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RECENT DEVELOPMENTS IN HYDROGEN PEROXIDE PUMPED PROPULSION

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ABSTRACT

This paper describes the development of a lightweight high performance pump-fed divert and attitude control system (DACS). Increased kinetic Kill Vehicles (KV) capabilities (higher Δv and acceleration capability) will especially be needed for boost phase engagements where a lower mass KV DACS enables smaller overall interceptors. To increase KV performance while reducing the total DACS dry mass (<10 kg), requires a design approach that more closely emulates those found in large launch vehicles, where pump-fed propulsion enables high propellant-mass-fraction systems. Miniaturized reciprocating pumps, on a scale compatible with KV applications, offer the potential of a lightweight DACS with both high Δv and acceleration capability, while still enabling the rapid pulsing of the divert thrusters needed in the end-game fly-in. Pumped propulsion uses lightweight low-pressure propellant tanks, as the main vehicle structure and eliminates the need for high-pressure gas bottles, reducing mass and increasing the relative propellant load. Prior work used hydrazine and demonstrated a propellant mass fraction >0.8 and a vehicle propulsion dry mass of ~3 kg. Our current approach uses the non-toxic propellants 90% hydrogen peroxide and kerosene. This approach enables faster development at lower costs due to the ease of handling. In operational systems these non-toxic propellants can simplify the logistics for manned environments including shipboard applications. This DACS design configuration is expected to achieve sufficient mass flows to support divert thrusters in the 1200 N to 1330 N (270 lbf to 300 lbf) range. The DACS design incorporates two pairs of reciprocating differential piston pumps (oxidizer and fuel), a warm-gas drive system, compatible bi-propellant thrusters, lightweight valves, and lightweight low-pressure propellant tanks. This paper summarizes the current development status and plans.

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INTRODUCTION

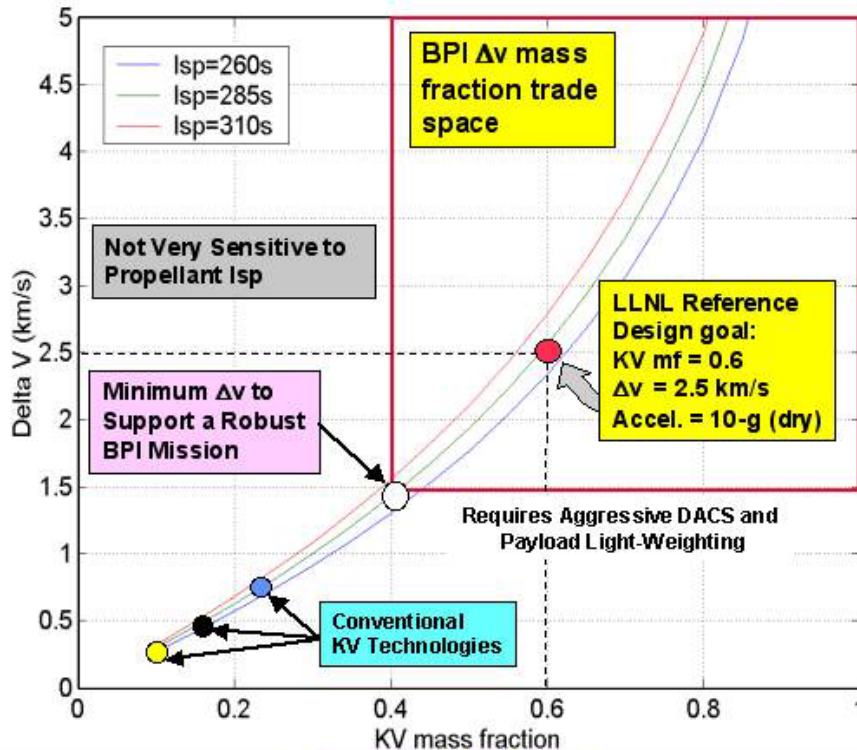
In Boost Phase Intercept (BPI) engagements the boosting target initially has a very large Predicted Intercept Point (PIP) error, which slowly decreases as the target burns up and drops its multiple stages.¹ Large lateral maneuvers (dog-legs) or depressed trajectories can generate large changes in the $\Delta v > 1.5$ km/s that a kinetic interceptor must expend to intercept the target in boost phase. End-game intercept maneuvers against a boosting target are also expected to drive up lateral divert acceleration capabilities to the 10-g range. Further, the sooner a kinetic Kill Vehicle (KV) intercepts a target while in boost the greater the shortfall of the debris generated by the intercept. An intercept post-boost does not reduce the kinematic-reach of the target or its debris. So in a BPI mission, a premium is placed on getting to the target earlier in boost, requiring higher Δv fly-out velocities than those found in a midcourse fly-out. To robustly respond to this need for greater KV Δv and acceleration capability, a high performance, low mass (<10kg) DACS is needed. These higher Δv and acceleration capabilities are especially critical for space-based boost-phase KV interceptor systems where overall launch mass is a significant cost driver.²

Pumped propulsion offers the potential for lower dry mass and higher propellant mass fractions (the ratio of propellant mass to wet propulsion system mass) than conventional KV pressure-fed propulsion systems. Previous work at Lawrence Livermore National Laboratory, during the Brilliant Pebbles development program that was sponsored by the Strategic Defense Initiative Organization (SDIO), pioneered the use of miniaturized reciprocating pumps that emulate launch vehicle technologies at a small scale.³ These reciprocating pumps enable higher KV propellant mass fraction designs (>0.5 to ~0.8), while still offering the rapid pulsing of the divert thrusters. These developments mainly used hydrazine as a mono-propellant, but later efforts demonstrated the feasibility of this approach with the toxic storable bi-propellants hydrazine and nitrogen tetroxide in a test chamber.⁴ A final flight experiment (ASTRID) successfully demonstrated the reciprocating pumped-fed propulsion concept in a small sounding rocket.³ This experiment reconfigured lightweight DACS components into a 1.8 m long sounding rocket with four

250 N thrusters. This vehicle had a mass fraction of >0.8, (a propulsion mass of ~3 kg and carried ~12.7 kg of hydrazine) and demonstrated the equivalent of 2 km/s vacuum Δv with a 21 kg vehicle wet mass.

Pumped propulsion has traditionally been used in large launch vehicles where high propulsion mass fractions (>0.8-0.95) are required to generate large impulses and corresponding large velocities (>2 km/s) per stage. In these systems hot gas from propellant combustion, is used to drive large turbo pumps that are fed from low-pressure thin-walled liquid tanks that make up the vehicle structure. These turbo pumps feed compact high-pressure liquid thrusters at high mass-flow-rates. For large launch vehicles, long steady-state rocket burns are needed, and turbo pumps are considered the best choice. For missile defense KV applications, where a series of short pulses are needed, reciprocating pumps are the best solution. These pumps maintain the propellants at the thruster feed pressures between pulses and can rapidly start and stop to provide the high-pressure-flows needed to keep up with the divert thruster demand. Pumped propulsion uses low pressure, lightweight tanks that enables a "tanks-as-structure" mechanical design approach, which significantly reduces the dry mass of the system, resulting in a high propellant-mass-fraction DACS.

Conventional KV DACS designs use either pressure-fed liquid propellants or the controlled hot-gas venting of solid propellants (Solid DACS). These systems require high-pressure propellant tanks, which typically have masses comparable to the propellants they carry. High pressures are needed in order to keep the thruster mass low. In liquid systems, the propellant tanks are pressurized using compressed gases from heavy high-pressure gas bottles. These heavy propellant tanks and pressurization systems have tended to limit the achievable propulsion propellant mass fractions to between ~0.25 to <0.5. In flight-tested systems, these conventional KV's have demonstrated attainable velocity changes in the 200 to ~500 m/s range. In a pump-fed DACS, the total volume of the high pressure pumps and gas generator is less than 5% of the volume of propellant tankage, resulting in a significant mass saving over the high pressure propellant tanks and pressurization bottles in a pressure-fed DACS. Figure 1 shows how the KV mass fraction drives the total Δv capability of the vehicle.



Representative Example:	
KV wet mass = 30 kg	DACS dry mass = 6 kg
Propellant Mass = 18 kg	Payload mass = 6 kg
KV mass fraction (mf) = (Prop. Mass)/(KV Wet mass) = 18 kg/30 kg = 0.6	
KV Mass Ratio: Wet/Dry = 30 kg/12 kg = 2.5	
DACS mass fraction (mf) = (Prop. Mass)/(DACS Wet Mass) = 18 kg/24 kg = 0.75	

Figure 1. Shows required KV vehicle mass fraction needed to achieve large Δv capability. For $\Delta v = 2.5$ km/s requires a vehicle mass fraction of 0.6. For a 30 kg wet KV, this represents 18 kg of propellant mass and 12 kg of dry mass. For an equal partition of mass between the DACS (6 kg) and the Payload (6 kg), this represents a DACS mass fraction of 0.75. A comparison is also made to conventional KVs.

Over the last several years we have been developing non-toxic reciprocating pump-fed propulsion components for micro-satellite and KV applications, that utilize 90% hydrogen peroxide (or high test peroxide – HTP) as a mono-propellant. We have integrated these into several ground test vehicles for system level testing.^{5,6} Figures 2a and 2b are photos of an earlier generation of pump-fed vehicle undergoing testing on a 40-meter air-rail test apparatus. The ground test KV is mounted at its center-of-gravity (c.g.) on a spherical air-bearing which allows it 3-degrees-of-freedom (3DOF) of angular motion and 1DOF of lateral motion. The vehicle can utilize its divert and attitude control system (ACS) for pointing while diverting. This low cost high fidelity testing provides an evaluation of the performance of the DACS, including vibration, impulse bit, stability and control, center-of-mass management, line-of-sight (LOS) jitter, duty cycle, sustaining thruster level, and simultaneous pulsing

operations with two thrusters, well in advance of a hover test or actual flight experiment. Once component development has reached an adequate level of maturity and integrated breadboard testing has established the basic DACS system level functionality, we believe this approach can reduce development risk as it enables the evaluation of the DACS performance in an integrated vehicle context. The thrusters in this test vehicle use a catalyst bed to decompose the hydrogen peroxide into oxygen and hot steam (1000°F) at high pressures, which when ejected generates thrust. The DACS in this vehicle uses four parallel tanks and an earlier generation lower capacity pump design. The vehicle shown is an interim test configuration that used cold-gas drive for the pumps. This still provides a significant mass savings in the lightweight propellant tanks, but required a high-pressure gas bottle for the drive gas.

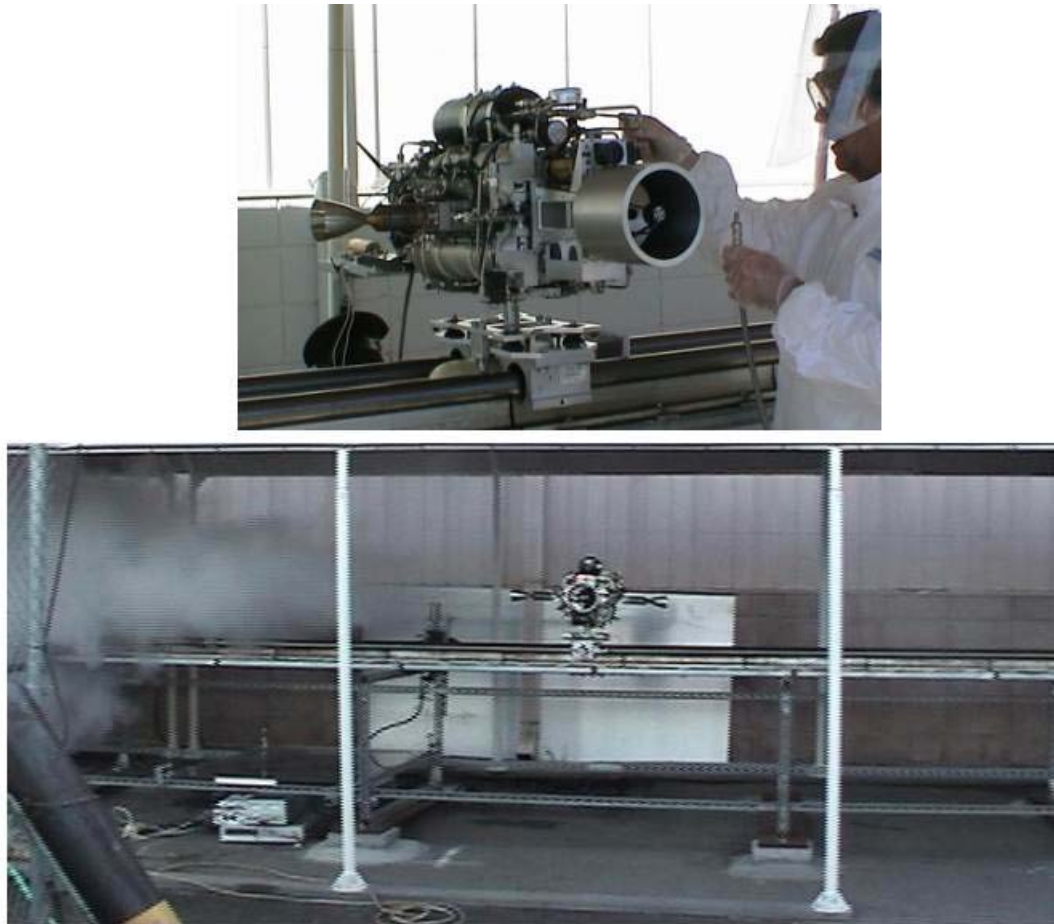


Figure 2a. (top) Shows a testbed vehicle with a pump-fed DACS mounted on an air rail test apparatus. Figure 2b. (bottom) Shows the testbed vehicle in operation, executing a sequenced thrust profile down the 40-meter rail.

Figure 3 shows a representative propulsion schematic diagram for the ground test vehicle shown in the photographs in Figure 2. In this schematic diagram, the hydraulic circuit has been configured for operation with warm-gas drive. The lower right hand side of the figure shows how a portion of propellant (~10%) is directed from the oxidizer pump outlet manifold through a regulator to a gas generator. Peroxide decomposes in the gas generator's catalyst bed to provide high-pressure warm gas (oxygen and steam) that is used three ways: 1) to drive the differential piston pumps, 2) to maintain the ullage volume pressures in the propellant tanks (75 psi using a step-down gas regulator) and 3) to the ACS thruster assembly, as high-pressure reaction gas. The differential pistons in the pumps increase the liquid pressure by a factor of ~1.5X from the warm-gas drive pressure, from 500 psi to 1000 psi, to the 750 psi to 1500

psi range. These gas driven pumps, use simple pneumatically controlled valves to immediately provide high-pressure flow upon demand (e.g., thruster valve operation).⁴ To the divert thrusters, a pump-fed DACS functions just like a pressure-fed system, with the pumps providing pairs of small high-pressure propellant reservoirs, that continuously supply on-demand flows to the output liquid manifold circuit. This mono-propellant DACS is being reconfigured into a new bi-propellant in-line configuration, that is currently under design. Recent efforts are focused on a significantly higher capacity pump, for higher mass flows, the development of a warm-gas drive circuit with matching drive capacity, and the transition to full bi-propellant operation, which will allow the use of propellants with specific impulses (vacuum) in the 280 to ~300 sec range.



Thrust levels selected will depend on the expected BPI KV dry mass and needed end-game lateral acceleration required to match the component of the target acceleration, lateral to the line-of-sight to the KV Seeker. In order to achieve high fly-out accelerations and high velocities from the interceptor booster (or kick stage) will drive the KV to minimum wet masses. For the end-game the nominal KV lateral burn-out accelerations have been set to 10-g's ($\sim 100 \text{ m/s}^2$). For a representative vehicle dry mass of 12 kg (see Figure 1), this will result in a required divert thrust of 1200 N ($\sim 270 \text{ lbf}$). A vacuum specific impulse (Isp) of 280 - 300 sec (expected for this propellant combination) leads to mass flows of 0.5 kg/s per each divert thruster. For a typical KV intercept, two orthogonal components of acceleration are needed in the end-game, requiring simultaneous thrusting from two orthogonal thrusters ($\sim 14\text{-g}$ of combined acceleration). Two divert thrusters operating at the same time will require mass flows of about 1 kg/s from the reciprocating pumps. For O:F (oxidizer-to-fuel) ratios of 7:1, almost

We expect that this prototype pump-fed DACS using non-toxic propellants will achieve system-level performance capabilities significantly in excess of current pressure-fed toxic propellant systems. The benefits of the non-toxic liquids stem from their greater safety and ease of handling, which is especially important for shipboard applications, where a high performance “safe” liquid DACS offers significant performance improvements over a solid DACS. The ease of handling results in shortened development cycle-times and lower development costs. However, if the more mature toxic propellants, such as hydrazine and nitrogen tetroxide are desired, we estimate that only small material changes and redesign would be needed to convert a functioning pumped non-toxic system into a pumped toxic propellant system.⁴ The engineering issues, for a transition from non-toxic to toxic propellants, are currently under investigation.

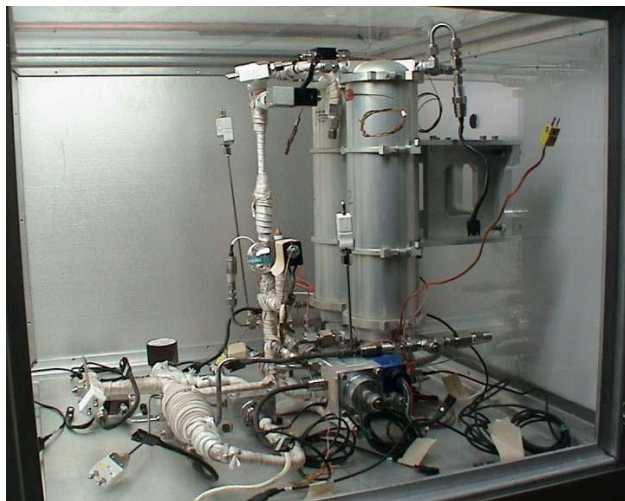


Figure 4. Breadboard Pump Test Station (BPTS). This is used for “unpackaged” component and subsystem development. The development station is fully instrumented to characterize temperature, flow, and pressure during an experiment.

Pump Development and Performance

Figure 4 shows a breadboard pump test station (BPTS) at LLNL. Current pump-pairs have been operated up to 10 Hz operational frequencies, and produced 655 g/s of HTP flow at 850 psi. This exceeded the original design goal of 0.5 kg/sec. DACS design evolution led us to consider half as many pumps, requiring double the flow rate, and we have now baselined a mass flow requirement of 1 kg/s at 1000 psi per pump-pair. Cumulated test time on the current design hardware, indicates it can operate far in excess of typical mission timelines. With a BPI KV propellant load of 18 kg and a mass flow of ~ 0.5 kg/s (for a single thruster firing), the pumps would empty the propellant tanks in less than 40 seconds. Current pumps have been operated for over 200 seconds without any failures, which is five-times that required. Design simplifications to the gas and fluid paths are currently underway to increase the volume/stroke and the operational frequency of the pumps. Figure 5 below shows a representative data run from the Breadboard Pump Test Station. The red trace (Δ) and green trace ($\circ$) are the gas drive pressures in the pump heads, and the blue line (at the top of the plot) represents the measured liquid pressure output from the pump pair. A schematic drawing of a pump-pair in operation is also shown.

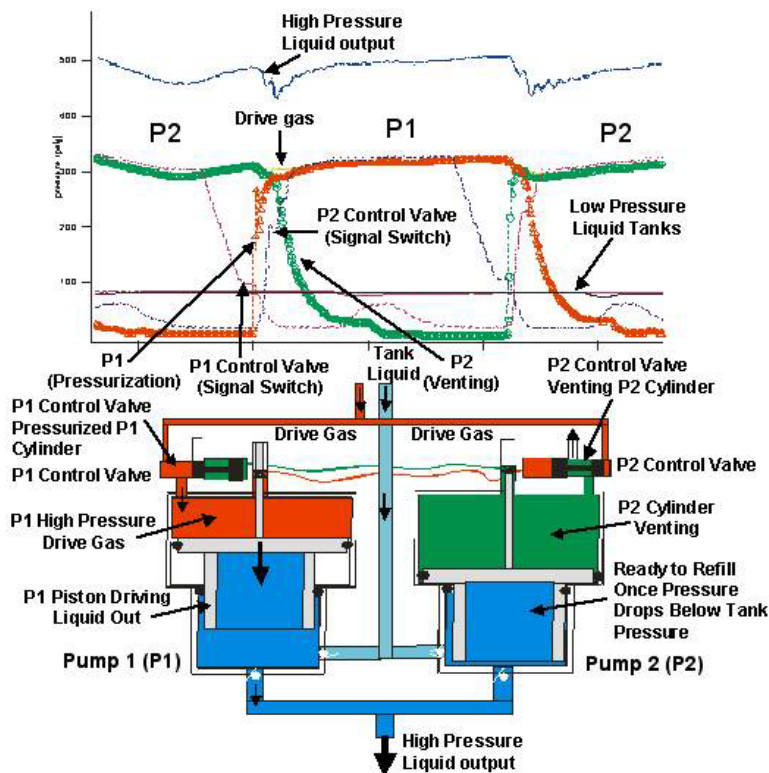


Figure 5. Shows the gas drive pressures {red (Δ) and green ($\circ$)} in the two pump heads that make up a reciprocating pump pair. The blue trace at the top is the boosted liquid output pressure of the liquid available to the divert thrusters. In this run the pumps boost the liquid pressure from 75 psi to ~ 500 psi.

Bi-propellant thruster development

General Kinetics, LLC (GK), has been under subcontract to LLNL to develop a series of bi-propellant thruster assemblies using hydrogen peroxide as the oxidizer and kerosene as the fuel. The thruster consists of a catalyst bed, fuel injector and combustion chamber/nozzle assembly that mate to the oxidizer and fuel valves. Peroxide is decomposed in the catalyst bed and the hot oxygen auto-ignites with the fuel and combusts in the chamber/nozzle assembly. Fast fuel valves supplied by Moog, Inc. were used in pulsed thruster testing at GK. This thruster development project successfully validated the catalyst bed and injector designs, and culminated in a 1115 N (250 lbf) (vacuum) bi-propellant thruster, that was tested during the August through November 2003 period. This is shown in Figure 6.⁷ Further light-weighting and design modifications for short-pulsed and higher temperature operation will be incorporated into the next thruster test-article. This thruster will be tested at GK and delivered to LLNL for use in an Axial Breadboard test apparatus. The Axial Breadboard (slated for operation by the end of FY04) will demonstrate all of the key components for a prototype DACS and is illustrated in Figure 7.

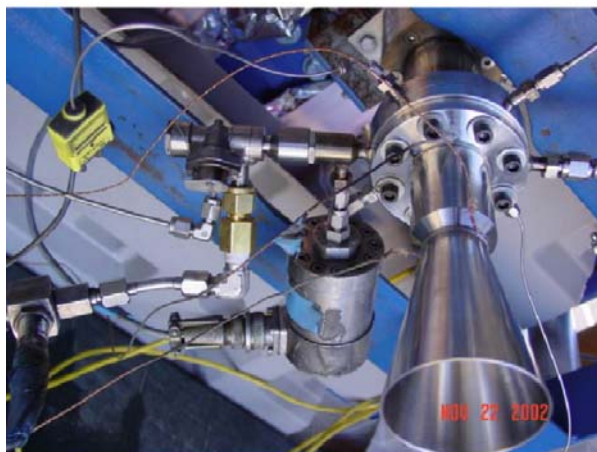


Figure 6. Bi-propellant thruster (~2-inch dia. nozzle) tested at General Kinetics, achieved bi-prop combustion with slow facility oxidizer valve, fast MOOG fuel valve, inconel- 625 chamber, no fuel and no ox purge, cat bed at flux of $\sim 1.0 \text{ lbm}/(\text{in}^2\text{-s})$ obtained combustion with O/F ~ 7.5 , Pchamber $\sim 475 \text{ psia}$, C* efficiency $\sim 93 - 94\%$, cat press drop $\sim 275 \text{ psia}$, roughness $< 1\%$ and start times $< 25 \text{ ms}$.

Axial Breadboard and Prototype DACS Design

The Axial Breadboard Figure 7, represents essentially one-half of the prototype DACS design and illustrates how a pump-fed propulsion system can also be used as a high mass fraction axial kick stage, which offers flexible on/off operation. The propellant tank, incorporates the non-toxic propellants 90% hydrogen peroxide and

kerosene in an optimum $\sim 7:1$ O:F mass ratio for this propellant combination. Due to the density differences in these propellants the O:F volume ratio, is $\sim 4:1$. The co-axial propellant tanks use pistons as the interface between the pressurization gas and the liquid propellants. The pistons match the shape of the inner tank end-caps to enable a very high percentage of liquid expulsion from the tanks $\sim 99\%$. The hydrogen peroxide oxidizer is located in the outer portion of the tank and an inner fuel tank carries the kerosene fuel. Separate tank end-caps are used to prevent any leakage path between the inner and outer tanks. Figure 8 shows the complete DACS core which shows the payload interface at the tank ends. The two pairs of pumps are located on the central bridge structure that holds the two co-axial tanks together. The bridge assembly will consist of a tubular structure with approximately the same diameter as the outer oxidizer tanks (full bridge structure not shown in these illustrations). This design approach results in a stiff tubular structure that spans the length of the DACS core, consisting of both outer propellant tanks and the bridge assembly. The pump-head assemblies are mounted equidistant from the four thrusters. Each oxidizer and fuel pump-head draws from both of their corresponding tanks simultaneously, which is expected to improve the passive balance capability of the system. Each pump pair supplies high-pressure liquid to an output liquid manifold (one for oxidizer and one for fuel) that feeds the four divert-thrusters (and an optional axial thruster, shown in Figure 9).

Preliminary Axial Breadboard Thruster Test Apparatus

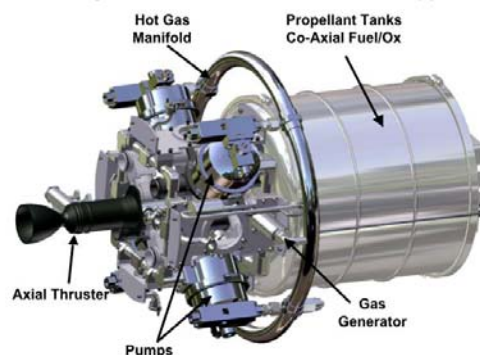


Figure 7. Illustrates the design of the Axial Breadboard Thruster Test Apparatus. This represents roughly one-half of a full DACS and incorporates all essential components in the DACS. This also illustrates how a pump-fed propulsion system could also be used as a high-mass-fraction KV kick-stage that can be flexibly started and stopped during operation.

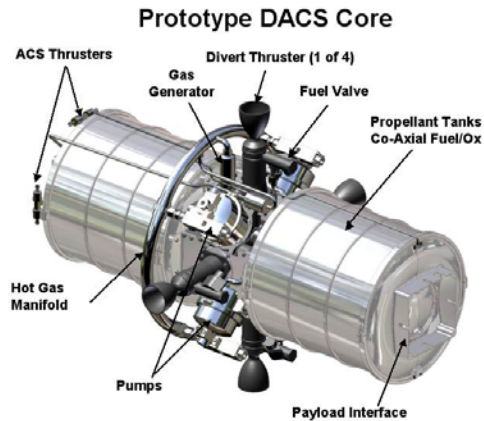


Figure 8. Preliminary design of the Prototype DACS core. The DACS contains four reciprocating pumps located between the four divert thrusters on a stiff bridge structure that carries the hydraulic system, plumbing, valves, regulators, gas generators, and lightweight tanks. Pump pistons are oriented towards the vehicle center-of-mass to minimize vibration. Payloads are mounted off the end-caps of the propellant tanks. Four ACS Thrusters pairs are used.

The hot gas drive is obtained by feeding ~10% of the oxidizer into a liquid regulator and gas generator. The gas generator is used to decompose the hydrogen peroxide into hot oxygen gas and steam (1000°F) at the liquid feed pressure. This high-pressure gas is used in the differential piston pumps to generate a pressure boost in the output liquid pressure that is then used in the gas generator circuit. The energy release and pressure boost, enable this system to operate in a "boot-strap" mode, which is able to start at the low liquid tank pressures (50-100 psi) and generate output liquid thruster feed pressures between 1000 - 1500 psi. As previously stated, this feature enables the liquid propellant tanks to be significantly lower in mass than those used in pressure-fed systems or in solid propellant DACS propulsion systems. The gas generator and pumps eliminate the need for high-pressure gas bottles and further reduce the mass of the DACS. This system also utilizes the warm drive-gas in the ACS reaction thrusters, and with a small step-down regulator, uses this gas to maintain a constant ullage pressure in the propellant tanks. The ability to use the oxidizer in this way allows for a very flexible propulsion system as opposed to a fixed allocation of cold gas for ACS.

Figure 9 illustrates the tanks-as-structure design concept, where the tanks form the central structure for the DACS and become the main-structure of the KV. This minimizes the structural mass of the vehicle. The front and rear payloads are directly integrated onto the tank end-caps and these are designed with the appropriate mechanical interfaces for the payload elements.

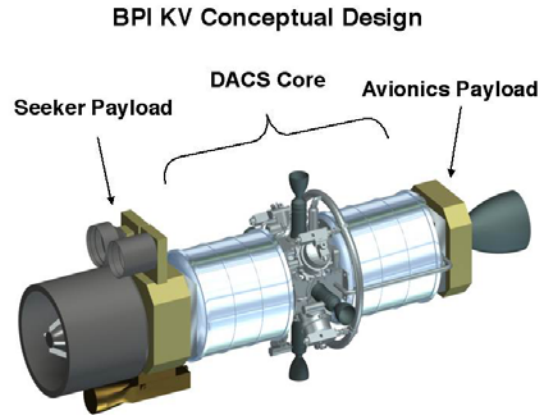


Figure 9. Illustrates the tanks-as-structure paradigm that is paramount in this design approach, where the tanks form the central structure for the DACS and become the main structure of the KV. Also illustrated is an optional axial thruster useful in BPI engagements.

Figure 9 also illustrates how a BPI KV could use an axial thruster for axial impulses throughout the KV fly-out. This feature enables the BPI KV to continuously track the boosting target while it generates the required Δv using both divert and axial impulses. In this design approach, the DACS is nearly mass-balanced, so only minor mass differences are allowed in the front and rear payloads. The KV's center-of-mass (both wet and dry) must be located in the divert-thruster-plane on the vehicle axis (the center of the bridge structure) in order to avoid any induced torques during divert thrusting. For small payload mass differences, the vehicle could be balanced by stretching the length of the mechanical interfaces on the lighter payload to provide an equal cantilever to the heavier payload. Alternately, trimming the mass differences by shifting some of the heavier payload's components (such as batteries) onto the surface of the propellant tanks, will hopefully minimize the need to add ballast-mass.

During DACS operation, if friction forces in the pistons cause any mass imbalance during propellant expulsion the propellants in the high-pressure manifolds can be directed back into any of the four propellant tanks (using small liquid valves). This can be used to rebalance the propellant load in the tanks, prior to the next series of divert pulses, which will minimize any thrust-induced angular jitter from any potential c.g. offset. This feature should maximize the KV's ability to observe and accurately determine the targets Line-of-Sight (LOS) rates for the required guidance commands to the DACS, even under very high lateral accelerations. We expect that only a relatively low ACS thrust-level ~5 to 15 N (~1 to 3 lbf) will be needed to maintain vehicle attitude control.

Air-Rail Testing

Air-Rail testing can wring out any technical issues relating to the integration of a pump-fed DACS to the design and development of a kill vehicle. The air-rail offers from 1DOF to 4DOF operation of the integrated DACS and a ground test vehicle, provides significant risk mitigation on vehicle operation and will provide a more seamless technology transfer to industry.

SUMMARY

Pumped propulsion potentially offers a significant improvement in both Δv and acceleration capability for kinetic kill vehicle systems and will be the enabling technology in boost phase intercept applications, especially for space-based interceptors. Prior developments utilized toxic propellants (hydrazine/nitrogen tetroxide) and supported smaller thrust levels (250 N divert thrusters). Efforts in non-toxic bi-propellants that utilize 90% hydrogen peroxide and kerosene, offer very high performance systems with $\Delta v = 2.5$ km/s and burn out accelerations of 10-g with total wet vehicle masses of 30 kg. LLNL has built small ground test vehicles and tested them on high fidelity air rail systems. These integrated tests enable the characterization of the DACS hardware to the greatest extent possible. Current component developments (pumps, warm-gas drive circuits and thruster/valves) are expected to enable higher thrust levels (1330 N) that are more consistent with the expected needs of an operationally capable BPI system. As a stepping stone to the prototype DACS under development, LLNL plans on demonstrating upgraded pumps, hydraulic circuit, and a medium weight non-toxic bi-propellant thruster, all packaged into an Axial Breadboard Thruster Testbed by the end of FY04. This testbed will demonstrate all of the key propulsion components that would later be incorporated into the prototype DACS during FY05. LLNL is prepared to continue to support MDA/AS in the development of a reciprocating pump-fed prototype DACS to bring this technology to required readiness levels and to transition it to industry.

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