

Performance Modeling and Validation of Vapor Pressurization (VaPak) based Propulsion Systems

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The concept of the VaPak propulsion system holds the promise of combining the operational simplicity and low cost of a solid rocket, with the performance advantage and restartability of a liquid propellant system. While VaPak based systems have a minimum number of parts and are simple in design, the VaPak propellant pressurization system's behavior is tightly coupled with that of the engines and the vehicle as a whole. This paper presents an approach to model the integrated system performance of a VaPak based launch vehicle, using a combination of industry standard and custom developed tools. The paper discusses the derivation of the fundamental VaPak equation using an enthalpy balance approach, and presents experimental data to validate the modeling approach from a variety of sources. Both transient and steady state behavior of liquid oxygen test data are discussed. Integration of the resulting VaPak tank pressure model with engine performance predictions is described using iterative execution of the VaPak model together with the OTIS4 trajectory analysis and optimization code. An example scenario is presented for a TSTO launch vehicle using a VaPak based propulsion system. It is shown that by judicious selection of system parameters, integrated vehicle performance can be achieved in conjunction with low system sensitivity towards variation in initial propellant conditions.

Nomenclature

h	=	enthalpy per unit mass
m	=	mass
ρ	=	density
t	=	time
C_v	=	constant volume heat capacity
EMF	=	Expended Mass Fraction
LOX	=	Liquid Oxygen
OF	=	Oxidizer / Fuel ratio
P	=	pressure
T	=	temperature
T/W	=	Thrust to Weight ratio
V	=	volume
VaPak	=	vapor pressurization

I. Introduction

THE continuing push for low-cost space access and long-duration, in-space operational systems indicates a clear requirement for low-complexity / high-reliability propulsion systems. In current trade studies of solid vs. liquid propellant based vehicle concepts, solid rockets tend to be selected for applications that place a premium on instant readiness, minimal support infrastructure, and high reliability in combination with low cost. Liquid propulsion systems dominate applications where restartability is a requirement, and performance considerations outweigh those of cost or complexity. Two general liquid feed systems have been employed, pressure fed and pump fed, with the highest performing system (turbo pumps) also being the most complex. The ideal propellant system would combine the operational advantages of a solid, with the restartability and performance of a liquid propellant design.

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In 1960 a unique light weight vapor pressurization system (VaPak) was conceived that combines the low-complexity and reliability of a solid rocket with some of the performance advantageous of a liquid propellant design.¹ The principle of VaPak propellant pressurization is similar to the process that pressurizes a simple can of hair-spray. In a VaPak propulsion system, the propellants are pressurized by the vapor pressure in the ullage volume, generated by the liquid propellant phase being maintained at a saturated state. VaPak systems hold the promise of low complexity propulsion systems for highly reliable and cost-effective vehicle designs – both for launch vehicle and in-space system applications. No high-pressure bottles, complex valving, or pumps are required, and in conjunction with appropriate engine design, the resulting systems are equally useable for trans-atmospheric or in space operations.

While the number of parts in a VaPak system is low, the physical behavior is complex and highly interrelated to the state of the vehicle during operation; this makes it difficult to model system behavior and obtain accurate performance predictions. Acceleration of the vehicle affects tank pressure, which alters the VaPak system behavior, in turn affecting engine performance and closing the loop back to the vehicle state. This paper describes a methodology developed to create an integrated performance model for vehicles based on VaPak propulsion technology. The presented method uses a combination of existing and custom developed tools to model the VaPak pressurization system behavior, engine performance, and integrated vehicle performance / trajectories.

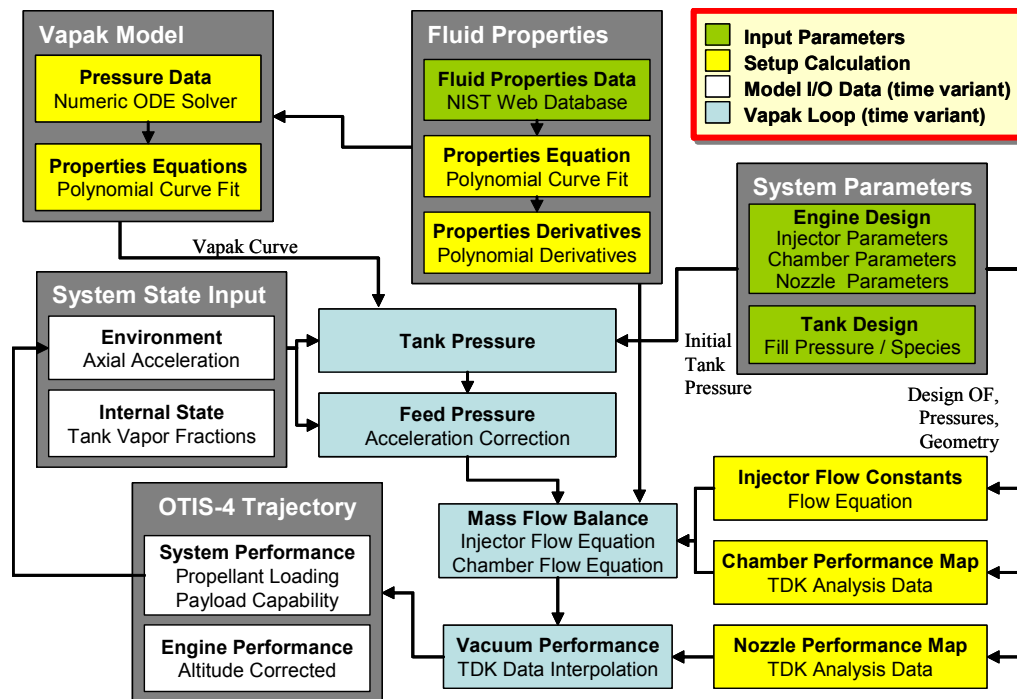


Figure 1. VaPak model components overview, combining industry standard and custom tools

The complete model consists of a number of discrete tools / components as shown in Figure 1. Saturated fluid properties (enthalpy, density, and temperature) for liquid and vapor phases are obtained from empirical data as a function of pressure. An enthalpy balance (VaPak Equation) is used to derive the equations that describe the equilibrium of the liquid and vapor phases as a function of tank pressure. Using the VaPak equations, data is generated for pressure and temperature as a function of expended mass fraction (EMF), and curve fitted for later use. The industry standard TDK code is used to generate a performance map of engine specific impulse and thrust, as a function of OF ratio, and chamber pressure. The rocket performance map is then combined with the VaPak results to produce a model of vehicle performance as a function of expelled propellant mass fraction (EMF), T/W, and initial system setup. Lastly, the VaPak data is integrated into the OTIS trajectory code to generate final vehicle performance curves. All custom developed components are implemented in the Matlab computing environment.

II. VaPak Model Derivation

The derivation presented in this section closely follows the original work put forward by Aerojet. Model derivation, validation with experimental data, and extension to non-ideal systems are discussed.

A. Saturated Fluid Properties

Data for saturated liquid / gas properties was sourced from webbook.nist.gov. Specific points are obtained by piece wise cubic interpolation between the tabular data points. Derivatives of enthalpy and density data are obtained from polynomial curve fit equations to the tabular data described above. The fit was performed as a function of a scaled value using the maximum pressure for which data was available as a normalization factor; this approach improves the curve fit accuracy.

B. VaPak Equation

The derivation of the VaPak model is based on an enthalpy balance, assuming an isentropic process, with both liquid and vapor phases at uniform temperature at a fully saturated state. Figure 2 illustrates the reasoning behind the model.

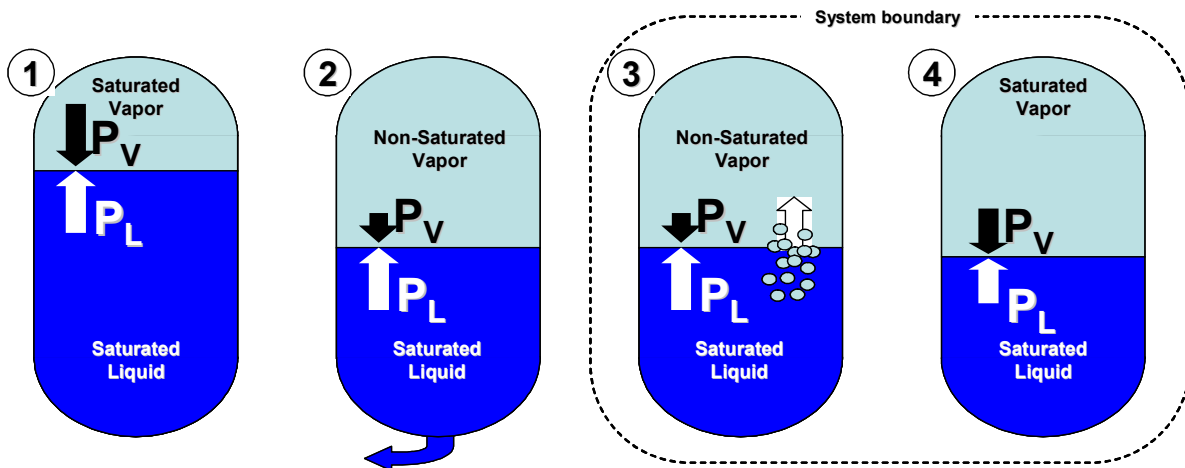


Figure 2. Thought experiment resulting in VaPak enthalpy balance equation

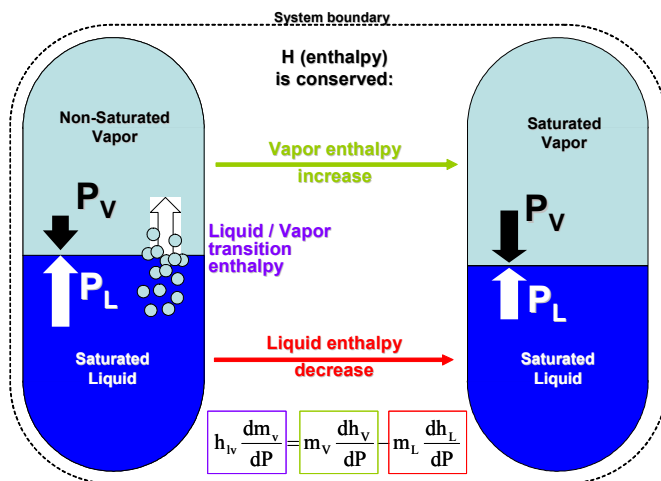


Figure 3. Enthalpy balance equation definitions

In step 1, the tank is closed with vapor and liquid phases fully saturated and pressures in equilibrium. In step 2, a small amount of liquid is instantaneously removed from the tank. In step 3, the pressure in the vapor is now below that of the liquid's saturation pressure resulting in bulk boiling of the liquid. In step 4, the vapor phase has been fully repressurized by the boiling liquid and the system is back in equilibrium (analogous to state 1, cycle repeats).

Looking at the transition from state 3 to state 4, it is possible to formulate an enthalpy balance equation for a closed system. The resulting pressure history curves neglect the effects of the flow work performed by the vapor in state 2 (pushing the liquid out of the tank), and any energy exchanged with the environment (heat losses / gains). Further refinement of the model to include these effects are discussed below.

Figure 3 shows the derivation of the enthalpy balance equation in notional form. The LHS indicates the energy (enthalpy) required to drive the process of vaporization, while the RHS represents the change of energy (enthalpy) in

both the liquid and gas phases. Manipulation of the enthalpy balance equation yields a first order ODE as a function of the vapor volume fraction (ratio of vapor volume over total tank volume) inside the tank.

$$\begin{aligned}
 h_{lv} \frac{dm_v}{dP} &= m_v \frac{dh_v}{dP} - m_L \frac{dh_L}{dP} && \text{use } m = \rho V \\
 \Rightarrow \frac{d}{dP}(\rho_v V_v) &= \frac{\rho_v}{h_{LV}} V_v \frac{dh_v}{dP} - \frac{\rho_L}{h_{LV}} V_L \frac{dh_L}{dP} && \text{use } V_T = V_v + V_L \\
 \Rightarrow \rho_v \frac{d}{dP} \frac{V_v}{V_T} &= \frac{\rho_v}{h_{LV}} \frac{V_v}{V_T} \frac{dh_v}{dP} - \frac{\rho_L}{h_{LV}} \left(1 - \frac{V_v}{V_T}\right) \frac{dh_L}{dP} - \frac{d\rho_v}{dP} \frac{V_v}{V_T} && \text{define } \bar{V} = \frac{V_v}{V_T} \\
 \Rightarrow \frac{d}{dP} \bar{V} &= \bar{V} \left(\frac{\rho_v \frac{dh_v}{dP} + \rho_L \frac{dh_L}{dP} - \frac{d\rho_v}{dP}}{\rho_v h_{LV}} \right) - \frac{\rho_L}{\rho_v} \frac{dP}{h_{LV}} && \text{1st Order ODE in } \bar{V}
 \end{aligned}$$

This equation yields the volume fraction of the tank occupied by vapor, as a function of pressure. If initial conditions are specified for pressure and vapor volume fraction, all other fluid properties can be determined by numerically solving the ODE.

The solver is stopped when all liquid has been expelled from the tank (the vapor volume fraction is unity). The ratio of expelled mass over mass when filled to capacity (Expelled Mass Fraction or EMF) is determined as follows:

$$\begin{aligned}
 \text{EMF} &= 1 - \frac{m_L + m_v}{m_L^0 + m_v^0} = 1 - \frac{m_L + m_v}{m_L^0} = 1 - \frac{\rho_L V_L + \rho_v V_v}{\rho_L^0 V_T} = 1 - \left(\frac{\rho_L}{\rho_L^0} (1 - \bar{V}) + \frac{\rho_v}{\rho_L^0} \bar{V} \right) \\
 \text{EMF} &= 1 - \left(\frac{\rho_L}{\rho_L^0} + \frac{\rho_v - \rho_L}{\rho_L^0} \bar{V} \right)
 \end{aligned}$$

C. VaPak Data

When designing a launch vehicle using VaPak propulsion, the engineer has a number of selection parameters at his disposal to achieve the desired vehicle performance characteristics. The specific propellants used, and the initial propellant conditions (ullage, pressure) will determine the shape and absolute value of the resulting VaPak curve for each tank (oxidizer, fuel). In addition, the T/W history of the vehicle will influence the VaPak system behavior, resulting in engine sizing and performance characteristics as additional parameters that allow for the fine tuning of the overall system. Since the tank pressure of the propellants varies as the tanks are depleted, the general aim is to minimize large swings in resulting engine OF ratio, and optimize overall system performance. Also, the oxidizer and fuel parameters must be matched to achieve VaPak to vapor mode transition in each tank near simultaneously, thus reducing the time during which the engine may be exposed to OF ratio spikes.

Figure 4 shows a typical family of curves for the pressure and temperature of the propellant as a function of EMF, for a propane tank at various initial conditions. The plots show data points as obtained from the ODE solver (red dots), together with polynomial curve fits to that data (blue line). Selecting initial starting pressure and ullage (equivalent to initial EMF), allows for shifting the absolute value and shape of the VaPak as desired for the overall system design. The pressure plots also shows the critical pressure and EMF when all liquid has been expended.

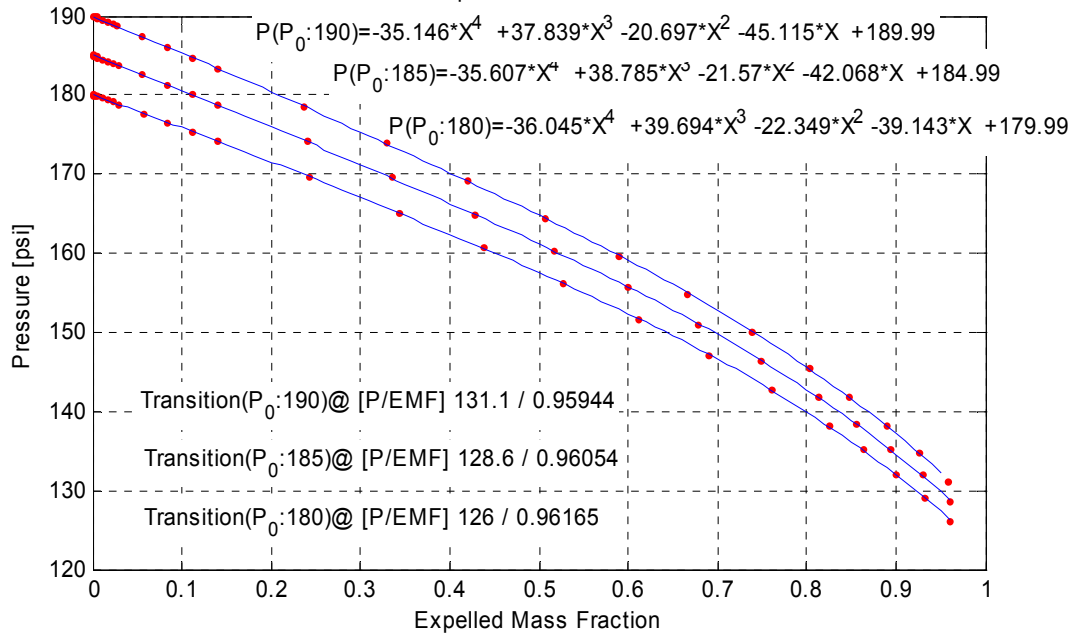


Figure 4. VaPak pressure as a function of EMF for propane, together with polynomial curve-fit equations and fluid state (temperature / pressure) at the critical point when all fluid as been expelled from the tank

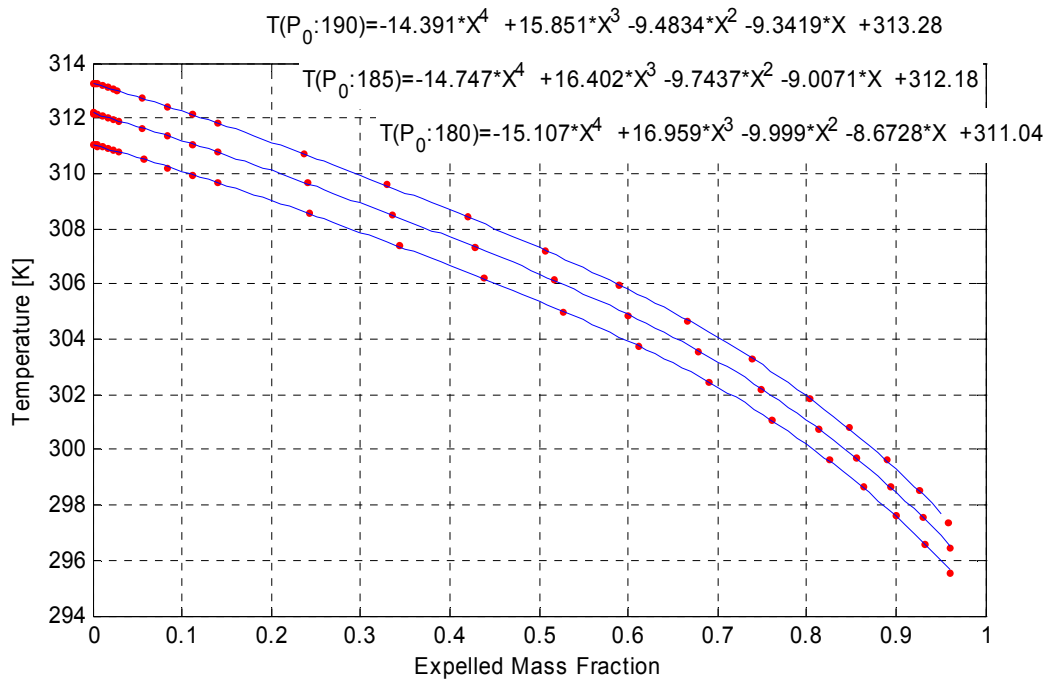


Figure 5. Fluid temperature as a function of EMF for propane, together with polynomial curve-fit equations as used in the integrated VaPak model

D. Model Validation

The enthalpy balance approach used to derive the VaPak equation as described above was adopted from the VaPak work originally performed at Aerojet. Aerojet performed several experiments of VaPak pressure tank behavior and reported good agreement between the predictions of the model and the experimental data. Figure 6 shows an overlay of Aerojet experimental data using Liquid Oxygen (LOX) with the prediction produced by the AirLaunch (AL) developed enthalpy balance model described above.

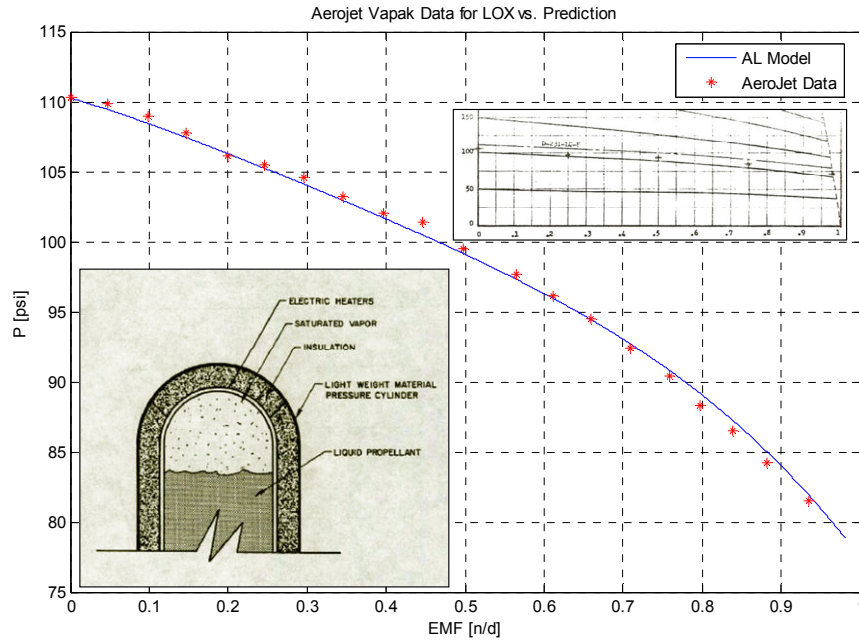


Figure 6. Aerojet experimental data for LOX vs. AirLaunch model prediction

In addition, Truax engineering has also performed VaPak experiments under a NASA SBIR, using liquid nitrogen. The data documented by Truax also matches very closely with the prediction of the model (Figure 7) using the same species and starting conditions.

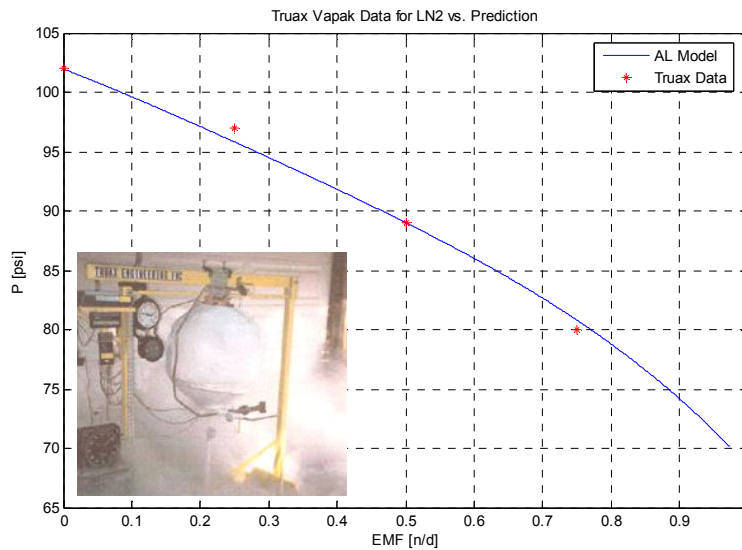


Figure 7. Truax Engineering VaPak experiment setup and data vs. AirLaunch model prediction

AirLaunch has conducted a number of flow tests using LOX as the working fluid. These tests were implemented on a Vertical Test Stand (VTS) in Mojave, CA, specifically designed to test the AirLaunch system, with the LOX contained in the tank of the Integrated Stage 2 (IS2) test article developed as part of the QuickReach vehicle development program. Figure 8 shows the IS2 on the VTS facility.



Figure 8. AirLaunch IS2 at the VTS.

Figure 9 compares the data gathered during test, to the prediction of the analytical model. The model was run with the identical initial conditions as were observed during the actual test run (inset table). As before, the data are plotted in the EMF domain.

The system exhibits a startup transient not described by the Enthalpy Balance Equation used to model the behavior. A similar phenomenon was reported by the Boeing Company during an investigation of self-pressurized nitrogen². In essence, the system first behaves similar to an ordinary gas expansion, but then recovers to follow the pressure trend predicted by the enthalpy balance equation approach.

The startup transient can be explained by the finite amount of time required to achieve bulk boiling of the saturated liquid in the tank; at initial valve opening the ullage gas is vented and pressure drops at the vapor/liquid interface. That pressure drop then results in boiling at the interface, and the consequential mixing of the fluid communicates the state change throughout the tank volume. In its study, the Boeing Company concluded that the duration of the startup transient can be affected by changing the availability of nucleation sites in the tank – either by the use of screens in the liquid or by increasing surface roughness inside the tank walls. As the magnitude and duration of the transient is dependent on the physical properties of the specific pressure vessel, it cannot be easily predicted in an analytic fashion. However, once captured by experiment, the analytic model can be easily adjusted to account for the startup deviation (Figure 13).

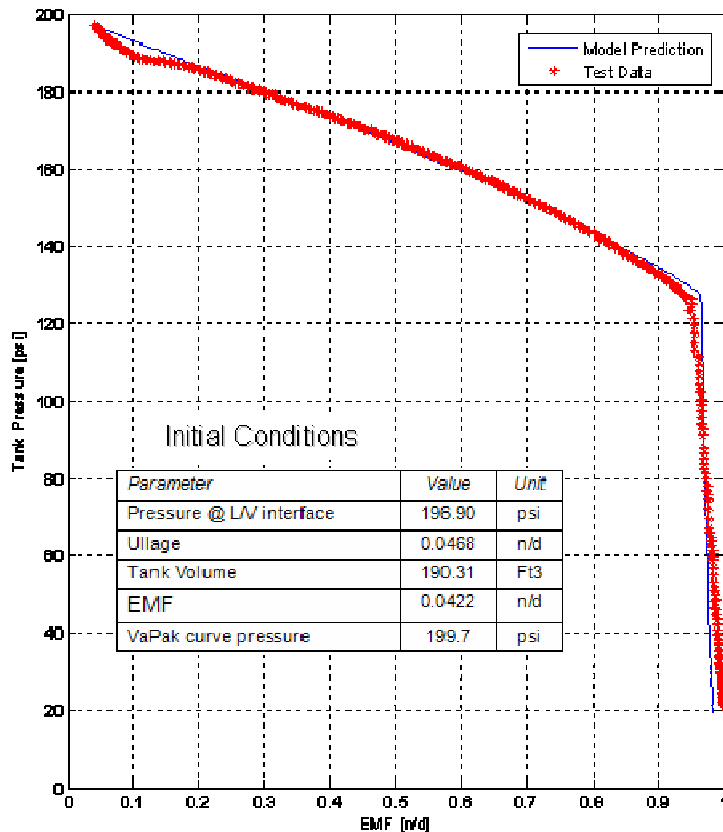


Figure 9. LOX pressure test data vs. prediction.

The second item of interest in the test data is the segment following the complete expulsion of all liquid from the tank. The critical EMF value where this transition occurs is slightly lower in the test data than the value predicted by the model. Also the pressure history following the transition to a pure gas expansion is different between the two data sets. The test data and prediction curves shown include non-ideal effects due to the non-adiabatic nature of the pressure vessel (see next section). The heat flux across the pressure vessel boundary during the test was slightly lower than what was predicted for the IS2 test article; therefore, the LOX did not heat as quickly, and the resulting shift in the VaPak curve was less than

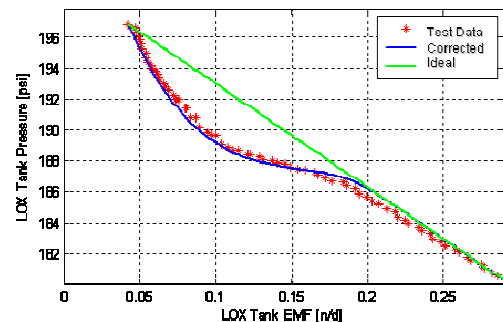


Figure 10. Corrected model to account for startup transient test observation.

predicted. This effect can also be corrected within in the model once test data for the specific application have been gathered.

E. Non-Ideal Effects

The initial derivation of the enthalpy balance equation neglected both flow work, and thermal interaction of the propellant tank with its environment. The following addresses how these two effects can be folded into the model. In

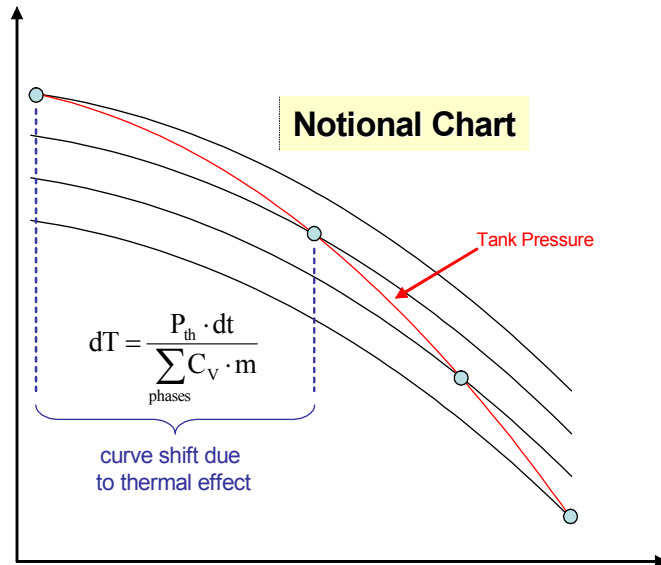


Figure 11. VaPak curve shift resulting from thermal effects

real-applications, the fluid in the tank will have a finite heat transfer rate with its environment. The resulting effect is that rather than following a single ideal VaPak curve, the system will smoothly traverse a family of VaPak curves during fluid expulsion. The model captures this effect by determining in each time step the change in fluid temperature, the resulting change in fluid pressure, and then shifting the model from the previous VaPak curve to a new VaPak curve that matches the changed fluid properties at the new system state. For a tank system with size typical for a launch vehicle application the effect is initially quite small. As the propellant is depleted and the thermal mass is reduced, the effect becomes more noticeable, but total variation of the pressure defining the VaPak curve is generally less than 1 psi. The thermal calculations use a constant thermal resistance across both the common bulkhead and from each tank to the outside environment. The environmental temperature is also held constant. Actual heat transfer is then determined as a function of the temperature differentials in each

time step of the solution.

Losses due to flow-work in state 2 of the VaPak derivation description can be implemented into the model in the same manner as the thermal effects, by causing the system to traverse a family of VaPak curves rather than a single ideal curve.

III. Propulsion System Performance

The modeling of the propulsion system addresses the performance response of the engine to the changing input characteristics throughout VaPak operation. In addition to the engine response itself, other system factors (acceleration head pressure, startup transient, liquid / vapor transition, etc.) also need to be accounted for.

A. Engine Modeling

The TDK code was used to model rocket performance for each engine on the various vehicle stages.³ A Matlab script was used to alter TDK input files from a template, and execute ~800 TDK runs for each engine, varying chamber pressure and engine OF. The input decks were set up to account for frozen flow losses, boundary layer effects, and chemistry. The enthalpy of the propellants is adjusted based on the saturated fluid properties at the injector for each chamber pressure value. Separate performance maps were generated for liquid/liquid burn, and vapor/vapor burn. Short transition periods (3 sec or less) of vapor/liquid combustion are modeled as vapor/vapor burns (conservative from a performance standpoint).

B. Engine / VaPak Integration

The relation of tank pressures to engine chamber pressure is derived from a basic mass-flow balance using a simple injector flow equation. Here P_T denotes tank pressure, P_H is head pressure due to acceleration, and P_C is the pressure in the combustion chamber. The flow parameter k is hardware design specific and assumed to be constant.

$$\dot{m} = k \cdot \sqrt{\rho \cdot \Delta P} = k \cdot \sqrt{\rho \cdot (P_T + P_H - P_C)}$$

The value of the constant k is determined from initial conditions, where it is assumed that no vehicle acceleration takes place. Here \dot{m} indicates total mass flow, OF is the oxidizer to fuel ratio, T is thrust, and g is standard Earth acceleration. Subscripted \dot{m} terms represent mass flow rate through the indicated injectors (oxidizer or fuel).

$$\dot{m}_O = \dot{m} \cdot \left(1 + \frac{1}{OF}\right)^{-1} \quad \dot{m}_F = \dot{m} \cdot (1 + OF)^{-1} \quad \dot{m} = \frac{T}{I_{SP} \cdot g}$$

$$k_O = \frac{T}{I_{SP} \cdot g} \cdot \left(1 + \frac{1}{OF}\right)^{-1} \cdot [\rho_O \cdot (P_T - P_C)]^{\frac{1}{2}}$$

$$k_F = \frac{T}{I_{SP} \cdot g} \cdot (1 + OF)^{-1} \cdot [\rho_F \cdot (P_T - P_C)]^{\frac{1}{2}}$$

The combustion chamber pressure is then calculated from a mass flow equilibrium, using the following relation and short hand notation:

$$\dot{m}_O + \dot{m}_F = \dot{m}$$

$$\Rightarrow A \cdot \sqrt{P_{FO} - P_C} + B \cdot \sqrt{P_{FF} - P_C} - \dot{m}(P_C, OF) = 0 \quad , \quad A = k_O \cdot \sqrt{\rho_O} \quad , \quad B = k_F \cdot \sqrt{\rho_F}$$

Here P_{FO} is the total oxidizer feed pressure, and P_{FF} is the total fuel feed pressure. Lastly, the OF is obtained from the ratio of injector mass flows.

$$A \cdot \sqrt{P_{FO} - P_C} + B \cdot \sqrt{P_{FF} - P_C} - \dot{m}\left(P_C, \frac{A \sqrt{P_{FO} - P_C}}{B \sqrt{P_{FF} - P_C}}\right) = 0$$

Typical traces for tank pressure and engine performance are shown in Figure 12 and Figure 13. In this case, the vehicle is operated on propane and liquid oxygen, and has a nominal initial vacuum thrust of approximately 170,000 lb. A two second startup ramp was also selected in the model. Note the transition from VaPak operation (liquid burn) to vapor operation (gas burn) at approximately 95 seconds, and the brief OF spike resulting from non-simultaneous transition in the oxidizer and fuel tanks.

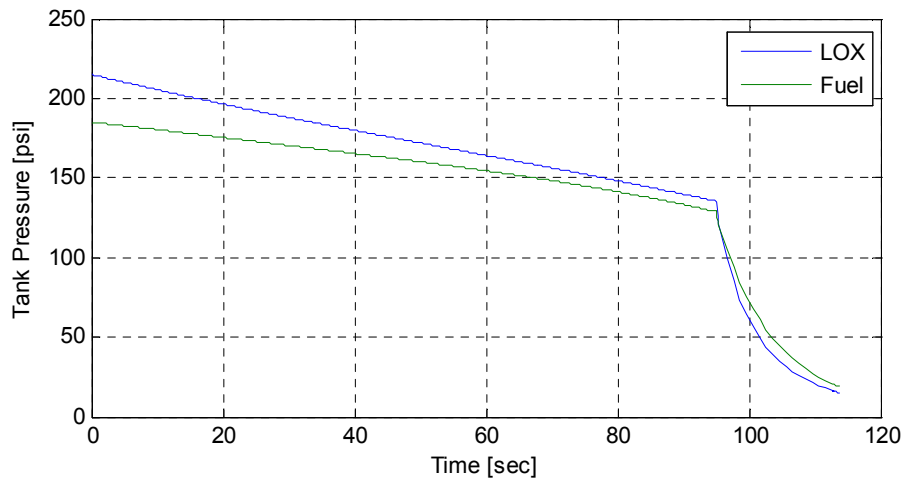


Figure 12. Tank pressure history vs. time (LOX starts at 215 psi, fuel at 185 psi)

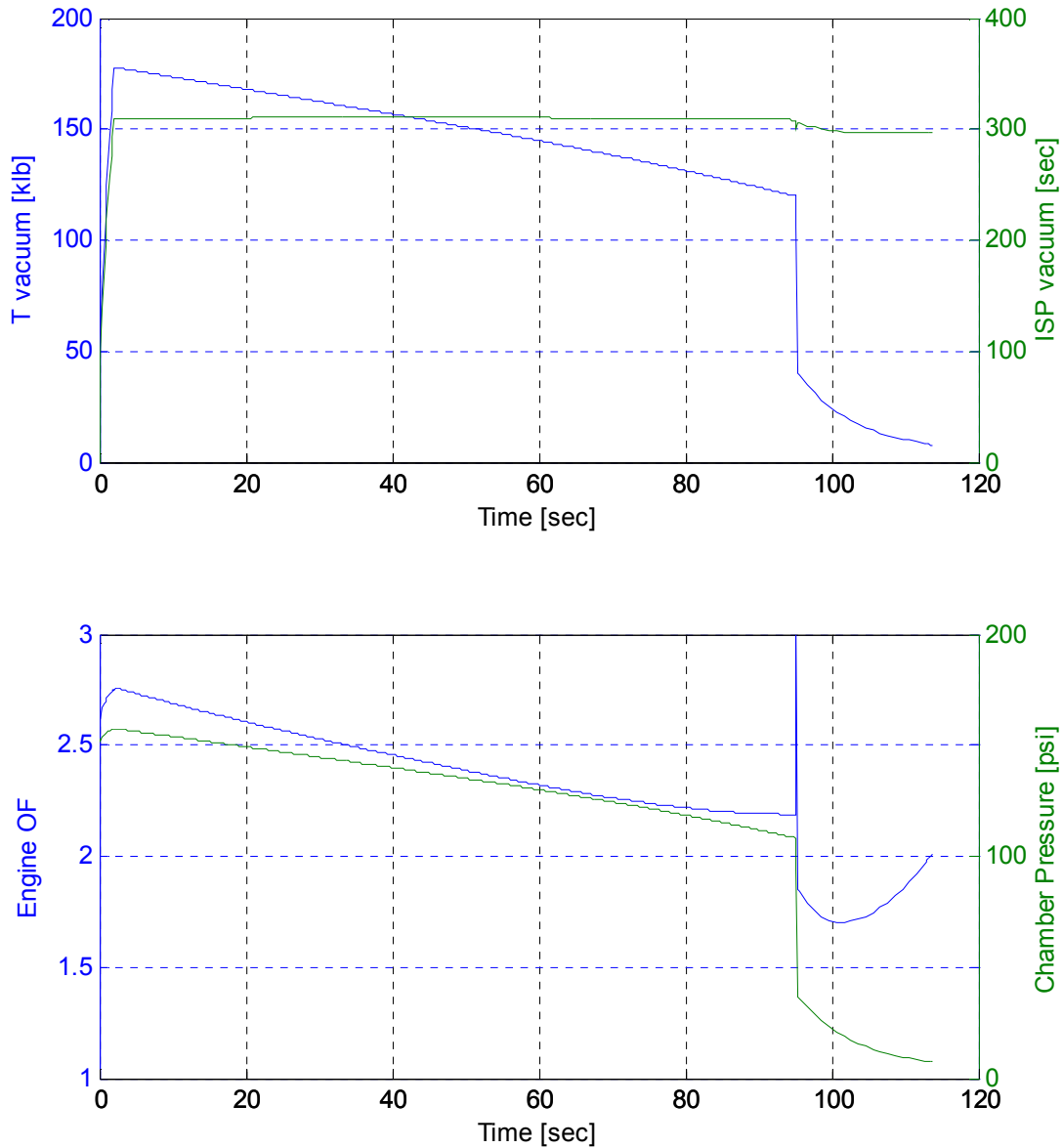


Figure 13. Engine vacuum thrust, vacuum specific impulse, OF ratio and chamber pressure vs. time

The slow drift of the engine’s OF ratio throughout the burn can also be observed, due to the different state properties and resulting VaPak curve shapes for the fuel and oxidizer. When designing a VaPak based vehicle it will be the aim of the designer to vary the initial propellant conditions until optimal overall vehicle performance is achieved. Note that this does not necessarily imply just maximum payload delivery; other desirable system characteristics are a small sensitivity to initial propellant conditions, minimal variation in liquid / vapor transition times (and resulting OF swings), etc.

C. Secondary Effects

When the expelled mass fraction falls below the point where all liquid has been removed from the fuel or oxidizer tank, the remaining pressure drop is modeled as an ideal gas / isentropic expansion. The state of the gas at the beginning of the expansion is determined from the VaPak model (setting the vapor volume fraction to unity). The density of the vapor at that point is determined from the EMF at liquid depletion. A constant value for gamma (ratio of specific heats) was assumed. Further improvement in model accuracy is possible by use of a real-gas model.

If either the oxidizer or fuel tank has been completely depleted, or the chamber pressure falls below a threshold value where combustion can no longer be sustained, the flow through the engine is modeled as cold flow using a

basic injector flow equation. The back pressure on the engine nozzle is given by the atmospheric pressure, while the engine cold flow constant is determined from design specifications. At engine start a ramp up time is assumed, and implemented via a quadratic ramp in thrust.

IV. Integrated Vehicle Performance

In order to achieve integrated vehicle performance predictions, the VaPak model is exercised based on an initial guess for ignition T/W, the resulting thrust and mass-flow data is then transferred to the OTIS trajectory tool, and a new ignition T/W may result. The two components of the model need to be iterated until convergence is achieved. The complete iterative loop is implemented as follows:

1. Assume propellant loading and initial T/W
2. Generate vacuum thrust and mass flow as a function of burn time
3. Insert T and m-dot functions as tabular data into OTIS
4. Optimize the trajectory and obtain new propellant loads
5. Adjust propellant load and T/W guess and repeat

The propellant mass and dry mass of all stages are fixed, while the initial mass of the vehicle is floating. The optimizer attempts to maximize initial mass by adding payload, within the constraints of the available propellants, orbit, etc. Masses are recalculated in the VaPak model and updated in OTIS until the desired payload performance is achieved.

A typical trajectory for an air-launched Two Stage To Orbit (TSTO) Low Earth Orbit (LEO) launch vehicle using a VaPak based propulsion system is shown in Figure 14. In this case, the launch vehicle is dropped from an aircraft and ignited at roughly 30,000 ft. The use of an air-launched scenario has the additional advantage that engine and tank pressures can be reduced without growing component sizes to a point where they become too heavy.⁴

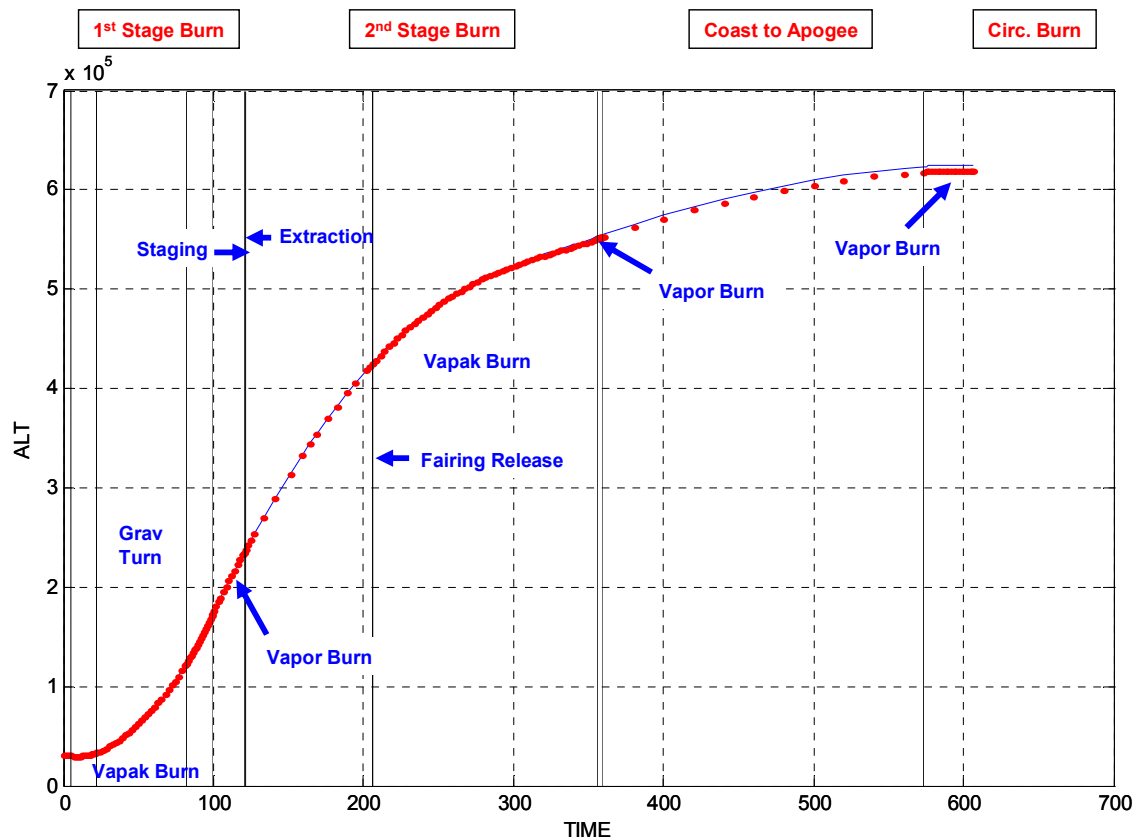


Figure 14. Trajectory structure for an air launched TSTO launch vehicle using VaPak propulsion systems

Following ignition, the vehicle aligns itself into the desired ascent trajectory and performs a gravity turn through the region of maximum dynamic pressure. In this segment the first stage engine operates on liquid combustion and tanks are pressurized using the VaPak mode. Once the liquid in the tanks has been depleted, the vehicle transitions to vapor burn mode, and both tank and engine chamber pressure drop rapidly. The stage is shut down and separated when the T/W falls below unity. Following separation, the second stage ignites under VaPak operation. The payload fairing is released when the environment outside of the vehicle is no longer harmful to the payload. The second stage burn is designed to transition to vapor operation prior to completion of the initial burn. This allows the second stage to restart following the coast to apogee, with only vapor in the propellant tanks, which eliminates propellant settling concerns. Lastly the second stage engine performs the final injection burn into a circular orbit.

V. Conclusion

The concept of the VaPak propulsion system holds the promise of combining the operational simplicity and low cost of a solid rocket with the performance advantage and restartability of a liquid propellant system. While VaPak based systems have a minimum number of parts and are relatively simple in design, the VaPak propellant pressurization system's behavior is tightly coupled with that of the engines and the vehicle as a whole. The preceding material presents an approach to model the integrated system performance of a VaPak based launch vehicle, using a combination of industry standard and custom developed tools.

The paper discussed the derivation of the fundamental VaPak equation using an enthalpy balance approach, and presented experimental data to validate the modeling approach from a variety of sources. AirLaunch generated test data using LOX as the working fluid were presented. Integration of the resulting VaPak tank pressure model with engine performance predictions is described using iterative execution of the VaPak model together with the OTIS trajectory analysis and optimization code.

An example scenario is presented for a TSTO launch vehicle using a VaPak based propulsion system. It is shown that by judicious selection of system parameters, integrated vehicle performance can be achieved in conjunction with low system sensitivity towards variation in initial propellant conditions. The presented approach and tool set for the modeling of VaPak based systems can be applied to the design of a wide variety of both launch and in-space rocket systems.

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