The Cold Equations Of Spaceflight

September 9 2005

In the past month, we have been blessed with numerous leaks from NASA of various study documents relating to the new boosters that will be needed to carry out the new manned moon program. I've been monitoring the large volume of Web chatter about these plans, and have noticed a disturbing theme therein.

Many Space Cadets are expressing dissatisfaction with these leaked NASA plans. They say that the Shuttle-derived boosters are too primitive, too expensive to develop, too expensive to operate, and not inspiring enough. They can't understand why we will be returning to the Moon with rockets and space capsules that look like minor variations of those used in the Apollo program 40 years ago.

"Where is the sexy new stuff?" they ask. "For that matter, where is the sexy old stuff? Why isn't Mike Griffin pulling out the blueprints for X-30/NASP, DC-X/Delta Clipper, or X-33/VentureStar? Billions of dollars were spent on these programs before they were cancelled. Why aren't we using all that research to design a cheap, reusable, Single-Stage-To-Orbit vehicle that operates just like an airplane and doesn't fall in the ocean after one flight?"

The answer to this question is: All of these vehicles were fantasy projects. They violated basic laws of physics and engineering. They were impossible with current technology, or any technology we can afford to develop on the timescale and budgets available to NASA. They were doomed attempts to avoid the Cold Equations of Spaceflight.

The rocket equation tells you that an SSTO booster using LH2 fuel and LO2 oxidizer needs a fuel mass fraction of around 0.92. That means that 92% of the take-off weight needs to be ascent propellant, and only 8% is left for everything else.

This is a very demanding requirement. The second and third stages of the Saturn V actually achieved a dry mass fraction of about 10%. But these are not complete spacecraft, only expendable stages without payload or recovery gear.

But the Space Cadets want a reusable booster than can quickly return to its launch site and take off again in a few days with another payload. This requires the addition of large amounts of weight which renders the vehicle incapable of orbital flight.

The biggest advance in rocket design was the replacement of the V-2's separate fuel tanks, load-bearing structure, and aeroshell with a single thin skin that serves all three functions. Every design since Redstone and Scud has used this principle (except Korolyov's dreadful N-1). This is the key to the low dry weight and high performance of modern booster stages.

But the reusable SSTO booster needs to reenter the earth's atmosphere at 17,500mph. Every square inch of its huge propellant tanks needs to be protected against reentry heat. This is far more difficult than protecting a small warhead or entry capsule. Most SSTO designers have adopted the old double-wall system of a separate fuel tank and heat shield separated by a space which often contains an elaborate structure. The following particularly bad example is from Bristol Spaceplanes' Skylon design:

This return to 1930s design concepts makes these recoverable vehicles unacceptably heavy, as we can see by looking at the DC-X. Of all SSTOs, this one was the closest to a traditional rocket. Its fuel tanks were mostly cylindrical, and instead of a heat shield it had a flimsy plastic aeroshell that broke twice and caught on fire once in only a dozen test flights.

Yet the DC-X had a fuel weight fraction of only 52%! This is less that that of the V-2 and absurdly short of the 91-92% projected for the operational Delta Clipper. The DC-X was not a meaningful prototype of a working spaceship, but merely the world's most inefficient VTOL aircraft, scarcely more advanced than the "Flying Bedstead" prototypes of the 1950s.

Space Cadets frequently claim that new materials like Al-Li or carbon-fiber composites as solving the weight problem, but they don't represent enough of an increase in strength/weight to make up for the massive increase in structural weight that wrapping an entire rocket stage in a heat shield implies. The DC-X was rebuilt as the DC-XA with composite propellant tanks, but its fuel fraction only went up to a pitiful 54%.

And after our overweight booster reenters, it has to land itself. We Space Cadets were so impressed by the smooth automated vertical landings of the DC-X that we never asked where all that fuel would come from in the operational Delta Clipper. It's not part of the %92 of GLOW that is fuel burned during ascent to orbit. It can't even be residual fuel carried by making the take-off tanks slightly oversized, since these big tanks would be impossible to keep cold during orbital flight and reentry.

The fuel for the retro-burn and the landing maneuver must be carried in a second, smaller set of cryogenic tanks that are carefully insulated and isolated from the vehicle's skin. Fuel, tanks, pipes, and landing legs all must be charged against that 8% dry weight.

The weight demands of the X-33/VentureStar runway-landing configuration were more subtle. The vehicle had a lifting-body shape which is less efficient than a cylinder, so more heat shield mass was needed. To fit inside that shape, propellant tanks had to be made in complex multilobed forms that required internal bracing to resist pressure. And then there was the dead weight of landing wheels, brakes, struts, doors, actuators, and structure to support them.

As development proceeded, the X-33 sprouted four large fixed tail fins and no less than ten movable control surfaces with associated hydraulic actuators and APUs. Lifting-bodies are particularly susceptible to control and stability problems and it seems likely that this elaborate tail structure was added to solve some unexpected problems that surfaced during wind-tunnel tests.

With all this burden of landing hardware eating away at that 8% dry weight fraction, it was no surprise that Lockheed kept cutting back the payload of the VentureStar - until one day Dan Goldin caught them and had that parameter contractually defined. After that, the weight and size of both VentureStar and its X-33 prototype grew uncontrollably with every design iteration until the program was cancelled. The very last VentureStar concept took the drastic step of eliminating the internal payload bay and carrying ISS supply modules externally.

Clearly X-33/VS suffered from fundamental problems that were not connected with the composite tank failure that was the official reason for cancelling the program. In failed aerospace projects, a particular technical hitch is often made the scapegoat for systemic management and engineering problems that are too embarrassing for the funding agency to admit.

The X-30 National Aero-Space Plane had even more strikes against it, because it relied on air-breathing scramjet engines to boost itself to orbital velocity while still inside the sensible atmosphere. This led to skin temperatures that would quickly melt any known material. Active cooling studies showed that the LH2 fuel could only absorb about 25% of this heat.

Furthermore, NASP needed at least two more engine sets (turbojet and ramjet) to boost itself up from the runway to scramjet ignition speed. These heavy engines then had to be sealed off from the hot hypersonic airflow and dragged uselessly all the way to orbit. It's no surprise that even senior NASA engineers working on NASP recognised that the project was hopeless right from the start. The projected gross weight of X-30 ballooned up from 50,000lb to ~450,000lb - a two-seat orbital B-52!

The Angry Reader is now saying, "If all this is so obvious, why did these hopeless designs get approved? Why did the US government spend billions of dollars on impossible projects? That makes no sense!"

Yes, it makes no sense - but it frequently happens that governments spend huge sums of money on aerospace projects that make no technical sense, for political reasons, or simple ignorance, or because the decision-makers have been bought. X-33 was born during Dan Goldin's reign of error at NASA, when all sorts of absurd projects were promoted for reasons that still defy any rational analysis.

In the cases of X-30 and DC-X, there WAS a reason to spend money on impossible vehicles. Both these doomed projects were sponsored by the old Strategic Defense Initiative Office, which was running an elaborate scam on the Soviet Politburo. In order to make credible their central fantasy project of orbital battle stations shooting down Red ICBMs, they had to run a parallel fantasy booster development program. The Space Shuttle was clearly not up to the task of launching serious "Star Wars" hardware.

These phony programs of the 1980s achieved their goal. Soviet intelligence looked at the press releases about X-30, and looked at the satellite photos of the 25,000' runway and huge hangar at Groom Lake / Area 51, and the disinformation about 'Aurora' in Aviation Leak, and evaluated them all as signs that the USA would soon have cheap frequent access to space.

And those old fossils on the Politburo remembered many previous occasions when the West had done things they couldn't - most notably Apollo. They ignored their own science advisers and spent millions of rubles on similar hopeless projects like Polyus
www.astronautix.com/craft/polyus.htm and Tu-2000
www.astronautix.com/craft/tu2000.htm

which helped drive their empire into collapse.

And it wasn't just dumb Communists who were fooled. In his fascinating memoirs, NASA-Dryden aerodynamicist Ken Iliff describes a meeting of the AIAA soon after the Challenger crash. In the morning session, the NASA Administrator described how they would build a replacement Shuttle Orbiter from the existing blueprints - for about $3B. After lunch, the head of the NASP project showed graphs indicating that the X-30 would be designed, built, and flown for only about $5B.

Afterwards at the coffee break, Iliff expected many of the experienced engineers in the audience to point out the obvious contradiction between these two presentations. But nobody else seemed to have noticed. Everyone was wildly enthusiastic about X-30 and seemed to have no doubt that all its super-advanced technologies could be perfected within this bargain-basement budget.

This little episode shows that even hard-nosed rocket scientists have an emotional weak spot. They are in love with the idea of space travel, and don't apply the same critical standards to space projects that they would to buying a used car. (If any of my old Space Cadet friends are reading this, they may recall a time when I was a DC-X fan myself.)

But 20 years later there is no longer any excuse for us to fool ourselves. The Cold Equations dictate that rockets need to look like oil storage tanks, not the sleek spaceships of science fiction. This will always be true until we have developed some totally new technology like "unobtainium".

And the Cold Equations also dictate that rockets need to operate like rockets, not like airplanes. New technologies have always required new ways of thinking. Firms that tried to build, sell, and maintain diesel locomotives in the same ways they had handled the old steamers all went broke, like all the alt.space booster companies that have followed the space airplane model.

Mike Griffin understands the Cold Equations. He has seven college degrees. He has taught aerospace engineering. He has a fixed budget and schedule to work with, and knows that there isn't enough money or time available to develope some magic technology that would make the simple one-piece spaceships of science fiction work.

Griffin's plan may well be too expensive and too boring to succeed, but returning to the fantasy projects of the 1980s and 1990s is not the way to fix it. We Space Cadets need to get this virus out of our system before it does any more damage to our future in space.

Jeffrey F. Bell is a former space scientist and recovering pro-space activist.