THE COST PER POUND TO ORBIT
THE ELEPHANT IN THE ROOM

Ronald Hattie
Honeywell Aerospace
rjhattie@gmail.com

ABSTRACT

We all want to get to Mars – and this means having economically sustainable long term access to Mars' surface allowing the establishment of a second home for humanity. However, the starting point on our trip to Mars is low earth orbit. Unfortunately, getting to low earth orbit currently costs ~$2200 through $10,000+ USD per pound! This is the largest single driver in the cost structure of getting to Mars, and absolutely must be tackled before Mars can become our new home. In practice, opening up the solar system for human exploration will require much lower travel costs – perhaps $100 per pound to low earth orbit. This talk will examine and break down the factors which are the biggest drivers in launch costs, and what can be done to breach the gap between where we are, and where we need to be in terms of launch costs. A history of past efforts in this regard along with the associated pitfalls (remember the Space Shuttle?) will be examined. Current programs will be analyzed in light of these cost factors, and future launch system evolution will be discussed.

SCOPE OF DISCUSSION

The next 25 years of human spaceflight could potentially be one of the most important eras of human history – the first push of earth life beyond the boundaries of the earth itself. We shall concern ourselves here with this period of imminent future history. As one of the initial goals will be humans to mars, this constrains the technologies and vehicles of interest. Specifically, we are interested in the economics of human rated launch systems, and launch systems capable of 10 tons or more of lift capability capably of lifting crewed vehicles to orbit. The propulsion technologies employed will (of necessity) be those which shall be proven flight worthy and safe within that period of time. Further, as there will not yet be an established human presence in space, launch solutions will not be able to rely on systems (such as a space elevator) which would require an established space industrial presence to build.

Finally, nuclear rockets (both of the nuclear thermal and Orion type) are ruled out. These are solutions that are possible in an engineering sense, but not in an environmental, safety, or economic sense due to fear of nuclear contamination. This leaves us with the conjecture that the launch systems which will be employed for the initial ascent into space will remain as they are currently – a chemically powered system which works on the rocket principle.

PHYSICS OF CHEMICAL ROCKETS FOR AN EARTH TO MARS TRIP

All systems which use their own fuel as the reaction mass are governed by the rocket equation as shown below[1]:

$$\Delta v = v_e \ln \frac{m_0}{m_f}$$

Where delta v is the mission velocity change
v_e is the exhaust velocity
m_o is the original mass (rocket + propellant)
m_f is the final mass (delivered rocket and payload)
The journey from Earth to Mars involves a series of four mission segments, with each succeeding mission segment constituting a payload for the mission segment proceeding it. These mission segments are as follows:

-Launch from Earth's surface to low earth orbit
-Injection into a transfer orbit from Earth to Mars (likely either a Hohmann orbit for freight, or free return for humans)
-Capture into Mars orbit, and transfer to LMO (low Mars Orbit)
-Descent to Mars surface

Each of these mission segments requires a large velocity change (referred from here forward as a delta V). Table 1 below shows the approximate delta V requirements of each mission segment.

Table 1 – Mars Outward Bound Mission Segment Delta V and Overall Mission Mass Ratio[2]:

Mission Segment	Delta V (Km/s)	Mass Ratio*
Ground to LEO	9.3-10	403
LEO to Mars Transfer	4.3	25
Mars Transfer to LMO	2.7	7
LMO to Mars surface	4.1	3
Total	**20.4 - 21.1**	1

*Mass Ratio calculated assuming overall mission (including all four segments) based on the rocket equation. Liquid O_2 + CH_4 propellant is assumed, with a specific impulse (Isp) of 350s.

Of special importance for Table 1 is the Mass Ratio column. Essentially, to get one unit of mass on the surface of Mars, a vehicle weighing 403 units of mass is required on a launch pad on th surface of Earth is required! All of this to launch 25 units of mass to low earth orbit, which is what is now available to conduct the remainder of the mission. Almost 94% of the initial rocket mass is consumed just getting to low earth orbit. This mass of propellant must be housed in insulated tanks, lifted by a propulsion system, and be controlled by a guidance system. The relative cost of each mission segment therefore scale roughly in accordance with the mass requirements of each mission segment. Clearly, it is this initial trip to low earth orbit is where the vast majority of resources (and hence money) are consumed!

Potential Solutions to the problem:

Examination of the rocket equation above indicates three potential paths forward. The first strategy is to minimize the mass requirements to be sent to Mars in the first place. Initial missions can travel light, live "off the land" by generating their return propellant on the surface of Mars using the Mars atmosphere, and using the Mars soil as radiation shielding. This is the solution employed by the Mars Direct plan[3]. While suitable for initial exploration of Mars, any permanent human presence on Mars will necessitate ever increasing mass delivery requirements to the surface of Mars to sustain the colony. Even with in situ resource use on Mars' surface, the launch costs will rapidly become excessive[4].

The second potential solution proposed to the rocket equation is a large increase in the rocket exhaust velocity. The required launch mass on the surface of Earth will drop exponentially as the rocket exhaust velocity increases. Unfortunately, the only immediately available option to do this is the nuclear propulsion option, which we have already dismissed above within the time constraints of the next quarter century.

This leaves one other option – accept the large mass requirement for the initial launch from the ground, but examine the situation from an economic perspective – is it possible to minimize the cost of this initial mission segment, even with the mass constraints in place?

CURRENT -VS- REQUIRED LAUNCH COSTS FOR SPACE COLONIZATION

Launch costs on a company by company data typically are proprietary, and so are not explicitly quoted here. However, in general launch costs will vary from the neighborhood of $10,000/lb[5] for older systems such as the space shuttle (retired) Atlas V or Delta IV heavy, down to perhaps $2000/lb for newer systems such as what SpaceX quoted for the Falcon 9 V1.1. Further cost drops to roughly $1000/lb are anticipated for the Falcon 9 Heavy[6].

Studies over the years conclude that a general range around $100[7] per pound ($220/Kg) is the threshold for enabling economic development of near earth space resources (solar power, LEO industries, Moon mining, colonization of Mars). Clearly there is a massive gap between where we are, and where we need to be! We need a cost reduction of roughly two orders of magnitude from current costs. To bridge this gap, we must examine the drivers of launch costs to determine where the potential savings are.

A STUDY OF COST DRIVERS FOR LOW EARTH ORBIT ACCESS

Launch Rate:

Figure 1 below is a Log-Log plot, with system launch rate in terms of fights/year on the X-axis, and Launch costs in terms of $/Lb on the Y-axis. Various predictions of launch costs -vs- launch rate are presented from various University and Industry groups. At a given launch rate, there appears to be a variation from minimum to maximum costs of roughly one order of magnitude.

However, across the range of launch rates on the X-axis, the average launch costs will decline over three orders of magnitude as we increase launch rate from the current levels of 10 flights/year through 1,000,000 flights/year. Launch rate is by far the greatest driver and indicator of launch costs. This is a classic economics of scale relationship often seen in other areas of human endeavor.

Another interesting aspect of Figure 1 may be appreciated by observing the "Low Prod 747" data. As it turns out, of one were to amortize the entire development and manufacturing budget of the 747 program over only four aircraft, build a separate hangar for each machine, custom manufacture parts as needed, and fly each machine only once per year, costs per flight in Space shuttle operating costs may be obtained. It is not the technology level, or even re-usability that sets launch costs – it's flight rate alone! Re-usability only helps with launch costs if it is combined with a quick turnaround time that translates into high flight rates.

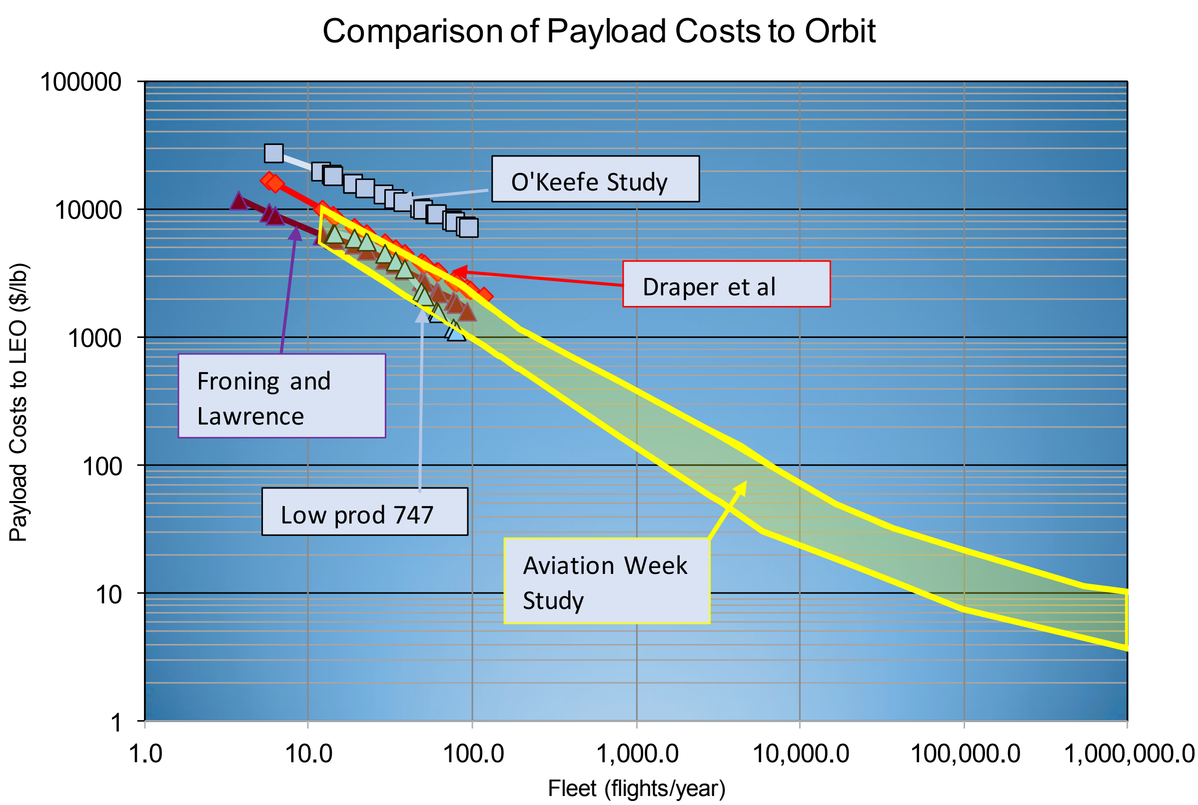

Figure 1 – Launch Costs/Lb -vs- Launch Rate[8]

Figure 1 above shows only the final launch cost as a function of flight rate. It is further useful to break down the cost structure of Figure 1 into its constituent parts to determine which are the largest cost drivers, and establish any relationships between the significance of each of these costs and launch rate. Doing so will enable a designer to optimize the cost of a launch vehicle if a known launch rate is to be targeted.

Some of these constituent contributors to the overall launch costs are:

-Propellant – Propellant cost scales linearly with launch count (each launch requires the same quantity of fuel)
-Infrastructure – Infrastructure cost increases linearly with launch rate (higher launch rate requires bigger factories, transportation facilities and launch pads), and declines with total number of launches
-Insurance, Maintenance and Production – cost per launch declines with increasing launch rate as risk can be quantified and minimized.
-Research, Design, Test, Engineering – This is a ONE TIME EXPENSE which must be amortized across all launches made with the final design.

As seen in Figure 2 below, the relative proportion of these expenses will vary as a function of launch rate only.

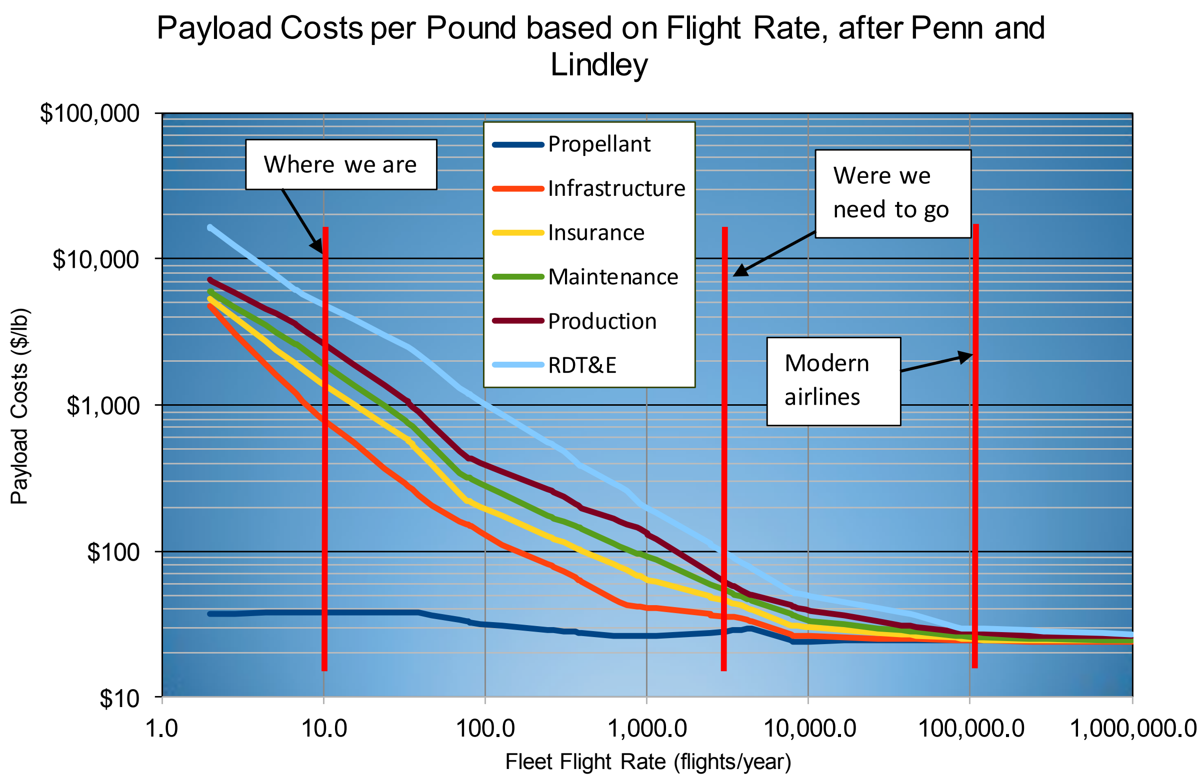

Figure 2 – Launch Cost Breakdown by Cost Driver and Launch Rate[9]

From here to there:

Table 2 next page is a snapshot of Figure 2. It examines a cost breakdown at 10 flights per year, and at 3000 flights/year (or roughly $100/lb). The changes are huge, are a direct result of the economics of SCALE.

Table 2 – Snapshot of Cost Breakdown at 10 and 3000 Flights/Year*

Cost	At 10 Flights/Year		At $100/lb ($220/Kg) ~3000 flights	
Contributor	Cost/lb	% of Total	Cost/lb	% of Total
Propellant	$ 38	0.8%	$ 28.03	28.0%
Infrastructure	$ 767	15.6%	$ 7.92	7.9%
Insurance	$ 587	11.9%	$ 9.98	10.0%
Maintenance	$ 554	11.2%	$ 8.76	8.8%
Production	$ 720	14.6%	$ 8.60	8.6%
RDT&E	$ 2,259	45.9%	$ 36.71	36.7%
TOTAL	**$ 4,925**	**100.0%**	**$ 100**	**100.0%**

*Data extracted from Ref 9.

As can be seen at 10 flights per year, amortized RDT&E absolutely dominates the cost structure at low flight rates, being worth 46% of each launch. Fuel cost are insignificant, and the other cost factors are worth roughly 10-15% each.

At 3000 flights/year, the situation becomes very different. Amortized RDT&E costs have shrunk enormously from $2259/Lb down to $36.70/Lb! Fuel costs, which remain similar to what they were at low launch rates are comparably priced, with the other cost drivers now being less than $10/Lb each. A service which is only affordable to large institutional entities at 10 flights/year becomes a consumer product at 3000 flights/year.

Other Cost Factors Besides Launch Rate:

At a given launch rate in Figure 1, a cost band stretching across an order of magnitude is defined. Here, we discuss some factors contributing to this spread in cost. A well known quality control metric is that 80% of the cost is designed in[10]. The launch vehicle must be designed for quick, easy turnarounds with only a visual and automated inspection between flights to achieve high launch rate. Design features which do not decrease turnaround time in general will not increase launch rate, and hence will not decrease launch cost. It is exceedingly difficult to “go back” and re-design an expendable launch vehicle to be re-used once it’s in service.

Production Costs generally go down as more rockets are made – a rough rule is that each time production is doubled, the next group will cost 90-95% what the previous group cost[11]

Finally, development costs per unit mass of payload drop exponentially as the payload size increases. Figure 3 illustrates a sample launch vehicle in the 10-20 ton payload class. Three curves are plotted: one for an expendable vehicle, one for a partially re-usable vehicle, and one for a fully re-usable vehicle. The figure is again a log-log plot, with payload mass on the X axis, and development cost in millions of dollars per pound of payload on the Y. It can be clearly seen that the development cost per pound of payload decreases rapidly as payload size increases.

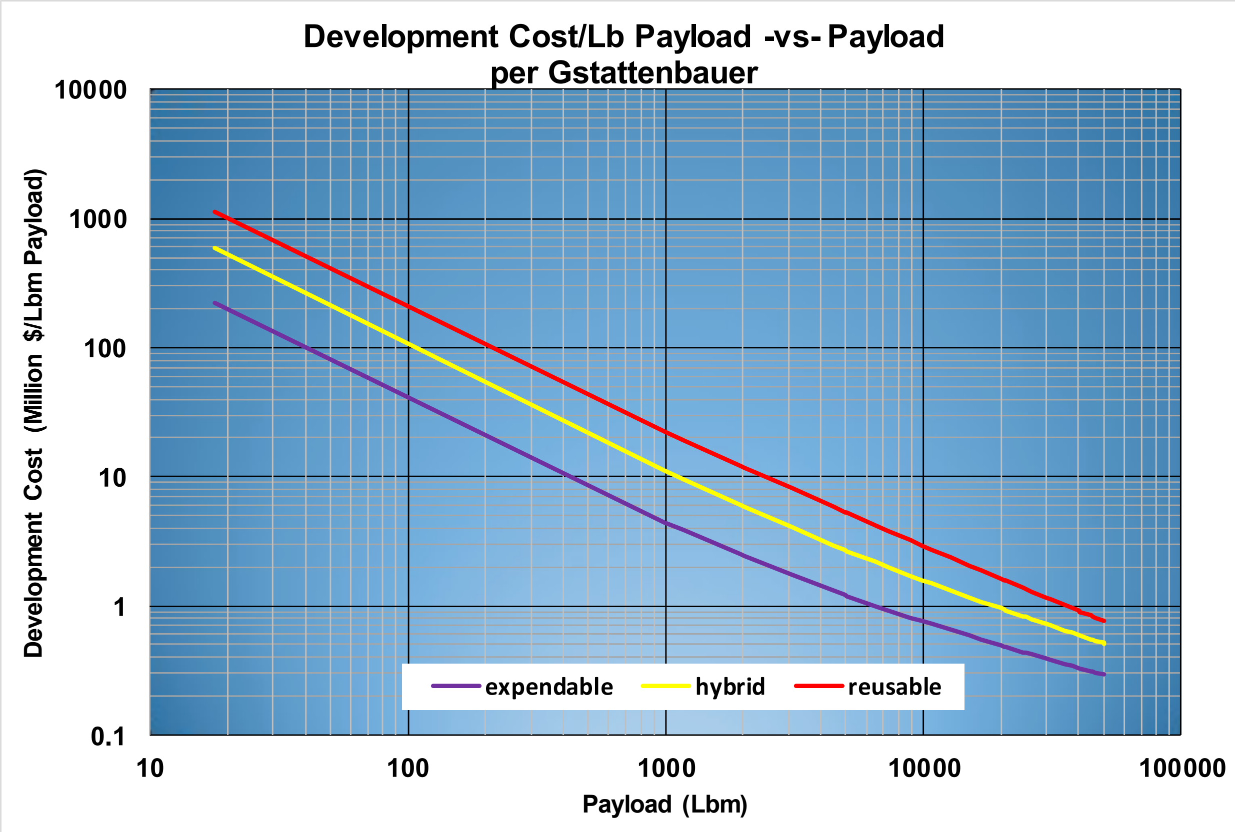

Figure 3 – Development Cost/Pound of Payload -vs- Payload Mass[12]

Summing up:

In effect, to control launch costs, design the vehicle from the start to be re-used easily with just a visual/system inspection between flight, build it big, Build Lots of it, ad fly each rocket many times. We are leveraging economics of scale in payload size, production, and launches per rocket booster!

OLD -VS- NEW SPACE, AND THE EXAMPLE OF THE SPACE SHUTTLE

There are two sectors operating at the moment in the launch market. "Old Space" consists of government controlled and owned industrial processes (such as Space Launch), and also include legacy aerospace companies based on cost plus contracts and government specifications (such as ULA). "New Space" consists of upstart companies which concern themselves with market share and launch costs only (SpaceX, Blue Origin)

Economic principles were of course known to the space shuttle designers – the initial goal of the program was to safely increase launch rate and reduce costs. Initially, 50 missions/year were planned, and costs of $1,400 / Kg ($635/lb) in 2011 dollars were anticipated for the program. These goals weren't met, with actual costs being more like $10,000/lb[13]. Here we shall examine some of the factors behind this.

Original intent of Shuttle Program:

The original concept began as a two-stage system, consisting of two all metal winged vehicles with one being a booster, and the smaller orbiter making it all the way to orbit. The system would launch vertically and land like any aircraft. Both vehicles were to be fully re-useable with rapid turn around. The vehicles' skin was to be the load bearing element with additional metal tiles and ablative coatings where needed for the heat of re-entry. This was based on prior successful X-15 testing. Finally, all liquid rocket motors were to be incorporated. Figure 4 below is an illustration of the baseline configuration[14].

Roll it out, tilt it vertical, and go!

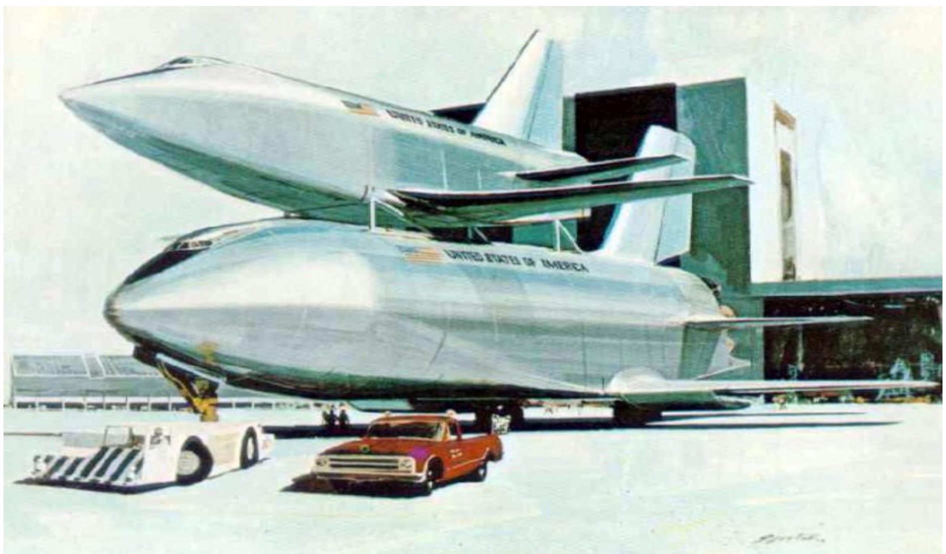

Figure 4 – Space Shuttle Initial Configuration

Conflicting goals:

In the era in which the Space Shuttle was developed, 50 flights per year was greater than the entire annual launch rate of the US. To get launch rate up for the shuttle, all other rocket progams were de-funded. All customers (with wildly different needs) had to use the shuttle. These customers generally fell into three catagories:

(1) The air force wanted a 1250 mile cross range capability[15], based on a requirement on a polar launch trajectory to be able to abort and land back within the US after a single orbit. The required large wings be incorporated into the design. Wings are heavy and expensive structural elements, which have to be lifted all the way to orbit, and be shielded from the heat of re-entry. Unfortunately, this consumes mass which could otherwise be sold as payload, and serves no purpose until the vehicle glides in for landing.

(2) Commercial customers wanted access to low and geo-synchronous orbit at a minimum cost. A crewed cabin served no purpose in lifting payload to orbit, but costs substantial amounts of mass which could otherwise be sold as payload.

(3) Nasa wanted crew a crew cabin for manned missions and access to a space station. Also, Nasa has a history of emphasizing technology over reliability. For example, the Space Shuttle Main Engines (SSME) had enormous performance with Isp values in excess of 450 s, with extreme chamber temperatures (6000ºF) and pressures (3000+Psi). The cost of this was that a complete teardown was required after every flight[16].

This conflict between the customer groups drove many design iterations, some of which are shown in Figure 5.

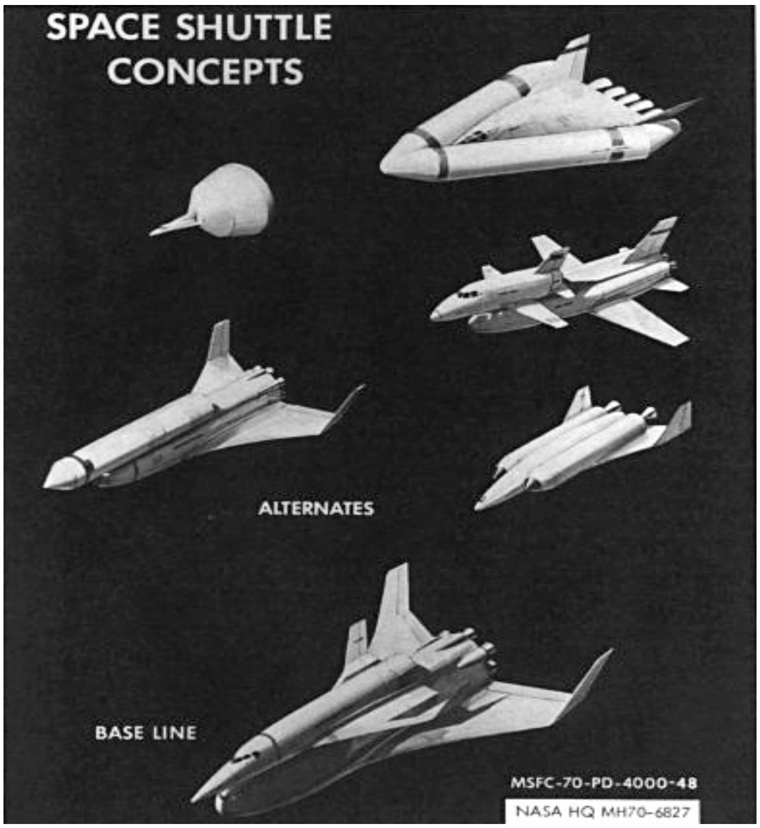

Figure 5 – A small sample of the many configurations investigated for the Space Shuttle[17]

The government budget cycle:

Another substantial obstacle to the Shuttle Program is traceable back to the federal government annual budget cycle. Federal law requires a new budget be set each fiscal year. Each program (including the Space Shuttle) must jockey for funding again with each new year. Nothing is funded on a program length basis. As a result, emphasis swung from life cycle costs and safety to minimizing the development cost in each fiscal year.

The all high temperature alloy frame was replaced with an aluminum frame, with ceramic and carbon-carbon tiles to protect it from the heat of re-entry[18]. As aluminum airframes have no intrinsic heat tolerance of their own, any failure in the thermal tile system could (and did) result in catastrophic failure of the vehicle. The large first stage winged booster was replaced by an expendable fuel tank and two solid fueled rockets which could NOT be turned around quickly.

In fact, it cost more to re-use the solid rocket boosters than it would have cost to just buy new ones for each flight. Finally, no emergency escape system was provided for the astronauts on liftoff.

Lessons we can learn:

The Space Shuttle program showed that mere re-usability of the craft in no way guarantees lower launch costs if it doesn't translate into quick turnarounds on the launch pad. Launch rate and reliability determine launch costs! As discussed earlier, these can only be achieved by designing based on life cycle costs and safety – and require complete focus from program inception to first launch! Robustness, redundancy and safety are more important than the fanciest, newest technology. In the end these features allow high launch rates.

Is the government really the best place to do this?

THE RISE OF NEW SPACE

SpaceX developed the Falcon 9 v1.0 rocket for $300 million. Nasa estimated that the same rocket would have cost $3.6 billion if developed through a traditional cost-plus approach[19]. For $263 million dollars, Nasa built a launch tower for the Aries I component of the Constellation program. That program was cancelled, and the tower torn down[20].

Once the "first mover" cost of a new technology is paid, and the field becomes a business, government programs typically cost 10 times as much for a unit of output as the equivalent private venture!

In the "Old Space" world, Space launch continues development with projected program costs, on a cost plus basis, expected to reach $17 billion through end of 2017[21]. Unfortunately, the projected launch rate is once every TWO years. As demonstrated earlier, this is NOT conducive to lower launch costs.

In the "New Space" world, SpaceX continues to develop the Falcon 9 with a first stage that is now re-usable. The Dragon I capsule has also been re-used. The Falcon 9 heavy is around the corner. Blue origin continues work on the New Glenn rocket with similar payload to Falcon 9 heavy, also with a re-useable first stage.

Commercial crew – Helping First mover costs:

We stand at a threshold moment – private companies are beginning to take over the role of space access! There is a fundamental problem which must first be overcome. Customers would want much lower launch costs before buying a large volume of launches numbering in the thousands per year. The private sector can't get to those larger launch rates without paying customers to fund them. SpaceX is flying roughly 10-20 flights/year. Launch rates on the order of 3000 flights/year are required to reach $100/pound.

NASA's commercial crew program can help bridge this gap. The program helps in two crucial ways[22]

(1) It helps to defray the enormous initial research, design, test an engineering costs which must be paid by any rocket company before any revenue can be had.
(2) As a paying customer to access low Earth orbit and the ISS, Nasa can begin the process of escalating the launch rate from the private sector, driving down costs overall.

CONCLUSIONS

Launch Rate, and the associated benefits of SCALE is the greatest driver of launch costs. In order to reach required launch rates to get costs to economic levels, low earth orbit, Moon bases, and Martian colonization must happen simultaneously to generate the needed demand. The private sector will have to lead the way with a for profit business model, with Government as a paying customer.

NASA should focus its resources in new technology development, initial exploration and mapping, and helping to cover first mover costs for new and required space systems. These would include re-entry and landing vehicles for the Moon and Mars, long term recycling life support systems, and habitation modules.

REFERENCES

[1] https://en.wikipedia.org/wiki/Tsiolkovsky_rocket_equation, accessed Aug, 2017
[2] https://en.wikipedia.org/wiki/Delta-v_budget, accessed Aug, 2017
[3] The Case for Mars, Robert Zubrin, 2011
[4] http://www.businessinsider.com/mars-one-mit-students-mission-not-feasible-debate-2015-8, accessed Aug, 2017
[5] https://www.nasa.gov/centers/marshall/news/background/facts/astp.html, accessed Aug, 2017
[6] https://www.nextbigfuture.com/2013/03/upgraded-spacex-falcon-911-will-launch.html, accessed Aug, 2017
[7] http://www.npr.org/sections/money/2011/07/21/138166072/spaceflight-is-getting-cheaper-but-its-still-not-cheap-enough, Accesed Aug, 2017.
[8] Future Spacecraft Propulsion Systems – Enabling Technologies for Space Exploration, 2nd Edition, Paul A. Czysz & Claudio Bruno, 2009, Figure 3.1
[9] Future Spacecraft Propulsion Systems – Enabling Technologies for Space Exploration, 2nd Edition, Paul A. Czysz & Claudio Bruno, 2009, Figure 3.2
[10] Design for Manufacturability: How to Use Concurrent Engineering to Rapidly Develop Low-Cost, High-Quality Products for Lean Production 1st Edition, Dr. David Anderson, 1990
[11] Cost Comparison of Expendable, Hybrid, and Reusable Launch Vehicles, Thesis by Greg J. Gstattenbauer, Second Lieutenant, USAF, DEPARTMENT OF THE AIR FORCE AIR UNIVERSITY AIR FORCE INSTITUTE OF TECHNOLOGY
[12] Cost Comparison of Expendable, Hybrid, and Reusable Launch Vehicles, Thesis by Greg J. Gstattenbauer, Second Lieutenant, USAF, DEPARTMENT OF THE AIR FORCE AIR UNIVERSITY AIR FORCE INSTITUTE OF TECHNOLOGY, data adapted from Figure 20.
[13] https://en.wikipedia.org/wiki/Space_Shuttle_program, accessed Aug 2017.
[14] https://io9.gizmodo.com/early-design-specs-show-the-space-shuttle-could-have-be-1528524224, accessed Aug 2017
[15] https://en.wikipedia.org/wiki/Space_Shuttle, accessed Aug 2017
[16] https://en.wikipedia.org/wiki/Space_Shuttle_main_engine, accessed Aug 2017
[17] https://en.wikipedia.org/wiki/Space_Shuttle_design_process, accessed Aug 2017
[18] https://io9.gizmodo.com/early-design-specs-show-the-space-shuttle-could-have-be-1528524224, accessed Aug 2017
[19] https://en.wikipedia.org/wiki/Falcon_9_v1.0, accessed Aug 2017
[20] https://www.nasaspaceflight.com/2010/07/unemployed-ares-i-mobile-launcher-crawler-trip-august/, accessed Aug 2017
[21] https://en.wikipedia.org/wiki/Space_Launch_System, accessed Aug 2017
[22] https://en.wikipedia.org/wiki/Commercial_Crew_Development, accessed Aug 2017