Vapor Pressurization (VaPak) Systems
History, Concepts, and Applications

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This paper discusses the concept of vapor pressurization (VaPak) and it's applications to aerospace systems. The history of VaPak technology development is summarized, and a brief introduction is given to the physical process underlying the VaPak technology. The unique promises of VaPak technology (low-complexity, low-cost, low-weight) are discussed, together with some of the challenges associated with VaPak implementation (handling of saturated fluids, pressure curve shaping, etc.). VaPak technology holds great promise for enabling both launch systems and in-space systems. Its unique abilities of long-term propellant storage with high reliability, and zero-g use without settling mechanisms are enablers to both conventional and ISRU based exploration architectures.

Nomenclature

CH4	=	Methane
C3H8	=	Propane
DARPA	=	Defense Advanced Research Projects Agency
EMF	=	Expended Mass Fraction
EMF/P	=	Fundamental EMF vs. Pressure curve
LOX	=	Liquid Oxygen
N2O	=	Di-nitrogen monoxide (nitrous)
ISP	=	Specific Impulse
ISRU	=	In Situ Resource Utilization
OF	=	Oxidizer to Fuel ratio
ORS	=	Operationally Responsive Spacelift
RLV	=	Reusable Launch Vehicle
SBIR	=	Small Business Innovative Research
VaPak	=	Vapor Pressurization

I. Introduction

In the early 1960s Aerojet Corporation investigated the concept of using saturated fluids as a means to pressurize rocket propellant tanks. This approach was called Vapor Pressurization or VaPak. Even then Aerojet understood the need for simple and highly reliable liquid rocket propulsion, especially in those applications where solid rocket solutions were used with the associated performance limitations. The greatest contributor to the complexity of a liquid propellant rocket system is the pressurization and propellant feed system. Two types of liquid propellant feed systems are generally in use, pressure-fed systems and pump-fed systems.

Pump-fed systems have the best performance and lowest weight for high chamber pressure applications. The use of a pump to raise pressure prior to injection into the combustion chamber allows for storing the propellant at pressure much below the chamber pressure. Unfortunately, the system with the greatest weight advantage (turbo pumps) is also the most complex, with the associated reliability concerns and cost disadvantages.

The less complex pressure-fed systems require heavier tanks (to withstand greater pressures) as pressure drops rapidly from the initial loading conditions, thus adding considerable weight to the system. This is especially true for ground launched applications, where higher chamber pressures are needed to offset the ambient atmospheric pressure and maintain good engine performance. When cold compressed gas is used for tank pressurization, the weight of the pressurization system can be as high as 40% of the overall propulsion system allocation. The use of hot gases, or gas generators burning liquid or solid fuel can reduce this fraction to 25% or less, but raises system complexity.

A. VaPak Concept

The VaPak concept developed by Aerojet in 1959 combines the low-complexity advantages of a pressure-fed system, with the performance advantages (low tank weight, improved chamber pressures) of a pump-fed system. While VaPak performance is handicapped for ground launch applications, the performance of in-space vehicles (upper stages, spacecraft, etc.) can be as good as that of a sophisticated pump-fed system.

VaPak pressurization utilizes the internal energy of a saturated liquid stored in a closed container to perform the work required to expel that liquid from the container. Initially, the liquid temperature is adjusted so that the vapor pressure equals the desired tank pressure. As propellant is drained and the pressure drops, the remaining liquid boils, and the released gas retains the tank at near constant pressure. Roughly 70% of the initial tank pressure remains at the point of liquid depletion. The rate at which the tank pressure decreases is a function of the thermodynamic properties of the selected propellant. Selection of propellant species and initial conditions allow the designer to tune the system for the desired application

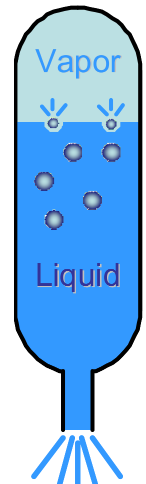

Figure 1: VaPak uses the internal energy of the fluid to pressurize the tank.

B. Development History

Aerojet initiated the development of vapor pressurization in 1959. Through 1964 a large number of tests were conducted that allowed for the derivation and validation of the fundamental VaPak physics[i,ii]. These tests included 38 cold-flow expulsion tests, using 8 different propellant species, 120 engine test firings using a bi-propellant rocket engine with up 6,000 lbf of thrust, and 14 simulated zero-g box-motor firings.

In 1983 the Boeing Company conducted a number of tests to investigate the storability of saturated propellants.[iii] These tests were aimed at better understanding the transient behavior of saturated propellants when liquid is first removed from the tank, and the relationship of that behavior to the rate at which the liquid is removed. It was found that vent rates of 0.1 to 0.4 ullage volumes per second were sufficient to initiate the VaPak process (flash boiling) in the system.

In 2000 the Dunn Engineering company in conjunction with the University of British Columbia (Canada) published a report on self-pressurized bipropellant liquid rockets[iv]. It used hydrogen peroxide as the oxidizer, and a variety of hydrocarbons as the fuel, both pressurized with the VaPak approach. In addition to the application of VaPak to rocket propulsion, the report also identified the advantages of VaPak for in space (zero-g) propellant transfers. The authors made use of flexible bladders to separate a VaPak and a conventional fluid inside a common pressure vessel. Test data showed a close adherence to the established VaPak physics model, with the exception of a transient pressure drop at system startup (the focus of the previously mentioned Boeing work).

In 2004 Scaled Composites was the first company to combine the concepts of air-launching (launching at altitude) and VaPak fed propulsion on the hybrid rocket engine of SpaceShipOne. The concept used a SpaceDev propellant grain fuel together with VaPak pressurized liquid nitrous oxide (N2O) as the oxidizer. The engine developed a chamber pressure of 37 atm, expanded through a 25:1 nozzle. Liquid nitrous oxide (N2O / dinitrogen monoxide / 'laughing gas') was the oxidizer of choice for the application because it was storable, and self-pressurizing to 48 atmospheres at 17 deg C. [v]

Figure 2: SpaceShipOne used a hybrid rocket engine with VaPak pressurized N2O oxidizer.

In 2006 Truax Engineering (founded by Captain Robert Truax, former Aerojet engineer) was awarded a NASA SBIR for the development of their low-cost Excalibur launch vehicle concept. The work included additional expulsion testing (cold flow) of saturated propellants. The test data further validated the VaPak physics models originally developed at Aerojet.[vi]

Figure 3: Test firing of the AirLaunch water-cooled LOX/C3H8 VaPak engine at the Mojave Spaceport test facilities.

In 2006 through 2008 AirLaunch LLC conducted extensive ground testing of a VaPak propulsion system in conjunction with a low-cost pintle rocket engine as part of the DARPA/USAF funded Falcon Small Launch Vehicle Program.[vii] Over 80 test firings were executed using propane and liquid oxygen as the propellants, both pressurized using VaPak. The engine was rated for 20,000 lbf and test durations were as long as 200 sec. The same engine was also fired using methane and liquid oxygen, demonstrating the versatility of the low-complexity VaPak approach.

II. Concept

This section gives a brief introduction to the physical process underlying the VaPak technology, and a discussion of the associated benefits and challenges in applying VaPak to operational systems.

C. Physics

Figure 4 illustrates the principals driving the vapor pressurization 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. The system is initially in equilibrium with both the liquid and the vapor inside the tank at the same pressure. As liquid is removed, the pressure in the vapor phase drops and causes the liquid to flash-boil. The gas released by the boiling process then repressurizes the vapor phase, until both liquid and vapor phases exist again at the same pressure (slightly below the initial starting pressure).

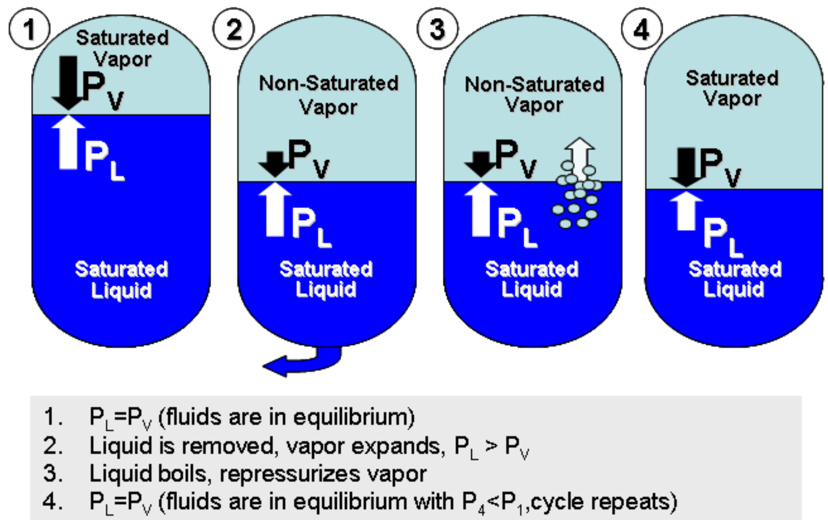

Figure 4: Vapor Pressurization (VaPak) process.

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 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 5. 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 use of EMF to characterize the VaPak pressure curve is attributed to the derivation of the VaPak behavior as pioneered by Aerojet. In the derivation, the system behavior is captured by use of an enthalpy balance. The underlying assumption is that no energy is added to or lost from the system during operation. In actual engineering applications this is not generally true, as heat is transferred across tank walls and work expended to push fluids through flow restrictions etc. Holder Consulting Group (HCG) has developed sophisticated modeling techniques to account for these types of non-ideal behavior. Another simplification of the ideal model is the absence of the startup transience; this will cause a momentary drop of pressure below the predicted value, followed by a recovery after a number of seconds. The exact duration and magnitude of this startup transient depends on the specifics of the system (tank geometry, surface roughness, etc) and the initial flow rate as the process is started.

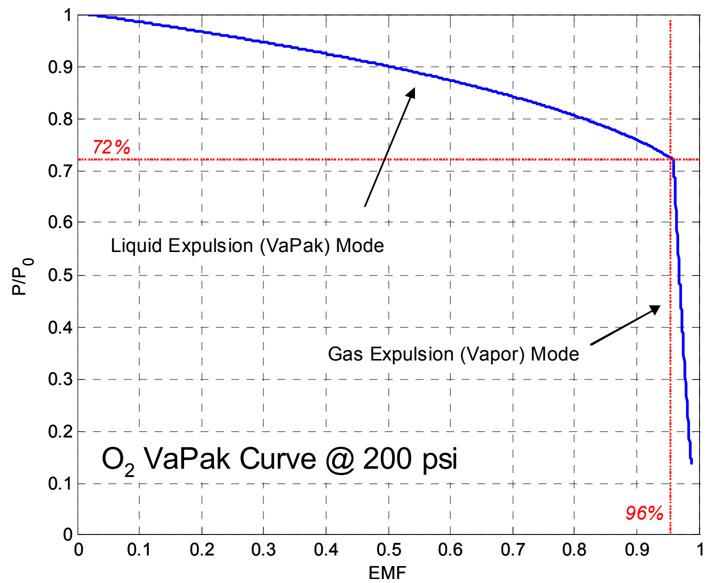

Figure 5: VaPak EMF vs. pressure curve for oxygen.

D. VaPak Features

The key advantage of a VaPak system is its ability to maintain propellant pressure at much higher levels than a traditional pressure-fed blow-down system, yet without the need for any kind of turbo-pump machinery or separate gas pressurization system. The low complexity (low parts count) of the system enables lower cost, lower weight, and improved system reliability. From a performance standpoint, VaPak systems offer the improved ISP of liquid propellant engines (when compared to solids). Compared to a traditional pressure-fed system, the reduced pressure drop throughout the burn enables lower initial storage pressure for a given target chamber pressure, which in turn makes it possible to use lighter tanks.

Another unique advantage of the VaPak system is the fact that the pressurization gas is also propellant. If the paired engine is capable of combusting both liquid and gaseous propellants (generally true since all propellants are vaporized as they pass through the injector into the combustion chamber), VaPak systems require no propellant settling in zero-g application. This is of key importance for upper stages that perform multiple burns, but also for propellant transfer in a zero-g environment from a depot to a vehicle or vice versa. Lastly, VaPak has particular synergism with air-launched rockets, where the reduced environmental pressure at ignition (high altitude drop) reduces the tank pressure requirement (=weight), and no settling is required if the engine is to be ignited after separation of the rocket from the carrier aircraft (especially important for safety in piloted aircraft).

Since the physics underlying the VaPak process are consistent across a wide variety or propellant species (both elements and compounds), it is easily adapted to In-Situ Resource Utilization (ISRU) mission architectures. For example, Mars sample return missions have been proposed where methane and oxygen are collected on Mars over several months to power the return flight. Both of these propellants are very suitable for VaPak applications, and the inherent reliability of the VaPak process (physics always work) is of great benefit to the problem of long duration storage.

E. VaPak Challenges

There are a number of unique challenges associated with the realization of VaPak's potential in any operational system. Foremost is the handling of propellants in a saturated state. Propellant tanks must be conditioned to accurate and uniform initial conditions to achieve the desired VaPak EMF/P discharge curve. This becomes increasingly difficult as the system size increases. Saturated liquids are also sensitive to any type of pressure drop, which will cause immediate flash-boiling. While this can be an advantage in the process of propellant mixing inside the combustion chamber, it becomes a concern in the remainder of the propellant feed system. Narrow diameter pipes, sharp bends, or obstructions from sensor equipment (e.g. mass-flow meters) all cause drops in fluid pressure and a portion of the propellant will transition to gas phase, this results in two-phase flow (liquid and vapor) which is difficult to analyze, predict, and manage.

Coordinating the operation of two separate VaPak systems in a bi-propellant rocket raises additional challenges. VaPak systems are self-correcting regarding their end state, but not in regards to the path they take to get to that state. This implies that while both propellants will be depleted near simultaneously, maintaining an optimal OF ratio throughout the burn is not guaranteed. Another 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. A perfectly simultaneous transition from liquid to gas expulsion in both propellants cannot be achieved outside of a computer simulation, and 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.

III. Applications

VaPak's potential for low-cost, high-reliability liquid propellant rockets has long been understood. There are several application areas where this technology offers unique benefits and displays significant synergism with other system elements.

Many programs have been attempted to leverage the reusability of launch vehicles as a mechanism to reduce cost. For any Reusable Launch Vehicle (RLV), one of the key design drivers is the manner in which the reusable components are returned to the original launch site. When analyzing the use of RLV's for the delivery of cargo, it quickly becomes apparent that the most cost effective solution is a reusable first stage booster, pared with a low-cost expendable upper stage (or stages). VaPak systems are ideally suited for this application, enabling high performance yet low-cost expendable upper stages to be paired with higher cost, fully reusable first stages. Fully VaPak driven launch vehicles are also possible when launched at altitude (air-launched).

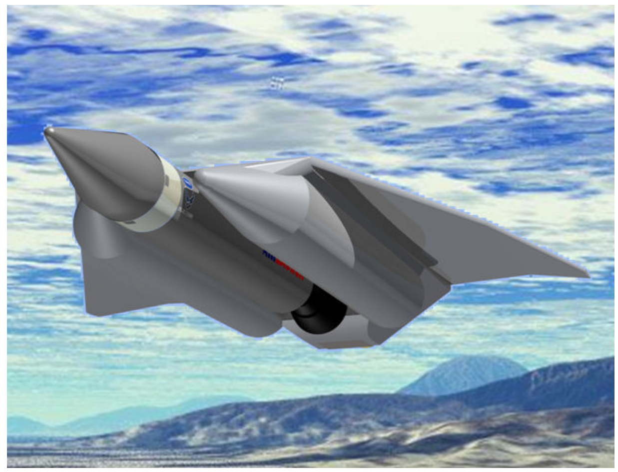

Figure 6: Operationally Responsive Spacelift (ORS) concept using RLV booster with VaPak driven expendable upper stage *(courtesy of Holder Aerospace)***.**

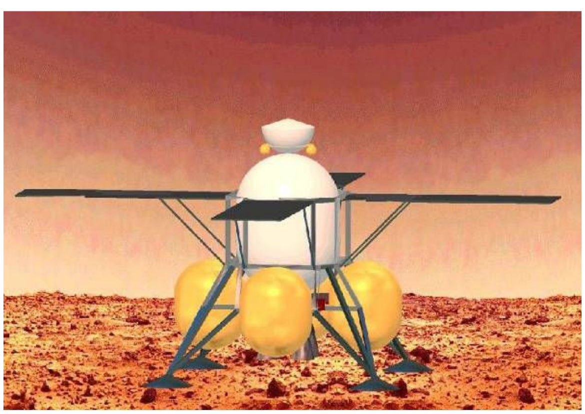

Figure 7: ISRU Mars sample return concept using LOX/Methane propellants.
(courtesy of University of Washington)

Figure 8: QuickReach VaPak driven Small Launch Vehicle test article deployed from a C-17 airplane.
(courtesy of AirLaunch LLC)

The ability to restart VaPak vehicles in zero-g without settling and their preference for low ambient pressure environments also makes them very attractive for upper stage vehicles. VaPak systems can be throttled (unlike solids), have the superior performance of liquid propellants, yet remain the low weight advantage critical for upper stages. The VaPak mechanism applies to a large variety of propellant species, both elements such as oxygen or hydrogen, as well as compounds such as hydrocarbons or monopropellants. This versatility makes it possible to use VaPak propellant concepts with ISRU mission architectures. Planetary exploration missions are enabled that range from surface hoppers, to robotic sample return, or automated propellant plants / depots which pre-collect the return propellants for a human exploration mission. Combining VaPak's zero-g capabilities with it's long duration storage / dormancy attributes also makes it ideally suited for in space propellant depots or vehicle-to-vehicle propellant transfer.

IV. Summary

The concept of VaPak (vapor pressurization) holds the promise of low-cost, highly reliable, liquid propellant rocket propulsion. The technology has been investigated by numerous organizations for almost 50 years, and has matured to present day human spaceflight applications. The physical mechanisms underlying the VaPak process are well understood and have been verified by extensive test data. VaPak has unique features that make it particularly attractive for applications where low chamber pressures are not a performance drawback (air-launch, upper stages, in-space propulsion). VaPak systems use propellant as the pressurization gas, and therefore require no settling in zero-g applications. Challenges introduced by the VaPak approach include the handling of saturated propellants, and accurate conditioning of propellants prior to engine burn. The wide variety of propellants which can leverage the VaPak approach enables the use of ISRU mission architectures; while the high reliability of these systems complements long duration propellant storage depots both in space (zero-g) and at extraterrestrial (Mars, Moon) locations.

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