The Future of Earth-to-Orbit Propulsion

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THE STORY OF TURBOPUMP ROCKET DEVELOPMENT is an interesting one of trial and error. Many sidelines were explored before the objectives of light weight and high performance were finally attained with the main engines for the Shuttle. Russian rocket development followed a somewhat similar path, and the end result was very similar: a topping cycle with high combustion chamber pressures.

But turbopump engines, whether high pressure or low, were a mistake from the very beginning. They simply are not worth what they cost in time and money. In all the early development efforts, pump-fed systems were preceded by a pressure-fed version. In every case, the mission was accomplished and the program goals met before the development of the pump system was completed. After the X-I broke the sound barrier with its pressure-fed rocket engine, who ever heard of the D-558-2-powered by a pump-fed engine?

"Technically simple two-stage launchers with pressure-fed engines and ocean recovery offer the economical operations that have escaped our high-technology turbopump rockets for more than four decades"

Economic considerations

How could an entire industry have gone so far astray? The answer is simple. In the commercial world, when technologies mature they eventually reach a point where further refinement is not economically justified. However, rocket development in both the U.S. and the Soviet Union had always been government-sponsored. It never had the benefit of the primary limiting influence-economic shakeout.

Development trends were dictated by engineers who strove for high performance. Most often they neither knew nor cared about the cost impact of their designs. High performance and light weight invariably led to complication and high cost. No development really focused on the economic aspects of high performance. No one wanted to. The engineering of complex systems is fun, and most programs were done on almost inexhaustible budgets. No one bothered to ask, "Is it worth the price?"

Back in 1959 I noted, to my great surprise, that the Agena, only one-fifth the size of the Thor intermediate-range ballistic missile, cost more, not less, than the Thor. Here were two liquid-propellant rockets, each comprising one set of tanks, one pump-fed engine, one autopilot, etc. The Agena was almost a scale model of the Thor. Following the accepted practice of the time, we had gone to great lengths to make both of them as small as possible so the mission could be accomplished.

For most missions, a less efficient rocket can do the job of a more efficient one by making the former a bit bigger. With the Agena/Thor situation, we had data that said that efforts to make a given rocket as small as possible might be grossly misdirected.

Another example of such misdirection was the Titan intercontinental ballistic missile (ICBM). The first stage (in 1959) used two engines of about 150,000 lb of thrust each. The single second-stage engine developed 60,000 lb. Again, I found that the smaller engine cost more. The size factor was only little over two, not five as in the case of Thor/Agena, but it still reflected the difference in launch weight between a simple vehicle and a sophisticated one. The absurdity of excessive emphasis on keeping the rocket small became clear.

A third example is the Atlas ICBM. For years the Atlas program had been kept on the back burner because it required a liftoff weight of almost 500,000 lb to throw a hydrogen bomb 6,000 mi. When the weight of the bomb was halved, the Atlas was suddenly considered practical. For some reason, cutting the liftoff weight from 500,000 lb to 250,000 lb made it acceptable.

Development of the 0.5-million-lb Atlas was well along when the order came to downsize it. The original design used five engines of the same size. Cutting the vehicle size in half required a complete redesign, and an entirely new sustainer engine had to be developed. Downsizing the Atlas was an unfortunate mistake. The smaller version cost more, took longer to develop, and provided a vehicle of half the capability.

Apparently, nobody thought of the idea of putting two warheads on an ICBM -- that idea came along much later. Had we developed the full-size version, we could have orbited both the Mercury and Gemini astronauts on the same vehicle. Actually, the Atlas never was any good as an ICBM; it came into its own only as a space launch vehicle.

Simplicity, not size, is the key

The key to low-cost space launch is the propulsion system (or systems). The two examples cited, Thor/Agena and Titan, are not flukes, but part of a general truth. (Note, too, that for the Titan engines, the cited cost disparity held true both for the development cost and the cost to manufacture.) This negative cost vs. size relationship seems to fly in the face of common sense. But it does turn out that the cost/size curve is very flat, and that things other than size can quickly outweigh the effect of size.

The explanation is both simple and logical. One has only to examine where the money goes. Long-range rockets or space launch vehicles, even relatively simple ones, are highly engineered devices. The cost to do this engineering is almost independent of the size of the parts, but heavily dependent on the number of parts.

The same calculations are involved in designing a big rocket and a small one (provided they are geometrically similar). Lab work is a function of the size of the testing equipment, not of the ultimate part. Instrumentation is identical for big and small rockets. Paperwork is a big cost element for each part, but the same piece of paper will serve to document a big part or a small one. About the only cost elements that vary more or less directly with size are raw materials and propellants, but these constitute only a tiny fraction of total launch-system price.

One can examine all the cost elements, and the answers are similar everywhere. Cost is much more a function of the number of parts than of their size. Perhaps the best example of this is the Saturn V. The first and second stages (S-I and S-11) were very similar in configuration and differed by a factor of five in weight. But the S-11 stage, the smaller one, cost more to develop, and only slightly less to produce! The J-2 engines for the S-11 stage, at only 200,000 lb of thrust, cost only slightly less (3.6%) to develop and 60% as much to build as the giant 1.5-million-lb-thrust F-1, 7.5 times bigger.

Of course, the S-11 stage and the J-2 engine used liquid hydrogen, whereas the S-I and F-1 were fueled with kerosene. But that simply makes my point: Other factors can completely swamp the effect of great variations in size. In fact, in most cases, building launch vehicles bigger is the cheapest way to get more payload!

The lesson to be learned, of course, is that to reduce cost, do everything possible to simplify the rocket, even at the expense of making the vehicle considerably larger.

Why wings?

Today, at last, there seems to be an effort under way to develop low-cost launch systems. But most people and organizations in the space community do not really want to develop cheap rockets. Fancy ones are more fun, and, at least at first blush, make more money, create more jobs for more people, and require large organizations to develop, manufacture, and use them.

However, in commercial space, as in most business ventures, cost is the primary consideration. Although perhaps not so obvious, cost is also of great importance in both the exploration of space and in using space for military purposes. It is long past time to stop designing and building engineering tours de force that produce marvelously intricate machines but make access to space more costly.

Many are also obsessed with the idea of flying into space. Why put wings on a space launch vehicle? Perhaps because there are so many airplane pilots in important positions. Perhaps because the Air Force runs the space end of national defense. Perhaps because NASA wants a bigger role for the first A in its name.

The only justification is the unproven (and I believe unfounded) assumption that if the configuration looks and acts like an airplane, it will have operating costs like an airliner's. This is the argument that NASA used for the Space Shuttle, but there was no background of experience to support that assumption. It has been proven to be a very costly error: The Space Shuttle represents a truly marvelous implementation of an absolutely absurd concept. Its development and use have cost some $20 billion-$40 billion, and it has set back economical access to space about 35 years.

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Shuttle's costly lessons

Many flawed design choices were made in arriving at the Shuttle's final configuration:
 - Wings and landing gear are the heaviest of all possible methods of recovery.
 - Parallel staging is less efficient than tandem. More importantly, it also prevents the upper-stage engine from being optimized for vacuum operation.
 - Use of two boosters doubles the probability of catastrophic failure. Multiple main engines increase probability of catastrophic failure by a factor of three, even though they may reduce the probability of noncatastrophic failure.
 - Opting for segmented booster cases increases the probability of case failure by unnecessarily complicating case design. Monolithic cases were proposed but rejected because Thiokol, a Utah company with no access to water transportation, had to propose a take-apart design.

- Putting a crew on the first flight requires a very high reliability based on ground tests alone. A more sensible procedure would have been to fly the vehicle unmanned for cargo missions until an adequate degree of reliability could be demonstrated, as was done with the Saturn V (the Soviets, incidentally, did fly their shuttle Buran, for the first and only time, without a crew).
- Use of solid propellants in the boosters minimizes the savings that can be had through recovery and reuse. Pressure-fed liquid-propellant boosters, as initially recommended by NASA-Marshall, would have required little more than a wash-down and refueling before reuse. Solids require disassembly and return to the factory, along with replacement of many parts. The cost of solid propellants runs about $7/lb vs. an average of about 10 cents for liquids.
- Throwing away the largest part of the system, the main fuel tank, adds about $50 million to the cost per flight.
- People and cargo should never be mixed. Payloads to be transported to orbit, even for missions requiring a human presence, are 95% "stuff' and at most only 5% "meat." The provisions and safety requirements for the latter cost an order of magnitude more than for the former. Mixing the two burdens cargo flights with the same elaborate safety measures required for people.

Parallel staging, incidentally, led to the need for extremely high engine chamber pressure-3,000 psi. The consequent requirement to pump hydrogen to 6,000 psi created a nightmare of ongoing problems. Had designers chosen to ignite the liquid-propellant engines at booster burnout there would have been no need for high chamber pressures. In fact, the chamber pressure could have been so low that no pumps would have been needed at all.

Engine performance at altitude is almost exclusively a function of the area ratio of the nozzle, and almost independent of combustion pressure. Low-chamber-pressure engines are larger, but no heavier, than those using higher pressure; nor need they occupy more space. If the pressure is low enough, the nose of the first stage can be inserted into the nozzle of the second, reducing (and possibly even eliminating) the interstage structure. Very high area ratios, even those having exit bells extending beyond the diameter of the first stage, can be obtained by corrugating the thin exit cone into a cylinder and draping it over the first stage. Since low-pressure nozzle skirts can be radiation cooled, they can be made of thin stock, and hence are very light.

The vacuum specific impulse calculated for the realistic case of shifting equilibrium changes by no more than 1.5% for chamber pressures ranging from 75 psi to 3,000 psi. True, at the lower pressures the equilibrium changes from shifting to frozen at a lower nozzle area ratio, but even so, the difference in specific impulse almost certainly will not exceed 5%. For a two-stage-to-orbit configuration, with an upper-stage ideal velocity change of 20,000 ft/sec, a 5% difference in specific impulse would change the payload by about 15%. A launch vehicle using a pressure-fed upper stage would therefore have to be only 15% larger to carry the same payload.

Since the relationship of cost to size is very flat, this small increase in size would produce a virtually undetectable increase in cost. It was for this piddling difference that we developed the enormously expensive Shuttle main engines. The payload increase gained by igniting the pressure-fed engine after burnout of the boosters would have more than offset the 15% loss resulting from the slightly lower specific impulse. Thus the Shuttle could have lifted more payload to orbit with a simple, low-cost, pressure-fed main engine.

There simply is no justification for using pumps on a stage that operates in a vacuum. Moreover, even with a first stage, although the difference in performance is somewhat greater, there is no economic justification for using pumps. If a pressure-fed first stage has to be a bit larger, the slight difference in cost attributable to the larger size will be overwhelmed by the incremental cost of developing, building, and using the more complex system. A completely reusable, pressure-fed two-stage launch vehicle can be built with a gross-weight-to-payload ratio of 35. The same ratio for the Space Shuttle is 68. All that cost and complexity produced a product only half as good! The ratio of parts count is at least a hundred to one; the disparity in cost would be at least as great.

"Winged vehicles can land only on very few, very special runways, an infinitesimal fraction of the surface of the Earth"

Recovery costs

Recovery appears to be a fruitful way of reducing the cost, but only if it can be done with a minor increase in complexity or a very small reduction in payload mass. Recovering the Shuttle's solid rocket boosters costs only a fraction of 1% of the mission cost of the Shuttle (it should cost only a few thousand dollars, and although it actually costs NASA about 10 times that, the retrieval cost is still a negligible fraction of the total operational mission cost). if refurbishing the solid rockets were not so expensive, the approach would be very cost-effective.

A pressure-fed liquid first stage, recovered by parachute in the ocean, could be readied for reuse with almost no refurbishment. Waterproofing a pressure-fed rocket is extremely simple, as has been demonstrated for a number of prior launch concepts (SeaBee, SeaHorse, Sealar, VaPak). The cost of such waterproofing was always trivial. Exposure of a launch vehicle to salt water is only for short durations. Ships and naval aircraft such as seaplanes and carrier based landplanes are exposed for very long periods to both salt water and salt air. They have somewhat higher maintenance costs, but they do not dissolve. Salt water is not a universal solvent.

Mounting concerns over launch safety and environmental damage have caused range costs to soar exorbitantly. A major portion of the current range costs can be avoided if we move not only recovery, but also the launches themselves, to sea. Sea launch is safe without elaborate range safety procedures. The immense expanse of flat and unobstructed surface is ideal for intrinsically hazardous rocket launches.

Moreover, with the right kind of vehicle, no "platform" is necessary for sea launch. Water will float any rocket with minimal special provisions. And the real estate is free. It would be very difficult to improve on the cost-effectiveness of a simple, pressure-fed booster, recovered in the ocean by parachute and retrieved by tugboat. After landing, returning spent stages to base is cheap and quick, regardless of the size of the stage. The retrieval time of about 20 hr will be a small fraction of the turnaround time for many years to come, possibly forever, and it actually costs less to return the Shuttle's solid rocket boosters to Kennedy Space Center than to move the Orbiter from the landing strip at nearby Patrick AFB back to the launch pad. (When the Shuttle has to land at Edwards, both the cost and the time are many times greater.)

In contrast, recovering the Orbiter by making it a manned glider cuts the payload it can carry by a factor of three. Add to this the high cost of developing, building, and operating the hypersonic Orbiter. No wonder it costs more to launch a payload with the Shuttle than with even the most expensive expendable launch vehicle.

Putting wings on a space launch vehicle makes little economic sense: They are heavy, costly, and unnecessary. Even if we succeed in developing and building an engine that will bum a fuel in air at hypersonic speed, the machine to do it will be larger, heavier, and much more complex than a ballistic rocket. Using wings to recover from orbit costs a major fraction of the recovered weight, compared with perhaps 10-12% for an ablating heat shield and a parachute.

Moreover, there is no point in flying the vehicle back to the launch point. Currently, most ascents are made over water, a large, flat, uninhabited region that covers most of the Earth. it also makes economic sense to recover both boosters and orbital stages in the ocean. Water is considerably softer than land. Parachute landings are simple, cheap, and reliable. They can be done in the ocean with little or no constraint due to location of the vehicle, timing, or weather. Even emergency landings will endanger no one. No landing aids are needed.

Winged vehicles can land only on very few, very special runways, an infinitesimal fraction of the surface of the Earth. They require a host of landing aids and are very sensitive to the weather.

Drawbacks of SSTO

Currently, the single-stage-to-orbit approach has many supporters. But, other parameters being constant, an SSTO vehicle can carry much less payload than one having two stages. A lot of dead weight has to be accelerated to orbital velocity at great cost, only to be brought back through the "thermal thicket" at equally great cost. Single-stage concepts might still have an advantage if the vehicle were simpler. This is not the case with any current concept, and probably never will be. Any SSTO rocket will have much less payload and be much more complex than a two-stage design and has many other serious drawbacks.

Combining SSTO with winged flyback is probably the worst combination of features that could possibly be incorporated into one design. It ignores all existing cost data and replaces hard figures with wishful thinking. Flying into space may be romantic, but it makes no economic sense. One proposed next-generation vehicle repeats all the errors made in the design of the Shuttle. Yet this is the approach on which we propose to spend a billion dollars in the next few years.

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Formula for cheap access to space

Getting into space is a simple problem. It need not be very expensive. It can be done with a simple rocket at very low cost. It takes a lot of energy, but that energy costs only about $6/lb of payload. No new technology at all is needed. But we have to use the right technology, most of which has been around for four or five decades. We must stop trying to do it the hard way. The formula for cheap access to space involves only a few rules:

- Make the rocket bigger than it has to be.
- Use two stages to orbit, with a single engine per stage.
- Make it simple, using pressure-fed propulsion for both stages.
- Conduct launch operations from the ocean, well offshore.
- Recover the first stage by parachute in the ocean.
- Probably recover the second stage by parachute in the ocean. (Some believe that launch vehicles can be made so cheap that there is no point in recovering them. While recovery of first stages by parachute is so easy that there is no question about the payoff, the jury is still out on upper stages. We have never tried to recover an upper stage using a heat shield plus a parachute.)
- Fly it without a crew, at least initially.

Sea launches and recoveries impose no limit on size. We must build our launchers big to achieve the really important uses for space, such as orbiting solar power stations, space factories, and manned missions to the planets. The technology to get us into space for $30/lb has been around for 40 years. In our infatuation with "high tech," we have simply refused to recognize it. We should throw out 90% of the "improvements" in liquid rockets made in the last four decades, refine pressure-fed rockets a little, and apply the technology of the '50s to recovering both vehicles as well as payloads.

We appear to have learned nothing from the Shuttle program, and are getting set to repeat the error. I hope this trend will not prevail.

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