Active Control of Vapor Pressurization (VaPak) Systems

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Vapor pressurized (VaPak) propellant feed systems hold great promise for the development of low-cost & highly robust rocket propulsion systems. The physics driving the VaPak process enable designs with the simplicity of traditional blow-down pressurization, while theoretically approaching the performance capabilities of turbo-pump systems. However, VaPak systems exhibit tightly coupled interactions with the overall system state (vehicle acceleration, feed line geometry, etc.) that cause deviation from the optimal operations point throughout a typical burn. Especially in bi-propellant applications, even minor deviation from anticipated conditions can cause significant variations in engine performance. This paper discusses a variety of approaches to implementing active control of the natural VaPak pressure discharge curve. The proposed designs add only a moderate level of complexity without negating VaPak's inherent advantages, yet introduce a significant system stability margin with, at times, surprisingly large performance gains. A four phase development program is described to investigate the feasibility of the various options, identify the most suitable approach, and demonstrate its abilities through both ground and flight testing.

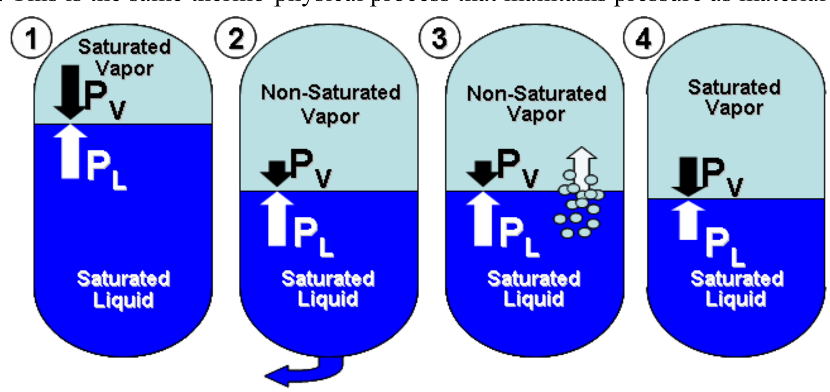
Nomenclature

EMF	=	Expended Mass Fraction
EMF/P	=	Fundamental EMF vs. Pressure curve
ISP	=	Specific Impulse
OF	=	Oxidizer to Fuel ratio
Pc	=	Chamber Pressure
T/W	=	Thrust to Weight ratio
VaPak	=	Vapor Pressurization

I. Introduction

VaPak (a term suggested by Aerojet in the 1960s) is a pressurization scheme that utilizes the internal energy of a liquid stored in a closed container to perform the work required to expel the liquid from the container. Figure 1 illustrates the principals driving the process. This is the same thermo-physical process that maintains pressure as material is expelled in butane cigarette lighters and common propane tanks used on BBQ grills. VaPak systems require no pumps and feature simplicity with the associated benefits of low cost and reduced number of failure modes.

Using VaPak, either saturated vapor or saturated liquid can be drawn from the tank. If liquid is drawn from the tank, only a fraction of the energy stored in the liquid is used to maintain pressure. The pressure at liquid exhaustion is usually 50-70% of the starting pressure, depending on the thermo-physical characteristics of the fluid. If the fluid is drawn from the tank as saturated vapor, the fluid uses a greater quantity of the energy stored



1. P_L=P_V (fluids are in equilibrium)
2. Liquid is removed, vapor expands, $P_L > P_V$
3. Liquid boils, repressurizes vapor
4. P_L=P_V (fluids are in equilibrium with $P_4<P_1$,cycle repeats)

Figure 1: Vapor Pressurization (VaPak) process.

in the liquid to create the replacement vapor. The result is a more rapid and complete pressure drop.

A typical VaPak pressure discharge curve is shown in Figure 2. The plot shows tank pressure normalized by its starting value against the Expended Mass Fraction (EMF). A tank completely full of liquid has an EMF=0, whereas a tank that is completely evacuated of both liquid and vapor has an EMF=1. The figure shows the pressure discharge curve for a tank containing saturated oxygen with an initial pressure of 200 psi. Up to 96% of the mass contained in the tank can be drawn as a liquid, with pressure dropping to only 72% from its starting value. At that point, only vapor remains in the tank (gaseous oxygen) and the pressure drops rapidly as the remaining propellant is expelled.

The key advantage of a VaPak system is its ability to maintain propellant pressure at much higher levels than a traditional blowdown system, yet without the need for any kind of turbo-pump machinery or separate gas pressurization system.

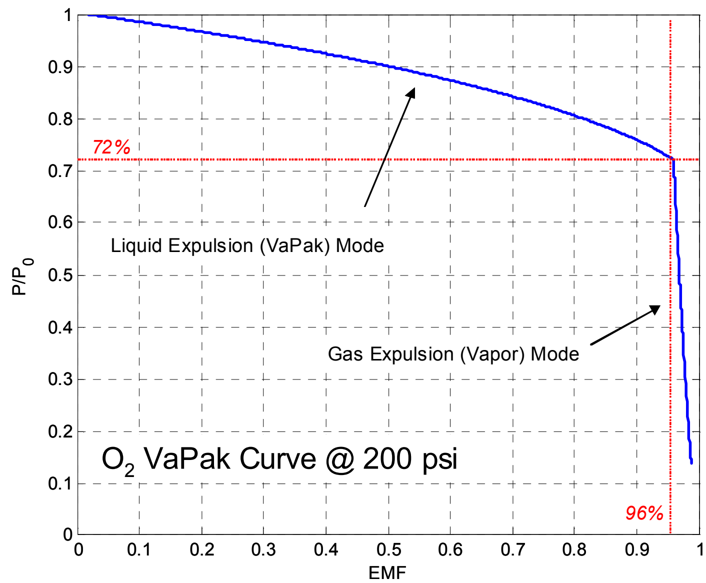


Figure 2: VaPak EMF vs. pressure curve for oxygen.

II. Problem Description

A pure VaPak system will expel propellants along the pressure curve resulting from the EMF vs Pressure relation discussed in the preceding section. The shape of the EMF/P curve is determined solely by the system's initial state (species, pressure, temperature, volume, etc.) and its physical characteristics (tank volumes and thermal insulation, feed line geometry, etc.). Once the process is set up by propellant conditioning and initiated through engine start, there is no control mechanism that allows for adjustment of the EMF/P curve. This implies that the system has to be set up perfectly, in order to achieve the desired pressure history during the burn.

VaPak systems are self-correcting regarding their end state, but not in regards to the path they take to get to that state. An illustrative analogy is the problem of releasing a boulder from the top of a mountain: it can be said with great certainty that the boulder will come to rest at the lowest point of the adjoining valley. However, if we also had to setup the boulder such that it will follow a specific path to reach that valley, the problem difficulty increases significantly. In the same vein, as a designer one is not only concerned with the propellant system's ability to utilize all available propellant, but we also wish to maintain a very specific history of flow conditions (mass-flow, propellant quality, etc.) in getting from the initial to the final state. This is especially difficult in a bi-propellant system, where two separate VaPak tanks need to be conditioned exactly right so the resulting (time dependent) oxidizer to fuel mixture (OF) throughout the burn is optimal for maximum performance. While this is achievable in computer simulations, the inherent uncertainties in real-world conditions will drive the system towards suboptimal performance. It is generally not possible to operate the engine at optimal mixture ratio for the entire burn duration. Instead, the system needs to be optimized to achieve maximum cumulative performance (payload to orbit),

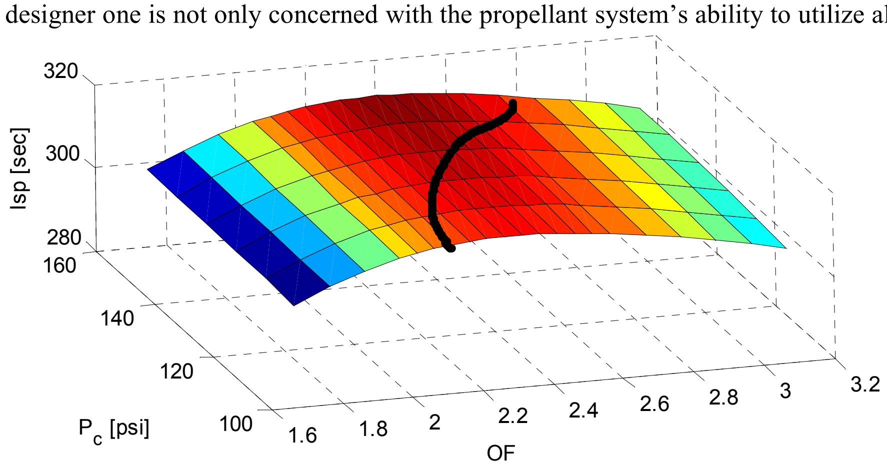


Figure 3: Typical engine ISP map, and path taken during VaPak burn.

while the engine traverses a range of operating conditions (Figure 3). As the tank pressure drops along the EMF/P curve, the chamber pressure (Pc) also drops. However, the EMF/P curve shape is generally not identical for both fuel and oxidizer, therefore OF changes as the tanks run down.

A second challenge in the use of bi-propellant VaPak systems is the "transition-gap". In a VaPak system, liquid is expelled from the tank until only saturated gas remains; however, unlike a traditional blow-down system, the pressurant gas in a VaPak system is itself also propellant and can be utilized in a suitable engine. For each system, there exists a critical EMF where this transition for liquid expulsion to gas expulsion takes place. The specific value for the critical EMF depends on the species, initial conditions, and other system parameters (such as tank volumes, acceleration history, etc.).

The difficulty that arises is that this value is generally different for the fuel and the oxidizer, unless the system is carefully tuned to experience transition in both propellants simultaneously. As with the previously discussed OF variation, this system tuning is accomplished by selecting the appropriate initial conditions. However, just as in the OF optimization problem, a perfectly simultaneous transition from liquid to gas expulsion in both propellants cannot be achieved outside of a computer simulation. The resulting transition gap (the time during which one propellant is liquid and the other is gaseous) will cause engine operation at very lean or very rich conditions. Depending on the accuracy of initial system setup, this transition-gap can last from 1 second to 1 minute. It is desirable – both for engine longevity and optimum performance – to keep the transition gap as short as possible. As it is impossible to predict the exact environment the system will operate in during flight (including the vehicle acceleration vs. time), a minimal transition gap is best accomplished using active control that forces the second propellant to switch from liquid to gas expulsion after the first has gone through its natural transition. Biasing the initial loading conditions within the margin of system uncertainty makes it possible to install the forced transition system in only one of the two propellant tanks.

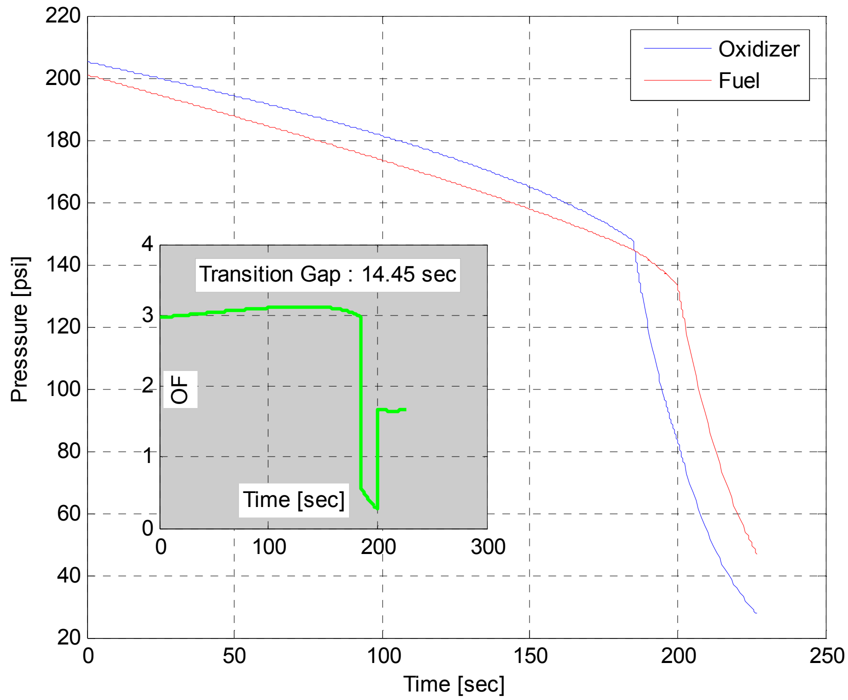


Figure 4: Transition-Gap from oxidizer/fuel VaPak curve mismatch.

A final consideration is that VaPak propellant feed systems exhibit a tight coupling with the state of the vehicle itself. As the pressure in tanks drops following the natural EMF/P curve, the declining inlet pressure to the engine will result in decreasing thrust. This in turn will result in reduced Thrust to Weight (T/W), which reduces pressure head due to vehicle acceleration, which reduces propellant pressure further, and so on. Also, propellants of different density and differing tank geometry (liquid column height) will be affected to differing degrees.

III. Active VaPak Control

All of these phenomena make it difficult to achieve truly optimal performance in a VaPak system, especially as the operating environment changes with mission, weather conditions, etc. However, the problems can be mitigated if a mechanism is implemented to actively shape the EMF/P curve during engine operation.

A. Survey of Approaches

There are several possible approaches to achieving a degree of control over the shape of the EMF/P curve during engine operation (Table 1). All approaches require a desired input signal, a measured output signal (objective), and an actuator of some kind to alter the measured state until it meets the desired condition.

Table 1: Methods of active VaPak system control and their characteristics.

No.	Signal		Actuator		Objective	Example
	Electronic	*Physical-Link*	*Tank Pressure*	*Flow Control*		
1	OF		Pressurant Gas		OF	Gas system with OF transducer
2	OF			Variable Orifice	OF	Flow control valves with OF transducer
3	OF, Pc		Pressurant Gas		OF & Pc	Gas system with OF & Pc transducers
4	OF, Pc			Variable Orifice	OF & Pc	Flow control valves with OF & Pc transducers
5		P-tank	Pressure		OF & Pc	Cross-tank plumbing with inert buffer fluid
6		P-tank		?	OF & Pc	
7	dP		Pressurant Gas		OF	Gas system with dP sensor & fixed orifices

The desired state signal can be an electronic source (pre-programmed curve or target OF), or a direct-linkage reference pressure input (e.g. cross-plumbing between the two tanks). In addition, the reference can be a desired tank pressure, a desired engine OF, a desired chamber pressure, or any combination thereof. Similarly, the measured signal (objective) can be absolute tank pressure, engine inlet pressure, differential pressure between tanks, engine OF, engine chamber pressure or a combination. The actuator of the system can directly affect tank pressure (e.g.., a gas pressurization system), or it can be a method of flow control to alter inlet pressure at the engine by throttling one or both propellant flows.

In the VaPak engine test program conducted by AirLaunch LLC under the DARPA/USAF funded Falcon program in 2008, a gas pressurization system was used to effectively "freeze" the propellant condition at a single point on the EMF/P curve regardless of the amount of propellant remaining in the tank. This was motivated by the desire to test the engine under unchanging operating conditions for a minimum duration of 20 seconds. The system used an inert gas pressurization system to change the effective volume of the propellant tank (volume within the tank not occupied by inert gas and thus available to hold propellant). In that manner, the EMF of the tank remained constant even as liquid was expelled throughout the burn. An electronic pressure regulator was used in conjunction with a differential pressure sensor, which, through a simple feedback loop, maintained the desired tank pressure. System "1" in the above table would use the same actuator (an inert pressurant gas like helium or nitrogen), but be controlled via direct measurement of engine OF. Only control of a single propellant (oxidizer of fuel) would be required to maintain optimal OF throughout the entire burn.

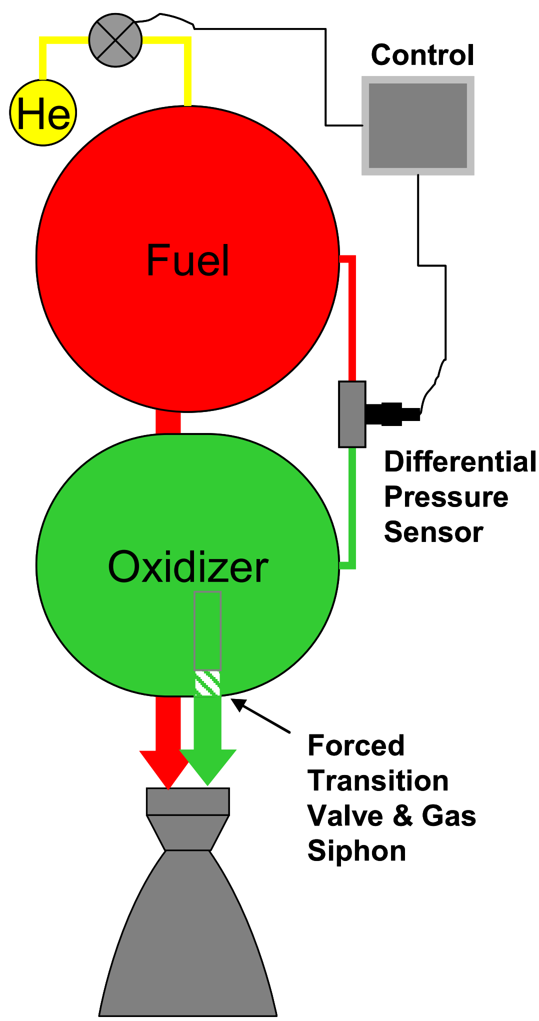


Figure 5: One possible method of controlling VaPak EMF/P curve and transition (System 7).

Another approach would be to control the flow of propellants into the engine (rather than propellant pressure in the tank), shown above as System "2". In this case the same signal is used (engine OF), but corrections are made by restricting or increasing flow from one propellant tank to the engine. This controls engine inlet pressure rather than tank pressure.

Systems "3" and "4" use the same methods as Systems "1" and "2", except in these cases the actuator is implemented on both propellants (fuel and oxidizer). This allows for control of both engine OF and Pc, allowing for optimization of the thrust curve in addition to mixture ratio.

Systems "5" and "6" do not make use of electronic sensing and software control algorithms to drive the control loop. Instead they use a physical linkage between selected reference points in the feed systems of the two propellants. One example (System "5") would be to connect the oxidizer and fuel tank to each other through some inert medium like a piston, diaphragm, bladder, or reservoir of inert fluid. This achieves thermal isolation, chemical isolation for safety, yet any pressure change in the oxidizer tank will directly alter the pressure in the fuel tank and vice versa. A system of this type can be very simple, using no software or sensors. On the other hand, it will also be limited in the range of pressure variations over which it can effectively compensate. System "6" uses the same physical linkage concept to obtain a signal of differing propellant pressures (in the tanks or at the engine inlet), but alters propellant flow instead of tank pressure as a result.

System "7" is controlled indirectly from the difference in tank pressure between the two propellants (rather than the resulting OF at the engine). A differential pressure measurement is used to control a solenoid valve that injects high-pressure helium into one propellant tank, ensuring the desired pressures at the engine inlet orifice and resulting optimal OF.

B. Development Approach

Table 2 summarizes a four phase technology development program; each phase has specific objectives, an associated cost estimate, and an approximate phase duration in calendar days.

Table 2: Technology development program definition.

Phase	Description	Objectives	Test Setup	Cost	Duration
1	Proof-of-Concept	• Analysis of proposed methodologies	Computer Simulation	\$100k	6 months
2	Application Survey	• Demonstrate application of preferred method to a variety of propellants (LOX/CH4, LOX/LH, etc) • Characterize response time, stability, range, etc for all identified options	Cold-flow of two VaPak fluids (e.g. O2 and N2)	\$600k	12-24 months
3	Product Development	• Develop commercial product for ground-test applications on 10-50klbf engines • Establish operational support, training, manuals, etc.	Bi-prop liquid rocket engine / thruster (50-1000 lbf)	\$2.5M	12 months
4	Flight Application	• Develop flight-system • Demonstrate system application	Small Launch Vehicle or Sounding Rocket	\$5M	2 Years

IV. Summary

The method of Vapor Pressurization (VaPak) for bi-propellant liquid rocket engines holds great promise to achieve the performance of a pump-fed engine in combination with the lower complexity and lower cost of a traditional pressure-fed system. However, the sensitivity of saturated fluids and the tight coupling of the VaPak system response to the overall vehicle state make it difficult to achieve optimal performance in a "set-and-forget" type application. The majority of the challenges with bi-propellant VaPak system variability during operation could be addressed by combining the VaPak approach with some form of active closed-loop control.

This paper presents a brief survey of possible approaches to active VaPak system control, which could significantly improve the operational robustness of a VaPak system with only minimal increases in system complexity. A four phase development program is described to investigate the feasibility of the various options, identify the most suitable approach, and demonstrate its abilities through both ground and flight testing.