High Performance Hybrid Upper Stage Motor

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Hybrid rocket propulsion is a tipping point technology in the sense that a small, short term investment could have game changing consequences in developing green, safe, affordable and high performance systems needed in future space missions. In order to demonstrate the advantages of hybrids most effectively, the effort should be concentrated on improving the Technology Readiness Level (TRL) of the technology for a carefully selected class of missions. Arguably upper stage motors used in small launch vehicles constitute a perfect platform for this purpose due their relatively small scale and high performance requirements. The advanced hybrid rockets that are being developed by SPG are believed to have the capability to deliver high performances desirable for upper stages, while retaining the cost, environmental and simplicity advantages of the classical hybrids. In order to demonstrate the performance capabilities of advanced hybrid rockets, a design study has been conducted to replace the Orion 38 solid rocket motor with a LOX/paraffin-based system. The LOX hybrids delivering the same level of total impulse as Orion 38 system are determined to be 15-18% lighter. It has been shown that switching to higher performance hybrid upper stages could lead to payload increases up to 40% for a typical launch vehicle. The additional cost, environmental, safety, stop/restart/throttling advantages are expected to make the hybrids desirable alternatives to the existing upper stage systems.

Nomenclature

\[
\begin{align*}
c* & : \text{ Characteristic velocity} \\
D_f & : \text{ Final port diameter} \\
D_i & : \text{ Initial port diameter} \\
\text{GITVC} & : \text{ Gas injection thrust vector control} \\
\text{LITVC} & : \text{ Liquid injection thrust vector control} \\
\text{LOX} & : \text{ Liquid oxygen} \\
\text{NTO} & : \text{ N}_2\text{O}_4 \\
\text{O/F} & : \text{ Oxidizer to fuel ratio} \\
R_f & : \text{ Port diameter ratio}
\end{align*}
\]

I. Introduction

Unlike the mature propulsion technologies (such as the solid and liquid rocket systems), which could only result in small incremental improvements, hybrids do have the potential
to become a game changing propulsion technology which could potentially lead to significant cost savings in a relatively short period of time. Building on the existing know-how, it is believed that developing advanced paraffin-based hybrid propulsion systems\textsuperscript{1} and \textsuperscript{2} to be used in a variety of NASA/DoD/commercial missions can be achieved with a relatively low level of effort. Due to the progress already made in the technology development and the inherently cost effective nature of hybrid motor testing, a small investment would lead to great advancements in this field.

SPG has been developing advanced paraffin-based hybrid rocket motors for the last 6 years under a contract from the Air Force Research Labs. Over the course the project great advances have been made in achieving a good level of understanding of the critical physical process that take pace in hybrid rocket motors. This understanding has been successfully utilized to build a set of scalable design tools for developing efficient and stable motors for which the inherent simplicity/safety of the hybrid systems could still be retained.

We believe that the first implementation of the advanced paraffin-based hybrid rocket technology should be to a smaller system such as an upper stage motor. Even though this technology is suitable for a wide range applications (including boosters, sounding rockets), the upper stage application mode/market makes more sense for the first implementation due to the following reasons:

- The high specific impulse performance of the liquid oxygen/paraffin-based hybrid rockets gives them a competitive advantage for upper stages which are known to be highly sensitive to this performance parameter.
- Upper stages are typically smaller pressure fed propulsion systems which makes them easier to develop compared to the heavier systems such as boosters used in medium/heavy launch vehicles.
- The technologies developed in this program can be adapted to the systems used in the suborbital space tourism, an emerging market with a large growth potential.

Key properties of some of the existing upper stage propulsion systems are listed in Table 1. Note that the solid rocket motors which are commonly used in small launch systems inherently have low Isp performance. Most LOX/kerosene based liquids operate at non-optimal O/F values, resulting in suboptimal Isp performance for this particular propellant combination. One exception is the Russian RD-58 engine which employs complicated technologies such as oxygen-rich gas generator. Note that despite their excellent Isp performance, LOX/H\textsubscript{2} engines are not ideal for small/medium size motors or air launch systems due to their poor density impulse performance along with the complicated operations associated with the hydrogen fuel. The storable NTO/hydrazine-based liquids have decent Isp performance and impulse density. However the toxicity and environmental unfriendliness of these propellants make the NTO/hydrazine-based liquids highly unpopular in modern systems. It is clear that an affordable and green upper stage system with reasonably good performance would be highly competitive with the systems listed in Table 1.
Table 1: Some of the existing upper stage propulsion systems.

<table>
<thead>
<tr>
<th></th>
<th>Propellants</th>
<th>Delivered Isp, sec</th>
<th>Launch System(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion 38</td>
<td>HTPB</td>
<td>289</td>
<td>Taurus/Pegasus</td>
<td>Low Isp</td>
</tr>
<tr>
<td>Orbus 21D</td>
<td>HTPB</td>
<td>293</td>
<td>Athena</td>
<td>Low Isp</td>
</tr>
<tr>
<td>Kestrel</td>
<td>LOX/Kerosene</td>
<td>324</td>
<td>Falcon 1E</td>
<td>Suboptimal</td>
</tr>
<tr>
<td>Scorpius Stage 3</td>
<td>LOX/Kerosene</td>
<td>323</td>
<td>Scorpius</td>
<td>Suboptimal</td>
</tr>
<tr>
<td>RD-869</td>
<td>UDMH/N2O4</td>
<td>317</td>
<td>VEGA</td>
<td>Toxic, Non US</td>
</tr>
<tr>
<td>RD-58</td>
<td>LOX/Kerosene</td>
<td>349</td>
<td>Proton</td>
<td>Non US</td>
</tr>
<tr>
<td>RL 10</td>
<td>LOX/H2</td>
<td>450</td>
<td>ATLAS V</td>
<td>Cryogenic</td>
</tr>
</tbody>
</table>

Development of a small upper stage hybrid motor is expected to be completed in a 2-3 year period and would require a relatively low level of investment (compared to the development of a comparable liquid or solid system). The advanced paraffin-based hybrids can also be applied to larger booster systems in the 250-1,000 klbs thrust range. However the higher development costs for these systems makes them a more risky first application for hybrids.

II. Advanced LOX/Paraffin-Based Hybrid Rocket Technology

The classical hybrid rocket systems suffer from two major shortcomings: 1) complex multiport fuel grains as a result of the poor regression rate performance of the classical polymeric fuels and 2) low frequency instabilities. In the past, the mitigation methods for these problem areas have introduced significant complexity to the motor design, compromising the simplicity advantage of hybrids. For example, the 250 klb thrust motor developed by American Rocket Company (AMROC) was based on a complex 15 port wagon wheel configuration (resulting in poor fuel utilization and expensive fabrication) and the motor stability was achieved by the continuous injection of a hazardous pyrophoric substance, triethylaluminum (TEA).

SPG’s paraffin-based/LOX hybrid rocket technology, which has an inherently high fuel regression rate, allows for the use of a simple single circular port fuel grain design approach. SPG has also developed a unique proprietary technology to eliminate the low frequency instabilities and acoustic instabilities in LOX-based hybrids without resorting to external heat or pyrophoric liquid addition at the fore end of the motor. These two technological advancements are crucial in keeping the hybrid concept cost effective, simple and safe compared to the state of the art liquid and solid rocket systems. The key virtues of the advanced LOX/paraffin-based motor technology and its impact at the systems level are summarized in Table 2.
Table 2: SPG’s enabling hybrid rocket technologies.

| Virtue                                      | Enabling Key Technology                  | Impact                                                        |
|---------------------------------------------|------------------------------------------|                                                              |
| Single Circular Port Design                 | Paraffin-based fuels                     | Simple, inexpensive grain                                     |
|                                             |                                          | High fuel utilization                                         |
| Adjustable fuel regression rate             | Fuel formulation tailored to mission     | Mission flexibility                                           |
| Stable and efficient combustion with no external heat or TEA addition | SPG proprietary injector/fore end design | High performance without compromising systems simplicity     |
| High Isp and impulse density                | Paraffin-based fuels and LOX             | Light and small systems                                       |
| Low cost, readily available propellants     | Paraffin-based fuels and LOX             | Reduced development and recurring costs                       |
| Simple motor design with no exotic materials| Advanced internal ballistic design and testing | Reduced costs and high reliability                           |
| Low environmental impact                    | Paraffin-based fuels and LOX             | Simplified operations and reduced costs                       |
| Safety                                      | Zero TNT equivalency                      | Ideal for manned systems                                      |
|                                             | Low fire hazard                           | Reduced development costs                                     |
| Throttling                                  | SPG proprietary throttling valve developed and tested | Mission flexibility                                         |
| Efficient gas phase combustion             | Tailored fuel grain technology            | Effective use of the pressurant as propellant                |
| Thrust vector control (TVC)*               | Liquid/Gaseous Injection Thrust Vector Control | Simple TVC capability                                     |

* This technology has been developed and demonstrated by AMROC and Whittinghill Aerospace.

Comparison to Other Chemical Systems:

The advanced LOX/paraffin-based hybrids have significant advantages over the solid rocket systems, some of which can be summarized as:

- Cost savings in motor development, manufacturing and launch operations: The savings stem from the inherent safety of the hybrid system and the simplicity of the motor fabrication which can be conducted even in light industrial zones. Transportation is also cost effective due to the non-hazardous classification of the paraffin-based motor. Currently SPG is shipping its motors to the test site using standard freight. Moreover the overall propellant cost for the paraffin-based/LOX system is at least an order of magnitude lower than the cost of a typical solid rocket propellant.
- Inherent safety in manufacturing, transportation, storage, testing and launch operation phases: One of the important implications of the zero TNT equivalency and motor shutdown capability of the advanced hybrid systems is the simplification of the range safety requirements which is known to be a major cost driver for launch systems.
Higher fault tolerance: Hybrids are not sensitive to cracks or debonding, eliminating the requirement for expensive quality control operations such as x-ray examination of the motor.

Environmental friendliness: Paraffin, its additives and LOX are all green and non-hazardous materials. Most high performance solid rockets contain ammonium perchlorate, a substance which presents hazard to the environment and shown to have adverse effects on human health\textsuperscript{4}.

LOX/paraffin-based hybrids have significant delivered Isp advantage (~35 seconds) over the solid rockets.

Hybrids can be throttled or can be shut down. This virtue introduces mission flexibility and improves the orbital insertion accuracy.

The primary disadvantage of the hybrid system compared to the solid rocket is its lower impulse density which results in a volume limited design approach for applications with strict geometrical envelope requirements.

Paraffin-based/LOX hybrids have also significant advantages over liquid rockets.

- Mechanical simplicity: Hybrids have significantly simpler liquid storage/feed systems and injectors (one liquid as opposed to two). Moreover no active cooling of the hybrid chamber is necessary, since it is protected by the fuel grain. The simplicity is expected to lead to significant cost savings.
- Structural mass fraction of a well designed LOX/paraffin-based system is expected to be better than a pressure fed LOX/RP-1 liquid rocket. Note that the pump fed liquid rockets are not expected to be cost effective for small propulsion systems.
- Hybrids are fault tolerant compared to liquids. The tolerance requirements on the machined parts can be much more relaxed in hybrids.
- Hybrids have reduced fire hazard compared to liquids.

III. State of the Advanced LOX/Paraffin-base Hybrid Rocket Technology

Under a contract from AFRL, SPG has been developing and testing advanced LOX/paraffin-based hybrid systems. The following is a summary of the important progress made in this ongoing program:

- Formulation and characterization of paraffin-based fuels with a wide range of internal ballistic properties. This effort included the development of mechanical and regression rate testing techniques for candidate fuel formulations. The ability to tailor the fuel formulation for a given set of mission requirements has also been achieved.
- Through formulation and improved motor design practices, paraffin-based fuel grains that can withstand the pressure/thermal/acceleration/handling loads have been developed.
Fuel processing technologies has been developed. SPG has now capability to cast grains up to 36 inches in diameter. Several 22 inch OD paraffin fuel grains (each weigh 1,540 lb) have been successfully fabricated using the existing facilities. Figure 1 shows a picture of the 22 inch diameter fuel grain and the casting facility.

Figure 1: 22 inch paraffin-based fuel and casting facility.

Close to 60 motor tests have been conducted using the 11 inch LOX motor, in the 7,000 lb thrust class. Figure 2 shows a picture of this motor during a firing in the Aerotec facility in Butte, MT.

A unique proprietary technology has been developed to eliminate the low frequency instabilities without resorting to heat addition or pyrophoric liquid injection at the fore end.

Methods have been developed and successfully implemented to eliminate the acoustic instabilities in hybrid systems.

Combustion efficiencies in the high 90’s have been consistently achieved in the 11 inch LOX motors.

A four axis composite winding machine has been acquired. This machine, which is capable of winding vessels up to 60 inches in diameter, has been used produce flight weight motors.

The 11 inch motor has been converted to a light weight carbon composite system. First firings using the flight weight motors have been successfully completed.

A scale up version of the flight weight system is currently being developed. The 22 inch diameter scale up motor will also use a carbon composite case.
Figure 2: 11 inch LOX/paraffin-based motor testing in the Aerotec facility in Butte, MT.

IV. Upper Stage Motor Concept

As stated earlier an upper stage motor is a suitable first application for the advanced hybrid rocket technology. Table 3 shows that once matured to high a TRL, advanced hybrids can be very competitive with the liquid and solid systems.

Table 3: Comparison of advanced hybrids to liquid and solid systems for upper stages.

<table>
<thead>
<tr>
<th></th>
<th>Propellant</th>
<th>Isp, sec</th>
<th>Examples</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid Motors</strong></td>
<td>HTPB/AP/Al</td>
<td>~290</td>
<td>Orion, Star</td>
<td>Low Isp, Safety, Environmental, Orbital Debris, Expensive</td>
</tr>
<tr>
<td><strong>Liquid Engines</strong></td>
<td>LOX/Kerosene</td>
<td>325-340</td>
<td>Kestrel, Scorpius</td>
<td>Complex, Expensive</td>
</tr>
<tr>
<td></td>
<td>N₂O₄/UDMH</td>
<td>~320</td>
<td>RD-869</td>
<td>Toxicity, Environmental, Expensive</td>
</tr>
<tr>
<td></td>
<td>LOX/H₂</td>
<td>~450</td>
<td>RL10</td>
<td>Low density, Expensive, Complex Operations</td>
</tr>
<tr>
<td><strong>Advanced Hybrid Motor</strong></td>
<td>LOX/Paraffin</td>
<td>~340*</td>
<td>NA</td>
<td>Low TRL</td>
</tr>
<tr>
<td></td>
<td>Nytrox/Paraffin</td>
<td>~310*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* estimated based on measured c* efficiencies

The key objectives of an upper stage project would be

- Develop a cost effective, safe, high performance, mission flexible, environmentally friendly upper stage motor series that can be used as
Upper stage for small launch vehicles
Trim stage for medium launch vehicles
In-orbit propulsion for satellites
Propulsion for deorbiting
In-space propulsion for NASA, ESA, JAXA missions
- Demonstrate the high performance and the other key virtues of the advanced hybrid rocket propulsion technology.
- Develop a marketable product using SPG’s advanced hybrid rocket technologies.

If the targeted price point is achieved, the upper stage hybrid is expected to capture a significant percentage of the following market segments

- Second stage for low cost nanosat launch systems
- Upper stage for horizontal takeoff two stage to orbit systems
- Upper stage for small launch vehicles
  - Taurus, VEGA …
- In-space and in-orbit motors

V. Hybrid Combines the Worst of Two Worlds?

It is often claimed that hybrids combine the low performance of a solid rocket and the complexity of a liquid engine. While this statement could certainly be true for a poorly designed hybrid (like any other system), it is NOT universally valid. A well designed hybrid could
- Deliver Isp performance much better than a solid (up to 35 seconds of improvement)
- Be much simpler than a liquid
  - Fault tolerance
  - No active cooling
  - Reduced plumbing/simpler injector

These advantages with the additional benefits such as inherent safety, easy throttling and environmental cleanliness make well designed hybrids highly desirable alternatives to the existing chemical systems.

VI. How to Make Hybrids Competitive?

For hybrids to be competitive with the existing liquid and solid rocket systems, they need to have equal or better performance while retaining their simplicity, low cost and safety advantages. The diagram shown in Figure 3 summarizes the key components needed to make hybrids viable alternatives to the existing chemical systems. Note that some of these virtues are competitive in nature such as the performance and simplicity while the others are complimentary such as simplicity and low cost.
Figure 3: Features necessary to make hybrids competitive.

In the following paragraphs two of these factors, high performance and low cost, will be discussed in detail.

Performance Drivers:

A quick examination of the rocket equation reveals that both the specific impulse and structural mass fraction are important parameters to achieve high performance (i.e. high delta V for a given gross mass and payload mass). A design/optimization effort that concentrates on only one of these two factors will most likely result in a suboptimal solution.

Specific Impulse:

The primary drivers for good specific impulse performance are outlined in Figure 4. Clearly selecting propellants with good theoretical performance is critical. Note that due to its excellent hydrogen to carbon ratio (in the class of all hydrocarbons fuels), the Isp of neat paraffin wax is fairly good. Metal and/or metal hydride additives can be included in the fuel formulation to further improve the performance. Since almost all of these performance additives are in solid phase at ambient conditions, they can be easily blended into the solid matrix resulting in the improved theoretical performance for hybrids over the liquid systems††. Moreover paraffin waxes are hydrophobic and metal hydrides that are sensitive to moisture can be safely used in paraffin-based binders. The vacuum Isp for the paraffin and paraffin/40% AlH$_3$ systems (for a chamber pressure of

†† The addition of powders into the liquid fuel can only be achieved by a significantly increase in the systems complexity.
500 psia and a nozzle expansion ratio of 70) are plotted as a function of O/F for a number of oxidizers in Figure 5. Note that theoretical Isp values up to 380 seconds are feasible with the LOX oxidizer.

Figure 4: The drivers for the specific impulse parameter.

Figure 5: Vacuum specific impulse as a function of O/F for various hybrid propellant combinations. Nozzle expansion ratio is 70. Equilibrium flow.

The performance for a number of propellant combinations (at their optimum O/F) is plotted in the density impulse/specific impulse plane in Figure 6. As stated before hybrids outperform the hydrocarbon based liquid rockets due to the easy inclusion of solid performance additives.
Achieving high combustion efficiencies is essential for developing high performance hybrid rocket motors. Note that $c^*$ efficiencies in the high 90’s have been consistently achieved in the LOX/paraffin motors fired at the 11 inch scale. Due to the improved residency times, the good efficiency performance is expected to persist at larger scales.

Since the chamber cooling or motor stability is not strongly affected by the motor O/F as it is in a liquid engine, hybrid motors can be operated at the optimum O/F. For example the F1 engine developed for the first stage of the Saturn V moon rocket operated at an O/F of 2.27 where the O/F corresponding maximum $I_{sp}$ takes place approximately at 2.7 for the LOX/RP-1 system. This inability to run at optimum O/F could lead to 20 seconds of decrement in the $I_{sp}$ performance for an upper stage motor.

In a hybrid motor, even for constant oxidizer flow rate, the O/F shifts in time due to the opening of the fuel port diameter. As an example, the O/F variation predicted during the operation of SPG’s 11 inch LOX/paraffin motor is shown in Figure 7. The fact that the instantaneous O/F is different from the optimum mixture ratio during most of the motor burn, results in a reduction in the effective $c^*$ efficiency for the motor. The $c^*$ efficiency drop due to O/F shift can be calculated as a function of the mass flux exponent of the regression rate law ($n$), ratio of the final to initial port diameters ($R_f = D_f / D_i$) and the average O/F of the motor. The $c^*$ efficiency due to O/F shift can be estimated by taking the ratio of the $c^*$ calculated by averaging over the entire burn and the $c^*$ value calculated at the average O/F of the motor.
Figure 7: O/F shift as a function of time during a typical operation of the 11 inch LOX/paraffin-based motor.

The O/F shift efficiency for the paraffin/LOX system (which has a flux exponent of 0.62) is plotted against the average O/F for various diameter ratio, $R_f$, values in Figure 8. As can be deduced from Figure 8, for $n$ exponents typical for paraffin-based systems, $c^*$ efficiency due to O/F shift is negligible. The effect of the shift increases as the flux exponent $n$ deviates more from the critical value of 0.5 for which the motor operates at a constant O/F. In fact, for the Nytrox$^5$/paraffin-based propellant combination, the flux exponent is 0.5 and there is no O/F shift. Figure 8 also shows that, at low mean O/F values, an increase in efficiency due to O/F shift is plausible.

Figure 8: Effect of average O/F on the inefficiency caused by O/F shift.

The final driver that significantly affects the Isp performance is the nozzle erosion rate. The primary issue associated with the nozzle erosion is due to the reduction of the nozzle
expansion ratio over time. Selection of suitable ablative materials for the nozzle throat is critical for the development of high performance systems.

**Structural Mass Fraction:**

Even though the structural mass fraction is primarily dictated by mechanical design and material selection for the major components, the following strategies unique to hybrid rocket systems are extremely critical in achieving good performance (listed in Figure 9)

- Multiport design should NOT be adapted for the fuel grains.
- Stability fixes should NOT include any external heating (i.e. with small hybrids) or injection of pyrophoric liquids.
- For pressure fed systems GOX pressurization should be employed and a large fraction of the pressurant should be combusted in the motor.

![Figure 9](image)

**Figure 9:** The drivers for the structural mass fraction.

The unburned fuel mass fraction is a very critical parameter that controls the ability for a hybrid system to deliver high performance. It can be shown that the high fuel sliver fractions typically observed in multiport hybrids are equivalent to a large reduction in the effective Isp of the system. A sample calculation has been conducted for a LOX system operating at optimal O/F. A baseline structural mass fraction with no fuel sliver is assumed to be 0.13. The results of this exercise are demonstrated in Figure 10 and 11. As shown in Figure 10, the equivalent Isp reduction for a typical multiport system can be as large as 25 seconds for a demanding mission. For a mission requiring 4,000 m/sec of delta V, each percent of unburned fuel roughly corresponds to a 0.5 percent reduction in combustion efficiency. As shown in Figure 10 and 11, the effective Isp (or efficiency) reduction due to sliver fraction in a single circular port hybrid is negligible. These results clearly prove that the multiport hybrids, which typically have fuel sliver fractions in the 10-15% range, are NOT suitable for missions requiring high performance.
Recurring Cost Drivers:

The following drivers should be considered to minimize the recurring cost of a hybrid rocket motor (at a given impulse class):

- Gross Mass: Everything else being equal, a system that weighs more will cost more.
- Number of fluids: The complexity of a system increases with the number different liquids involved. It would be helpful to minimize the number of fluids for keeping the cost levels low.
• Propellant cost: Per pound cost of the propellant could be a critical driver especially for systems using expensive propellant components such as hydrazine.

• Processing/fabrication: The following are the critical factors that influence the fabrication costs:
  o Fault tolerance
  o Process hazard
  o Parts complexity
  o Ease of machining for the selected materials

• Hazard class: Hazard class significantly influences the systems cost.
  o Toxicity of the propellants
  o Chemical stability of the propellants
  o Fire hazard
  o Corrosiveness of the propellants

• All complexity drivers such as 1) multiport grain design or 2) need for an external heat source would also drive the cost of system.

• Materials selection: Use of exotic metals, expensive ceramics or plastics should be avoided if possible.

The cost drivers for the advanced hybrid rocket systems are evaluated in Table 4. The lack of cost drivers (with the exception of AlH₃ for the high performance option) for the advanced hybrids indicates that these systems are expected to be highly cost effective.

**Table 4: Cost driver evaluation for advanced hybrids**

<table>
<thead>
<tr>
<th>Cost Driver</th>
<th>Advanced Hybrids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driver</td>
</tr>
<tr>
<td>Number of Fluids</td>
<td>Oxidizer and pressurant</td>
</tr>
<tr>
<td>Propellant Cost</td>
<td>AlH₃ is an expensive additive</td>
</tr>
<tr>
<td>Processing/Fabrication</td>
<td>Solid performance additives complicates fuel casting</td>
</tr>
<tr>
<td>Hazard Class</td>
<td>Cryogenic hazard for LOX</td>
</tr>
<tr>
<td>Motor Complexity</td>
<td>NA</td>
</tr>
<tr>
<td>Materials Selection</td>
<td>NA</td>
</tr>
</tbody>
</table>
**VII. Systems Calculations – Orion 38 Replacement**

A systems/optimization study has been conducted to evaluate the performance of a series of paraffin-based hybrid rocket concepts as replacements for the solid rocket motor Orion 38 (see Figure 12). This motor, which is manufactured by ATK, is selected in this study since

- It is currently used in a wide range of launch vehicles including Pegasus, Taurus and Minotaur.
- It is a state of the art solid rocket system.

Some of the important properties of the Orion 38 motor are listed in Table 5.

**Table 5:** Summary of data for the Orion 38 solid rocket.

<table>
<thead>
<tr>
<th>Motor</th>
<th>Orion 38</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Total Impulse, lb-sec</td>
<td>491,000</td>
</tr>
<tr>
<td>Burn Time, sec</td>
<td>67.7</td>
</tr>
<tr>
<td>Outside Diameter, in</td>
<td>38.0</td>
</tr>
<tr>
<td>Average Chamber Pressure, psia</td>
<td>572</td>
</tr>
<tr>
<td>Average Nozzle Area Ratio</td>
<td>49.3</td>
</tr>
<tr>
<td>Length, in</td>
<td>53.0</td>
</tr>
<tr>
<td>Gross Mass, kg</td>
<td>1,967</td>
</tr>
<tr>
<td>Structural Mass Fraction</td>
<td>0.124</td>
</tr>
<tr>
<td>Delivered Isp, sec</td>
<td>289.0</td>
</tr>
</tbody>
</table>

**Figure 12:** Orion 38 motor (from Ref. 6)

In the design process, the total impulses of the hybrid systems have been matched to the Orion 38 value. Total impulse matching is preferred over delta V matching, since the latter requires the arbitrary selection of a payload mass. The burn times for the hybrids have been increased to 120 seconds in order to minimize the component weights and also to reduce the acceleration loading on the payload. Even though a formal optimization on the burn time has not been conducted, it has been determined that the system gross mass
was fairly flat within the burn time range of 100-200 seconds. A burn time close to the lower end of this range has been selected to minimize the heat loading on the motor internal components.

The overall diameter for the LOX based systems have been kept below the diameter of the Orion 38 system. For the Nytrox based system this arbitrary assumption has been relaxed. The gross mass and the overall length of the hybrid systems are left free to change to meet the desired performance requirements.

Several propellant combinations have been considered in the study for comparison purposes:

1) LOX/Paraffin: This is the baseline propellant combination using the high performance cryogenic oxidizer. In order to keep the recurring and development costs low, no performance additives have been included in the fuel.

2) LOX/Paraffin-20% AlH$_3$: In this variation 20% AlH$_3$ (by mass) in the powder form has been included in the fuel in order to improve the specific impulse and the density impulse performance of the system. Note that the hydrophobic nature of the paraffin binder allows for the safe operation with the water sensitive metal hydrides.

3) Nyrox80/Paraffin-20% Aluminum: This is a storable (days on the launch pad) but lower performance system. Note that the temperature of Nytrox is selected to be -80 C. 20% aluminum powder (by mass) has been included in this variation in order to a) improve the Isp performance, b) densify the fuel and c) increase the regression rate of the fuel. In order to minimize the material and processing costs low, an aluminum powder with micron sized particles has been selected over the nano sized aluminum powder.

Note that only nontoxic, environmentally green, low cost, chemically stable and readily available (with the possible exception of AlH$_3$) propellants have been considered in this investigation. For simplicity the oxidizer mass flow rate is assumed to be constant in time. Throttling can easily be implemented, if it is required for a certain class of missions.

Due to the relatively small scale of the motors, all hybrids included in this study are selected to be pressure fed systems. It is determined that the details of the pressurization system design on the system performance are critical. Nytrox systems are partially self-pressurized. They start at high pressures but in the blow down mode they lose pressure at a fast rate, since oxygen is expected to come out of solution rather slowly. Thus they require a supplementary pressurization system. This can be achieved either by helium or gaseous oxygen. The advantage of helium is its lightness. However helium is a limited natural resource and it has become quite expensive and inaccessible in recent years. This trend is expected to get worse in the upcoming years. The other alternative is to use gaseous oxygen as the supplementary pressurant for the Nytrox systems. For such a system, at the end of the liquid burn most of the vapor is composed of oxygen (typically more than 90%). Note that the optimal oxidizer to fuel ratio for the oxygen paraffin system is around 2.5 as opposed to 8 in the case of N$_2$O. As discussed above, the sudden reduction of oxidizer flow rate in transition to the vapor phase, which results in a
significant drop in the oxidizer to fuel ratio, is ideal for an oxygen/paraffin hybrid. It is shown by motor tests that the combustion process in this GOX hybrid operating close to its optimum O/F can be sustained much more readily than the combustion with the pure N₂O vapor (also note that oxygen is a much more energetic oxidizer). SPG’s extensive experience with gaseous oxygen/paraffin hybrids indicates that the oxygen rich gas phase combustion mode is expected to be stable and efficient. Based on these arguments, we have included the contribution of the gas phase combustion to the total impulse. The high efficiency gas phase combustion in oxygen pressurized Nytrox systems has been demonstrated in motor testing.

Gaseous oxygen is selected as the pressurant gas also for the LOX motors. Note that combustion of the gaseous pressurant in the hybrid motor chamber is also feasible in the LOX based systems.

The systems calculations have been conducted using SPG’s hybrid vehicle design code. Since the complicated mission requirements have been replaced by the simple total impulse matching on the propulsion system, the flight modules have been disabled. The structural mass fraction is estimated within the code using the preliminary design equations for the major components such as the oxidizer tank, combustion chamber, pressurization system and nozzle. Available mass data have been used for small components such as valves, regulators and ignition system. A mass margin of 20% has been added to the calculated structural mass. The code outputs all of the relevant performance, weight and geometrical parameters which are summarized in Tables 6 and 7 for the systems considered in this study. For simplicity, the cost function for the optimization process is taken to be the gross mass of the motor. Note that for an upper stage system any reduction in the gross mass corresponds to an increase in the payload mass for a given delta V requirement.

The oxidizer tank material selected for the Nytrox system is aluminum lined carbon-epoxy. For the LOX systems three tank materials have been considered in this investigation: 1) Low cost option: Al 2219, 2) Al 2195- Weldalite and 3) linerless composite. The combustion chambers are made out of graphite-epoxy composite with a thermoset liner.

For the cryogenic LOX system, an insulation thickness of 0.5 inches has been used in the calculations. For the Nytrox system the insulation thickness of 0.2 inches has been determined to be adequate even for long storage periods on the launch pad.

In order to simplify the fabrication process and minimize the fuel sliver fraction, all motors are designed to use a single circular port fuel grain. The initial mass flux selection is based on the limitations on the port Mach number and the hoop stresses that occur on the port surface due to internal pressure loading. The thickness of the motor insulation liner is 0.2 inches for all systems. A fuel sliver thickness of 0.1 inches has been assumed at the end of the burn. This corresponds to a fuel utilization of 98% or better for the systems considered in this study. Note that the small sliver fractions have been successfully demonstrated in paraffin-based hybrid motor testing.
The nozzles are made out of ablative silica phenolic inner shell and a structural outer shell made out of glass phenolic. An erosion rate 0.005 in/sec has been assumed at the reference chamber pressure of 300 psi. A linear variation for the erosion rate is assumed with the chamber pressure. Moderate variations in the erosion rate are not expected to affect the system performance appreciably.

For systems with no performance additives, the $c^*$ and nozzle efficiencies are assumed to be 0.96 and 0.98, respectively. For the systems utilizing fuel grains with Al or AlH$_3$ additives, the nozzle efficiency is reduced to 0.97 to account for two phase losses. Note that the assumed combustion efficiencies have been demonstrated in motor testing conducted by SPG. An injector pressure drop of 70 psi is assumed for all motors.

Another key advantage of the hybrids over solid systems is related to the fact that, in a hybrid motor, the chamber pressure can be used as a free parameter in the optimization process due to the lack of pressure dependency of the regression rate. Since chamber pressure can be selected independent of the internal ballistic considerations, more effective optimization is possible (essentially one of the constraints is lifted). The other parameters included in the optimization process are O/F and nozzle expansion ratio.

In the baseline configuration, as shown in Figure 13, a total of 8 cylindrical tanks have been used parallel to the combustion chamber. This particular scheme is selected to minimize the overall system length and diameter of the motor. A total of 4 spherical pressurization tanks have been used in the baseline design. The liquid oxidizer is fed into the motor by the use of dip tubes in each tank. Note that dip tubes are commonly used in the ground testing of hybrid rocket motors.

Figure 13: Baseline motor configuration: Cylindrical tanks in parallel with the chamber.
A variant of the baseline design uses one torroidal oxidizer tank as opposed to 8 cylindrical tanks (Figure 14a). Even though the torroidal tanks are heavier and more expensive than the cylindrical tanks, for missions requiring compactness this design could be beneficial.

Finally, if the length is not a critical constraint, a system that uses a single spherical tank in series with the combustion chamber could be used (Figure 14b). This long configuration is the most efficient structural design due to the use of a single spherical tank for oxidizer storage.

The general properties of the optimum Orion-38 replacement motors are summarized in Table 6. As shown in Table 6, despite their reduced chamber pressures, all systems, deliver a significantly better Isp than the Orion-38 system. The Isp for the LOX motors are significantly higher. The structural mass fractions (stage burn out mass over the stage gross mass) of the replacement systems are in the 0.120-0.139 range. This range covers the reported Orion-38 value. Note that hybrids optimize at much lower chamber pressure levels (200 psia). As expected, the systems using tanks made out of Weldalite and linerless carbon composite have lower structural mass fractions.

![Figure 14: Optional motor configurations: a) Torroidal tank, and c) Spherical tank in series.](image)

The propulsion system weights for all systems are listed in Table 6 for the Orion-38 replacement. Note that all hybrids are distinctly lighter than the Orion-38 motor. Specifically the LOX based systems are 15.2-18.1% lighter and the Nytrox based system
is 8.9% lighter. The weight distribution for the major components is shown in Table 7. The “other mass” category reported in Table 7 includes small components such as valves, regulators, piping and structures.

The overall lengths and diameters of the hybrid systems are also included in Table 6. Note that all systems are longer than the solid motor due to the low effective density of the hybrid propellants. The shortest of all the systems considered in this study is the aluminized Nytrox80/paraffin motor. All LOX based systems are slightly longer than the Nytrox option. In this study no effort has been made to minimize the length of the replacement hybrid systems. We believe that substantial reduction in length is feasible with small penalty in the vehicle gross mass (the gross mass is very flat around the optimum point).

### Table 6: Properties of the systems considered in the systems study.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Weldelite Tank</th>
<th>Composite Tank</th>
<th>High Performance</th>
<th>Storable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Propellant</strong></td>
<td>LOX/Paraffin</td>
<td>LOX/Paraffin</td>
<td>LOX/Paraffin</td>
<td>LOX/Paraffin-20% AlH&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Nytrox80/Paraffin-20% Al</td>
</tr>
<tr>
<td><strong>Oxidizer Tank Material</strong></td>
<td>Al 2219</td>
<td>Al 2195-Weldalite</td>
<td>Linerless Composite</td>
<td>Al 2195-Weldalite</td>
<td>Al Lined Composite</td>
</tr>
<tr>
<td><strong>Average O/F</strong></td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.2</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>Chamber Pressure, psia</strong></td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td><strong>Initial Nozzle Area Ratio</strong></td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td><strong>Burn Time, sec</strong></td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td><strong>Effective Isp, sec</strong></td>
<td>338.0</td>
<td>338.0</td>
<td>338.0</td>
<td>343.1</td>
<td>310.1</td>
</tr>
<tr>
<td><strong>Overall Length, in</strong></td>
<td>106.6</td>
<td>106.6</td>
<td>106.6</td>
<td>107.3</td>
<td>82.8</td>
</tr>
<tr>
<td><strong>Overall Diameter, in</strong></td>
<td>37.2</td>
<td>37.1</td>
<td>37.1</td>
<td>35.6</td>
<td>45.5</td>
</tr>
<tr>
<td><strong>Structural Mass Fraction</strong></td>
<td>0.139</td>
<td>0.126</td>
<td>0.120</td>
<td>0.121</td>
<td>0.126</td>
</tr>
<tr>
<td><strong>Gross Mass, kg</strong></td>
<td>1,668</td>
<td>1,644</td>
<td>1,633</td>
<td>1,610</td>
<td>1,792</td>
</tr>
<tr>
<td><strong>Gross Mass Decrease, %</strong></td>
<td><strong>15.2</strong></td>
<td><strong>16.4</strong></td>
<td><strong>17.0</strong></td>
<td><strong>18.1</strong></td>
<td><strong>8.9</strong></td>
</tr>
</tbody>
</table>

In order to quantify the payload increase caused by switching to high performance hybrid motors for the upper stage, a launch vehicle resembling the Pegasus system is used as an example. Orion 50S and Orion 50 motors are used as the first and second stages, respectively. For the baseline system, Orion 38 has been used as the upper stage motor. For the all solid launch vehicle, the payload capability has been estimated as a function of mission delta V and plotted in Figure 15. Similar calculations have been conducted using the hybrid replacements instead of the Orion 38. For simplicity we have limited the study to two hybrid motors: 1) baseline LOX/paraffin and 2) high performance LOX/paraffin-20% AlH<sub>3</sub>. The first two stages are kept the same for all calculations.
The payload mass is plotted as a function of mission delta V in Figure 15 for launchers using the hybrid upper stage. As shown in the figure the payload capability for the hybrids are significantly higher than the solid based system. The high performance hybrid system delivers a slightly more payload compared to the baseline LOX/paraffin motor. Figure 16 contains a plot of the percent payload mass increase over the Orion-38 solid motor as a function of mission delta V. Note that substantial payload increases has been achieved especially for demanding missions requiring large delta V performance (i.e. 40% payload increase at a mission delta V of 9,500 m/sec).

**Table 7:** Mass breakdown for the hybrid systems considered in the study.

<table>
<thead>
<tr>
<th>System</th>
<th>Baseline</th>
<th>Weldelite Tank</th>
<th>Composite Tank</th>
<th>High Performance</th>
<th>Storable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion System Mass, lb</td>
<td>1,668</td>
<td>1,644</td>
<td>1,633</td>
<td>1,610</td>
<td>1,792</td>
</tr>
<tr>
<td>Structural Mass, lb</td>
<td>231.9</td>
<td>207.5</td>
<td>196.6</td>
<td>194.9</td>
<td>226.6</td>
</tr>
<tr>
<td>Tank Mass, lb</td>
<td>67.1</td>
<td>47.2</td>
<td>38.4</td>
<td>37.0</td>
<td>74.9</td>
</tr>
<tr>
<td>Chamber Mass, lb</td>
<td>46.1</td>
<td>46.1</td>
<td>46.1</td>
<td>46.7</td>
<td>28.2</td>
</tr>
<tr>
<td>Pressurization System Mass*, lb</td>
<td>17.2</td>
<td>17.2</td>
<td>17.2</td>
<td>16.3</td>
<td>20.1</td>
</tr>
<tr>
<td>Nozzle Mass, lb</td>
<td>32.6</td>
<td>32.6</td>
<td>32.6</td>
<td>32.6</td>
<td>37.3</td>
</tr>
<tr>
<td>Other Mass, lb</td>
<td>29.5</td>
<td>28.9</td>
<td>28.6</td>
<td>28.9</td>
<td>27.1</td>
</tr>
<tr>
<td>Margin, lb</td>
<td>39.5</td>
<td>35.5</td>
<td>33.7</td>
<td>33.3</td>
<td>39.0</td>
</tr>
</tbody>
</table>

*Excluding burned gas mass

**Figure 15:** Payload mass as a function of mission delta V for three different upper stage motors.
VIII. Risks and Technical Challenges

As in any new technology, challenges and risks exist in the implementation of the advanced hybrid rockets to an actual flight system. The two high risk areas are identified as 1) Retaining high efficiencies and good stability for long duration burns and 2) controlling/limiting the nozzle erosion rates.

Improved technologies are needed in the following areas:

- Nozzle development
- Vacuum ignition and multiple ignitions
- Throttling
- LITVC or GITVC capability

IX. Conclusions

The following general conclusions can be drawn from this study:

- Hybrid rockets are a tipping point technology. A small investment could make a big difference in the field of chemical rocket propulsion. In the case of matured solid and liquid technologies, improvements are expected to be gradual.
- A well designed hybrid can deliver good performance while retaining its inherent simplicity, safety and cost advantages.
- It would be beneficial to develop a high performance system to demonstrate the capability of advanced hybrids. An upper stage motor is an ideal application.
• The advanced hybrid rockets designed as replacements for the Orion 38 solid rocket motor are appreciably lighter than the solid motor.
• A simple launch vehicle calculation revealed that the use of hybrid upper stages instead of the Orion 38 motor could results in substantial increases in the payload capability. Improvements of 40% or higher are possible for demanding missions.

References