The Case for Liquids
A feasibility study

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November 25, 2015

Abstract

Discusses the practicability of a CUSF Liquid-Fuelled Motor project, and techniques and approaches which might help to bring the difficulty thereof within realistic levels.

1 Rationale

The advantages of liquid systems over solid rockets are evident: the ability to terminate thrust on command simplifies abort modes, there may be a throttle capability (giving system flexibility), and the rocket can achieve much longer burn times than a solid, which reduces aerodynamic loads (as the acceleration takes place in thinner air) as well as acceleration loads. While it is commonly considered that liquid fuels also offer higher specific impulse, this may not be the case when there is a requirement for fuels which are easy to handle (low toxicity, etc.), which would presumably be necessary for a CUSF project.

But these advantages are, largely, shared by the hybrid motor, as already being worked on by CUSF. What, then, do liquid fuels offer that hybrids do not?

The challenges in developing the two types of motor are very different in nature. While a hybrid is not a complex design, making it actually work can be a finicky business. CUSF's first Quasar was difficult to ignite, and when it did so the exhaust contained large particles of unburnt fuel, which drastically lowers performance. Moreover, a hybrid, like a solid, inherently requires a large pressure vessel, and *unlike the pressurised tanks which may be required by a liquid fuelled system*, this pressure vessel is exposed to hot combustion gases. The combustion chamber of a liquid-fuelled motor is much smaller, and can more easily be regeneratively cooled by the propellant.

There are, of course, difficulties for liquid-fuelled motors; they are merely different ones. But they have a different character: while a hybrid is easy to make but hard to make *work*, a liquid motor has a lot of components to design and problems to consider, but once these have all been addressed the finished article is much more likely to function correctly.

2 Propellants

There are a wide variety of safe, nontoxic liquid propellants that could be used. Potential fuels include light hydrocarbons and alcohols; for oxidisers the nitrous oxide used in Quasar remains an option. However, the design of the motor can be considerably simplified if a hypergolic combination is used, or if ignition can be simplified by exothermic decomposition of one propellant. For this reason, systems based on hydrogen peroxide are attractive, particularly if they can be made to work with fairly low concentration peroxide. For example, the approach of dissolving a catalyst in the fuel to make it hypergolic with peroxide may be workable even with commercial-grade (circa 30%) *stabilised* peroxide, although some experiments would be needed to verify this. My favourite combination is iron (II) chloride dissolved in tetrahydrofuran, an industrial solvent, but there are plenty of other options here.

A further advantage of hypergolic fuels is that they are in some respects safer, as in the event of an explosion they will be quickly blown away from each other by their reaction, preventing an intimate mixture from forming and reducing the proportion of the fuel which is burnt. (This, incidentally, is why Project Gemini was able to use ejector seats rather than a launch escape tower, the Titan II being hypergolically fuelled.)

However, if hypergolic propellant development is considered too high-risk, it would still be possible to use conventional propellants along with an igniter system; there are several igniter options, such as pyrotechnic, spark, or pyrophoric (a.k.a. hypergolic starting slug -

though this last does involve somewhat hazardous chemicals, they are used in much smaller quantities than the main propellants).

It is likely that finding a suitable propellant combination will be the least of our worries; moreover, a rocket motor that doesn't depend on any special properties of its propellants often needs little modification to run on a different combination. (For example, the hydrolox RL10 has been successfully run - with only minor modifications - on LOx/CH_4; they've also tried it with propane, flox, and LF_2. It can handle all these because it's a simple, robust engine, with a fairly low chamber pressure and a nice uncomplicated expander cycle.) So we shouldn't worry too much about propellants just yet.

2.1 A short digression on hydrogen peroxide

The danger of High Test Peroxide comes from being above a threshold, about 67% concentration, where the energy released in decomposition exceeds that needed to vapourise the substance, thus allowing runaway thermal decomposition. This is also a necessary condition for *monopropellant* use, including use in a catalytic gas generator for pump drive; but it is *not* necessary when burning with another fuel, as the fuel-oxygen reaction releases additional energy; it is also not necessary for the thermal decomposition expander cycle, where the extra heat comes from regenerative cooling of the engine. As long as you don't care about the performance impact, watered-down peroxide is fine. (And, by the way, even the concentrated stuff isn't nearly as dangerous as some people would have you believe - see [6] - so while HTP is probably still not suitable for CUSF, mere dilute peroxide shouldn't scare anyone.)

3 Pumps

3.1 Pressure-fed

The simplest engine cycle of all is the pressure-fed system, and this would be a useful starting point for developing combustion chambers, nozzles, etc. Either nitrogen or helium would be a suitable pressurant gas; CUSF already has some experience with handling the latter, from its balloon work, though *cold* He would introduce new challenges.

However, the low pressure ratio attainable with pressure-fed rockets might encourage the development of a pump-feed system, probably as a follow-on project after pressure-fed motors have been demonstrated. Turbopumps are conventionally the most troublesome part of liquid rocket motor design, but the use of reciprocating pumps may simplify this.

3.2 Reciprocating Pumps

Reciprocating pumps for rocket use were first developed by LLNL in the early '90s; they are much simpler to design and build than 'traditional' rotary turbopumps (as Jordin Kare put it, "lathe & drill press vs. multiaxis milling machine"[1]), and they scale down much better to small rockets ("potentially superior at small size (very roughly, <5000lb thrust)"[1]). Another advantage of the reciprocating pump is that it does not have the inlet pressure requirements of the turbopump: conventional rocket turbopumps cannot tolerate cavitation as it disrupts their flow pattern causing rapid unplanned disassembly, whereas the reciprocating pump is robust to cavitation (it will lose outlet pressure and flow rate, but not sustain damage). Again, the rotating shaft seals of the turbopump (often separating hot fuel-rich gas from the oxidiser being pumped, or vice-versa) are replaced by sliding piston seals. Finally, it is feasible to run the pumps off inert gas warmed by a heat exchanger; LLNL's 'Mockingbird' design[2], a proposed reusable SSTO, suggested cold He could be used in this way; as [1] notes, the exhaust velocity of room- temperature He is 200s, so the performance cost is not great.

Pure-reciprocating pumps do not involve any complex mechanical linkages - unlike the more usual crank-driven pump, which must convert rotary to linear motion, pumps of this type simply connect the linear motion of the drive piston to that of the pump piston. The main sources of complication in their design are (a) the valves and valve timing gear, and (b) the piston seals. Both of these problems have been routinely solved since the age of steam, though (a) may be made more difficult by high speeds, and (b) by the need for seal compatibility with the fuel and oxidiser used.

Vibration can be avoided by the use of paired pumps, or by paired pistons in a single cylinder, moving in opposite directions.

Pump development could take place as a self-contained programme, using (e.g.) pressurised inert gas to drive the pump, and an inert liquid as the pumped medium. Assuming materials had been selected for propellant compatibility, the resulting unit would be directly applicable to the rocket project.

4 Engine Cycles

To go beyond the pressure-fed rocket requires not only a pump, but also a way to power it. Besides the cold-He system mentioned in the previous section, there are three main engine cycles for pump-fed rockets: Staged Combustion, the Gas Generator, and the Expander cycle.

4.1 The Expander Cycle

The expander cycle is by far the simplest of the three: one propellant is used to regeneratively cool the engine and in doing so gains enough heat to change phase. The resulting gas is used to drive the pumps, then either vented overboard or fed into the combustion chamber. However, this system does require that the propellant is stored near to its boiling point, and works best if that boiling point is low (i.e. cryogenic fuels). It might be practical for light hydrocarbons; liquefied natural gas, for instance, might be doable. Liquefied petroleum gas might not be able to give sufficient pressure; I would need to consult the literature to find out just *how* 'cryogenic' a fuel needs to be for the expander cycle to be workable. Wikipedia, for instance, says that "All expander cycle engines need to use a cryogenic fuel"[3], but others contradict that, for example Henry Spencer says only that "You do need at least one propellant which can go from liquid to gas (preferably by the supercritical route rather than boiling) without thermal deterioration, which RP-1 can't."[4] Perhaps it is just that rocketry's 'traditional' fuels are divided into the definitely cryogenic (LOx, methane, etc.) and the not remotely cryogenic (like RFNA+UDMH), without really having a middle ground.

Related to the expander cycle is the use of the thermal decomposition of, for instance, hydrogen peroxide; instead of using a catalyst as in the 'cold' peroxide pump, one can run the peroxide through a heat exchanger using heat from the combustion chamber to decompose the peroxide. However, this probably won't do much to cool the combustion chamber, and the hot decomposition products may be somewhat hard on the pump; this isn't my favourite option.

4.2 The Gas Generator Cycle

The gas generator cycle might be feasible. We can't, however, take the enticing approach of catalytic decomposition of hydrogen peroxide to drive the pumps, as it requires concentrated peroxide with no stabiliser. A gas generator would have to actually burn both propellants in a second combustion chamber, although the temperature can be kept down by working off-ratio. On reflection, the performance benefits of the gas generator are probably not worth the complication.

4.3 Staged Combustion

Staged combustion makes everything harder, and we don't need the extra performance - it's not like we're trying to reach orbit!

4.4 Combustion tap-off

There is also one other option, the "tap-off" cycle: some of the combustion chamber gases are tapped off to drive the pump, then vented overboard. This is similar to the gas generator cycle, but avoids the complication of a separate pre-burner chamber, instead performing all the combustion in one place. It does however somewhat complicate combustion chamber design. The tap-off cycle lacks 'pedigree' compared to the others, but is used in, for instance, Blue Origin's BE-3 engine.

5 Chamber and Nozzle Cooling

One of the difficulties in rocket engine design is the extreme temperature at which combustion takes place. As most materials cannot directly withstand this temperature, the design must allow for this, and there are a number of possible approaches.

5.1 Ablative cooling

Ablative cooling is the simplest to understand: the chamber wall is designed to 'burn off' during motor firing. Such a system is inherently single-use, which is awkward for testing. However, the chamber is easy to manufacture - wooden combustion chambers (bound with metal hoops) have been seriously proposed (see [5]) for inexpensive single-shot rocket motors.

5.2 Regenerative Cooling

Regenerative cooling, as well as being essential for the expander cycle, is popular in general for performance reasons, as the ‘waste’ heat is used to increase the energy of the incoming fuel. However, it cannot be used for propellants which will thermally degrade - for instance, sulphur impurities in hydrocarbon fuels can cause coking of the cooling passages. So, for example, the stenchants added to natural gas would cause problems. Moreover, regenerative cooling by itself is usually insufficient to cool the engine and thus it must be combined with other methods.

5.3 Curtain Cooling

Curtain cooling is the standard approach, and involves designing the injector to produce a layer of fuel (or oxidiser!) flowing nonturbulently over the chamber wall, thus minimising heat transport. This does however require much cleverness in injector design, and any combustion instability can disrupt the curtain layer - meaning that if anything goes wrong, the combustion chamber will burn through in, often, less than a second. This also tends to limit the throttling capabilities of the engine, though that may not be an issue for our potential use cases.

The failure mode of curtain cooling can be made much less drastic by combining it with ablative cooling; effectively, the safety factor is increased but at a cost in increased engine weight. In that case, a loss of curtain cooling will simply increase the rate of ablation; in static firings there would be time to shut the motor down, while in an actual rocket launch the vehicle might still blow up, but it wouldn’t blow up near the ground - an important distinction! Again, we can probably live with the performance cost, and should do so in the interests of safety.

5.4 Nozzle Cooling

Cooling of the nozzle is much easier than that of the combustion chamber; in particular, radiative cooling may be feasible. Though radiatively cooled nozzles normally require expensive nozzle materials, they get easier the smaller the engine, roughly because of the square-cube law; some fairly reasonable alloys might be up to the job. Alternatively, the same options as for the combustion chamber are all still available.

6 Injectors

A liquid bipropellant rocket requires that its injector provide good mixing of the fuel and oxidiser, to allow smooth and stable combustion of the fuel in a small volume. Again, there are a number of approaches.

Impinging jets of propellant are a popular way to disperse the fuel, either with fuel impinging on oxidiser, or with fuel-fuel and oxidiser-oxidiser impingers. The latter gives better stability in some respects, as both jets have the same density etc. and thus react equally to accelerations. “On the other hand,” as Henry Spencer points out in [7], “because of the more effective mixing [of unlike impinging], you can afford to make the individual injection elements bigger, and *that* definitely helps stability. The tradeoffs here have not been examined well."

Impinging sheets, rather than jets, can also be used, possibly allowing for fewer injection elements. A related option is the coaxial pintle injector, where a cylindrical sheet of one propellant impinges on a flat disc or cone of the other. This also typically makes throttling quite easy. And, it's not too difficult to rig it so that it also produces a curtain layer for cooling. This makes the coaxial pintle my preferred choice of injector.

If one propellant can be injected as a gas rather than a liquid (e.g. if the expander cycle is used), that simplifies matters considerably, giving much more efficient mixing.

The smaller the engine, the easier combustion stability is to achieve.

One other issue that must be addressed is that the injector, being inside the combustion chamber, shares its cooling requirements. Fortunately, it is easy to create a curtain layer over the injector which, unlike the larger layer to protect the whole engine, will not be disrupted even by major instability.

7 Other Problems

7.1 Pogo Oscillation

This occurs when the natural frequency of a propellant feed line (typically driven by cavitation at the pump inlet) matches a resonant frequency of the vehicle structure. The phenomenon is fairly well understood and a number of different types of Pogo suppressor (such as the trapped-gas standpipe, the bladder accumulator and the piston accumulator) have been successfully used in various launch vehicles. A suitable suppressor should be designed into the system from the beginning, as this is easier than attempting to retrofit one to an already-designed engine. If this precaution is taken, there is little risk of trouble with Pogo oscillation.

7.2 Starting

Pump-fed engines generally need some form of bootstrap, either to start the propellant flow to the pre-burner (for gas generator and staged combustion) or to light off the chamber (for the expander and tapoff cycles). With reciprocating pumps this is probably most easily done with a small supply of pressurised gas to drive the pumps until the engine can take over.

8 Example Design Sketches

In roughly increasing order of difficulty:

1 Gas/gas or gas/liquid pressure-fed ablative motor. Using, say, nitrous oxide (in either phase) with a gaseous hydrocarbon (e.g. natural gas); this system would enable us to gain confidence and experience with fluid bipropellant systems (such as injector and combustion chamber design), though obviously vehicle performance would be too low to be of practical use.

2 Fully liquid pressure-fed motor with curtain and ablative cooling, with any of the propellants discussed earlier. To build experience with chamber cooling techniques and liquid/liquid injectors.

2a As (2) but with regenerative cooling added. Learning how to implement regenerative cooling is a necessary precondition to using the expander cycle.

3 Tap-off cycle pump-fed motor with curtain and ablative cooling.

3a Expander cycle pump-fed motor, developed from (2a).

Either (3) or (3a) would, if static firing were successful, be suitable for use in an actual vehicle.

To give an idea of how hard I rate each of these: with the proper tools I expect I could build (1) without any serious research being needed (though of course I would need to learn some new fabrication techniques); after all, (1) is really little more than a welding torch with a DeLaval nozzle! (2) would probably be a several-year project needing expertise from someone with much more engineering training than me, but the difficulty is probably comparable with that of developing a viable hybrid motor. Getting to (3) or (3a) would definitely come under the heading of "long-term goals", but would result in a vehicle capable of low-cost suborbital launch for small payloads. In particular, the vehicle could feasibly be a single stage and incorporate a recovery system, thereby making it reusable (except for the chamber ablator which would need to be replaced after each flight).

9 Conclusion

While liquid-fuelled rocket motors are more difficult than solids or hybrids, they also offer a greater pay-off as their higher performance and longer burn times simplify the engineering of other parts of the vehicle. Moreover, new techniques developed in the last two to three decades have brought small- scale liquid-fuelled motors within the grasp of the amateur. For this reason, I believe a liquid-fuel programme is a worthwhile project for CUSF to undertake, and I would be interested in participating in such a programme if it were to be accepted.

10 Design Study: GLARE - Gas/Liquid Ablative Rocket Experiment

10.1 General outline of the baseline design

GLARE is a rocket motor for static tests, using a pressure feed of nitrous oxide (stored as a compressed liquid) and a hydrocarbon such as natural gas (stored as a pressurised gas). The combustion chamber is ablatively cooled, while the nozzle is radiatively cooled. The injector is of pintle type, though other injector designs may also be investigated.

10.2 Combustion chamber

This is constructed from an inner wood layer, wrapped with sheet metal to improve strength. For slow ablation, a hard wood such as oak is preferable.

The chamber is polygonal in cross-section (probably hexagonal or octagonal) allowing the wooden component to be built up from (six or eight) parts, with mechanical joints between the parts. The longitudinal profile is a lozenge, as shown below:

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```

The converging portion at the throat is shallower (hence longer) than the diverging portion at the injector face.

The chamber is constructed with grain radially inward, so the charred wood doesn't flake off. This reduces the strength of the wood, hence why we use the reinforcing metal outer layer (and why building up from multiple wooden staves doesn't cost us much strength).

Ideally, the wood is wet, so the water vapour provides transpiration cooling.

10.3 Injector

The injector is coaxial, with oxidiser emerging from the outer pipe in a cylindrical sheet which then impinges on a cone of fuel formed by deflecting the fuel flow from a cone or disk. This cone or disk has a small hole at the apex, allowing some of the fuel to pass through and cool the reverse side.

It may prove more effective to reverse the roles of the fuel and oxidiser in this arrangement; it should not be difficult to test both.

The injector is constructed from sheet copper, for thermal conductivity.

10.4 Nozzle

The converging/diverging nozzle is made of copper, and held in place mechanically by the throat of the combustion chamber; the chamber has a step just upstream of the throat providing a recess for the nozzle assembly, thus ensuring that the nozzle does not stand proud of the chamber wall.

If necessary, the nozzle can be water-cooled during test firings.

As performance is not a concern, the nozzle profile is chosen for ease of construction, rather than most efficient expansion. Throughout the profile, underexpansion is preferred to overexpansion as the latter can lead to flow separation.

10.5 Ignition

There are a number of options for ignition, and experimentation is likely needed. Baseline ideas are (1) a spark plug, (2) a small solid motor (A) used as a pyrotechnic igniter, or (3) a charge of powdered metal (eg. Mg) ignited by an e-match in the chamber with a slow flow of oxidiser. But I expect others can contribute better suggestions based on Quasar experience.

10.6 Dimensions

I haven't really thought much about this yet, because I don't know what controls (for instance) the optimum fineness ratio of the chamber, or the required nozzle throat area. But as to overall size, the first iteration probably can be quite small, say a chamber volume of 150cm and other parts sized accordingly. Any smaller than that and the injector gets rather too fiddly, while turbulence probably dominates gas behaviour.

10.7 Programme Order

Probably the best way to approach this is to first build an injector, possibly testing it initially with compressed air rather than nitrous oxide, and essentially operating as a flare or torch. Once good burning at atmospheric pressure has been achieved, the combustion chamber can be added, and finally the c-d nozzle in an attempt to obtain choked flow.

11 References

1 "Pumps", Yarchive.net: `http://yarchive.net/space/rocket/pumps.html`

2 "Mockingbird Technical and Programmatic Overview": `http://diyhpl.us/~bryan/papers2/mockin`

3 "Expander cycle", Wikipedia: `https://en.wikipedia.org/wiki/Expander_cycle`

4 "Expander cycle", Yarchive.net: `http://yarchive.net/space/rocket/expander_cycle.html`

5 "Chamber materials", Yarchive.net: `http://yarchive.net/space/rocket/chamber_materials.ht`

6 "Hydrogen Peroxide", Yarchive.net: `http://yarchive.net/space/rocket/fuels/peroxide.html`

7 "Injectors", Yarchive.net: `http://yarchive.net/space/rocket/injectors.html`