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CENTAUR ZERO GRAVITY COAST AND ENGINE RESTART DEMONSTRATION ON THE TITAN/CENTAUR (TC-2) EXTENDED MISSION

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16. Abstract

The Centaur propellant management and thermal control techniques required for zero gravity coasting were successfully demonstrated during an extended mission following spacecraft separation on the TC-2 flight. As part of the demonstration, two successful engine starts were accomplished. The first engine start followed a one-hour zero gravity coast, and the second engine start followed a three-hour zero gravity coast. All of the Centaur systems performed satisfactorily, the design parameters for zero gravity coasting were verified, and no significant problems were encountered. The flight results showed that the propellant location and behavior, propellant heating, and tank pressure rise rates observed during the zero-gravity coasts were less severe than expected. Consequently, the majority of the propellants remained at the tank bottom, the propellant collection times were very short, and more than 7 hours of coast could have been achieved before a tank venting was required. The tank pressurization prior to the engine starts provided boost pump Net Positive Suction Head values well in excess of the values required. The LO_2 tank pressurization was accomplished by a new bubbler method that greatly reduced the helium usage.

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SUMMARY

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The flight results showed that the propellant location and behavior, propellant heating, and tank pressure rise rates observed during the zero-gravity coasts were less severe than expected. Consequently, the majority of the propellants remained at the tank bottom, the propellant collection times were very short, and more than 7 hours of coast could have been achieved before a tank venting was required. The tank pressurization prior to the engine starts provided boost pump Net Positive Suction Head values well in excess of the values required. The LO_2 tank pressurization was accomplished by a new bubbler method that greatly reduced the helium usage.

INTRODUCTION

The Centaur space vehicle was originally designed as an upper stage with the capability of either a single burn or two-burn mission profile. The two-burn profile contained an engine restart sequence following a limited period of low gravity orbital coast. The Centaur LH_2 tank sidewall was uninsulated and resulted in high sidewall heating rates that increased the ullage pressure and necessitated a tank vent a few minutes after the start of a space coast, and operationally a continuous venting of the tank thereafter (Ref. 1). Consequently, a continuous low level of thrust was required to maintain the LH_2 in a settled condition at the tank bottom. This thrust was provided by two 3-pound H_2O_2 axial thrusters. However, the large H_2O_2 usage resulting from the continuous application of these thrusters, and the large hydrogen boiloff losses from the sidewall heating, resulted in a practical limit of less than one hour for a Centaur space coast.

In order to increase the Centaur space coast duration and performance, the Centaur was modified to enable it to perform a zero gravity coast. There were six major modifications:

1. The addition of a three-layered aluminized mylar, radiation shield to the LH_2 tank to reduce the sidewall heating rate from 28,000 BTU/Hr. to less than 500 BTU/Hr.

2. The incorporation of a tank vent control system to permit the propellant tanks to be vented only when required.

3. The firing of H_2O_2 axial thrusters only to collect the propellants prior to a tank vent or engine restart.

4. The addition of purges to maintain certain lines and components free of liquid.

5. The incorporation of a 180^o thermal roll every 28 minutes to provide uniform heating of the vehicle throughout the long coast.

6. The revision of the propellant tank pressurization techniques to reduce pressurant consumption while still insuring sufficient Net Positive Suction Head (NPSH) for the Centaur boost pumps.

The adequacy of these modifications, and the flight verification of the Centaur zero gravity coast capability, was to be demonstrated by special experiments and engine starts during an extended mission of the TC-2 flight following spacecraft separation. The TC-2 flight results prior to spacecraft separation are presented in reference 2.

The pertinent data obtained from the TC-2 extended mission is used herein to describe three primary areas as they relate to and demonstrate the Centaur zero gravity coast capability. These areas are:

1. The propellant behavior and location within the tanks throughout the zero gravity coast.

2. The propellant tank heating rates and pressure histories.

3. The propellant NPSH behavior and helium usages during tank pressurization prior to an engine start.

TC-2 Extended Mission Description

The extended mission profile planned for the TC-2 flight, following spacecraft separation comprised two major experiments. The first experiment was an engine restart following a one-hour zero g coast. And the second experiment was an engine restart following a three-hour zero g coast. Both experiments were designed to demonstrate the Centaur zero g coasting capability for direct application to future missions; and in particular synchronous orbit missions requiring a long duration zero gravity coast. Approximately 17% of the Centaur propellants were available at spacecraft separation to perform this extended mission.

The first experiment in this extended mission started at spacecraft separation. The Centaur stage was backed away from the spacecraft by a retrothrust obtained from the blowdown of a helium storage bottle. This bottle blowdown provided an average thrust of 38 pounds (300 pounds decaying to one pound) for a period of 18 seconds. Following the retrothrust manuever and throughout the ensuing zero gravity coast, the Centaur propellants were permitted to move freely in the tanks.

At the completion of one hour zero gravity coast, the following sequence of events was initiated to position the propellants, pressurize the tanks, start the boost pumps, and chill down the engines and propellant ducts for the main engine restart #3 (MES-3):

MES 3-420 sec. - fire two 6-pound H_2O_2 thrusters for 300 seconds to collect propellants.

MES -120 sec. - fire two additional 6-pound H_2O_2 thrusters, and enable tank vent if required.

MES -43 sec. - pressurize LH_2 and LO_2 tank.

MES -28 sec. - start boost pumps.

MES -17 sec. - start chilldown (prestart).

MES 0 sec. - main engine start #3.

These events were to culminate in an engine start and firing for 11 seconds.

The second extended mission experiment, designed to obtain Centaur thermal control and propellant management data for a long duration zero gravity coast in order to demonstrate the Centaur capability for a coast to synchronous orbit, started at main engine cutoff #3 (MECO-3). This zero gravity coast was programmed for 3 hours and the propellants were again permitted to move freely about in the tanks.

During this second coast, the Centaur was programmed to perform a 180° roll every 28 minutes, a 10-second firing of the four H_2O_2 axial thrusters every 50 minutes for thermal conditioning of these thrusters, and a vent sequence at 145 minutes into the coast to demonstrate the tank venting technique. At the end of the coast the same propellant collection, tank vent and pressurization, and engine start sequencing were used as after the one-hour zero gravity coast. Exceptions, however, were that the engine chilldown time was extended to 24 seconds and the tank pressurization levels were reduced. At the end of this sequence the engines were to be started and fired until terminated by a weight cutoff.

Preflight Predictions

1. Propellant Behavior:

Prior to the TC-2 flight, drop tower tests and analyses were performed to determine propellant collection times. (The collection time is defined as the time to collect or position all of the liquid to within 0.1 tank diameter of the high Bond Number, static, interface.) (Refs. 3, 4). These determinations were based on assuming the worst possible propellant locations, with all of the liquid at the forward end of the tank prior to collection, as shown in figure 1. In the liquid oxygen (LO_2) tank the thrust barrel was assumed to be initially empty.

The propellant behavior during collection was shown by drop tower testing to be very turbulent, especially in the LH_2 tank configuration. This turbulence resulted in the generation of large bubbles at the tank bottom. A typical example of a complete propellant collection for LH_2 is shown by the simulation in figure 2. The LO_2 collection time, including LO_2 tank thrust barrel filling, was found by drop tower tests to be significantly less than the LH_2 collection time. For the TC-2 flight conditions, the LO_2 collection time would be less than half as long as for the LH_2 collection.

The required propellant collection time based on LH_2 conditions as scaled from drop tower testing, at the TC-2 LH_2 tank liquid loading and Bond Number of 990 (assuming two 6-pound H_2O_2 axial thrusters firing), is 110 seconds. This time increases to 155 seconds if a one H_2O_2 thruster failed condition is assumed. The actual times selected for propellant collection for the TC-2 extended mission were 180 seconds for a collection prior to a vent sequence, and 300 seconds for a propellant collection preceding an engine start sequence.

During venting, two additional 6-pound H_2O_2 thrusters are fired to increase the acceleration while venting. Drop tower testing had shown (Ref. 5) that at this acceleration, at the Centaur LH_2 tank vent rates for saturated vapor, the liquid bulk would not move toward the vent. After the vent period prior to an engine start, 53 seconds was provided for the bubbles generated during propellant collection and venting to rise away from the tank bottom before the start of tank pressurization. A bar chart of these event times is shown in figure 3.

All of the selected times were well in excess of the times determined from drop tower testing in order to provide a margin to cover any uncertainties in scaling of the drop tower test results. For future mission applications it was expected that the propellant collection times, based on TC-2 flight experience, could be greatly reduced.

2. Propellant Tank Heating:

Preflight thermal analyses of the propellant tanks had estimated the maximum net LH_2 tank heating rate at about 3000 BTU/Hr. and a maximum net LO_2 tank heating rate of about 2000 BTU/Hr. for the zero gravity coasts. The primary variable affecting the determination of the tank heating rates, and the corresponding tank pressure rise rates, is the propellant location. The worst case propellant locations for the maximum tank pressure rise rates are the same as shown in figure 1, with the propellants forward and dry walls aft. The maximum predicted pressure rise rates were 3.6 psi/hr. and 4.3 psi/hr. for the LH_2 tank and LO_2 tank respectively. These worst case pressure rise rates were well within the Centaur operational suitability for a zero gravity coast, since over 3 hours of coast could be achieved before the upper tank pressure limits would be reached and a tank venting sequence would be required. The vent sequence initiation pressures (selected to be conservative with respect to the upper tank pressure limits) for the TC-2 extended mission were 27.5 psia and 42.0 psia for the LH_2 tank and LO_2 tank respectively.

3. Tank Pressurization:

There were three primary concerns with tank pressurization after a zero gravity coast:

1. The tank bottom and sump area may be filled with bubbles which collapse when the tanks are pressurized to locally increase the saturation temperature of the propellant.

2. If the LH_2 is not properly settled, the helium required to pressurize the tank may greatly increase due to ullage chilling. In the LH_2 tank a new helium energy dissipator was provided at the pressurant inlet to reduce the incoming helium flow velocity. This new dissipator was required because of the closer proximity of the liquid surface, and the lower acceleration levels that can exist during pressurization of a Titan/Centaur LH_2 tank.

3. In the LO_2 tank a new method of pressurization was used. In this method, helium is injected beneath the surface of the LO_2 through a perforated tube (bubbler) in order to vaporize oxygen and thus greatly reduce the helium required. While extensive ground testing of this method of pressurization was used to determine the bubbler performance (Refs. 6 to 8), there were still some uncertainties of how the bubbler would perform under low gravity conditions, especially for the TC-2 flight application. On TC-2 the LO_2 liquid level after a propellant collection would be only 3.25 inches above the bubbler for MES 4. This low liquid level above the bubbler could result in helium jet penetration into the ullage, or bubble frothing around the tube, which would greatly reduce the bubbler effectiveness.

The preflight predicted helium usages, based primarily on ground test results (Ref. 6) are listed in the following Table:

TABLE 1

Preflight Helium Usage Predictions

Flight Sequence	Helium Usage - Pounds LH2 Tank	Helium Usage - Pounds LO2 Tank
Pre-MES 2 (After a Settled Coast)	0.81 ± .08	.09 ± .03
Pre-MES 3 (After 1 Hour Zero g Coast)	2.41 ± .25	.65 ± .21
Pre-MES 4 (After 3 Hour Zero g Coast)	.91 ± .16	.48 ± .08

The dispersions in the predicted helium usages result primarily from the dispersions with the tank pressure increase and deadband control. The pressurization control system was programmed to provide at least a 3 psi tank pressure increase for both tanks for pre-MES 2 and pre-MES 3 pressurizations. This selected pressure increase was well in excess of the boost pump NPSH requirements of 0.1 psid and 0.8 psid, for the LH_2 and LO_2 pumps respectively, in order to cover the uncertainties associated with the propellant saturation temperature.

For pre-MES 4 pressurization the tank pressure increases were considerably reduced. The time available for pressurization was shortened so that the pressurization NPSH margins could be evaluated.

TC-2 EXTENDED MISSION RESULTS

The experiments performed during the TC-2 extended mission were accomplished as planned. Two successful engine restarts were performed and the results of the zero gravity coasting compared favorably with the preflight predictions. The specific results of the TC-2 extended mission are as follows:

1. Propellant Behavior. One Hour Zero Gravity Coast:

The Centaur LH_2 tank had 12 liquid-vapor sensors to monitor the position of the liquid throughout the zero gravity coasts. The location of these sensors is shown in figure 4. The sensors are similar in construction to those described in ref. 8. There were no liquid-vapor sensors in the LO_2 tanks, so the location of the liquid in this tank had to be inferred from tank pressure behavior, preflight analysis, and drop tower test results.

The LH_2 motion at MECO 2 may be obtained from the LH_2 liquid-vapor sensor activation times as shown in figure 5. The successive wet indications after MECO of CM251X, CM252X, CM248X, CM247X, CM319X, and CM241X indicate that LH_2 had progressively flowed up the tank walls and had reached the top of the tank at the start of the retrothrust at MECO-2 + 72 seconds. This flow probably resulted from slosh amplification at MECO and the boost pump deadhead return flow that occurs during the boost pump spin down after MECO (see Ref. 2).

At the start of the retrothrust period the two bottom sensors CM255X and CM256X went dry, and the sensor CM242X at the top center of the tank went wet, indicating that the retrothrust had resulted in producing rapid flow away from the tank walls and into a column flow up the center axis of the tank. This type of behavior and flow pattern has been observed in drop tower tests (unpublished) for high Bond Number reorientation. An example of this behavior is shown in the drop tower test photo in figure 6A. After the column flow impacted the top of the tank it apparently recirculated back down along the walls to the tank bottom. Sensor CM242X remained wet for only about 120 seconds, then it went dry for the remainder of the zero gravity coast. Sensors CM255X and CM256X returned to a solid wet indication within 120 seconds after the start of the retrothrust. Even with the extremely high negative Bond Numbers (greater than 20,000) provided by the retrothrust the majority of the LH_2 still wound up at the tank bottom as a result of the recirculation.

In the LO_2 tank, the LO_2 thrust barrel was completely covered at MECO 2. The retrothrust was sufficient to drain about 20% of the thrust barrel volume (assuming that the bottom holes of the thrust barrel were instantly exposed), and to flow most of the liquid around the thrust barrel toward the top of the tank. An example of the assumed LO_2 behavior during retrothrust is shown in the drop tower test photo in figure 6B (unpublished). After the retrothrust period the propellants floated freely for about 310 seconds until the start of the propellant collection for the third engine start sequence. During this time the LH_2 and LO_2 achieved a steady state location in the tanks.

A schematic of the probable location of the LH_2 at the start of the propellant collection is shown in figure 7. This figure presents a folded view of the liquid-vapor sensor locations to show their respective distances from the tank wall. The liquid-vapor sensor activations at this time are shown as part of figure 8. Since sensor CM242X is dry, and CM241X is wet, the actual interface at the top of the tank must be located somewhere between the two sensors. The maximum quantity of LH_2 in this location, while maintaining the required spherical shaped interface, is about 70 $ft.^3$. At the bottom of the tank, sensors CM251X, CM252X, CM253X, and CM254X were oscillating between wet and dry thus indicating that the liquid-vapor interface was close to these sensors. The crevice at the tank bottom apparently retains the liquid in a large fillet shape. Unpublished drop tower test data have shown that this crevice retains a small quantity of liquid, even under small negative accelerations.

The stability criteria for this attraction is not fully understood. Since the Bond Number is near zero at this time the interface must be spherical. The minimum amount of LH_2 in the crevice to produce a spherical fillet to contact the sensors is about 170 $ft.^3$. It is also reasonable to assume that a small fillet of LH_2 clings to the forward slosh baffle as shown in figure 7. The maximum amount of LH_2 in this location, assuming a spherical interface is about 10 $ft.^3$. The three liquid locations shown in figure 7 account for nearly all of the liquid present in the tank. The LH_2 liquid location configuration shown in figure 7 is considerably different that the worst case locations (figure 1) assumed in determining the propellant collection time.

In the LO_2 tank the probable liquid location prior to collection is shown in figure 9. The LO_2 that flowed forward during the retrothrust must seek the minimum tank radius, along the tank wall, in the absence of drag forces. This configuration is based on analyses in Ref. 9 and is consistent with the tank heating rates and pressure rise rates observed (see propellant heating section). Note that a small fillet of LO_2 is assumed to remain at the top of the tank to cover the LO_2 tank standpipe entrance.

A spherical bubble is shown inside the thrust barrel. However, depending on how much liquid drained out of the barrel during retrothrust, an elliptical bubble could exist. A large fillet of LO_2 is retained in the crevice between the tank and the thrust barrel in much the same manner as maintained in the LH_2 tank crevice. Here again, for the LO_2 configuration, the liquid locations are considerably less severe than the worst case locations, shown in figure 1, for the preflight analyses.

During the propellant collection period, two 6-pound H_2O_2 axial thrusters are fired providing a Bond Number of 990 and 2410 in the LH_2 tank and LO_2 tank respectively. As shown by the sensor activation sequence in figure 8, the LH_2 was collected in about 40 seconds, and the liquid motion was reduced to low level slosh (less than 10-inch slosh amplitude, below sensors CM251X and CM252X) in about 140 seconds.

All of the LH_2 during collection apparently did not flow down the tank walls. As indicated by the activation of sensor CM242X in the tank center which went wet for 8 seconds, a column flow is evident down the tank centerline. This type of flow during a collection was also observed in some drop tower tests (Ref. 3). Because of this column flow, and the small quantity of liquid at the top of the tank, the collection time was only 40 seconds in comparison with the 300 seconds provided for collection, and the 110 seconds determined for the worst case. The additional time allowed for collection, however, did result in reducing LH_2 slosh, and the liquid-vapor interface level, by providing time for the bubbles generated during collection to rise out of the liquid bulk.

From 140 seconds after collection, thru MES 3, only very low level slosh was indicated by the periodic activations of sensors CM25[illegible] and CM253X located about 1 inch below the static liquid surface. [illegible]e were no signs of splashing, or excessive slosh, during the tank [illegible]rization and engine start sequences. (There was no tank venting at [illegible]tart of the 24-pound thrust period since the tank pressures were no[illegible]gh enough to initiate a vent.) The engine start (MES 3) that terminat[illegible] this one-hour zero gravity coast was completely normal, and it was the first successful engine restart for a cryogenic stage after a zero gravity coast.

2. Propellant Behavior. Three Hour Zero Gravity Coast:

The LH_2 liquid-vapor sensor activations after MECO 3 are shown in figure 10. As after MECO 2, some liquid moves rapidly up the tank wall as shown by the successive wet indication of CM253X, CM254X, CM251X, CM247X and CM248X. Since sensors CM319X and CM320X indicated wet at about 8 seconds after MECO 3, there may have been some LH_2 splashing, possibly as a result of the LH_2 boost pump spin down. The uppermost sensor, CM241X, did not indicate wet until 1500 seconds after MECO 3. Since there was no retrothrust after MECO 3, there was no negative acceleration to quickly relocate large amounts of LH_2 to the forward end of the tank as occurred after MECO 2.

In the LO_2 tank, the initial liquid level at MECO 3 was about one-inch below the top of the thrust barrel. This condition would result in some vapor being trapped in the barrel.

For 8560 seconds after MECO 3 the propellants were permitted to float freely except for two 10-second periods when 4 H_2O_2 axial thrusters were fired for warming (at MECO 3 + 3000 seconds and MECO 3 + 6000 seconds). During these warming firings there were indications of liquid motion along the tank walls, primarily with activations from CM319X and CM320X.

The probable LH_2 configuration at MECO 3 + 8560 seconds is shown in figure 11. The configuration is very similar to the configuration shown for the one hour zero gravity coast except that the oscillating wet-dry indications of sensor CM241X indicates that a much smaller quantity of LH_2 is at the top of the tank. The amount of LH_2 in the tank crevice is also assumed to be the same since the behavior of the bottom sensors was similar.

The LO_2 configuration is assumed to be very similar to the configuration shown in figure 9 except for about 10 ft.^{3} less LO_2 along the tank sidewall.

At 8560 seconds the MECO 3, two 6-pound H_2O_2 thrusters were fired for 180 seconds to collect the propellants for a tank vent demonstration. This thrusting provided Bond Numbers of 1075 and 2660 for the LH_2 tank and LO_2 tank respectively. As shown by the sensor activation data presented in figure 12, the LH_2 was again collected in about 40 seconds, and again some flow was indicated down the tank centerline by sensor CM242X.

Following the collection, the LH_2 and LO_2 tanks were enabled to vent for 40 seconds. The LH_2 remained in a stable, low level slosh mode, throughout the vent period, and there was no indication of LH_2 splashing or forward bulk motion. The LO_2 tank was also vented at this time, and no liquid entrainment was indicated by the LO_2 vent system instrumentation. The propellant collection and vent sequence demonstration was successful with no apparent anomalies.

The LH_2 behavior after the command vent thrusting is also shown in figure 12. Again, the successive wet indications of CM252X, CM247X, CM248X and CM251X show that LH_2 is moving slowly up the tank walls. The movement, however, is much slower than the movement observed after MECO 2 and MECO 3 which was affected by the engine shutdown and boost pump spin down disturbances. Surprisingly, sensor CM241X at the top of the tank goes solidly wet at 140 seconds after thrust termination and remains wet for the remainder of the coast. This wet indication, although real, seems to be anomalous since no intermediate sensor activation was observed. A reasonable explanation of this wet indication is that during the vent period globules of LH_2 were entrained by the drag of the venting vapor breaking from the liquid surface as a result of the bulk boiling. These globules continued to migrate, due to their own inertia, to the top of the tank after the simultaneous vent and thrust termination, and apparently managed to miss sensor CM242X along the way. This type of behavior during venting was previously observed by a TV camera during the second vent sequence of the SIVB AS203 flight, as reported in ref. 10. However, for this explanation to hold, approximately 9 ft.^{3} of LH_2 would have had to be entrained in the vent flow.

After the command vent the propellants again floated freely for the next 1590 seconds. The propellants appeared to assume the same configuration as prior to the commanded vent.

The LH_2 liquid-vapor sensor activations prior to and during the pre-MES 4 propellant collection period are shown in figure 13. The LH_2 flow during collection was very similar to the flow observed during the two previous propellant collection periods. Both wall flow and centerline flow were observed, and the collection time was about 37 seconds, well within the 300-second time period provided. Low level slosh was indicated throughout the subsequent tank venting, tank pressurization, and main engine start sequence. The engine start (MES 4) that followed this 3-hour zero gravity coast was successful and normal.

Throughout the entire one-hour and three-hour zero gravity coasts, the majority of the propellants were retained at the tank bottom and sump areas. The LH_2 tank crevice, and LO_2 tank thrust barrel and crevice, appear to act as propellant acquisition devices in maintaining liquid at the proper tank locations for an engine start attempt. It is believed that this behavior is normal for a Centaur zero gravity coast where no large drag forces are acting on the vehicle for long periods of time.

3. Propellant Heating and Tank Pressure Rise Rates:

During both the one-hour and three-hour zero gravity coasts, the Centaur vehicle was exposed to full broadside heating from the sun. The longitudinal cone angle with respect to the sun was between 95° and 75° throughout most of coast time. These cone angles produced maximum space heating for the LH_2 tank, and near maximum heating for the LO_2 tank.

The LO_2 and LH_2 tank pressure histories during the one-hour zero gravity coast are presented in figure 14. The tank pressure increase, from MECO 2 + 100 seconds to the start of tank pressurization at MECO 2 + 3180 seconds was only 1.3 psi for the LH_2 tank and 1.6 psi for the LO_2 tank. The one-hour coast was accomplished without the need to vent the tanks. At the observed average tank pressure rise rates of 0.026 psi/min. for the LH_2 tank, and 0.031 psi/min. for the LO_2 tank, a tank vent sequence would not have been initiated until more than 7 hours after MECO 2. These tank pressure rise rates were much less than the worst case preflight predicted rates, primarily as a result of the less severe propellant locations in the tanks which prevented significant heating directly to the tank ullage.

The sharp increase in tank pressure that occurred at MECO 2 is primarily due to the release of energy from the propellant at engine shutdown. At main engine thrust termination head pressure is lost, and propellant is vaporized as it attempts to come into equilibrium with the ullage pressure. This post-MECO pressure behavior has also been observed during settled coasts (Ref. 2).

At the start of the propellant collection period for the programmed vent sequence there is a small decrease in the LH_2 tank pressure (0.1 psi) and LO_2 tank pressure (0.2 psi) which indicates that some slight superheat had accumulated in the ullage during the coast. For all practical purposes, it can be assumed that the liquid absorbed all of the incoming heat to the tanks during the coast.

Part of the observed tank pressure rise during the coast resulted from the effects of the zero gravity helium purges that discharge into the tanks. In the LH_2 tank, the effect of the 0.048 pound/hr. helium purge into the liquid at the top of the tank, thru the energy dissipator, contributed about 0.06 psi/hr. to the pressure rise rate. This contribution can be considered negligible. In the LO_2 tank, however, the effect of the helium purge can be significant if the purge bubbles thru liquid. For the LO_2 liquid locations shown in figure 9, the 0.0422 pound/hr. purge through the standpipe, and the 0.0134 pound/hr. purge through the bubbler can bubble into liquid. This bubbling will vaporize oxygen, as it does during LO_2 tank pressurization, and can contribute as much as 1.2 psi/hr. to the tank pressure rise rate. This contribution is about 70% of the average pressure rise rate observed during the one-hour coast. If only the partial pressure of the helium purge is taken into account, the resulting pressure rise contribution reduces from 1.2 to 0.1 psi/hr.

The tank pressure histories during the 3-hour zero gravity coast are presented in figure 15. The tank pressure increase, from MECO 3 + 100 seconds to the start of the propellant collection for the command vent at MECO 3 + 8560 seconds, was 2.5 psi for the LH_2 tank and 2.0 psi for the LO_2 tank. The periodic thermal roll maneuvers and H_2O_2 axial thruster warming firings, which occurred during the coast served to depress the tank pressure rise rate by mixing the liquid and ullage, or by spreading the liquid out to provide large surface areas for cooling the ullage by conduction. The roll maneuvers and thruster firings reduced the accumulated superheat as shown by the slight pressure dips or levelings in figure 15. The resulting overall pressure rise in the LH_2 tank was very close to the rise expected for thermodynamic equilibrium conditions. The LH_2 saturation pressure corresponding to the temperature indicated by the sump temperature probe (CP32T) followed the ullage pressure very closely. The net LH_2 tank heating rate, as calculated by assuming thermodynamic equilibrium conditions in the tank with all of heat input going into the liquid, was determined to be 1970 BTU/Hr.

In the LO_2 tank part of the pressure rise is produced by the helium purges and, as a result, the saturation pressure of the liquid bulk is difficult to determine. A maximum conservative estimate of the LO_2 tank heating rate can be calculated by assuming that none of the purges passes through liquid, and that the entire tank pressure rise results from the propellant saturation pressure increase. Based on this assumption, the LO_2 tank net heating rate is 1670 BTU/Hr.

The net heating rates to either propellant tank are quite low, and within the preflight predictions. These net heating rates include the heating across the common bulkhead. The low LH_2 tank heating rate did verify that the new LH_2 tank sidewall, 3 layer, radiation shield had performed satisfactorily. (The outer shield temperatures varied from $+100^{o}F$ to $-200^{o}F$ as the sun cycled from one side of the vehicle to the other.)

4. Vehicle Thermal Roll:

The 180^{o}, 90-second, thermal roll maneuver performed every 28 minutes throughout the 3-hour zero gravity coast was generally satisfactory in providing uniform heating of the Centaur propellant tanks, and forward and aft components. However, as a result of this selected 180^{o} roll, and since the vehicle was moving radially out from the earth, the same components would arrive at the same position with respect to the sun, after every other roll. Consequently, certai components continually increased in temperature during the coast. An example of this temperature behavior is shown in figure 16, for the Centaur S band transmitter. As shown in this figure, the transmitter temperature had cyclically increased to near its upper temperature limit of $176^{o}F$ by MECO 4. In order to avoid this type of temperature behavior for future missions, a different thermal roll is recommended. Either a continuous slow roll, or a roll that indexes at an angle to avoid frequent, exact, repetition of the sun view angle, would be satisfactory.

5. Tank Pressurization:

The LH_2 and LO_2 tank pressure histories, together with the propellant saturation pressure histories, during the tank pressurizations prior to MES 2, MES 3, and MES 4 are shown in figures 17, 18, and 19. The propellant saturation data were obtained from the boost pump inlet temperature probes located in the tank sumps. A schematic of the probe locations with respect to the boost pumps is shown in figure 20.

The pertinent data from the 3 pressurizations are summarized in the following table. The NPSH listed is the difference between the tank ullage pressure and the propellant saturation pressure as obtained from the figures.

TABLE 2

TC-2 Pre-MES Tank Pressurization Data

Tank	Press. Phase	Tank Press. Increase, PSID	Helium Required Pounds	NPSH at B/P Start PSID	NPSH at Prestart PSID	NPSH at Engine Start PSID	Tank Ullage, $Ft.^3$
LH_2	MES 2	3.3	0.76	1.8	2.8	3.4	314
LO_2	MES 2	4.0	0.14	0.3	3.2	2.9	87
LH_2	MES 3	3.2	2.10	0.7	3.5	3.9	1112
LO_2	MES 3	3.5	0.57	0.5	2.7	2.3	315
LH_2	MES 4	1.3	1.10	0.0	1.0	1.4	1149
LO_2	MES 4	2.9	0.56	0.0	1.7	2.3	325

The tank pressurization prior to MES 2 followed a 22-minute settled propellant coast. Prior to boost pump start, the propellant saturation pressure in the sump initially increases at the same rate as the tank ullage pressure (figure 17). This increase in saturation pressure is attributed to bubble collapse and condensation within the sump volume, and is typical of the behavior observed during previous settled coast missions. The vapor is generated during coast by space heating to the sumps and propellant feed line. In the LO_2 tank the saturation temperature begins to fall immediately at boost pump start, but in the LH_2 tank there is characteristically about a four-second delay because of the temperature probe location.

After boost pump start, cool liquid is drawin in from the tank bulk by the boost pump deadhead operation, which results in a decrease of the sump liquid saturation temperature. By the time of prestart, the propellant saturation pressures are well below the tank pressures, thus resulting in boost pump NPSH values well in excess of the minimum requirements.

For the pre-MES 3 and MES-4 tank pressurizations, after the zero gravity coasts, there was concern that the quantity of vapor in the sump, as a result of propellant movement, may be significantly greater than the typical vapor volume (about 10%) existing after a settled propellant coast. In addition, there was concern that the bulk itself may contain vapor bubbles as a result of tank heating, or from turbulence during propellant collection, or from bubble generation during the venting of saturated vapor. These large quantities of vapor could collapse and increase the bulk propellant saturation levels to greatly affect the boost pump NPSH conditions.

The behavior of the propellant saturation pressures during the pre-MES 3 and MES-4 tank pressurizations was remarkably similar to the pre-MES-2 saturation pressure behavior. The saturation pressure increased prior to boost pump start at the same rate as the tank pressure (figures 18 and 19), and after boost pump start the saturation pressure decayed in the same manner as observed during the pre-MES-2 pressurization. The resulting NPSH values from prestart through MES, for the pre-MES-3 and MES-4 pressurizations, were still well above the minimum boost pump values required. For the pre-MES-4 pressurization it should be noted that the tank pressurization levels were significantly reduced.

The similarities in the saturation pressure behavior compared to a settled coast condition resulted from the sumps remaining filled with liquid throughout the entire zero gravity coast periods. In addition, the liquid surrounding the sump areas was apparently bubble free as a result of providing adequate propellant collection and bubble rise times. Based on the TC-2 flight results, it is apparent that a significant tank pressurization reduction, from the normal 3.0 psid level, can be achieved and utilized.

The helium usages for the tank pressurizations are also listed in Table 2. These usages are very close to the expected usages presented in Table 1. The new method of pressurization in the LO_2 tank through the bubbler proved to be very reliable, controllable, and predictable. The bubbler pressurization reduced the LO_2 tank helium usages by a factor of 4 in comparison with direct ullage pressurization, even for the pre-MES-4 pressurization where the LO_2 level was only 3.25 inches above the bubbler. The LH_2 tank helium usages and tank pressurization rise rates indicate that no liquid splashing was generated by the helium flow through the new helium energy dissipator, even for the pre-MES-2 pressurization where the liquid level was within 6 feet of the dissipator exit.

CONCLUSIONS

The results of the TC-2 extended mission showed that the propellant location and behavior, propellant heating, and tank pressure rise rates for Centaur zero gravity coasting were less severe than expected. Most of the propellants remained at the tank bottoms, resulting in propellant collection times much shorter than the worst case preflight predictions. Most of the tank heating was absorbed by the liquid, resulting in tank pressure rise rates much lower than the maximum predicted rise rates. A significant portion of the LO_2 tank pressure rise was produced by the tank zero gravity purges. More than 7 hours of zero gravity coasting could have been achieved before a tank venting was required.

The tank pressurization prior to the engine starts provided NPSH values well in excess of the values required. The helium usages for the pressurizations were in good agreement with the preflight predictions. The LO_2 tank pressurization was successfully accomplished by helium injection through a bubbler that greatly reduced the helium usage.

All of the Centaur systems and design parameters required for zero gravity coasting, were verified, and no significant problems were encountered.

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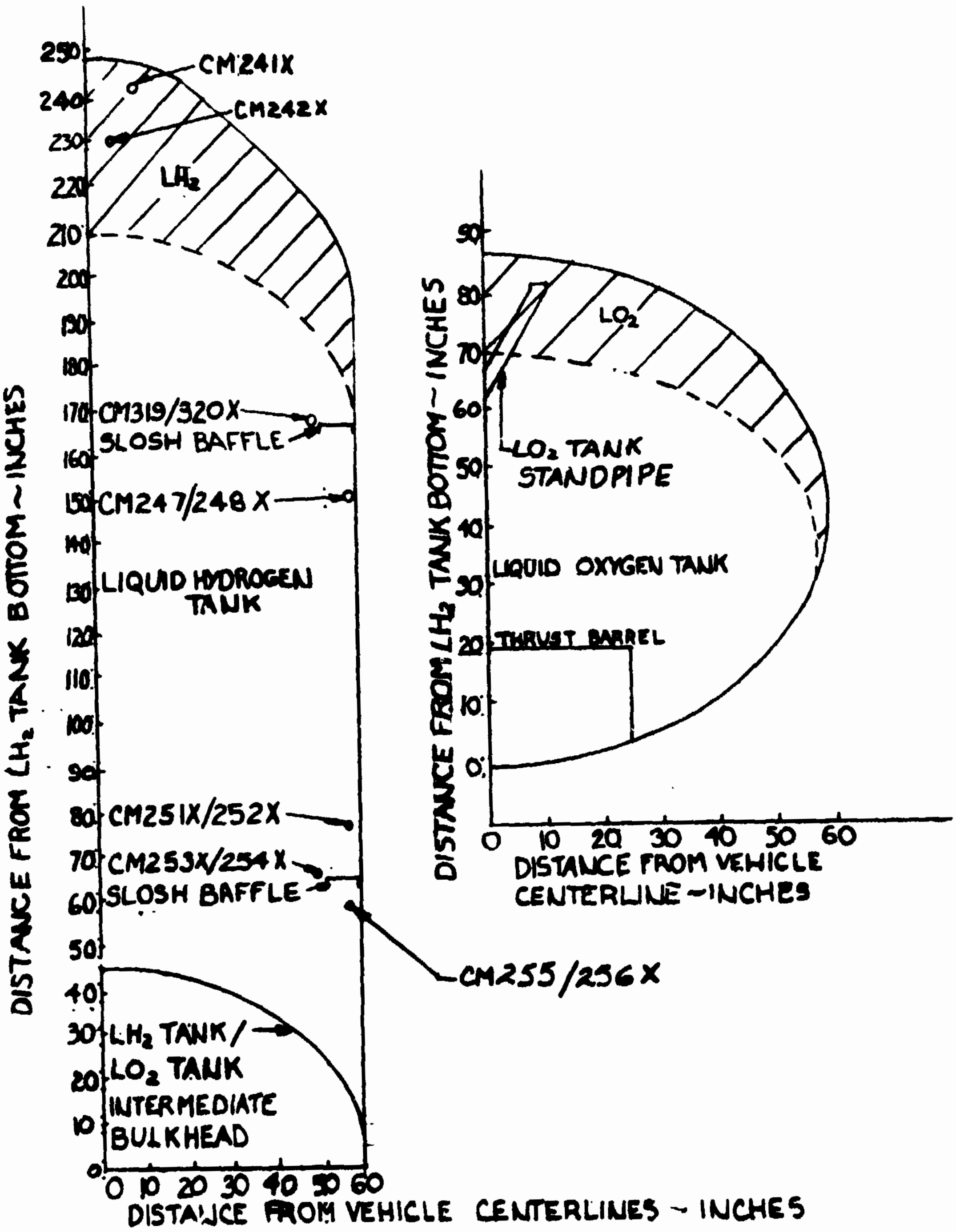

Figure 1 Propellant Locations Prior to Collection, Assumed for Preflight Analyses and Testing

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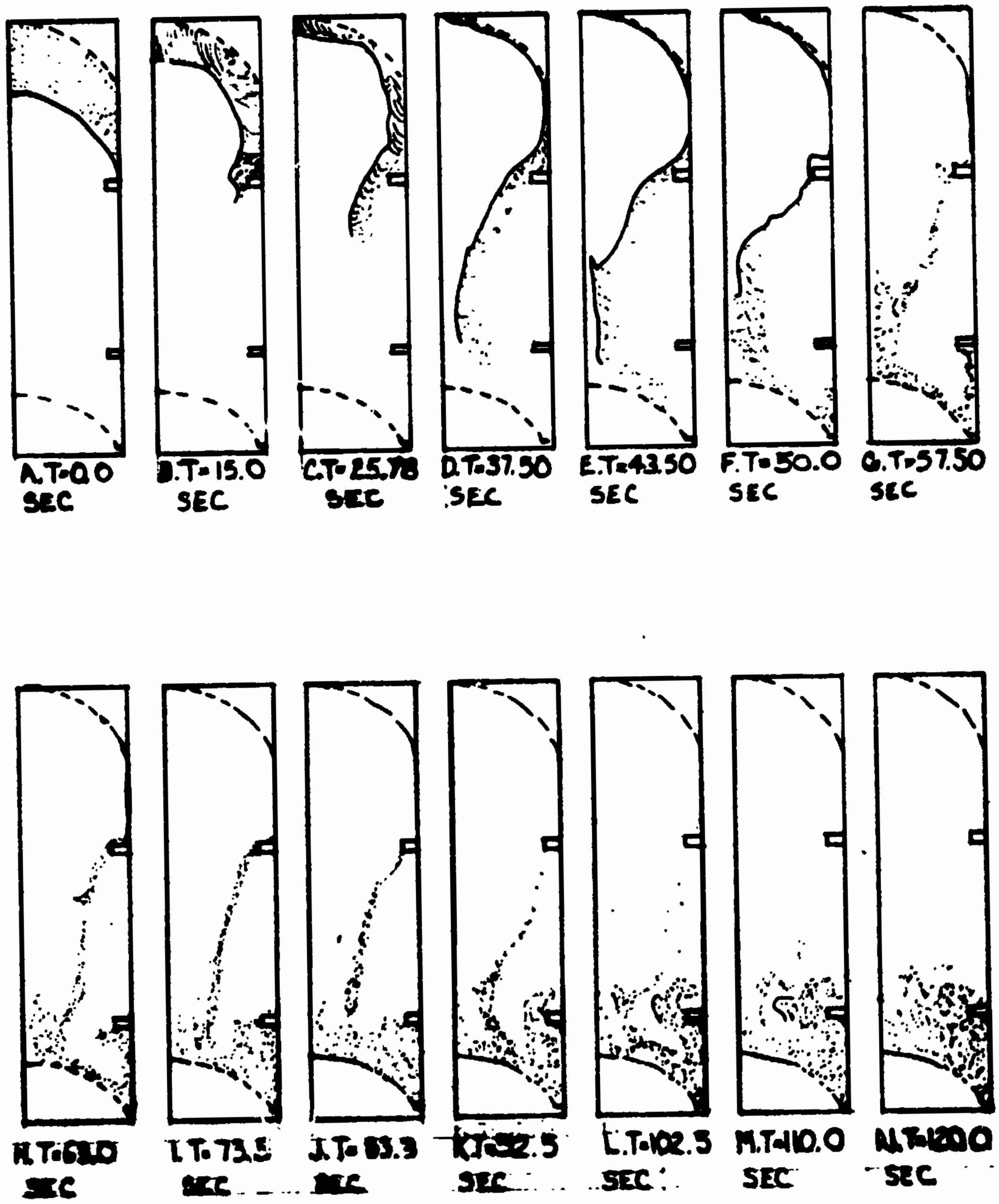

Figure 2 A Computer Simulation of Liquid Hydrogen Collection at a Bond Number of 575

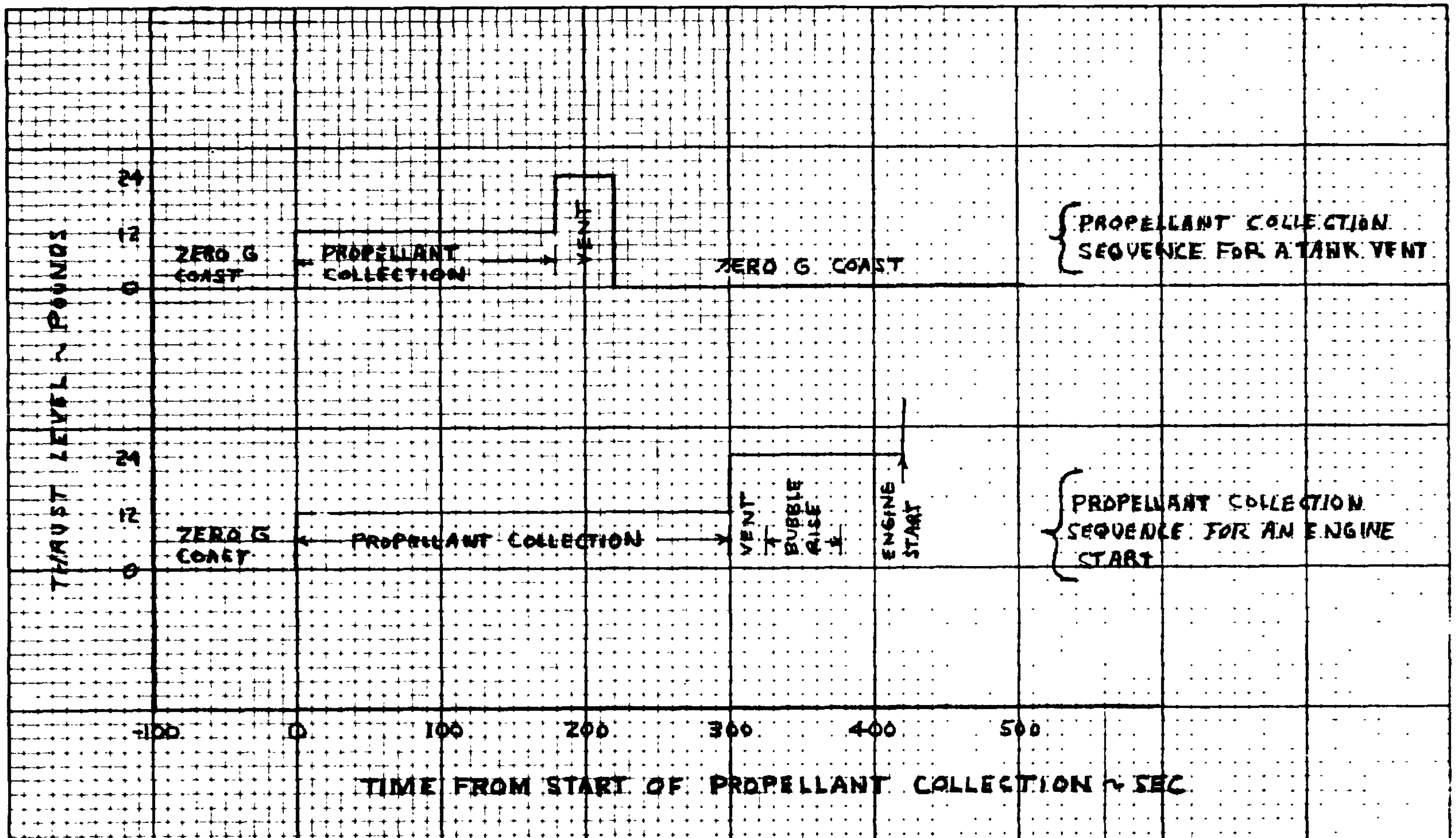

FIGURE 3 TC-2 PROPELLANT COLLECTION SEQUENCES

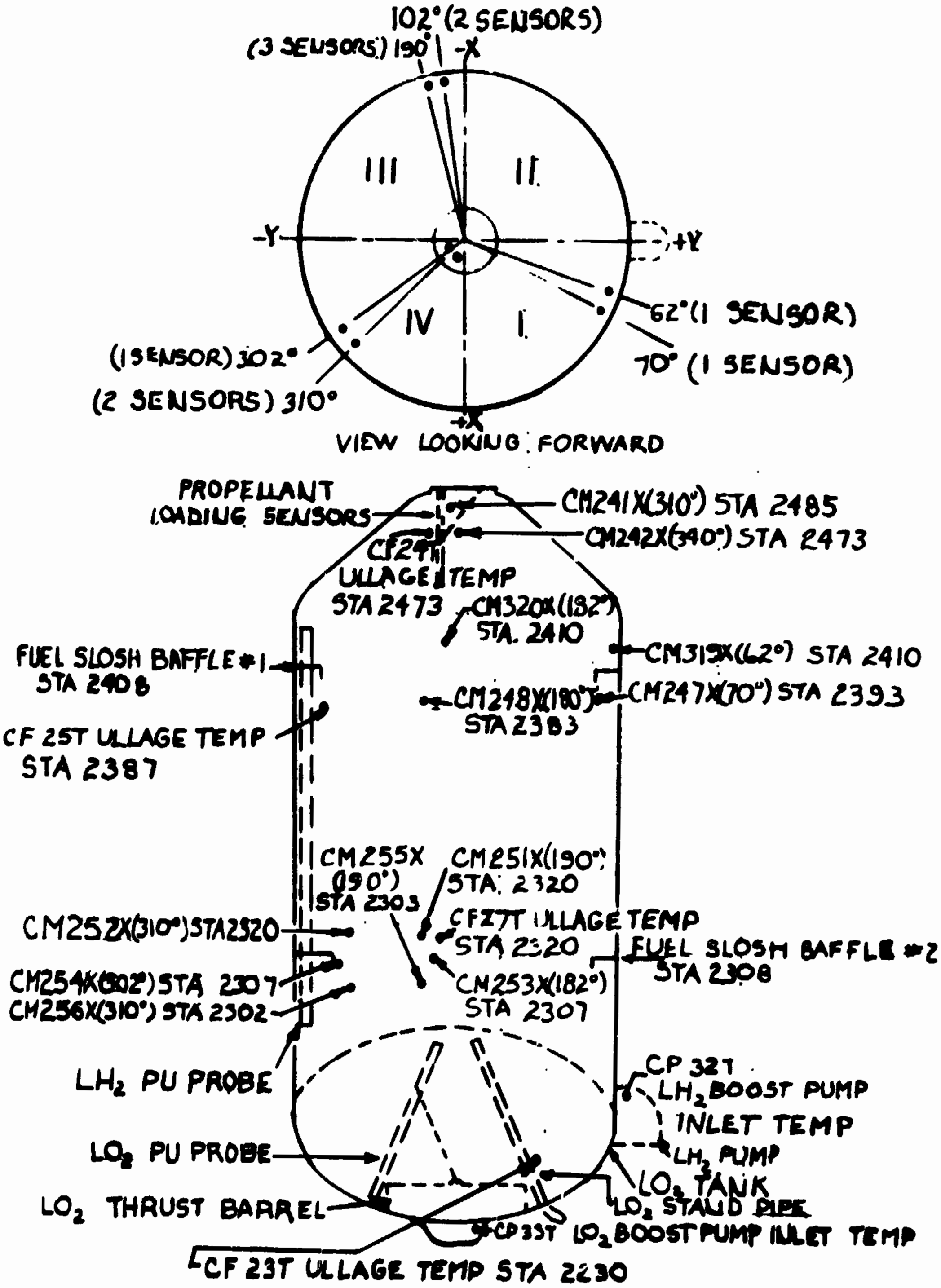

Figure 4 Centaur LH_2 Liquid/Vapor Sensors

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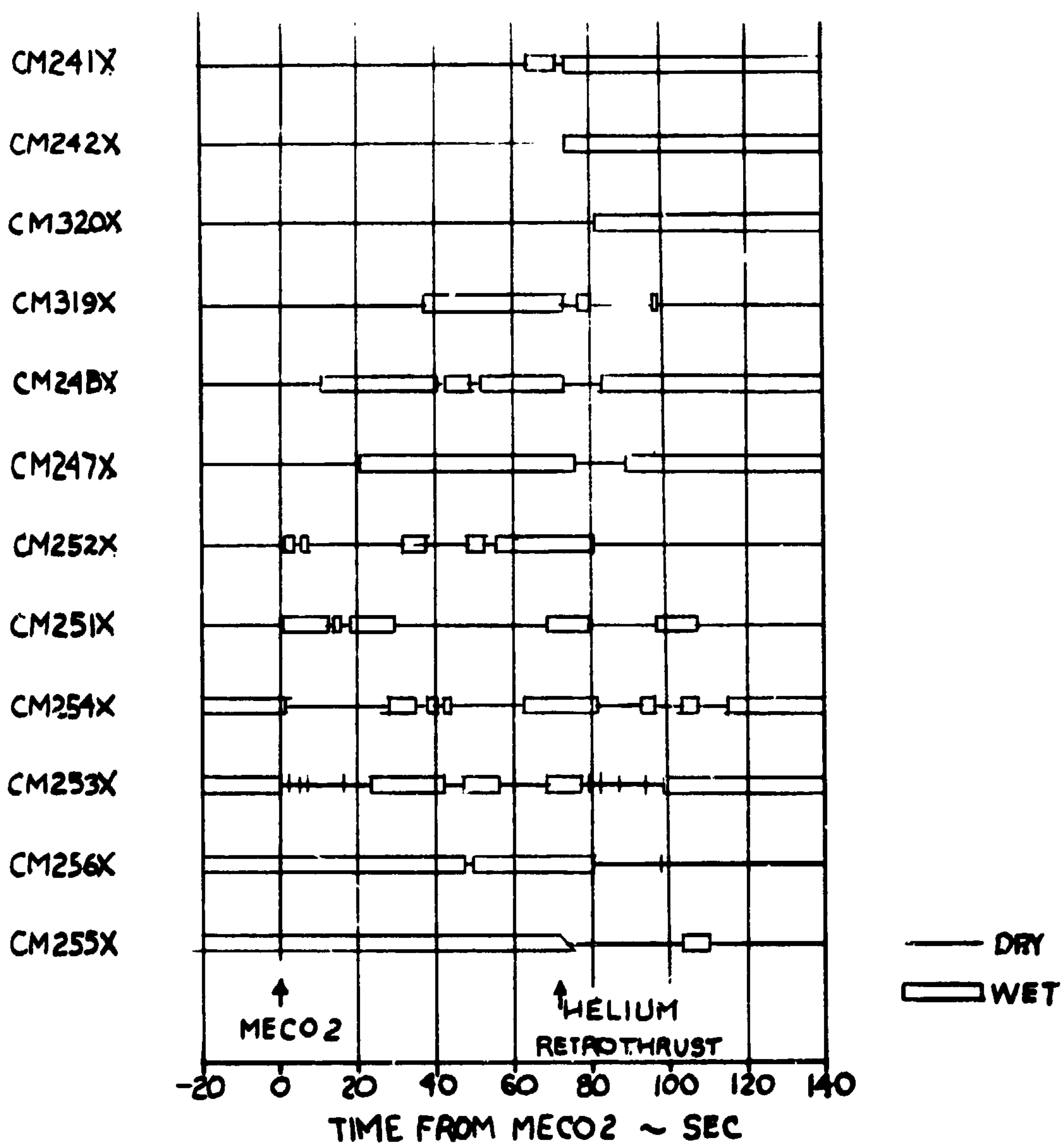

Figure 5 Liquid Hydrogen Behavior at MECO 2

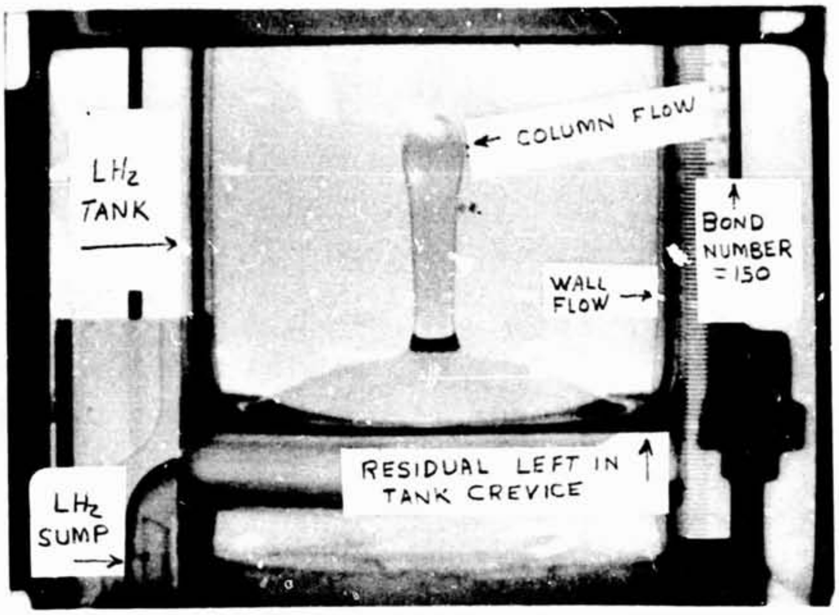

FIGURE 6A. EXAMPLE OF COLUMN FLOW UP TANK CENTER OBSERVED DURING DROP TOWER TEST IN 20 CM. TANK.

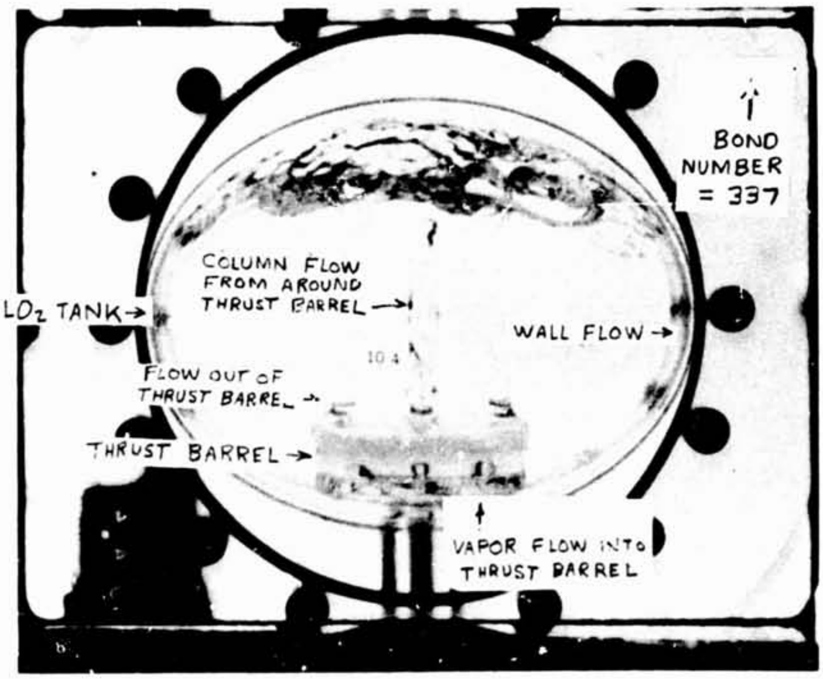

FIGURE 6B. EXAMPLE OF REORIENTATION FLOWS AT HIGH BOND NUMBERS OBSERVED DURING DROP TOWER TEST IN 15 CM. TANK

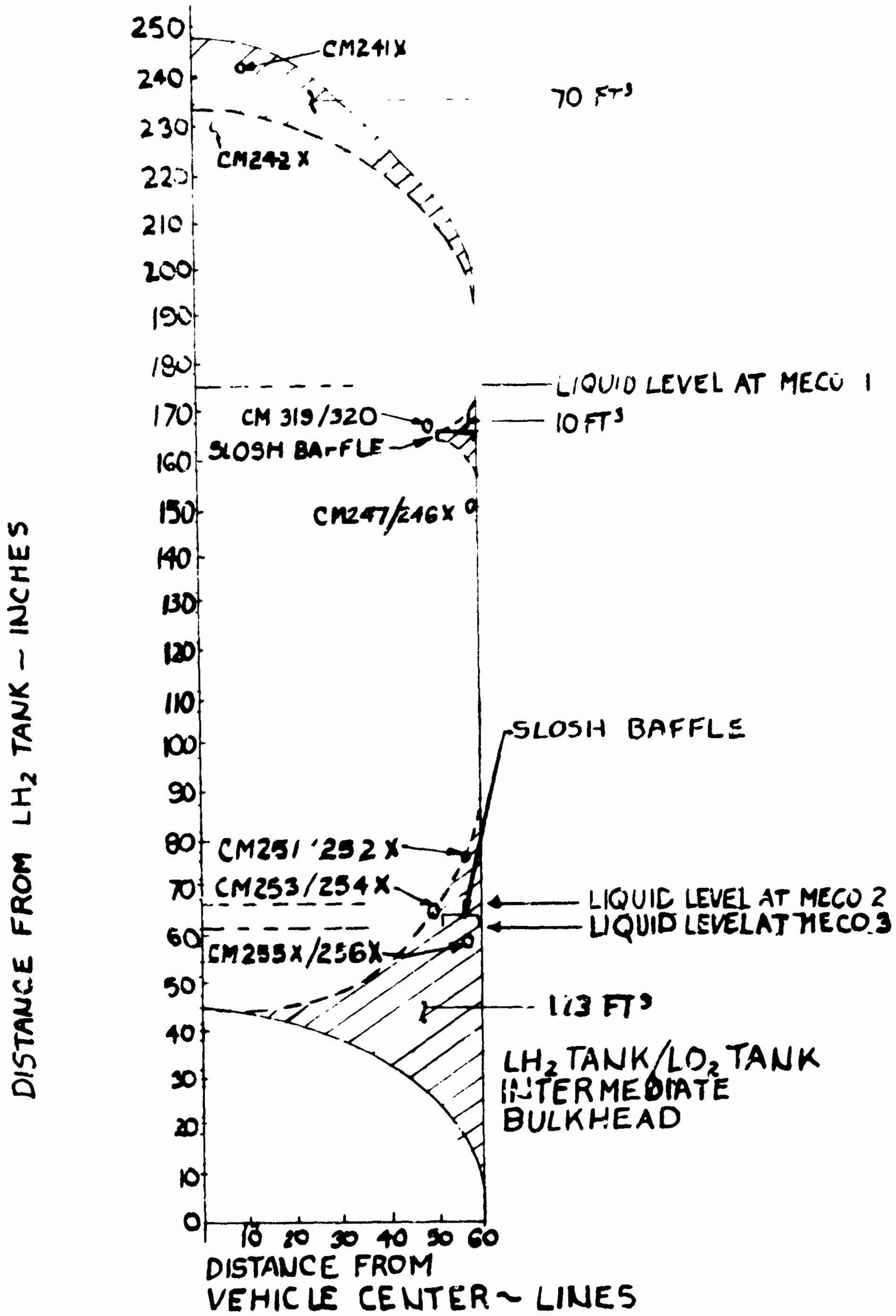

Figure 7 Liquid Hydrogen Location Prior to Propellant Settling for MES 3

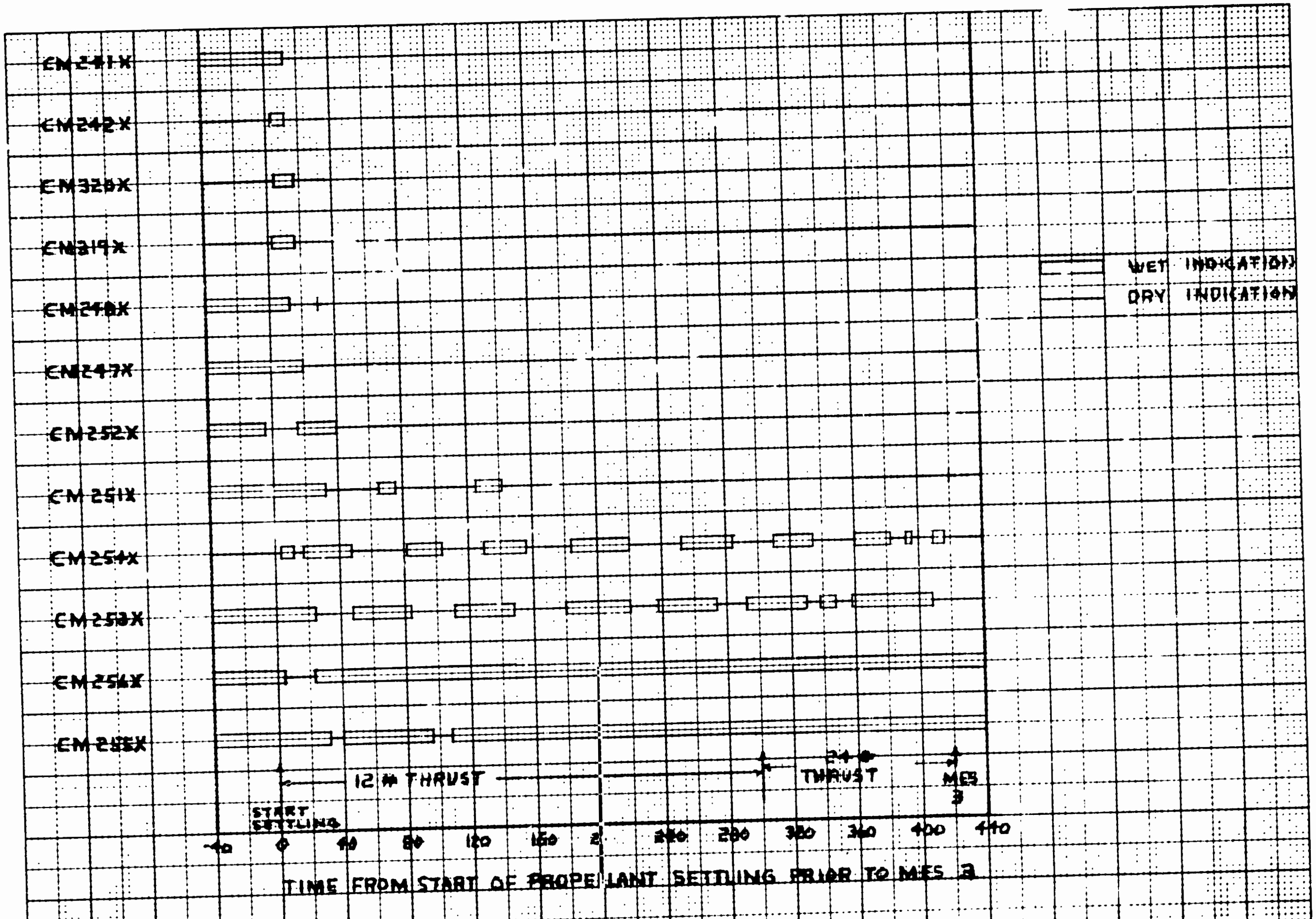

FIGURE 9 LIQUID HYDROGEN BEHAVIOR PRIOR TO MES 3

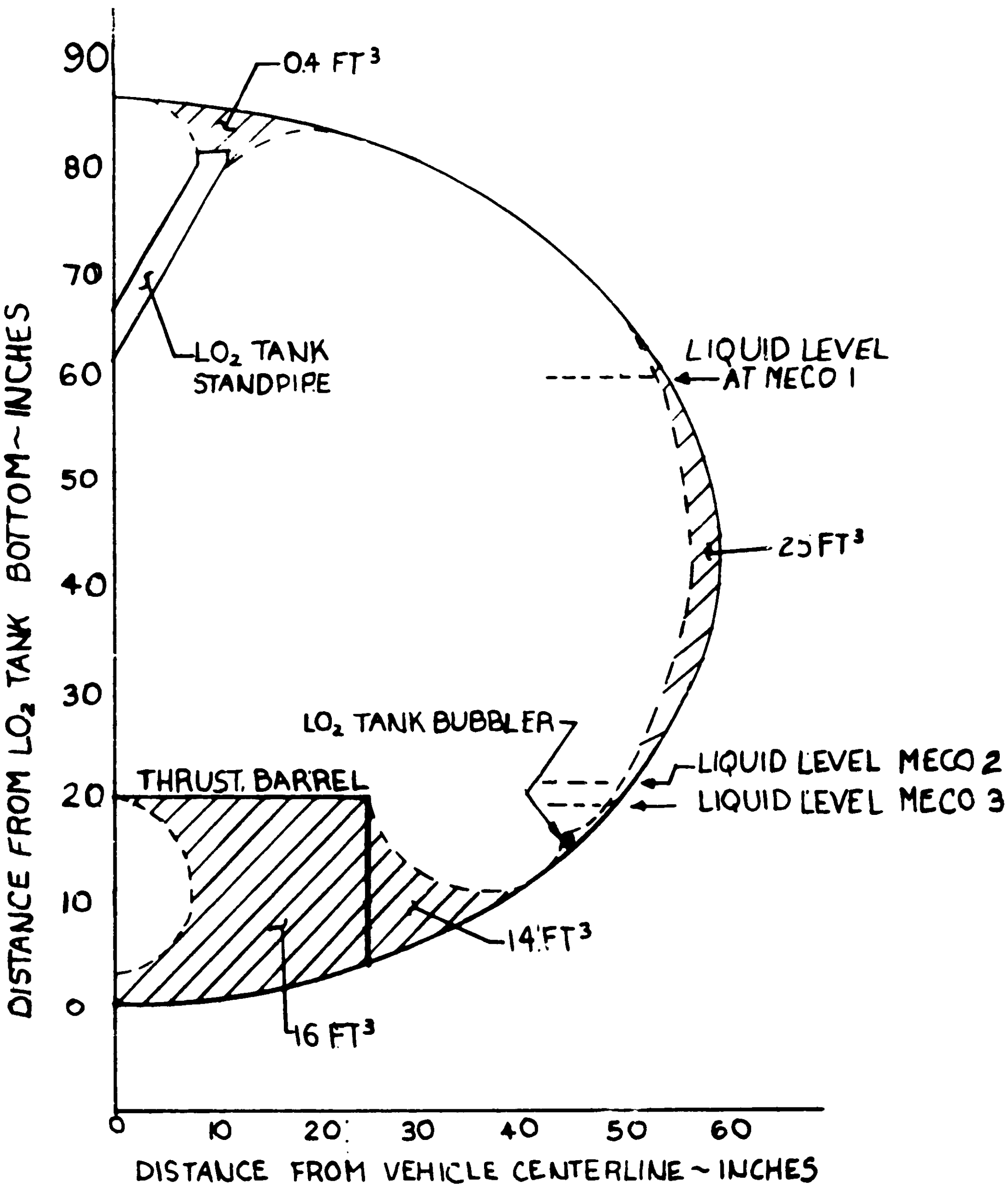

Figure 9 Liquid Oxygen Location Prior to Propellant Settling for MES 3

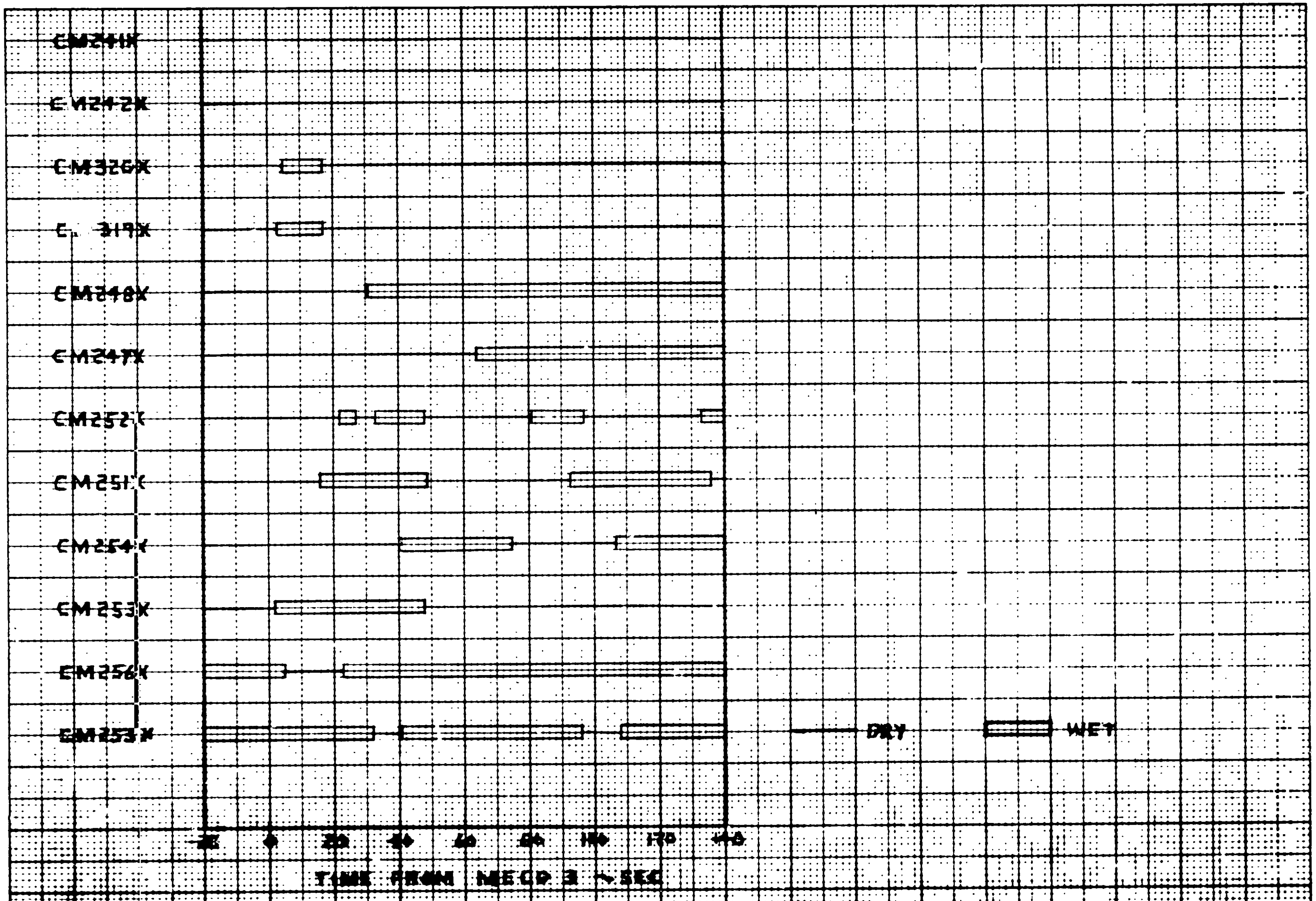

FIG. 8.10 LIQUID HYDROGEN BEHAVIOR AT MECO 3

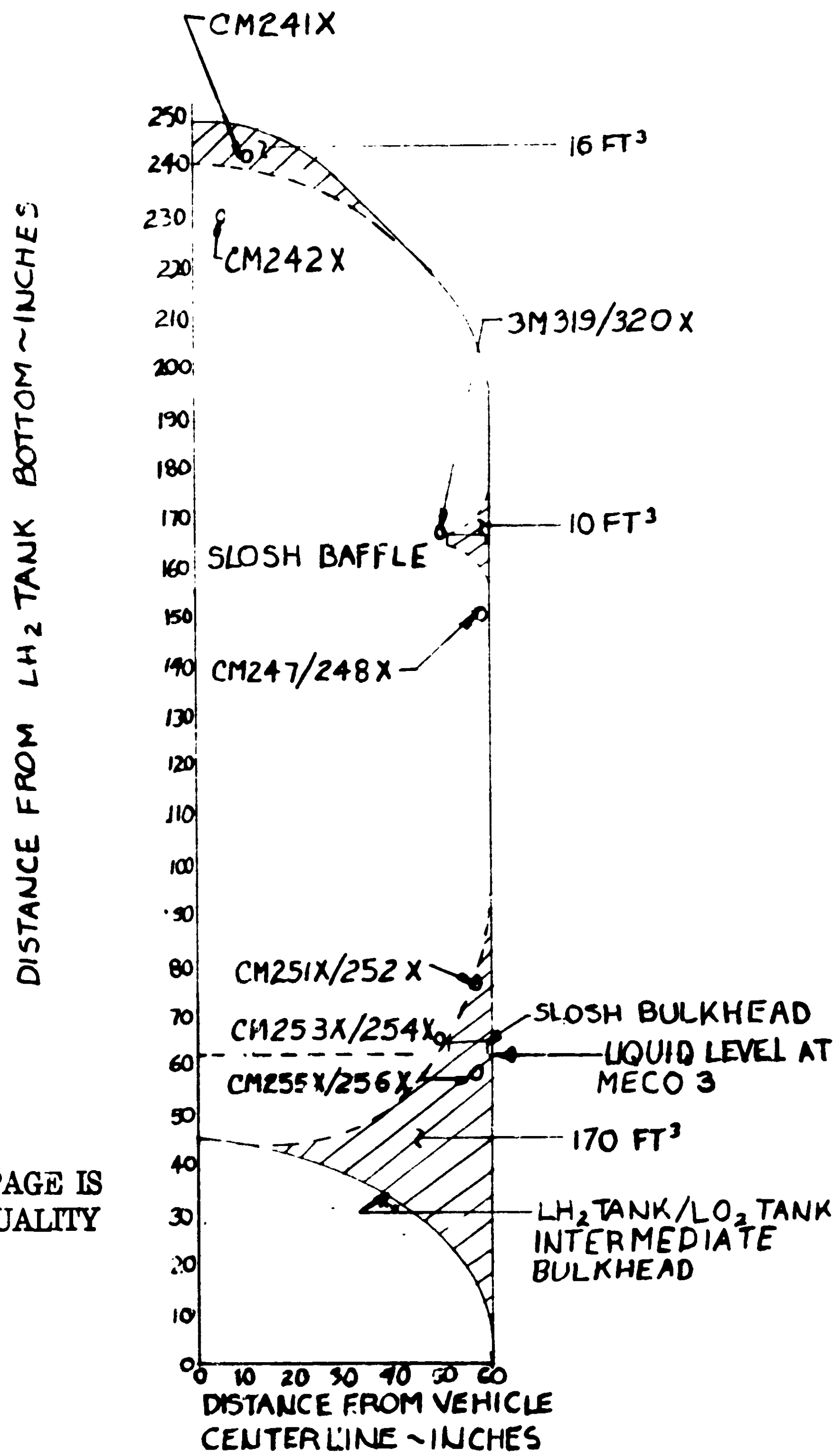

Figure 11 Liquid Hydrogen Location Prior to Propellant Settling for the Command Vent

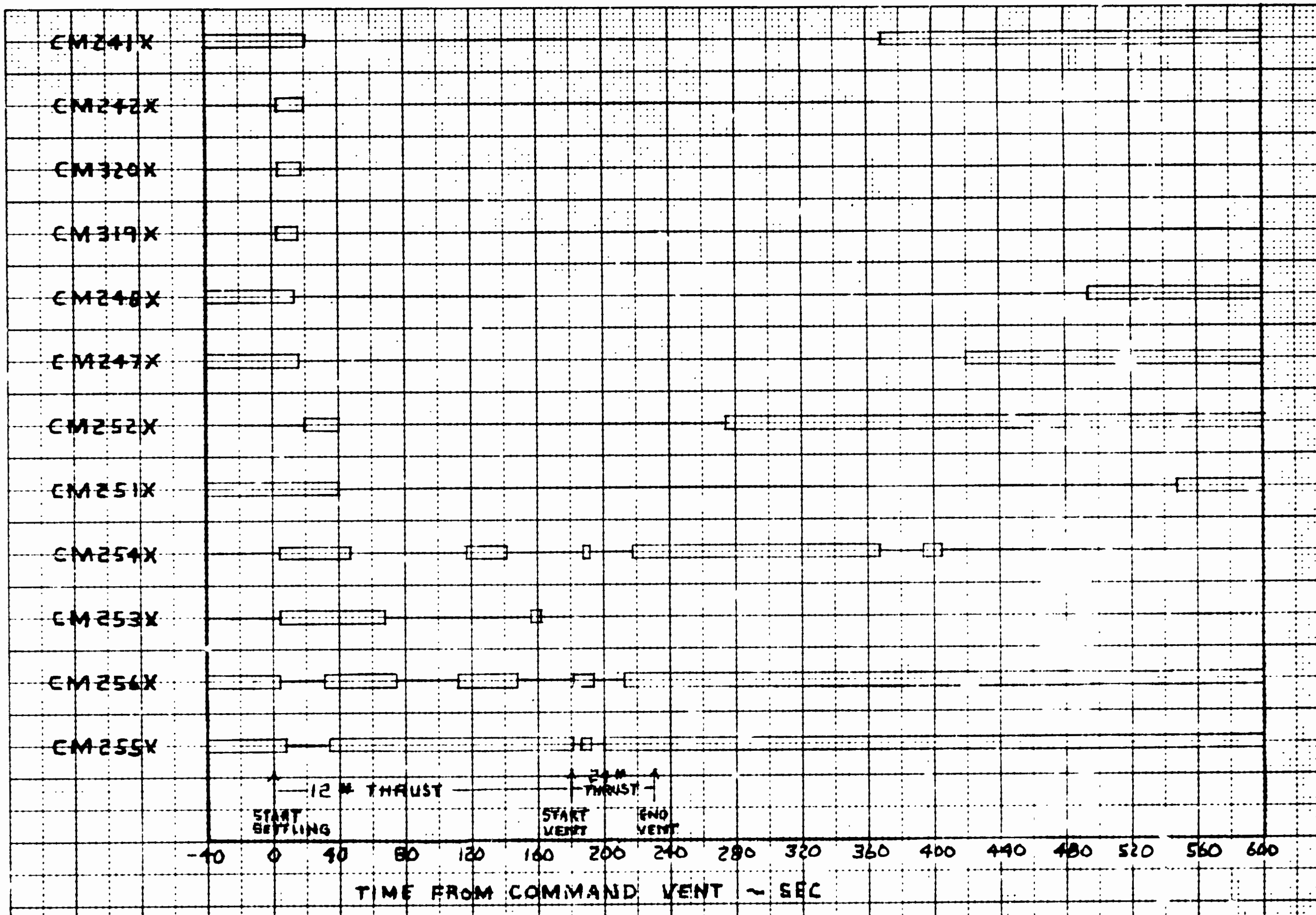

FIGURE 12 LIQUID HYDROGEN BEHAVIOR AT COMMAND VENT (MECO 3 + 8559 SEC)

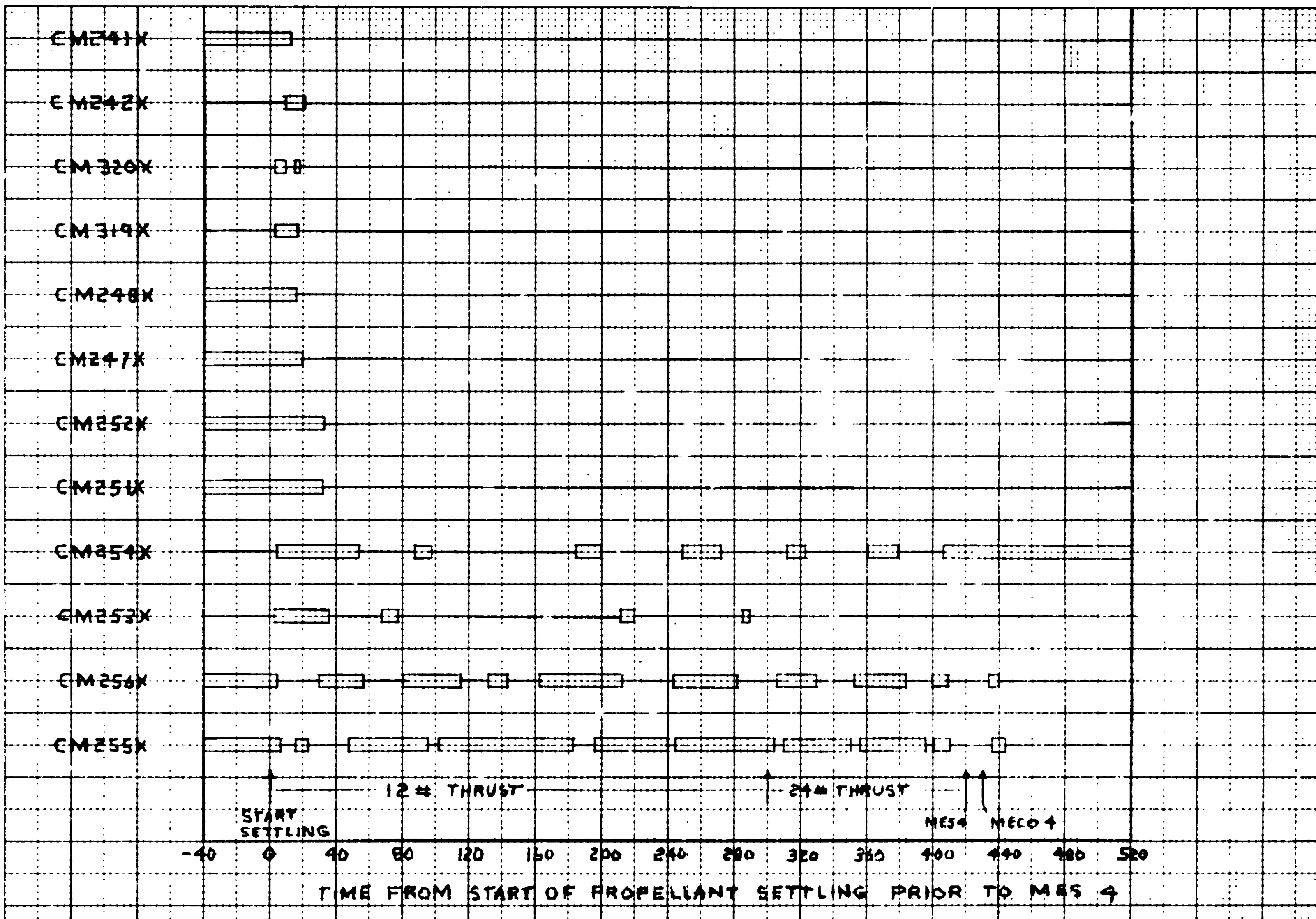

FIGURE 13 LIQUID HYDROGEN BEHAVIOR PRIOR TO MES 4

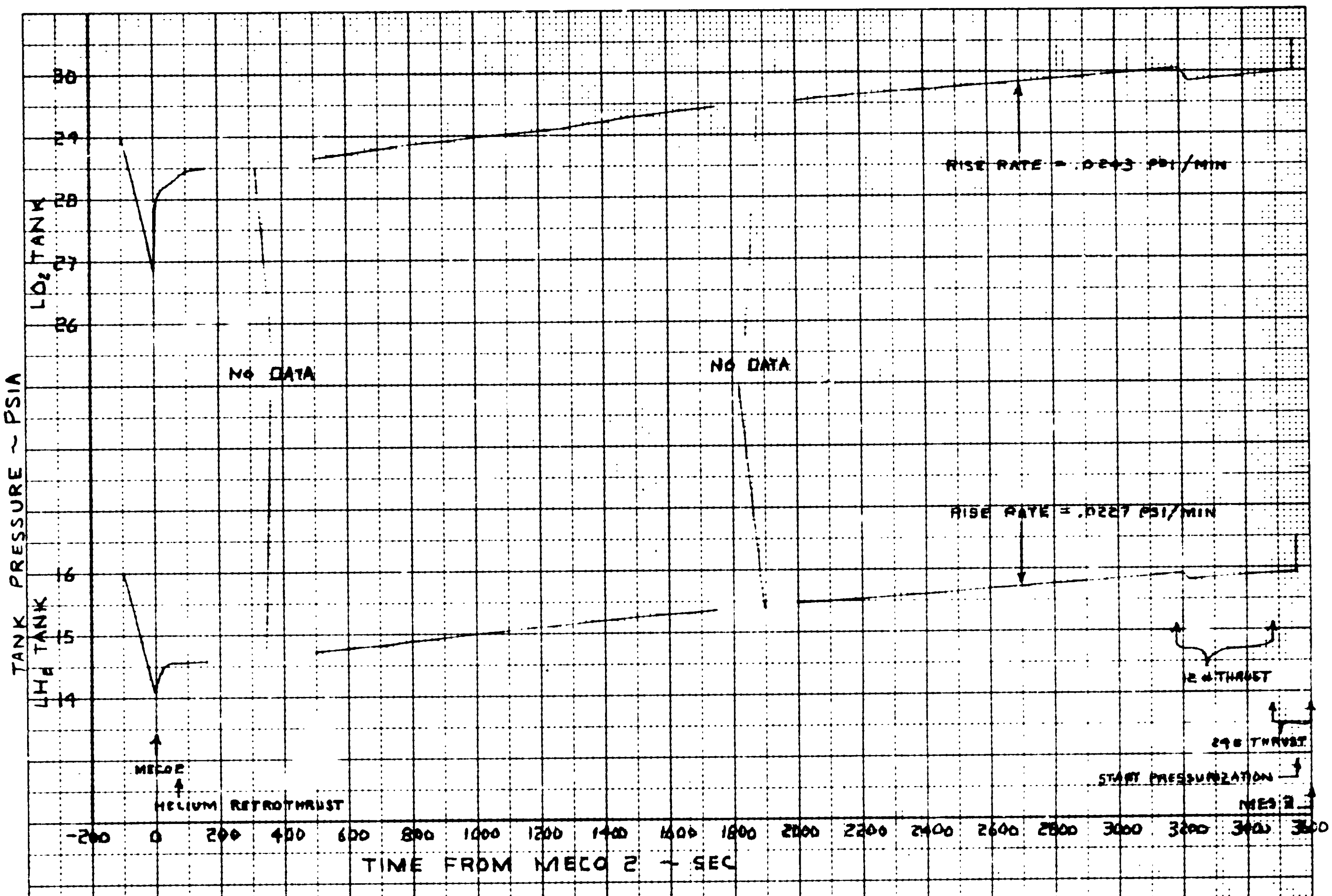

FIGURE 14 PROPELLANT TANK PRESSURE HISTORY DURING ONE HOUR ZERO G COAST

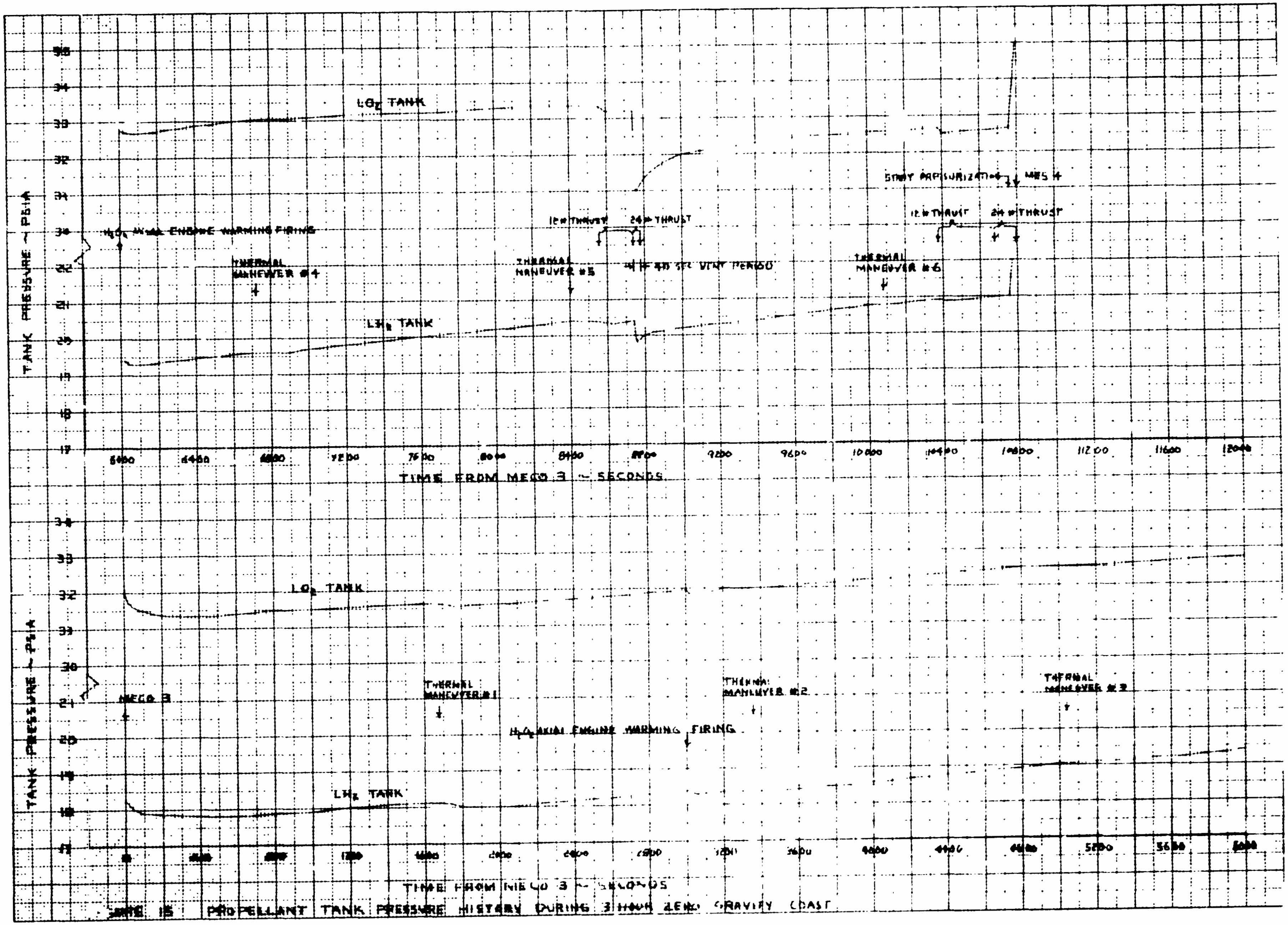

FIGURE 15 PROPELLANT TANK PRESSURE HISTORY DURING 3 HOUR ZERO GRAVITY COAST

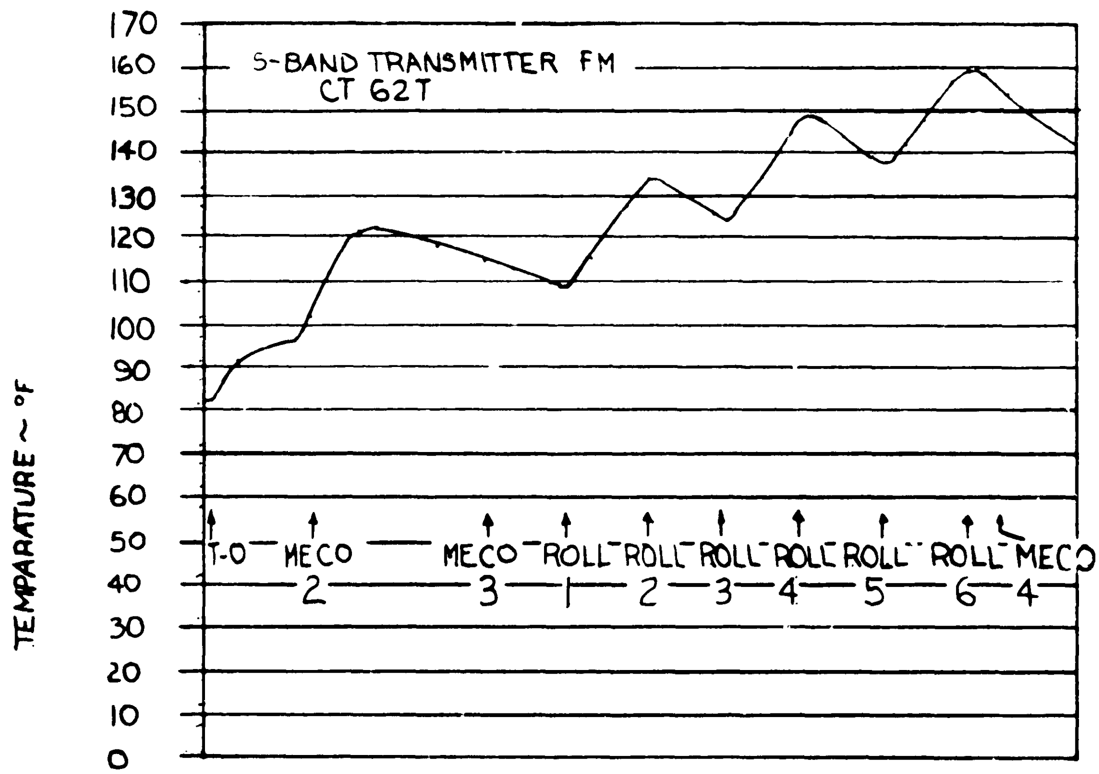

Figure 16 Example of Centaur Electronic Package Temperature Increase During the Vehicle Thermal Rolls

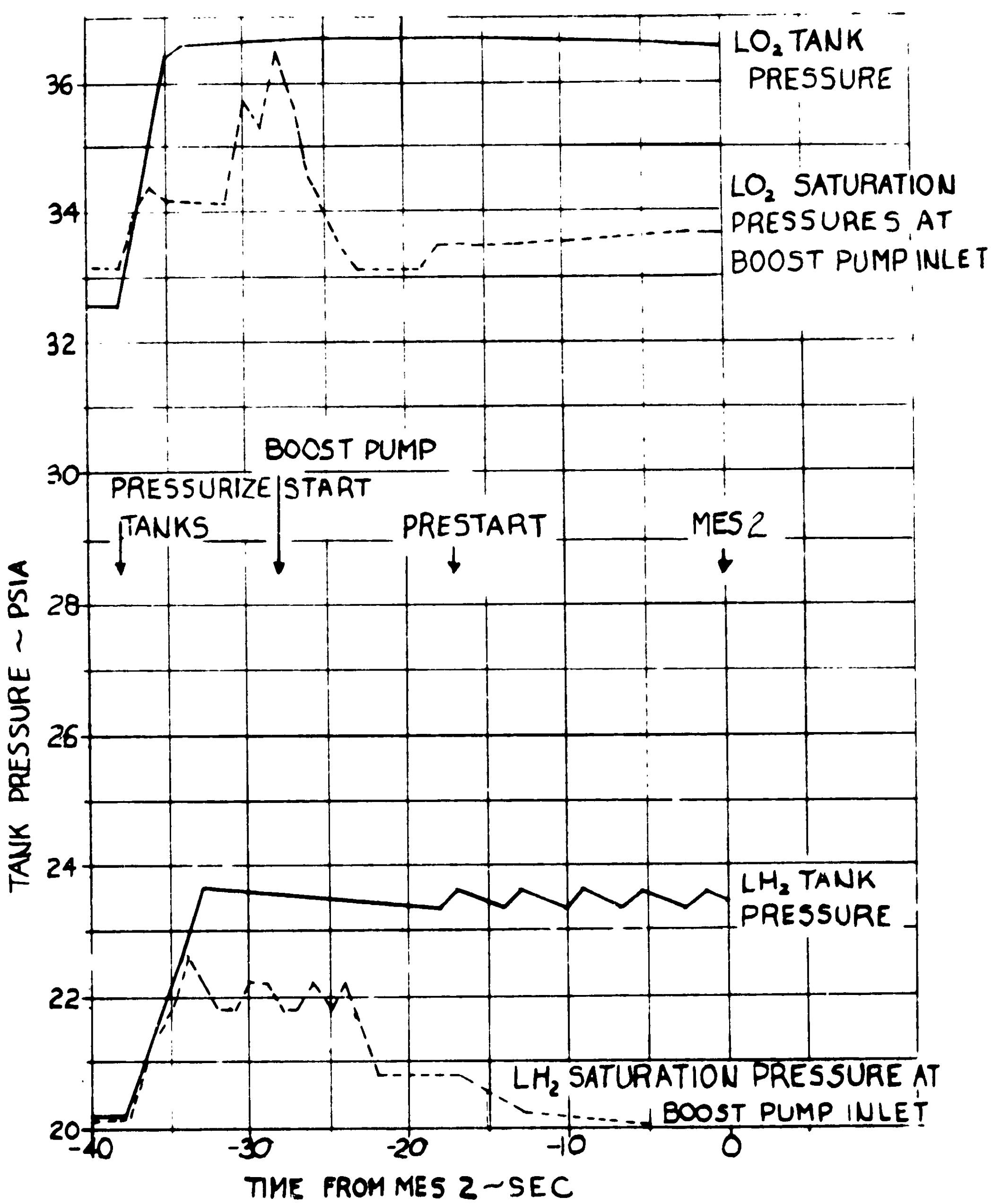

FIGURE 17 - PRE MES 2 PROPELLANT TANK PRESSURE AND PROPELLANT SATURATION PRESSURE HISTORIES

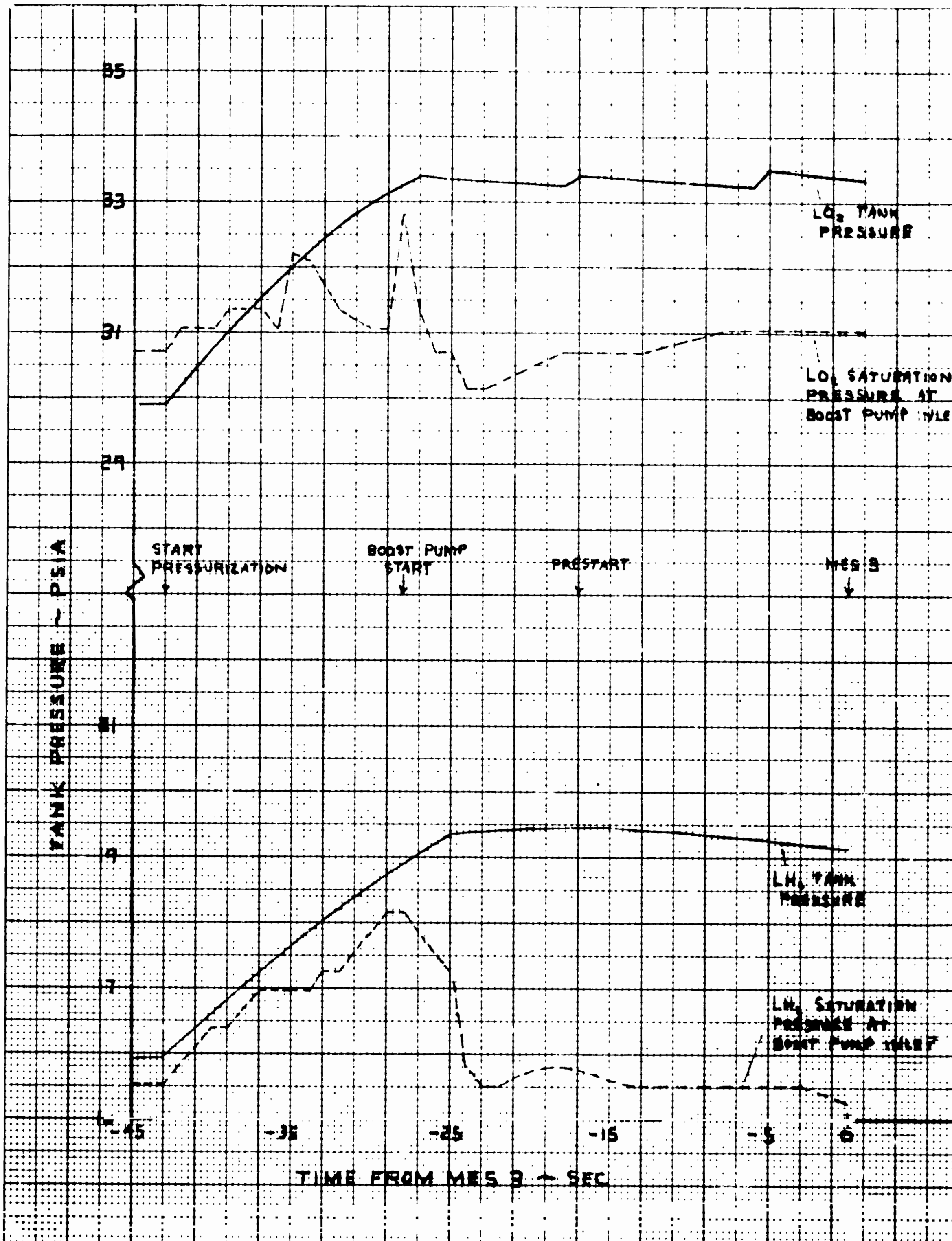

FIGURE 18 PRE MES 3 PROPELLANT TANK PRESSURE AND PROPELLANT SATURATION PRESSURE HISTORIES.

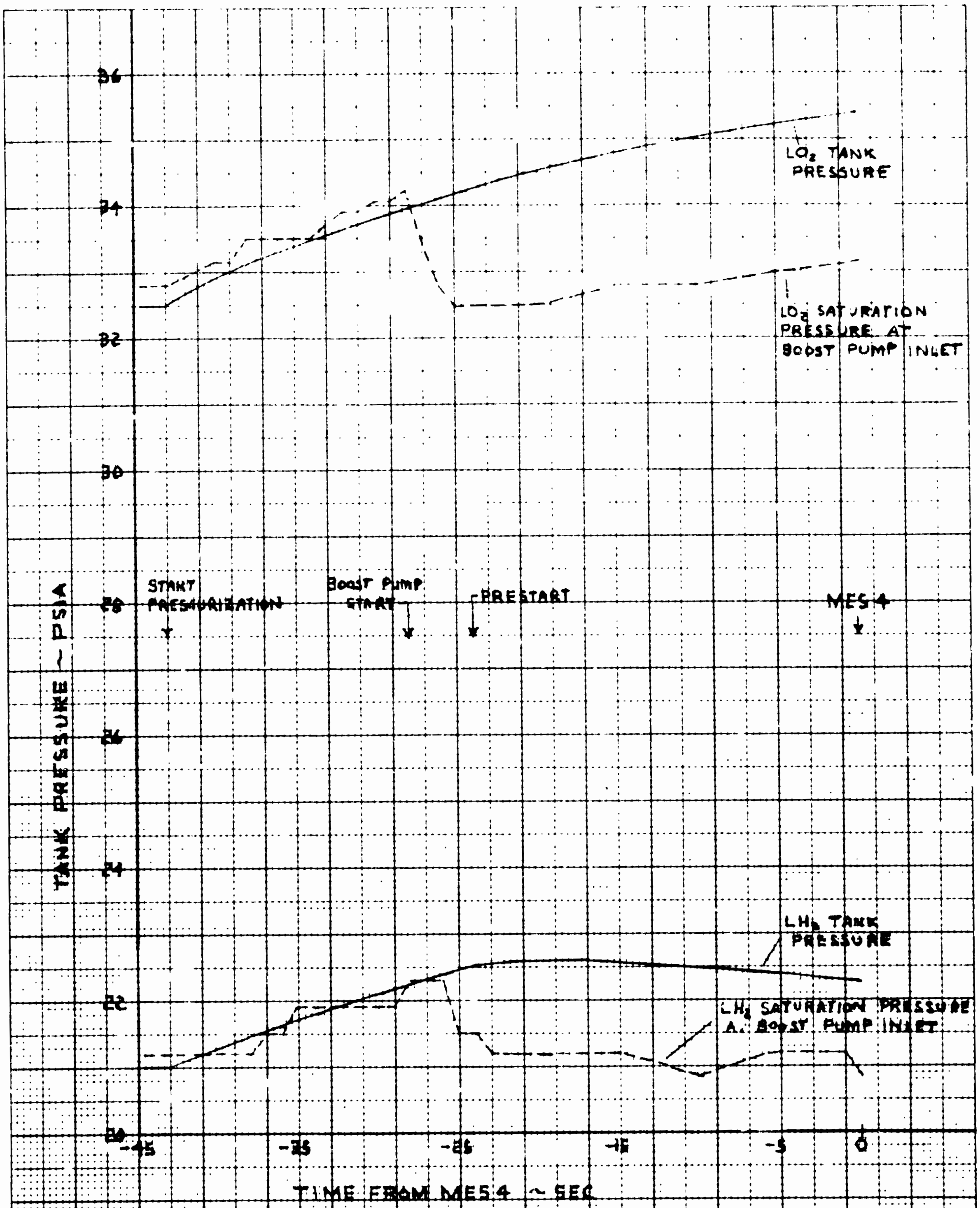

FIGURE 19 PRE MES 4 PROPELLANT TANK PRESSURE AND PROPELLANT SATURATION PRESSURE HISTORIES

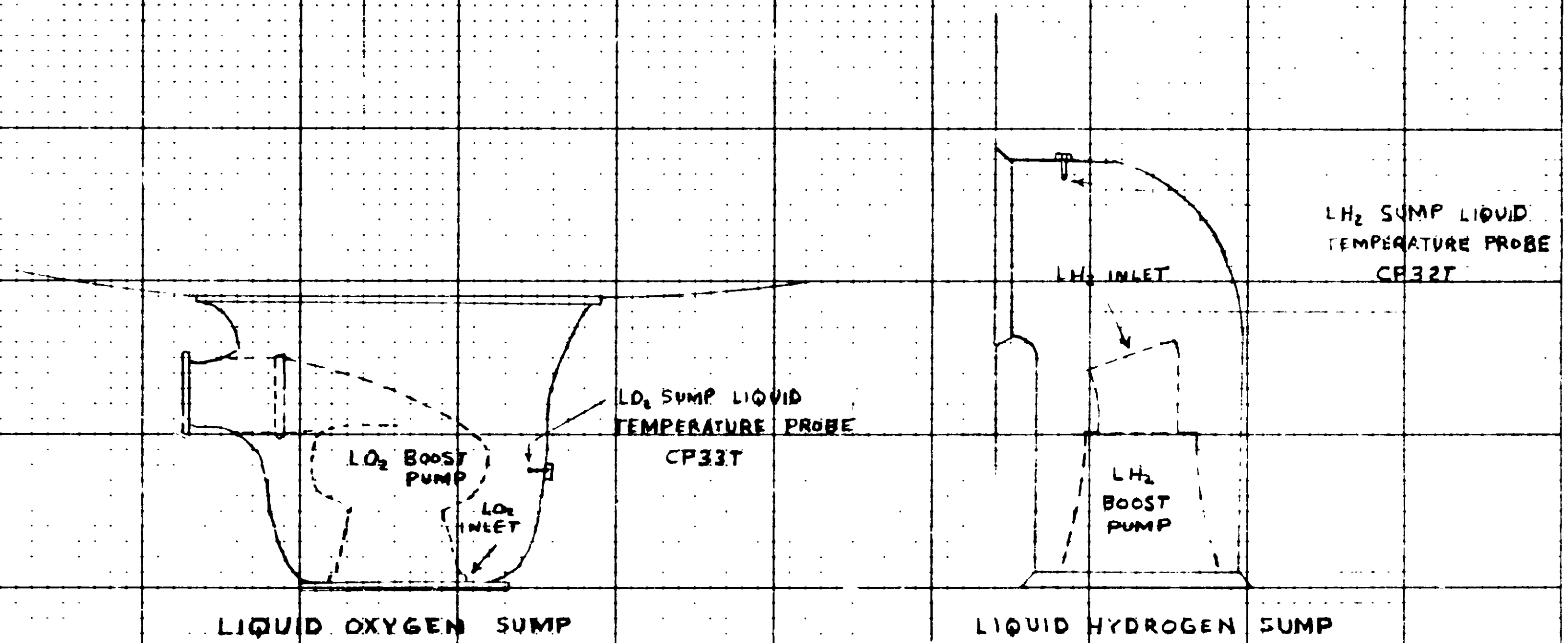

FIGURE 20 LO_2 TANK AND LH_2 TANK SUMPS