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Shuttle Shortfalls and Lessons Learned for the Sustainment of Human Space Exploration

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Much debate and national soul searching has taken place over the value of the Space Shuttle which first flew in 1981 and which is currently scheduled to be retired in 2010. Originally developed post-Saturn Apollo to emphasize affordability and safety, the reusable Space Shuttle instead came to be perceived as economically unsustainable and lacking the technology maturity to assure safe, routine access to low earth orbit (LEO). After the loss of two crews, aboard Challenger and Columbia, followed by the decision to retire the system in 2010, it is critical that this three decades worth of human space flight experience be well understood.

Understanding of the past is imperative to further those goals for which the Space Shuttle was a stepping-stone in the advancement of knowledge. There was significant reduction in life cycle costs between the Saturn Apollo and the Space Shuttle. However, the advancement in life cycle cost reduction from Saturn Apollo to the Space Shuttle fell far short of its goal. This paper will explore the reasons for this shortfall.

Shortfalls and lessons learned can be categorized as related to design factors, at the architecture, element and sub-system levels, as well as to programmatic factors, in terms of goals, requirements, management and organization. Additionally, no review of the Space Shuttle program and attempt to take away key lessons would be complete without a strategic review. That is, how do national space goals drive future space transportation development strategies? The lessons of the Space Shuttle are invaluable in all respects – technical, as in design, program-wise, as in organizational approach and goal setting, and strategically, within the context of the generational march toward an expanded human presence in space. Beyond lessons though (and the innumerable papers, anecdotes and opinions published on this topic) this paper traces tangible, achievable steps, derived from the Space Shuttle program experience, that must be a part of any 21st century initiatives furthering a growing human presence beyond earth.

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Nomenclature

ASTP = Apollo Soyuz Test Project
CPI = Consumer Price Index
EVM = Earned Value Management
LEO = Low Earth Orbit
LPY = Launches per Year
R&D = Research and Development
SPST = Space Propulsion Synergy Team
STS = Space Transportation System

I. Introduction

The Space Shuttle is a wondrous achievement. It is not the purpose of this paper to second guess the past but rather, to learn from the past and move forward. Any technology attempting to open a new frontier will inevitably have shortcomings. Later systems with mature technology often forget past systems that helped to understand fundamentals. In this respect it is critical to realize that the Space Shuttle was born amidst an environment that stressed economics and capabilities – the principal selling point of the Shuttle "Space Transportation System" (STS) was to provide an "economical capability for delivering payloads of men, equipment, supplies and other spacecraft to and from space by reducing the operating costs an order of magnitude below those of present systems[5]". The Space Shuttle was born during a dire federal budget situation that would last a decade, a federal budget environment where NASA, regardless of the then recent colossal success of the 1969 Moon landing, was to see the same budget pressures as other federal agencies. NASA's response as the initial planning years of Shuttle evolved was to turn to reusability. It is with this in mind – reusability – that many lessons can be discerned that are as relevant today as back then.

II. Looking Back, Saturn to Shuttle

To understand the lessons of Shuttle it is first necessary to look back to the NASA budgets at a point in time when the last lunar exploration capability existed. By 1970 the hand writing on the wall spelled the end of the Saturn Apollo program at the same time as the new Shuttle program was being formulated. The similarity to the current situation, the Shuttle being retired and a new system, Constellation, being developed, is not made lightly or by chance. The last "Apollo" mission was in July 1975, the joint Apollo-Soyuz Test project (ASTP) and the "gap" in human space flight would then last until April 1981, the first Space Shuttle flight, almost six years later. Selling the Shuttle on cost and capabilities was a response to the Saturn Apollo budgets of the time. On this later point of budgetary pressures the analogy to the current situation, arising from the loss of Columbia in 2003, would appear to draw a difference. On further analysis it will be shown there is still similarity.

A review of the Saturn Apollo budgets immediately begs the question – was the Shuttle truly a more affordable system than Saturn Apollo or was it merely doing less and thus costing less?

Shown in Figure 1 is an excerpt of the Saturn Apollo budget from 1960 to 1973[6]. Observe the following, with the intent of determining a "rough cost per year" to produce the expendable hardware and operate and launch such hardware to provide a lunar exploration capability:

1. The budget peaked two years before the first Moon landing.
2. The costs on 1971 and 1972 drop significantly as compared to the previous two years.
3. The system was fully expendable.

From this it can be surmised that hardware flown any year would have had some actual costs in previous years as production lagged the actual delivery, integration, checkout and launch. It is suggested that the use of 1969 budget data for Apollo would give a fair estimate of the cost per launch as there were three Lunar and one earth orbit launches that year.

[5] "Space Shuttle, A History of Developing the National Space Transportation System, 2nd Edition, The Beginning through STS-75", (1997), Jenkins, Dennis R., pg. 74.
[6] Apollo by the Numbers, A Statistical Reference for the Manned Phase of Project Apollo, (1996), Orloff, Richard W., pg. 22.

- Using the values from 1969, where four Saturn V launches, occurred the budget for Apollo was $2.03B or about $$506M each flight. Adjusted to 2009 dollars, this would be $3.32B per launch.
- Using a value "between" the 1970 and the 1971 budget would yield: $1,299,907,000 (average, then year) which adjusted to 2009 dollars[7] would be $3.75B/launch for a couple of lunar launches per year - However, these years did not have any flight hardware production cost included for 1971.
- Using the value of 1971 would yield simply $913,669,000 (then year) which adjusted to 2009 dollars would be $5,274,611,100. (i.e., $5.3B/yr for a couple of lunar launches per year *or* $2.8B/launch. However, again this year did not have any flight hardware production cost included.

Now there are numerous and endless ways in which the prior calculation could be adjusted, refined, diced, spliced and debated. Some will yield numbers higher or lower than these notional calculations, but the same valid point would likely remain always – The United States federal budget, under numerous pressures, looked to NASA in the early 1970's to do more than a couple of lunar launches per year for what were then "space transportation" budgets in the rough order of today's human spaceflight space transportation budgets. As significantly, the desire was that no space related development again require the levels of peak funding that would add to a total agency level that approached 4% of the total federal budget in 1966[8]. Today NASA's budgets stand at about ½ of a percent of the federal budget.

This begs the question about the Shuttles budgets. To best make this comparison it's important to have a couple of snapshots in time. This is because accounting in NASA of what's "in" a programs budget and what's "out" has evolved and changed many times over the years. Consider a sample budget from 1994 in what was at the time referred to as "pre"-full-cost (but which was pretty close to eventual "full cost").

	Shuttle 1994	
1.	Shuttle Operations	$3,375.7 M
2.	STS Capability Development	$672.5 M
3.	Shuttle Production and Operations Capability	$925.2 M
	SUM =	$4,973.4 M

It's important to understand that items 2 and 3 above, while non-recurring development items, were continuously funded in one form or another throughout the Shuttle's lifetime (the name changing constantly as well). The actual recurring yearly production and operations are in line item 1 (line item 3 naming being a misnomer at that time).

Considering the Saturn costs from above, but translated to comparable *1994 dollars*, would yield values for the Saturn Apollo's four lunar launches per year of $9.596B/yr, or $2.4B/launch using just the 1969 budget. Compare this to the Shuttle's 1994 value of $4.9B/yr. for seven launches or $0.7B/launch.

The differences to reconcile in such comparisons become launch rate; i.e., Shuttle's demonstrated seven flight per year delivery rate (1992 through 1997) vs. Saturn-Apollo's three launches-per-year capability, the potential learning curve that Saturn-Apollo production and operations would have seen had it operated for a couple of decades, an effect seen in Shuttle as positive, and the qualitative value of two trips to the Moon, and obtaining lunar rock samples vs. the qualitative value of more flights to Low-Earth-Orbit (LEO) and the Shuttle's in-orbit flexibility.

[7] Using the NASA New Start Inflation Index, http://cost.jsc.nasa.gov/inflation/nasa/inflateNASA.html, a better adjustment than the Consumer Price Index (CPI) per se as it accounts better for the lack of mass production advances which have driven down the CPI over time.
[8] http://en.wikipedia.org/wiki/NASA_Budget

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	Program Total
Advanced Technical Development Studies	$100	$1,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,100
Orbital Flight Tests	$0	$0	$63,900	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$63,900
Biomedical Flight Tests	$0	$0	$16,550	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$16,550
High-Speed Reentry Tests	$0	$0	$27,550	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$27,550
Spacecraft Development	$0	$0	$52,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$52,000
Instrumentation & Scientific Equipment	$0	$0	$0	$11,500	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$11,500
Operational Support	$0	$0	$0	$2,500	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,500
Little Joe II Development	$0	$0	$0	$8,800	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$8,800
Supporting Development	$0	$0	$0	$3,000	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$3,000
Command and Service Modules	$0	$0	$0	$345,000	$545,874	$577,834	$615,000	$560,400	$455,300	$346,000	$282,821	$0	$0	$0	$3,728,229
Lunar Module	$0	$0	$0	$123,100	$135,000	$242,600	$310,800	$472,500	$399,600	$326,000	$231,433	$0	$0	$0	$2,241,033
Guidance & Navigation	$0	$0	$0	$32,400	$91,499	$81,038	$115,000	$76,654	$113,000	$43,900	$33,866	$0	$0	$0	$587,357
Integration, Reliability, & Checkout	$0	$0	$0	$0	$60,699	$24,763	$34,400	$29,975	$66,600	$65,100	$0	$0	$0	$0	$281,537
Spacecraft Support	$0	$0	$0	$0	$43,503	$83,663	$95,400	$110,771	$60,500	$121,800	$170,764	$0	$0	$0	$686,401
Saturn C-1	$0	$0	$0	$90,864	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$90,864
Saturn I	$0	$0	$0	$0	$187,077	$40,265	$800	$0	$0	$0	$0	$0	$0	$0	$228,142
Saturn IB	$0	$0	$0	$0	$146,817	$262,690	$274,185	$236,600	$146,600	$41,347	$0	$0	$0	$0	$1,108,239
Saturn V	$0	$0	$0	$0	$763,382	$964,924	$1,177,320	$1,135,600	$998,900	$534,453	$484,439	$189,059	$142,458	$26,300	$6,416,835
Engine Development	$0	$0	$0	$0	$166,000	$166,300	$134,095	$49,800	$18,700	$0	$0	$0	$0	$0	$534,895
Apollo Mission Support	$0	$0	$0	$0	$133,101	$170,542	$210,385	$243,900	$296,800	$0	$0	$0	$0	$0	$1,054,728
Manned Space Flight Operations	$0	$0	$0	$0	$0	$0	$0	$0	$0	$546,400	$422,728	$314,963	$307,450	$0	$1,591,541
Advanced Development	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$11,500	$12,500	$0	$24,000
Flight Modules	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$245,542	$55,033	$0	$300,575
Science Payloads	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$60,094	$106,194	$52,100	$0	$218,388
Ground Support	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$46,411	$31,659	$0	$78,070
Spacecraft	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$50,400	$50,400
Apollo Program	$100	$1,000	$160,000	$617,164	$2,272,952	$2,614,619	$2,967,385	$2,916,200	$2,556,000	$2,025,000	$1,686,145	$913,669	$601,200	$76,700	$19,408,134
NASA Total	$523,375	$964,000	$16,717,500	$3,674,115	$3,974,979	$4,270,695	$4,511,644	$4,175,100	$3,970,000	$3,193,559	$3,113,765	$2,555,000	$2,507,700	$2,509,900	$56,661,332
Apollo Share of Total Budget	>1%	>1%	1%	17%	57%	61%	66%	70%	64%	63%	54%	36%	24%	3%	34%

Figure 1

Apollo Program Budget Appropriations, $K[9]

[9] Apollo by the Numbers, A Statistical Reference for the Manned Phase of Project Apollo, (1996), Orloff, Richard W., pg.22.

To mitigate these differences in a comparison one must return to the main issue at hand, the expendable nature of one system vs. the semi-reusable nature of the other. Essentially one equivalency possible in comparing a Saturn Apollo to a Shuttle is that mass placed in LEO. In so far as the Saturn Apollo placed an S-IVB third stage into orbit along with an instrument unit, a command module and a service module, and a lunar lander, the total weights inserted into Earth orbit (gross) would be[10]:

Saturn Apollo:

SIV-B	170,000 lb
Instrument Unit	4,400 lb
Command / Service Module	66,871 lb
Lunar Lander	32,399 lb
Total =	273,670 lb

X 3 Launches per year = 821,010 lb / year
(plus 3 X 3 crew X 7 day missions = 63 crew days in space per year)

Plus - usable "cargo" – fractional, as returned lunar samples, small instrument packages

Shuttle

Shuttle Orbiter	240,000 lb (gross lift-off weight)
Payload	55,240 lb
Total =	295,240 lb

X 7 Launches per year = 2,066,880 lb / year
(plus 7 X 7 crew X 14 day missions = 686 crew days in space per year)

Plus - usable "cargo" – 55,000 lbs/launch, and in-orbit servicing, assembly and retrieval flexibility

It becomes clearer from the prior metrics then that in a sense the Shuttle did advance many metrics vs. Saturn Apollo, *even on a cost basis,* depending on the value judgment of lunar missions vs. in-orbit operations, but costs were not advanced as much as promised by the holy grail of (semi) reusability. Supposing the Saturn Apollo continuation cost at a value close to Shuttle's 1994 cost, that is both in the *range* of $5B a year (1994 dollars) one would still have to consider the budget viability or "affordability" of the "scenarios" as follow:

Scenarios –

- Continue Saturn Apollo — $5B/year (1994 dollars, content=2 LPY to the Moon)
- Funding to launch the other 5? payloads — $Unknown amount, likely significant

or

- Shuttle — $5B/year (1994 dollars, content=7 LPY to LEO)
- Funding to launch the other 7 payloads — $Included in above

It is above (putting aside only the value judgment of "lunar" scientific return vs. "LEO" scientific return) that it's seen that the Shuttle was more clearly an advance over Saturn Apollo, in terms of budgetary "affordability" on a recurring basis for human space flight, not just a matter of costing less to do less. While improving on affordability there were in Shuttle also simultaneous steps to further the technology of reusability, albeit with success and failure and much still to learn. Yet the goal of reusability as a "how" for affordability was tied to the basic notion that throwaway hardware offered no clear path for furthering the long term affordability of human access to space. This brings us to lessons learned and what Shuttle did show about reusability for a next generation wishing to simply make access to space increasingly more affordable and routine with every system that evolved. The former – making

[10] All weight values from the applicable "wiki" on that element, URL at: http://en.wikipedia.org/wiki/Main_Page

human access to space increasingly more affordable and routine – are aspects that an expendable system has never pretended to focus on as a long term goal. On the value proposition of "lunar" vs. "LEO" the question to also add is – at what price (or value proposition) do we place knowledge of reusable space planes?

III. Shuttle Design Lessons Learned

There are three key categories under which the most valuable technical lessons can be summarized for the Space Shuttle as related to affordability. These are complexity, reliability and maintainability.

Complexity: This metric is indicated by the number of parts, sub-systems, systems, or flight elements. It can be considered as "how much" of something has been designed into the launch vehicle or spacecraft in order to meet the functionality desired.

Reliability: This metric applies best at the component level. Reliability here refers to the probability a part will behave as required when tested, used, operated, powered, etc. Health can be detected at any time there is some visibility into the parts health. Even when a system has dual or triple redundancy a failure (or even a suspect condition) detected in one part will require action, either further test or often removal and replacement. Therefore, as complexity (parts count) increases, even when applied as a redundancy to increase system level reliability in flight, the actions required on the ground during processing are additive rather than multiplicative. This adversely affects affordability and system weight.

Maintainability: This metric is a measure of how easily a part, sub-system, system or element flows through the processes required to prepare and launch. It is a measure of labor intensiveness of the design. It is a measure of smarts, the ability to quickly test or diagnose, as well as design, such as ease of access to accomplish work, as well as of operability, as in ease of handling and servicing. Toxic fluids, for example, make working with a design difficult, by needing special gear and suits for workers, as well as making servicing difficult, if there is a leak, or merely as added safety precautions.

All these metrics can interact. If there are four tanks with a toxic fluid using low reliability (but redundant) valves here or there, then all other things being equal, the system is (a) more complex than a system with two tanks, (b) less reliable than a system where the valves had undergone more rigorous test-fail-fix cycles and (c) less operable than a system with a more benign fluid.

The Space Propulsion Synergy Team (SPST) has previously developed excellent examples of these lessons from Shuttle, on the need to focus on simplicity, reducing parts count, such as by improved functional systems integration, on the need to improve reliability, such as through robustness, and on the need for improved operability, such as by employing non-toxic systems.

The key technical "hows" arising from the Space Shuttle to improve on a future reusable launch vehicle are routinely repeated. A next generation concept must address some principal design and development "musts" as follows[11]:

1. Fewer separate vehicle propulsion systems (engines, thrusters, tanks, fluids, controls, actuators, etc).
2. Fewer engines total
3. Fewer tanks total
4. Fewer ground to flight interfaces
5. Greater automation in test and checkout
6. Fewer closed compartments and associated purges
7. Fewer unique fluids; increase the commonality of physical tanks and any fluids used across distinct functions, e.g., orbital maneuvering same as main propulsion
8. Increase reliability through assorted strategies, including, but not limited to, robustness, significantly separating the operating conditions from the variance possible, adding margin, or by more test-fail-fix / re-design cycles early in design development.

[11] Space Transportation Systems Life Cycle Cost Assessment and Control, AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 20-23 July 2008

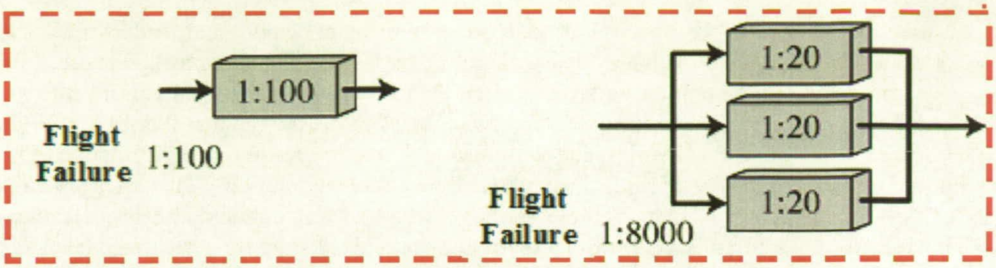

Figure 2

The later point on reliability is well known, yet the relation to the issue of volumes of production is often neglected. Consider that the lesson of Shuttle on reliability says "make it more reliable" - which is hardly worth noting. This is a trivial observation. The real lesson may lie in asking – why does the Shuttle have the reliability problems in ground processing that are reflected in data? One notion relates the lesson of reliability to that of simplicity as shown in Figure 2. To save upfront funding, parts with low individual reliability can be ganged to get a multiplicative redundancy benefit to systems reliability. The improvement in flight reliability occurs but there is, as in the example, 15 X times more likely hardware change-out on the ground (the sum of 1/20+1/20+1/20=3/20 divided by 1/100). If the system on the left of the figure had only two parts of 1/100 reliability in dual redundant mode the flight reliability would be 1/10,000 and have one less component than the triple redundant system to the right. Yet the ground operations perspective would be that the reliability burden was merely 13% of the triple redundant system with low reliability components (the sum of 1/100+1/100=2/100 vs. the 3/20).

Alternately a reliability strategy could add margin to a given design with fewer test / fail / fix cycles so as to still save up-front costs. Variance would be high but could in theory be tolerated well at reliabilities higher than current approaches with low margin. Figure 3 shows this relationship.

All this begs the question – "why has this lesson not received the attention on the solution that it deserves considering the promising benefit to affordability and safety?" Further in depth work is required in this area to address possible or *perceived* barriers such as (a) rocket equation limits, physics and all rationale against such reliability improvement that falls in the category of "it weighs too much" and (b) volumes of production which relate to national space transportation system goals.

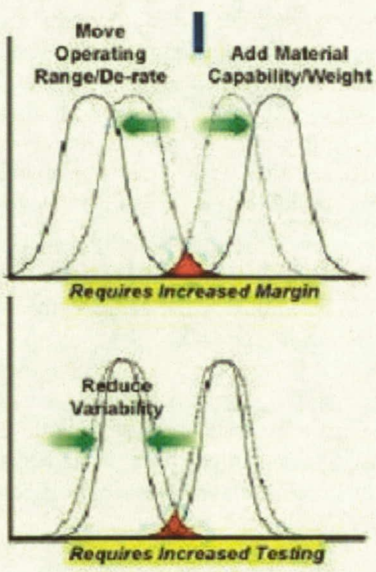

Figure 3

IV. Shuttle Programmatic ("Management" and "Leadership") Lessons Learned

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Cost Control

A principal lesson learned from the Space Shuttle in the area of management and leadership has to do with cost control across a life cycle. That which is not a focus can not be expected to be a controlled result. In an engineering and science driven organization the culture will, more often than not, push cost considerations into a realm between the neglected and the reactionary. Cost control becomes reactionary to the degree that it does not drive the vehicle or ground system design, these decisions being made with nearly all weight falling to performance requirements, near term costs (if any costs are emphasized), and rocket system weight considerations. This later reactionary method is what pushes off ever developing a smart vehicle (remove weight from onboard, push costs into the future as operations). This reactionary system is what results in an unaffordable system on a recurring basis, as the emphasis was up-front costs and the "sell" and the "get there". In addition the degree to which cost control is neglected means that the process of cost control is relegated to a budgetary process, a reporting process (such as Earned Value Management, EVM) or an assessment process (such as review boards, independent or otherwise). None of these are effective "control" processes that can change a design based on a future outcome of production, manufacturing or operations cost.

For this single area leadership is crucial as it is only leadership that can intervene to put an end to dysfunctional budgetary processes that are essentially dishonest and delusional. Current dynamics favor all things being optimistic and unrealistic when a program wishes to get started but making all such programs heavy and expensive once they get going. Only a leadership that refuses to partake of such a process can divert energies into more functional, credible and productive planning with expectations across all stakeholders, internal or external (Congress, the Office of Management and Budget (OMB), the Whitehouse and the scientific community) that are healthy and effective.

Supply Chain Management

A second crucial lesson in management derived from the Shuttle comes from observing the Space Shuttle extended supply chain. That is the series of practices, processes and technology that use information to enable the flow of physical material. This flow of information is intrinsic to the materials flow. Work in this area has developed preliminary simulations and the data effort involved has shown tremendous potential for reducing costs[12] across the functional areas that support the production, manufacture, assembly/integration, launch and mission/flight operations of a space transportation system. This issue goes to the heart of a healthy industrial base as well[13].

Simply put the process by which a document is generated, controlled, changed, scheduled, called up and eventually marked as containing completed requirements is a function of the system composed of practices (guidance, policy), processes (steps, people) and technology (software etc). Examples like this abound in both the contractor world as well as in government operations. These "in-direct" functions from contractor configuration control: scheduling, document generation, work control, requirements management, problem reporting, engineering drawings, change processes, etc.; to government configuration control: finance, procurement, drawings, human resources, engineering, etc. add up to significant percents (up to 50% at total levels) of complex operations such as the Space Shuttle. Left to themselves they will likely again be significant costs in any future system as legacy practices, processes and technology transfer to new systems without any understanding of the eventual costs.

Applying modern supply chain practices, even at low aerospace volumes, would mean first, understand, and second, control these in-direct costs. This crucial lesson falls in the category of low-hanging-fruit.

V. Human Space Flight Strategic Lessons Learned

There are various lessons from Shuttle that fall into the category of the strategic that are lessons for NASA as a whole and the space industry of which NASA is a part.

Strategic Lesson 1: Make sure it adds up long term by assuring recurring costs, such as for space transportation, do not consume future plans. When a space transportation system is developed and flies, such a success should not be considered strategic off-hand. It may be a tactical success and a strategic failure. In this sense the Shuttle experience has mixed results. Tactically the Shuttle was a success, a long lived system that served this nation for

[12] "Making the Case for a NASA Advanced Supply Chain Management Initiative", (2008), Zapata, E., NASA Kennedy Space Center. Also at: http://science.ksc.nasa.gov/shuttle/nexgen/Making_Case_SCM.htm

[13] "Counting the Links in the Supply Chain", NASA Rendezvous Magazine, (2008), Galluzzi, M., NASA Kennedy Space Center and Bujewski, T., The Aerospace Corporation. Also at: http://science.ksc.nasa.gov/shuttle/nexgen/SCM_Galluzzi_Bujewski.htm

three decades. Strategically it was a success in the sense that it enabled a Space Station and a human presence in space, making the notion of humans in space continuously a customary notion, a normal expectation. Alternately the system was a strategic failure to the degree its high recurring costs consumed many future plans. As shown in Figure 4 there were many plans[14] for what was to come once an affordable Shuttle was operational. Note the way the Shuttle budget rises and then drops in the figure, a behavior that actually became a peak followed by a steady and at times increasing yearly cost.

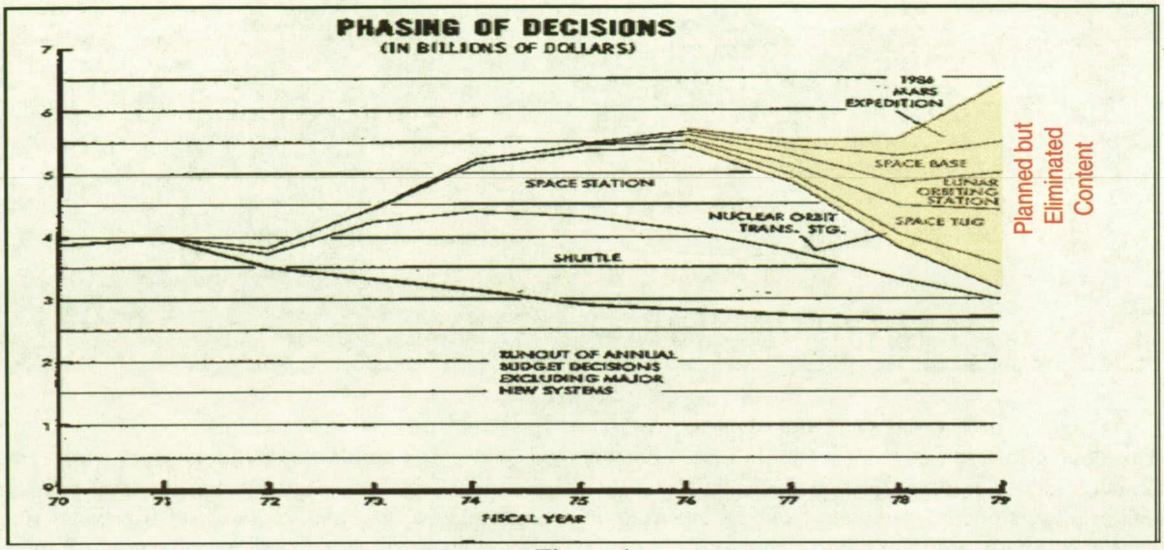

Figure 4

On the matter of Lesson 1 it is important to note that the new Constellation program sees this issue and references in assorted documents the need to have an "operations costs … sufficiently low to permit the simultaneous operation of near-term systems and the development of ongoing lunar and Mars systems." But also worth noting, Constellation does not show a "drop" once operations in 2020 begin with both the planned crew and cargo vehicles simultaneously. Observe the picture of events[15] in Figure 5, noting that the peak funds planned in 2017 do not (a) significantly drop after that and (b) are nearly twice, even in inflation adjusted terms, the current Shuttle space transportation allocated recurring yearly budget.

Strategic Lesson 2: Encourage competition explicitly, backed by funds, policy or lawmaking, rather than sponsoring government or private sector monopolies. The matter here may sound odd. Multiple companies large and small (Lockheed-Martin, Boeing, Space X, etc) compete for dollars. To understand this issue the question will be phrased differently –

- Do we allow manufacturers of passenger jet aircraft (such as Boeing) to sell only to themselves (as airline operators) to deliver mostly government employees and cargo?

The actual answer is yes, once we did, in the past. Anti-trust legislation, recognizing this was not a good arrangement (i.e., Boeing and United Airlines) put an end to this to encourage the growth of air travel. Multiple operators could then buy airplanes and more importantly encourage safety, affordability and reliability by competing one manufacturer against another. The operators could walk away from concepts that benefitted manufacturers only (such as by needing extensive overhaul, parts and related support). Operators could vote with their money and their feet.

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[14] Report of the Space Task Group-1969, NASA Historical Reference Collection, NASA History Office, Wash., D.C.

[15] "Visualizing the Generational Advance of NASA and Space Exploration", NASA Cost Symposium, (2008), Zapata, E., NASA Kennedy Space Center

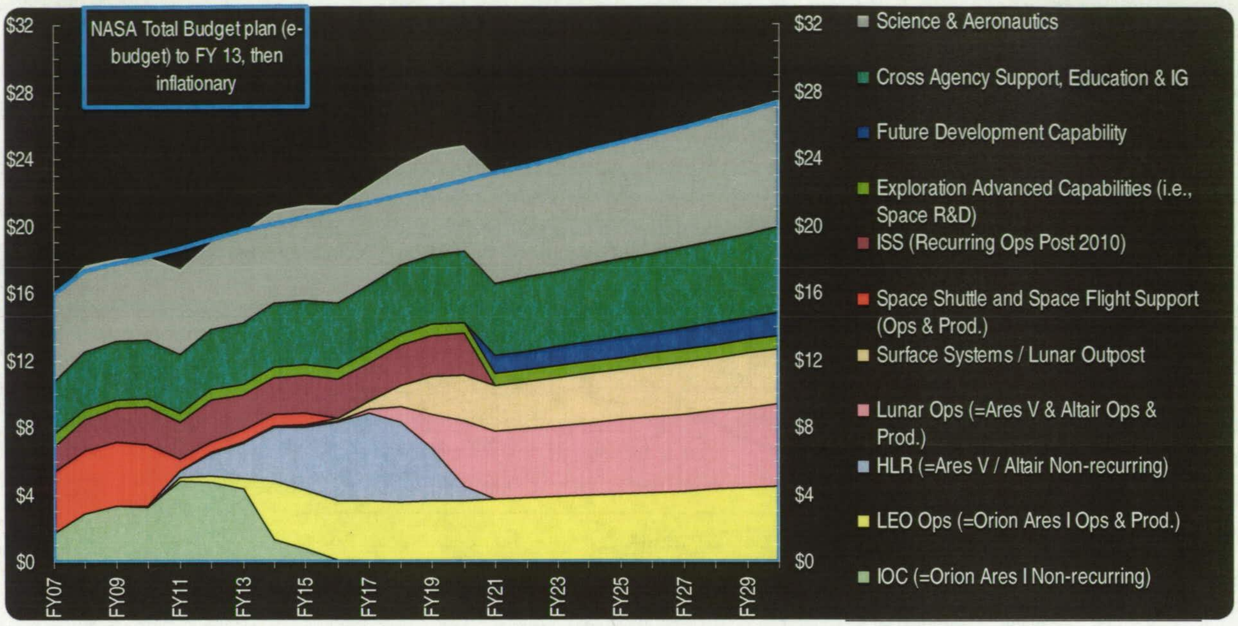

Figure 5

This strategic lesson of competition has been documented before[16] as both an operator issue and an acquisition issue, but it is also a policy issue at the National level. It is not inconceivable that at some future time a breakup of the major players encourages manufacturers to sell to any operators (such as NASA, or any other private company, perhaps even internationally) while also making it illegal for the manufacturers of rockets and spacecraft to operate these same systems. Such a breakup, akin to the breakup of "Ma'Bell[17]", could encourage competitiveness in ways never before imagined as happened with telephony breaking a path into the age of the internet.

VI. National Goal Setting Lessons Learned

The prior sum of technical, management and leadership, and strategic and policy lessons all ultimately come face to face with the matter of National goals in the human exploration of space. Is access to space and space exploration, robotic, human or otherwise, to be a government sponsored enterprise as far as the eye can see? While the goal of becoming a space-faring civilization is generally accepted in any conversation among most space community stakeholders it is not as easily backed by actions consistent with the widespread proliferation of launch vehicles and spacecraft. "Proliferation" is in fact an undesirable outcome in many a space community circle. To address the technical issue of volumes of production, which relate to reliability, reducing complexity, creating knowledge and learning of what is operable and what is not, and thus to furthering affordability, a very basic question must be addressed. Is a healthy and growing access to space, leading to many hundreds of launches per year and costs that add players rather then exclude them, truly at odds with a world that is safe from space systems as weapons? Notably, the sale of airliners, cars, trains and all level of advanced technology from the United States to the rest of the world are *usually* encouraged. It is understood that having a product does not of necessity surrender all knowledge of how to make the product.

None of this can come about without expanded Research and Development (R&D), which, ironically, is best funded when operable systems allow it to be funded at the levels that lead to actual systems level knowledge. This R&D would feed a development program focused on recurring affordability, creating a virtuous cycle from which

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[16] "Independent Space Transportation Operator Concept, A Breakthrough Acquisition Strategy Using Independent Space Transportation Operators, Making Affordable and Sustainable Space Transportation Possible", C. McCleskey, Systems Engineering Office, Spaceport Engineering & Technology Directorate, NASA John F. Kennedy Space Center, Florida, May 18, 2004. Also at: http://science.ksc.nasa.gov/shuttle/nexgen/space_trans_afford_main.htm

[17] Bell System divestiture, Wiki at: http://en.wikipedia.org/wiki/Bell_System_divestiture

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aerospace can escape from the prevailing chicken-and-the-egg syndromes of short term decision creating inoperable systems that neglect lessons and which then pressure future R&D and developments budgets.

Without addressing this matter of our National goals most other matters of lessons expressed here will be correct, but woefully underutilized in most any scenario - *with the exception of technology surprises or disruptions as knowledge spreads, nonetheless.*

VII. Conclusions

There are tangible, achievable technical, management and leadership, and strategic and policy lessons that can and must be executed in any next generation space transportation system. These are realities by which any program will either succeed or fail. These are independent of funding as they are about what to do once funding is available, "how to think" at least, even in a constrained budget environment, or measures by which outcomes can be seen and planned around. The following technical, management and leadership, and strategic lessons learned conclusions are presented as what should be done versus what has been done in the past.

- Technical
  - (a) Expendable hardware production costs appear to require a higher operational budget to sustain than reusable systems (Apollo vs. Shuttle program comparison).
  - (b) Simplification by Functional Integration vs. Complexity by Decomposition
  - (c) Reliability that's Inherently Safer vs. Redundancy for Flight (perform design corrective action with more extensive test / fail / fix cycles in order to lower the recurring operations cost)
  - (d) Maintainability (Operability) vs. Development-Near-Term Focused Design Decisions
- Management, Leadership
  - (a) Cost Control vs. Cost Assessment
  - (b) Design the Extended Supply Chain Alongside the System vs. Just Seeing Flight Hardware
- Strategic Lessons Learned
  - (a) Having a Long View, Doing Strategic Planning, vs. Cannibalizing Future Programs
  - (b) Policy: Assure Competition vs. Competing the Acquisition of Monopolies

Examining the Shuttle shortfalls also leads to conclusions about the goals that should be pursued in the future.

- National Goals
  - (a) A Healthy R&D level, infusing a Healthy Developmental Capability, Handing off to Operations
  - (b) Volume, Growing an Industrial Base, Spreading Knowledge