S-IVB Restart Chilldown Experience

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Experience gained in Saturn V/Apollo flights adds significant knowledge regarding liquid rocket engine chilldown in orbital operations. Chilldown experiments were conducted on the Saturn S-IVB stage using real time ground commands. The series dumping mode which was investigated, defined maximum and minimum chilldown time models for the systems. Experiment results also indicated prechill effects on hardware chilldown at the g levels encountered. These experiments showed that in the series dump mode, a compromise would exist between hardware chilldown requirements. An attractive future restart chilldown system is the dumping mode applied individually to each of the components requiring chilldown.

Introduction

Alternative methods of restart chilldown were considered during the flight planning stages of the Saturn V/Apollo missions. These procedures were for use in the event of failure in the normal forced recirculation restart chilldown system. The procedures selected consisted of dumping propellants through either the main oxygen or main fuel valve of the engine, depending upon the location of the failure. Since individual valve command circuits had been installed for ground test and checkout purposes, inflight command capability was obtained with little change to the stage. Failure detection and verification techniques were developed using stage and engine instrumentation. All of the alternate procedures involved the use of propellant dump for chilldown and were included in flight procedures as "Mission Rules" to be followed in the event failure occurred.

Two experiments were performed to define the restart and chilldown characteristics of the propellant dumping mode and to develop required operational sequences. The characteristics thus developed were used to establish the propellant dump times included in the alternate procedures.

The two experiments were performed in the terminal phases of the Saturn SA-504[1] and SA-505[2] flights. The results of these experiments, and considerable additional data concerning liquid migration and low-g phenomena, are presented in the following sections of this paper. A description of the normal Saturn S-IVB restart chilldown system is presented as a necessary prelude.

Normal S-IVB Restart Chilldown

Major features of the chilldown system are depicted in Fig. 1. The positions of the valves and the propellants during coast are illustrated in the simplified diagram in Fig. 2a. Hydrogen boiloff during coast is discharged overboard through a continuous vent (thrust) system which controls the position of the propellants in the tanks. Heat added to the propellant feed ducts, the turbopumps, and the thrust chamber, must be removed prior to restart. Normally, this is accomplished in two chilldown phases. The first phase conditions the propellant ducts and the turbopumps. The second phase conditions the thrust chamber.

In the first phase, fully immersed electrical motor driven centrifugal pumps circulate propellants through the inlet ducts and the pumps for 300 sec prior to engine start. During this period the prevalves and the main propellant valves are closed and the bleed valves are open as shown in Fig. 2b. Propellants flow from the tanks through the inlet ducts and the turbopumps in a normal engine operating flow direction. Return flow to the tanks takes place through the bleed valves and the recirculation lines. At the end of this phase the ducts and pumps are fully conditioned and the propellants in the pumps have the desired amount of subcooling.

In the second phase, the main fuel valves (MFV) is opened at engine start command, as depicted in Fig. 3a, and fuel flows through the engine for 8 sec. Helium purge also occurs during this fuel lead period. During fuel lead the desired thermal conditions are established in the cooling passages of the thrust chamber, the injector, and the augmented spark igniter (ASI). The ASI valve in the LOX supply line also is open, and combustion occurs in the ASI. At the end of the fuel lead the thrust chamber is adequately conditioned for the 2.5-sec start transient resulting in mainstage operation.

Figure 3b shows an example of a time critical event associated with the failure of the main fuel valve to close at the end of the first burn. Control system response analysis revealed that an undesirable flow of LOX into the LH_2 feed system would occur when the most effective corrective action was applied. Further analysis revealed that this could be tolerated for a few seconds. A preprogrammed ground command sequence which provided the desired time limitation made this corrective action feasible.

The normal temperature profiles experienced during the coast and chilldown phases of the Saturn V/Apollo missions are shown in Fig. 4. At the end of the first burn, the fuel turbine inlet temperature is 1600°R and it decreases to 600°R during the coast period. Thrust chamber is nearly stabilized at 520°R at the end of coast. Fuel injector temperature increases to 300°R during this period. The fuel injector transducer during coast is exposed to vacuum and the thermal environment of the engine injector.

The temperatures of the fluids in the inlets and outlets of the pumps increase during coast. Discharge temperatures increase at a faster rate, however, and also stabilize at a higher temperature, due to differences in environmental heating and cooling rates. Major influencing factors are residual heat in the turbines at the end of burn and liquid propellant migration into the feed system under the influence of the propellant settling acceleration applied to the vehicle.

The desired temperature changes occur, as shown in Fig. 4, in the two major chilldown phases. In the first phase, pump

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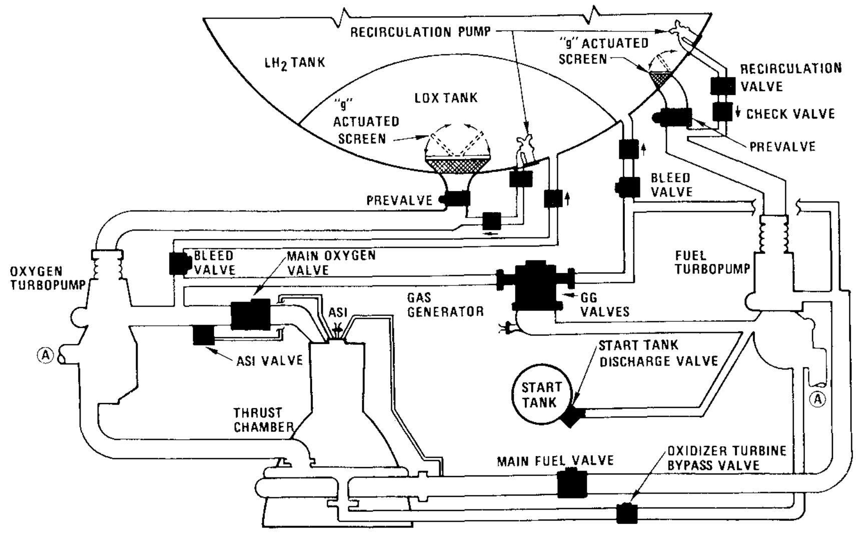

Fig. 1 S-IVB/J2 engine chilldown system.

chilldown, the inlet ducts and the pumps are chilled and in the second phase, the thrust chamber is chilled. The change in thrust chamber temperature is greater than that indicated by the thrust chamber jacket temperature measurement. This measurement primarily is used during relatively stable periods when a fast response is not required. Therefore, it does not indicate accurately during the highly transient fuel lead period.

Alternative Chilldown Methods

Individual chilldown system component failure possibilities were analyzed for failure effect and corrective action potential. These analyses were deeply involved in three major areas: 1) the immediate and subsequent effects of the failure, 2) the potential effectiveness of the corrective action that could be taken with existing onboard equipment, and 3) the feasibility, from the flight control standpoint, of effectively identifying the failure and implementing the corrective action. From these analyses, NASA established mission rules covering the most critical identifiable failure possibilities. Implicit in these procedures was the implementation of real time ground command capability.

Minor changes made in the S-IVB provided the desired control circuits. In some cases, however, alternative procedures (to be followed in the event of failure) were compromised to a minor extent by the characteristics previously developed into the onboard control systems. Difficulty also was encountered with variations in ground command response time. This occured in instances where accurate control of the time between events was required in the onboard systems. This difficulty was overcome by including time critical events in preprogramed sequences initiated by single ground commands.

The main fuel valve failure illustrated in Fig. 3b was analyzed for its effect on the subsequent chilldown operations and for its immediate mission effects. Other chilldown failures such as electrical pump failures, prevalve failures, and bleed valve failures also were considered and included in the operational prospectus. In all of the failure cases the most logical alternate chilldown procedure involved either no additional chilling operations, or additional propellant dumping (LOX or LH_2) operations (by ground command) for certain prescribed time periods. Since dumping mode chilldown and restart characteristics had not been fully developed, additional data were desired.

Chilldown Experiments

Propellant lead experiments were conducted on SA-504 and SA-505 flights after the primary objectives of the flights had been completed. Flight profiles and experiment conditions were different due to different primary mission objectives. Significant external conditions of the experiments are presented in Table 1.

The SA-504 experiment was conducted without operation of either the LOX, or the LH_2 pump chilldown (recirculation) systems. An engine restart was attempted using a 52-sec fuel lead to condition the LH_2 inlet ducts, turbopump, and the thrust chamber. The engine started successfully at the end of the fuel lead period. However, undesirable combustion characteristics were triggered either by an overchilled

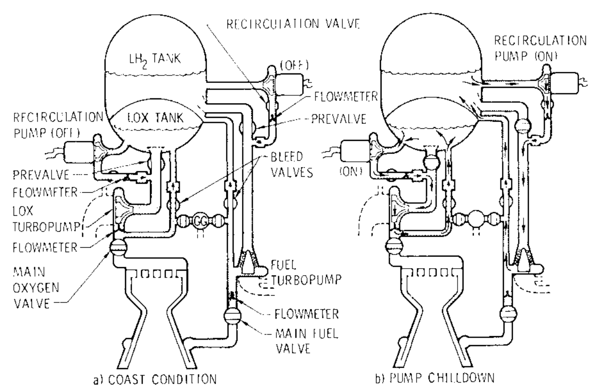

Fig. 2 Coast condition and pump chilldown flow diagrams.

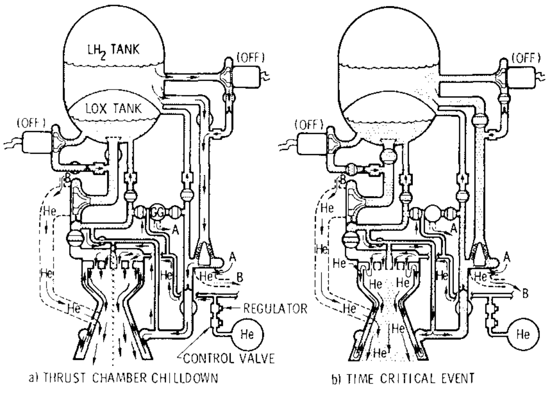

Fig. 3 Thrust chamber chilldown and critical event flow diagrams.

condition in the thrust chamber or by the combination of overchill on the fuel side and underchill on the LOX side. Analysis of the data from this experiment indicated that an 8-sec fuel lead period would have been adequate for thrust chamber conditioning.

The SA-505 experiment also was conducted without operation of either the LOX, or the LH_2 pump chilldown (recirculation) systems. The sequence of events indicated in Fig. 5 was controlled entirely by ground command from the NASA Mission Control Center in Houston. The continuous vent system was not in operation and settling thrust was not applied to the stage during the 2.11 hr translunar coast period. The two 70-lbf ullage motors were fired for 280 sec immediately following the coast period to settle the liquids in the tanks. The ullage motors were turned on 17 sec prior to LOX tank repressurization and were turned off 4 sec after the start of fuel lead. An 8-sec LOX lead was used prior to fuel lead to condition the LOX turbopump, and the LOX and fuel leads were separated by a 100-sec time period to evacuate the thrust chamber. Since restart was not attempted, the fuel lead period was again extended to obtain additional data regarding LH_2 flow in a low-g self-ullaging dumping mode.

The propellant tanks were repressurized using gas stored in the ambient repressurization system which is sized for normal restart conditions. Since experiment ullage volumes were greater than normal, the ambient repressurization system was not able to pressurize the tanks to normal restart pressures. LOX and LH_2 ullage pressures during the experiment were 30 and 21 psia, respectively. Normal pressures are 40 and 31 psia, respectively.

Chilldown characteristics demonstrated during the SA-505 experiment are indicated by the temperature curves in Fig. 5. Turbine inlet temperature and thrust chamber jacket temperature at the end of coast both indicate the effects of a shorter coast period as compared to the normal coast period in Fig. 4. Normal coast occurs in a 100 naut mile earth orbit. The SA-505 experiment was conducted while the S-IVB was in a translunar trajectory between the altitudes of 171 and 19,800 naut miles.

Post flight evaluation established that chilldown rate is relatively insensitive to small initial temperature differences. Therefore, the different coast conditions (Table 1) between the SA-504 and the SA-505 experiments were not a major factor. The most significant factor was the prechilling effect of the applied settling acceleration. As indicated in Table 1, a factor of 42 exists between the total applied prechill acceleration of the SA-505 experiment and the SA-504 experiment. The prechilling effect of this difference in acceleration environment is discussed under Operational Characteristics. Theoretical calculations indicated that 120 sec of settling time would be required for the liquid phase to migrate into the fuel pump inlet in the ullage motor accelerating environment of the SA-505 experiment. Actually, liquid appeared at the pump inlet 66 sec after the ullage motors were turned on.

Table 1 Experiment conditions

Parameter	Experiment SA-504	Experiment SA-505
Vehicle mass, lbm		
LOX	108,609	5,740
LH_2	23,627	1,150
Other	32,853	31,477
Total	165,089	38,367
Settling acceleration[a]		
Thrust, lbf	140	140
Intensity, g's	8.5×10^{-4}	3.65×10^{-3}
Duration, sec	30	280
Coast condition	1.33 hr in 100 naut miles Earth orbit	2.11 hr in translunar trajectory

[a] Applied to vehicle prior to fuel lead.

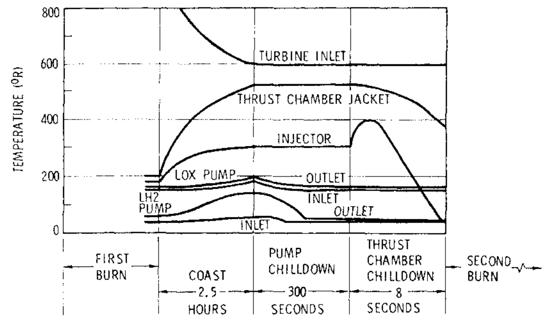

Fig. 4 Normal chilldown.

This indicates a factor of 0.55 between calculated and actual migration time in the LH_2 system.

The acceleration impulse applied to the oxygen system prior to opening the main oxygen valve (MOV) was 0.191 g-sec in the SA-504 experiment and 0.603 g-sec in the SA-505 experiment. In the first experiment it was applied at the ullage motor thrust level shown in Table 1 and, in addition, by the 52-sec fuel lead at an average thrust of 400 lb. In the second experiment, it was applied only by the ullage motors intensity indicated in Table 1. In neither experiment was the settling impulse sufficient to cause a liquid indication at the LOX turbopump inlet prior to opening the LOX valve. Calculation indicates that liquid migration to the pump inlet should have occurred in each case with approximately half of the settling impluse actually applied. These data therefore indicate that a factor of at least 2 exists between calculated and actual LOX migration times. Both tanks have 100 mesh, 0.0045-in. diam wire screens at the outlets. Calculations indicate that the applied acceleration was insufficient to overcome capillary forces in the screens; however, the screens are normally actuated open below 0.5 g and they should not have affected liquid migration during the experiments.

Data Interpretation

Examples of the data received from the propellant lead experiments are presented in Fig. 6. The fuel pump inlet temperature indication is obtained from a platinum wire resistance-type temperature sensor. Fuel pump inlet pressure is obtained from a potentiometer-type pressure transducer. Both measurements are transmitted by pulse code modulation telemetry at a data sampling rate of 12 samples per sec. The prepressurization operation and valve positions indicated on the figure show the actual event times that were achieved as a result of ground commands.

As shown by the "MOV open" bar on Fig. 6, LOX lead started at 17,301 sec. Fuel pump inlet pressure and temperature were constant and at a saturated condition during LOX lead. Fuel pump inlet measurements indicated that a saturated liquid/gas condition existed starting at 66 sec after the ullage motors were turned on.

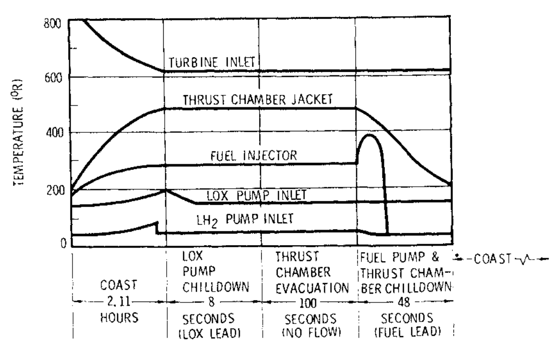

Fig. 5 SA-505 experiment chilldown.

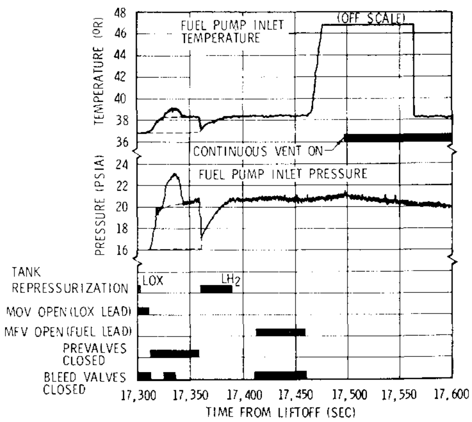

Fig. 6 Typical experiment data for SA-505 experiment.

During the period that saturation was indicated, the temperature-pressure relationship was in good agreement with the characteristic vapor pressure curve. This characteristic was used as a means of "inflight" calibration to provide the accuracy required to establish the amount of subcooling that existed.

At the end of LOX dump the MOV was closed and the LOX and LH_2 bleed valves were opened. Because of a characteristic of the engine control system, the bleed valves were again closed at 17,325 and reopened at 17,336 lb. This action resulted from opening the engine helium control valve which was required to obtain helium flow for a 10-sec thrust chamber purge. The LOX and LH_2 prevalves have a common control module and cannot be actuated independently. They were actuated closed during the time period shown in Fig. 6 to simulate the alternate procedure that would be followed in the event of an actual LOX chilldown system failure.

The first rise in the pressure and temperature plots shown in Fig. 6 is due to the valve position combinations, as previously described, that were required with the existing engine control system. Referring to the schematic diagram (Fig. 1), it can be seen that the feed system becomes a closed system when the MFV, the prevalves, and the bleed valves are all closed. At the end of LOX lead, only the bleed valves are open. The boiloff that occurs during this period causes the pressure and the temperature to increase until a relatively stable point is reached at the 20 psia level. At this condition the boiloff is being returned to the tank through the bleed valve, the check valve, and the recirculation line. As shown in Fig. 6, the flow rate through these components results in a 4 psia pressure differential between the feed system and the tank.

Another pressure increase occurs when the bleed valve is closed at 17,325 sec. In this case, the system is completely closed except for a thermal relief valve in the prevalve. The pressure, therefore, increases to the setting of the relief valve and remains at this level until the bleed valves are opened at 17.336 sec. Following opening of the bleed valves the pressure again follows the characteristic established by boiloff through the bleed valve and the recirculation line.

During these transients the pump inlet pressure measurement accurately indicates the pressure in the major cavities

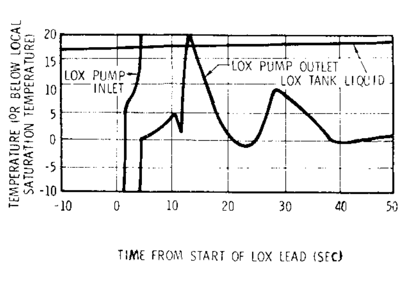

Fig. 7 Pump chilldown during LOX lead for SA-505 experiment.

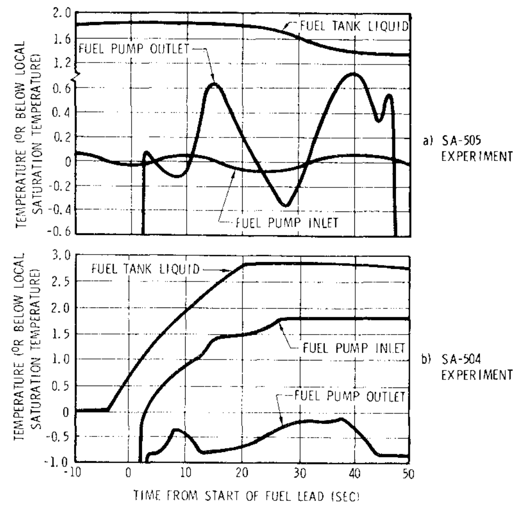

Fig. 8 Pump chilldown during fuel lead.

of the LH_2 feed system. Also, it always indicates the saturation pressure corresponding to the highest liquid temperature in the system. The temperature measurement indicates only the temperature of the platinum wire in the sensing element. During transients this indication may be strongly influenced by local flow and local heating conditions and the thermodynamic effects of globs of liquid that may attach to the temperature sensor.

The temperature trace in Fig. 6 indicates that saturation characteristics were predominant during the periods leading up to LH_2 tank repressurization. The lower dashed lines indicate the pressure and temperature that would have been indicated if the prevalves had been left open. The upper dashed lines show the pressure and temperature that would have been indicated if the bleed valves had been left open. Fuel tank repressurization started at 17,357 sec and ended at 17,386 sec. The prevalves were open during this time thus equalizing the pressure between the feed system and the propellant tanks. Fuel pump inlet temperature went off-scale high following fuel lead but came on scale and again indicated a saturated condition 68 sec after the continuous vent system was turned on.

At the start of LOX lead the liquid in the LOX tank was 17° subcooled. As shown in Fig. 7, the LOX pump inlet indicated a subcooled condition 2 sec after the start of LOX lead. The pump outlet indicated a saturated condition at 4 sec of LOX lead, and was two or three degrees subcooled at the end of the LOX lead period. Follwing the LOX lead, the inlet definitely remained subcooled. The outlet was either slightly subcooled or saturated for the remainder of the experiment.

Fuel pump and tank conditions during fuel lead are shown in Fig. 8. In Fig. 8a the amount of subcooling in the fuel tank

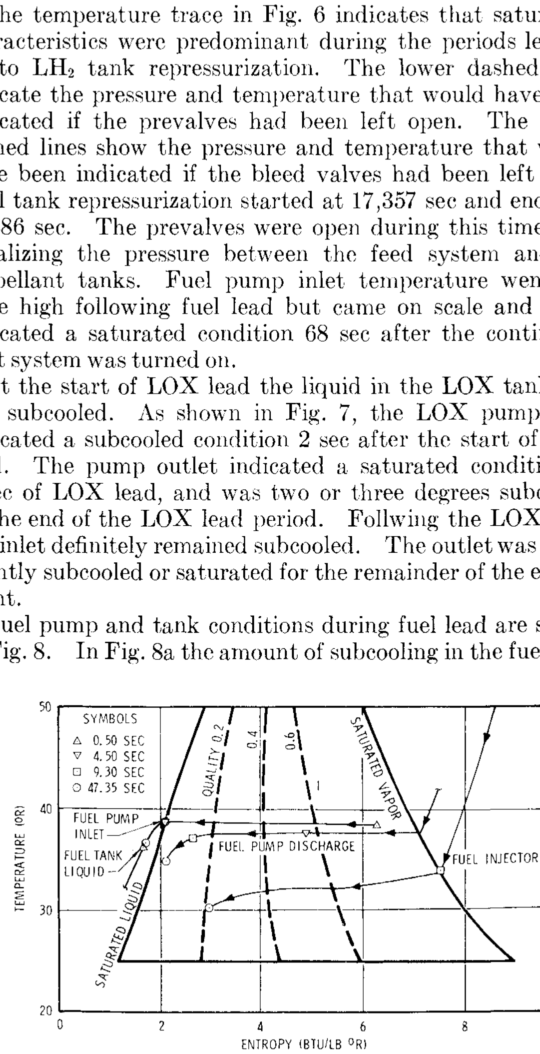

Fig. 9 Temperature-entropy during fuel lead for SA-505 experiment.

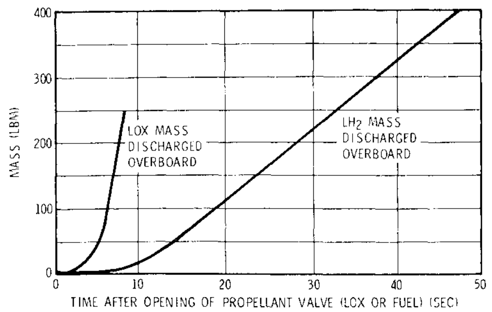

Fig. 10 Propellant lead mass consumption for SA-505 experiment.

decreased from 1.8° to 1.35° during the 48-sec fuel lead period. Apparently, this decrease was due to a thermal gradient in the tank. This amount of subcooling in the tank apparently was not enough to provide a clear indication of a subcooled condition at the pump inlet. These data, therefore, indicate that 1.8–1.35° of subcooling was lost between the tank and the pump inlet. A similar characteristic is indicated in Fig. 8b which shows a loss of 1.4–1.1° for the SA-504 extended fuel lead experiment. In the SA-504 experiment, LH_2 tank pressure was increasing during fuel lead, which accounts for the increasing tank NPSH characteristic in the figure.

As fuel lead progressed, the fluid quality (lbm gas/lbm mixture) decreased at the pump discharge and at the injector. The system operating paths are shown on a temperature-entropy diagram in Fig. 9. The fluid quality at the pump discharge stabilized at 0.05 at 15 sec after initiation of fuel lead. The fluid quality at the injector decreased from 1 (all vapor) at 9.3 sec, to 0.2 at 30 sec after start of fuel lead. The fuel qualities tended to stabilize as the heat input rates and flow rates stabilized.

Propellant consumption during the respective lead periods of the SA-505 experiment are shown in Fig. 10. Since LOX flow resistance is very low, a high LOX flowrate was achieved in a short time. No indications of any appreciable ullage gas ingestion were observed. Also, ullage pressure was constant during fuel lead and no self-pressurizing was observed following fuel lead. Therefore, it was concluded that gas ingestion did not occur.

Operational Characteristics

The following propellant lead chilldown characteristics are based on data received from the experiments corrected to the conditions of an operational S-IVB Apollo Lunar Mission restart. For example, LOX and LH_2 tank pressures are higher during operation; therefore, experiment flowrates are scaled up to reflect the influence of higher tank pressures. Chilldown rates and temperature levels also have been adjusted to reflect an operational condition.

It is predicted that the temperature of the LOX in the tank will be obtained at the LOX pump inlet in 3 sec. Also, that with an 8-sec LOX lead, the engine mainstage command, which occurs at start tank discharge valve opening (STDV), may be delayed up to 150 sec before the normal LOX NPSH start limit is reached. Normally, this event occurs at the end of the 8 sec fuel lead period. LOX chilldown characteristics are shown in Fig. 11a. The 8 sec chilldown time curve in this figure was demonstrated during the experiment. Other LOX lead time curves in the figure are based on the observed chilldown rate and calculated heatup rates.

Fig. 11b shows the relationship between LOX lead time, dwell time, and fuel injector temperatures at the start of fuel lead. For example, an 8-sec LOX lead followed by a 100-sec time delay results in a fuel injector temperature of 261°. This is 19° less than the 280° that would have existed if there had been no LOX lead.

Fuel injector temperature during fuel lead is plotted in Fig. 12 for a constant time of 108 sec between LOX lead start and fuel lead start for two chilldown models. The maximum prechill model (SA-505 experiment) is a minimum fuel lead time case, as maximum feed system chilling prior to fuel lead occurred in this case. As shown in Table 1, the ullage motors were on for an extended period of time prior to fuel lead and were most effective in settling propellants into the fuel feed system. The applied LOX lead settling thrust chilled the thrust chamber directly, and, also, indirectly chilled the inlet system by adding settling impulse.

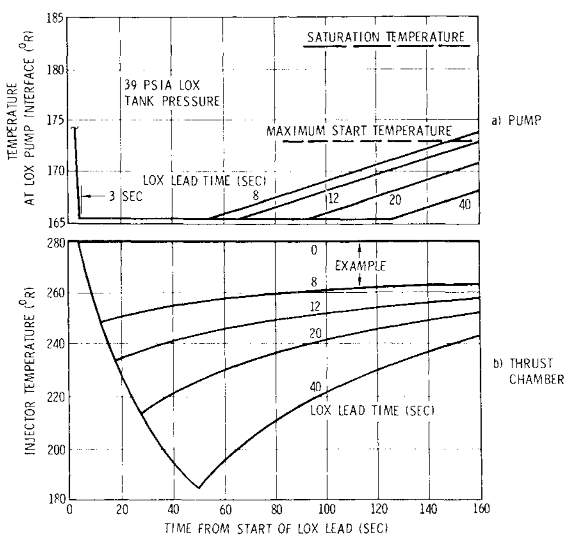

Fig. 11 LOX lead chilldowns.

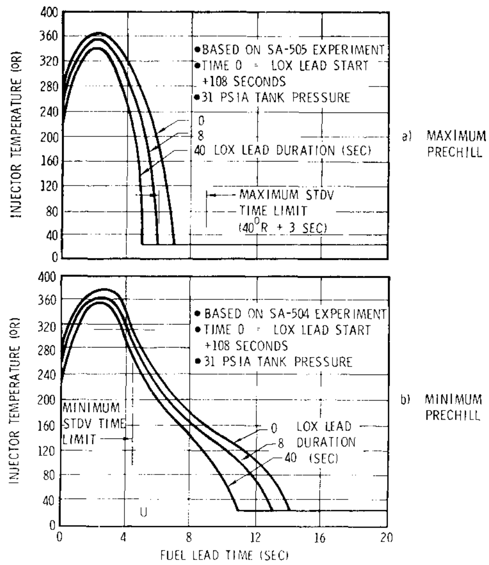

Fig. 12 Thrust chamber chilldown models.

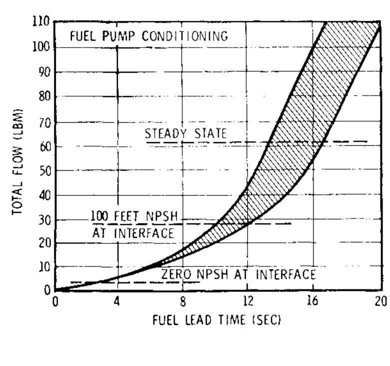

Fig. 13 Fuel pump chilldown.

The minimum prechill model shown in Fig. 12b (SA-504 experiment) is the maximum chilldown time case. In this case, ullage motor operation was at a minimum and vehicle mass was high. This resulted in a minimum amount of inlet system chilldown prior to fuel lead. Also, in this case, LOX lead was not used. Therefore, no prechill resulted from this source. The 8 and 40 sec LOX lead curves in this figure were calculated using the 0 LOX lead time curve as a base.

The prediction band is bounded by the 8 sec curves of Figs. 12a and 12b. The 8-sec LOX lead is followed by a 100-sec wait period. The minimum allowable fuel lead time, as established by a 310°R maximum injector temperature limit, is 4.5 sec. The maximum allowable fuel lead time is 9 sec and was established by the engine requirement that the temperature should not be at or below 40°R for more than 3 sec prior to STDV.

Fuel pump inlet conditioning criteria are shown in Fig. 13. The shaded area in this figure is due to the effects of prechill and is based on flowrate characteristics of the maximum and minimum prechill models. The dashed lines indicate the major phases of the conditioning progress based primarily on data from the SA-504 experiment. At approximately 3 sec of fuel lead, all-liquid at zero NPSH will exist at the stage-engine interface. It is predicted that a minimum of 10, and a maximum of 12.5 sec will be required to achieve 100 ft of NPSH. A constant initial quantity line is used as the NPSH criteria on the basis of constant initial hardware temperature, and constant heat removed per pound of propellant discharged.

The fuel pump 100 ft NPSH limit in Fig. 13 is an engine requirement that is desired at STDV but which is marginally acceptable if it does not occur until the time of mainstage operation. The figure shows that at the end of a 9 sec fuel lead a subcooled fuel condition would exist at the pump inlet. Fuel flowrate would accelerate rapidly following STDV, which should result in more than 100 feet of NPSH at 3.75 sec after STDV. If less than 100 ft of NPSH is available at STDV +3.75 sec, a high probability of low engine performance would exist. Low engine performance at this time would initiate a safe shutdown by internal engine logic. Additional fuel lead time would be beneficial to pump chilldown but would risk the probability of thrust chamber overchill that could result in undersirable combustion characteristics.

As previously discussed, chilldown effects of ullage motor operation prior to fuel lead were observed in these experiments. The pump chilldown effect from this source appears to be in the order of 2 sec. This is the width of the prediction band in Fig. 13 at the 100 ft NPSH line. The effect on thrust chamber chilldown is indicated by the difference between the maximum and minimum chilldown models with an 8 sec LOX lead in Figs. 12a and 12b. At the maximum temperature limit (310°R), one second is indicated. At the lower temperature limit (37°R), 7 sec is indicated. While this variation is attributed primarily to prechilling of the pump inlet, it is recognized that the condition of the propellants in the tanks (NPSH) has significant influence and could account for part of the difference.

Concluding Remarks

From the operational experience and the experiments described in this paper, we conclude that:

1) Restart chilldown can be achieved by simple operations involving dumping of propellants through the main propellant valves of the engine. However, this is not the most effective method for two reasons: a) propellant losses are excessive, and b) a compromise is required between pump chilldown and thrust chamber chilldown. If propellant dump is allowed to continue until the pump is well chilled, the thrust chamber may be overchilled. And, conversely, if the dumping operation is terminated when the thrust chamber is optimally chilled, the pump may be underchilled.

2) The most effective restart chilldown system may be achieved with a dumping mode applied individually to each of the subsystems requiring chilldown. A simple valve and orifice system sized for optimum flowrate would result in efficient LH_2 pump chilldown with the desired margin of safety. A similar system sized for the thrust chamber would result in optimum conditions for that system. LOX pump chilldown could be provided in the same manner, and a high degree of redundancy could be provided in each system.

3) The initial design and development phase of future engines should include in-depth considerations of the total effects of engine start system requirements. Analytical models of the various available engine start systems should be combined with various available stage system models to determine the most effective over-all configuration. This assessment should include a realistic definition of major mission events in the basic, alternate, and future mission profiles.

4) The initial design and development phase of future vehicles should include a detailed consideration of projected engine and vehicle control systems. The systems should be analyzed for applicability to the expected operational philosophies regarding failure effects and the use of ground commands for corrective action.

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[2] "Saturn S-IVB-505N Stage Flight Evaluation Report," Rept. MDC G0008, Aug. 1969, McDonnell Douglas Astronautics Company—West, Huntington Beach, Calif.