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INVESTIGATION OF THE CENTAUR BOOST PUMP OVERSPEED CONDITION AT MAIN ENGINE SHUTDOWN ON THE TITAN CENTAUR TC-2 FLIGHT

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SUMMARY

An investigation was conducted to evaluate a potential boost pump overspeed condition which could exist on the Titan/Centaur launch vehicle after main engine shut-off. Preliminary analyses indicated that the acceleration imparted to the unloaded boost pump-turbine assembly, caused by purging residual hydrogen peroxide from the turbine supply lines, could result in a pump-turbine overspeed. Previous test experience indicated that turbine damage occurs at speeds in excess of 75,000 rpm.

Detailed theoretical analyses, in conjunction with pump tests, were conducted to establish the maximum pump-turbine speed at main engine shut-off. The analyses predicted a maximum speed of 68,000 rpm. Testing showed the pump-turbine speed to be 66,700 rpm in the overspeed condition. Inasmuch as both the analysis and tests showed the overspeed to be sufficiently less than the speed at which damage could occur, it was concluded that no corrective action would be required for the launch vehicle.

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INTRODUCTION

During the Centaur main engine shutdown sequences on the Titan/Centaur TC-2 flight a prolonged and somewhat unusual acceleration characteristic of the propellant boost pumps was observed. At each main engine cutoff (MECO) the pump speeds would drop momentarily and then reaccelerate for up to 15 seconds; following which the pump speeds decayed in a normal manner.

The pump overspeed during this time period resulted from energy being supplied to the turbine wheel as the result of purging residual hydrogen peroxide (H_2O_2) monopropellant from the turbine supply lines. In addition the boost pumps were only partially pumping due either to cavitation or loss of propellant at the pump inlets caused by engine shutdown disturbances. Typical boost pump performance data showing these conditions at MECO on the TC-2 flight are shown in figures 1, 2, 3, and 4.

The worst case overspeed condition that could exist would be for a combination of these events; a complete lack of pumping while sustaining the high initial acceleration rate for the entire 15 seconds. Using the maximum acceleration rate of 2600 rpm/sec. observed on TC-2 at MECO-1 would result in a speed increase of 39,000 rpm. Assuming a normal LH_2 turbine speed of approximately 41,000 rpm at MECO would then result in a final turbine speed of 80,000 rpm.

Previous destructive testing of Centaur boost pump turbine drives indicated that turbine speeds in excess of approximately 75,000 rpm would result in damage to the drive. Hence, a speed of 80,000 rpm would likely result in a turbine failure. The maximum post-MECO turbine speed during the TC-2 flight, however, was only 48,100 rpm. This speed was well below the critical 75,000 rpm, but the pumps were not completely void of liquid for the entire 15 seconds since partial pumping was evident.

An investigation was initiated to determine if the magnitude of the potential overspeed condition was indeed a problem. The investigation was conducted in three steps as follows:

1. Review of boost pump data from previous flights to evaluate post-MECO acceleration characteristics and determine if the worst case postulation was feasible (complete loss of pumping for the first 15 seconds after MECO).

2. Perform theoretical worst case maximum speed calculations based on conversion of energy in the residual H_2O_2 into an increase in the kinetic energy of the rotating boost pump.

3. Conduct no-load tests with an LH_2 boost pump to obtain boost pump acceleration characteristics and verify the maximum speeds predicted by the theoretical calculations.

BOOST PUMP H_2O_2 SUPPLY SYSTEM CONFIGURATION

The gaseous helium purge of the boost pump H_2O_2 supply (which causes the boost pump overspeed condition at MECO) was incorporated on

Centaur vehicles after the flight failure of Atlas/Centaur vehicle AC-17. Restart of the Centaur main engines on this vehicle, after a one-hour earth orbit coast, was not achieved. The failure was attributed to blockage of the H_2O_2 supply lines to the Centaur boost pumps. The blockage was believed to have resulted from a cryogenic leak impinging on the boost pump H_2O_2 supply line during the coast, and consequently freezing stagnant residual H_2O_2 remaining in the lines after the first burn.

One of the corrective actions taken on subsequent vehicles was the addition of the gaseous helium purge of the H_2O_2 supply lines to the boost pumps. The purpose of the purge was to expel the residual H_2O_2 from the lines as quickly as practical after each MECO, and to maintain a low flow (250 SCIM) purge through the lines during the remainder of the coast. This corrective action reduced the probability of line blockage due to residual H_2O_2 freezing. The first Centaur flown with the purge was AC-18. Single burn Centaur vehicles AC-19 through AC-22 were flown without the purge, but all Centaur vehicles subsequent to AC-22 have incorporated the purge.

The boost pump H_2O_2 supply systems flown on Centaur vehicles thus far have been one of two basic design configurations. The original design is referred to as a "non-redundant" configuration, and is effective for all Atlas/Centaur vehicles through AC-35. The newer design is referred to as a "redundant" configuration, and is effective for all Atlas/Centaur vehicles beginning with AC-36, and for all Titan/Centaur vehicles beginning with TC-1.

Flow schematics comparing the two configurations are shown in figure 5. The non-redundant system comprised a single H_2O_2 flow control valve, and a single supply line to each boost pump turbine. The redundant configuration, however, incorporated a secondary H_2O_2 flow control valve and a secondary parallel H_2O_2 flow path to the LH_2 boost pump turbine in order to eliminate single point failure modes.

As a result of the configuration differences between the redundant and non-redundant systems, the time required to purge residual H_2O_2 from the supply lines after MECO is different. On the non-redundant configuration, the purge removes residual H_2O_2 from the LO_2 boost pump supply line first in approximately 3 seconds. On the redundant configuration, the increased line volume and different line routing results in the purge removing residual H_2O_2 from the LH_2 boost pump primary supply line first and it takes approximately 15 seconds.

In either case, residual H_2O_2 is purged through both the LO_2 and LH_2 turbines at relatively high pressure and flowrate until the H_2O_2 is expelled from the supply line to one of the turbines. Subsequently, the purge gas pressure is greatly reduced and the H_2O_2 flow rate out the line to the other turbine decreases significantly. During the 3 or 15 second purge period, depending on system configuration, the H_2O_2 residuals are flowing through and decomposing in the catalyst bed. Energy is thereby supplied to the turbine wheel at a decreasing rate from approximately 80 percent to 50 percent of the normal operating level.

An overspeed of the boost pump after MECO was not considered a potential problem on the non-redundant configuration. The 3-second purge duration was not sufficient to accelerate the turbines significantly. The advent of the redundant configuration with a 15 second purge period, however, might conceivably provide sufficient time to potentially overspeed the turbines.

ANALYTICAL AND TEST PROCEDURES

Review of Previous Flight Data: The review of previous flight data was made to determine if the postulated worst case condition (complete loss of pumping action for the entire 15 seconds of purging) was feasible. The turbine speed, turbine inlet pressure, and pump delta-p traces were examined to determine the relationship between turbine acceleration, degree of pumping action, purge time period, and maximum turbine speed.

Post-MECO boost pump performance data were obtained for all Centaur flights which incorporated the gaseous helium purge of the H_2O_2 supply lines. The vehicles included were AC-18, AC-23 through AC-34, TC-1, and TC-2. These flights included both single burn and multiple burn missions with various propellant levels in the tanks at each MECO.

Instrumentation provided data from a delta pressure (delta-p) transducer installed on each boost pump to measure pump headrise on vehicles AC-18, -26, -28, -29, -31, -32, -33, TC-1, and TC-2. Turbine speed measurements were obtained on all flights.

The turbine acceleration was determined from the slope of the speed trace. A relative measure of the degree of pumping action was determined from the pump delta-p trace for those flights which had the delta-p measurement. A general correlation was evident between turbine speed and pump delta-p during the post-MECO coastdown.

When the pump was actually pumping fluid (delta-p relatively high), the turbine speed decreased at an exponential rate. Conversely, when pumping ceased (delta-p essentially zero), the turbine speed decreased at a linear rate. This relationship was used to judge the degree of pumping on the flights without pump delta-p instrumentation.

The AC-32 post-MECO boost pump performance data shown in figures 6 and 7 were typical for the non-redundant H_2O_2 supply systems. Comparison of these figures with figures 1, 2, 3, and 4 for TC-2 with the redundant H_2O_2 supply systems illustrated the effect of the configuration differences on post-MECO boost pump performance characteristics.

Theoretical Calculation Method: The theoretical maximum possible turbine speed after MECO was calculated using an energy balance method. A worst case condition of no pumping action (no turbine load) during the entire 15 second purge period was assumed. Calculations were limited to the LH_2 boost pump because its normal operating speed at MECO exceeds that of the LO_2 boost pump by 7000 rpm (41,000 rpm versus 34,000 rpm), and it would therefore reach the 75,000 rpm damage speed first.

The energy balance technique assumed that the energy absorbed by the turbine wheel, as the result of H_2O_2 decomposition during the 15 second purge period, was reflected in an increase in the kinetic energy of the rotating parts. The effects of friction were conservatively neglected. The equation resulting from the energy balance was:

$$\eta_T W_{H_2O_2}(h_e - h_l) = \frac{1}{2} I (\omega_f^2 - \omega_i^2)$$

Where:

η_T = LH_2 turbine wheel efficiency

$W_{H_2O_2}$ = Total quantity of H_2O_2 expelled through the LH_2 turbine during the 15 second purge period (lbm)

h_e = Specific enthalpy of the decomposition products entering the turbine wheel (ft.-lbf/lbm)

h_l = Specific enthalpy of the decomposition products leaving the turbine wheel (ft.-lbf/lbf)

I = Mass moment of inertia of the rotating parts (ft.-lbf-sec.^{2})

ω_f = Final LH_2 turbine speed at the end of the 15 second purge period (rad/sec.)

ω_i = Initial LH_2 turbine speed at MECO when the 15 second purge is initiated (rad/sec.)

The turbine wheel efficiency (η_T) was obtained from a turbine efficiency map published by the turbine manufacturer. A constant efficiency value of 0.4 was assumed for the entire 15 seconds. This assumption was not technically valid because the actual efficiency is a function of the turbine wheel speed, the velocity of the gas entering the turbine wheel, and the pressure ratio across the turbine wheel. The maximum error in final turbine speed as a result of this assumption was estimated to be less than seven percent.

The total quantity of H_2O_2 ($W_{H_2O_2}$) expelled through the turbine was determined from the actual TC-2 post-MECO-1 turbine inlet pressure measurement data (CP28P), which is shown in figure 8. Correlation of turbine inlet pressure to H_2O_2 flowrate was established from previous ground tests. Integration of the H_2O_2 flowrate over the 15 second purge period resulted in 0.389 pounds of H_2O_2 expelled through the LH_2 turbine.

The specific enthalpy change of the hot gases flowing through the turbine wheel ($h_e - h_l$) was determined from the enthalpy-entropy diagram for the decomposition products of 90 percent concentration H_2O_2, which is included as figure 9. The hot gases were conservatively assumed to expand isentropically from an initial temperature of 1350°F (1005 °K), and an average initial pressure of 57.6 psia (see figure 8), to a final pressure of 1 psia.

Calculations were made using two values for the mass moment of inertia of the rotating parts. An approximate value of 0.005 ft.-lbf-sec.^{2} was calculated for the LO_2 boost pump in support of a previous investigation of another problem. The LO_2 and LH_2 turbine wheels are identical and are the most significant contributors to the effective mass moment of inertia. Thus, 0.005 was considered a reasonable value for the LH_2 boost pump. A second value of 0.0033 ft.-lbf-sec.^{2} was referenced in documents published by the turbine manufacturer as the design value for both the LO_2 and LH_2 boost pump turbine drives.

The actual value of the mass moment of inertia for the LH_2 pump and turbine assembly probably is somewhere between 0.0033 and 0.005. It should be noted that the mass moment of inertia of the LH_2 pump and turbine assembly was the one parameter which raised the greatest doubt in regard to the validity of the theoretical turbine speed calculations.

The initial turbine speed (ω_i) was selected at 40,000 rpm, as it represented the maximum initial speed observed during the MECO sequences in previous flights.

Test Procedure: Tests to obtain acceleration data for an unloaded boost pump at various turbine inlet pressures were conducted at LeRC in the Rocket Lab Test Cell No. 23 H_2O_2 test facility. Testing was initiated January 17, 1975, and completed on January 29, 1975.

The turbine drive was bolted to a heavy metal fixture which was secured to the floor of the test cell. A protective enclosure was placed around the boost pump during the tests. The facility vacuum system was connected to the turbine exhaust to simulate the back pressure of space flight. H_2O_2 was supplied to the turbine from the facility H_2O_2 system.

The forward bearing of the LH_2 pump is normally cooled and lubricated by a forced flow of LH_2 through the bearing during pump rotation. Since the Phase III tests required operating the pump without LH_2 in the pump, the forward bearing was lubricated with low viscosity grease before the test.

In addition to the normal test facility instrumentation, measurements for turbine speed, turbine inlet pressure, turbine exhaust pressure, and gearbox skin temperature were recorded for each run.

The testing was accomplished in four separate phases as summarized in Table 1. Each phase consisted of four test runs with a different, but constant, turbine inlet pressure for each run. Phases I, II and IV utilized an LH_2 turbine without the pump attached, whereas Phase III utilized an LH_2 turbine with the pump attached. The objective of each test phase was as follows:

Phase I: Using a turbine drive only, determine the stabilized (self-limiting) speed at various constant turbine inlet pressures. No resisting load was applied to the drive output shaft.

Phase II: Using a turbine drive only, determine the acceleration characteristics between the speed range of 40,000 to 70,000 rpm for various constant turbine inlet pressures. No resisting load was applied to the output shaft.

Phase III: Using a turbine drive with pump attached, determine the acceleration characteristics between the speed range of 40,000 to 70,000 rpm for various constant turbine inlet pressures. The pump was operated in ambient air (no liquid in the pump) to simulate a complete loss of pumping action in flight.

Phase IV: Repeat of the Phase II tests to determine if the acceleration characteristics for different turbines were comparable. Turbine S/N 66 was used for this test whereas S/N 52 was used for Phase II.

The run sequence for each of the four runs of Phase I consisted of setting the H_2O_2 supply tank pressure for the desired turbine inlet pressure, opening the H_2O_2 flow control valve until the turbine speed stabilized, and then closing the H_2O_2 flow control valve.

The test sequences for Phases II, III and IV were as illustrated in figure 10. Basically the sequence consisted of setting the H_2O_2 tank pressure to obtain the desired turbine inlet pressure for the first run, opening the H_2O_2 flow control valve until the speed reached approximately 60,000 rpm at which time the valve was closed and the speed allowed to decay to 40,000 rpm. At 40,000 rpm, the valve was re-opened and the turbine accelerated to 70,000 rpm which constituted the first run. The valve was closed at 70,000 rpm and the turbine speed allowed to decay to 40,000 rpm; during this coastdown period the tank pressure was adjusted to give the desired turbine inlet pressure for the next run. At 40,000 rpm, the valve was again opened to begin the second acceleration run. This procedure was repeated until four runs at different turbine inlet pressures were completed for each phase. The turbine inlet pressures used were chosen to cover the expected range of pressures encountered in flight.

DISCUSSION OF RESULTS

Review of Previous Flight Data: A summary of the post-MECO boost pump data from previous Centaur flights is presented in Tables 2 and 3 for the LO_2 and LH_2 boost pumps, respectively. Also included for comparison are acceleration data at boost pump start (BPS) at full power, and data for the TC-2 flight. The following observations were noteworthy:

1. Acceleration rates at BPS are greater than the post-MECO rates, as expected.

2. Acceleration rates at BPS No. 2 are greater than at BPS No. 1, as expected (turbines were hotter at BPS No. 2, therefore less friction and more rapid decomposition).

3. The LH_2 boost pump post-MECO acceleration rates were generally greater, and resulted in greater peak speeds than for the LO_2 boost pump.

4. The maximum post-MECO acceleration rate was 2950 RPM/sec. for the LH_2 boost pump (AC-25 MECO No. 2).

5. The maximum post-MECO LH_2 boost pump turbine speed was 48,100 RPM (TC-2).

6. The post-MECO degree of pumping was generally good for MECO No. 1 of a multiple burn mission; but ranged from none to good for the MECO of a single burn mission or final MECO of a multiple burn mission.

The data from previous flights also showed that the LH_2 boost pump delta-p almost always drops to essentially zero for the first 3 or 4 seconds after each MECO (see figures 6 and 7 for typical data). During the same time period, the greatest acceleration rates were evident. Subsequently, pumping action usually resumed in varying degrees, and the boost pump acceleration ceased. Unfortunately, the purging of residual H_2O_2 through the turbines also ceased at approximately the same time (3 or 4 seconds after MECO). It was therefore impossible to determine from the previous flight data whether the decrease in acceleration rate was due to resumption of pumping, or termination of the purge.

Theoretical Calculations of Maximum Turbine Speeds: The maximum LH_2 boost pump turbine speed calculated for the two assumed values of mass moment of inertia were:

$$\omega_{max.} = 59{,}800 \text{ RPM for } I = 0.005 \text{ ft.-lbf-sec.}^2$$

$$\omega_{max.} = 68{,}000 \text{ RPM for } I = 0.0033 \text{ ft.-lbf-sec.}^2$$

Boost Pump Acceleration Tests: The LH_2 turbine speed data from the Phase I tests are plotted in figure 11. The results indicate that an unloaded LH_2 turbine can, if given sufficient time, attain speeds near the damage speed of 75,000 RPM with relatively low turbine inlet pressures. A stabilized speed of 68,000 RPM was achieved after 345 seconds of operation at a turbine inlet pressure of 21.4 psia. This pressure represents approximately 20 percent of the normal steady state operating pressure (100 psia) for the Centaur LO_2 and LH_2 boost pump turbine drives.

The LH_2 turbine speed data from the Phase II, III, and IV tests are plotted in figures 12, 13, and 14, respectively. The turbine speed versus time curves in figures 12 and 14 compare favorably, indicating the turbine-to-turbine differences were insignificant.

The LH_2 turbine speed data from the Phase II, III, and IV tests were used to calculate the turbine speed during the first 15 seconds after MECO on a Centaur flight. These calculations represented a worst case condition of no liquid in the pump combined with continuous application of energy to the turbine wheel for the entire 15 seconds.

The method of calculation assumed a turbine inlet pressure history identical to the TC-2 post-MECO No. 1 data shown in figure 8. An initial turbine speed of 40,000 RPM was assumed at MECO. An incremental integration was then performed by determining the average turbine inlet pressure over a one-second time period, determining the average acceleration rate from figures 12 or 13 over the one-second interval, and then calculating the turbine speed at the end of the 1-second interval. This procedure was repeated in 1-second intervals over the 15-second time period.

Calculations were made for a turbine only configuration (no pump attached), and for a turbine with a pump attached. The results of these calculations are shown in figure 15. The resulting maximum calculated speed for a pump and turbine combination was 66,700 RPM at the end of the 15-second time period. The maximum calculated speed for a turbine only was 68,100 RPM which verified that the mass moment of inertia of the pump was small compared to the turbine drive.

A plot of the actual TC-2 post-MECO No. 1 turbine speed is shown in figure 15 for comparison to the calculated worst case speed. The slope of the curves agree favorably for the first 3 seconds when essentially no pumping was present on TC-2. However, after 3 seconds the flight data curve diverges significantly from the calculated speed because partial pumping resumed on TC-2 at this time.

CONCLUSION

An analytical and experimental investigation has verified that a potential boost pump overspeed condition does exist after MECO on the Centaur vehicles with the redundant configuration H_2O_2 supply system.

The overspeed condition results from purging the residual peroxide in the supply lines through the turbines at a time when liquid propellants are displaced from the pump inlets. However, the energy input from the residual peroxide is limited and the peak turbine speed is well below the critical turbine damage speed.

A review of previous Centaur flight data indicated that the overspeed potential exists primarily for MECO conditions with low propellant residuals. These conditions will exist at the final MECO of a multiple burn mission, or at MECO of a single burn mission. The degree of pumping after the first MECO of a two-burn mission, when relatively large propellant residuals existed, was considered good. However, the degree of pumping with low propellant residuals varied from good to essentially none.

Thus, it is feasible that a complete loss of pumping action could prevail during the 15-second post-MECO purge period for the redundant system. It was not possible to determine from previous flight data (with non-redundant H_2O_2 supply systems) whether the acceleration rates observed during the first 3 or 4 seconds after MECO would have been sustained if the purge continued for 15 seconds.

Theoretical calculations using an energy balance technique resulted in a maximum possible LH_2 turbine speed of 59,800 to 68,000 RPM. However, the validity of the theoretical calculations were questionable because the mass moment of inertia essential to the calculations was not precisely known.

No-load acceleration tests were subsequently conducted using an actual LH_2 turbine and pump which yielded acceleration data directly, and eliminated the inertia parameter from the calculations. Based on the test data the calculated maximum possible LH_2 turbine speed during the 15-second purge period after each MECO was 66,700 RPM. This calculation was based on the worst case assumption that there was no pumping action for the full 15 seconds. The 66,700 RPM value was well below the turbine damage speed of 75,000 RPM.

It was therefore concluded that no critical overspeed problem exists and that the existing system operation will pose no hazard to the success of future Centaur flights. No corrective action was deemed necessary.

TABLE 1: SUMMARY OF LH_2 BOOST PUMP NO-LOAD ACCELERATION TEST CONDITIONS

Test Date (1975)	Test Phase	Run[(1)] Number	Turbine Inlet Pressure (PSIA)	Turbine Exhaust[(2)] Pressure (PSIA)	Turbine[(3)] Serial No.	Pump Serial No.
January 17	I	1	21.4	3.5	52	None Used
		2	21.0	3.0	52	None Used
		3	15.5	2.4	52	None Used
		4	13.0	1.8	52	None Used
January 22	II	1	37.5	0.7	52	None Used
		2	45.8	0.8	52	None Used
		3	56.7	0.9	52	None Used
		4	69.8	1.2	52	None Used
January 30 (A.M.)	III	1	54.8	0.8	66	1212
		2	69.2	0.9	66	1212
		3	83.4	1.2	66	1212
		4	62.0	0.9	66	1212
January 30 (P.M.)	IV	1	48.6	0.6	66	None Used
		2	60.3	0.8	66	None Used
		3	75.6	0.9	66	None Used
		4	40.5	0.5	66	None Used

NOTES: (1) Warming runs were conducted prior to the first run of each phase to warm the gearbox.

(2) After completion of Phase I, the facility vacuum lines connected to the turbine exhaust were modified to reduce the line pressure drop.

(3) During the coastdown of Phase II, Run No. 4, the turbine failed and serial number 52 was replaced by serial number 66 for all subsequent runs.

TABLE 2: LO_2 BOOST PUMP POST-MECO PERFORMANCE SUMMARY FOR ALL FLIGHTS WITH PURGE OF H_2O_2 SUPPLY LINES

Flight Number		Acceleration at Start-up (RPM/Sec.)	Turbine Speed at MECO (RPM)	Turbine Inlet Pressure at MECO (PSIA)	Post-MECO Acceleration (RPM/Sec.)	Post-MECO Peak Speed (RPM)	Post-MECO Coastdown Time (Sec.)	Relative Degree of Post-MECO Pumping Action
AC-18*	Burn #1	Not Avail.	34,860	98	Not Avail.	Not Avail.	Not Avail.	Very Poor
	Burn #2	Not Avail.	35,160	99	Not Avail.	Not Avail.	Not Avail.	Poor
AC-23		4000	33,600	95	2,860	36,000	184	Poor
AC-24		4140	- Destroyed Before MECO; Turbine Speed was 42,000 RPM at Destruct -					
AC-25	Burn #1	4000	33,600	95	1,120	38,400	85	Good
	Burn #2	5000	34,800	100	3,000	36,000	167	Intermittent
AC-26*	Burn #1	4200	34,800	105	1,200	37,800	70	Good
	Burn #2	5200	34,800	105	1,000	34,800	143	Fair for 15 Sec., then Poor
AC-27		4220	34,800	95	2,300	36,000	Signal Lost	Poor
AC-28*	Burn #1	4440	36,000	92	1,500	36,000	40	Good
	Burn #2	5300	36,000	92	2,600	37,200	130	Fair for 15 Sec., then Intermittent
AC-29*	Burn #1	4500	33,600	90	1,200	38,400	83	Fair to Good
	Burn #2	5470	34,200	92	1,200	34,800	117	Fair for 15 Sec., then Intermittent
AC-30		4650	35,100	92	845	37,700	193	Poor
AC-31*	Burn #1	4060	33,800	99	0	33,800	43	Good
	Burn #2	5000	33,150	100	800	33,800	160	Good for 15 Sec., then Poor
AC-32*	Burn #1	4330	33,150	98	0	33,800	43	Good
	Burn #2	4920	33,150	98	0	33,150	91	Good for 12 Sec., then Poor
AC-33*		Failure at Booster Jettison Resulted in Mission Loss Before MECO						
AC-34	Burn #1	4060	33,800	100	0	33,800	50	Good
	Burn #2	4810	33,800	100	2,600	35,000	Signal Lost	Intermittent

TABLE 2 (CONTINUED)

Flight Number	Acceleration at Start-up (RPM/Sec.)	Turbine Speed at MECO (RPM)	Turbine Inlet Pressure at MECO (PSIA)	Post-MECO Acceleration (RPM/Sec.)	Post-MECO Peak Speed (RPM)	Post-MECO Coastdown Time (Sec.)	Relative Degree of Post-MECO Pumping Action
TC-1* Attempt #1	-LO_2 Boost	Pump Failed to	Rotate -				
Attempt #2	-LO_2 Boost	Pump Failed to	Rotate -				
TC-2* Burn #1	4330	33,800	102	(Negative)	<MECO Value	120	Good
Burn #2	Poor Data	33,800	102	1,180	<MECO Value	Signal Lost at 100	Good for 16 Sec., then Poor
Burn #3	4800	33,800	102	500	<MECO Value	335	Good for 20 Sec., then Poor
Burn #4	5000	33,800	102	1,410	48,100	>280	Good for 6 Sec., then Poor

NOTE: Asterisk indicates flights having pump instrumented with delta-p measurement.

TABLE 3: LH_2 BOOST PUMP POST-MECO PERFORMANCE SUMMARY FOR ALL FLIGHTS WITH PURGE OF H_2O_2 SUPPLY LINES

Flight Number		Acceleration at Start-up (RPM/Sec.)	Turbine Speed at MECO (RPM)	Turbine Inlet Pressure at MECO (PSIA)	Post-MECO Acceleration (RPM/Sec.)	Post-MECO Peak Speed (RPM)	Post-MECO Coastdown Time (Sec.)	Relative Degree of Post-MECO Pumping Action
AC-18*	Burn #1	Not Avail.	41,110	94	Not Avail.	Not Avail.	Not Avail.	Good
	Burn #2	Not Avail.	41,110	94	Not Avail.	Not Avail.	Not Avail.	Poor
AC-23		4,140	40,300	95	2,370	47,450	247	Very Poor
AC-24		3,830	-Destroyed Be	fore MECO; Turb	ine Speed was	>65,000 at	Destruct-	
AC-25	Burn #1	3,600	40,300	95	2,260	44,200	78	Good
	Burn #2	4,400	39,000	95	2,950	41,000	99	Good
AC-26*	Burn #1	4,060	42,200	95	2,340	45,500	80	Good
	Burn #2	5,230	41,600	95	2,600	44,200	160	Fair for 21 Sec., then Poor
AC-27		3,850	42,900	95	2,890	48,000	Signal Lost	Very Poor
AC-28*	Burn #1	3,720	40,900	92	2,820	44,900	91	Fair to Good
	Burn #2	5,280	41,600	92	2,170	44,200	220	Intermittent
AC-29*	Burn #1	3,820	40,900	90	2,790	44,800	81	Good
	Burn #2	4,640	41,600	92	2,060	46,700	153	Fair for 15 Sec., then Intermittent
AC-30		3,160	40,900	95	2,340	45,500	193	Very Poor
AC-31*	Burn #1	3,940	40,300	95	1,755	45,500	82	Good
	Burn #2	4,780	40,300	96	1,950	44,200	212	Fair for 20 Sec., then Very Poor
AC-32*	Burn #1	Not Avail.	40,300	98	2,080	45,500	90	Good
	Burn #2	4,920	40,300	98	2,600	44,200	169	Fair for 20 Sec., then Very Poor
AC-33*		Failure at B	ooster Jettison	Resulted in Mi	ssion Loss Be	fore MECO		
AC-34	Burn #1	3,820	40,900	100	1,950	42,900	78	Good
	Burn #2	4,640	41,600	100	2,600	45,500	Signal Lost	Fair for 20 Sec., then Poor

TABLE 3 (CONTINUED)

Flight Number	Acceleration at Start-up (RPM/Sec.)	Turbine Speed at MECO (RPM)	Turbine Inlet Pressure at MECO (PSIA)	Post-MECO Acceleration (RPM/Sec.)	Post-MECO Peak Speed (RPM)	Post-MECO Coastdown Time (Sec.)	Relative Degree of Post-MECO Pumping Action
TC-1* Attempt #1	- Turbine Speed Transducer Failed -						
Attempt #2	- Turbine Speed Transducer Failed -						
TC-2* Burn #1	4,060	40,300	102	2,600	48,100	102	Fair for 20 Sec., then Poor
Burn #2	Poor Data	40,300	102	2,700	48,100	Signal Lost at 100	Fair for 20 Sec., then Poor
Burn #3	4,640	40,300	102	Negative	<MECO Value	60	Good
Burn #4	4,810	41,600	102	1,625	48,100	118	Fair for 18 Sec., then Very Poor

NOTE: Asterisk indicates flights having pump instrumented with delta-p measurement.

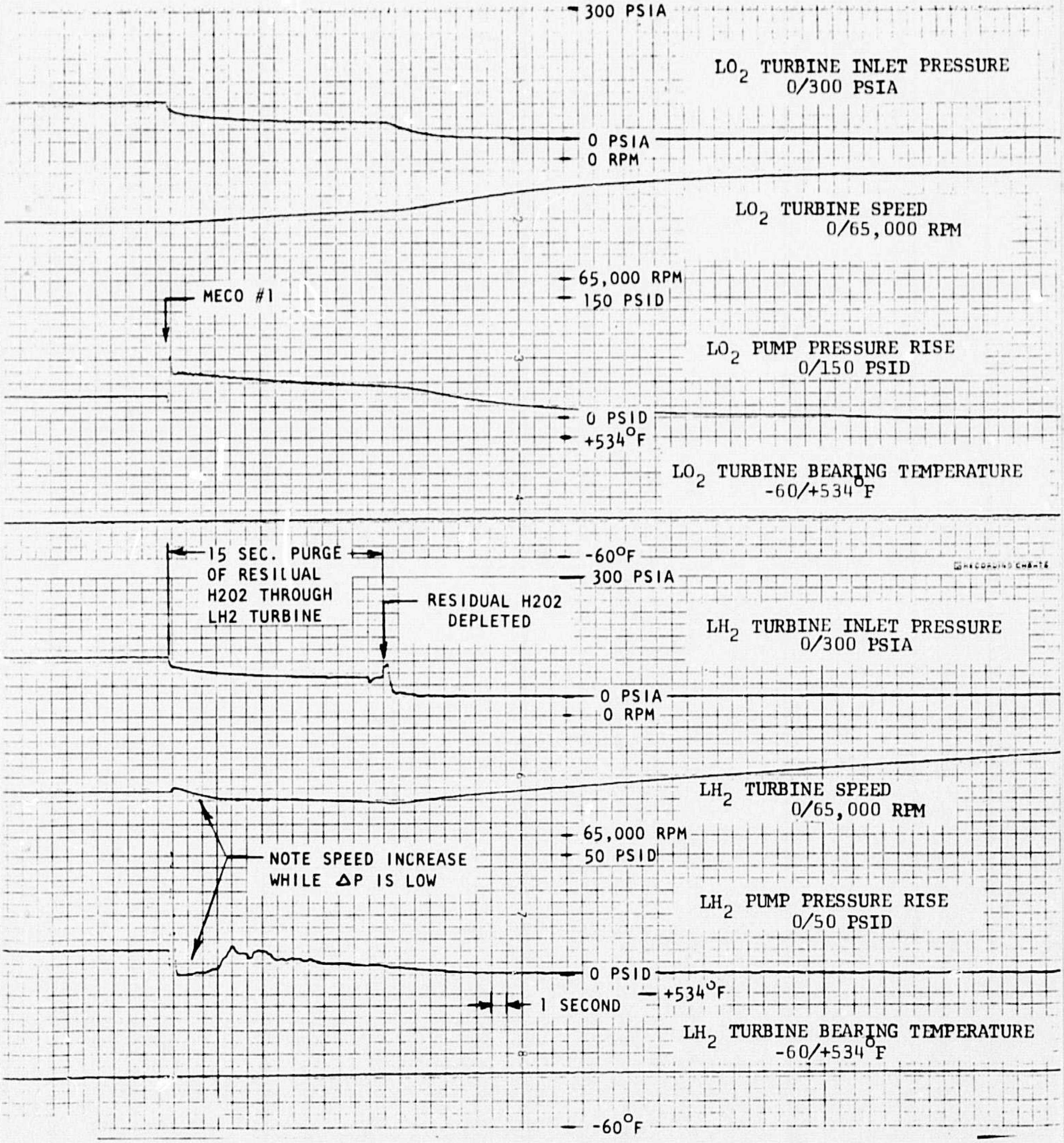


FIGURE 1: TC-2 POST-MECO #1 BOOST PUMP PERFORMANCE TELEMETRY DATA

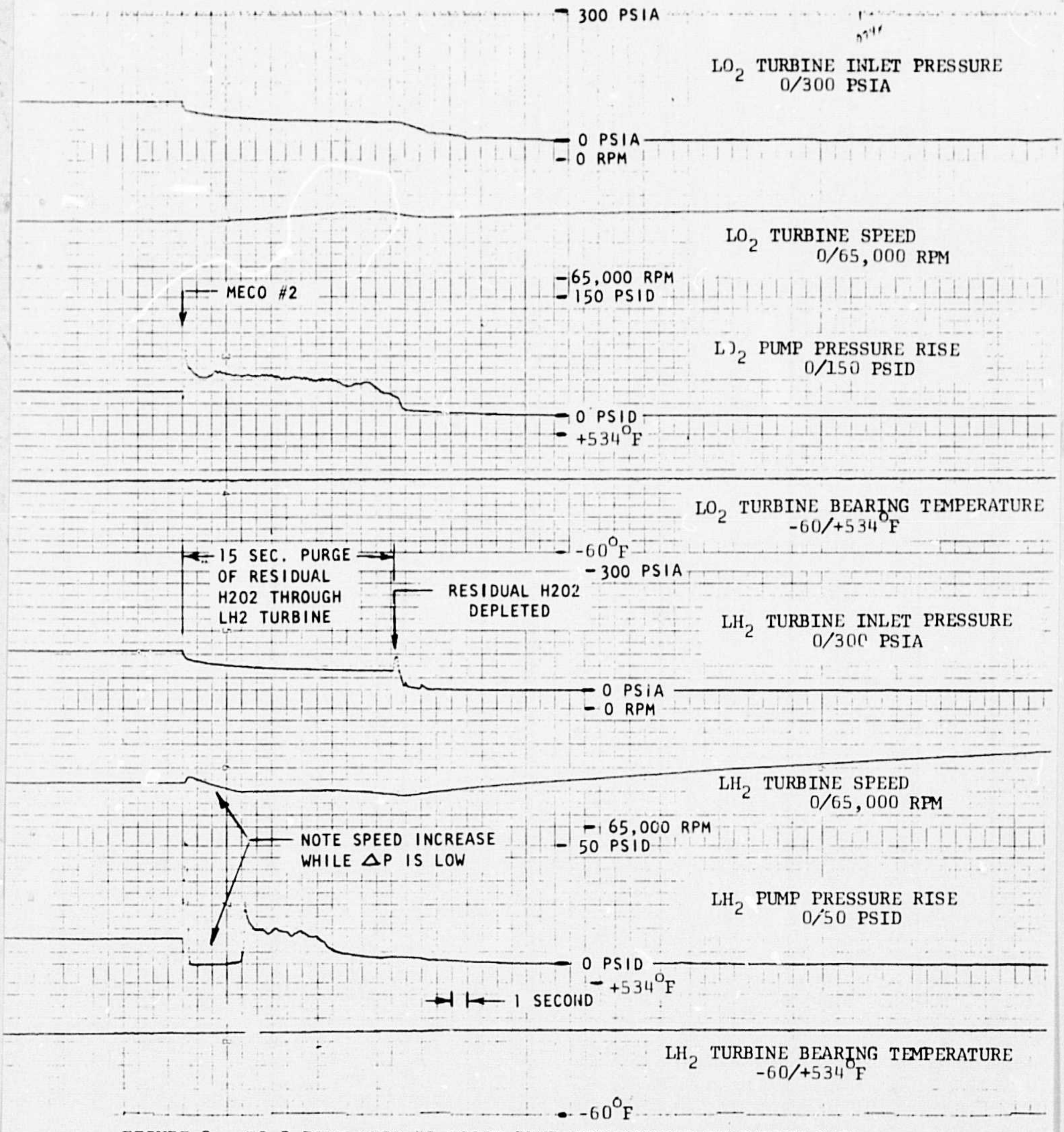


FIGURE 2: TC-2 POST-MECO #2 BOOST PUMP PERFORMANCE TELEMETRY DATA

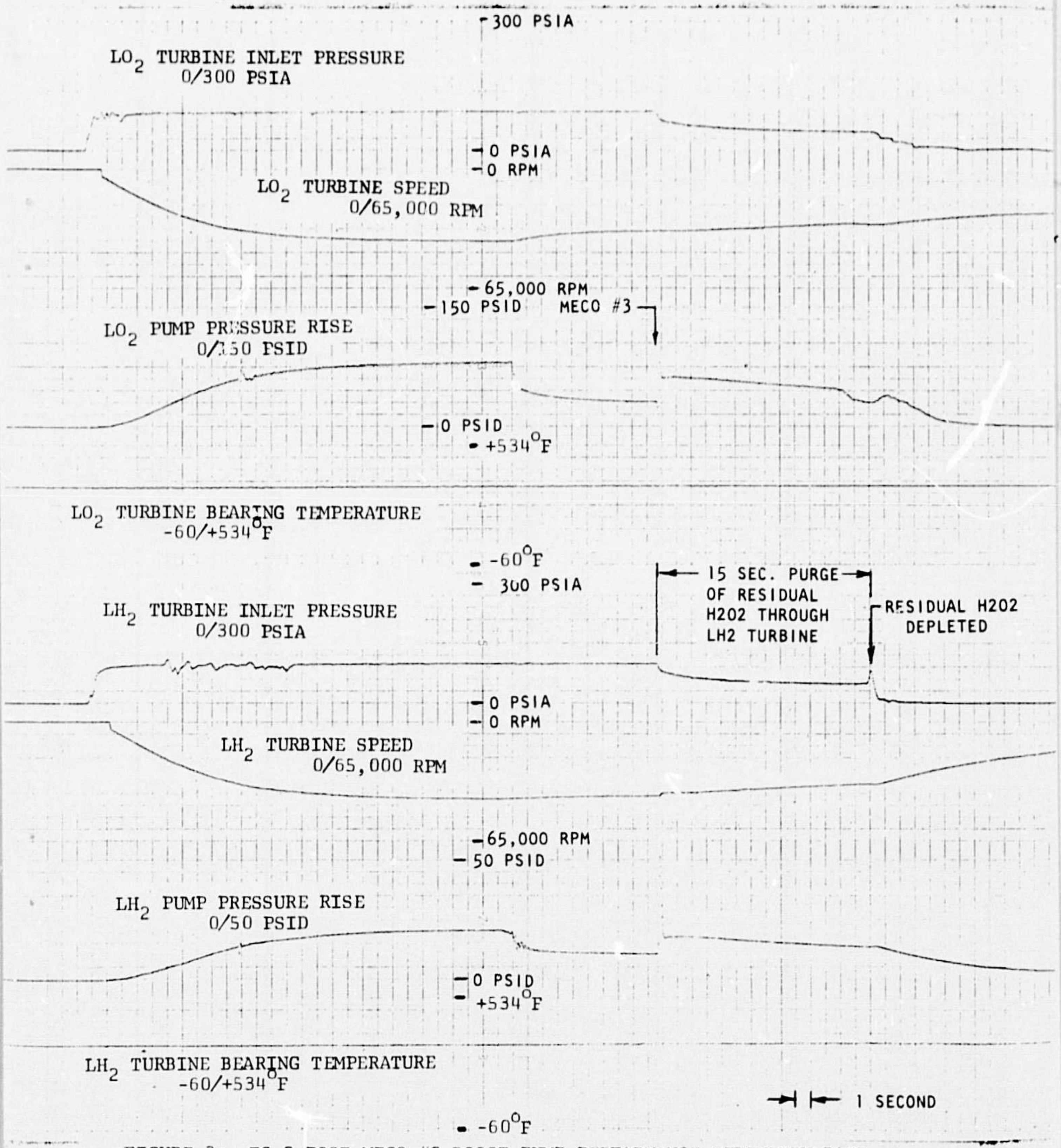


FIGURE 3: TC-2 POST-MECO #3 BOOST PUMP PERFORMANCE TELEMETRY DATA

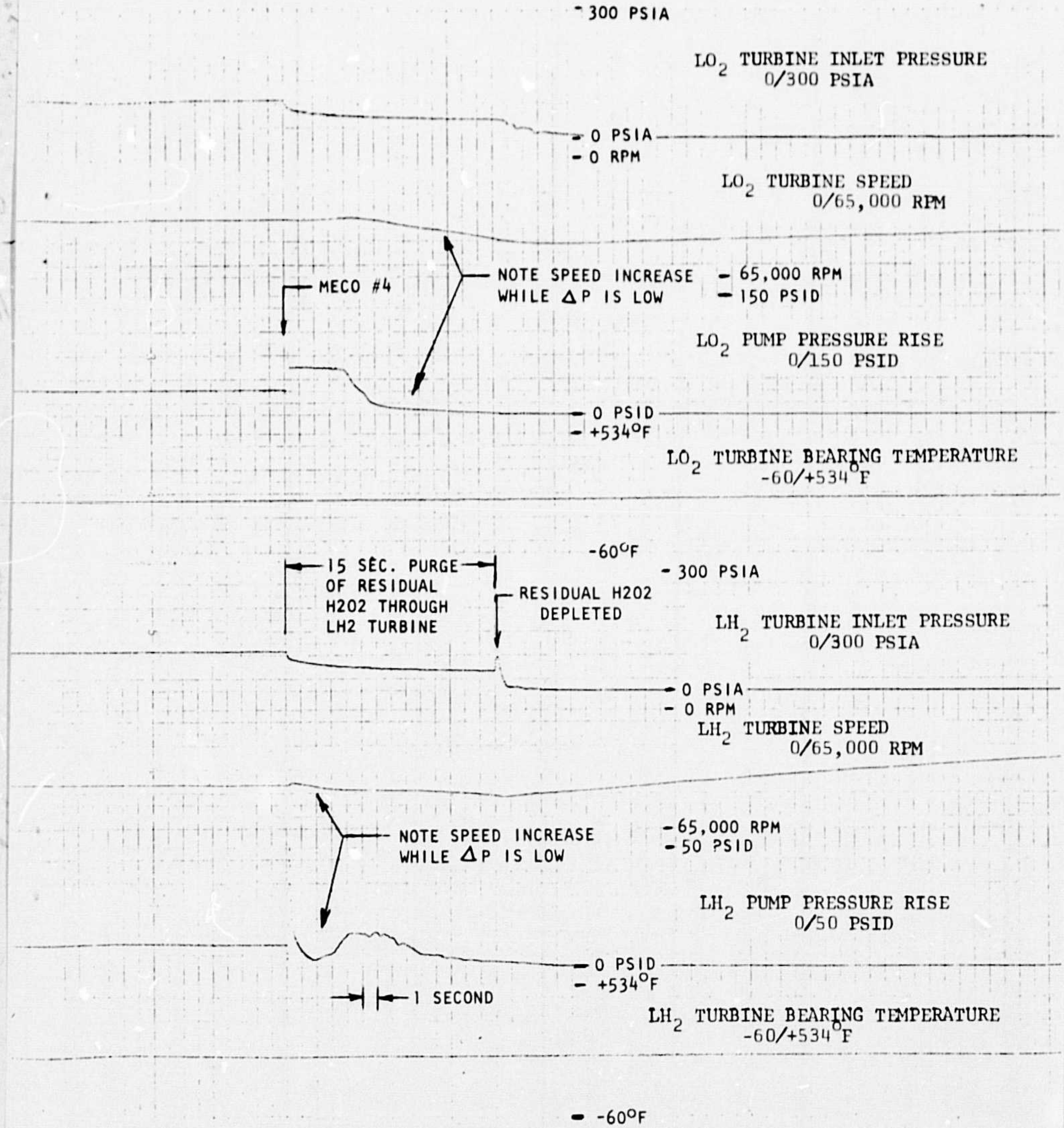


FIGURE 4: TC-2 POST-MECO #4 BOOST PUMP PERFORMANCE TELEMETRY DATA

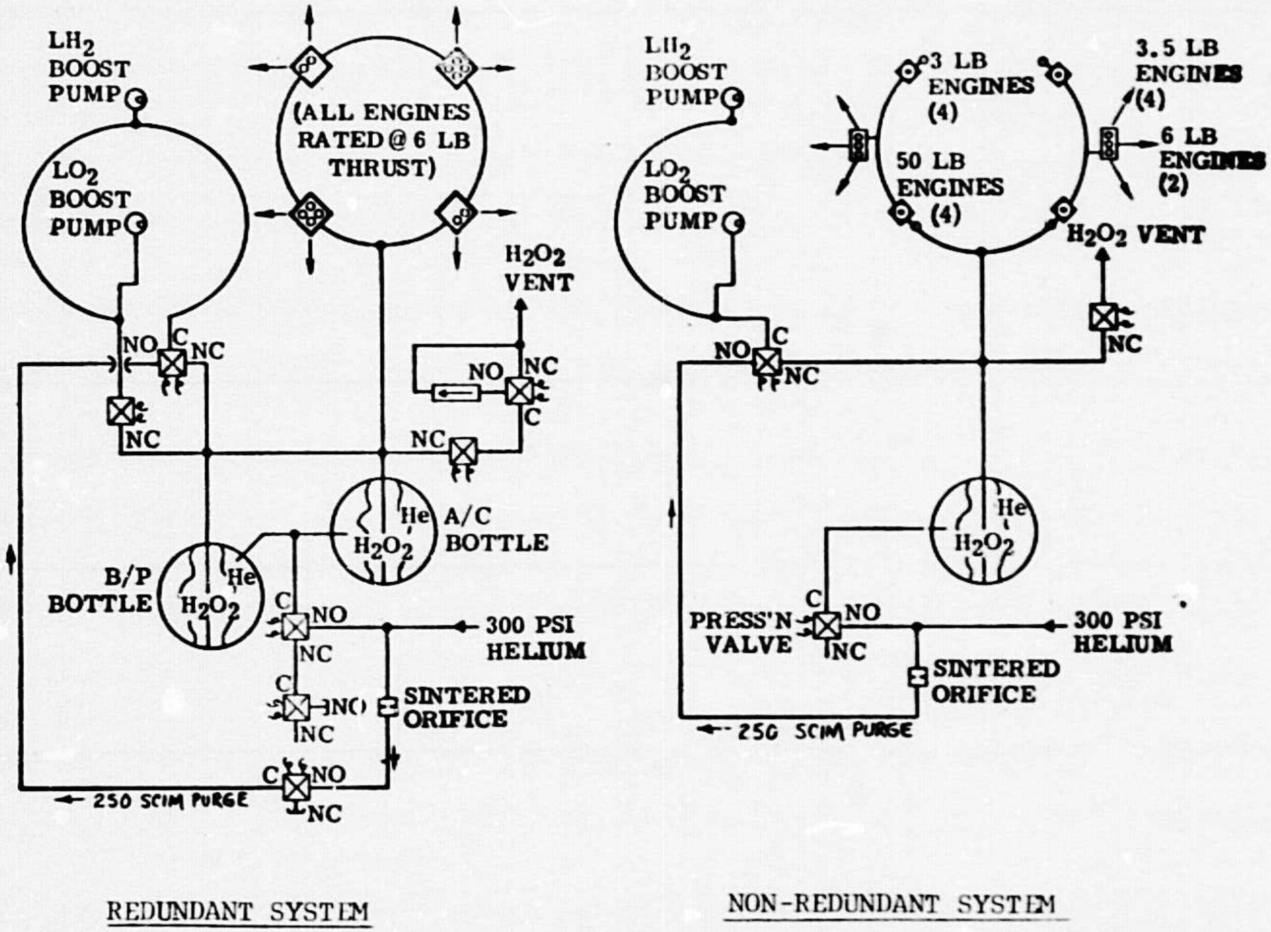


FIGURE 5: COMPARISON OF REDUNDANT AND NON-REDUNDANT HYDROGEN PEROXIDE SUPPLY SYSTEM CONFIGURATIONS

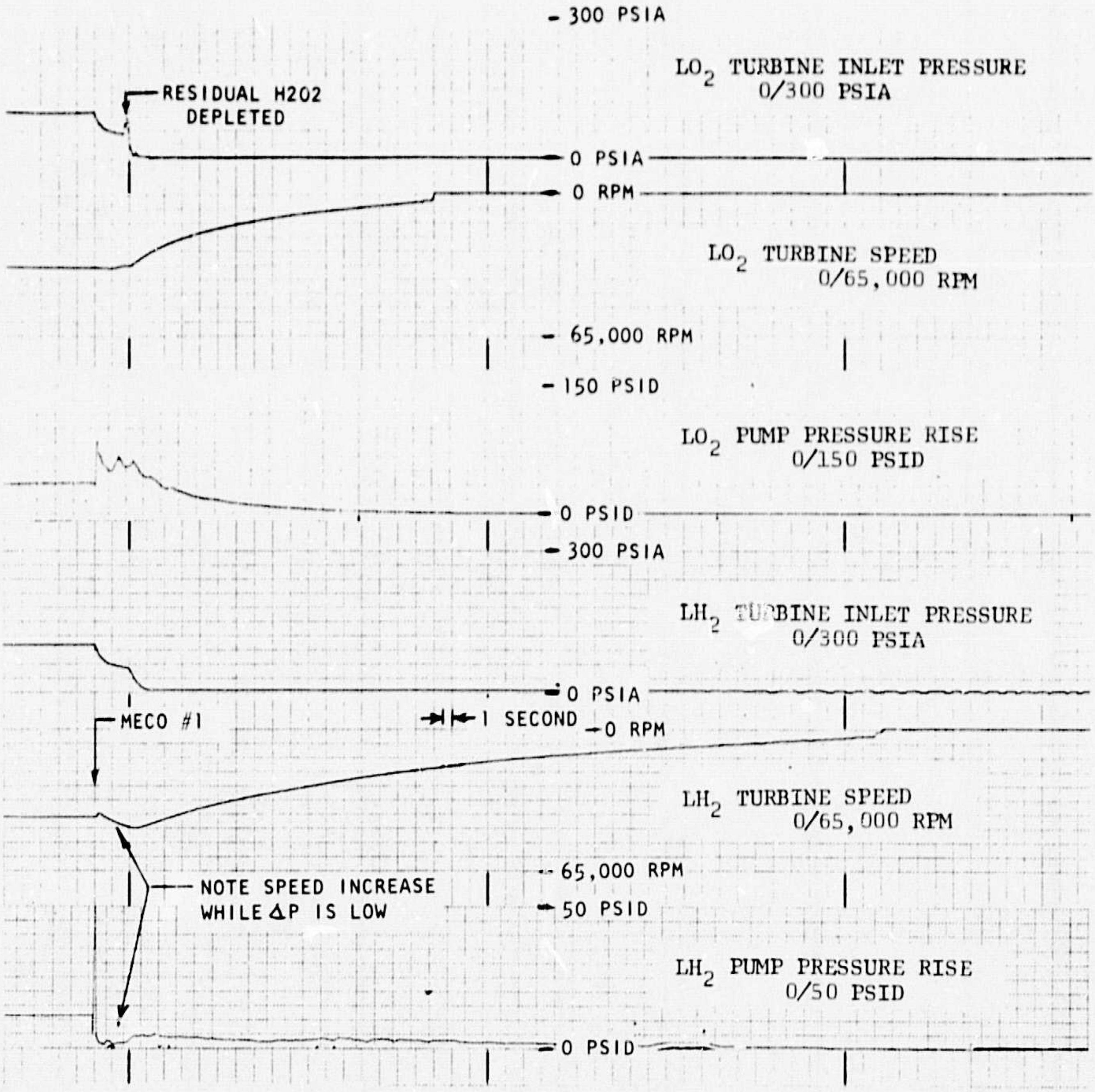


FIGURE 6: AC-32 POST-MECO #1 BOOST PUMP PERFORMANCE TELEMETRY DATA

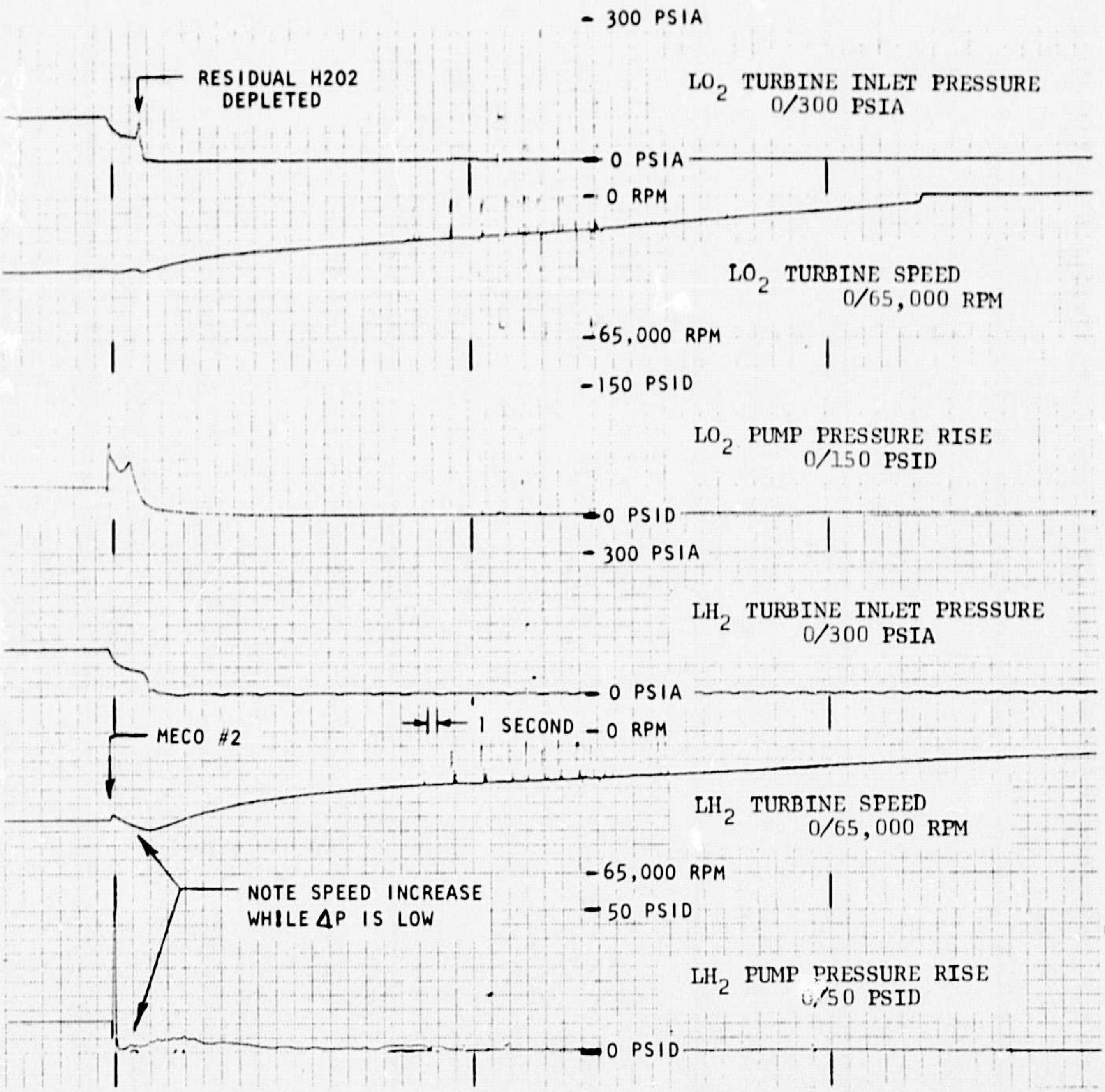


FIGURE 7: AC-32 POST-MECO #2 BOOST PUMP PERFORMANCE TELEMETRY DATA

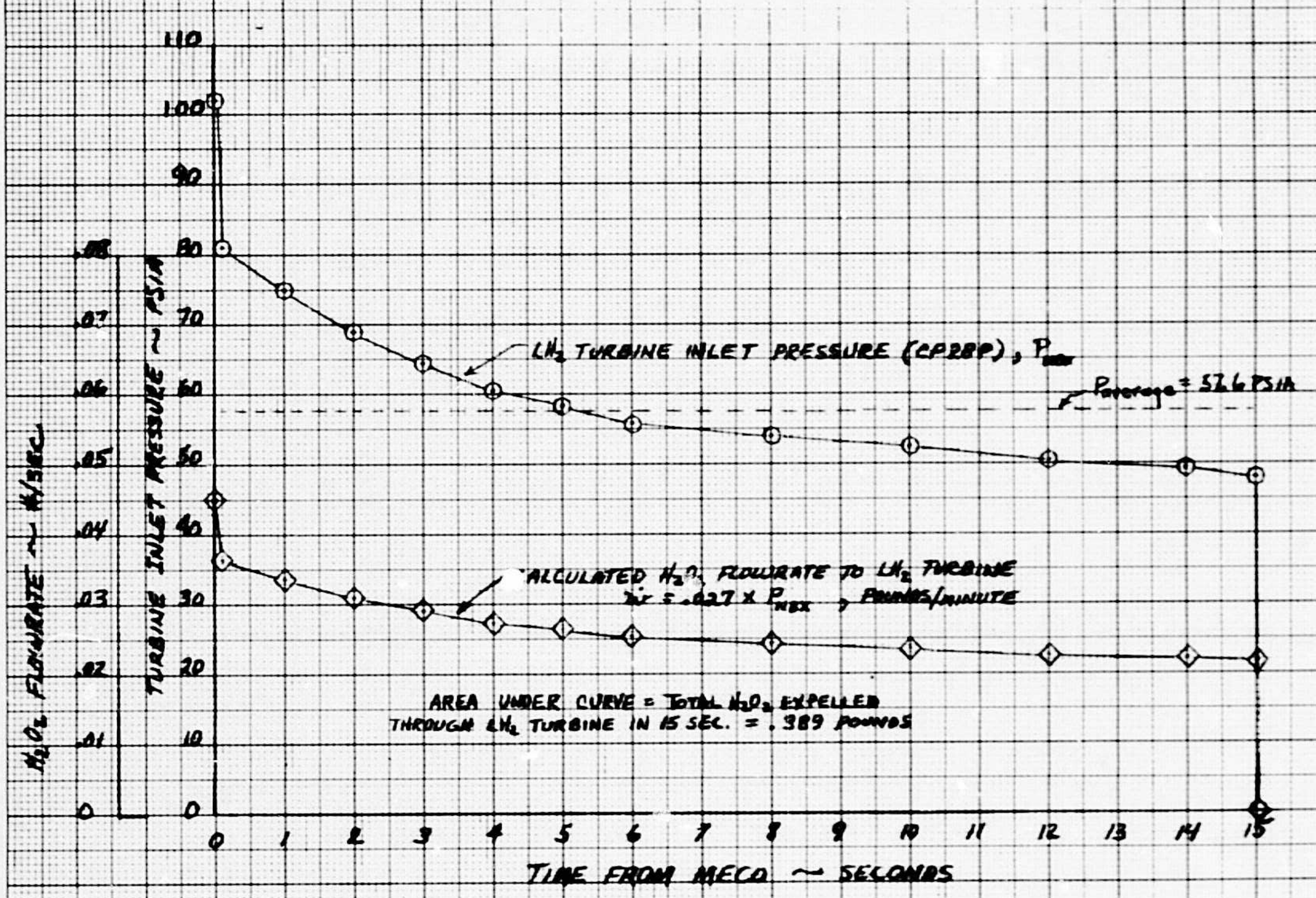


FIGURE 8 : LIQUID HYDROGEN BOOST PUMP TURBINE INLET PRESSURE DURING FIRST 15 SECOND TIME PERIOD AFTER TC-2 MECO #1, AND CALCULATED 90% CONCENTRATION HYDROGEN PEROXIDE (H_2O_2) FLOWRATE.

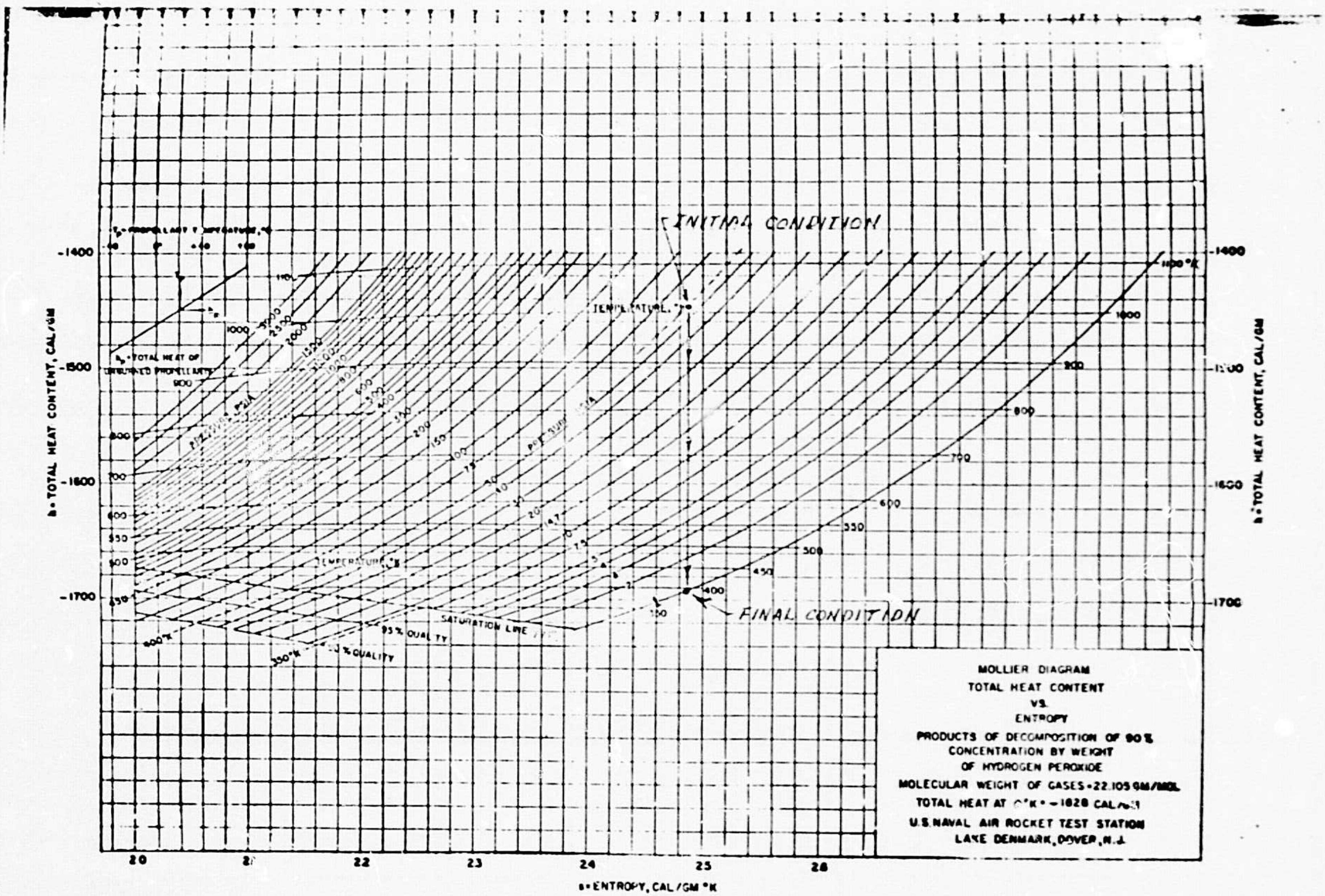
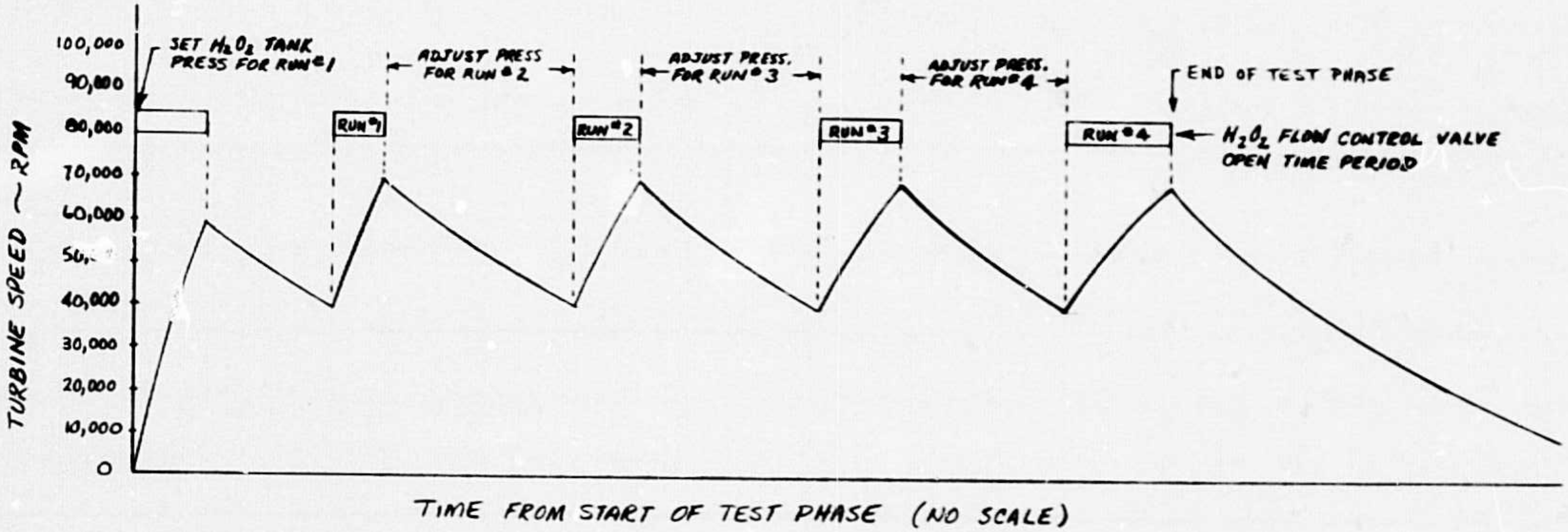


FIGURE 9: ENTHALPY-ENTROPY DIAGRAM FOR HYDROGEN PEROXIDE



SEQUENCE:

1. SET H_2O_2 TANK PRESSURE TO GIVE DESIRED TURBINE INLET PRESSURE FOR RUN #1.
2. OPEN H_2O_2 FLOW CONTROL VALVE AND ACCELERATE TO ~ 60,000 RPM.
3. CLOSE H_2O_2 FLOW CONTROL VALVE AND ALLOW SPEED TO DECAY TO 40,000 RPM.
4. AT 40,000 RPM, OPEN H_2O_2 FLOW CONTROL VALVE AND ACCELERATE TO ~ 70,000 RPM (RUN #1).
5. AT 70,000 RPM, CLOSE H_2O_2 FLOW CONTROL VALVE. WHILE TURBINE SPEED IS DECAYING TO 40,000 RPM, ADJUST H_2O_2 SUPPLY TANK PRESSURE TO GIVE DESIRED TURBINE INLET PRESSURE FOR THE NEXT RUN.
6. REPEAT STEPS 4 AND 5 FOR RUN #2.
7. REPEAT STEPS 4 AND 5 FOR RUN #3.
8. REPEAT STEPS 4 AND 5 FOR RUN #4.

FIGURE 10: ILLUSTRATED RUN SEQUENCE TYPICAL FOR TEST PHASES II, III, AND IV.

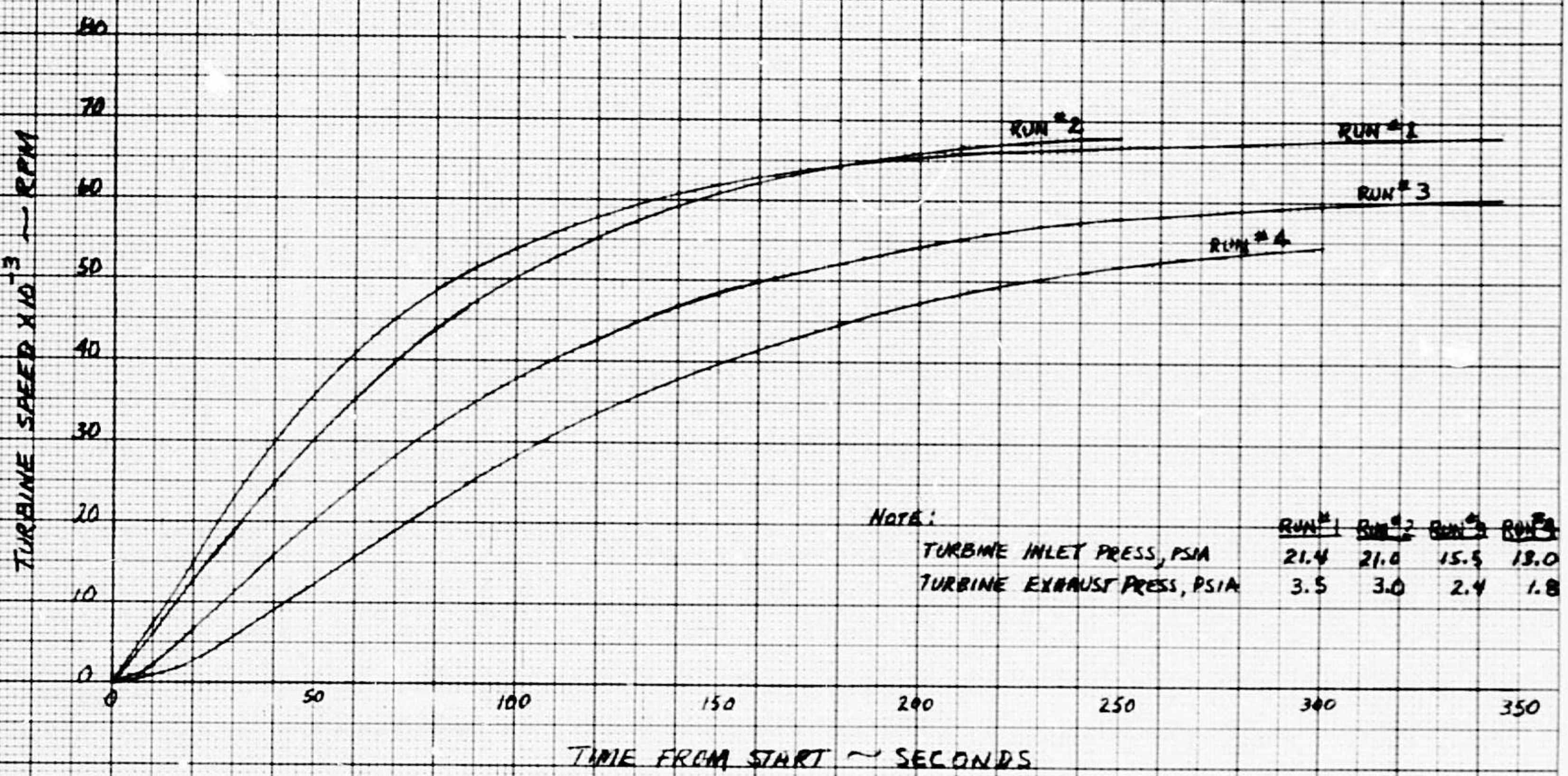


FIGURE 11 : STEADY STATE LIQUID HYDROGEN TURBINE SPEED AT CONSTANT TURBINE INLET PRESSURE ; TESTS CONDUCTED USING TURBINE SERIAL NUMBER 52 WITHOUT A PUMP ATTACHED (PHASE I TESTS).

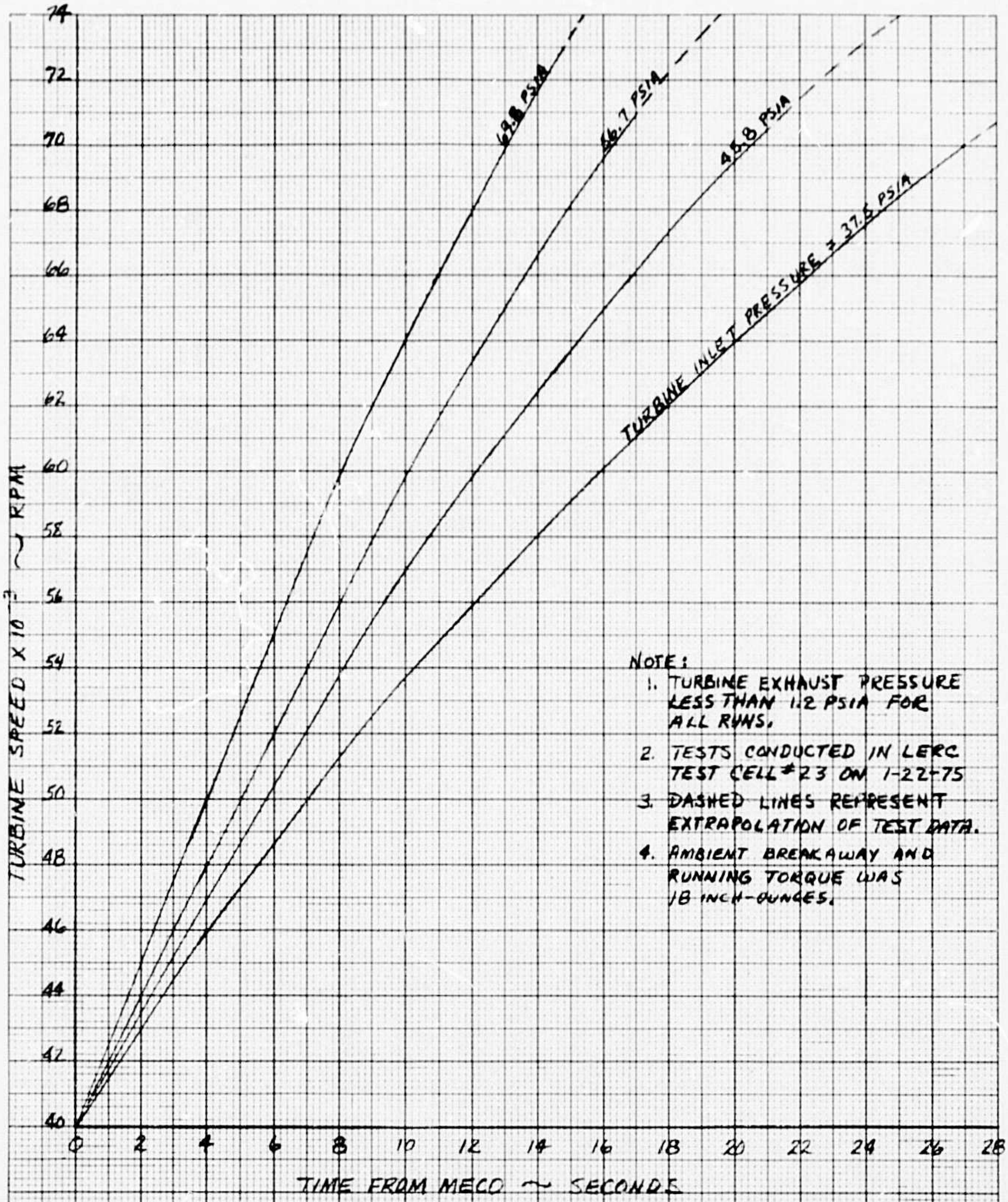


FIGURE 12: LIQUID HYDROGEN TURBINE DRIVE SERIAL Nº 52 ACCELERATION AFTER SIMULATED FLIGHT MAIN ENGINE CUTOFF FOR VARIOUS TURBINE INLET PRESSURES (WITHOUT A PUMP INSTALLED), PHASE II.

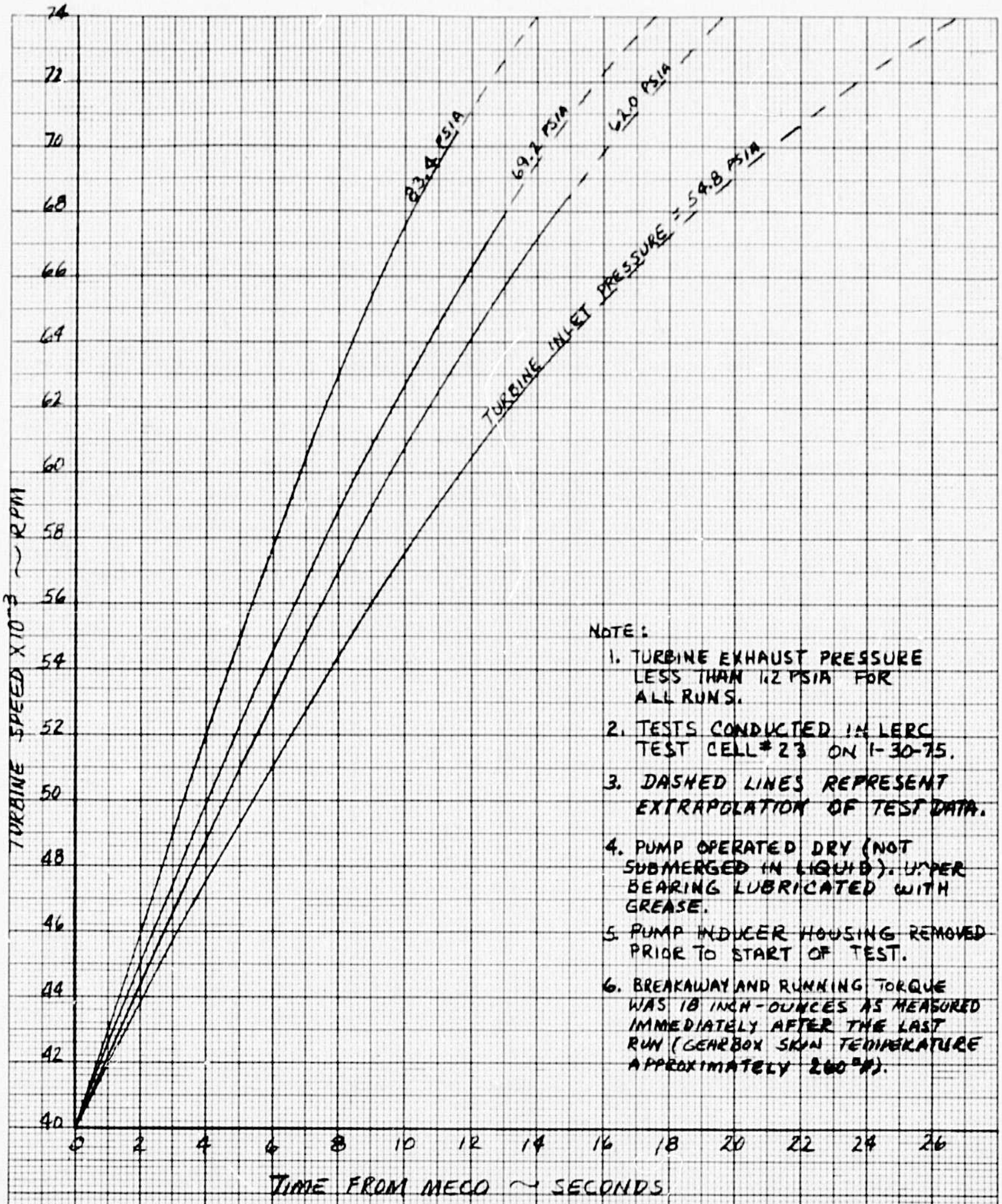


FIGURE 13: LIQUID HYDROGEN BOOST PUMP AND TURBINE DRIVE SERIAL Nº 1212166 ACCELERATION AFTER SIMULATED MAIN ENGINE CUTOFF FOR VARIOUS TURBINE INLET PRESSURES (PUMP MATED WITH DRIVE), PHASE III.

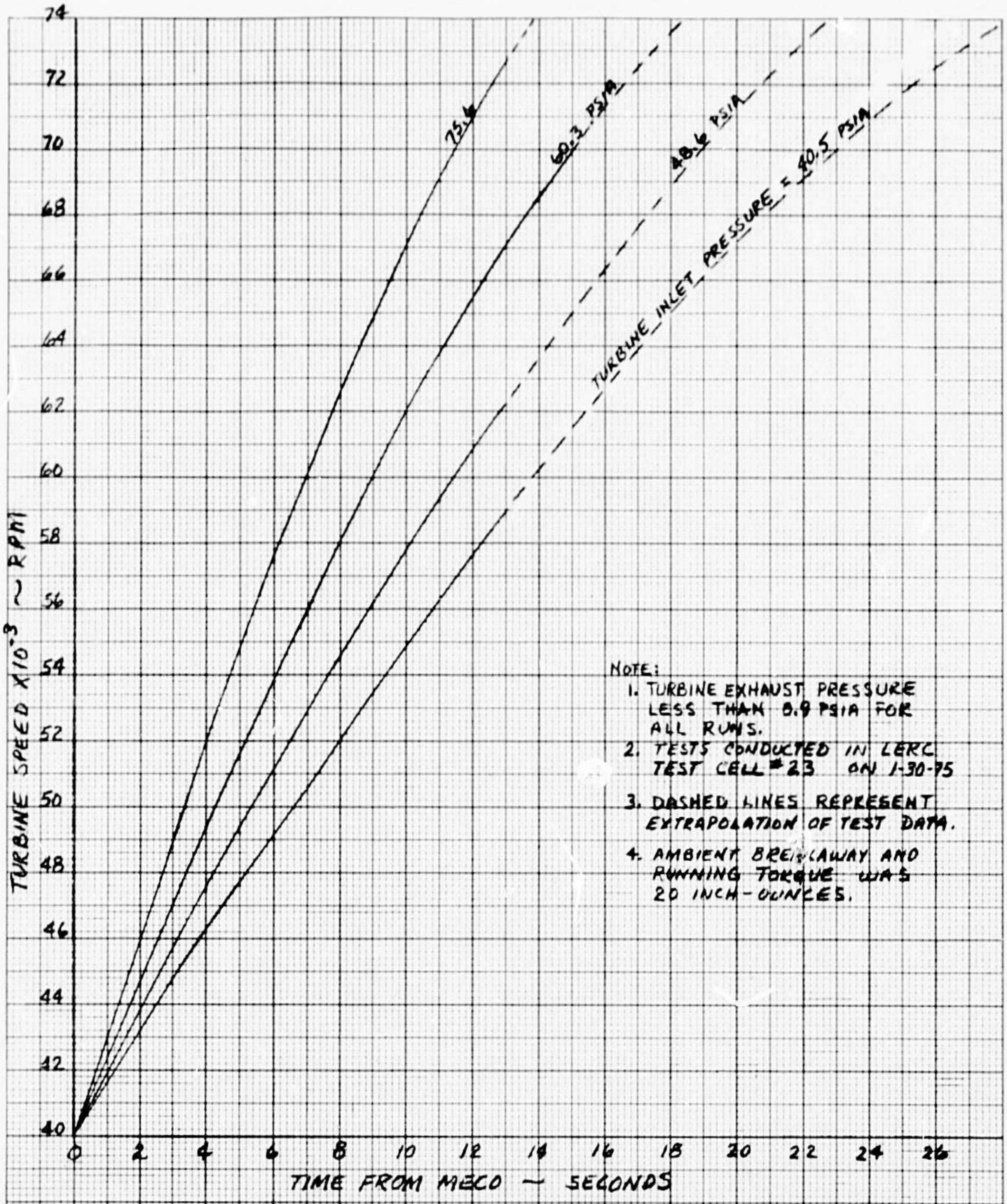


FIGURE 14: LIQUID HYDROGEN TURBINE DRIVE SERIAL Nº 66 ACCELERATION AFTER SIMULATED FLIGHT MAIN ENGINE CUTOFF FOR VARIOUS TURBINE INLET PRESSURES (WITHOUT A PUMP INSTALLED), PHASE IV.

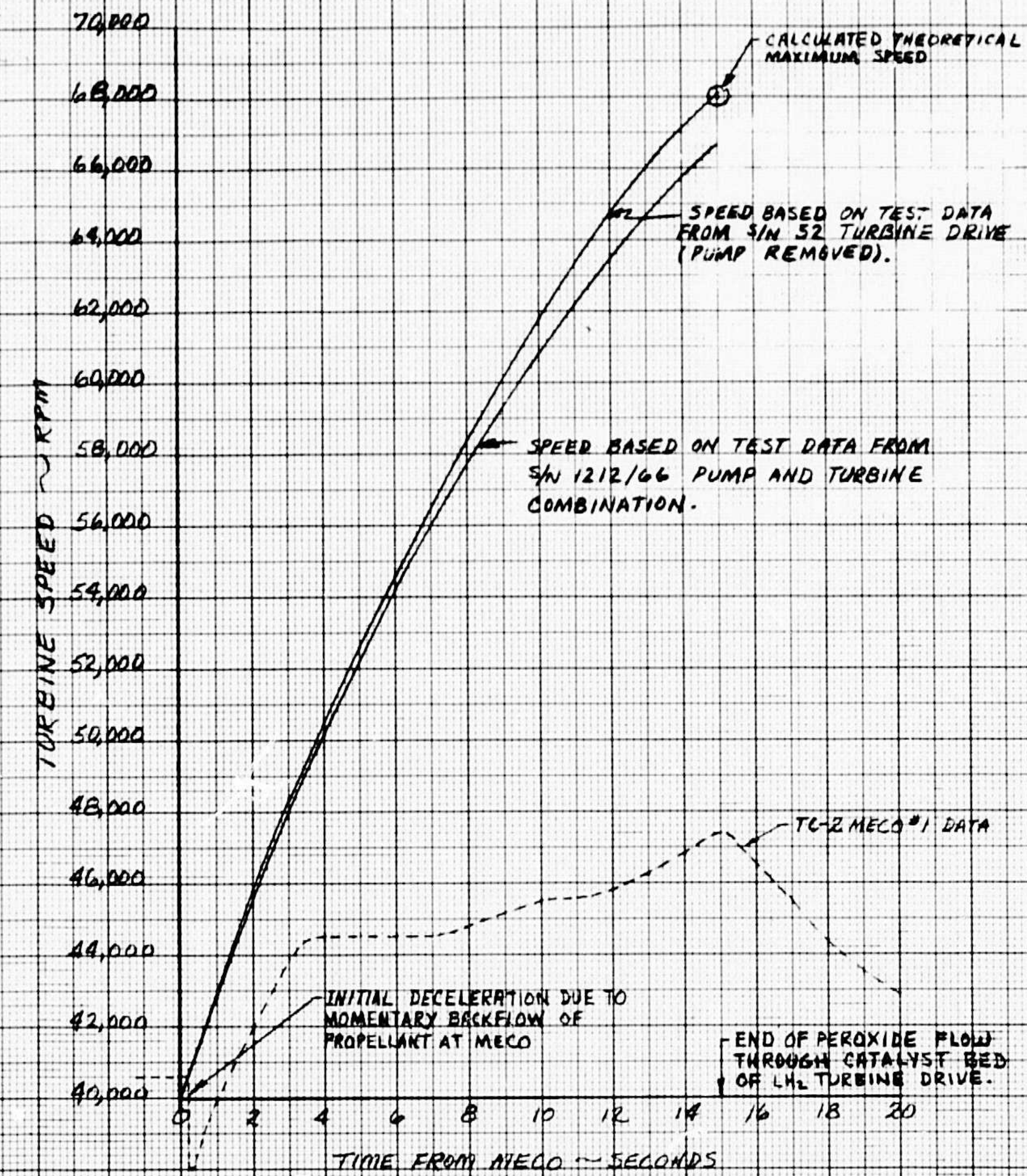


FIGURE 13 : CALCULATED LIQUID HYDROGEN BOOST PUMP TURBINE SPEED VERSUS TIME AFTER MAIN ENGINE CUTOFF UNDER WORST CASE CONDITION OF NO LIQUID AT PUMP INLET.