An Assessment of Cost Improvements in the NASA COTS/CRS Program and Implications for Future NASA Missions

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In May 2012, the SpaceX Dragon spacecraft became the first commercial spacecraft to arrive at the International Space Station (ISS). This achievement, and that of other partners in the NASA Commercial Orbital Transportation Services (COTS) program, would surface difficult questions about NASA's other more traditional development processes and their traditionally high costs. The cost of the non-traditional COTS public private partnership for the development of spacecraft and launch systems, and later the prices for services to deliver cargo to the ISS, would be praised or criticized by one measure of cost versus another, often with little regard for consistency or data.

The goal here is to do the math, to bring rigorous life cycle cost (LCC) analysis into discussions about COTS program costs. We gather publicly available cost data, review the data for credibility, check for consistency among sources, and rigorously define and analyze specific cost metrics.

This paper shows quantitatively that the COTS development and later the operational Commercial Resupply Services (CRS) are significant advances in affordability by any measure. To understand measureable improvements in context, we also create and analyze an apples-to-apples scenario where the Space Shuttle would have fulfilled the ISS cargo requirement versus the COTS/CRS launchers and spacecraft. Alternately, we review valid questions that arise where measures or comparisons are not easy or break down, with no quantitative path to clear conclusions. Understanding the costs of the Commercial Crew Program (CCP), the sister program to the COTS cargo program, and other programs made possible from post-Shuttle funding, is inseparable from these more difficult questions.

In addition, we review briefly the significance of the COTS/CRS and CCP in estimating potential costs to NASA for future deep space exploration systems using public private partnerships. These future programs need many new spacecraft, launch vehicles and facilities. As NASA struggles with the cost of a Journey to Mars, the significance of new, improved cost data in liquid propulsion, stages, spacecraft, avionics, infrastructure and more will prove *priceless*.

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https://science.ksc.nasa.gov/shuttle/nexgen/EZBio.htm

Nomenclature

CCP	=	Commercial Crew Program
CCtCap	=	Commercial Crew Transportation Capability
COTS	=	Commercial Orbital Transportation Services
CRS	=	Commercial Resupply Services
DoD	=	Department of Defense
FAA	=	Federal Aviation Administration
FAQ	=	Frequently Asked Questions
GAO	=	Government Accountability Office
ISS	=	International Space Station
LCC	=	Life Cycle Cost
LEO	=	Low Earth Orbit
MPLM	=	Multi-Purpose Logistics Module
NAFCOM	=	NASA Air Force Cost Model
OSP	=	Orbital Space Plane
OTA	=	Other Transaction Authority
R&D	=	Research and Development
RLV	=	Reusable Launch Vehicle
SAA	=	Space Act Agreement
SLS	=	Space Launch System

I. Introduction

One of the first reports drawing attention to the significant improvement seen in the costs of the NASA COTS program for cargo to the ISS was NASA's 2010 Commercial Market Assessment for Crew and Cargo Systems.[1] This report sparked the debate about the significance of commercial / public private partnerships, not just for one of two launch systems, but also around spacecraft atop those vehicles and commercial versus traditional acquisition practices in general. The report stated -

> *"Under methodology #1, the cost model predicted that the Falcon 9 would cost $4.0 billion based on a traditional approach. Under methodology #2, NAFCOM predicted $1.7 billion when the inputs were adjusted to a more commercial development approach. Thus, the predicted the cost to develop the Falcon 9 if done by NASA would have been between $1.7 billion and $4.0 billion.*
>
> *SpaceX has publicly indicated that the development cost for Falcon 9 launch vehicle was approximately $300 million. Additionally, approximately $90 million was spent developing the Falcon 1 launch vehicle which did contribute to some extent to the Falcon 9, for a total of $390 million. NASA has verified these costs.*
>
> *It is difficult to determine exactly why the actual cost was so dramatically lower than the NAFCOM predictions. It could be any number of factors associated with the non-traditional public-private partnership under which the Falcon 9 was developed (e.g., fewer NASA processes, reduced oversight, and less overhead), or other factors not directly tied to the development approach. NASA is continuing to refine this analysis to better understand the differences."*

Getting cargo to the ISS was not the first time that a major NASA program used a commercial acquisition approach. An earlier experience was SpaceHab in the late 1980's. Then as now, there were indications that a commercial approach offered significant cost savings to NASA, with analysis seeing a billion dollar cost of ownership versus a $159M cost of a lease. That analysis stated - "Thus, the lease cost is 16% of the purchase cost."[2] Depending on the specific numbers used, a factor of 8 improvement in costs in the recent NASA COTS experience has been quoted[3] as repeating this older experience with SpaceHab.

It's not easy to ignore cost improvements measured in large factors, reductions in cost multiple times over. This is especially so when too many studies to count about what was to come after the Space Shuttle had come back with either sticker shock or diminished ambition or both. In the 1990's NASA's studies focused on ambitious, large single-stage-to-orbit launchers with large price tags to match. Costs were in the range of 10's of billions for development.[4,5,6] By 2002, just before the loss of Columbia, the price tags had not varied much. Yet for these amounts rather than fleets of assorted rockets and reusable launch vehicles, the studies were honing in on a small Apollo style capsule (which later became the Crew Exploration Vehicle, which became the current Orion capsule) atop existing launchers or Shuttle derived stacks. Clearly, significant reductions in operational *and* up-front development costs were required, with high development costs being unacceptable even when justified by some payback on the investment.[7] As with SpaceHab earlier, necessity (or perhaps innovation by desperation) set the stage for NASA going "commercial" to meet its need for getting cargo to the ISS once the end of the Shuttle became policy.

There is one difference between SpaceHab and commercial cargo or crew to the ISS – the freshness of the more recent programs, especially considering that SpaceHab actual costs and mid-deck locker usage eventually exceeded original estimates[8] but cost analysis were never updated. The window of opportunity is now open to capture COTS and CCP cost data before, as with SpaceHab, it becomes especially difficult to deconstruct due to age.

II. Historical Background

Although a brief history on the NASA's public private partnerships for cargo and crew could begin with the start of these in 2005 and 2010, the events that started NASA down these and other paths actually begins with the tragic loss of the Space Shuttle Columbia and her crew of seven on February 1, 2003. The construction of the ISS was a work in progress. The Orbital Space Plane (OSP) program was looking at what would follow the Space Shuttle one day, just the latest in a slew of studies, technology and demonstration programs asking that question since the 1990's. Previous NASA ambitions about a post-Shuttle world of commercial single stage to orbit reusable launch vehicles (RLVs),[9] air-breathing[10] spaceplanes like an Orient Express,[11] and multi-stage reusable and expendable launch vehicles separating crew and cargo,[12] had devolved into studies of small spacecraft, including Apollo-style capsules, on expendable launch vehicles.

In 2004, President George W. Bush presented his Vision for US Space Exploration.[13] The Space Shuttle would resume flights only to complete the construction of the ISS. The President also directed NASA to:

Separate to the maximum practical extent crew from cargo transportation to the International Space Station and for launching exploration missions beyond low Earth orbit;

- *Acquire cargo transportation as soon as practical and affordable to support missions to and from the International Space Station; and*
- *Acquire crew transportation to and from the International Space Station, as required, after the Space Shuttle is retired from service.*

As to how, NASA was to:

Pursue commercial opportunities for providing transportation and other services supporting the International Space Station and exploration missions beyond low Earth orbit.

Adding to an ambitious set of goals, NASA was also to:

- *Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020; and -*
- *Use lunar exploration activities to further science, and to develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations.*

From this 2005 mandate to separate cargo from crew as "practical", and to "pursue commercial opportunities" to support the ISS, the NASA Commercial Orbital Transportation Services (COTS) program was born. For funding, the NASA Administrator "allocated"[14] a fixed $500M to the program with the support of congress and the administration. In January 2006, the $500M became the "anticipated funding"[15] announced in the initial solicitation for proposals from industry.

Eventually, a nominal amount of *about* $800M would be spent *by NASA* through completion of *development* on *systems* by two partners for delivering cargo to the ISS - with the keywords emphasized just a few of many to be elaborated upon ahead.

III. Methodology for Analyzing the Data

A. Setting the Stage

Useful discussions about the life cycle cost of the NASA commercial cargo program need basic distinctions and terminology. If the goal is to deconstruct a pile of numbers, then put them back together in a way that tells a story, making it easier to understand what's going on, these distinctions include -

1) **What - Itemizing**: Costs are for specific things, all of which entail flight systems and ground systems, from conception to manufacturing to launch and in-space operations, with a workforce of employees and suppliers. These distinctions especially help with later assessments of something new, but similar.
    a. Launch systems – Antares, Falcon 9, flight and ground
    b. Spacecraft systems – Cygnus, Dragon, flight and ground

2) **When - Development vs. Operations**: Separate the development cost data, an up-front cost that does not repeat, from the operational cost data, which repeats with every purchase.
    a. Operational cost data includes manufacturing cost data for anything expended every launch, like the launcher and spacecraft.

3) **Who - Cost to NASA vs. Total Cost**: Distinguish between what NASA paid vs. the total investment, public and private. Distinguish between companies.
    a. This distinction means taking a "**price**" from a partner as a "**cost**" to NASA. Most all of the costs to NASA are in the **procurement** dollars for the product/service.
    b. **Government personnel** costs (civil servants), the cost of NASA managing the acquisition, including program and project management, is part of the total cost to NASA.
    c. The cost to NASA (procurement dollars) is different from the cost (price) to a private sector customer for assorted reasons (paying more for a Falcon 9 launch than a private sector customer would pay).
    d. The structure of the purchase, how (below), for a product vs. a service, or as a traditional contract vs. a partnership, especially affects this procurement *cost to NASA* , but also the price to the private sector outside NASA.

4) **How - Commercial vs. Traditional**: A NASA acquisition contracting with an organization for products or services is more or less "commercial" or "traditional" along a spectrum. If a project uses "cost-plus" contracts, puts all the cost risk with the government, meaning the government pays any cost overruns, or uses a partner where NASA as the only customer for the item, the project is *more* "traditional". If the project is sharing cost risk, using Firm Fixed Price (FFP) contracts, and the partner has NASA as one of many customers for the item, then it is *more* "commercial". Figure 1 is a NASA picture worth a thousand words consistent with this distinction. (Once upon a time, semi-related distinctions were "Business as Usual" vs. "New Ways of Doing Business".)[16]
    a. This distinction is necessary to have something to compare against, going beyond what something costs into what it might cost by other means. A NASA partnership approach assumes there are many different means to an end.
    b. A "public private partnership" is one form of a "commercial" acquisition, using NASA's Other Transaction Authority (OTA), commonly referred to as Space Act Agreements (SAA).[17] The term "commercial" throughout this work is about NASA's public private partnership approaches (not to be confused with businesses that have no government customers, or nearly none, or do not depend on government business to be profitable.)
    c. A partnership contract for a *service* never takes ownership of hardware. The purchase is for the service, not the vehicle, stage, spacecraft, etc. providing the service. In a "cost-plus" contract the hardware, a launch vehicle, a spacecraft, a piece of equipment, eventually passes hands and becomes property of the US government. While other contractors prepare and launch that hardware under government oversight, with the support of the manufacturer who delivered it, the hardware nonetheless has become US government property.
    d. Broadly, partnership contracts are more about "what" vs. "how". This is consistent with a focus on results (commercial) vs. effort (cost-plus).

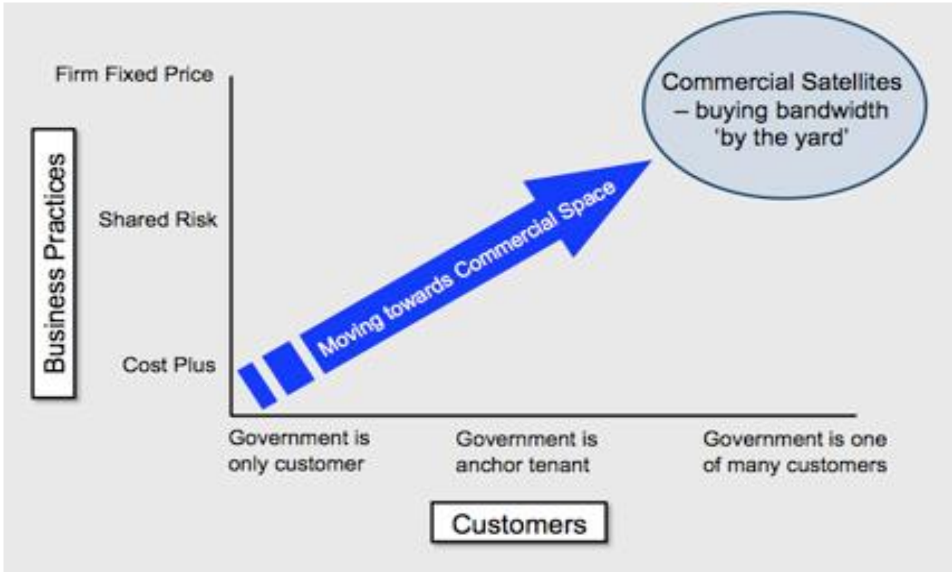

Figure 1. The basic characteristics of a project along a continuous spectrum of being more vs. less commercial.[18]

The last distinction about what is commercial vs. traditional can include more characteristics than just the type of contract or if the government is the only customer. Is NASA thinking like an investor, is NASA commercial friendly, open to new companies, and is the company responsible for cost over-runs?[19] These commercial features, creating an alignment of incentives where one party wins only if the partner also wins, is especially important in understanding what is more commercial vs. traditional. We address this alignment of incentives in the ISS cargo program in more depth ahead in the broader context of human space flight costs and benefits, including crew.

5) **Why - Benefits**: Analyzing cost data is incomplete without understanding why an effort occurs in the first place, the benefit. At its simplest level, benefits are just the statement of the desired end-product, for example:
    a. A requirement for some kg of cargo delivered to the ISS.
    b. A requirement for pressurized and unpressurized cargo delivery capability.
    c. A requirement to return cargo from the ISS to Earth.

    There are broader benefits to consider as well, alongside costs, to complete the picture. For example:

    d. Lowering recurring prices to the government for other services, like launch when providing the payload or spacecraft to the company (when not procuring the spacecraft like Cygnus or Dragon).
    e. Increasing launch market capture and demand by US companies through lower prices for the private sector, improving global competitiveness and increasing indirect US economic benefits.

As a cost estimating saying goes – *if you find cost estimating difficult, you're going to love estimating benefits.*

B. Behind the Scenes

Many other details have to be included of as a matter of course in analyzing historical cost data. In the interest of brevity, a few of the most important details include:

6) **Inflation**: Cost inflation is a complete topic unto itself. The formal rates used for taking historical data from a large-scale defense or aerospace project are more likely to be what is approved for a government budget process than what is indicated by history, or even reasonably likely. This leads to projects that are "systematically under-funded,"[20] inflation/deflator adjustments that are "inappropriate,"[21] and a dis-regard of real-world experience with cost inflation that can approach double-digits (as in science probes).[22] Nonetheless, any discussion about the costs of a NASA project means asking - in what year dollars?
    a. All adjustments to current year 2017 dollars use the NASA's official inflation indices.[23]

7) **Process Costs**: The NASA commercial cargo program funded a partner, Rocketplane Kistler, who did not proceed past early funding. The NASA commercial crew program invested in many potential providers not selected to provide services. A NASA public private partnership expects to fund partners that by design or difficulties do not proceed to complete their project and provide services to NASA. Booking this as a "process cost" is important for completeness, in the sense that NASA spends funds in a process to achieve certain outcomes, the projects that did finish developing capabilities chosen to provide services to NASA.

8) **Failure Costs**: NASA's commercial cargo partners have each suffered catastrophic failures. Just as costs data is parsed and tracked, cargo delivered is assessed and tracked. Cargo delivery is the outcome desired.
   a. Failures are booked in analysis to date as zero-mass delivered, but with NASA nonetheless incurring the same costs as for any flight (making the same payment). Actual payment on a failed launch is actually slightly less than full payment. This measurement's result will change (positively) as the partners deliver the total masses originally contracted for in future flights.[24],[25]
   b. Parse losses as public (like the loss of a NASA docking ring) or private (loss of satellites).

In sum, the methodology for analyzing a projects cost data follows a simple set of rules –

- Use primary data sources (NASA, GAO, official company statements); avoid "spacejoeforum.com" sources
- Use numeric data (avoid generalities)
- For all numbers, assume nothing. What do the numbers really refer to (development, operations, vehicle, spacecraft), and spent by who (public, private, company A, company D)?
- Assess metrics; be clear on the requirements
- In the end, reconcile any metrics against top-line NASA budget data and product to date
  - Caveat: Be aware that government budgets may not have been spent entirely any current or previous year, the government having some flexibility to carry over unspent funding, or inversely, that a past or current year's budget may have been obligated or paid toward a future outcome (kg delivered etc.) not a deliverable to date. An assessment measure dividing budget's to date by some product outcome to date (cargo kg, crew flights, etc.) will always be slightly off due to this, but the effect on a metric lessens the longer project data accumulates.

IV. The Data

Figure 3 deconstructs the available COTS/CRS cost data for what, when and who. The flow of dollars is in nominal year dollars as well as current year dollars reflecting inflation. Process costs are included. The cost data sources favored as credible were primary, for example NASA reports on nominal up-front costs per partner,[26] other costs,[27] awards for providing services,[28] and Government Accountability Office (GAO) reports on contractual milestone payments.[29] The kg of cargo actually delivered to the ISS, the tangible benefit purchased, came from NASA reports for past Space Shuttle missions, from "Payload Chargeable" data.[30] For the actual kg of commercial cargo to ISS, we tabulated NASA, company statements or similar source data (for example a NASA Mission Press Kit detailing the payloads on a CRS mission.)[31]

Figure 2. Cargo spacecraft. Left to right, the Orbital ATK Cygnus cargo spacecraft at the ISS, the SpaceX Dragon cargo spacecraft approaching the ISS, and the Space Shuttle delivering cargo to the ISS via the MPLM cargo carrier inside the Space Shuttle Discovery. Images NASA.

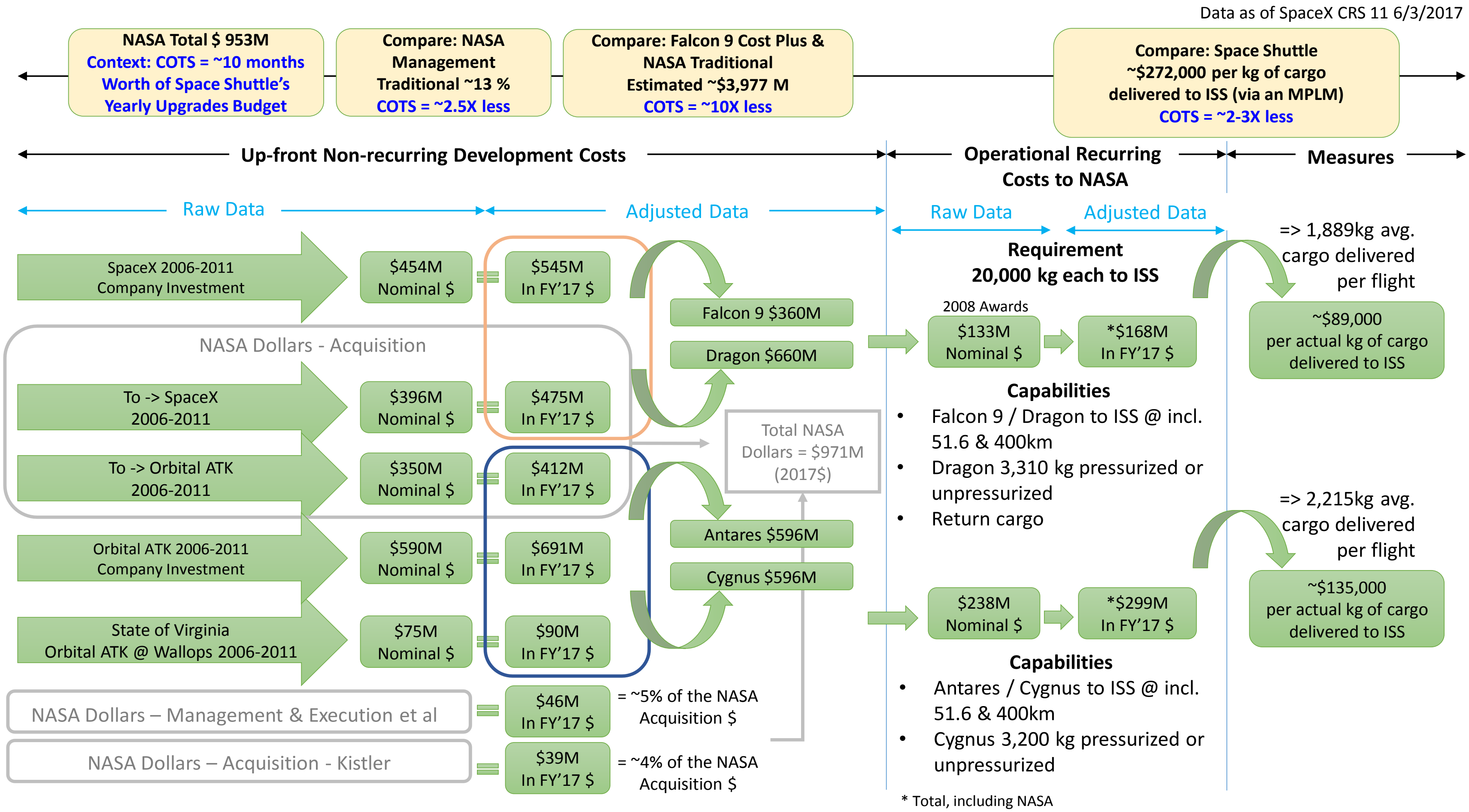

Figure 3. The COTS/CRS historical data. Measures of cost per kg of cargo shown are for the actual tonnage delivered, not the maximum the spacecraft or carriers are capable of hauling. The measure includes the cost to NASA for launch services where the launch failed, with zero payload delivered. As of SpaceX CRS-11, 6/3/2017.

V. LCC Assessment – NASA Cargo Costs ONLY

Measures comparing how the partnerships approach has fared vs. the Space Shuttle that previously delivered cargo to the ISS using the Multi-Purpose Logistics Module (MPLM) shown in Figure 2 include:

1) The operational cost, measured in cost per kg delivered to the ISS
2) The up-front costs for the program elements[b], launchers, spacecraft
3) The cost of managing the program, NASA personnel costs

Table 1 summarizes what the commercial cargo program historical data reveals about measures of improvement.

Measure	COTS / CRS (2017$)	Comparison (2017$)	Improvement / Context
Total Up-front Cost to NASA	$971M	↓	Context: About 10 months' worth of Shuttle Upgrades budgets
Launcher Development, Up-front Cost	Falcon 9 (Unknown for Antares)	Falcon 9 "What-if" traditional	Estimated as much as ~**10X times less** vs. traditional cost-plus approach
Spacecraft Development, Up-front Cost	See Figure 4, Figure 5		Context: Indirect indication of significant improvement in COTS/CRS vs. traditional
NASA Management Cost	~ 5 % of Total Yearly Funds under Management	Traditional ~ 13 % of Total Yearly Funds under Management	COTS/CRS ~**2.5 times less** than traditional
Operational recurring cost per actual kg of cargo delivered to the ISS	SpaceX **$89,000/kg** Orbital ATK **$135,000/kg**	Space Shuttle "what-if" scenario ~ **$272,000/kg**	COTS/CRS ~**2–3X times less** than the "what-if" Space Shuttle scenario

Table 1. Summary of measurable cost data for commercial cargo to ISS as of SpaceX CRS-11, 6/3/2017. The operational recurring cost per kg of cargo delivered to the ISS using the commercial partners is significantly less than the scenario where the Space Shuttle would have continued fulfilling the cargo requirements. This figure includes government management costs (civil servants).

Before the commercial cargo providers, Orbital ATK and SpaceX, the Space Shuttle Orbiters and their crews delivered most cargo to the ISS inside an MPLM. Larger than the Dragon or Cygnus the MPLM held up to 9,000 kg of cargo to the ISS. As well, the Shuttle would typically hold some cargo elsewhere, being capable of delivering up to 16,050 kg of payload to the ISS. At this point, a useful distinction follows – ***payload vs. cargo***. As some of this Shuttle "payload" capability was the MPLM itself, the actual "cargo" delivered was less. This is the same as how the Cygnus and Dragon spacecraft are "payload" to their rockets and only what is inside these is "cargo" to the ISS. We are after understanding measures of what is useable, the "cargo" end item, not the means (*the clothes packed, not the luggage*).

[b] "Elements", albeit NASA formally *invested* with industry toward developing *capabilities*. Later NASA *acquired* specific *services*, not specific elements of hardware.

1) From NASA data,[32] the average flight of an Orbiter / MPLM delivered 13,841 kg of cargo to the ISS per flight
2) SpaceX Dragon flights have delivered an average of 1,889 kg of cargo to the ISS per flight to date (as of June 2017)
3) Orbital ATK Cygnus flights have delivered an average 2,215 kg of cargo to the ISS per flight to date (as of April 2017)

Calculating total costs for all this cargo to date are another matter, simpler for commercial cargo, but more complex when creating a realistic cost picture for an alternate Shuttle scenario. This surfaces an important issue while highlighting the difference between the commercial cargo approach and the Space Shuttle – *a systems flight rate per year*. When a delay occurs in the commercial cargo contracts, the firm fixed price contract does not change. Eventually the cost to NASA does occur, later, as the partner fulfills the contract ending with cargo delivery (and return as required). For these commercial "services", calculating the cost per kg now, next year, or the year after gets the same number. This acquisition model is passing along cost risk to the partner. With the risk of using analogies, it's worth saying that NASA's **commercial cargo contracts purchase cargo to the ISS *by the yard*.** When calculating the delivery of cargo to the ISS for a realistic, alternate Shuttle scenario, the spread of flights over time does affect the number, the cost per kg to the ISS. For example, if the plan were to get 40,000 kg of cargo to the ISS via Shuttle over two years versus one, then the cost per kg calculation has to include the yearly costs of the Shuttle's fixed labor and infrastructure[33] twice versus once, but divided over the same cargo mass. At the risk of using an analogy again, NASA's use of **Shuttle Orbiters for cargo to the ISS was akin to *having to buy a whole bolt of cloth, when needing just a few yards*.** This matter of cost risk and who carries it is often misunderstood. Like the Space Shuttle and contractors, the current partners also have fixed and variable costs. Having more or less insight or data on these two costs in one system or another does not change the critical parameters - (1) the scale of total operational costs, (2) how NASA spreads these costs over time for the requirement (here just cargo).

For the cost per kg calculation in Figure 3, only operational recurring costs to NASA (or prices) are used, including the government management costs (civil servants and support). The Shuttle flight rate was set at two per year to meet the exact same ISS cargo requirement as both current commercial providers (20,000 kg each). For comparison (as of April 2017) Orbital ATK has delivered a total of 15,505 kg of cargo in 6 (of 7) successful flights, of 8 contracted initially. SpaceX (as of June 2017) has delivered a total of 20,774 kg of cargo in 10 (of 11) successful flights, of 12 contracted initially.

There are various frequently asked questions (FAQ) when calculating costs per kg of cargo to the ISS –

1) What if partners used different launch vehicles?
2) What-if up-front costs were amortized into the costs of operational flights?
3) What-if NASA packed the maximum cargo each time in the MPLM, Cygnus, or Dragon?
4) What-if the Shuttle MPLM delivered its average cargo each flight rather than being limited to the 20,000kg of cargo required in the commercial contracts?

The short answer to question 1 is somewhat demonstrated in the recovery by Orbital ATK after the failure of the CRS Orb-3 mission. Atlas rockets have launched Cygnus vehicles three times (as of April 17, 2017 / CRS OA-7) with no change in pricing terms toward fulfilling the original 20,000kg of cargo contract.[34] A broader analysis is beyond the scope of this paper but we review related issues ahead when addressing benefits. The short answer to question 2 is commercial cargo remains much more attractive, not forgetting that the Space Shuttle's often quoted up-front cost of about $15 billion[35] needs to be adjusted upwards to current year dollars, or $64 billion, and then amortized as well into its operational costs. By definition, additional Shuttle flights after the 135 on the record would accrue slowly to meet the current requirements for cargo, even considering crew requirements, a topic assessed ahead. We can join questions 3 and 4 at the hip, packing MPLMs fully each of the two flights per year. Here the Shuttle MPLM cargo costs drop dramatically, to just $170,000 per kg, but as the same ground rule could stuff the Dragon and Cygnus to their maximums, the corresponding SpaceX and Cygnus costs also drop, to $51,000 per kg and $93,000 per kg. The Shuttle's operational cargo costs to ISS remain 2-3X times higher than the commercial rates on a comparable basis.

On specific up-front costs, for individual program elements like rockets and spacecraft, and for managing the program, NASA civil servants, we see similar improvements as in operational measures. The improvement in NASA management could prove significant, especially as budgets tighten and even small amounts can prove critical. Going from a traditional NASA personnel / management rate of about 13%[c] of the contract money managed to 3% - 5%,[36] is a factor of about 2.5 to 4X times improvement. The truly significant up-front cost improvement occurred in the partner contracts, "*where the money is*". Just for context, the commercial cargo program's up-front development cost to NASA was a total amount over 6 years equal to about what NASA would have spent in 10 months on the ever-present Space Shuttle "upgrade" developments.

The most significant improvement, beyond even the improvements of 2-3X times reviewed to here, was in the development of the Falcon 9 launch system, with an estimated improvement at least 4X to perhaps 10X times over traditional cost-plus contracting estimates, about $400 million vs. $4 *billion.*[37] The measures of improvement in specific spacecraft development, Cygnus and Dragon, is beyond the scope of this paper but also holds special importance in the development of future exploration systems from habitation to landers.[38]

An analysis of up-front costs similar to that of the Falcon 9, which originally drew attention to the need to dive deeper into the commercial cargo cost data, is lacking on the Spacecraft side. Nonetheless, context is possible by setting diverse spacecraft development and per unit data side by side as shown in Figure 4 and Figure 5. The picture here is still moving for commercial crew spacecraft, a work in progress. On a dry mass basis, thus normalizing for scale, the cost per kg of developed spacecraft hardware, or the cost per kg of spacecraft hardware purchased, the commercial programs are showing the potential for improvement as well over a traditional cost-plus acquisition approach. Further measures and assessment here will be a matter for an update as the commercial crew program completes development, including the possibility that Dragon 1.0 (cargo) and Dragon 2.0 (crew) could become a single generic model of spacecraft, with or without unique crew features like life support systems.[39]

It's worth noting that many an internet discussion about the cost of commercial cargo to the ISS have failed to draw the distinctions that make for rigorous analysis, or even trying to account for major factors. Common errors include using the Space Shuttle programs historical average cost per flight[d] to calculate costs per kg to the ISS at a low yearly flight rate as a multiple of that average, incorrectly treating the Shuttle's per flight costs as if NASA could purchase those flights *by the yard*. To make matters worse, other common errors forget that Shuttle upgrades, though not a recurring yearly operational cost, were a large, ever present and continuous capital expense in every yearly budget. Operating a Shuttle meant continually funding Shuttle upgrades. Other typical errors include using the Shuttle's maximum payload (not cargo) of about 27,500kg to Low Earth Orbit (LEO) at 200km, then comparing against the commercial prices for ISS cargo (not payload) delivered to the actual, higher 400km ISS orbit. With errors like these such analysis are incorrect (though "not even wrong" might also apply.)

However, an obvious and valid topic has likely been nagging the mind of the reader who has wandered this far, in this narrow discussion around assessing the cost of NASA getting "cargo" to the ISS. That topic is *crew*, and the questions that arise - how any comparative analysis can think of the Space Shuttle as merely a cargo vessel, and how this affects measuring improvement in contracting for cargo commercially? Reviewing the Commercial Crew Program (CCP) that follows the cargo program is inseparable from this question.

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[c] This is a composite of the entirety of government personnel compensation and benefits over the entirety of a program / projects funds. It can vary from knowing that for all of NASA the ratio is ~15% or at the level of a major program like Exploration it is ~11%. That is, this is a measure of how many personnel NASA are on a program. This data is usually found in the Supporting Data (SD) of any years NASA budget estimates, for example the 2015 NASA Budget Estimates at: https://www.nasa.gov/sites/default/files/files/508_2015_Budget_Estimates.pdf

[d] Even at this extreme, in the what-if scenario of 5 Shuttle MPLM flights per year (average cargo load), the Shuttle's cost/kg remains slightly higher than one of the two commercial cargo providers, coming in at $96,000/kg.

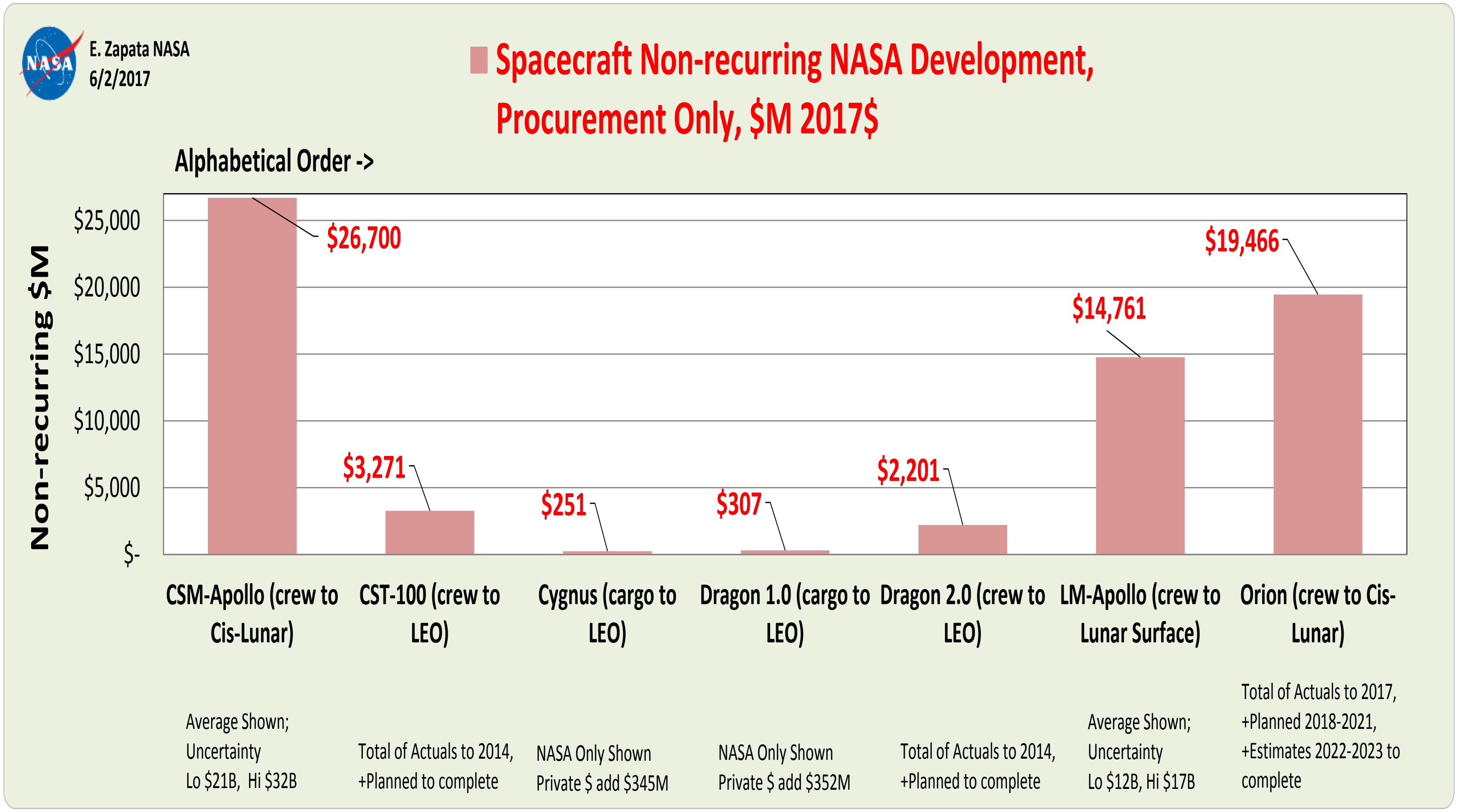

Figure 4. Assorted up-front spacecraft development costs. These are up-front development costs for the spacecraft only, not the associated launchers. There are contractual differences, with commercial spacecraft (CST-100, Cygnus, Dragon 1.0 and 2.0) up-front cost including the development of the required ground and mission capabilities, versus the cost-plus / traditional spacecraft acquisitions (Apollo, Orion) where the development of associated ground and mission capabilities is not included. There are also differences in functional capability as indicated (LEO, cis-Lunar, Lunar Surface).

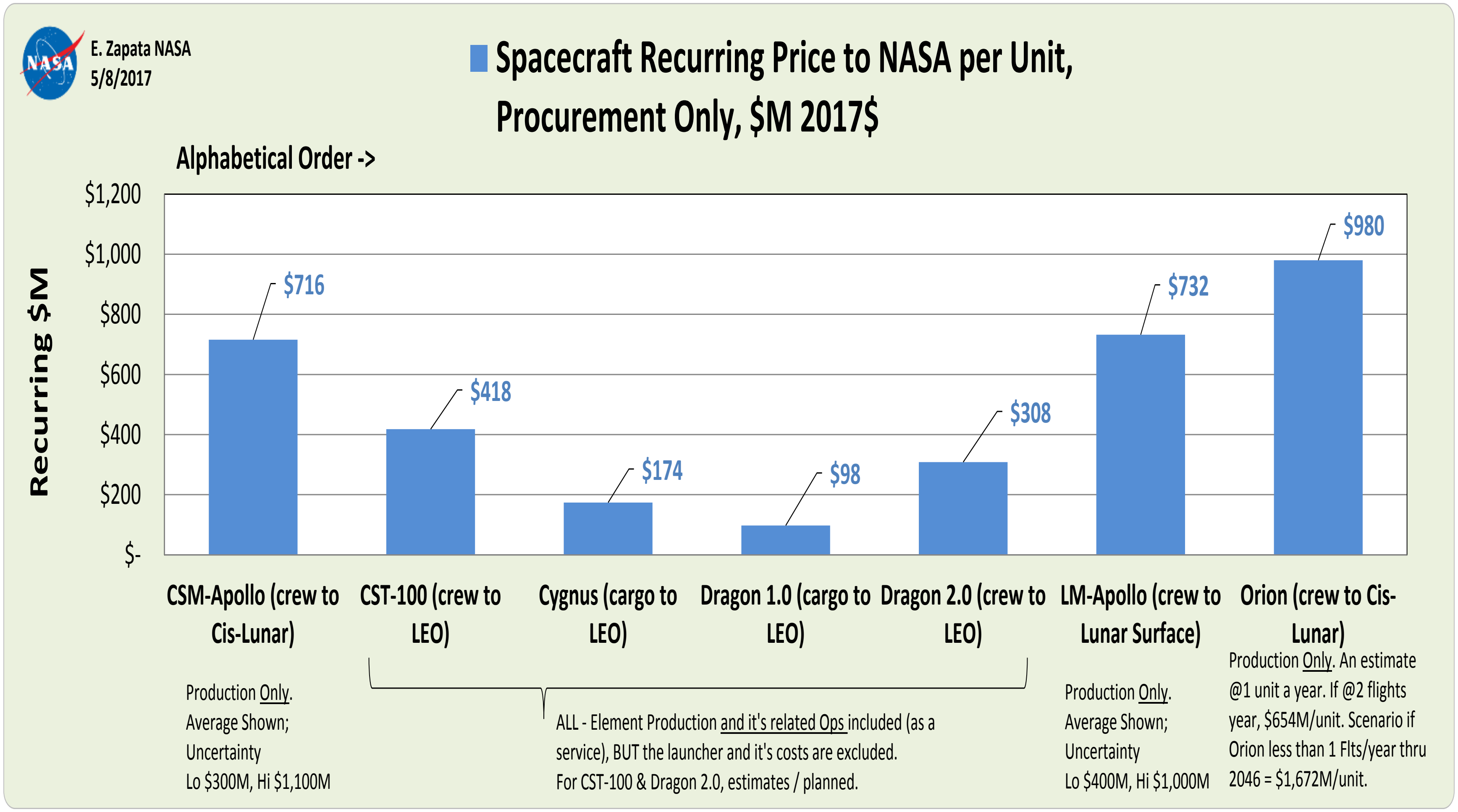

Figure 5. Assorted operational spacecraft per-unit costs. These are per-unit costs for the spacecraft only, *without the cost of the associated launchers*. There are contractual differences, with commercial spacecraft (CTS-100, Cygnus, Dragon 1.0 and 2.0) per-unit costs include an entire service, including the required ground, launch and mission operations, versus the cost-plus / traditional spacecraft acquisitions (Apollo, Orion) where the per-unit costs do not include ground, launch or mission operations. There are also differences in functional capability as indicated (LEO, cis-Lunar, Lunar Surface).

VI. LCC Assessment – NASA Cargo PLUS Crew Costs

As covered previously, the loss of Columbia led to the Vision for US Space Exploration under President George W. Bush, directing NASA in 2004 to -

> "*Separate to the maximum practical extent crew from cargo transportation to the International Space Station and for launching exploration missions beyond low Earth orbit*"

By the time the Shuttle flew its last flight in 2011, completing the construction of the ISS, the commercial cargo program was 1 year away from its first operational flight and the commercial crew program had just received its first year of substantial funding. Measures of cost improvement in the narrow terms of just cargo have been covered, but as the commercial cargo *and* crew programs together fulfill the whole function previously performed by the Space Shuttle's, it's necessary to take a step back to capture the whole picture. This means a similar review of commercial crew cost data as done with cargo.

Figure 6 shows the NASA budget since 2003 including the budgets for the commercial cargo and crew services and the Space Shuttle. An initial *temptation* might be to compare the ~ $2.6 billion in 2017 for commercial cargo and crew to the ~ $3.1 billion in 2010 for the Space Shuttle. It *appears* the Space Shuttle costs had dropped to just a few billion in 2010, and perhaps the higher costs before were related to the loss of Columbia? In 2010, the Space Shuttle had launched 3X times, with 19 crew and a total cargo capability that would dwarf the later commercial capabilities. These interpretations are mostly *incorrect*, neglecting what a more holistic look deeper into the data actually reveals. A deeper look into the NASA budget over this time reveals:

1) **Accounting Shifts**: The Space Shuttle budget drop seen in 2007 is unrelated to Columbia (that is, it's not a drop after a temporary rise). Note that all the NASA programs at this time see similar budget drops, a result of accounting shifts, moving around how funds for supporting, indirect costs were booked. All program budgets drop, including Science and R&D, not just the Space Shuttle's (a view that would be lost by just focusing on the Space Shuttle's budget data). Proportionally, the budget for Cross Agency Support increases dramatically. Assorted agency indirect and support budgets previously allocated to programs and labeled as such were now bookkept inside a total "support" function.
2) **What appears to go up actually went down**: The Space Shuttle budget appears to rise in 2005. This is obvious visually - and incorrect. The Shuttle's budget actually drops in 2005, as Shuttle Upgrades, a continuous yearly capital expense (inside "Diverse R&D") mostly ended. This move was possible knowing the Shuttle program would end at the completion of the ISS. So began the shift of development funds in 2005 to what was then the Constellation program development, which goes up that year. Figure 6 shows this as the "Cx Budget Shift Begins". (Another view that would be lost by just focusing on the Space Shuttle's budget data.)
3) **Requirements**: As before, comparisons of funds need to level for requirements, how much cargo and crew to where how often?
4) **Inflation and/or Budget Ups/Downs**: As before, comparisons of funds across years need to adjust for cost inflation and/or budget ups/downs.

With these caveats in mind, there are various ways of assessing measures for the costs of NASA's commercial cargo *and* crew programs. All methods and conclusions are tentative, as the commercial crew program's development phase is in progress and operations have not yet begun as of this assessment. One approach is to take the Space Shuttle's cost data and adjust this upwards for inflation to 2017. Another approach is to take the Shuttle's costs and adjust upwards only for the budget increases NASA has actually seen since the Shuttle was operational. The latter is the more realistic and consistent option.

Figure 7 shows the 2003 Space Shuttle budget taken to 2017 with its budget consistent with NASA's budget increases since. Again, leveling for the exact same cargo *and crew* delivered to the ISS, it would appear that a Shuttle flying twice a year, as with the previous MPLM analysis would have required a yearly budget exceeding that of the current commercial cargo and crew programs. We discuss the matter of crew measures and value further ahead, especially distinguishing crew rotated in and out of the ISS, the actual requirement, from all the other crew on a Shuttle flight. A distinction is required between *means vs. ends (the requirement).*

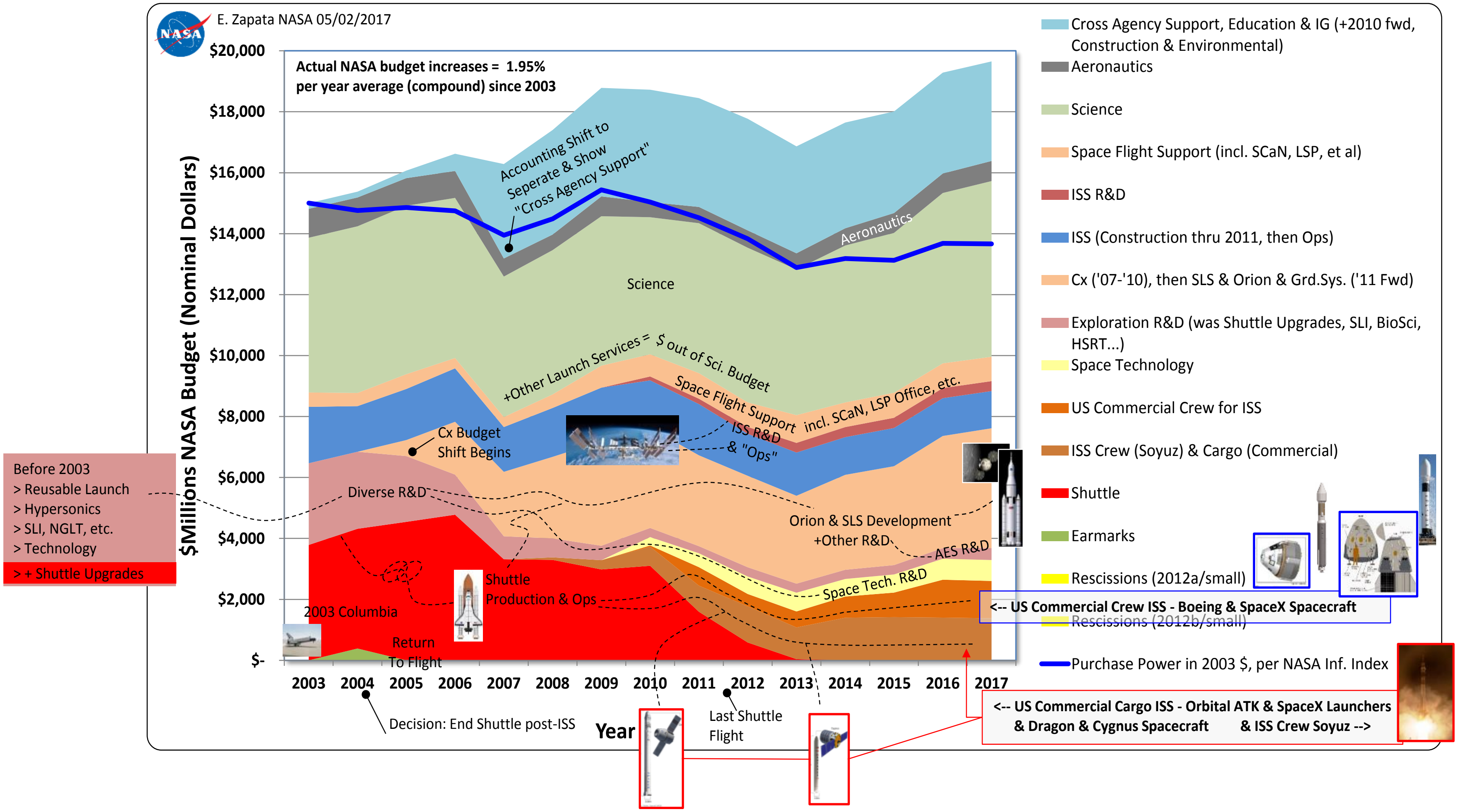

Figure 6. The NASA budget and shifts since 2003. Spaceflight development funds in 2003 shifted into other development, currently the Space Launch System (SLS) and Orion. Space Transportation recurring production and operations funds shifted from the Shuttle into some development, eventually becoming space transportation production and operations funds again, the commercial crew and cargo programs.

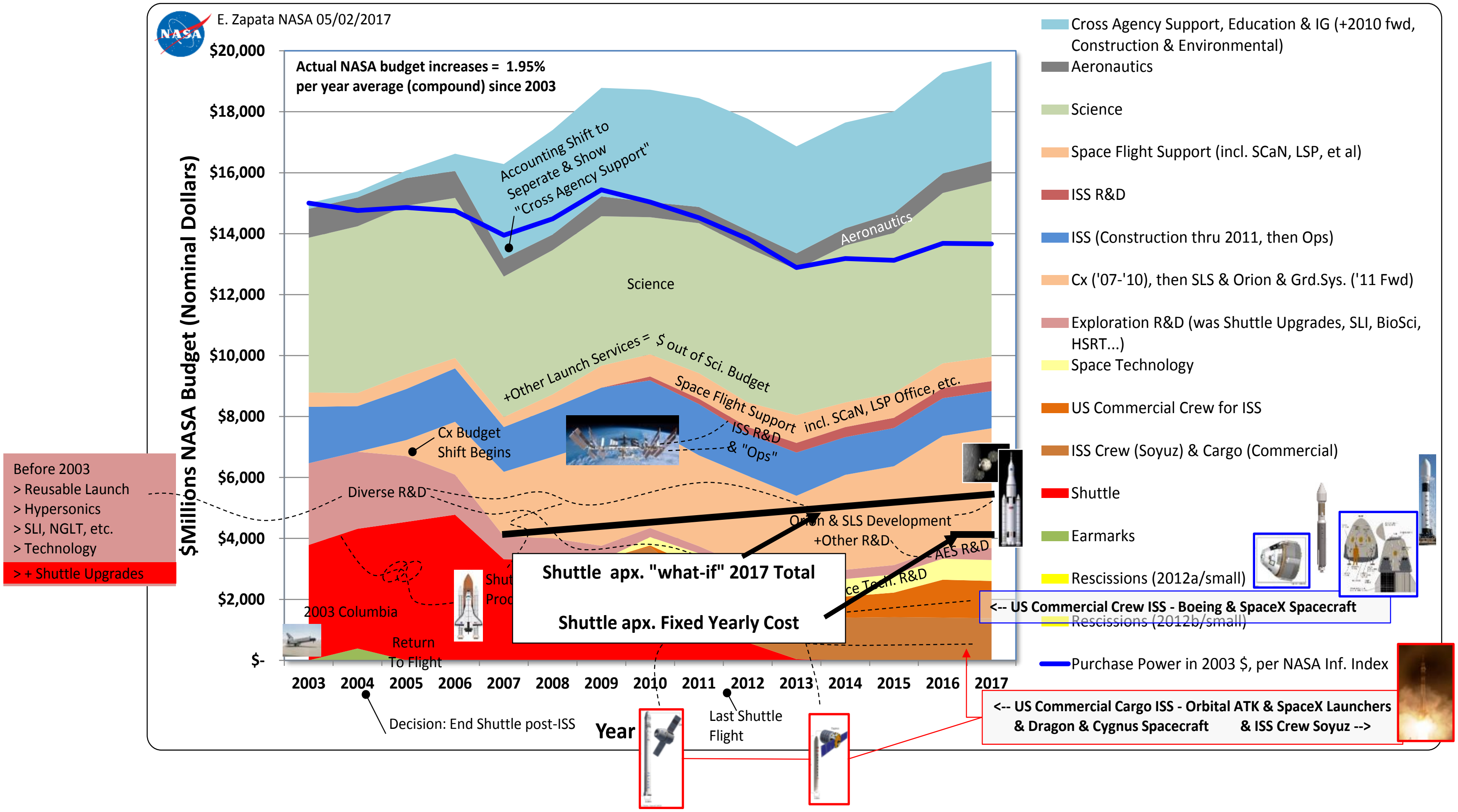

Figure 7. The "what-if" Space Shuttle 2017. Note the fixed costs of the Space Shuttle. There are assorted ways of estimating the Space Shuttle's costs had it been carried forward, for example using all its historical life cycle cost data or instead departing from the most recent budgetary data. The view here extrapolates from the most recent budgetary data taking into account that the operation of the Space Shuttle historically always had a sizable continuing yearly capital expense (an ever present development activity) for upgrades.

Another way to assess improvement in the commercial cargo and crew programs steps away from the top-down view of the NASA budget. This method delves into the commercial crew cost data and combines this with the commercial cargo cost data. Both methods, top-down or bottoms-up, are compared and reconciled at the end.

Whereas the commercial cargo program has concluded development, awarded multiple firm fixed price operational services contracts, and had 16 deliveries (and 2 failures) as of June 2017, meaning relatively good historical cost data, commercial crew cost data by necessity has to include estimates. There are some complications encountered in such analysis, (1) the intermingling of commercial crew development funding with commercial crew operational funding, (2) budget data for commercial cargo that in its line item includes procuring Soyuz for US crew, and (3) setting a benchmark, what to compare against?

The latest publicly available Commercial Crew program budget planning shows development completing by 2020, with "Commercial Spaceflight" running down to near zero dollars by then. In the same timeframe, operations would ramp up as "ISS Crew and Cargo Transportation" budgets start to rise.[40] In 2015, following 4 years of earlier development work, NASA awarded the Commercial Crew Transportation Capability (CCtCap) contracts, in amounts of $4,200M to Boeing and $2,600M to SpaceX.[41] For this analysis, disentangling up-front development dollars from future operational services dollars and reconciling contract award amounts against budget data requires knowledge of a specific requirement – the number of ISS crew rotations required per year. From NASA we know this number is two flights per year, and the actual number of crew per flight lies within that requirement -

"The CTS shall be capable of at least two crewed launches to the ISS per year.
Rationale:
Normal ISS Increment is 180 days
Two Rotations a year

The CTS shall be capable of exchanging up to four NASA ISS crewmembers every 150 to 210 days.
Rationale:
150 days drives supply chain and manufacturing capability for mission flexibility
210 days drives vehicle on-orbit endurance"[42]

Figure 8. Crew spacecraft. The Boeing CST-100 Starliner and the SpaceX Crew Dragon. Images NASA.

After disentangling the array of budgetary versus contract award data, and separating up-front development data from later recurring flight data, Table 2 summarizes these for commercial crew program life cycle costs.

Measure	SpaceX Crew Dragon (2017$)	Boeing CST-100 Starliner (2017$)
Up-front Cost to NASA, SpaceX & Boeing only	**$2,201M** (estimate to completion)	**$3,271M** (estimate to completion)
Up-front Costs to NASA, other partners not chosen for later services, Blue Origin, Sierra Nevada, ULA, Paragon	**$440M** (historical data)	
Operational cost per crew rotation, SpaceX & Boeing (includes everything - launcher, spacecraft, ground operations and launch and mission operations up to the ISS)	**$405M** (estimated)	**$654M** (estimated)
NASA Management (civil servants), Related Costs and Other Execution Costs	~ 5 % of Total Yearly Funds	

Table 2. Summary of measurable cost data to date, with estimates for forward years, commercial crew to ISS. The up-front development of the Commercial Crew capability is not yet complete, but the nature of these contracts places most cost risk with the commercial partner. This means delays may occur but this should not cause the up-front costs to NASA to rise. Operational costs to NASA per crew rotation derive from public budget documents, contract awards and requirements documentation (see side-box ahead "*All Cost Data Sources are Public*").

At this point, it's possible to compare the combined commercial cargo and crew programs to the "what-if" scenario of a Shuttle flying in 2017. This has some usefulness as a measure of improvement, but also carries the first in a series of comparability issues discussed further ahead. A flaw typical in such comparisons compares per flight costs using average Shuttle launch costs. This approach is inappropriate and gives incorrect results. The correct approach recognizes the high fixed costs of the Space Shuttle program. As shown in Figure 9, the Space Shuttle program's Zero Base Study of 1994 characterized its high fixed costs where flying just once per year would incur 80% of the costs of flying 5 times a year.[e]

Table 3 shows where the comparison we have been striving for starts to fray at the edges. It is not possible to have our comparative systems meet exactly the same requirements. If the Shuttle flies only once per year it does not meet the requirement for two crew rotations a year (putting aside the low flight rate issue). If the Shuttle flies twice a year, its cargo delivery is no longer comparable to the commercial cargo delivery data point chosen (2016). Nonetheless, in all cases, even in the latter case, which benefits the Shuttle metrics by delivering in effect free payload, the metrics show how the commercial cargo and crew contracts are still more cost effective.

[e] Although high fixed costs leave a seemingly attractive proposition regarding the Shuttle's variable costs, having paid for one launch, getting a bargain difference in costs for the second, assorted factors beyond the scope of this paper argue against getting too excited - in practice any launcher needs a payload, a purpose, which is itself another expense.

All Cost Data Sources are Public

As with all the data in this review, all sources are public documents. For US Commercial Crew, a full picture of costs must review and combine multiple public data sources. This is usually the case for any project when separating one-time, up-front development costs from downstream, repetitive operational costs.

For example, the data in Table 2 is traceable to multiple data sources, specifically (1) the NASA 2016 budget estimates –

https://www.nasa.gov/sites/default/files/files/NASA_FY_2016_Budget_Estimates.pdf

- where in BUD-5, "Commercial Spaceflight" goes to near zero by 2020 (a development ending) while "ISS Crew and Cargo Transportation" increases (an operation beginning) and (2) the award of the Commercial Crew Transportation Capability (CCtCap) contracts –

https://www.nasa.gov/content/commercial-crew-program-the-essentials/

The former data allows itemizing costs by phase, the latter by company (awards and budgets ultimately reconcile). Macro-level parsing of cost data by when (develop, operate) and who (companies) follow from this relatively simple review and parsing of public data. Adjustments for subtracting US commercial cargo and/or Russian Soyuz seat purchases (also public data) complete the picture.

A US commercial crew "cost per seat" calculation is not included, being potentially misleading. The actual NASA requirement is a number of crewed launches per year of a certain crew carrying capacity (in Firm Fixed Price contracts). If NASA puts more or less crew on a specific flight such a cost measure would be more an indication of NASA's utilization of an asset rather than a measure of the partner's price to provide the requirement - a crew flight capable of carrying a range of crew.

All data sheets are available upon request in the interest of receiving feedback, collaboration and the cost estimating community improving its historical data.

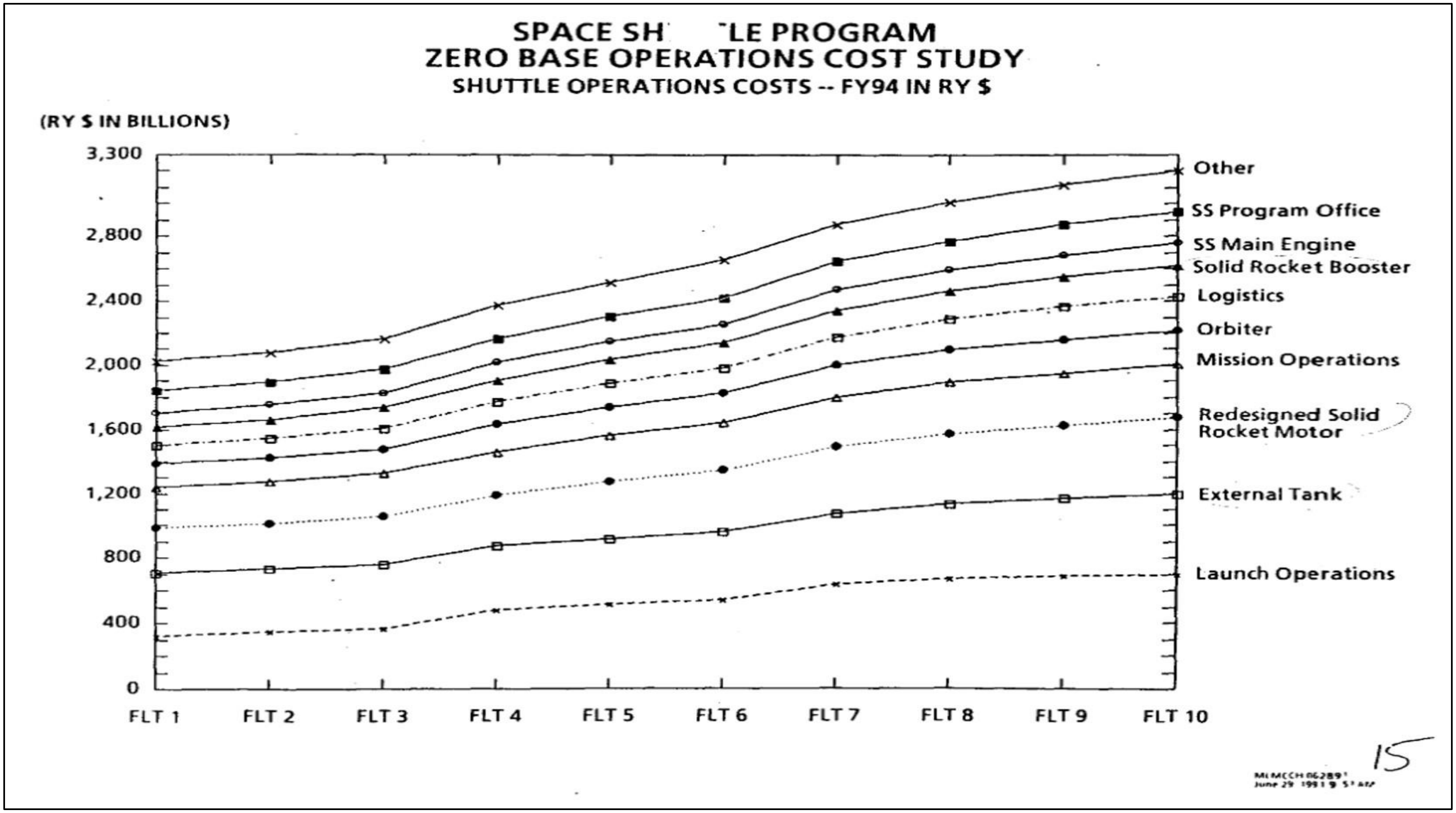

Figure 9. The Space Shuttle's "Zero Base" costs. This 1994 study showed how many Shuttle costs were relatively insensitive to flight rate. Flying once a year incurred about 80% of the costs of flying 5 times a year.[43] Interpretation requires caution, as the temptation is to believe that if fixed costs are high, then variable costs must be low, permitting an open-ended flight rate. This interpretation is incorrect. Each element of fixed costs also had low productivity, meaning that to further increase the flight rate significant additional capital expenses were required, negating the seeming advantage of the lower variable costs.

Requirement	US Commercial Cargo & US Commercial Crew Costs per Year **(2017$)**	If cargo repeats the 2016 experience = 11,218kg total delivered over 4 flights		Space Shuttle Costs per Year **(2017$)**	If cargo repeats the Shuttle/MPLM experience = 13,841kg delivered each flight
Cargo 2 Flights	$335M	**$62,597/kg** SpaceX Dragon 1.0 & Falcon 9		All cargo flies with crew ↓	
Cargo 2 Flights	$597M	**$101,913/kg** Orbital ATK Cygnus & Antares / Atlas			
Crew Rotation 1	$654M	Boeing CST-100 & Atlas	1st Shuttle Flight per Year	**$5,046M**	**$364,582/kg**
Crew Rotation 2	$405M	SpaceX Dragon 2.0 & Falcon 9	2nd Shuttle Flight per Year	**$5,445M**	**$196,682/kg**
	$1,991M		**Yearly $ = 37 to 39% of Shuttle**		

Table 3. A holistic view of NASA's requirement for cargo and crew to the ISS. The apples-to-apples comparison of commercial services versus the Space Shuttle, though curious, starts to break down around here. Most of this is a desirable breakdown, stemming from NASA's move to separate cargo from crew. Cargo data for 2016 only, the most recent complete year of data.

A sanity check of the prior bottoms-up analysis against the top-down public budget data also lands at about 40%, a result of taking the US Commercial Cargo budget line "ISS Crew (Soyuz) and Cargo (Commercial)" and the US Commercial Crew line "Commercial Spaceflight" (Figure 6) and dividing over an estimate of the Shuttle's yearly costs in 2017. This trivial, gross sanity check has certain issues, like the exclusion versus inclusion of yearly Soyuz crew costs, but overall it supports the prior integrated analysis and metrics for commercial cargo/crew.

VII. LCC Assessment – Other NASA Costs

Besides the commercial crew program as a work in progress, with data still streaming in, there are additional factors that make a holistic commercial crew & cargo analysis tentative, with the measureable improvements identified so far requiring an update in the future. These factors include -

1) **US Crew on Soyuz**: From 2006 to 2018, NASA will have spent $3.4B on the purchase of 64 seats aboard the Russian Soyuz.[44] NASA incurred these costs concurrent with 20 Space Shuttle flights from 2006 to 2011 and the Shuttle having resumed flights in 2005 after the loss of Columbia. The average price per seat on Soyuz climbs from $25M to $81M a seat over this time, exceeding any inflation adjustment from the 2006 price using NASA's official inflation indices (the 2018 price would have been $32M/seat otherwise). This cost of Soyuz seat purchases is associated with the retirement of the Space Shuttle while awaiting new US systems. Albeit, US crew were on Russian Soyuz launchers well before this (since Expedition 1 to the ISS in 2000), but related to the international collaboration in the construction of the ISS.

2) **Cost of Failures**: As of April 2017, NASA's Commercial Cargo service providers have suffered two failures.
    a. Antares October 2014, first stage failure: Destruction of NASA's cargo manifest including supplies and experiments.
    b. Falcon 9 June 2015, second stage failure: Destruction of NASA's cargo manifest including a docking adapter (a cost to replace of at least $9M or more),[45,46] supplies and equipment.

3) **Cost of New Capabilities**: NASA announced in 2016 the award of additional commercial cargo contracts. Besides Orbital ATK and SpaceX continuing to provide cargo runs (with minimum awards of six more each), the CRS II contracts awarded a minimum of six cargo flights to Sierra Nevada. The Dream Chaser will provide an additional capability for commercial cargo services to and from the ISS, immediate access to cargo on return after a runway landing.[47] The addition of the Sierra Nevada Dream Chaser spacecraft (Figure 10), scheduled for first flight in 2019,[48] as far as further development is required, implies an ongoing capital expense for establishing new partners in the commercial cargo program. That is, to date the commercial cargo cost data was clearly non-recurring, developmental and up-front or recurring and operational. By virtue of the desire to maintain a healthy alignment of incentives, an openness to new partners and new capabilities (or perhaps not renewing prior partner contracts) implies there is a recurring but non-operational expense baked into commercial programs for establishing new capabilities. This is very similar to the Shuttle upgrades paradigm, a non-recurring capital expense to NASA from the point of view of any specific project having a beginning and an end date but a continuous expense if viewed at the program level. Establishing new capabilities becomes a continuous capital expense baked into acquiring an ongoing result, cargo (and eventually crew) to the ISS.

Figure 10. The Sierra Nevada Dream Chaser spacecraft. The vehicle will deliver cargo under the NASA CRS II contract award. Image NASA.

On these other costs, while the Soyuz and failure costs may seem substantial, none of the metrics analyzed previously are appreciably different by their addition. Soyuz costs for example, included in the prior analysis as a top-down budgetary ratio in 2016, do not cause a significant deviation from the more detailed cost data analysis (each approach at about 40% of the Shuttle benchmark budget). As well, for the commercial cargo launcher failures the cost of these to NASA are addressed in the prior analysis by including their launch cost to NASA with *zero mass delivered*. The other costs to NASA, in the category of the NASA provided docking ring as well as supplies and equipment are not included in the prior metrics and analysis as minor, but similarly the comparative measures for the Space Shuttle do not include the loss of the Space Shuttle's Challenger and Columbia (that is the comparison remains consistent). The goal here was to address mostly regular non-recurring and recurring costs of ownership or of using a launch and delivery service.

On the cost of new capabilities, NASA has not yet contractually defined specific CRS 2 flight costs. NASA is structuring these to maintain flexibility, eventually ordering from a "menu of mission options at fixed prices, as needed."[49] NASA contracts have redacted[50] specific menu item prices as company sensitive. Nonetheless, there is enough public cost data at a higher level to support some broad observations. Under options from the first round of commercial cargo contracts (CRS 1), NASA awarded SpaceX 12 additional flights bringing the total there to 20. The value of the five last additional flights was $700M[51], or about $140M a flight. This compares favorably with the 2008 award to SpaceX at $133M a flight, which if adjusted for inflation using NASA's inflation indices would be $156M a flight in 2017. The recent cargo awards to SpaceX would thus appear to be demonstrating, compared to the original 2008 awards, *cost growth less than inflation*.

Similarly, in CRS 2 Orbital ATK announced that the additional award was for "six initial cargo missions, valued at about $1.2-$1.5 billion."[52] The cost per flight here, at $200M-$250M per flight for Cygnus, again compares favorably with the original awards in 2008. The original award to Orbital ATK in 2008 was for $238M a flight, which adjusted for inflation alone would be $284M a flight in 2017. Again, the cost to NASA for acquiring these services for delivering cargo to the ISS has indications of *cost growth less than inflation.*

With Sierra Nevada, the holistic approach of assessing the costs to NASA for commercial cargo and crew as a single large program takes on new significance. As shown in Table 2 Sierra Nevada received funding under the commercial crew program from 2011 to 2014. Most of the funding of other partners not chosen later for commercial crew services was invested in Sierra Nevada, $402M of the $440M (in 2017$). Arguably, this investment benefitted the maturation of the system later awarded the commercial cargo contracts in CRS 2. Here a NASA *process cost* becomes an *investment cost* as one program (crew) spends on many partners at the start of an acquisition, but does not choose all of these for acquiring later services, while the sister program (cargo) later does choose that company to provide services. A scar cost, NASA spending on partners not carried further becomes a significant part of the investment cost maturing a partner actually used for an adjacent need.

More broadly, the cost of establishing new capabilities and the recurring costs of new systems like Dream Chaser will require an update of the analysis here as data that are more public becomes available. Some complications in the life cycle cost analysis of future partner investments and systems will be similar to those seen already. The Dream Chaser for example exceeds the current cargo delivery requirement[53] (at a capability of 5,500kg to the ISS, though the high end of the requirement is 5,000kg[54]). As with Dragon, eventually cargo and crew variants will mix, creating challenges in parsing and assigning NASA investments to one or the other. Rigorous review of primary sources, definition of what, when, who and how, with proper adjustments should lead the way at that time.

VIII. LCC Assessment – Non-NASA Costs

An assessment of the costs for developing and operating all these systems in the NASA cargo and crew partnerships would be incomplete if it didn't include other funding, money the efforts required but not paid for by NASA. Figure 3 shows the raw data for other people's money in the commercial cargo effort, the partners themselves and state entities. The grand total of NASA ***and*** other private or non-NASA investments in commercial cargo systems development was $1.9B (in nominal dollars) of which 47% was government (NASA or state) funding. Operational flights for NASA are a different matter where any discussion about non-NASA funding must get into the matter of benefits, such as how non-NASA business assists the NASA business case indirectly, a desirable ingredient of these programs approaches and addressed ahead. There is no similar quantitative public data for private or other investments in the commercial crew program. NASA did require that proposals for providing commercial crew services tabulate their "Life Cycle Cost Risk Assessment – Offeror Investment Contribution".[55] Some private investments in commercial crew are "*substantial* financial contributions"[56] (Sierra Nevada).

While knowing the cost to NASA is important to planning how to fit into its yearly budget, when a project would complete, or how many services a year's budget might purchase, knowing the company investments is important to understanding total effort. From there future partnerships can assess how NASA/private investment splits add up or not to achieve some capability.

As with NASA's losses due to failures, there were also non-NASA losses.

1) Antares October 2014, first stage failure: Destruction of 26 Planet Labs cube-sats.
2) Falcon 9 September 2016, second stage failure on pad: Destruction of the Israel Aerospace Industries AMOS-6 satellite (covered by the satellite manufacturer's insurers at $173M, among other costs).[57]

All this just leads to a review of benefits at this point. As with costs inside and outside NASA, benefits will also occur inside or outside NASA. Again, the notion of *buying by the yard vs. buying a whole bolt of cloth when wanting just a few yards* is important in understanding the jumble of numbers to this point. What is of value to stakeholders or decision makers inside or outside of NASA? Suppose a person especially values the capabilities that come from a vast collection of tools in the garage. Perhaps there's no desire to give up any tools, perceived as dearly paid for and seen as having a value that requires no further explanation. Decisions follow from the emphasis on the tools in the garage, finding funds for weekend projects perhaps considered unrelated. Alternately, suppose a person values potential projects, valuing any tools in the garage only to the extent they are useful in carrying out a project. Difficult decisions follow in any case, assuming it's not possible to have it all. The jumble of life cycle cost numbers, raw cost data, adjusted cost data, dollars per kg or dollars for two crew rotations a year, or total yearly costs for cargo and crew, only address half the question. We must also put any given cost, analyzed or measureable as these may be, in the context of benefits.

IX. Benefits and Issues

A. Direct Benefits

To here, our analysis emphasized tangible outcomes as benefits. A certain number of kg or a certain number of crew go to the ISS and return. The tangible benefit is supporting and maintaining a space station. The public-private partnerships invested in by NASA for cargo and crew to the ISS also have other benefits built into the approach. A few of the more noted benefits in the partnerships include redundancy, reduced cost risk to NASA, and simplified NASA program management.

1) **Redundancy for NASA**: Having multiple providers is intrinsic to the public private partnerships NASA uses for cargo and crew to the ISS. Orbital ATK and SpaceX both currently provide commercial cargo to NASA. Sierra Nevada will provide cargo services starting in 2019. Boeing and SpaceX will provide crew transportation to the ISS. NASA invested in even more partners in these programs earlier development phases, before selecting who would provide services. Investing to help partners mature their capabilities follows best practices whereby new product development decisions are delayed as long as possible,[58] gathering practical knowledge along the way to establish each business case. This runs counter to traditional competitions which, even though involving many bidders, make this critical decision early (seeming decisive) and select one provider based only on the pile of bids. Stepping back beyond the commercial cargo and crew providers, Russia's Proton and Soyuz capability provides even more redundancy. When failures occur, as seen with Russia's Proton (2013), Soyuz/cargo (2016), or has occurred with Antares (2014) and Falcon 9 (2015, 2016), the supply chain is robust because of the redundancy in the ISS approach to acquiring capabilities for cargo and crew.

	Launch	**Spacecraft**
Cargo to the ISS	**Operational**	
	Japanese H-II Russian Soyuz US Orbital ATK Antares US SpaceX Falcon 9 Launcher	HTV (H-II Transfer Vehicle) Progress Cygnus Dragon
	In Development	
	US Sierra Nevada Atlas V	Dream Chaser Spacecraft **TOTAL = 4 Options, Cargo to ISS**
Crew to the ISS	**Operational**	
	Russian Soyuz	Soyuz Spacecraft
	In Certification/Development	
	US Boeing Atlas V US SpaceX Falcon 9	CST-100 Starliner Spacecraft Dragon Spacecraft **TOTAL = 3 Options, Crew to ISS**

Table 4. Operational or planned capabilities for cargo or crew to the ISS.

2) **Reduced Cost Risk to NASA**: The contractual nature of the NASA cargo/crew public private partnerships (Space Act Agreements, Fixed, Milestone Payments and Firm Fixed Price contracts for services) is such that cost over-runs are unlikely to mean more cost to NASA. In contrast, traditional "cost-plus" contracting is process driven, not results driven, paying for effort that may or may not be enough to achieve the goal. By way of analogy, in a firm fixed price contract NASA pays a person to mow the yard, whereas in a cost-plus contract NASA pays a person to *try* to mow the yard. Costs are difficult to control in the latter, while the former partnership approach assures everyone is pulling the mower in the same direction. Reduced cost risk to NASA goes with the notion that partners have "skin in the game"[59] and will try to control costs better when they are also investing their own private capital or trying to develop a system that will be affordable to others outside NASA. The potential for private sector customers with all manner of ideas for future business cases, like constellations of thousands of satellites,[60] can encourage operational affordability and reliability in a way that mere NASA operational guidance[61] never could.

3) **Simplified, Smaller NASA (Civil Servants) Program Management**: Although covered in cost metrics, that a traditional allocation of NASA personnel to a program is usually about 13% atop the funds under management, versus partnerships at 5%, simplified program management has other benefits. As far as costs and quality in any product are due to effort, "*how"* not "*what"*, simplified NASA management opens the door to innovation in "*how*". Simplified NASA management means partner improvements of all sorts find a welcoming NASA, rather than endless, non-value added layers of process.

Less thought of or documented as benefits from the cargo/crew partnerships are two factors that are nonetheless just as immediate as having multiple providers, a fixed price contract, or a smaller program office. Learning opportunities for NASA and industry immediately increase when non-NASA customers use systems that are competitive, with price points that are attractive to many, systems NASA investment and purchases made possible. Immediately too, the partnerships approach combined with the separation of cargo from crew provides NASA fiscal advantages from purchasing by the yard that it otherwise would never enjoy.

4) **Learning, Potential for Reliability, Safety & Further Cost Improvements**: NASA's relatively low flight rate requirements place a limit on the opportunities for learning and improving any launch or space system. A move to "separate to the maximum practical extent crew from cargo transportation", like in the Vision for Space Exploration, gives industry the opportunity to improve launch and spacecraft systems faster and more affordably since these are also used for non-NASA customers. As of this date, non-NASA customers routinely use the Falcon 9 launch system (used for ISS cargo, in certification for crew) and some commercial customers use the Atlas V launch system (in certification for crew). The Soyuz vehicle also uses an approach of first proving out modifications on cargo flights before crew flights.[62] A growing space sector increasing launch rates can conceivably improve reliability and safety metrics for launch and space systems far beyond what NASA could ever assure mathematically with a system used only for NASA flights. An opportunity for open-ended growth in the volume of production and operations for launch and space systems matters to NASA, especially if it avoids using NASA's limited resources. Eventually an expanding sphere of economic opportunity around Earth could create extremely mature, reliable, safe and low cost space systems, with NASA focusing its limited mandate and resources only on systems well beyond that sphere. NASA would procure all systems within the near economic sphere as one of many customers for these routine, safer, and lower cost systems.

5) **Downside Supply Chain Flexibility**: A list of benefits to NASA from the cargo/crew partnerships might over-look a measure used more in the private sector. This measure is "downside supply chain flexibility".[63] When a company's requirements increase, it wants to meet the new requirement quickly, meaning new business and more revenue. Inversely, when a company's requirements drop, as with a drop in demand, it's important that its costs also respond, not being frozen, so fixed that costs are insensitive to reduced requirements. If the requirement is less, costs should react and drop, otherwise there is a problem. The commercial cargo/crew partnerships, as pointed out previously, have a *purchase by the yard* nature. Table 3 shows this effect where the reduced requirement of two crewed launches to the ISS per year also has costs drop significantly.

Other direct benefits from public private partnerships for getting cargo and crew to the ISS include commercial friendly intellectual, data and physical property rights, limited termination provisions and use of a simplified Federal Aviation Administration (FAA) licensing and liability scheme. Limited termination provisions are especially important, encouraging private sector investment by not allowing the government to terminate the contract easily (as in "for convenience"). In balance, walking away from the agreements and price commitments by the private sector partner is also difficult.

B. Indirect Benefits

Indirect benefits are a step removed from direct benefits. This is not to say they are unimportant. Being a consequence of some other benefit, effect or ingredient in commercial partnerships can still be intentional and important, beyond what's measurable, like prices to NASA, or intentional like redundancy and controlling costs.

1) **Amortizing Costs over Government and Non-Government Customers**: Related to the benefit of more opportunities for learning, where a system NASA invests in developing and later employs is also a system in demand by private sector customers, there is amortization of costs. As a partner company's non-government

business case grows, it spreads fixed costs over more customers. Prices can be lower while company yearly revenue can increase. Incentives align. Compare this to NASA expecting cost improvements, meaning lower revenue for a company, from a partner whose only business is NASA. Incentives will not align. If fixed costs spread over many customers, NASA and private, industry can achieve reduced prices for everyone without NASA alone having to buy more to get these beneficial per-unit effects.

2) **Private Capital and a Second Set of Books**: Related to the direct effect of learning and the indirect effect of amortization, any non-government business a partner gets means more capital on a technology than if NASA was the lone user. A NASA budget chart (like in Figure 6) is one set of books around certain investments. As private capital flows into the intersection of NASA needs and new private sector markets there will increasingly be a second set of books. How much NASA capital went into crewed spacecraft versus how much private capital? Just as NASA's aeronautics investment of about $600M a year is a small portfolio compared to a US aircraft and airline sector measured in the *hundreds of billions a year*, NASA human could conceivably be a small part of a much larger sector one day. This will inevitably change the nature of NASA's approach to it's scientific and exploration missions. From a suite of private sector systems or capabilities, and all the capital making these infinitely more affordable, NASA might conceivably assemble scientific missions that would otherwise never have been achievable.[64] In addition, a growing space sector indirectly makes it easier for NASA to maintain the direct benefit of redundancy in the future, with that redundancy as competition outside NASA creating incentives to continue to reduce costs further. This benefits NASA procuring future services long term.

By way of data, NASA's commercial cargo program *leveraged 1.4 other dollars to every 1 NASA dollar*, the ratio of private sector or other funding to NASA procurement funding for launchers, spacecraft and infrastructure development. The second set of books was larger than the amount on the 1st set of books – NASA's books. Looking ahead, private sector capital is developing reusable first stage boosters (SpaceX, Blue Origin) and partially reusable first stages (United Launch Alliance)[65] primarily predicated on pushing prices lower.[66] SpaceX also announced a paying customer for a private ride to lunar orbit and back.[67] To the degree NASA investments succeed in creating launch and spacecraft options that are competitive outside NASA, the potential exists to kick start a virtuous cycle. Here NASA invests in systems and providers that are competitive outside NASA, offering prices attractive to private sector enterprises. These create non-NASA private sector market growth, and that growth benefits NASA in the future providing safer more affordable options, allowing more NASA investment. All this conceivably matures and improves safety, reliability and affordability over time for all manner of future launch and spacecraft system applying private sector capital in a way a limited NASA budget for a limited number of flights could never do.

More simply, increasing private capital in the space sector is very much about making the pie bigger so to speak, making its slices increasingly relevant to ever increasing numbers of people year after year, versus handing out thin slices of the same small pie, or a shrinking one, forever.

Another indirect benefit that is often overlooked comes from just following the immediate commercial partnerships business cases. A US investment in the space sector is for NASA's needs, but when the resulting enterprise gets other US or non-US customers there will be additional US economic activity. The US government investment can very tangibly recoup it's initial investment. This effect of *onshoring* is easily traceable, if still indirect to NASA's immediate goals, versus indirect benefits like spin-offs where adjacent economic effects are more difficult to trace.

3) **Onshoring and US Economic Benefit**: As of June 25, 2017, SpaceX has launched 20 payloads for private sector customers (excluding NASA and DoD). Most of the return of private sector launches to the US since 2012 appears due to the success of SpaceX attracting these customers. To the extent that many of these customers in the US and around the world would have gone elsewhere if an attractively priced US launcher were not available, a behavior seen in the decade before 2012 (Figure 11), that capital would have gone abroad. As occurs, that money ended up in the US – 20 times. This is about $1.2 billion dollars in payments for launch services that stayed in the US rather than going abroad (at ~$60M per launch). Considering NASA invested only about $140M attributable to the Falcon 9 portion of the COTS program, it is arguable that the US Treasury has already made that initial investment back and then some merely from the taxation of jobs at SpaceX and its suppliers only from non-government economic activity. The over $1 billion (net difference) is US economic activity that would have otherwise mostly gone abroad. This is very different from the economic benefit when NASA is a sole user of a system. When NASA is the only user of a system, as with the Space Shuttle, it can never mathematically get 100% of the money spent initially back to the US Treasury through non-government economic activity. An easily traceable US economic benefit from NASA's

commercial partnerships is a good thing. Direct non-government use of a company product/service along these lines can eventually create easily traceable economic benefits that dwarf government expenditures, up-front or recurring. Achieving this easily traceable US economic benefit is mathematically impossible with a system developed and used only by the government.

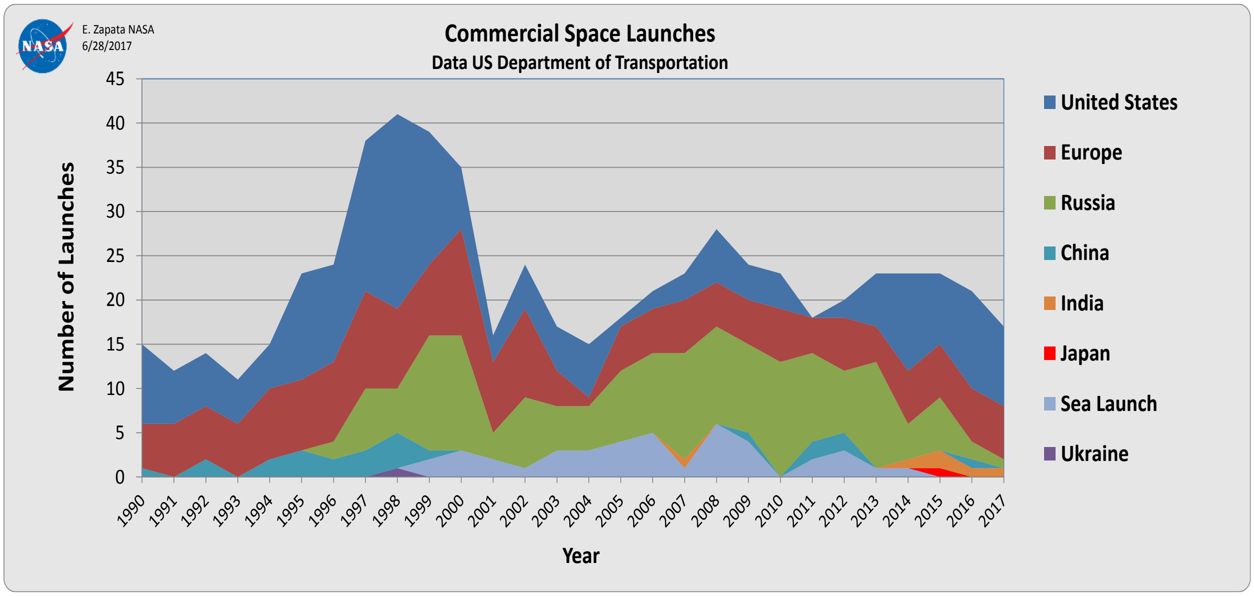

Figure 11. Number of commercial space launches by year. Data through 2014 is from the US Department of Transportation.[68] Data for 2014-2017 through 6/28/2017 comes from tracking individual launches.

4) **Competition, Alignment of Incentives**: A complete review of incentive structures in government contracting is beyond the scope of this work. Briefly, NASA's commercial partnerships approach –

"…builds in an automatic incentive for companies to complete the effort on or under cost and as soon as possible so they can be reimbursed and move forward to the next milestone. COTS companies are also highly incentivized to hold cost and schedule because of our strategy to invest in multiple companies. This engages the engine of competition where companies strive to offer the best value and capture a share of existing markets or create new markets as soon as possible."[69]

It's historically difficult in large aerospace projects for any less tangible, far-term outcome such as operational affordability, readiness or effectiveness to drive near term development and budgets. Immediate development challenges and technology are real. It's safe to ignore anything (or anyone) talking far term. In the US Department of Defense (DoD) "The Pentagon is like the student grading its own exam paper in these operational test situations, and we are going to have to end that."[70] For NASA, partnerships offer an opportunity for future operations to properly incentivize and drive development. There is a contract that does not pay more should a systems recurring price be more than the partner signed up for, a NASA office that can choose among many operational partners, and above all a private sector that can easily walk away from inoperable, unaffordable systems. The private sector votes with its feet, something government operations can't do. By comparison, this is not the incentive structure for most cost-plus developments with hardware delivered at a spaceport to be government property. There the government operator, the customer, has no incentive or ability to walk away should the system have ignored operational factors - recurring costs, safety and other long-term concerns. A healthy alignment of incentives strengthens a project at its start by encouraging early decision making that focuses on future operational results like unit costs, reliability, maintainability or safety. Inversely, a poor incentive structure encourages short-term thinking that makes future results and operational considerations an afterthought, leading to systems that are ever more expensive to fly and that only the government can afford.

C. Issues

A review of the benefits seen in these recent partnerships would be incomplete without listing potential problems. Every solution breeds new problems.

1) **Partner Financial Health**: It's possible for many companies and customers to benefit in an industry while the companies that are the core reason anyone is around do not. By way of example, airlines have suffered financially at times, even as customers find good fares, aircraft manufacturers grow orders, and their information technology partners make handsome profits.[71,72,73]

As well, a failed commercial business case in a partnership with the US government, a failure to attract private sector customers, can lead to a blame game over who pays the bills. In the Evolved Expendable Launch Vehicle (EELV) program, a commercial acquisition by the DoD, Boeing reclaimed part of the private investment it had made in the 1990's. Boeing billed the government for this investment cost originally to be recovered from non-government customers who failed to arise.[74,75,76] While moving more cost-risk to the private partner is a key ingredient of a partnership, including having private capital in early development, this can have unintended consequences on a partners financial health, especially if the only means to make money is lost. NASA reimbursed SpaceHab $8M after the loss of their commercially provided research double module on the Shuttle Columbia[77], an amount contractually limited and agreed to. The SpaceHab private investment though was around $150M.[78] Putting aside partnerships, fully private space businesses beyond traditional communications satellites have had their share of financial difficulties. XM Satellite Radio and Sirius Satellite Radio eventually merged, neither having turned a profit.[79] Similarly, multiple imagery companies had to combine to survive DoD budget cuts affecting the purchase of private sector imagery, becoming today's DigitalGlobe.[80,81]

Context for the issue of partner financial health is especially important. A non-traditional agreement with a private partner, an investment legally divorced early on from an expectation of use, has legal flexibility precisely applying the broad notion of a *public purpose*.[82] A public purpose is precisely that, broad, at a distance, with a bigger picture in mind. There is no connection to a specific company's health, by definition, the interest being much broader. Industry outcomes are not the same as specific company's outcomes. This topic, beyond the scope of the work here, is ripe for further exploration.

2) **Stakeholder Expectations**: It's appropriate near the end here to discuss the intangible, stakeholder expectations, a moving target where what impresses one day can be inefficient the next or just mundane. Commercial partnership expectations are by necessity, legally very defined, as NASA and companies enter into contracts that are binding to both. NASA has limited contract termination provisions, unlike in traditional contracting where it's easier for the government to end a contract for a matter as simple as convenience. Companies have contractual obligations that are very specific on prices and deliverables, even if leaving leeway on schedule. Measuring everything in kg or crew rides to the ISS inevitably misses many valuable expectations stakeholders may come to expect. The Space Shuttle had a Remote Manipulator System (RMS), a robotic arm, but if that was not enough, astronauts could step outside and grab a satellite with their own hands (Figure 12). More recently, loud cheers as well, as a Falcon 9's first stage lands back at Cape Canaveral.

Figure 12. Space Shuttle STS-49 Endeavour Intelsat VI Repair. Astronauts Thuot, Hieb and Akers take manual hold of the satellite as commander Brandenstein delicately maneuvered the orbiter to within a few feet of the 4,215kg communications satellite. Image NASA.

Clearly, there are capabilities and stakeholder expectations that will present a moving target for NASA's commercial partnerships. How many people get to space in a year, public or private, or what happens when they are there, shapes the expectations of many stakeholders. How this is done, what kind of contract, or by who can be secondary to many stakeholders. There is an intangible value to some stakeholders from *any* people and *any* activity in space. How NASA's partnerships and other efforts are measured ultimately may not be by the numbers of $ per kg, or $ per crew, but as said eloquently by John Marburger - "questions about the vision boil down to whether we want to incorporate the Solar System in our economic sphere, or not." How NASA's investments say yes to this vision will be their ultimate measure.

X. Opportunities

It would be a sterile exercise to gather up cost data, parse it, review it and cover its nuances and rhyme or reason, if NASA didn't use the experience to guide future actions. If the experience already behind us was extremely positive, and pending outcomes are just as promising, the natural question becomes how to repeat the success. By the simple metrics of dollars of development per pound of complex space system, or per pound of manufactured unit, partnerships with Boeing, Orbital ATK, Sierra Nevada and SpaceX show that launch systems, with engines, avionics, flight systems and their ground and mission systems can be developed for far less than traditional contracting and historical experience would indicate. In-space systems also benefit, cargo and crewed, again with all the complexities of everything from propulsion to avionics and systems for entry, descent and landing. These are all the ingredients of systems for deep space exploration as well, for in-space propulsion, stages and propellant depots, or for spacecraft like landers for the Moon and Mars, or habitats for the journey and at the destination. These opportunities are promising and effort is justified to explore commercial deep space systems, with no assumption that commercial partnerships arbitrarily end at LEO.[83]

The next obvious question is how NASA might assemble all the prior opportunities from piece parts into a complete human spaceflight exploration architecture that fits within predictable budget constraints. Does a second set of books, fundamentally about increased private investments in the space sector, clear the path for NASA crews and probes to explore the solar system faster? Or perhaps adding up and fitting in budgets when no other options ever will at all? This too is an opportunity where an effort to understand partnerships for deep space exploration architectures is justified based on the data presented here.[84]

XI. Conclusions

We presented a rigorous review of the NASA commercial cargo and crew life cycle cost data, including benefits and issues. Data were adjusted for consistency, to same year dollars and the same requirements, as well as for what (cargo or crew), when (development or operations), and who (NASA or companies) to assess the value of the ISS cargo and crew public private partnerships. Process costs, failure costs and other costs were included. For completeness, we also reviewed non-NASA costs, raw data that's valuable to scoping whole efforts.

We analyzed a "what-if" Space Shuttle scenario as a point of comparison where the Shuttle would have continued flying and fulfilled the current cargo requirements and the planned crew requirements. By isolated measures or by the most holistic measures, the ISS cargo partnerships are a significant advance in affordability and the ISS commercial crew partnerships appear just as promising.

To summarize, Table 5 (ahead) organizes most of the cost data to date. As US commercial crew flights have yet to start, these data are "contracted / estimated". Since the cargo flights already have actual cost data, these are "actual to date". Note that all the original nominal year data was converted to the same year 2017 dollars.

	Commercial Cargo and Crew Partners **(2017$)**	Comparison Point 2 Space Shuttle Flights per Year each with an MPLM's Historical Cargo Load **(2017$)**
Recurring *Operational, Recurring, Cargo *Total, Price/procurement dollars plus NASA management & other costs	Orbital ATK **$135,000/kg** (actual to date) SpaceX **$89,000/kg** (actual to date)	**$197,000/kg**
Operational, Recurring, Crew Rotations, 2 per Year	Boeing **$654M** (contracted / estimated, 1 flight per year) SpaceX **$405M** (contracted / estimated, 1 flight per year)	**$5,500M** a year for 2 cargo/crew flights (combined)
Non-Recurring	NASA Cargo 2 Launchers & 2 Spacecraft **$953M** Private Sector & Other **$1,044M** **NASA Leverage ~ 2:1** NASA Crew 2 Spacecraft Boeing **$3,271M** SpaceX **$2,201M** Analysis of one part of the cargo & crew system, the Falcon 9, indicates the development cost was **4 to 11X times less** than a traditional cost-plus acquisition	*A straight comparison is inapplicable, but for* ***context:*** The Space Shuttle's development cost of $15B in the 1970's is **$64B** in today's 2017 dollars. During operations, the Space Shuttle's yearly development expenses, ongoing "upgrades", were ~ **$1,000M a year**.

Table 5. Commercial cargo and crew cost data to date, short version, with Shuttle comparison. As of SpaceX CRS-11, 6/3/2017.

Appendix

CARGO	Data	Total Actual Cargo to Date	Average Actual Cargo to Date		Total Recurring Cost to NASA, Cargo to ISS, incl. Gov't Costs	Specific Costs to NASA, Cargo to ISS
		kg	kg		$M 2017$	$/kg
Recurring						
Launcher / Cargo Carrier				Flights per Year		
Antares / Cygnus	6 successes, 1 failure	15,505	2,215	n/a, each flight same cost	$ 299	$ 134,833
Falcon 9 / cargo-Dragon	10 successes, 1 failure	20,774	1,889		$ 168	$ 88,781
Shuttle / Orbiter / MPLM	11 flights w. MPLM	152,255	13,841	1	$ 5,046	$ 364,582
				2	$ 5,445	$ 196,682
				3	$ 5,843	$ 140,716
				4	$ 6,241	$ 112,733
				5	$ 6,640	$ 95,943
Sierra Nevada	Data pending					
Non-recurring	NASA Investment, Incl. Gov't Costs	Add Amortization per Flight to Date	Additional Amortized Specific Cargo Costs			
Launcher / Cargo Carrier	$M 2017$	$M 2017$	$/kg			
Antares / Cygnus	$ 437	$ 62	$ 28,213			
Falcon 9 / Dragon	$ 495	$ 45	$ 23,850			
Shuttle / Orbiter / MPLM	$ 64,134	$ 475	$ 34,322			
CREW	Data				Estimated Recurring Cost to NASA, Crew to ISS, incl. Gov't Costs	Estimated Non-recurring Cost to NASA, Crew to ISS, Procurement Costs Only (Excludes Gov't)
Recurring					$ per Crew Rotation Flight	$M 2017$
Launcher / Crew Carrier						
Atlas / CST-100	NASA public budget docs				$ 654	
Falcon 9 / crew-Dragon					$ 405	
Non-recurring						
Atlas / CST-100						$ 3,271
Falcon 9 / crew-Dragon						$ 2,201

Table 6. Commercial cargo and crew cost data to date, long version, with Shuttle comparison. As of SpaceX CRS-11, 6/3/2017.

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