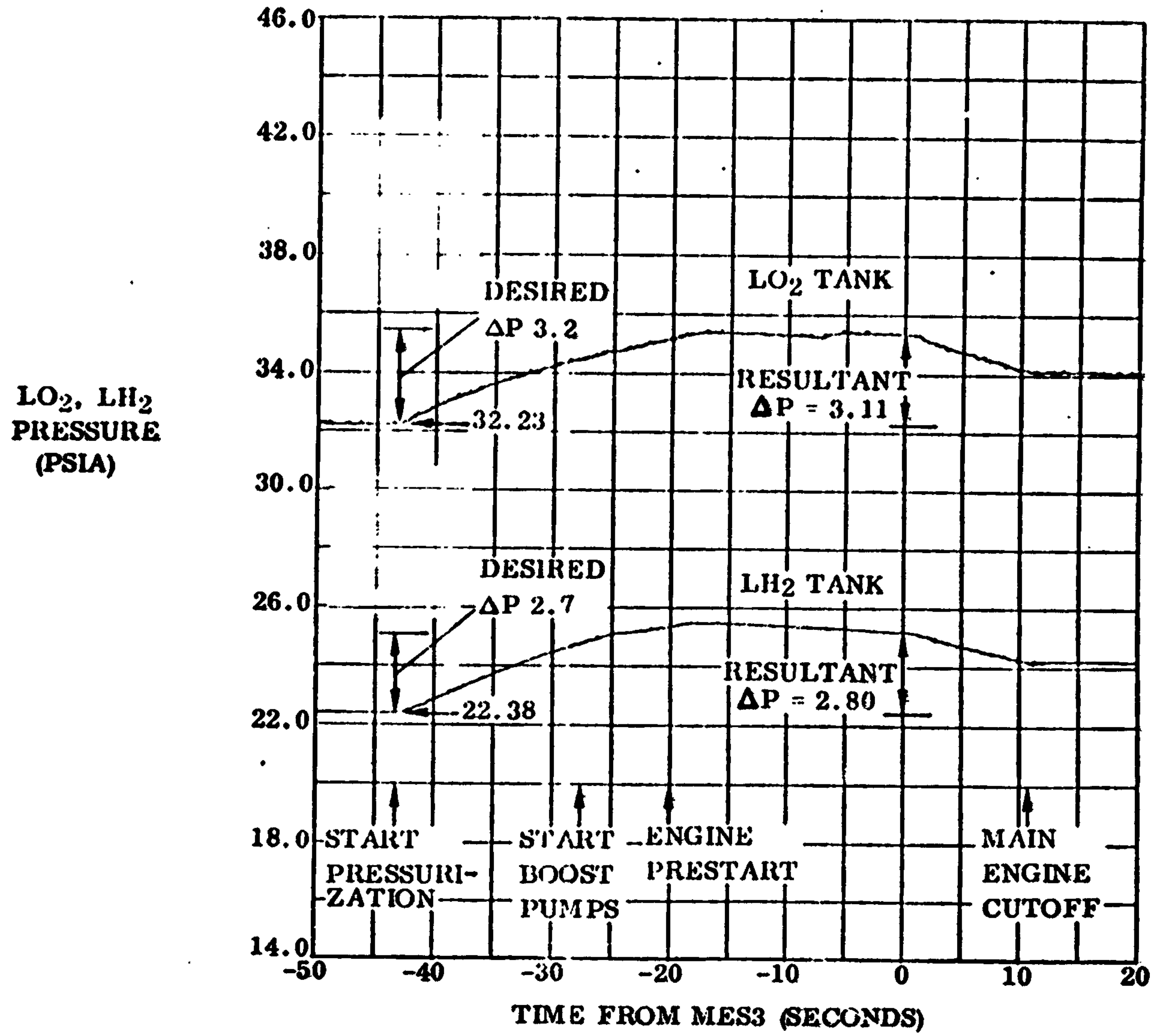


FIGURE 10. PRE MES 3 TANK ULLAGE PRESSURE HISTORIES.

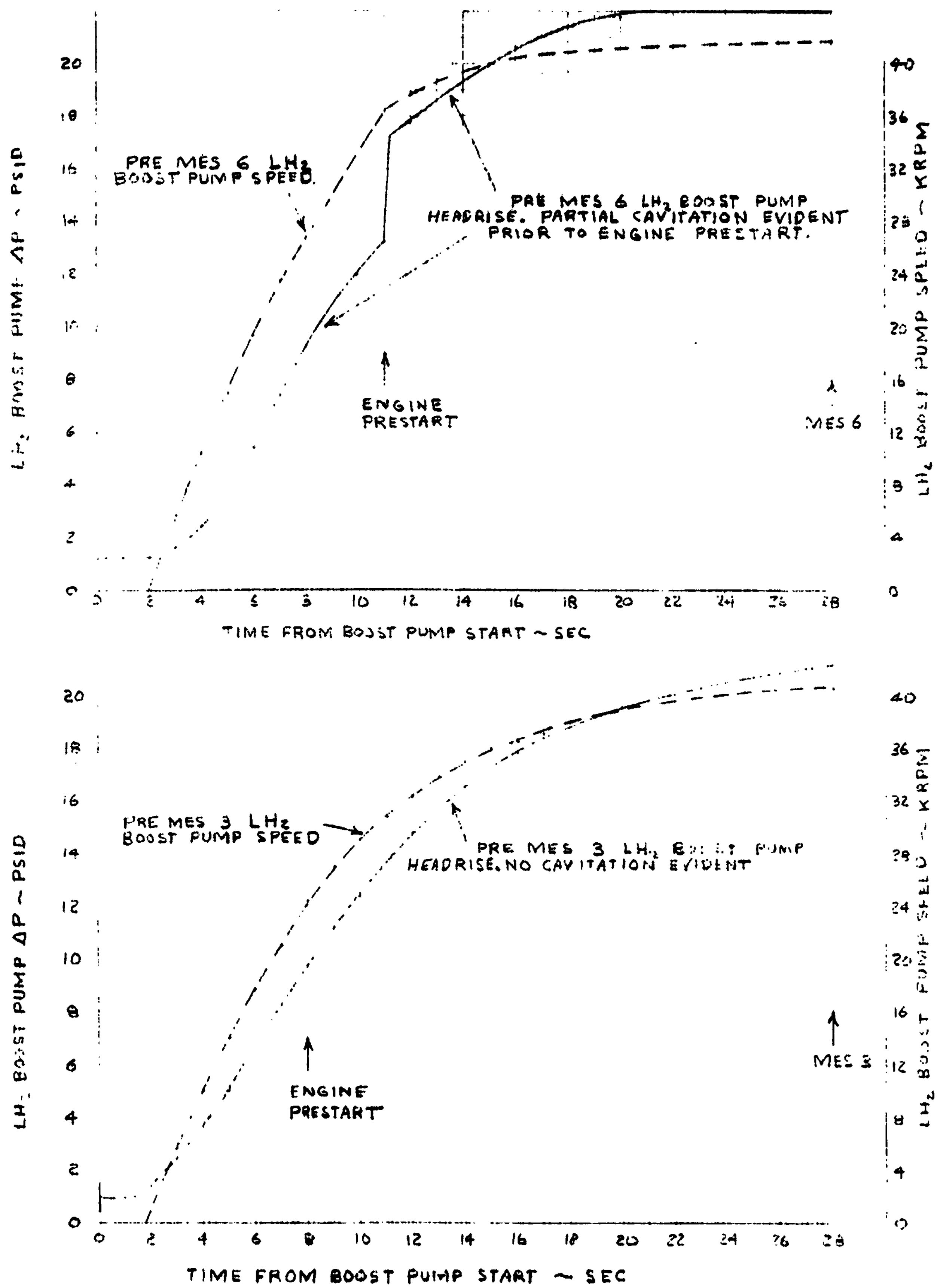


FIGURE 11. LH_2 BOOST PUMP PRE MES 3 AND PRE MES 6 PERFORMANCE

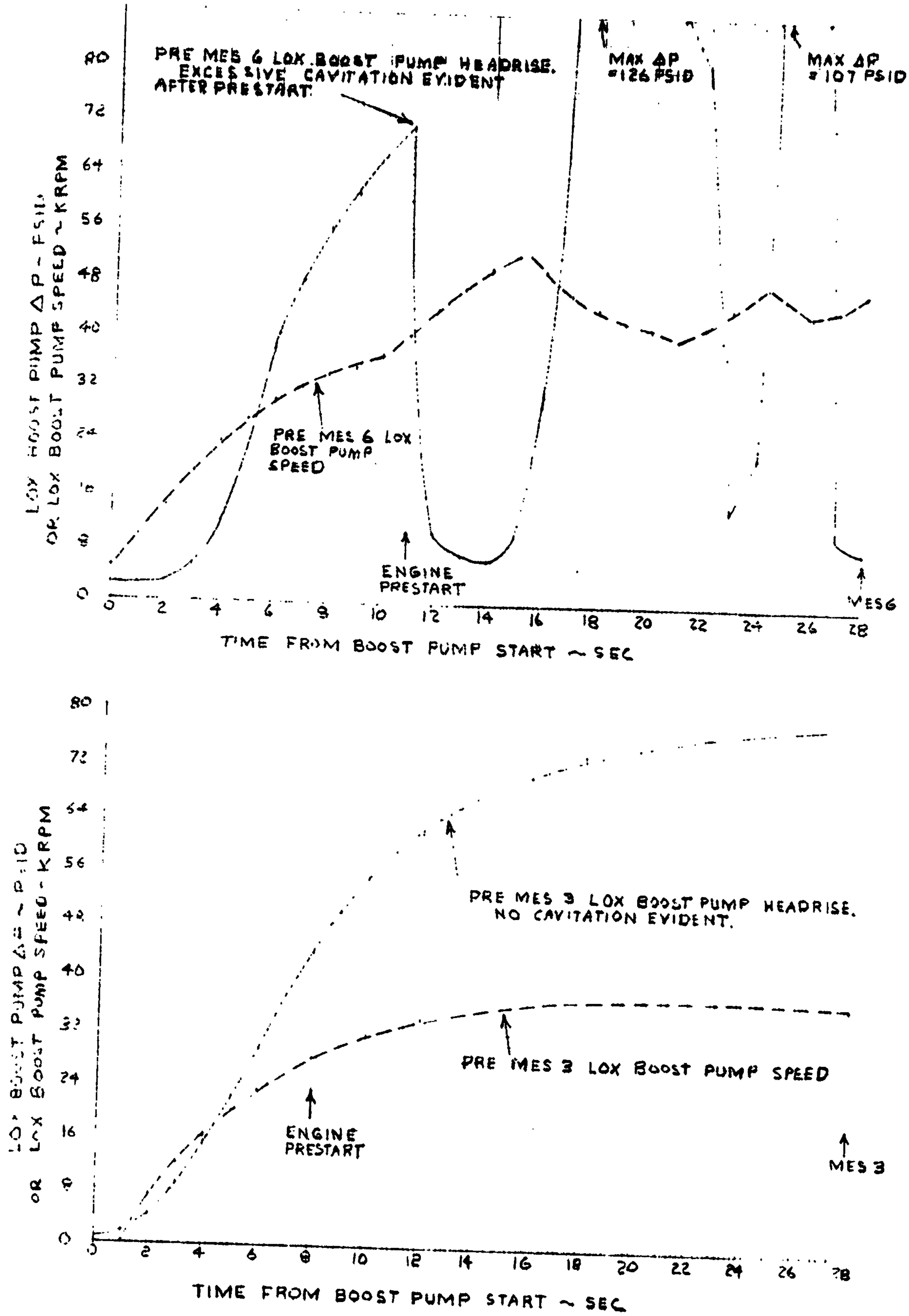


FIGURE 12. LOX BOOST PUMP PRE MES 3 AND PRE MES 6 PERFORMANCE.

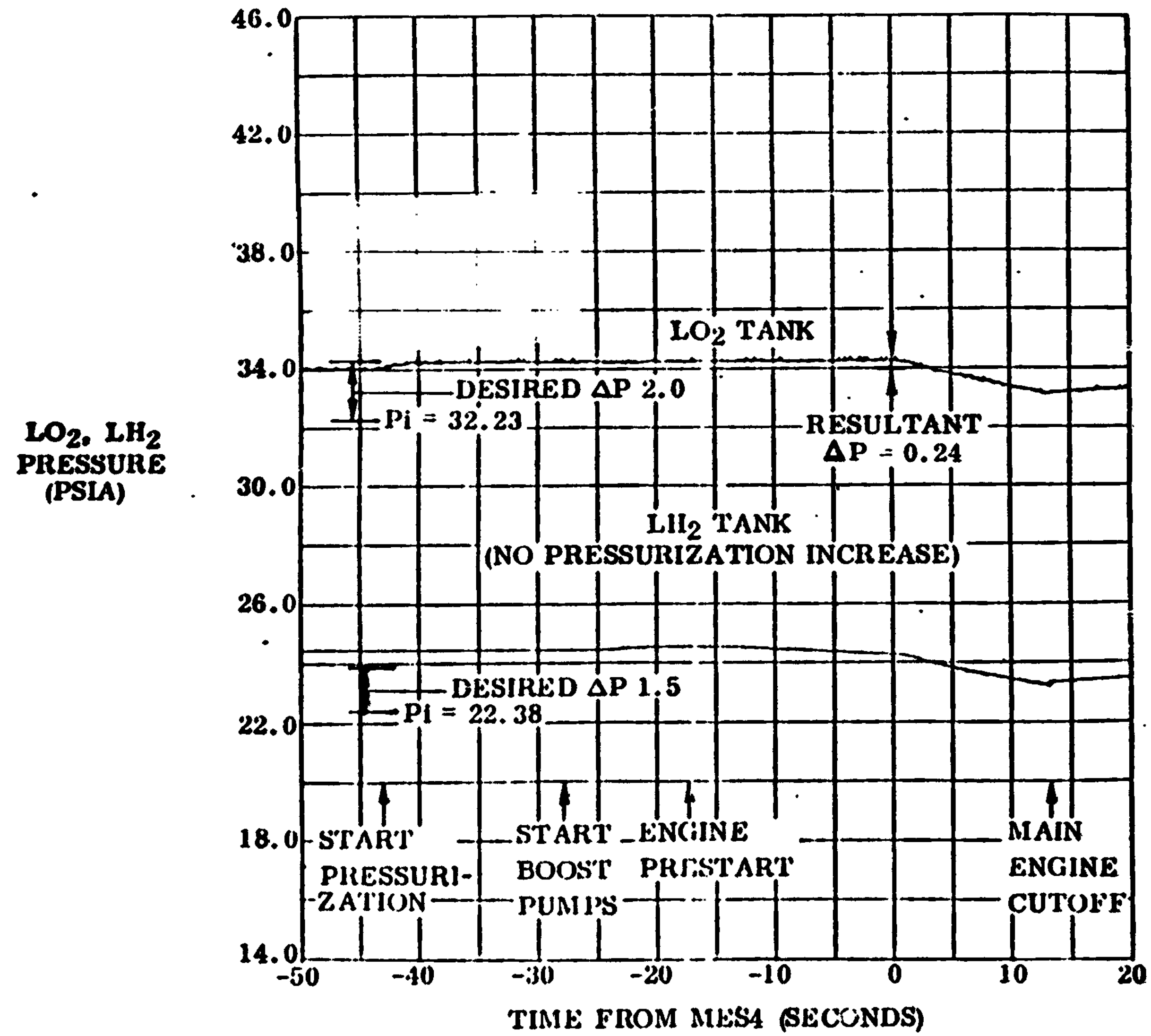


FIGURE 13. PRE MES 4 TANK PRESSURE HISTORIES

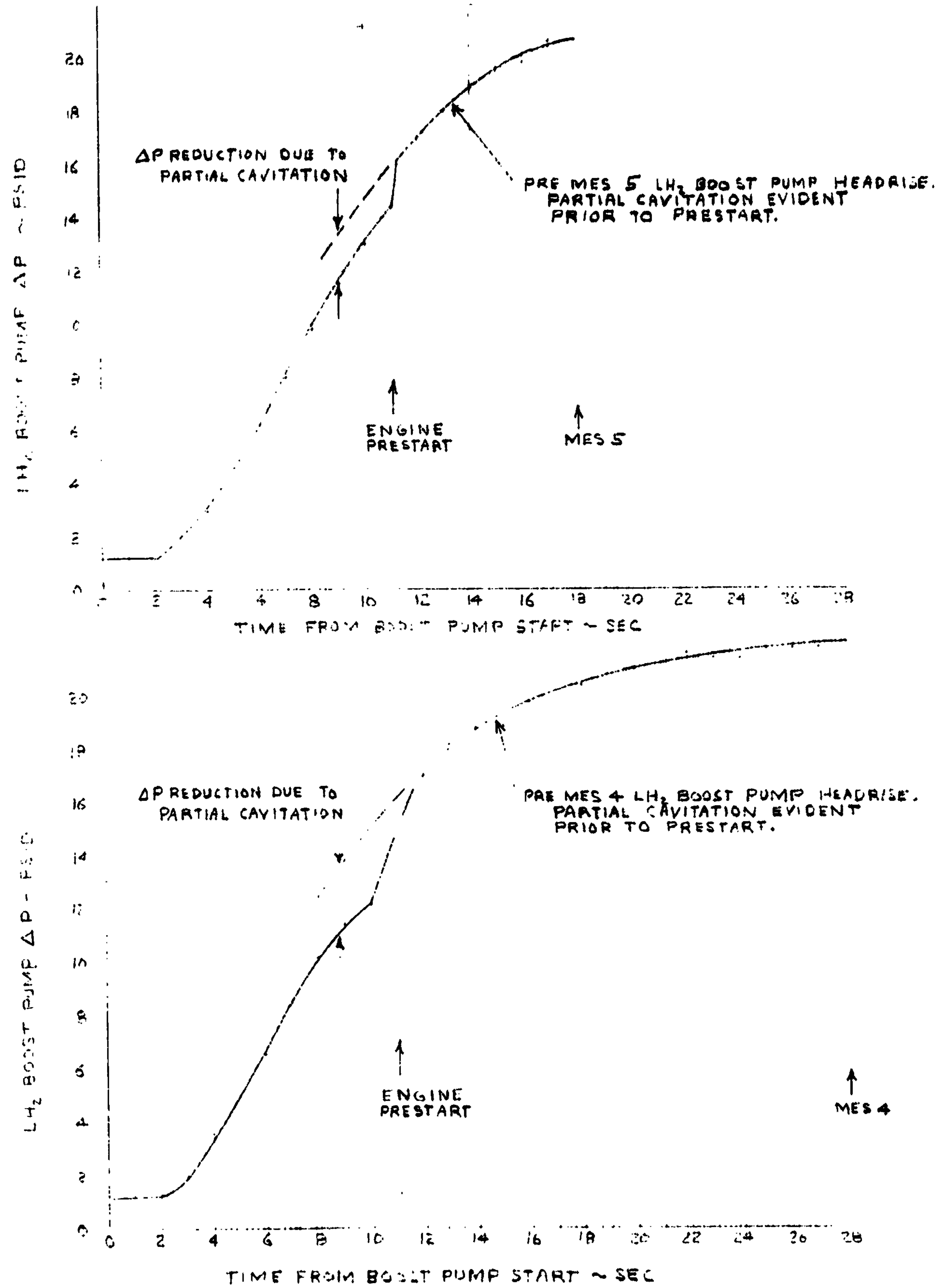


FIGURE 14. LH_2 BOOST PUMP PRE MES 4 AND PRE MES 5 HEADRISE

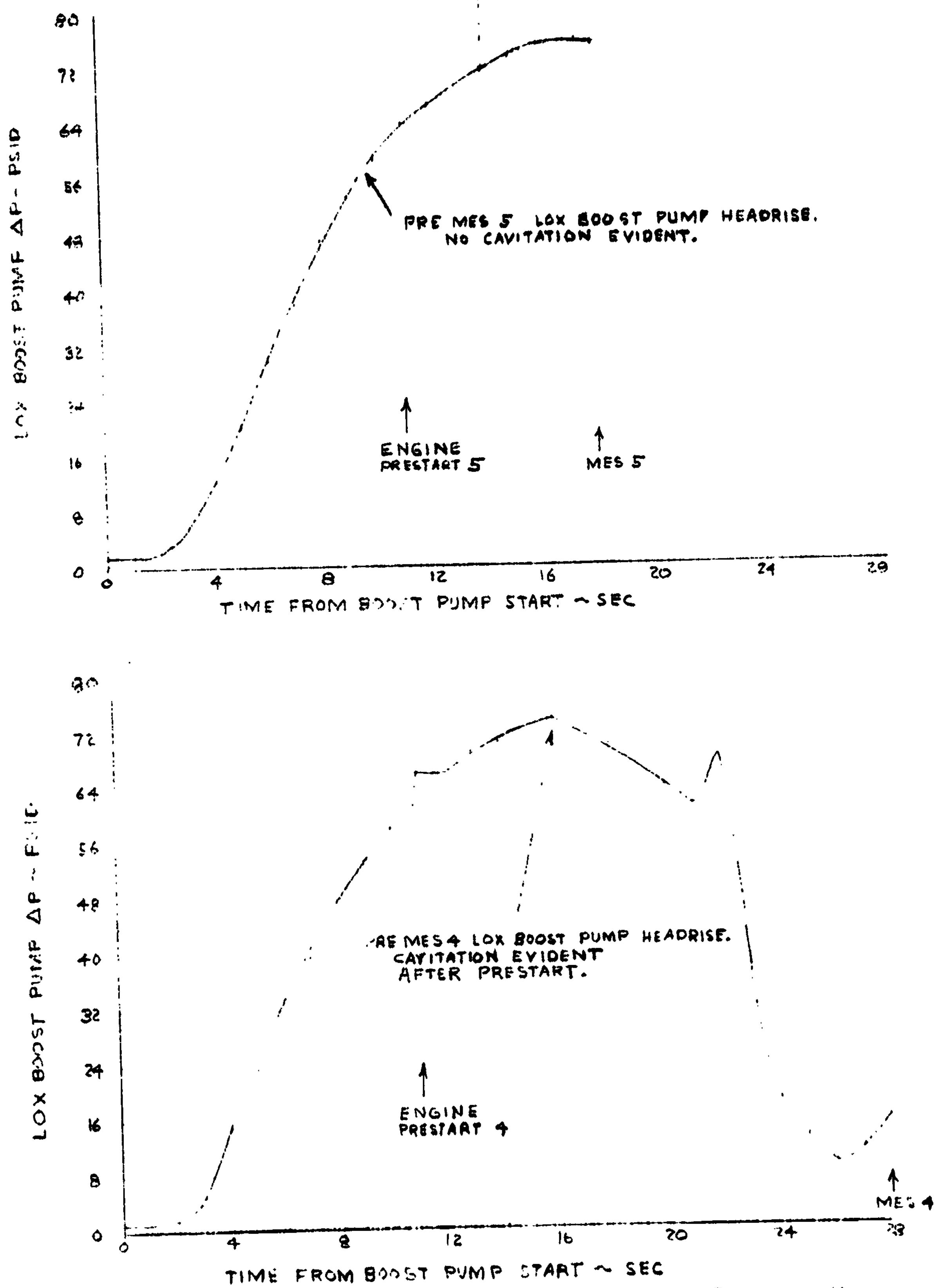


FIGURE 15. LOX BOOST PUMP PRE MES 4 AND PRE MES 5 HEADRISE.

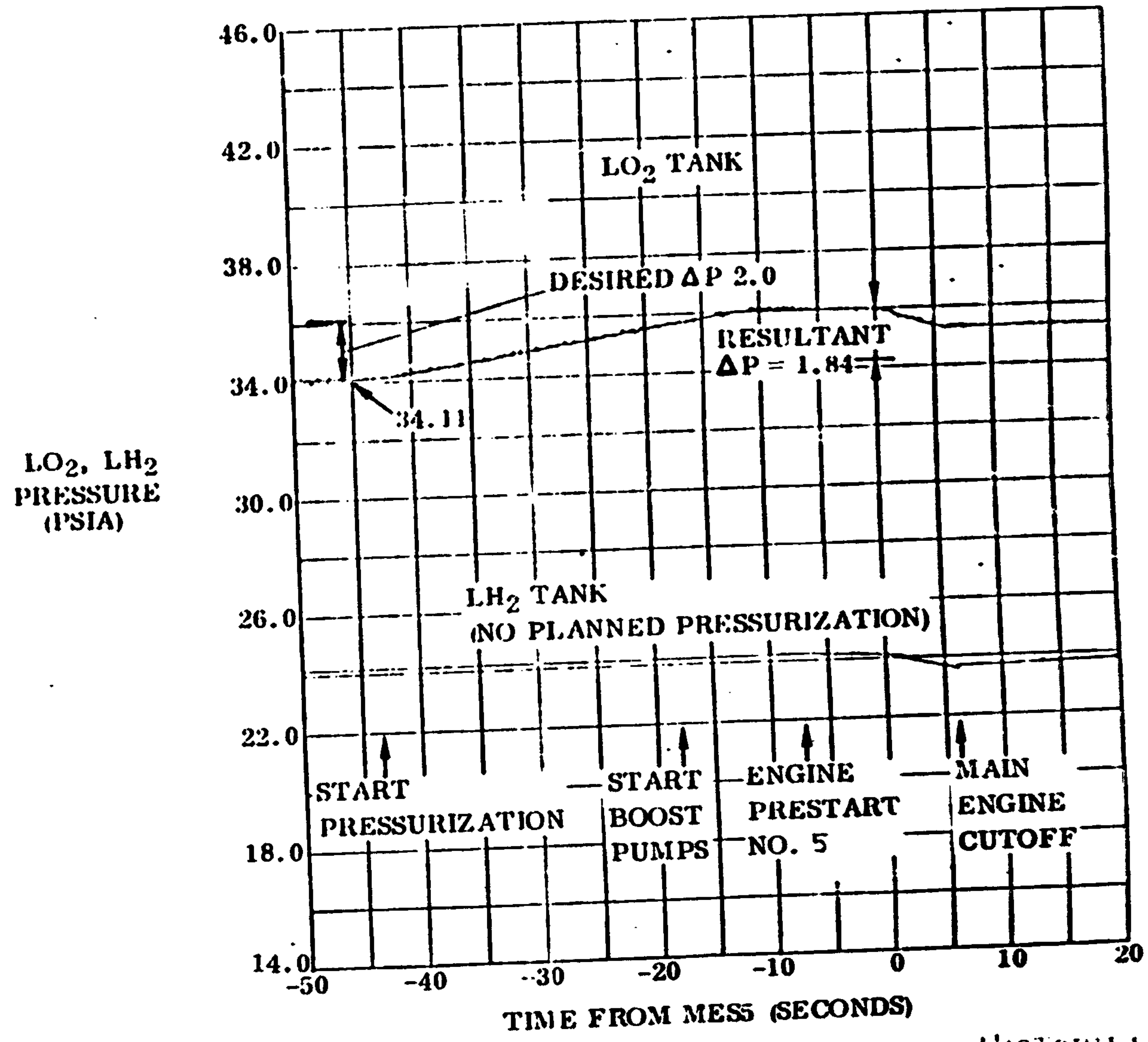


FIGURE 16. PRE MES 5 TANK PRESSURE HISTORIES

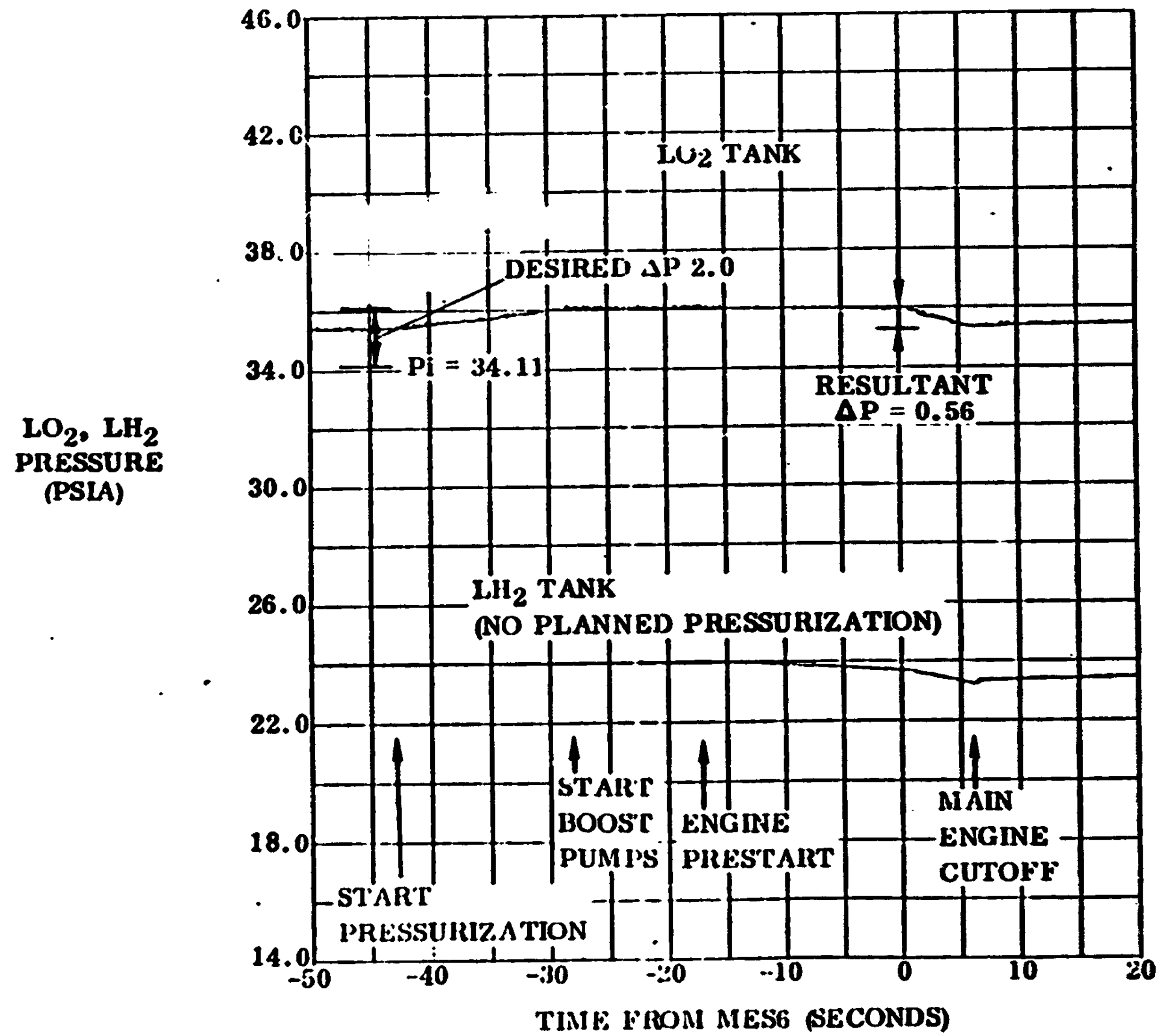
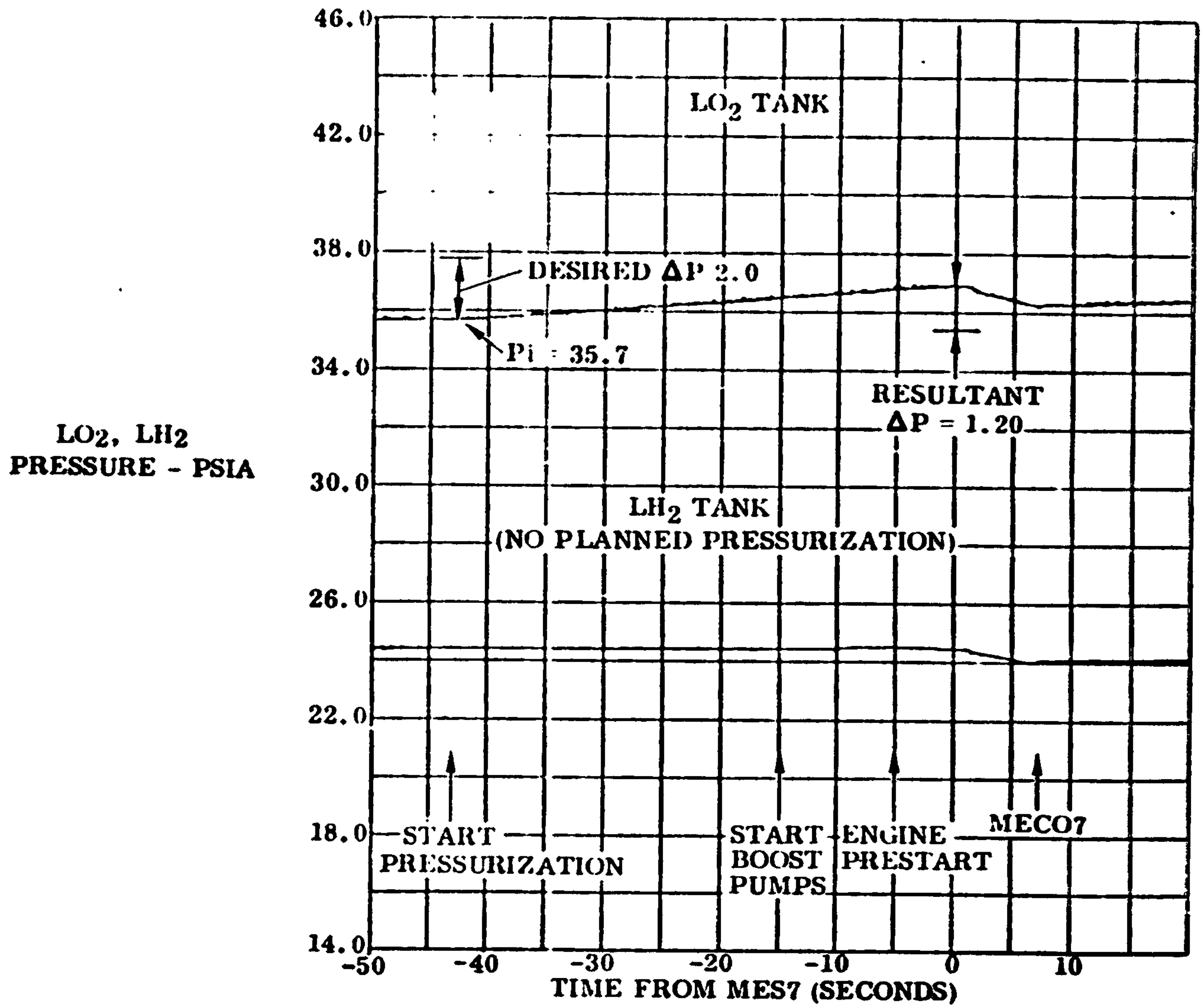


FIGURE 17. PRE MES 6 TANK PRESSURE HISTORIES


LO2, LH2
PRESSURE - PSIA
46.0
42.0
38.0
34.0
30.0
26.0
22.0
18.0
14.0
LO2 TANK
DESIRED ΔP 2.0
Pi = 35.7
RESULTANT
ΔP = 1.20
LH2 TANK
(NO PLANNED PRESSURIZATION)
START
PRESSURIZATION
START
BOOST
PUMPS
ENGINE
PRESTART
MECO7
-50
-40
-30
-20
-10
0
10
TIME FROM MES7 (SECONDS)

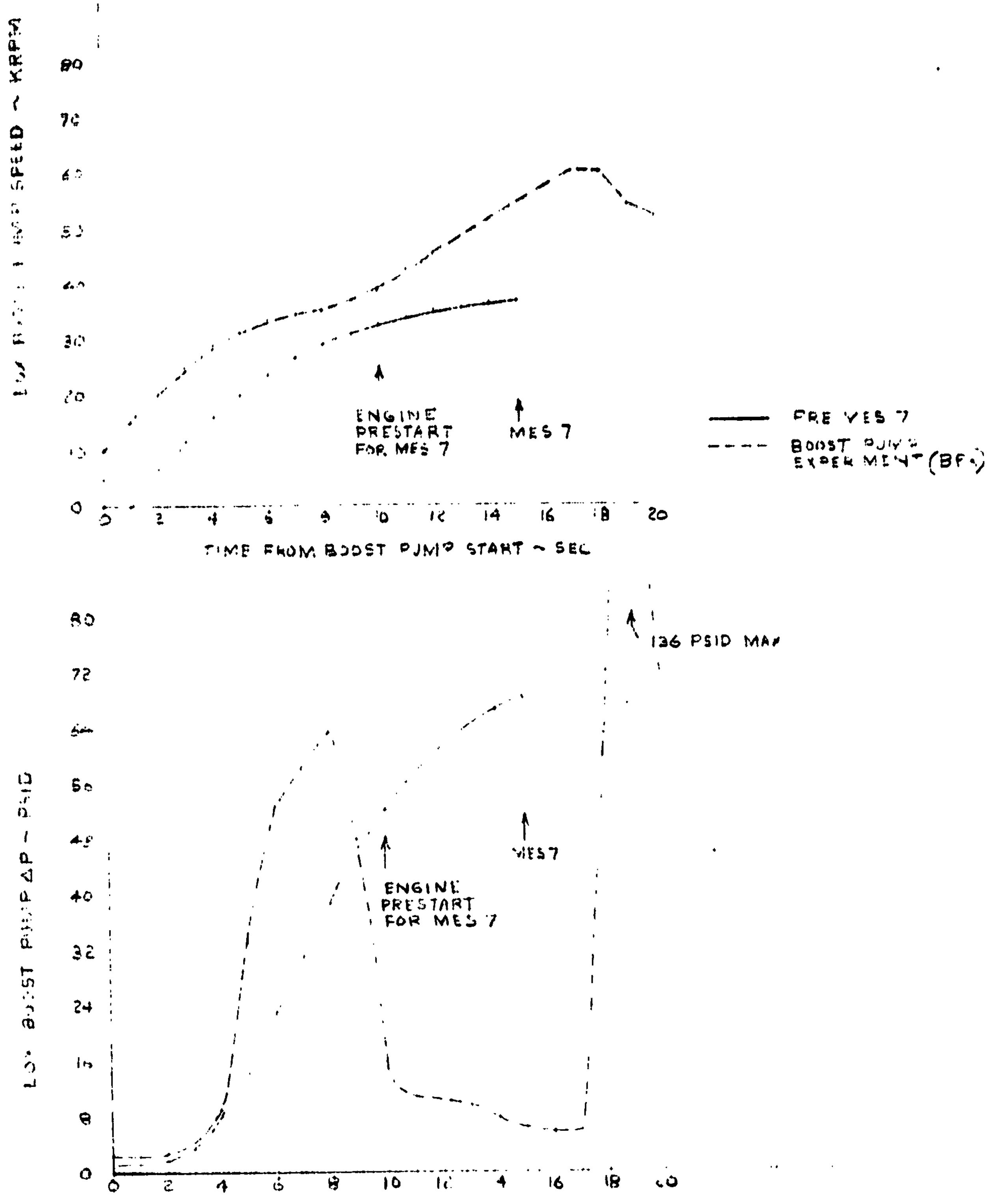


FIGURE 19. LOX BOOST PUMP PRE MES 7 AND BPX PERFORMANCE

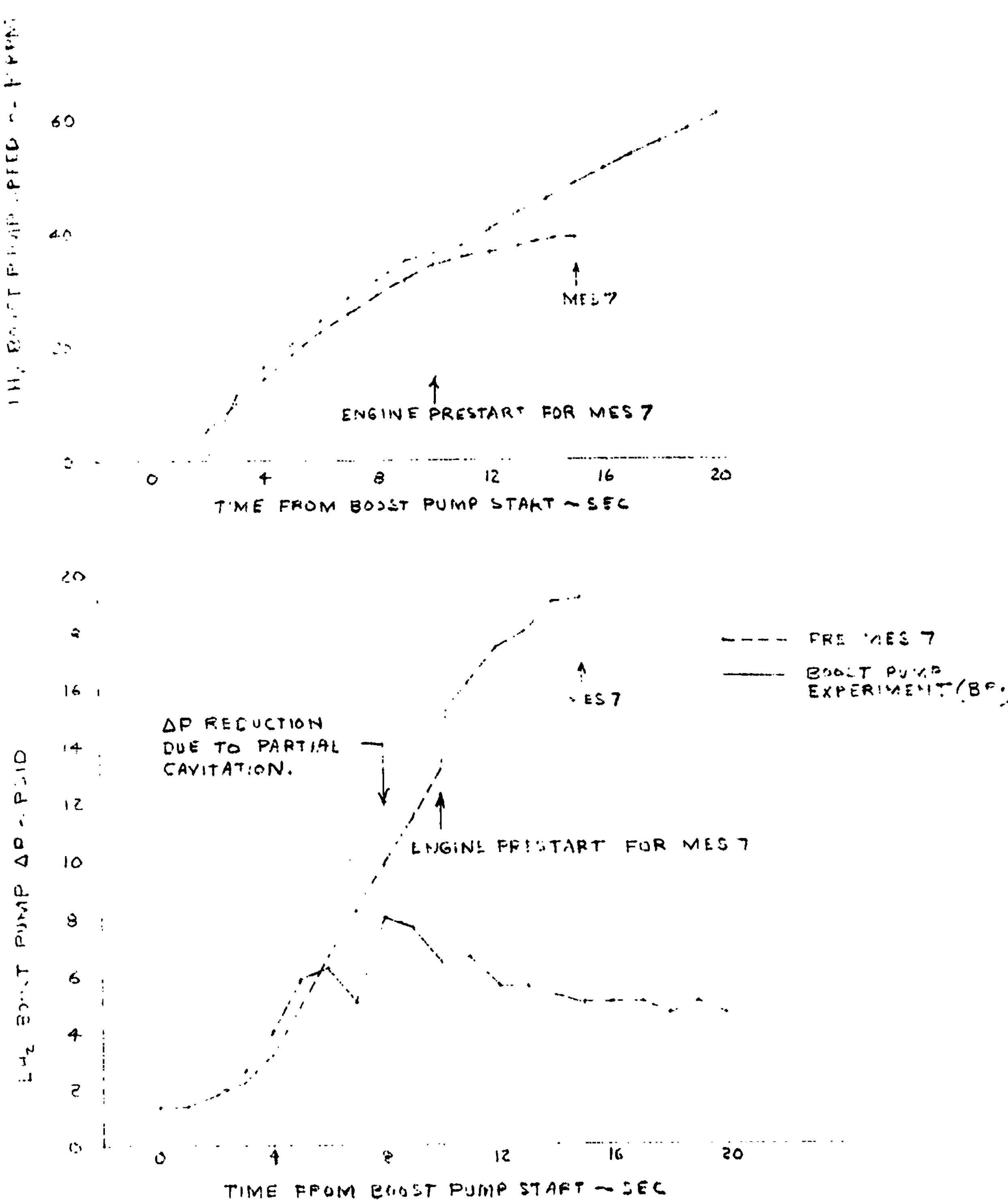


FIGURE 20. LH_2 BOOST PUMP PRE MES 7 AND BPX PERFORMANCE.

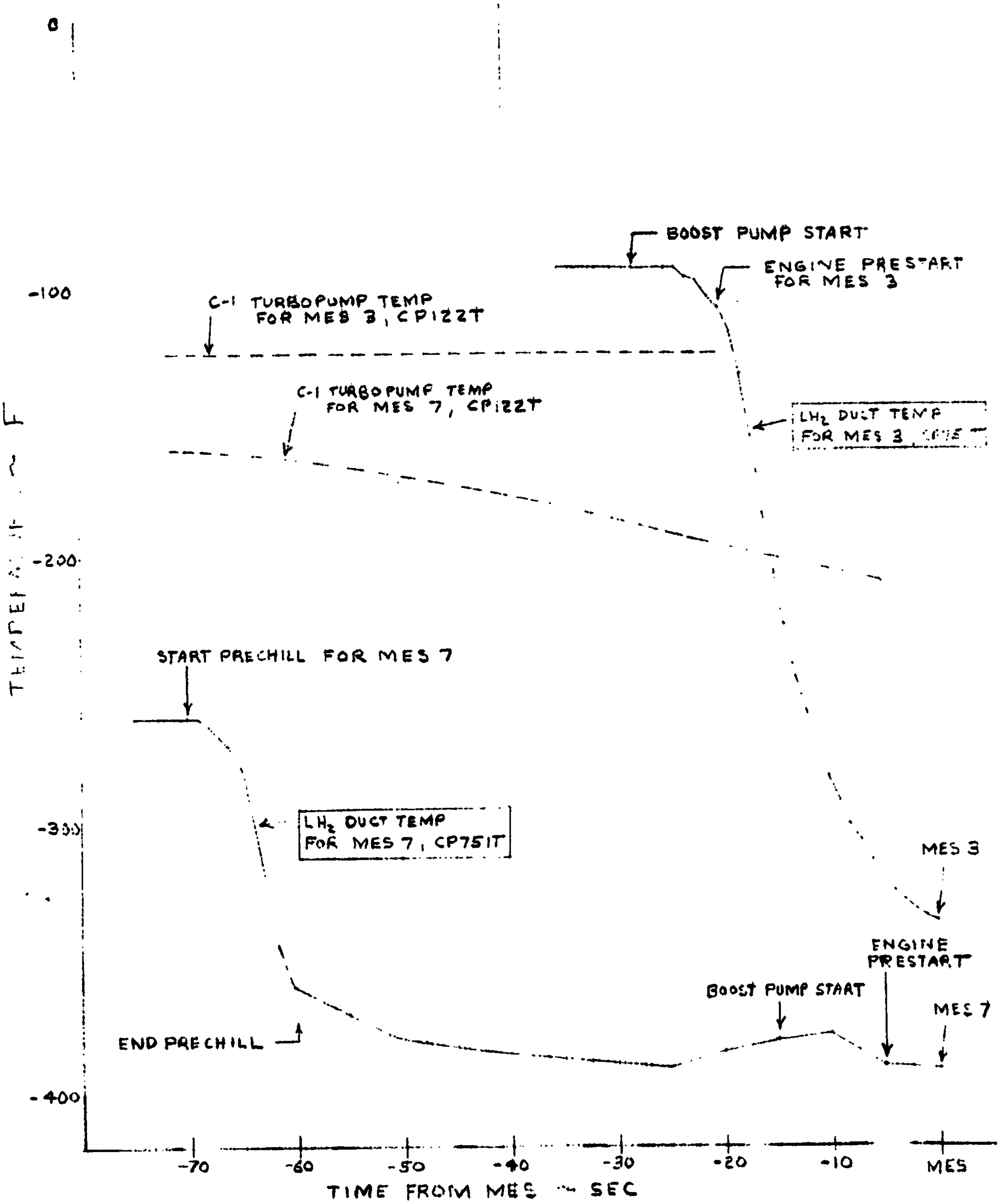


FIGURE 21. COMPARISON OF PRE MES 3 AND PRE MES 7 LH_2 DUCT CHILLDOWNS.