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Reusable Rocket Propulsion for Space Tourism Vehicles

Douglas Jones
XCOR Aerospace, Inc, PO Box 1163, Mojave, CA 93502

Space tourism vehicles must fly frequently to amortize fixed costs over many customers: we only make money when the wheels are off the ground. Therefore the rocket propulsion system must be designed for safe, routine and economical operation with minimal labor requirements for refueling, inspection, and overhaul. These design goals are served by features such as ignition interlocks, ganged propellant valves, and cascaded purges. These positive safety features add some necessary system complexity. Some features primarily intended for frequent operation indirectly reduce operating cost while improving safety.

I. Introduction

Safety and reliability are the most important criteria for the design of rocket propulsion systems for space tourism applications. With the prospect of flying more people into (suborbital) space in a single year than in the previous four decades, ships for space tourism must be at least an order of magnitude safer than the present state of the art. The public perceives that rocket vehicles have poor safety and reliability, but this is not inherently so. Fortunately, suborbital spaceflight places less severe technical demands on the spacecraft and allows large gains to be made in safety. Therefore great strides in operational experience can be made before passenger orbital vehicles are designed in years to come.

II. Design Goals for Reusable Rocket Propulsion

The goals are these: the propulsion package must be extremely safe in operation, be very reliable, have long useful life with low costs, and be reusable many times per day. The first two goals are absolutely mandatory for crew and passenger safety; the others are economic requirements, although some of the features that allow frequent inexpensive reuse also enhance safety and reliability.

Figure 1. XCOR EZ-Rocket in flight. This operations demonstrator has been used to gain experience and verify cost models.

III. What to Avoid

Maximum performance, whether measured in specific impulse, mass fraction, chamber pressure, expansion ratio, or any of several similar criteria, is not an appropriate goal for safe and reliable rocket vehicles. Many features required for high performance can reduce reliability or safety. These include reducing structural safety margins, introducing fatigue life problems, or adding operational restrictions. Also to be avoided are hypergolic propellants which tend to be corrosive, toxic, and almost inevitably unstable. Toxic or unstable propellants require expensive safety and handling equipment as well as complex, labor-intensive procedures. In contrast, liquid oxygen and kerosene, though unglamorous and requiring proper care, have well-known handling and usage characteristics. Their simple and safe handling methods and low toxicity largely explain their low cost. Augmented-spark igniters can provide cheap, reliable, safe ignition for these inexpensive and readily available propellants.

Finally, pyrotechnics must be ruled out. Every item on a reusable space vehicle must be fully *reusable*. Single-use igniters and pyro-driven fasteners such as explosive bolts are expensive, untestable, and often require special hazardous material handling precautions. Pyro devices intended only for use in catastrophic situations, such as for canopy jettison and ejection seats, are acceptable only if they do not require frequent maintenance or inspection (the recent trend for automotive air bags to use compressed gas cylinders instead of combustion devices is instructive). Disassembly and reassembly of the propulsion system to replace ablated components, start cartridges, or fuel grains is also ruled out. A vehicle should be able to top off propellants, gases, and batteries, and then *fly*.

IV. Safety Features

Many of the detail and system design choices are driven more by safety considerations than by performance. In development and flight test, some mission aborts and flight cancellations were caused by the safety systems. We identified the problems, fixed the underlying issues and flew again in relatively short order. In one case, a higher level safety consideration made it difficult to shut an engine off, a feature designed in after sober consideration.

Rendering a rocket engine difficult to shut down may seem counter intuitive, but perhaps a better description is "unlikely to shut down unexpectedly." To achieve this, we have to anticipate fault conditions where the pilot might not have complete control of the engines, and this actually occurred during Flight 11 of the EZ-Rocket.

Early in the design of the EZ-Rocket propulsion, we chose to gang the main propellant valves with the fuel and oxidizer valves on one actuator *without* spring return to close. We called this "fail operational" or "fail consistent," so that a complete electrical failure would not change the engines' current state. Thus, if the pilot ignited one or both engines, started his takeoff roll, and the engine control sequencers then failed, the engines would continue to run. Propellant tank pressurization and engine feed are independent of the electrical system, and after start the engines will continue to run to depletion. This choice was made to ensure that even a complete electrical failure would not leave the pilot at low altitude with no propulsion and few options, much as a standard piston aircraft engine can continue to run on magnetos with no electrical requirements even if the alternator and battery are dead. This was directly counter to our practice on static test stands, where any electrical malfunction would cause instant shutdown; in engine development and test there is no harm in stopping an engine. With a flight vehicle, loss of power is far more hazardous than possible excess thrust.

On Flight 11 of the EZ-Rocket, the flight plan called for a two-engine takeoff, climb to landing pattern altitude, shut down of both engines, a low pass over the runway, and relight for a zoom climb and wingover. However, during the 45 second takeoff and climb, some frost from the liquid oxygen fill line dislodged and entered the Programmable Logic Controller (PLC) for the Number Two engine. There it melted and shorted out the controller, so that when the pilot commanded that engine off, no action followed. After reporting the malfunction, the pilot then used the redundant master propellant cutoff to shut the engine down, opened the emergency LOX dump to lighten the craft, and did a normal gliding landing. Had the electrical failure caused the engine to shut down prematurely, the flight abort may not have been so successful. (After this incident, we put the engine controllers into their own enclosures to protect them from debris, and flew again two weeks later.)

Figure 2. EZ-Rocket dumping LOX during intact abort, Flight 11. (Image from video capture.)

Conversely, the igniter pressure interlock has from time to time during system development prevented *start* of the main rocket engine chamber. Since we routinely do igniter tests and engine hot-fire checkouts before every flight, this merely resulted in canceled flight attempts. In the one exception an engine did not restart during an attempted touch-and-go flight in January 2002, after working well just moments earlier for the initial takeoff and go-around. We soon found that a commercially available pressure switch operated very sluggishly when it was cold, and although the igniter worked well, the controller did not see the "igniter okay" feedback within the required time, and did not open the main propellant valves. The pilot braked to a halt and the offending pressure switch was soon replaced with our own custom design with wider temperature limits (fully functional down to 90K).

Figure 3. Oxygen-kerosene igniter during statistical testing (note shock diamonds in plume).

The igniter pressure interlock prevents the main propellant valves from opening until the augmented-spark igniter (itself a tiny rocket engine of roughly 2 lb thrust) has reached normal operating pressure, proving that there is a robust supersonic hot plume ready to ignite the main chamber. This prevents any possibility of pooling propellants in the main chamber before ignition, and thus prevents hard starts. In more than 2,000 rocket engine runs, we have had no engine hard starts and we have good reasons to believe we never will.

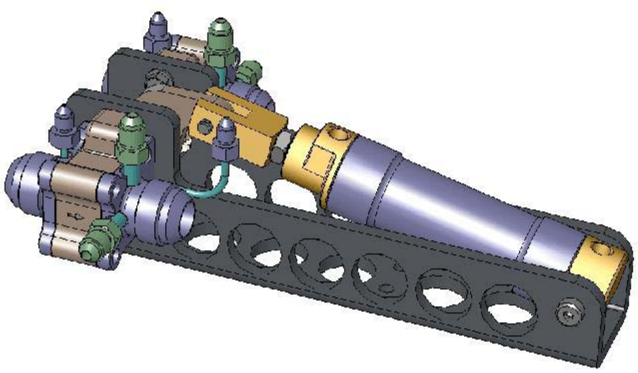

Figure 4. Ganged-actuator LOX-fuel valves with purge and igniter tapoff ports, using COTS cryo-rated valve components.

The main propellant valves are ganged on the same actuator, so that a single propellant cannot flood the chamber in the absence of the other. If a LOX prime is needed to condition the injector, a separate priming valve is used, preserving the ganged valves' purpose. In the event of electrical failure, the actuator remains in the last position commanded, giving fail-operational reliability.

Pressure cascaded inert gas purges are provided on the downstream face of each main propellant valve, ensuring that the engine shuts down cleanly, with very little residual propellant trapped where it could later leak out. This is of great importance particularly for low-volatility propellants like kerosene which could otherwise contaminate the oxidizer galleries, possibly leading to a dieseling ignition when oxidizer is again admitted.

Figure 5. Cascaded purges in action. Residual propellants are safely blown out of an engine at shutdown.

Similarly, dry-residue-free fuels are strongly advisable, so that greasy films cannot be created by fuel spills. We have had good results in using 99% isopropyl alcohol as fuel; we even use the same supply for the cleaning solvent to prepare the oxidizer plumbing. In the transition to kerosene based fuels, we have settled on a grade of kerosene equal or even superior to RP-1, a multiply-distilled product with no non-volatile components. Conventional Jet-A or JP-4 has too many high molecular weight species, aromatic compounds, and sulfur content to be used in a long-life regeneratively cooled rocket engine where low coking is mandatory. The jet fuels leave long lasting residues, incompatible with oxygen, if spilled.

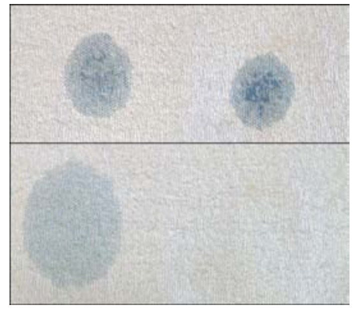

Figure 6. Jet-A, left, vs high grade kerosene on right. High grade kerosene evaporates completely in 10-20 minutes.

Propellants must be managed so that the oxidizer is exhausted first, or if the fuel (which serves as engine coolant) is exhausted, the engines must immediately shut down automatically. In a deliberate destructive test, we demonstrated that fuel exhaustion with oxidizer remaining results in substantial engine damage (melting and slumping of the chamber wall), but no catastrophic failure. While not directly a safety feature, this relaxes a constraint on the pilot's operation of the engines.

In support of the East Kern Airport District launch site license application (Mojave Spaceport), XCOR developed standards for energetic liquids handling. AST regulations require an explosives site plan as a precondition for a launch site license, and XCOR's standards, (developed with reference to existing OSHA, NFPA, CGA, and DOD standards[1-5] for combustible liquids, gases, and oxidizers) were included in that site plan.

The energetic liquids handling standards state in part,

> … 5. Both the fuel and oxidizer lines must contain two independent, redundant valves to shut off the flow in the event of a malfunction…. 9. The fuel and oxidizer systems must be separated from each other; it must not be possible for any commanded or accidental valve action to cross-connect the fuel and oxidizer system, and the design of the ullage pressurization system must prevent cross-flow of fuel and oxidizer…. 12. The vehicle tankage must be protected from fragments produced by an engine hard start…. 14. There must be no common bulkhead between fuel and oxidizer; the space between them must be drained and vented. The intention is that it takes two independent punctures of fuel and oxidizer tanks to make mixing possible, and that a small leak would not pose such a risk since it would be drained from the intertank volume….

Most of these standards are designed to prevent any mixing of propellants other than in the engine (disallowing common bulkheads for that purpose), prevent accidental spills, or damage to the tanks which could lead to spills and mixing. With careful attention to vehicle and systems design, there is no credible way for propellants to mix outside of the engines- and the engines are armored so that the vehicle will survive even in a worst-case engine hard start. As a result of XCOR's rigorous safety standards and demonstrated record of safe operation, FAA/AST determined that no explosive hazard was present, even aboard a fully loaded vehicle ready for flight.

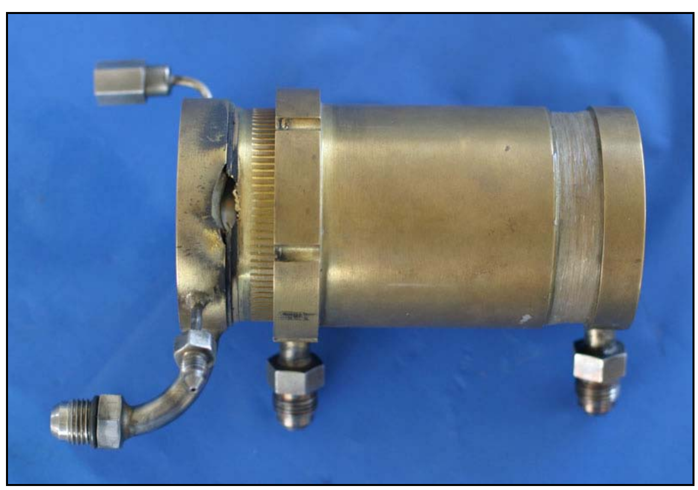

Figure 7. Why flame-to-world seals are to be avoided. Chamber and injector damaged by escaping flame. (Jacket pulled back to show detail.)

A more subtle issue is designing with no flame-to-world seals, as in the STS SRB field joints. One of our early development engines had an O-ring face seal between the combustion chamber and the injector head. The O-ring failed and allowed hot gasses to escape, which quickly eroded a large hole in the injector face and chamber. Although this author was only a few feet away at the time, the secondary confinement described below prevented personal injury and damage to the test stand, and the simple expedient of turning the engine off reduced the impact of the burn through. (Solid fuel rocket engines are utterly unsuited for main propulsion for this reason.) In all engines since, the chamber seals are designed to keep the propellants out rather than the flame in; the joints have either the fuel coolant or an inert purge at higher pressure than the chamber. Of course, we do have propellant-to-world seals, but propellant leaks will not quickly erode and grow as flame leaks can.

Secondary confinement structures around the engines are not optional. In all our test stands and vehicles, we have incorporated shields sized to contain the blast and fragments from the worst-case engine hard start. On static test stands, the shield includes transparent polycarbonate windows to allow observation of the engine, while the shields on flight vehicles are opaque but very lightweight composite structures using multiple layers of ceramic, graphite, and Kevlar for heat resistance, strength, and energy absorption. Each engine is individually shielded to prevent fratricide in the event of a catastrophic engine failure. The small size of the engines relative to the vehicle allows this shielding to be achieved at little cost in mass and complexity.

Figure 8. Test stand and flight vehicle safety shields allow convenient operation without bunkers for personnel protection.

Some vehicle operating concepts, such as horizontal take-off and landing (HTHL) with powered go-around capability, require an engine restart capability so the pilot can add energy to a low approach, or even go around the pattern again. Many of the design features described here will allow reuse of the main engines without needing inspection or preparation for the relight. Design for economical operation also provides improved safety.

V. Reliability Features

Robust, reliable, single-purpose components go a long way toward reducing nuisance problems. One example is the use of a Programmable Logic Controller (PLC) for engine purge, prime, start, and shutdown sequencing in preference to desktop, laptop, or embedded computers running general-purpose operating systems. These PLCs have a microprocessor inside, but its entire function is to emulate an array of relays and timers. The device is programmed by drawing ladder logic as if it were a collection of relays. Commonly used in industrial settings such as machine shops, they tolerate wide temperature extremes, contamination, and vibration (though as we found on EZ-Rocket Flight 11 they do have their limits), and for operational vehicles we will replace then with a hardware circuit using rad-hard solid state components with no programmable features. Automotive engine controller boards are another option. They have substantial sensor and actuator capabilities built in, with simple firmware reprogramming available.

Figure 9. Very simple engine control interface for pilot.

In some cases, tight sequences of operations must prepare an engine for start, such as prechilling of cryogenic lines, purges of manifolds, and priming of liquids up to valves. As much as possible, these should be done autonomously by the engine sequencer without pilot input needed. A plethora of manual controls invite operator error. The one-man-band aspect of starting some aircraft engines is not the model to follow.

Since rocket powered vehicles typically have high thrust to weight ratios and excellent initial acceleration (which only improves as propellants are burned off), breaking the total propulsion up into several engines will allow for a safe takeoff even in the event of an engine failure. As an example, our Xerus suborbital vehicle will have four engines, but would be able to take off on two and climb on just one engine. Thus, even if one or more engines fail after decision speed is passed, the mission might be aborted but the vehicle could land safely.

The best way to achieve good reliability is to keep unnecessary hands off the engines; it is well known in aviation that many accidents occur right after overhauls or shop visits, where inadvertent errors by mechanics can have dire results. Simple maintenance means fewer opportunities for mechanic error (the loss of the DC-XA is a prime example of a mechanic-induced accident). Thus we are driven to design the propulsion system to require overhaul or invasive inspection only rarely.

VI. Long Life Features

For economical operation, rockets for space tourism must have long life with little routine maintenance required. This eliminates ablative engines at the outset, since they require frequent (typically once per mission) replacement of the sacrificial liners. This leaves only regenerative and transpiration cooled engines; most will likely be regenerative.

Figure 10. Externally slotted chamber with split saddles. (Photo courtesy of SPL).

One of the greatest life-limiting problems with regeneratively cooled engines is thermal fatigue of the hot side of the combustion chamber wall. Because the outer side of the chamber wall is far cooler than the inside wall while the engine is running, and is typically rigidly connected to it as in a milled slot plated closeout design, large thermal strains are imposed during each run. This places in compression the relatively weak (typically copper alloy) inner wall, which yields plastically, then suffers a tensile load when it cools again after shutdown. Repeated thermal cycles eventually produce cracks, allowing coolant to leak directly into the chamber and reducing combustion efficiency. The leakage can also starve the coolant passages beyond the leak, leading to thermal overload, burnout, and catastrophic chamber failure.

XCOR and others such as the Swiss Propulsion Laboratory (SPL) have built regenerative engines using separate chamber, throat saddle, and outer jacket. A typical engine by SPL is shown here to conceal certain XCOR proprietary techniques (while the SPL engine uses aluminum extensively, XCOR has used copper alloys and other materials with excellent results). The outer jacket is not shown in this image, but the crucial feature is this: the jacket does not constrain the chamber's thermal expansion during firing. Thus the thermal strain, plastic yield and cracking cycle never gets started. In our engines with hundreds of full power runs, we have seen no distortion, yielding, or cracking, and the flame side wall remains as smooth as when it was first fabricated.

This construction can also contribute to long life by making it feasible to disassemble an engine and remove coking deposits if needed, although we have not yet seen significant coking with the high purity low sulfur fuels we routinely use, and we do not anticipate a need for this. If necessary, we can also add anticatalytic coatings to the exposed coolant passages to reduce coking rates.

Much like the radially unconstrained chamber, adding axial compliance to the chamber and jacket system prevents the induction of high axial stresses when the thermal strain is imposed at engine start. The cost of this compliance is that the chamber must be slightly heavier than an optimum plated closeout design, since it must withstand the external pressure load of the fuel without buckling.

VII. Low Cost Features

It is difficult to find propellants cheaper than liquid oxygen and kerosene. LOX is as low as $0.08/lb by the tank-truck load (including amortized local bulk storage costs), and of all liquid oxidizers, liquid oxygen is by far the most commonly used in all industries (roughly 15 million tons/yr in the United States alone). The technology for delivering and handling it is completely mature, and no safety gear more exotic than gloves, face shield, and perhaps coveralls are needed. For routine, frequent operations, nontoxic propellants with reasonable handling requirements are a must. Not only are these propellants inexpensive to buy, they are inexpensive to use because no breathing apparatus, whole-body impermeable clothing, or sophisticated ground handling equipment are needed. Regulatory agencies do not place substantial requirements for worker and public safety or environmental protection on users of these materials.


Figure 11. Mechanic wearing face shield, hearing protection and gloves loads liquid oxygen into EZ-Rocket.

Both to achieve fast turnaround and to keep labor costs down, the rocket propulsion system must need minimal maintenance between flights, and maximum time between overhauls so that the vehicle remains in revenue service as much as possible. With the EZ-Rocket we have demonstrated true gas-and-go operations, turning the vehicle around for a second flight in five hours (half that time was waiting for a LOX shipment to arrive). We confidently expect to be able to turn around our suborbital vehicle in about an hour, which is comparable to other transport aircraft.

Many of the safety features described above (cascaded purges, residue-free fuels, no flame seals, etc) allow us to eliminate redundant inspections or cleanings between flights, keeping labor needs low and checklists short. The propulsion system must have enough layers of safety and redundancy that minor errors or omissions in the flight preparation will not cause hazards. Designing without common bulkheads may slightly lower performance by creating redundant structures, but the increased inherent safety also reduces inspection and overhaul requirements, saving greatly on labor expenses. In many cases, designing for low maintenance requirements helps prevent errors caused by excessive handling of the vehicle.

VIII. Summary

Economically viable space tourism vehicles must support a profitable business plan. This supreme requirement drives the highest level system architecture, clarifies engineering design choices, and allows engineering managers ruthlessly to discard the “better” in favor of the “good enough.” Many features selected for safety and reliability lead to lower operations costs, and some selected for simple operations lead to greater safety; with rational design there is no need to sacrifice safety for expediency. Above all, all of us in this emerging field must realize that a single explosion or similar incident leading to an injury of a passenger could stop the industry.

Acknowledgments

The author thanks Bruno Berger of the Swiss Propulsion Laboratory for permission to use the chamber photo in Figure 10.

References

[1]California Code of Regulations, Title 8, Subchapter 7, Group 20, "Flammable Liquids, Gases, and Vapors"

[2]Occupational Safety & Health Administration, 29 CFR 1910.104, "Oxygen,"29 CFR 1910.105, "Nitrous Oxide," 29 CFR 1910.106, "Flammable and Combustible Liquids"

[3]Compressed Gas Association, CGA G-4-1996, "Oxygen"

[4]National Fire Protection Association, NFPA 30, "Flammable and Combustible Liquids Code," NFPA 430, "Code for the Storage of Liquid and Solid Oxidizers

[5]Rewrite DoD 6055.9-STD, rev. 3, 1 Sep 2003, "DoD Ammunition and Explosives Safety Standards"