



LOX SYSTEM PRESTART CONDITIONING ON X-34

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ABSTRACT

The X-34 is a reusable launch vehicle that will be carried underneath an airplane to altitude of 35000 feet where it will be launched. It utilizes a single Fastrac 60K rocket engine for propulsion. This engine burns RP-1 and Lox as propellants and has a single shaft Lox and RP-1 turbopump. With these features there are three important requirements that must be met during the prestart thermal conditioning of this engine and feed system. First, the Lox temperature prior to starting the engine must be cold enough to be in the predefined start box at that pressure. Second, the RP-1 in the single shaft turbopump in close proximity to the lox must not freeze significantly where it effects turbopump or engine operation. Third, the chill phase of the prestart countdown has been allocated 700lb of Lox which if exceeded starts to effect mission performance. Extensive testing and analysis has been performed to evaluate the chill characteristics of the Fastrac Engine as well as test facilities and X-34 Lox feed and bleed systems.

INTRODUCTION

The captive carry phase of the X-34 launch is the period that the X-34 is attached to the L1011 aircraft and the aircraft is airborne. During development of the Fastrac engine, it has been thermally conditioned before start, using many different procedures and with many different facility configurations. None of which have exactly duplicated the X-34 captive carry flight conditions. The X-34 feed line is smaller than any in the ground test program. The flight environment as well as the helium supply to the turbopump buffer seal is expected to be much colder. A thermal model is being developed to assist in determining the flight chill procedure and to show that the requirements can be met given the vehicle configuration and the colder conditions.

Experiments have been performed to characterize the RP-1 freezing hazard and to determine Lox and LN2 boiling heat transfer coefficients. A thermal model using SINDA has been created that simulates the chill down of all the mass in the feed system, turbopump, and bleed system. An integral flow model of the Lox is included to get the transient flow rate through the system. Logic is included which will simulate each of the ground test facilities and X-34, Lox or LN2, and with actual valve sequences and tank pressure profiles.

FUNDAMENTAL TESTING

RP-1 FREEZING CHARACTERISTICS

Simple tests were performed to provide an experimental basis for some aspects of this problem. All that was known of frozen RP-1 was the freezing temperatures listed in text books and property books. RP-1 was

frozen in an aluminum tray using liquid nitrogen and as the RP-1 thawed the temperature was measured and physical properties were observed. The results indicated that there is no freezing temperature but a transition that occurs between the temperatures of 400 R and 350 R. As temperature is reduced below 350 R the solid wax increases in hardness. These temperatures are approximate because during thaw there were many phases, and temperatures existing simultaneously in the tray. This test showed conclusively that 400 R would be a safe lower limit, and that 335 R represents a significant risk to turbopump operation. RP-1 is shown in figure 1 with a temperature of 373 R (-87 F). Table 1 lists the temperatures and corresponding physical observations.



Figure 1: Freezing RP-1 In a Tray

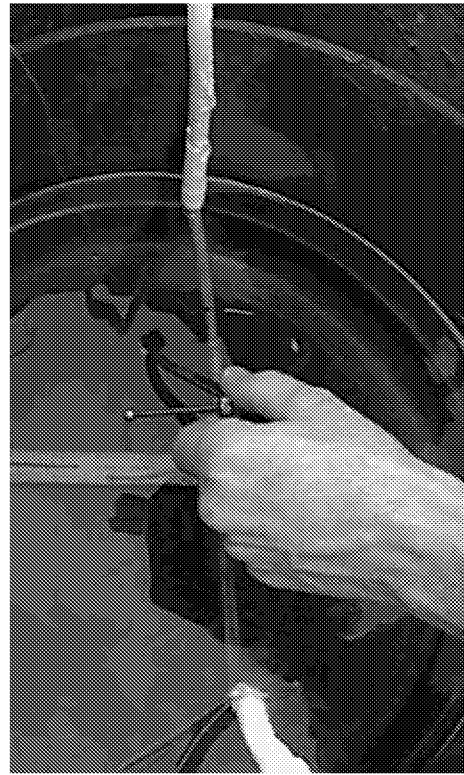


Figure 2: Freezing RP-1 on Tube Wall

A second test was performed to determine how much frozen RP-1 would accumulate on a cold wall submerged in warm RP-1. LN₂ flowed through the tube, and the wall temperature was measured to be 160 R. Again there was no solid liquid boundary but a transition that occurred as the distance from the wall increased. This made thickness measurements rather subjective. This test showed that if bulk RP-1 temperatures remained warm no significant buildup of solid RP-1 can take place. A conservative approach to calculating frozen thickness was developed. Figure 2 shows a thickness measurement being taken in this experiment and table 2 shows the values for four separate measurements and an average.

Table 1: Frozen RP-1 Observations

Temperature	Description
302 R	Hard wax
335 R	Solid wax, softening some
350 R	Soft wax
355 R	Gel
380 R	Gel, thick liquid, rapid warm up
420 R	Liquid RP-1 with some solid present

Table 2: Steady State Thickness Values

Measurement	Value
A.	.044 inches
B.	.082 inches
C.	.074 inches
<u>D.</u>	<u>.024 inches</u>
average	.056 inches

BOILING HEAT TRANSFER COEFFICIENTS

Two experiments were performed to investigate Boiling Heat Transfer Coefficients (HTC). The first test measured 17 impeller surfaces as it was chilled in liquid nitrogen. Figure 3 shows a chilled impeller in a vertical orientation. Figure 4 shows the impeller being submerged in liquid nitrogen in a horizontal orientation. The second test measured the surface temperatures of two steel plates chilled in liquid oxygen. Figure 5 shows the plates in lox and figure 6 shows the instrumented plates on the table. A one dimensional thermal model was used to derive the boiling HTC as a function of surface temperature from the measured data. The impeller test showed no significant variation with orientation. This test shows that when LN2 envelopes the impeller that all surfaces were chilled in 140 seconds. Figure 7 shows the measured data from an impeller test. Figure 8 shows predicted impeller surface temperatures for metal of different thickness using the derived LN2 boiling HTC curve. Figure 9 shows the derived curves for Lox and it is an average of these lox curves that is used in the thermal model. The critical boiling characteristics apparent from testing were the film boiling HTC and the transition region from minimum to maximum heat flux.

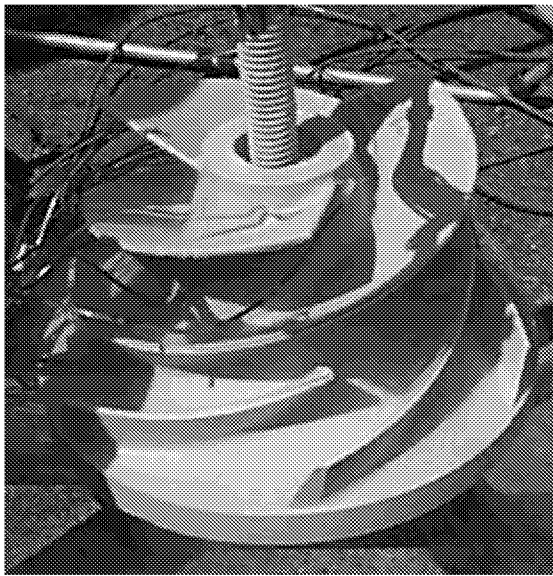


Figure 3: Chilled Lox Impeller



Figure 4: Chilling Lox Impeller in LN2

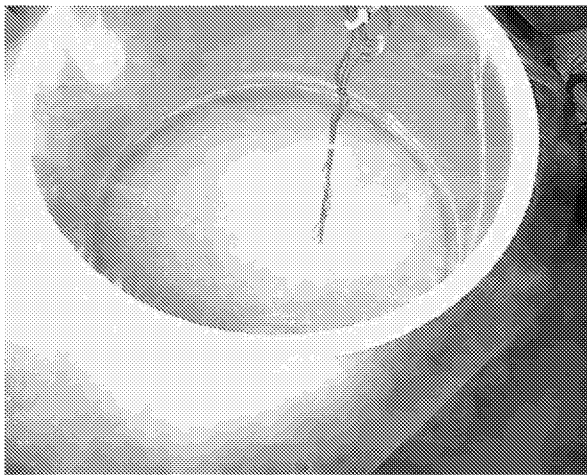


Figure 5: Chilling Steel Plates in Lox

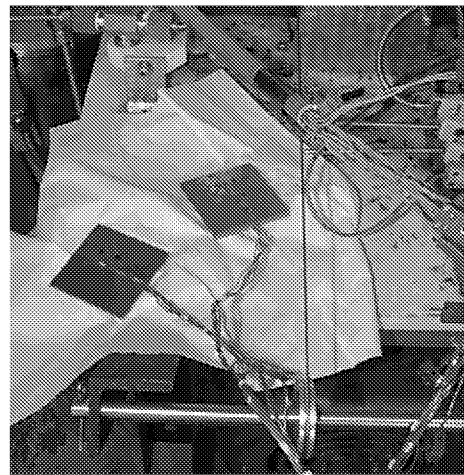


Figure 6: Instrumented Steel Plates

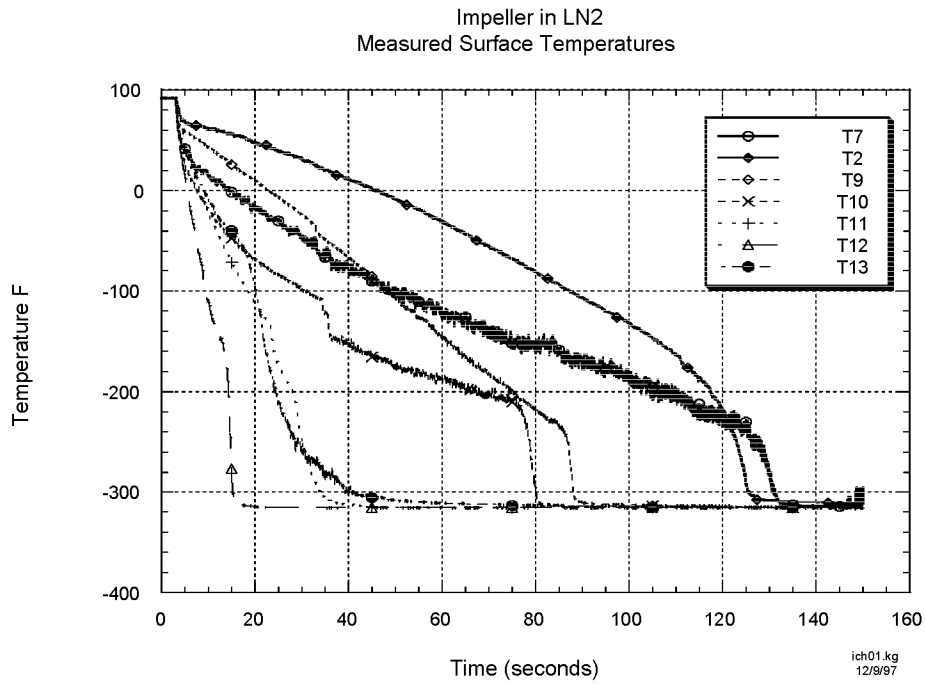


Figure 7: Measured Surface Temperatures, LN2 Impeller Test

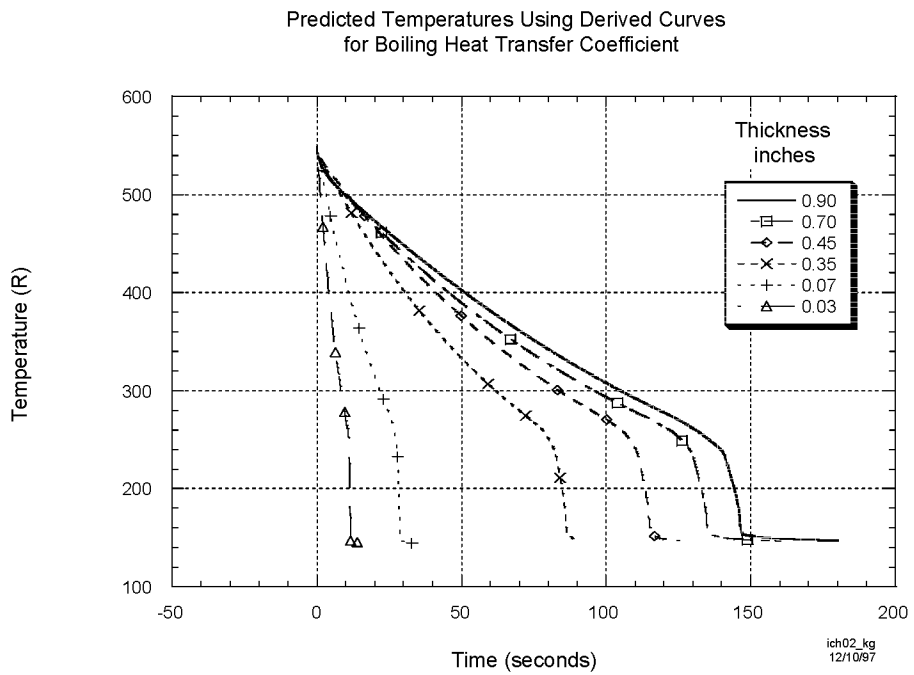


Figure 8: Predicted Impeller Surface Temperatures from Derived HTC Curve

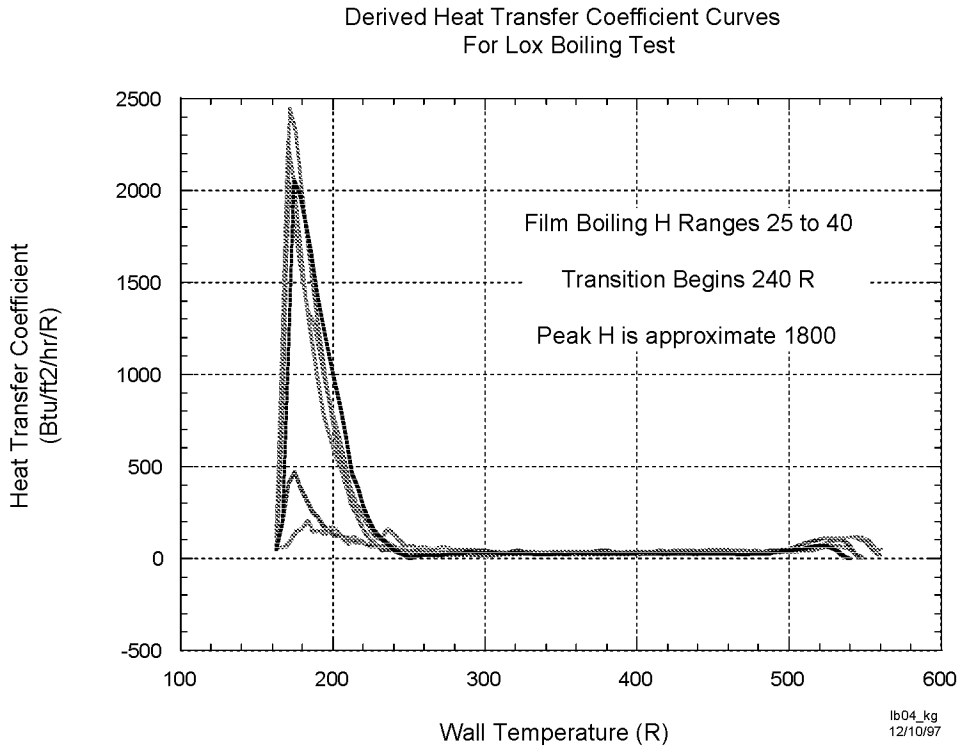


Figure 9: Derived HTC Curves from Steel Plates in Lox

COMPONENT AND ENGINE TESTING

The first component test series had the turbopump only with an upper lox line bleed and a turbopump bleed for thermal conditioning prior to start. There were many pressure and temperature measurements in the lox system and on the external surfaces of the turbopump. There was no flow meter installed which could measure the low bleed flow rates during chill. The first attempt to chill through the turbopump bleed was much too slow so an alternate plan to chill through the Lox throttle valve was incorporated. This valve at 40% open and a 4.5 inch diameter line simulates the main oxidizer valve on the engine. There was a temperature probe installed in the fuel bearing coolant line to measure the fuel temperature behind the impeller. Many changes were made to the model after this first series. The tests revealed that the 9 tooth Kel-F labyrinth seal ring and the warm helium are important in maintaining warm fuel temperatures. External thermocouples on the IPS housing matched well with the model predictions.

The first engine level testing occurred on the Horizontal Test Facility. This series provided the first flow rate data through the engine bleed which was critical information for model correlation. This facility also had many pressures and temperatures measured in the lox system. The 9 tooth labyrinth seal ring material changed to nickel 200 which had a larger operating clearance than the Kel-F. To maintain warm fuel temperatures helium cavity pressure was raised in the Inter Propellant Seal (IPS). Another significant chill test was performed on HTF where the engine and lower feed line were chilled with flow through the main oxidizer valve only. The actual flow rate was 43 lbm/sec which was lower than expected. There was an unexpected 30 psi pressure drop between pump inlet and discharge which happened when the pump spun to

2000 rpm. Turbomachinery provided the negative head portion of the pump map and it was incorporated into the thermal model. Another unexpected result was the slow rate at which the main injector lox dome temperature decreased after dropping below the saturation temperature. Horizontal test facility and the component testing has supplied vast amounts of data for model correlation. Figure 10 shows the turbopump.

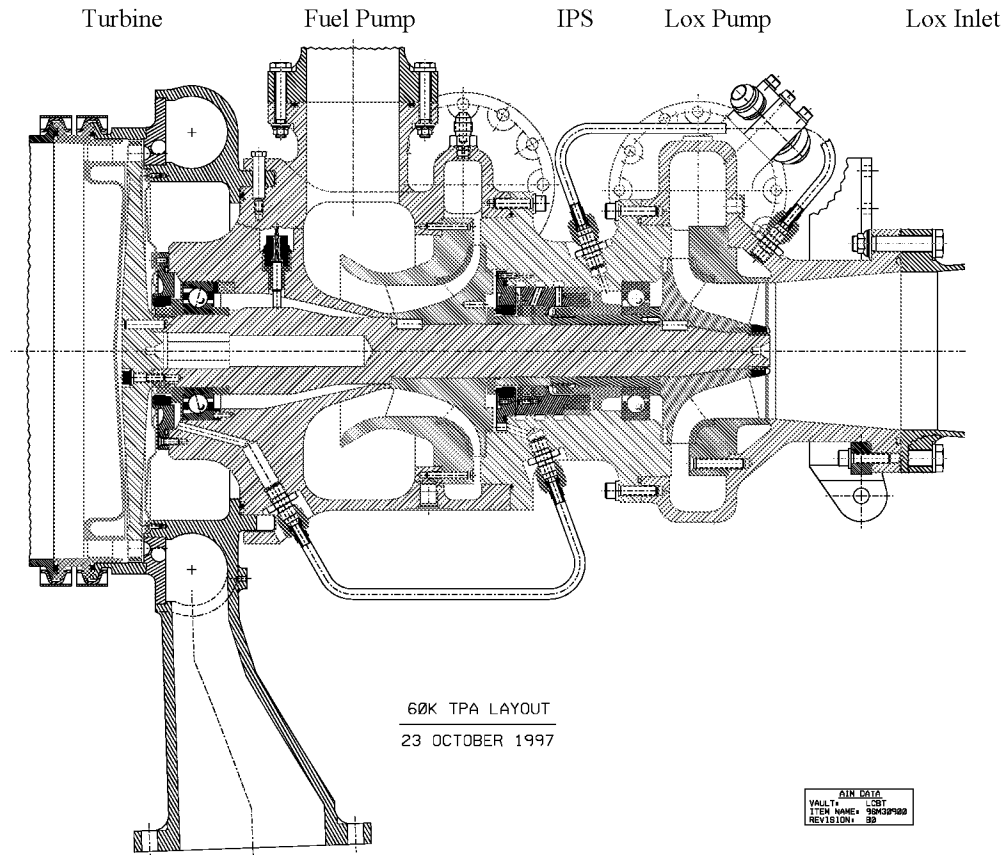


Figure 10: Turbopump Cross Section

X-34 SYSTEM AND ENVIRONMENTS

There are significant differences between the flight and ground test experience in terms of configuration and environments. The flight lox feed line has much less mass and is shorter than HTF or the Component Stand. The bleed line on X-34 has an inner diameter of 0.62 inches and is 5 to 6 feet long. At the end is a check valve with an Equivalent Sharp Edge Orifice Diameter (ESEOD) of .43 inches. On HTF the Engine bleed line is 0.884 inner diameter and 20 feet long with no check valve. The engine with the HTF bleed configuration flows approximately 3.5 lbm/sec of lox with 67 psia at the engine interface. Helium, Fuel and ambient air temperature has always been warm in ground testing. The flight cold case helium temperature is 417 R, fuel temperature 460 R and engine compartment purge temperature reaches a low of 449 R at engine start. Bleed exit pressure on the ground has been 14.7 psia where flight will be 3 psia at an altitude of 35000 feet. To alleviate some of the cold environments the X-34 will have a warm purge on the ground. In addition, a turbopump heater will add 200 watts to the IPS fuel side flange on the ground and 100 watts during the captive carry phase.

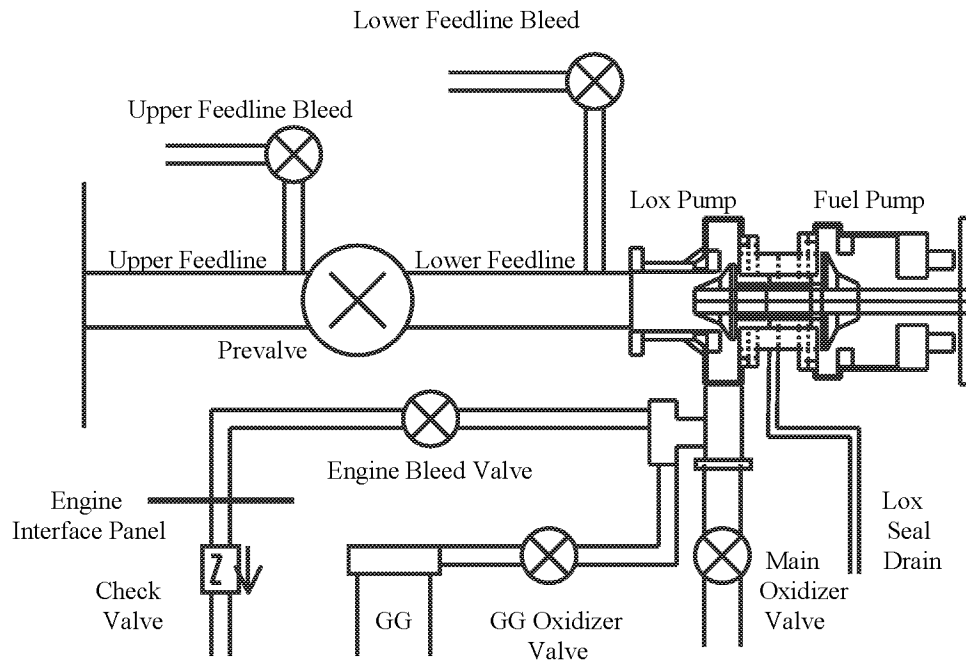


Figure 11: Typical Lox Feed and Bleed System

THERMAL MODEL

A thermal model was created to determine the important parameters that drive the thermal conditioning of the turbopump prestart. It encompasses the feed line, bleed lines, and most of the turbopump. There is detailed modeling of the lox also since transient flow rates and lox quality are such important aspects of this problem. The approach taken is to model the ground test hardware, environments, valve sequences, pressures and correlate the model. Only then can the X-34 condition be predicted with confidence. As more test data has been produced the model has evolved to be more complex to match the data. The following major changes to the model have taken place in chronological order. The first improvement was the detailed modeling of the Inter Propellant Seal to match the warm fuel seal drain temperature that was seen on the component stand. These changes include a variable clearance in the 9 tooth labyrinth seal and fluid nodes with heat transfer for the helium. Then heaters were added along with logic to simulate the flight designed thermostat set points and tolerances. Then the necessary logic to model all facilities with all the flow circuits was added with the capability to run complicated pressure and valve position profiles. Properties and lox temperatures are determined from calculated enthalpy to better model the saturated and subcooled fluid and the heat transfer occurring in the lox system.

INTEGRAL FLUID MODEL

The fluid in the lox feed and bleed system has been divided in to approximately 60 nodes. At each location the state of the lox is dependent on the energy balance including the stored energy, energy in and out from mass flow, and the convective energy transferred to the fluid in the volume. The enthalpy is calculated and

used to determine the fluid properties. For nodes which contain saturated liquid and vapor, all properties are calculated based on volume fraction of vapor, and saturated vapor and liquid properties. The approach to calculating heat transfer coefficient (HTC) is to calculate a vapor and liquid HTC and then average the two based on the vapor fraction by volume.

The flow rate calculation has proven to be the most difficult. The first approach was simple and used loss factors and Bernoulli's equation to iterate on a flow rate in each bleed path. The difficulty has come from the fact that there are large variations in density and HTC that occur, causing the flow rate prediction to be unstable. At a pressure of 50 psia saturated liquid is 77 times more dense than vapor. Nucleate boiling HTC is as high as 1800 btu/ft²/hr/F and film boiling HTC is as low as 20 btu/ft²/hr/F. The flow calculation was stabilized and a good correlation was achieved for an engine bleed only chill on HTF. Correlation to the MOV chill on HTF however has been difficult. The current version of the chill model has a more complicated solution that includes conductors for choked flow and cavitation. It is incomplete at this time.

HARDWARE TEMPERATURE PREDICTIONS

All the mass which must be chilled or that may transfer heat to any of the lox flow circuits is included in the model. The turbopump is modeled in greater detail in order to address the fuel side temperature requirements as well as match any IPS and turbopump surface temperatures measured in the ground test program. The feed lines and bleed lines are modeled simply with approximately 60 nodes, each with the correct surface area and mass. External heat transfer is included or disabled if the line is insulated.

RESULTS FOR HTF AND X-34

The results presented in this paper are from a version of the model which correlated well with an engine bleed test on HTF and then was used to predict the X-34 chill. This version of the model did not correlate well with the HTF test where the engine, feed and bleed system were chilled through the Main Oxidizer Valve (MOV). The results presented here are for illustration of what the model capabilities are, recognizing that more features are required to match all the test data.

On HTF the chill sequence typically involves a low pressure chill of the upper feed line through the upper feed line bleed. When cold liquid is evident upstream of the pre valve, the pre valve is opened beginning the chill of the lower feed line through the lower feed line bleed and engine bleed. Shortly after pre valve opening the upper feed line bleed is closed and the tank is pressurized taking the engine interface pressure from 18 psia to 68 psia. Figures 12 shows the predicted mass flow rate. The first hump in this curve is the low pressure upper feed line chill. The second hump is lower feed line chill with both lower valves open and engine interface pressure at 80psia. Flow rate drops in half to 4.5 lbm/sec when the lower lox line bleed is closed. The next drop in flow rate occurs when the tank is vented. While vented the lower lox line bleed is opened again and at approximately -1700 seconds the tank is pressurized to 68 psia. Shortly after pressurization the lower lox line bleed is closed again. Figures 13 and 14 show analysis and test data respectively for engine interface temperature and how it compares to saturation temperature at that pressure. Figures 15 and 16 show predicted and measured gallons of lox in the tank. Figures 17 and 18 show predicted and measured fuel seal drain temperature. It is interesting to note how this temperature rises at -3200 seconds when tank pressure is reduced and how it drops again at -1700 seconds when the tank pressure is increased again.

The X-34 analysis is much more simple in terms of tank pressurization and valve sequences. Tank pressure starts at 13 psia and the pre valve and engine bleed are opened at 0 seconds. Soon the tank pressure is ramped to 58 psia which is the start pressure for the engine. Figure 19 shows the engine interface temperature as well as the saturation temperature at the interface pressure. The plot shows the engine interface temperature constraint being met at 410 seconds. The lox consumption curve is shown in figure

20 and with this chill procedure shows 700 lb consumed at 710 seconds. The start window then will occur between 410 and 710 seconds. Figure 21 shows that in this window the fuel seal drain temperature at an acceptable level and consistent with the ground test experience of 400 R. Figure 22 shows the predicted transient flow rate for the X-34 bleed line at the low exit pressure.

FUTURE TESTING AND ANALYSIS

There is a planned test on HTF with a simulated X-34 bleed line. Downstream of the Engine Interface Panel there currently is a bleed line 20 feet long with inner diameter of .884 inch. The last 5.5 feet of this line is to be modified to inner diameter of .62 inch and with an orifice at the end with diameter of .43 to simulate a check valve which is in the X-34 bleed line. The X-34 vehicle itself is scheduled to ground tested with an engine firing included so there will be chill data for the flight feed and bleed system prior to first flight.

The thermal model is currently being modified to include flow conductors to calculate choked flow and cavitating flow for valves and orifices in the lox feed and bleed system. Once that version is operational and predicting stable flow rates, correlation to test data will begin.

Analysis, HTF Test, Lox Mass Flowrate

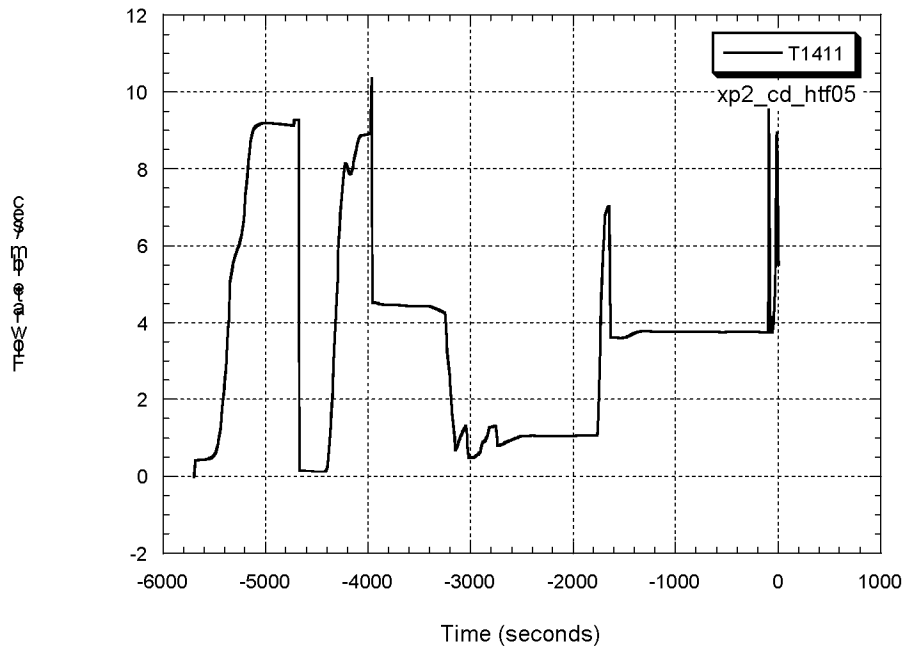


Figure 12: Predicted Feed line Flow rate

Analysis, HTF Test, Engine Interface Temperature

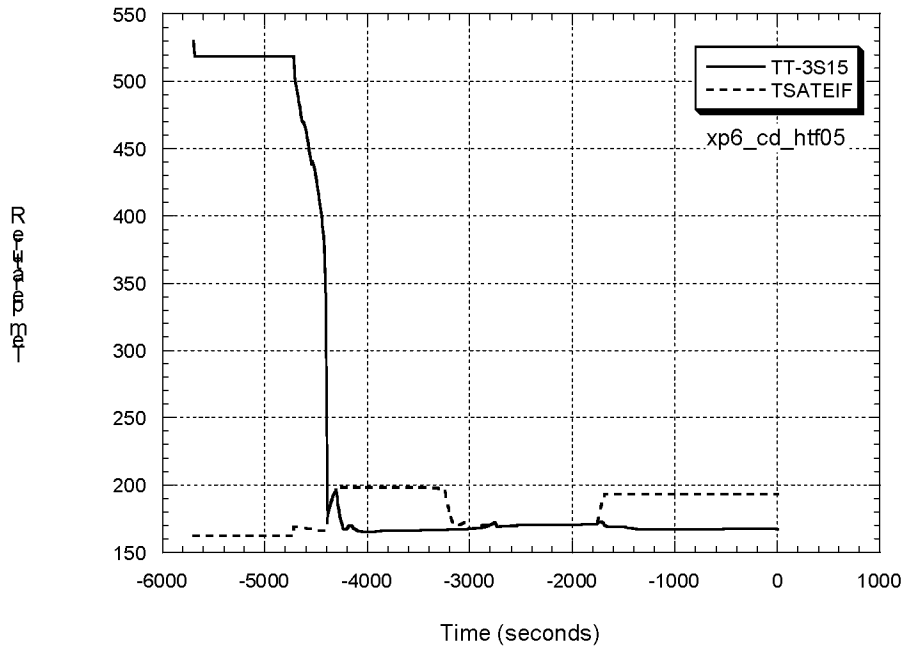


Figure 13: Predicted Engine Inlet Temperature

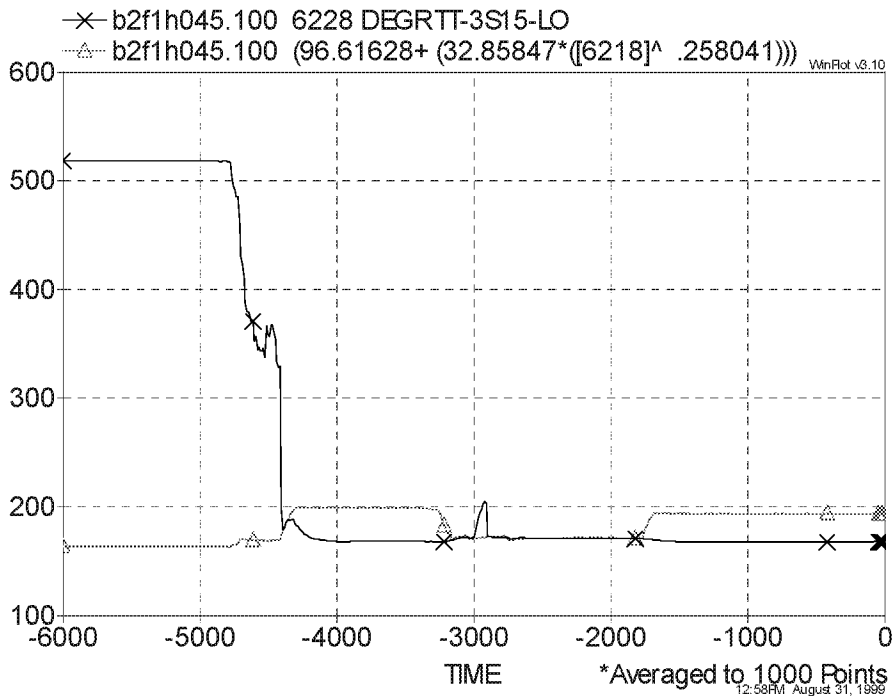


Figure 14: Measured Engine Inlet Temperature

Analysis, HTF Test, Lox Volume Gallons

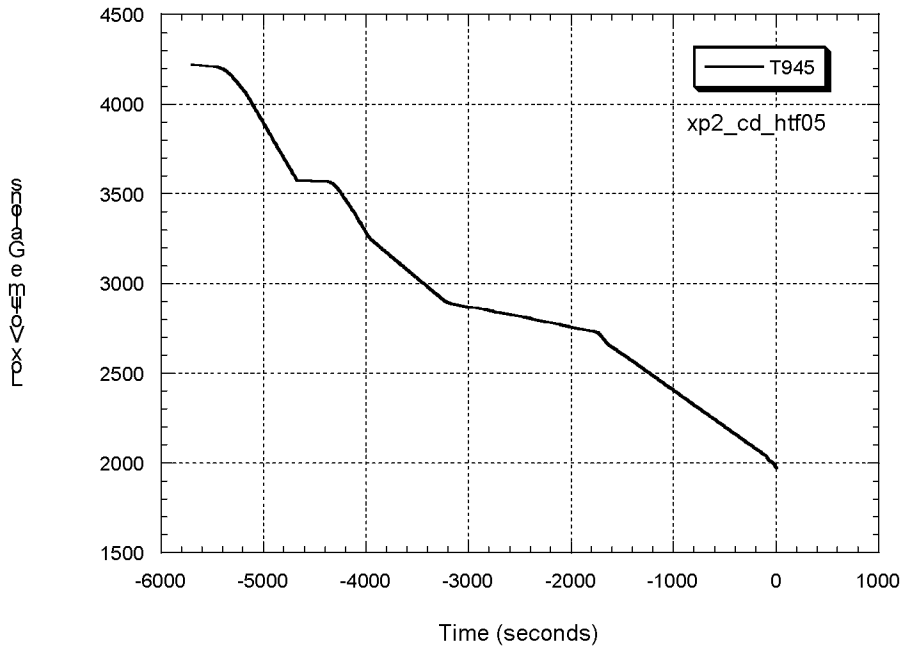


Figure 15: Predicted Lox Volume in Gallons

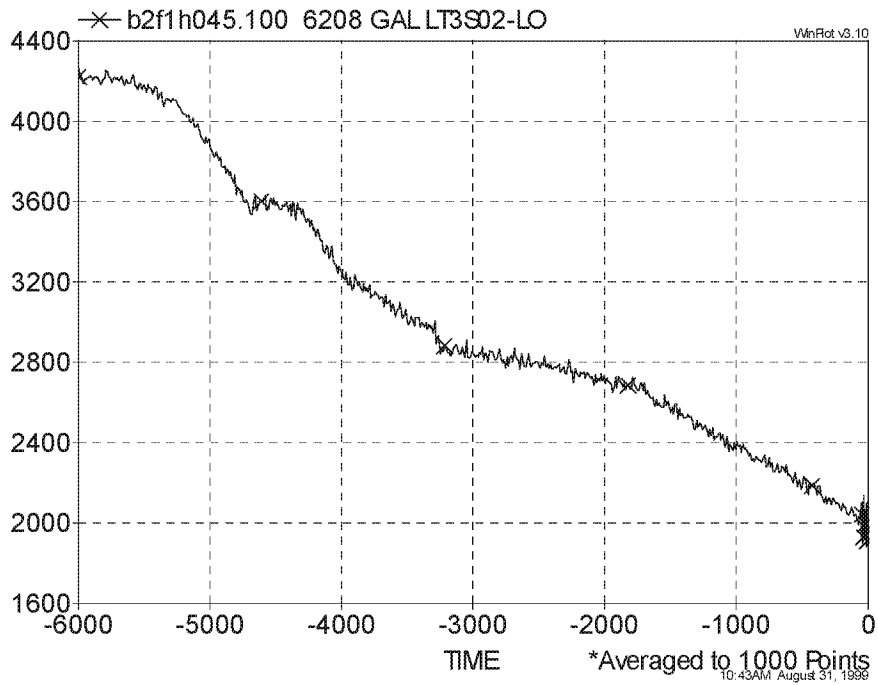


Figure 16: Measured Lox Volume in Gallons

Analysis, HTF Test, Fuel Seal Drain Temperature

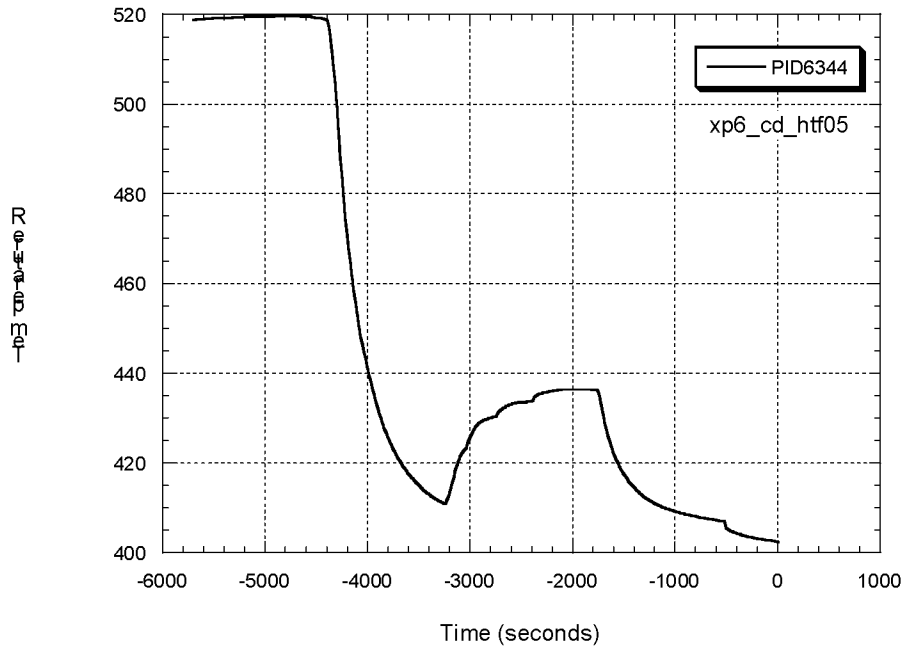


Figure 17: Predicted Fuel Seal Drain Temperature

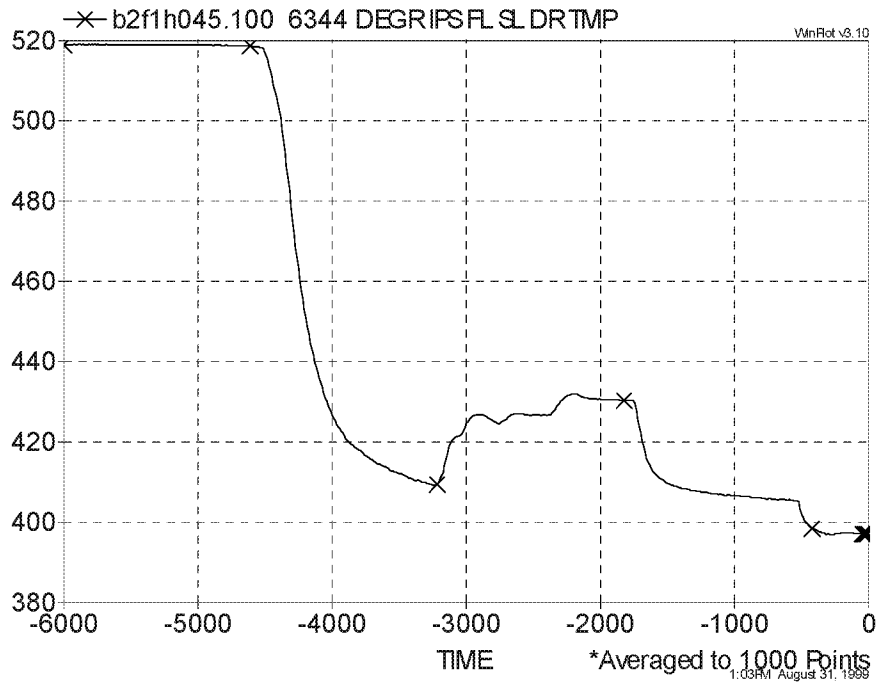


Figure 18: Measured Fuel Seal Drain Temperature

Analysis, X-34 Cold Case, Engine Interface Temperature

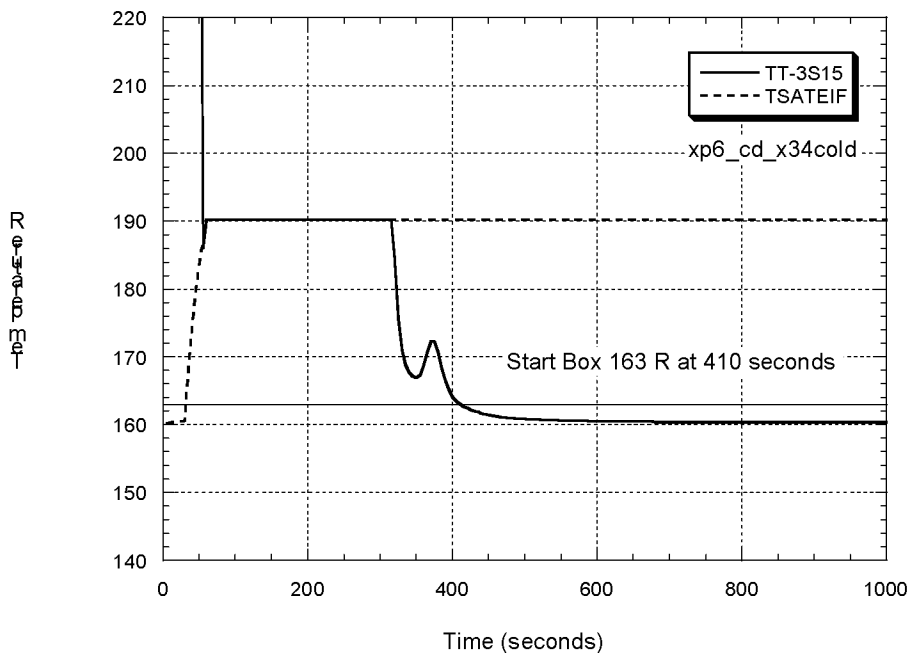


Figure 19: Predicted X-34 Engine Inlet Temperature

Analysis, X-34 Cold Case, Lox Consumption

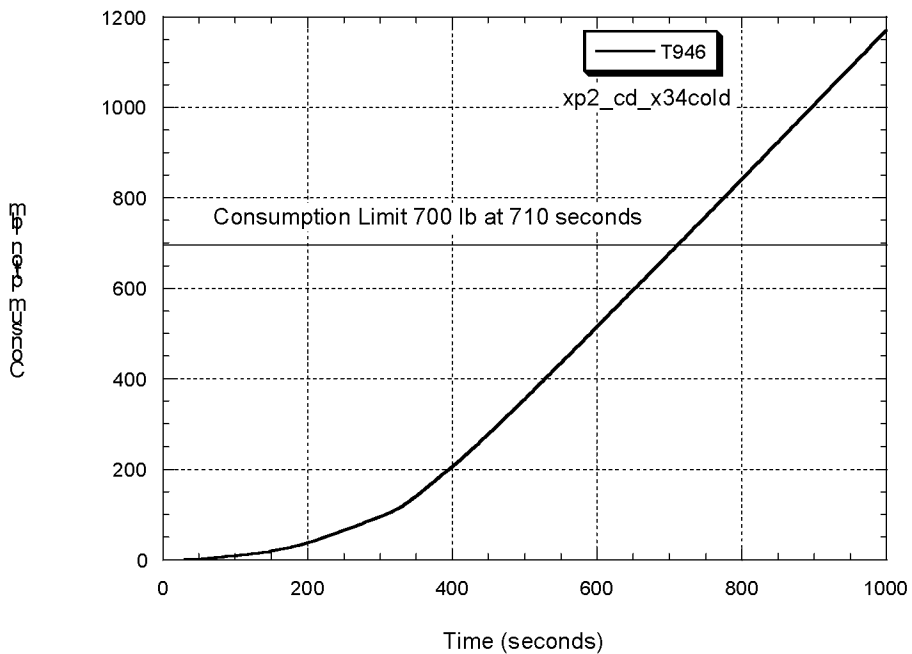


Figure 20: Predicted X-34 Lox Consumption

Analysis, X-34 Cold Case, Fuel Seal Drain Temperature

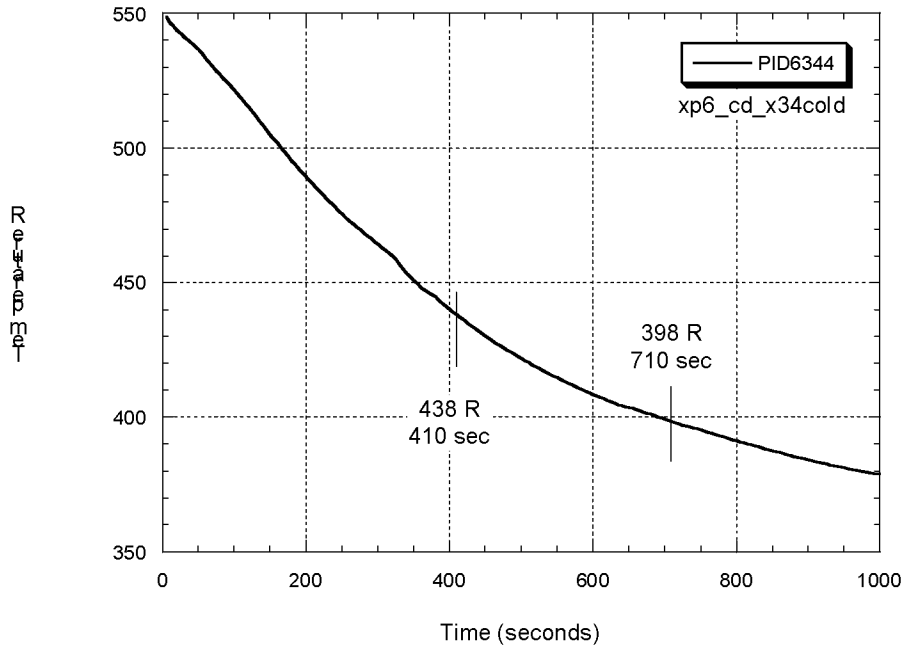


Figure 21: Predicted X-34 Fuel Seal Drain Temperature

Analysis, X-34 Cold Case, Lox Flowrate

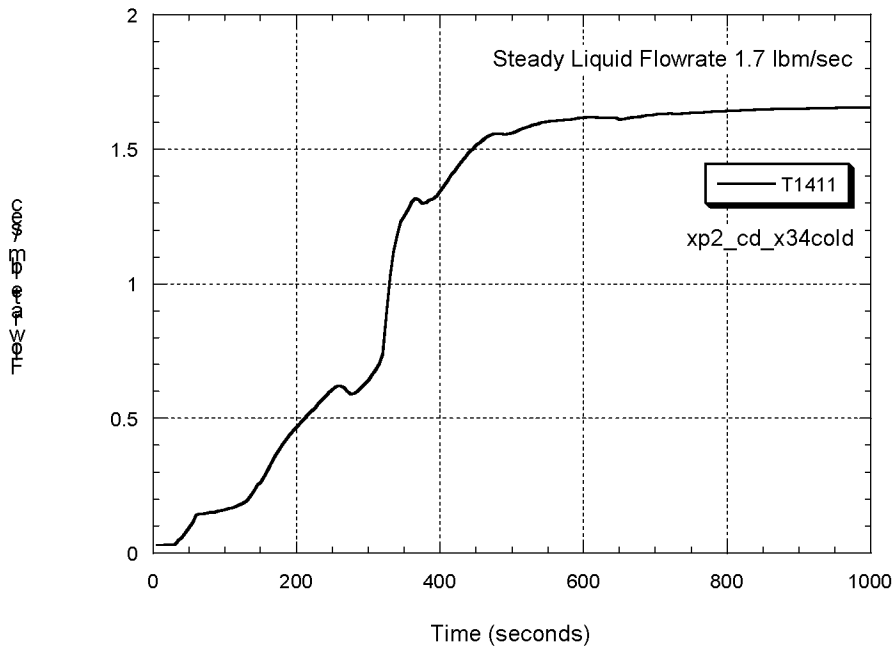


Figure 22: Predicted X-34 Lox Flowrate

CONCLUSIONS

Current analysis indicates that all the prestart thermal conditioning requirements can be met although the exact procedure and timing for the start window can't exactly be determined. There is some flexibility in the procedure in that the MOV can be opened to accelerate the opening of the start window. Also, once the liquid starts flowing in the bleed line the tank pressure can be reduced to reduce consumption and delay the closing of the window.

ACKNOWLEDGEMENTS

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