Cost Estimates of Near-Term, Fully-Reusable Space Access Systems[*]

James Michael Snead, P.E.[†]
Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio

Abstract

The Air Force Research Laboratory and the Air Force Aeronautical Systems Center have completed in-house and contracted conceptual design analyses of near-term, two-stage, vertical takeoff and horizontal landing, fully-reusable space access systems to transport passengers and cargo to and from low Earth orbit. These efforts have identified closed vehicle designs using mature technologies. These designs and related estimates for ground support requirements have been used to prepare rough order of magnitude (ROM) estimates for the development, production, and recurring operational costs of these systems. The costing methodology in Koelle's Handbook of Cost Engineering for Space Transportation Systems has been used to estimate the development and production costs. A separate methodology, based on estimates of the direct support labor requirements, has been used to prepare an estimate of the recurring costs. This paper summarizes the conceptual reusable space access system design results, describes the application of Koelle's costing methodology, reports the ROM cost estimates, and compares these costs against prevailing space access costs. The paper concludes with a brief discussion of an infrastructure-style funding approach to develop and acquire these near-term, fully-reusable space access systems.

Introduction

In the accompanying paper, "Achieving Near-term, Aircraft-like Reusable Space Access," the introduction discusses the existence of a perceived barrier to achieving near-term, fully-reusable space access for transporting passengers and cargo to low Earth orbit (LEO) with aircraft-like safety and operability. [1] Overcoming this barrier is critical if the United States is to become a true spacefaring nation. That paper detailed arguments on why reusable space access systems were the preferred choice for the routine transport of passengers and cargo to low Earth orbit (LEO); how reusable space access systems with aircraft-like safety and operability could be developed; and, what near-term, fully-reusable space access system concepts could be pursued. This paper picks up where that paper left off by addressing the critical issue of the cost and affordability of developing and operating near-term, fully-reusable space access systems. This paper begins with a more detailed description of how the near-term, fully-reusable space access system

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[†] Aerospace engineer, AFRL/XPA, AIAA Senior Member, jamesmsnead@aol.com

concepts were generated and how these government estimates compare with those generated by industry. The paper continues with a description of the process used to generate development, production, and operational rough order of magnitude (ROM) cost estimates for a near-term, two-stage-to-orbit (TSTO), fully-reusable space access system. Finally, the paper concludes with a summary of the cost estimates and a brief discussion of how these costs can be borne within the current federal government budget.

Section 1: Background

Defining a "Near-Term" System Design

A near-term system design is one that can enter full-scale system development without first requiring significant additional enabling technology maturation. Within the aerospace community, one method commonly used to assess the maturity of a proposed system design is to evaluate the maturity of the enabling technologies. For this purpose, the National Aeronautics and Space Administration (NASA) has developed a Technology Readiness Level (TRL) scale on which any technology—from the initial raw observations to the final operational application—can be ranked (see Figure 1). To be considered a mature design sufficient to support a decision to proceed with full-scale system development, all enabling technologies need to have achieved at least a TRL of 6—"system/subsystem model or prototype demonstration in a relevant environment (ground or space)"—prior to a formal decision to initiate system development.

With this level of maturity, a normal pace of system development will produce a production design in 3-4 years and a first production article in 5-6 years. A relevant

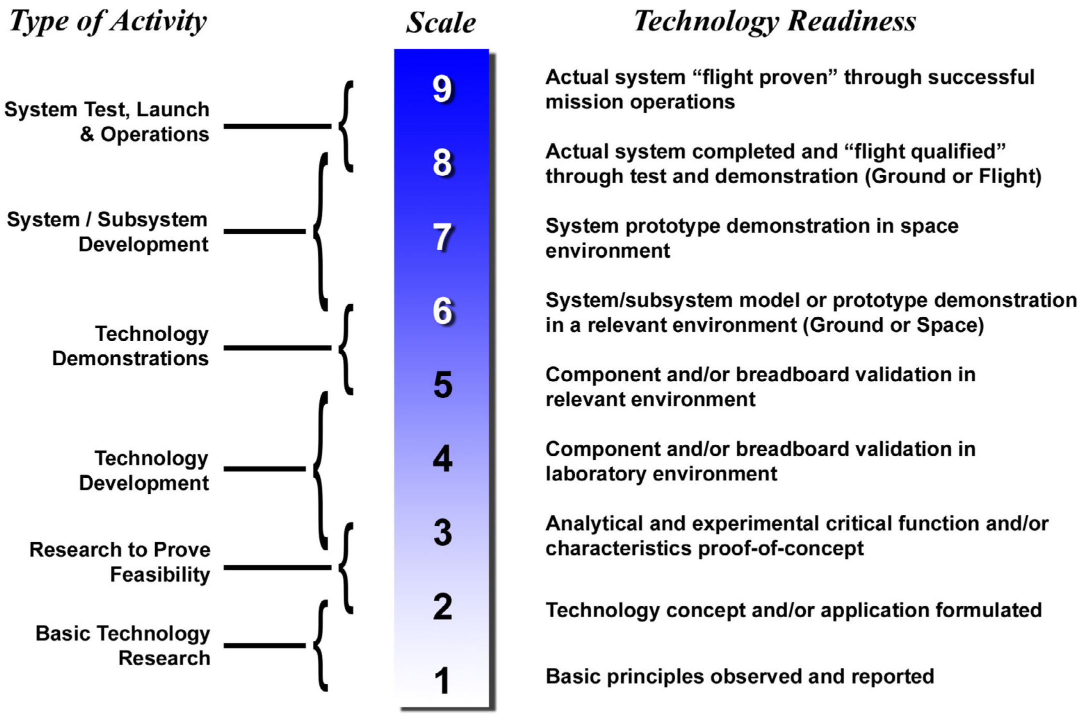


Figure 1. Technology readiness level scale (courtesy of NASA).

benchmark is the Space Shuttle that started development in 1972 and was ready for first flight in 1980—about 8 years. However, many critical technologies, such as the thermal protection tiles and reusable rocket engines were only TRL 3-4 at the beginning of the system's development resulting in the development period being extended 2-3 years. Another relevant benchmark was the early 1990s Delta Clipper Experimental single-stage rocket technology demonstrator. This 40,000 lb subscale, liquid hydrogen/liquid oxygen fueled, reusable rocket engine-propelled, low-speed demonstrator of a single-stage reusable space access system used TRL 8-9 technologies and went from the preliminary design review to the first flight in about 18 months, demonstrating the value of using mature technologies.

Reusable Military Launch System Design/Analysis Team

As Air Force interest in reusable space access and, in particular, operationally responsive spacelift re-emerged in 2001, efforts were initiated to improve the Air Force's ability to predict and compare conceptual designs for fully-reusable and partially-reusable space access systems. An informal joint government-industry partnership, called the Reusable Military Launch System (RMLS) Team, was organized. This team included the Air Force Research Laboratory (AFRL), Air Force Materiel Command's Aeronautical System Center's Engineering Directorate (ASC/EN), Air Force Flight Test Center, Air Force Space Command, NASA Kennedy and Johnson Space Centers, and industry. A primary product of this team's efforts has been the development of an integrated set of parametric, geometry-based, conceptual design computer tools for partially- and fully-reusable space access systems. Developed under the leadership of ASC/EN and AFRL, these tools enable the preparation of conceptual design estimates of the size, weight, and performance of both near-term and other more advanced reusable space access systems. ASC/EN and AFRL have used these tools to provide support for several recent Air Force studies, including one for Air Force Space Command. [2]

AFRL and ASC Concept Synthesis Study of Near-Term, Reusable Space Access Systems

From 2002 through 2005, the ASC/EN Aerospace System Design & Analysis Group conducted a conceptual design study of fully-reusable space access systems at AFRL's request. The study's focus was to use the RMLS integrated system sizing methodology to conceptualize designs of near-term (TRL 6-9), two-stage, fully-reusable space access systems representative of what industry *should* be able to develop and that are suitable for the routine transport of passengers and cargo. Using the output quantitative definition of weights and performance, a preliminary estimate of the development, production, and operational costs and mission capabilities of the system could then be developed.

Rationale for a Fully-reusable Space Access System

As discussed in Reference 1, the choice of a fully-reusable system transportation system, intended for the routine transportation of the public, is rooted in safety, operability, and recurring operational cost. Examination of terrestrial public transportation fails to identify any examples of either non-reusable systems or partially-reusable systems being used for routine public transport. Even during a time when costs

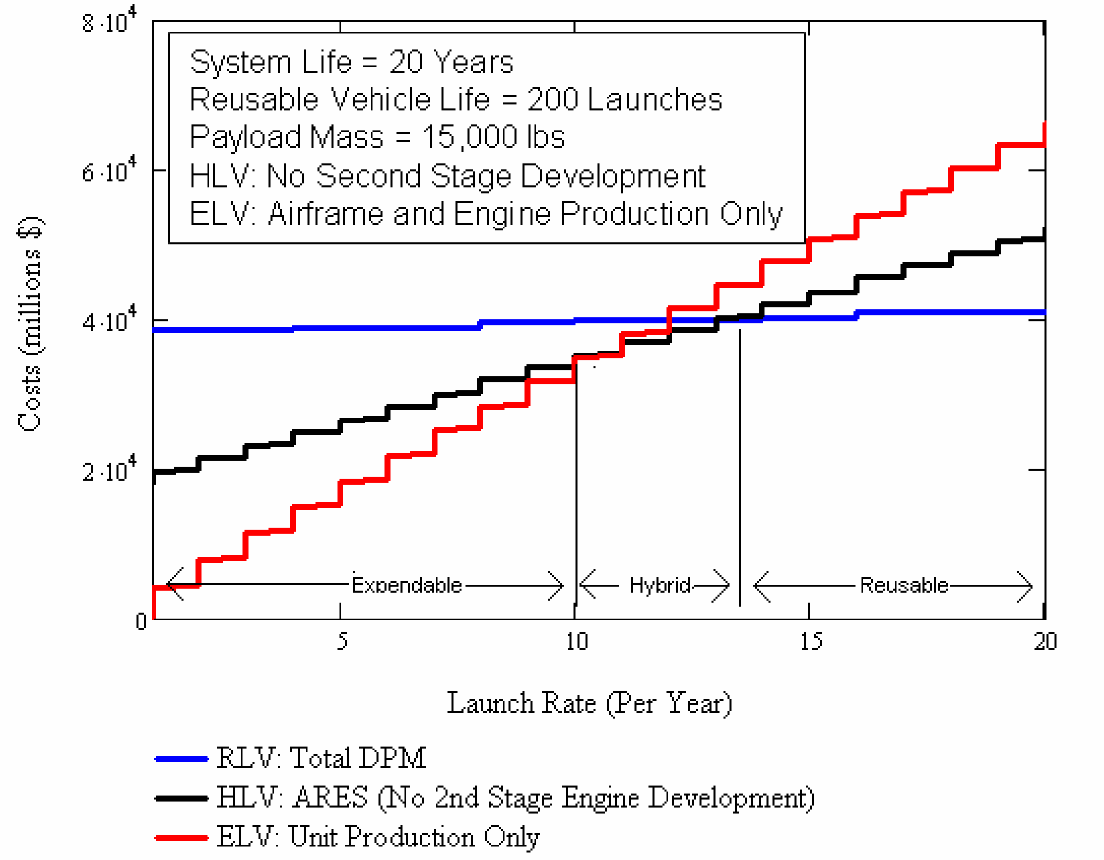


Figure 2. Cost comparison for RLV (fully-reusable launch vehicle), HLV (partially-reusable or hybrid launch vehicle), and ELV (expendable launch vehicle) as a function of launches per year (Courtesy: Greg J. Gstattenbauer).

of the production of complex systems have fallen dramatically, as they have in recent years due to the use of overseas production, no suitably safe and economical non-reusable mode of terrestrial public transportation has been successfully implemented. Hence, a primary argument against an expendable or partially reusable/hybrid space access system rests on the knowledge that no successful terrestrial analogs exist.

Advocates of expendable and hybrid space access systems typically emphasize the reduced life cycle cost of developing, producing, and operating these approaches compared with a fully-reusable approach. Figure 2 shows the results of one analysis of this cost comparison recently performed.[3] In this figure, the life cycle cost of three alternatives—an existing expendable launch vehicle, a partially-reusable or hybrid launch vehicle with a new reusable first stage and an existing expendable second stage engine, and an entirely new fully-reusable space access system—are compared as a function of the annual launch rate. Noting that this is the most favorable set of cost circumstances for the expendable and hybrid solutions because significant developmental costs are avoided through the use of existing systems, this figure indicates that the fully-reusable space access system is more cost-effective at annual launch rates greater than about 13 flights per year.

This cost comparison highlights the "Catch 22" for improving the cost of space access that has existed for the last quarter century. Excluding safety considerations, low launch rates, as experienced in recent years, favor expendable solutions even though the mission cost is high. This high mission cost discourages new space missions, such as space tourism and expanded human space exploration, which need higher launch rates. The resulting lack of new missions keeps launch rates low which favors expendable solutions, but with higher mission costs.

To respond to the increasing importance of space to the U.S., space access must become safe, routine, and significantly more frequent than about one launch per month. For this to occur, space access must transition to fully-reusable space access systems with aircraft-like safety and operability. When this happens, these new systems will become more cost-effective than expendable and partially-reusable hybrids. The design and cost analyses reported in this paper are intended to reinforce this conclusion with specific design, performance, operability, and cost data.

Section 2: Near-Term, Fully-reusable Concept Selection

As explained in Reference 1, the design of fully-reusable space access systems can take many forms. They can be single-stage or multiple-stage systems using rocket or a combination of airbreathing and rocket propulsion. They can carry all of the propellants at takeoff, consume oxygen from the atmosphere during part of the ascent, or "manufacture" and store oxidizer in flight for later use with rockets using some form of oxygen extraction and collection system. They can take off horizontally on a runway, launch vertically, lift off a powered sled or ramp, or be shot from a gun. They can land vertically or horizontally under power, glide to an unpowered horizontal landing or land using a parachute or another form of aerodynamic deceleration. Finally, they can climb and descend a space cable as in the proposed space elevator. Regardless of the design, what they must have in common is sufficient performance to achieve orbit and the system integrity that provides for safe and routine space access for passengers and cargo.

Of the alternative design approaches listed, only a two-stage system using primarily rocket propulsion is considered a near-term design with TRL 6-9 enabling technologies. Conceptual design studies conducted by ASC/EN indicate that any conventional single-stage system requires advanced technologies that are not yet mature. The same can be said for any multiple-stage concept that, in flight, separates and stores oxygen, uses a powered sled or ramp for takeoff assistance, is shot from a gun, or uses advanced airbreathing propulsion. And, certainly, any space elevator concept does not yet have a mature set of enabling technologies. Hence, absent a remarkable new design innovation for a single-stage system, the only expected near-term solution is a fully-reusable, TSTO space access system shown generically in Figure 3. [Note that this illustration is intended to only depict the arrangement of the elements of the system and does not represent a sized concept design as later shown in Figure 7.]

Concept Synthesis Parameters

As shown in Figure 3, the starting point for the ASC/EN study was selected to be a two-stage, rocket-powered, vertical-takeoff and horizontal landing system. It features a side-by-side configuration with the second stage along side the first stage. The airframe

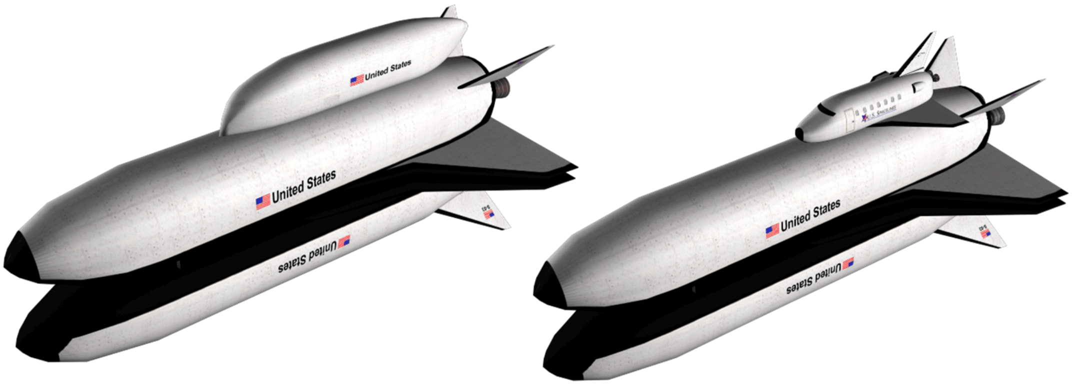


Figure 3. General configuration of a two-stage, vertical-launched, horizontal-landing, fully-reusable space access system with cargo container (left) and passenger transport spaceplane (right) (Courtesy of ASC/EN).

was modeled as traditional aluminum primary structure and propellant tanks. The thermal protection system was modeled as passively cooled secondary structures with bonded-on ceramic tiles and blanket insulation and rigid ceramic wing leading edges and nose cap. Critical subsystems—electrical power generation and distribution, avionics, propellant handling and distribution, on-orbit propulsion, etc.—were modeled using existing Space Shuttle and aircraft subsystem weights and performance. For propulsion, the first stage's four engines were modeled as RD-180-equivalent engines (same thrust, specific impulse, and engine thrust-to-weight) while the second stage's four engines were modeled as RD-120-equivalent engines with the addition of thrust-gimballing. [4] Both of these are production engines. Payload carriage was using an externally mounted cargo container while passenger transport was to be with an externally carried passenger spaceplane.

Comparison with the design and operation of the Space Shuttle orbiter indicates that the conceptual model of the two-stage reusable space access system closely mimics the design of the Shuttle's orbiter—aluminum structure, type of thermal protection system, ascent trajectory, reentry profile, landing modes, etc. These technologies are not only TRL 9, but the vehicle's subsystem weight equations are also well characterized because they are based on actual weights of production components used in similar applications under similar flight conditions. The operability and support requirements for these subsystems are also well characterized permitting, as discussed later, estimates of the turn-around time and required maintenance work-hours to be made.

Propellant and Engine Selection Considerations

Both stages were modeled using kerosene and liquid oxygen (LOX) as the propellants. This provides operability advantages with using only the mild cryogen LOX and the room-temperature storable kerosene. Liquid hydrogen (LH2) and LOX is the other near-term propellant combination choice. These, it has been found through previous conceptual design analysis, generally yield slightly better performance with the same gross weight due to the higher performance of LH2/LOX engines. A system design using LH2/LOX on both stages or a mixed design using kerosene/LOX on the first stage and LH2/LOX on the second stage are alternative near-term options also suitable for a near-term system. Because kerosene/LOX produces a more conservative (i.e., heavier empty weights) estimate, this was selected for the conceptual design analyses.

Expendable solid-fueled rocket boosters were not used due to their lower performance and, equally important, unacceptable failure modes. Alternative main engine propellants (such as methane, hybrid solid fuel/LOX engines) or airbreathing engines (such as scramjets) were not selected due to their technological immaturity. Methane, as discussed later, is seen as a good choice for certain near-term space propulsion applications.

One unfortunate impact in the continued emphasis of expendable over reusable launch systems during the last 40 years has been the lack of development of reusable, high-thrust rocket engines suitable for first stage booster engines. The LH2/LOX Space Shuttle Main Engine (SSME) is the only U.S.-designed operational reusable engine. The development of several other LH2/LOX and kerosene/LOX engines have been started over the years as either company-funded programs or government-funded technology development efforts. These can serve as the starting point for new reusable engines as this market grows. However, at this time, the two primary choices for near-term reusable space access are the SSME and the RD-180.

The first stage main engines are modeled based on the kerosene/LOX RD-180. This is a twin-combustion chamber design, 860,000-lb thrust rocket engine developed in the late 1990s for the U.S. Atlas V ELV (see Figure 4). It is a derivative of the four-combustion chamber RD-170 rocket engine, providing approximately one half the thrust of the RD-170. The RD-180 was designed and is today produced in Russia and provided for U.S. use through a U.S.-Russian industry partnership. While characterized as an

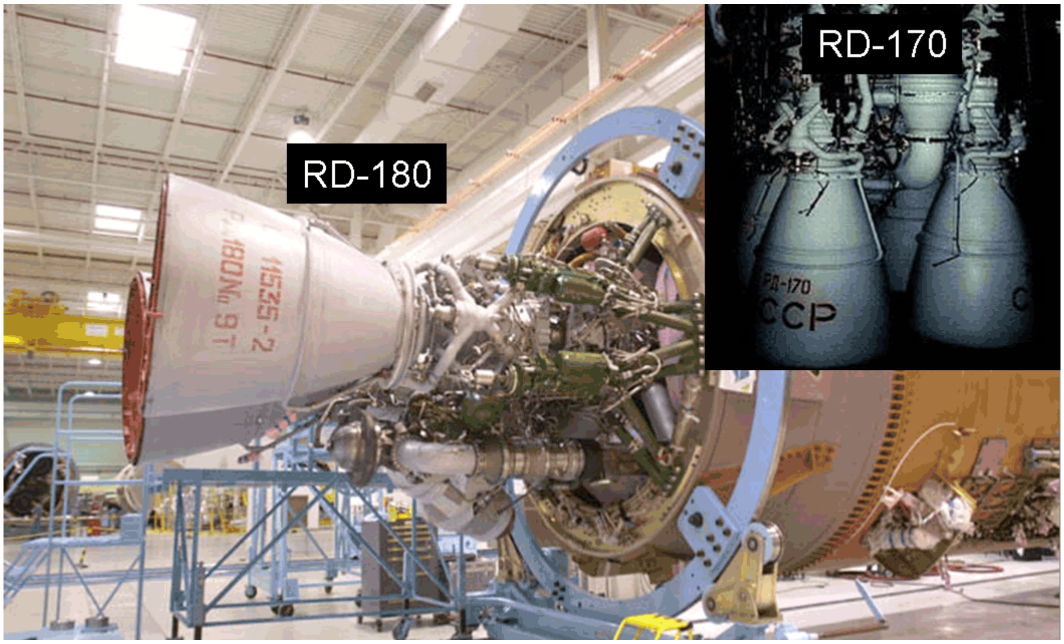


Figure 4. RD-180 twin-combustion chamber engine mounted on the Atlas ELV; insert picture is of parent RD-170 four-combustion chamber engine.

expendable engine, the production RD-180 is certified for five engine starts with one of these being used in Russia to test fire the engine prior to its shipment to the U.S. Hence, the RD-180 represents a TRL 9 engine with known performance, weight, and installation requirements.

What makes the RD-180 attractive for the reusable space access system is that the RD-170 was designed, at about the same time the SSME was being developed, as a reusable engine for the Russian Buran Space Shuttle system. Today, it powers the first stage of the Russian Zenit ELV rocket used by the U.S.-led Sea Launch Corporation. One RD-170 test engine has achieved over 10 mission firings. Hence, the engine's enabling technologies for reusability have been demonstrated to be at least TRL 6—system/subsystem model or prototype demonstration in a relevant environment (ground or space). This leads to the conclusion that a *version* of the RD-180 *may be* suitable for use on a near-term reusable space access system. Based on discussions with industry, a reasonable study assumption was that an equivalent U.S.-provided engine will be able to achieve 10 full mission reuses by the time the space access system reaches an initial operational capability (IOC) status and 25 full mission reuses by the time a full operational capability (FOC) status is achieved. Because the kerosene-LOX RD-120 represents the same fundamental engine technologies, an equivalent U.S.-provided engine, *it is also believed*, would provide suitable performance and acceptable reusability for a near-term space access system's second stage. [Note: careful evaluation of main engine technology maturity for reusable use would be a key part of a formal readiness-to-proceed assessment for near-term, fully-reusable space access systems.]

At first glance, the replacement intervals of 10 engine missions at IOC and 25 engine missions at FOC appear to be low and uneconomical. Yet, closer examination shows that this is a good match for the rate of flight operations expected for a near-term, fully-reusable space access system. Figure 5 shows the apportioned cost per mission for replacing the engine as a function of the number of missions between engine replacements. From this figure, it is seen that the break in the curve occurs at about 10

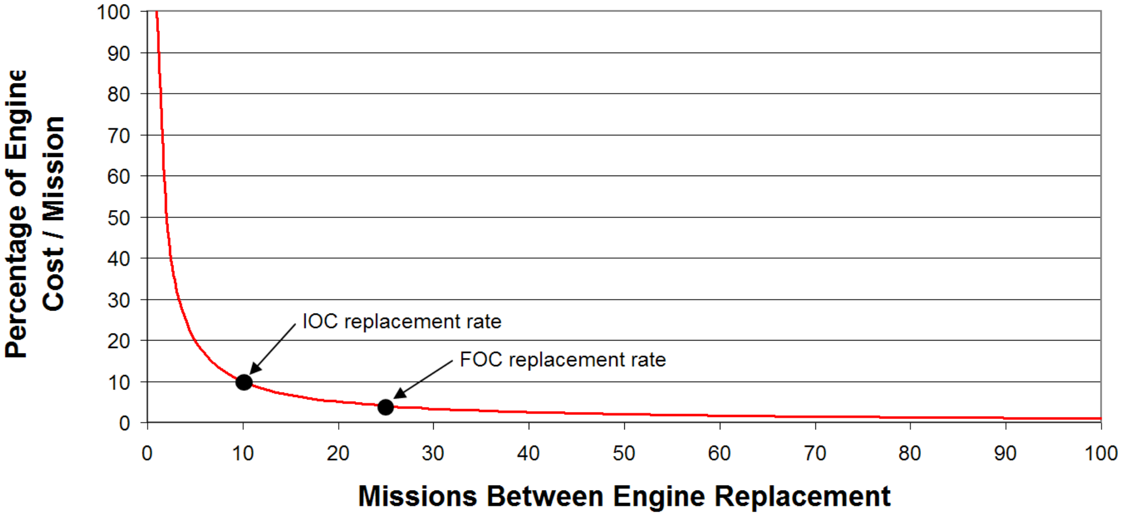


Figure 5. Allocated cost of replacing the main engines as a function of the missions between replacement.

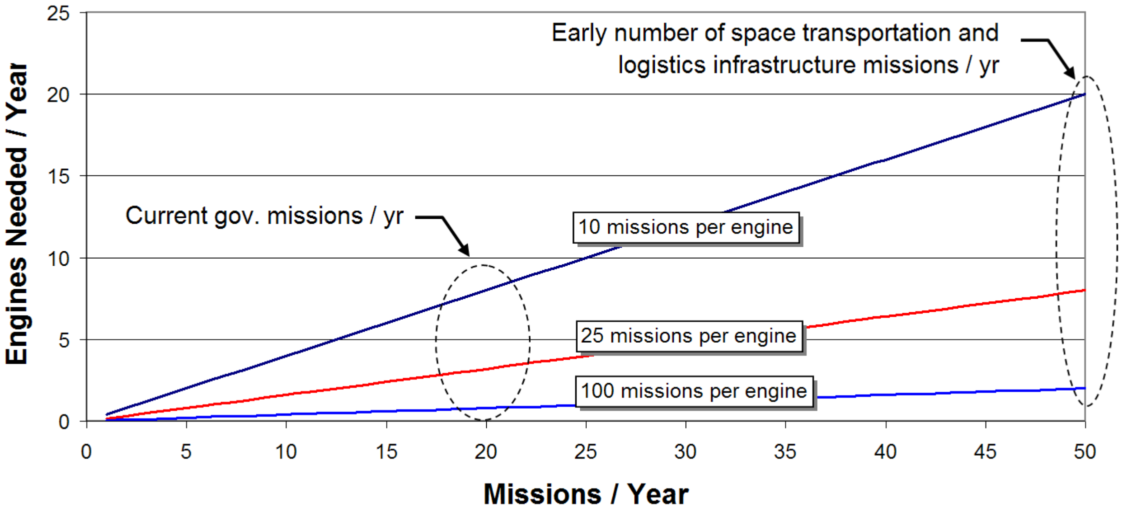


Figure 6. Impact of the number of missions per engine and flight rate on engine production requirements.

missions between replacement. This is the replacement interval selected as the IOC objective. At the FOC objective of 25 missions between replacement, the apportioned cost per mission is 4 percent. Some argue that it is only reasonable to expect that the reusable engines should achieve 100 missions between replacement before reusable space access systems make sense economically. Yet, as seen in this figure, the FOC objective of 25 missions achieves nearly all of the cost savings due to engine reusability and accomplishes this with what industry believes to be near-term engine capabilities.

An equally important economic consideration is the impact of the number of missions per engine on the engine production industrial base. Figure 6 shows an estimate of the number of new engines needed to be produced each year as a function of the number of missions flown per year and the engine replacement interval. These calculations are based on four engines on the first stage. If reusable rocket engines capable of achieving 100 missions were available today, the low projected initial flight rate of about 20 government missions per year would create a demand for, on average, about one new engine per year. If the flight rate were to increase to 50 missions per year, the demand for new engines only increases to about three per year. Obviously, this is an uneconomical production rate and much of the cost savings achieved through reusability would be lost with uneconomical production overhead costs. What this simple trade study does indicate is that the IOC objective of 10 missions per engine and the FOC objective of 25 missions per engine will create the demand for reasonable numbers of new engines per year. This would enable a more competitive and healthy industrial base to be established that would benefit both first and later generations of fully-reusable space transportation systems.

Two sizes of RD-180-equivalent technology engines were used in this study. Four current RD-180 thrust level engines are used on the first stage of the smaller fully-reusable space access systems (Configurations 1 and 2) while four 120 percent growth versions are used on the larger fully-reusable space access systems (Configurations 3 and 4). Recall that the standard RD-180 is a 50 percent version of the RD-170. Hence, scaling the RD-180 equivalent technology engine up by 20 percent does not exceed the demonstrated capabilities of the RD-170. Also, replacement of the twin-nozzle design with a single nozzle design, as will probably be desirable for reduced manufacturing costs and easier installation, appears to also be a readily achievable improvement.

Additional Concept Synthesis Conservatisms and Design Requirements

To add additional conservatism to the design, the ASC/EN study incorporated three additional elements. First, an empty weight margin of 15 percent was added to all non-primary propulsion weights. This empty weight margin reflects uncertainty with the detailed design of a specific configuration not reflected in the subsystem weight and performance estimating relationships used in the RMLS models. Employing such a design margin is typical during conceptual design and, as discussed later, is the value recommended by Koelle for a near-term concept. This margin was not applied to the main engine weights, however, as these are established production values.

The second conservatism was the imposition of an engine-out requirement. The reusable space access system would be capable of conducting the mission while incurring a safe shutdown of any of the first or second stage engines at any time following first stage engine ignition at launch. This makes the design more “aircraft-like” in the same manner that a takeoff or in-flight engine-out capability would be included in the criteria for the conceptual design of a new aircraft.

A final layer of conservatism is the use of weight estimating relationships based on the state-of-the-art structures and subsystems from 10-25 years ago. Design and manufacturing technologies have significantly advanced leading to more weight-efficient and economical designs found in production systems today. For example, the new Boeing 787 will make extensive use of advanced composites to reduce the airframe weight and maintenance requirements. While not quantified in this study, this approach adds a further measure of confidence in the ability to produce near-term, fully-reusable space access designs that reflect what industry should be able to now provide.

The two design requirements imposed on the study were the size of the payload being transported and the orbital parameters to be achieved. For the external cargo module, the cargo envelope dimensions were 12 ft (3.7 m) in diameter by 30 ft (9.6 m) in length if the cargo container is to be returned to the Earth. If the cargo container is expendable, its maximum diameter would be 15 ft (4.8 m). This enables the fully-reusable space access systems to transport payloads representative of those carried on most medium-class ELVs as well as accommodating the needs of passenger transport and logistics materiel transport, as discussed below. The design orbital parameters are discussed in the following.

ASC/EN Synthesis Results of Near-Term, Two-Stage-To-Orbit, Fully-Reusable Space Access Systems

An illustration of the ASC/EN-generated configuration of a TSTO fully-reusable space access concept developed the RMLS conceptual design analysis methodology is shown in Figure 7. The predicted weight and values for three closed system designs are summarized in the following with further details provided in Table 1. [Note: The methodology used to prepare these estimates is described in Reference 5.]

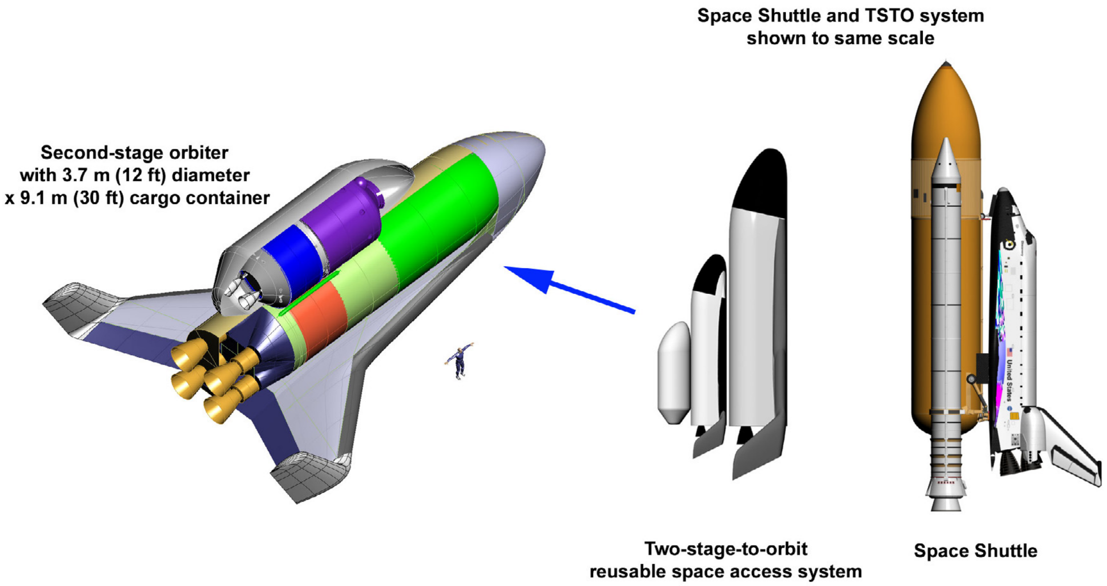


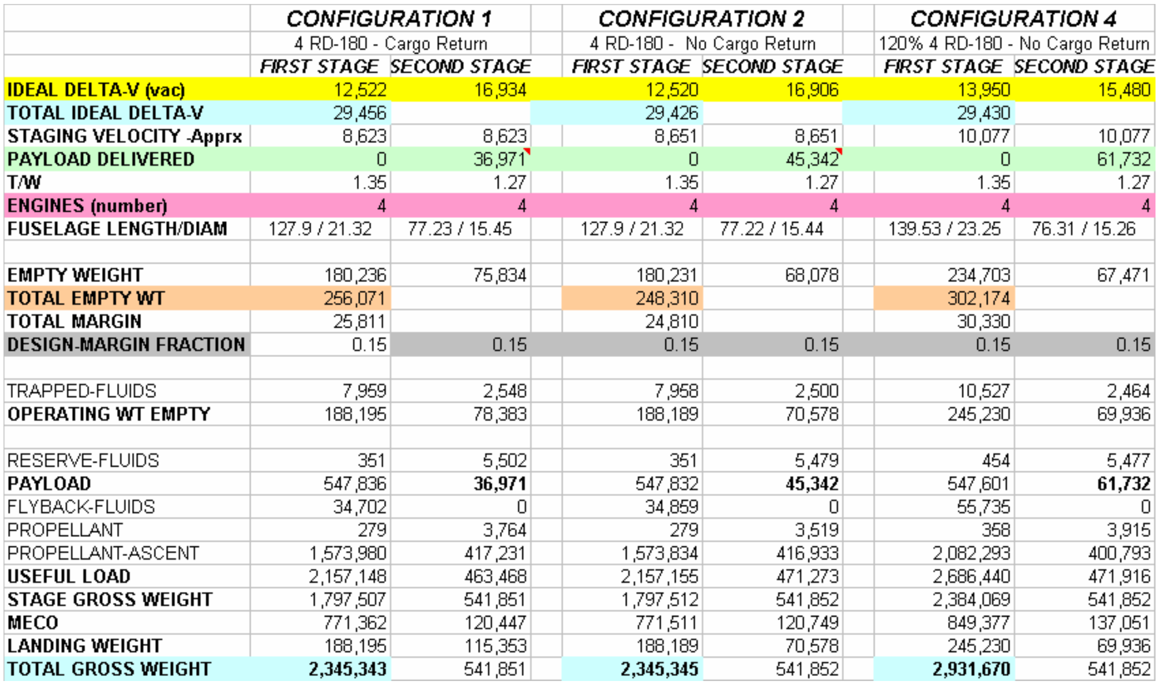
Figure 7. Illustrations of ASC/EN's near-term, two-stage-to-orbit, fully-reusable space access concept compared to Space Shuttle orbiter.

Configuration 1 uses four RD-180-equivalent technology engines and is sized to return *with* a loaded cargo module. It is capable of transporting a cargo module weighing 37,000 lb (16,800 kg) to the 100 nm (185 km) circular orbit due east from Florida. The net cargo weight is 27,700 lb (12,600 kg) assuming that the cargo container weighs 25 percent of the total weight. The gross weight of this system is 2.3 million lb (~1 million kg). The payload percentage of the gross weight is 1.58 percent.

Configuration 2 also uses four RD-180-equivalent technology engines, but is sized to return *without* the cargo container. This enables the empty weight of the second stage to be reduced by about 8,000 lb as the wing and landing gear shrink in size. This configuration is capable of delivering a cargo module weighing approximately 45,000 lb (20,400 kg). In this case, the cargo could be an expendable payload, such as a tank transporting water. The gross weight of this system is 2.3 million lb (~1 million kg) and the payload is 1.93 percent of the gross weight.

Configuration 4 uses four 120 percent RD-180 equivalent technology engines on the first stage. Like Configuration 2, it is sized to return *without* the cargo container and is capable of transporting a cargo module weighing 62,000 lb (28,000 kg). The gross weight of the system is 2.9 million pounds (~1.3 million kg) and the payload is 2.11 percent of the gross weight. Essentially Configuration 4 is a growth version of Configuration 2.

Using the payload performance of these three cases, the payload performance of a Configuration 3 system was then estimated. Configuration 3 would have the same gross weight as predicted for Configuration 4. Like Configuration 1, the second stage would be sized to return *with* a loaded cargo module. The estimated payload percentage is 1.73 percent. The gross weight delivered to a 100 nm circular orbit at 28.5 degrees inclination is estimated to be 50,400 lb (22,900 kg). [Note: The appropriate change in the estimate



	CONFIGURATION 1		***CONFIGURATION 2***		***CONFIGURATION 4***	
	4 RD-180 - Cargo Return		4 RD-180 - No Cargo Return		120% 4 RD-180 - No Cargo Return	
	FIRST STAGE	***SECOND STAGE***	***FIRST STAGE***	***SECOND STAGE***	***FIRST STAGE***	***SECOND STAGE***
IDEAL DELTA-V (vac)	12,522	16,934	12,520	16,906	13,950	15,480
TOTAL IDEAL DELTA-V	29,456		29,426		29,430	
STAGING VELOCITY -Apprx	8,623	8,623	8,651	8,651	10,077	10,077
PAYLOAD DELIVERED	0	36,971	0	45,342	0	61,732
T/W	1.35	1.27	1.35	1.27	1.35	1.27
ENGINES (number)	4	4	4	4	4	4
FUSELAGE LENGTH/DIAM	127.9 / 21.32	77.23 / 15.45	127.9 / 21.32	77.22 / 15.44	139.53 / 23.25	76.31 / 15.26
EMPTY WEIGHT	180,236	75,834	180,231	68,078	234,703	67,471
TOTAL EMPTY WT	256,071		248,310		302,174	
TOTAL MARGIN	25,811		24,810		30,330	
DESIGN-MARGIN FRACTION	0.15	0.15	0.15	0.15	0.15	0.15
TRAPPED-FLUIDS	7,959	2,548	7,958	2,500	10,527	2,464
OPERATING WT EMPTY	188,195	78,383	188,189	70,578	245,230	69,936
RESERVE-FLUIDS	351	5,502	351	5,479	454	5,477
PAYLOAD	547,836	**36,971**	547,832	**45,342**	547,601	**61,732**
FLYBACK-FLUIDS	34,702	0	34,859	0	55,735	0
PROPELLANT	279	3,764	279	3,519	358	3,915
PROPELLANT-ASCENT	1,573,980	417,231	1,573,834	416,933	2,082,293	400,793
USEFUL LOAD	2,157,148	463,468	2,157,155	471,273	2,686,440	471,916
STAGE GROSS WEIGHT	1,797,507	541,851	1,797,512	541,852	2,384,069	541,852
MECO	771,362	120,447	771,511	120,749	849,377	137,051
LANDING WEIGHT	188,195	115,353	188,189	70,578	245,230	69,936
TOTAL GROSS WEIGHT	**2,345,343**	541,851	**2,345,345**	541,852	**2,931,670**	541,852

Table 1. Summary of the ASC/EN conceptual design analysis results of TSTO reusable space access systems.

of the empty weight of the second stage, to reflect the larger wing and heavier landing gear, was used in the following cost estimates.]

The payload performance for Configuration 3 is plotted in Figure 8 as a function of orbital inclination and altitude, assuming circular orbits. The 100 nm (185 km) circular orbit is assumed to be the initial parking orbit for the second stage. The 270 nm (500 km) circular orbit is assumed to be the altitude of an orbiting space logistics base—the destination of the cargo and passengers. The net payload delivered to the 270 nm circular orbit was estimated based on the second stage conducting appropriate orbit transfer maneuvers to change altitude from 100 nm to 270 nm, deliver the payload, and then deorbit. As noted previously, the net cargo assumes that the cargo container is 25 percent of the gross cargo weight delivered to orbit.

Two payload design points are also noted in Figure 8. The first is the estimated weight of a small reusable spaceplane that would be carried in place of the cargo container to transport 6-10 passengers to LEO. Its estimated gross weight at separation from the second stage is 40,000 lb (18,000 kg). The spaceplane would be dropped off in the 100 nm circular orbit where it would, under its own power, conduct the orbit transfer maneuvers to rendezvous and dock with a space logistics base at the higher altitude. After the passengers disembark, the spaceplane would conduct deorbit maneuvers and reenter and land much as the Space Shuttle orbiters do today.

The second point in Figure 8 is a 24,000 lb (10,900 kg) net (useful) cargo weight capable of being delivered directly to the orbiting space logistics base at 51.6 degrees inclination.

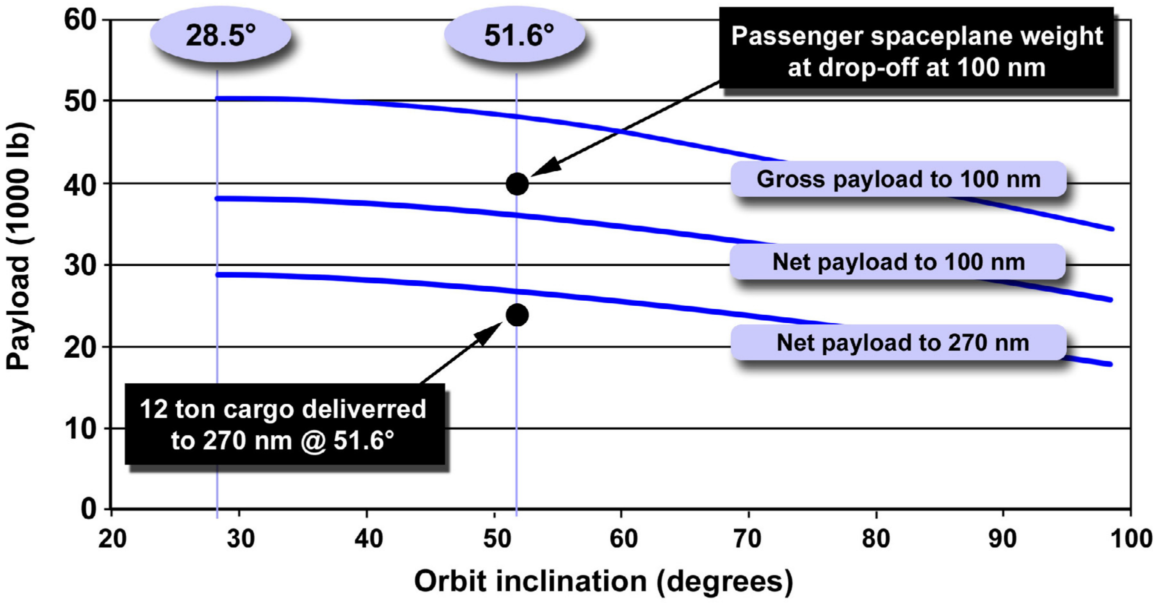


Figure 8. Performance of Configurations 3 two-stage-to-orbit, fully-reusable space access system.

AFRL Contracted Study Results

Lockheed Martin has been involved in a number of recent reusable space access studies for the Air Force and NASA. In a modest study undertaken for AFRL, Lockheed Martin used their reusable space access system conceptual design methodology to prepare initial estimates of several near-term configurations. In these efforts, they were free to select the configuration, empty weight margins, etc., representing their preferred configuration. AFRL only specified a medium-class payload size and weight and the use

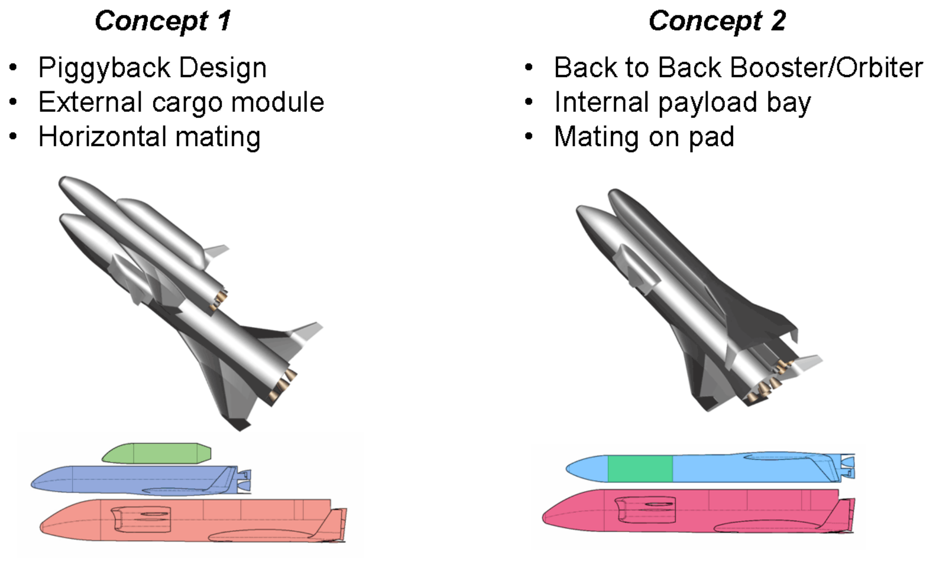


Figure 9. Lockheed-Martin concepts for near-term, fully-reusable space access systems (Illustrations courtesy of Lockheed Martin).

	Concept 1		Concept 2	
	External payload		Internal payload	
Weight	Small	Large	Small	Large
W-takeoff (klb)	3,515	4,278	3,610	4,559
W-empty (klb)	461	543	483	583
W-payload (klb net/gross)	20 (35)	36 (51)	20	37
1st stage wt. margin	83	97	83	101
2nd stage wt. margin	18	22	23	28
Payload margin (klb)	30	36	35	42
Length (ft)	165	175	166	179
No. Engines	6/3	7/4	6/3	7/4

Table 2. Summary of results of Lockheed-Martin study.

of technologies consistent with what the contractor believed to represent a near-term design. Two of these configurations are shown in Figure 9. Concept 1 has an externally-mounted cargo container while Concept 2 uses an internal payload bay. Table 2 summarizes the results of the analysis of these two configurations where two different size payloads were analyzed for each configuration. Both of these designs were sized to deliver the payload to a 100 nm, 28.5 degree inclination, circular orbit launched due east from Kennedy Space Center, Florida.

The Lockheed Martin configurations are larger than the comparable government configurations. The primary reason for this difference is that Lockheed Martin used a larger 22 percent empty weight margin applied to the entire system. The ASC/EN estimate used a 15 percent margin applied to everything but the main first and second stage engines. The contractor stated that, from their experience, this was an appropriate level of conservatism at this early stage of design synthesis, especially given the modest effort of this contracted study.

Table 2 also lists the first and second stage empty weight margins, as well as an estimated payload margin for the four configurations. This “payload margin” is the author’s estimate of what increase in payload would be achieved if none of the empty weight margin was actually needed. In this case, the entire second stage empty weight margin and a percentage of the first stage’s margin would translate into added payload mass. Note that the magnitude of the payload margin is comparable to the useful payload. This shows the sensitivity that these vehicles have to weight growth and emphasizes the importance of using mature technologies, as was done in these studies, to enhance the accuracy of the early weight estimating relationships.

The selection of the actual design margins to be used in system development is usually undertaken during the preliminary design phase. It is at this point that the required engine thrust levels, Delta-V split between the first and second stage, design payload weights, etc., are established. The imposition of design margins that are too conservative will lead to high payload margins that could result in a system larger and more expensive to develop and operate than desired. Conversely, the use of design margins that are too small creates a "weight growth crisis" that can cause significant program execution difficulties. Because of the lack of industry experience with actually building reusable space access systems, this is likely to remain an area warranting significant attention during the preliminary and early detailed design phases for the first fully-reusable space access development programs.

On a related note, the Space Shuttle experienced a 25 percent weight growth during its development. This was for a system using virtually all new technologies for propulsion, large tankage, reusable thermal protection system, etc. The current focus on the use of state-of-the-art technologies is, in part, intended to help prevent such dramatic weight growth and related program schedule and cost risk during system development. From the point of view of the government's near-term reusable space access system synthesis methodology, this Shuttle weight growth has already been reflected in the weight estimation relationships and was one reason why the government estimate used a lower empty weight margin.

Government–Contractor "Match Case" Comparisons

As stated previously, the intent of the government design synthesis efforts was not to define an optimum configuration but to predict concepts representative of what industry could build. To help establish the confidence in the government's estimation methodology, "match case" comparisons have been run using the government's tools and the contractor's assumptions. Such comparisons help to identify significant differences in weight estimation relationships and imbedded assumptions.

For comparing government results with Lockheed Martin, the second stage empty weight reflects a good point for comparison because this is the weight that achieves orbit. ASC/EN input the contractor's configuration specific information (such as the number of engines, separation velocities, and empty weight margins) into the government synthesis methodology and "turned the crank" to produce a sized second stage configuration. No changes in the weight and performance estimation relationships were made. In comparing the results, the government's estimate of the second stage total empty weight varied from that of the contractor's by less than one percent while individual subsystem-by-subsystem comparisons showed variances in the 5-10 percent range—typical of conceptual design methodologies. In another reusable space access system design study, ASC/EN performed another match case comparison with estimates prepared by Boeing. In comparing empty weight, gross weight, propellant weight, residuals, and weight at main engine cutoff, the government estimate differed from the contractor's estimate by less than 0.25 percent. Generally, government synthesis methodologies are expected to be able to make predictions, when industry's assumptions are used, within 5-10 percent of the values generated by industry.

Conclusions Drawn from Government and Contractor Conceptual Design Analyses

Both government and contractor conceptual design analyses have yielded reasonable estimates of closed designs of fully-reusable, two-stage, vertical-launched, horizontal-landing space access systems that can transport passengers and cargo to LEO. In both cases, the designs utilize TRL 6-9 technologies reflecting mature conceptual designs. These favorable results argue that the U.S. aerospace industry has the capability to initiate the development of TSTO, fully-reusable space access systems.

Section 3: ROM Cost Estimate of Near-Term TSTO Solutions

The ASC/EN predictions of the weights, described in the previous section, combined with separate ASC/EN predictions of the work-hours required to turn-around a reusable space access system were used to prepare ROM cost estimates of the development, production, and recurring cost of operation of Configurations 1 and 3. Specific cost estimates discussed in the section include:

- Development and production costs for:
    - First stage airframe
    - Second stage airframe
    - Cargo container
    - Passenger-carrying spaceplane
    - First stage booster engine
    - Second stage booster engine
    - Spaceplane orbit transfer engine
- Recurring cost of operation
- Total program cost
    - U.S. government “business as usual” estimate
    - Cost-engineered estimate

Assumptions Used in the Preparation of the ROM Cost Estimates

1. To meet the needs of assured space access, two types of design-independent, TSTO, fully-reusable space access systems are to be developed and brought into production. This means that the total estimated development and production costs for Configuration 1 will be doubled to include two types with comparable performance and payload carriage capabilities being fielded. Likewise, the total estimated development and production costs for Configuration 3 will also be doubled to include two types being fielded.
2. Two ASC/EN concepts are used:
    - Configuration 1 with a 37,000 lb (16,800 kg) gross payload capability.
    - Configuration 3 with a 50,400 lb (22,900 kg) gross payload capability.

[Note: Recall that the detailed estimated weights for Configuration 3 are to be based on the estimates of Configuration 4. The first stage empty weights are assumed to be the same. The empty weight of the second stage of Configuration 3 is assumed to be 61,700

– 50,400 = 11,300 lb (5,100 kg) heavier than Configuration 4’s second stage empty weight. This accounts for the increased wing and landing gear weight needed to land with the payload.]

3. The passenger spaceplane is assumed to have a gross weight of 35,000 lb (15,900 kg) for Configuration 1 and 45,000 lb (20,400 kg) for Configuration 3. [Note: This brackets the ASC/EN early weight estimate of 40,000 lb.] The 10 passengers and 2 crew members combined weight is assumed to be 3,600 lb (1,600 kg). The empty weights of the spaceplanes without engines and propellants are assumed to be 23,000 lb (10,400 kg) and 30,000 lb (13,600 kg).
4. The cargo container is assumed to weigh 25 percent of the gross payload weight: 37,000 lb x 0.25 = 9,300 lb (4,200 kg) for Configuration 1 and 50,400 lb x 0.25 = 12,600 (5,700 kg) for Configuration 3. [Note: This is assumed to be a basic unpressurized container providing only minimal power and data communication to the payload. Specialized containers providing additional services for a specific payload would be developed as needed.]
5. For estimating production costs for each of the two types of the Configuration 1 system and each of the two types of the Configuration 3 system:
    - Five total flight systems will be produced of each type: three systems for flight operations, one equivalent system for ground support and training, and one equivalent system for major component operational spares.
    - Seven cargo containers will be produced: six for operational use and one for ground payload fit-check testing.
    - Three spaceplanes will be produced: two for operational use and one for ground support and training.

[Note: the cost of prototypes is assumed to be included in the system development cost estimate.]

6. For estimating the primary propulsion development costs, new engines are assumed to be developed for each of the two types of the Configuration 1 system and each of the two types of the Configuration 3 system. Each engine development cost includes the engineering and manufacturing development as well as approximately 1,000 engine firings to verify engine performance, operability, and suitability.
    - For Configuration 1, a *new* first stage engine, equivalent to the RD-180 in weight, thrust, and specific impulse, will be developed and a *new* second stage engine, equivalent to the RD-120 in weight, thrust, and specific impulse, will also be developed. [Note: The weight of the RD-120 was increased by 17 percent to add engine thrust vectoring to the second stage.]
    - For Configuration 3, a *new* first stage engine, equivalent to a 120 percent scaled RD-180, will be developed and a *new* second stage engine, equivalent to the RD-120 in weight, thrust, and specific impulse, will also

be developed. [Note: The weight of the RD-120 was increased by 17 percent to add engine thrust vectoring to the second stage.]

  - One new engine for each type of spaceplane will be developed.

7. Twenty-eight production engines are included in the production cost estimate for both Configuration 1 and Configuration 3. Four first stage and four second stage production engines are included for each of the three operational systems of each type. Two additional production engines for each stage are procured for initial spares.
8. Six spaceplane production engines are included in the production cost estimate for both Configuration 1 and Configuration 3. Two engines are procured for each of the three operational spaceplanes of each type and one additional engine is procured for an initial spare for each spaceplane type.
9. In accordance with the engine-out criteria, the main first stage and second stage engines have a nominal mission maximum thrust of 92 percent of the maximum available thrust.
10. Six-month-long phase inspections of each operational system will occur every five years or 100 missions, whichever comes first.
11. At IOC and for the next five years, the first and second stage engines will be replaced after 10 missions. Starting at FOC, the engines will be replaced after 25 missions.
12. The space access systems are developed under reduced government oversight consistent with the use of TRL 6-9 technologies and more commercial-like contracting arrangements. [Note: This is discussed later in this section.]
13. Recurring cost estimates are based on an assumption of 10 missions per year per system type at IOC and 50 missions per year per system type starting at FOC. This is primarily used to establish engine production rates and associated learning curve values.
14. The cost of the average aerospace work-year (wk-yr) used in the estimate was $250,000 representing the approximate cost for 2005.

HANDBOOK OF COST ENGINEERING
FOR
SPACE TRANSPORTATION SYSTEMS
(Revision 1)

WITH

TRANSCOST 7.1
Statistical-Analytical Model for
Cost Estimation and Economical
Optimization of Launch Vehicles

Author: Dr. Dietrich E. KOELLE
Report No. TCS-TR-175

Published by:

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Liebigweg, Germany
e-mail: dekoelle@transcost.com

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Figure 10. Author's illustration of the cover of Koelle's handbook.

Cost Methodology Used

The cost methodology used to prepare the ROM cost estimate is taken from Dr. Dietrich E. Koelle's *Handbook of Cost Engineering for Space Transportation Systems* (see Figure 10). [6] First developed as a doctoral thesis 35 years ago, this handbook has progressed through seven major revisions and is used worldwide for preparing early program cost estimates. The current revision incorporates historical data from 1960 to 2002. [Note: While believed to be useful for preparing ROM cost estimates of reusable space access systems, it is not a replacement for formal cost estimating methodologies used elsewhere in the government.]

"Cost engineering," as used by Koelle, relates to designing space transportation systems that lead to lowest cost but not necessarily lowest empty weight, lowest gross weight, or highest technology standard. In applying this methodology, Koelle provides cost engineering design guidelines to help achieve lowest cost. These include:

- account for maintainability and refurbishment needs consistent with the goal of routine operation,
- size engines for normal operation at 92-95 percent of the maximum thrust,
- apply new technology only where it improves cost efficiency, and,
- minimize the number of stages consistent with the above.

Koelle's methodology, which will only be briefly discussed herein, first develops a U.S. government "business as usual" (BAU) development and production cost estimate because the methodology is largely based on U.S. historical program development costs. This estimate is made in terms of work-years of effort. Multiplying the number of work-years by the current average cost per work-year yields a total estimated contract cost. Koelle then estimates a program cost reduction that, he argues, can be achieved through the application of the cost engineering methodologies. Essentially, Koelle's intent is to focus on cost and not, as has happened in the past with the National Aerospace Plane and X-33 programs, on leading-edge technology as the primary program approval criteria.

It is important to understand that the baseline estimate of the BAU cost is based not on program proposal costs, but reflects actual historical program expenditures of completed programs. As a consequence, *the BAU estimate includes a 15-20 percent margin for unforeseeable technical problems or delays experienced by many programs.* Koelle also advocates the use of a 15 percent empty weight margin for programs such as reusable space access systems. This is the value that has been used in the preparation of the government's weight estimates, as explained earlier.

Historical Program Costs in Terms of Work-Years

As the basic cost estimates are in terms of work-years and not dollars, an historical perspective, drawn from Koelle's handbook, is useful. Table 3 lists the historical work-years of effort for a mixture of space and aviation programs, as shown in Koelle's handbook, undertaken by the U.S. government as well as commercial efforts. Almost any major aerospace program requires tens of thousands of *work-years* of effort. Large stages of space launch systems, e.g., the Saturn S-1B, were nearly as "expensive" to develop as advanced aircraft of the same time period, e.g., the XB-70. From this historical information, an interesting point of comparison with the work-year estimates for the TSTO reusable space access systems developed in this paper is that the total development cost for the Shuttle Orbiter and SSME was 93,100 work-years. At $250,000 per work-year, this totals approximately $23 billion. [Note: This does not include the

System	***Work Years***
Saturn S-IB	35,000
Saturn F-1 Engine	18,000
Shuttle Orbiter	75,000
SSME (1972-1982)	18,100
Concorde	58,000
XB-70	50,000
Apollo Command Module	20,000
Boeing 777	25,000

Table 3. Comparison of historical programs' work-years.
(Source: Koelle's handbook)

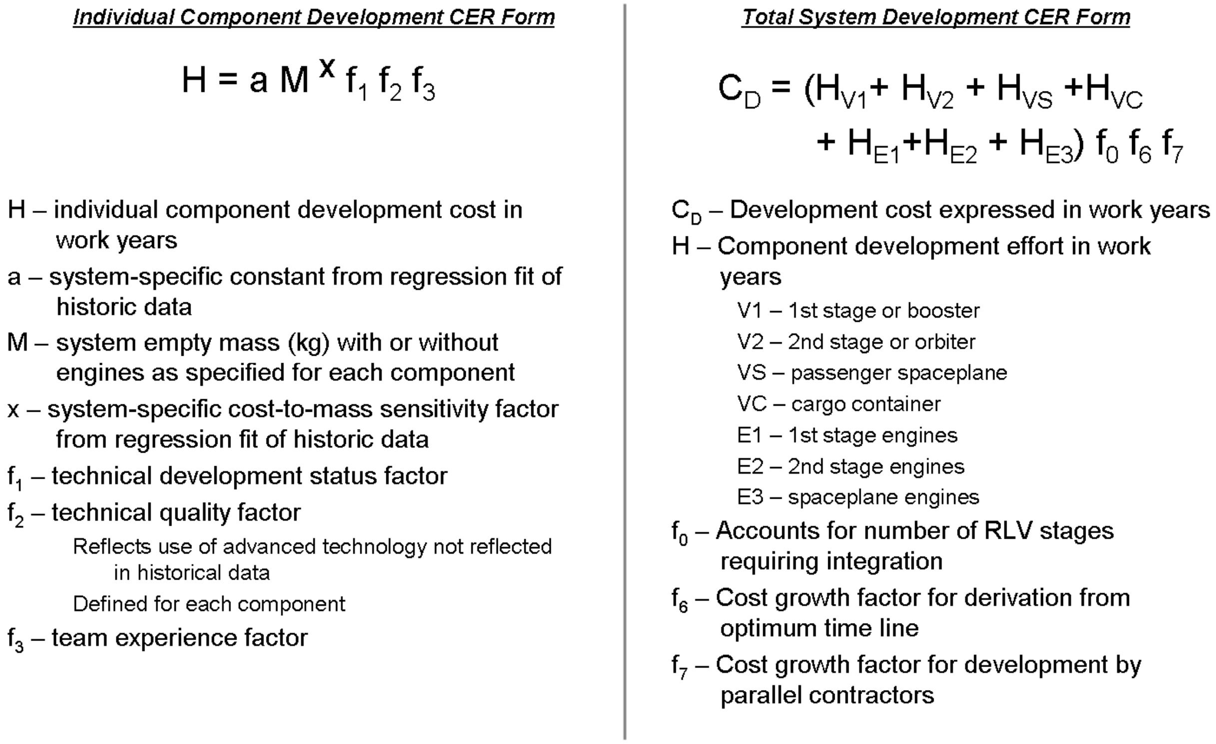
external tank and solid rocket boosters, so it is not a total Space Shuttle transportation system cost.]

All of the examples, except for the Boeing 777, were before the modern era of aerospace design and manufacturing methods. In other words, they were designed largely in the era of drafting boards, slide rules, and limited computer-aided design and manufacturing capabilities. It is also important to note that most programs in the cost data base reflect first-of-a-kind development efforts where the technology readiness level of the enabling technologies was less than six at the start of development. This in part may account for the 15-20 percent program typical cost growth due to unforeseeable technical and schedule issues. Yet, these and similar programs form the basis for Koelle's historically-derived BAU cost estimate. The application of modern, industry-standard computer-aided design/manufacturing processes and the general advance of the state-of-the-art of aerospace technology have been seen to significantly lower the work-year estimates for a comparable program undertaken today. Note that the Boeing 777 required far fewer work-years than the Concorde or XB-70.

The estimates of the BAU development and production costs for the TSTO systems, discussed in the following, are high. In part, this is because of the historical data used, but primarily it is because these systems are multi-stage designs. *A TSTO system carrying a spaceplane is essentially three major development and production programs undertaken concurrently.*

Development Cost Estimating Relationships

Koelle has used appropriate historical data to develop cost estimating relationships (CER) for the airframe and engines for reusable space access systems. The general form of the CER, expressed in terms of work-years, is shown in Figure 11. Each component—first stage, second stage, main engine, etc.—has a specific CER. The value of the mass, expressed in megagrams, is the primary input. Koelle provides, from the historical data, the means and guidance to select the values for "a" and "x". Each of these individual component CERs is then summed, also as shown in Figure 11. [Note: The reader should



Individual Component Development CER Form

$$H = a\,M^{x}\,f_1\,f_2\,f_3$$

- H – individual component development cost in work years
- a – system-specific constant from regression fit of historic data
- M – system empty mass (kg) with or without engines as specified for each component
- x – system-specific cost-to-mass sensitivity factor from regression fit of historic data
- f_1 – technical development status factor
- f_2 – technical quality factor
  - Reflects use of advanced technology not reflected in historical data
  - Defined for each component
- f_3 – team experience factor

Total System Development CER Form

$$C_D = (H_{V1} + H_{V2} + H_{VS} + H_{VC} + H_{E1} + H_{E2} + H_{E3})\,f_0\,f_6\,f_7$$

- C_D – Development cost expressed in work years
- H – Component development effort in work years
  - V1 – 1st stage or booster
  - V2 – 2nd stage or orbiter
  - VS – passenger spaceplane
  - VC – cargo container
  - E1 – 1st stage engines
  - E2 – 2nd stage engines
  - E3 – spaceplane engines
- f_0 – Accounts for number of RLV stages requiring integration
- f_6 – Cost growth factor for derivation from optimum time line
- f_7 – Cost growth factor for development by parallel contractors

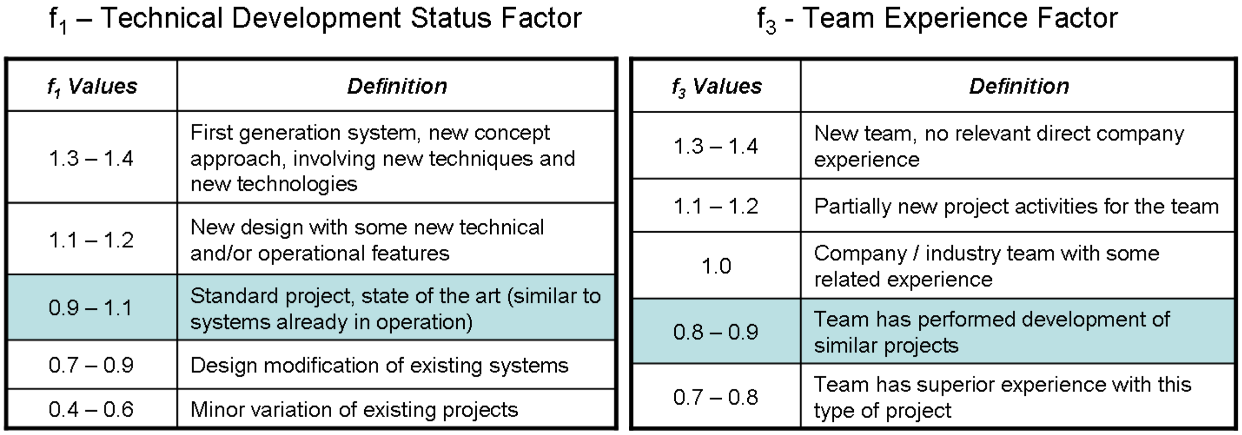
Figure 11. Development cost estimating relationships. (Source: Koelle's handbook)

refer to Koelle's handbook for its more thorough explanation of the proper application of these CERs to other space access system concepts.]

In applying these CERs, three "factors"—f_1, f_2, and f_3—are used to modify the mass based term. The f_2 term is a function of a specific component and its value is provided by Koelle as part of the statistical correlation of the mass and cost. The first and third factors are selected by the analyst as part of applying Koelle's cost engineering methodology to a specific space transportation system. The definition of these two terms is provided in Figure 12. Both of these two terms, it should be noted, linearly influence the component cost estimate. A key part of "cost engineering" reusable space access is to select system configurations that minimize the values of these two terms while yielding acceptable performance and mission capabilities.

The f_1 technical development status factor is directly related to the specific concept for which a cost estimate is being developed. The blue highlight in Figure 12 is the value selected for a near-term, two-stage, fully reusable space access system based on guidance provided by Koelle. If a single-stage system was technically feasible at this time, then the value of f_1 would probably be in the top range of 1.3-1.4. If a two-stage system with an airbreathing propulsion element was to be developed, then the appropriate value for f_1 would appear to be 1.1-1.2. For a two-stage system employing near-term technologies and using standard rocket propulsion, then the values of 0.9-1.1 appear appropriate.

The f_3 team experience factor relates to the strength of the industrial base. Again, based on the explanation and examples of the use of this factor described by Koelle, the blue highlighted range of values of 0.8-0.9 is used in this cost estimate. The key point with this factor is that as the industrial base weakens, as it has to a remarkable degree in



f_1 – Technical Development Status Factor

f_1 Values	Definition
1.3 – 1.4	First generation system, new concept approach, involving new techniques and new technologies
1.1 – 1.2	New design with some new technical and/or operational features
0.9 – 1.1	Standard project, state of the art (similar to systems already in operation)
0.7 – 0.9	Design modification of existing systems
0.4 – 0.6	Minor variation of existing projects

f_3 - Team Experience Factor

f_3 Values	Definition
1.3 – 1.4	New team, no relevant direct company experience
1.1 – 1.2	Partially new project activities for the team
1.0	Company / industry team with some related experience
0.8 – 0.9	Team has performed development of similar projects
0.7 – 0.8	Team has superior experience with this type of project

Figure 12. Development cost estimate factors. (Source: Koelle's handbook)

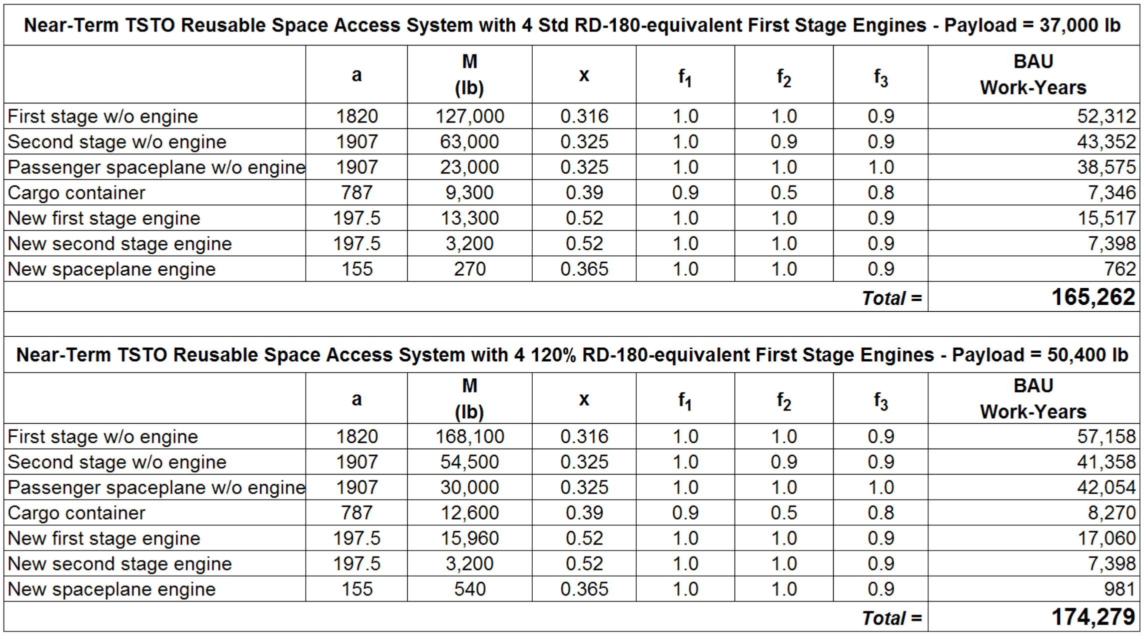
the last 20 years with respect to reusable space access system design and analysis, the value for f_3 to apply to the cost estimate can rise quickly. A wait of only 10 years, given the demographics of the aerospace engineering workforce and the continuing consolidation of the industrial base, could result in an increase of up to 50 percent for even a "near-term" reusable space access system. Further, a delay driven by waiting for requisite technology development that has minimal benefit—for example, a reusable engine with a 50-100 mission life—could be counterproductive in that the modest decrease in recurring operating costs will be overwhelmed by the increase in development costs due to the combination of the increased values for factors f_1 and f_3.

ROM Development Cost Estimates

The "business as usual" ROM cost estimate, expressed in work-years, is shown in Table 4. [Note: This is not yet a total cost estimate for the development of the system. The total development cost is addressed below. Also, the weight expressed earlier in pounds has been converted to megagrams for the calculation.]

In reviewing these individual cost estimates, several points are noteworthy:

1. The total "cost" is greater than the cost of the Space Shuttle Orbiter and SSME combined. This provides an indication that this methodology does not yield low-ball estimates.
2. The cost of the first stage engine development at 15,500-17,000 work-years is comparable to the historical values for the Saturn F-1 engine and SSME, both at approximately 18,000 hours. As Koelle notes, the driving cost is the number of engine tests required to achieve a demonstrated level of statistical reliability. Engine development remains a high-cost, long-lead item indicating that the potential to make use of existing or derivative engines can save considerable time and cost.
3. An increase of only 5 percent in development cost yields a nearly 36 percent increase in delivered payload weight. The significance of this is discussed later in this section.



Near-Term TSTO Reusable Space Access System with 4 Std RD-180-equivalent First Stage Engines - Payload = 37,000 lb

	a	M (lb)	x	f_1	f_2	f_3	BAU Work-Years
First stage w/o engine	1820	127,000	0.316	1.0	1.0	0.9	52,312
Second stage w/o engine	1907	63,000	0.325	1.0	0.9	0.9	43,352
Passenger spaceplane w/o engine	1907	23,000	0.325	1.0	1.0	1.0	38,575
Cargo container	787	9,300	0.39	0.9	0.5	0.8	7,346
New first stage engine	197.5	13,300	0.52	1.0	1.0	0.9	15,517
New second stage engine	197.5	3,200	0.52	1.0	1.0	0.9	7,398
New spaceplane engine	155	270	0.365	1.0	1.0	0.9	762
						Total =	**165,262**

Near-Term TSTO Reusable Space Access System with 4 120% RD-180-equivalent First Stage Engines - Payload = 50,400 lb

	a	M (lb)	x	f_1	f_2	f_3	BAU Work-Years
First stage w/o engine	1820	168,100	0.316	1.0	1.0	0.9	57,158
Second stage w/o engine	1907	54,500	0.325	1.0	0.9	0.9	41,358
Passenger spaceplane w/o engine	1907	30,000	0.325	1.0	1.0	1.0	42,054
Cargo container	787	12,600	0.39	0.9	0.5	0.8	8,270
New first stage engine	197.5	15,960	0.52	1.0	1.0	0.9	17,060
New second stage engine	197.5	3,200	0.52	1.0	1.0	0.9	7,398
New spaceplane engine	155	540	0.365	1.0	1.0	0.9	981
						Total =	**174,279**

Table 4. Individual "business as usual" ROM development cost estimates for elements of the TSTO reusable space access system using Koelle's methodology.

The total BAU development cost estimate takes the sum of the individual element costs and applies three factors, as shown in Figure 11. Factor f_0 introduces the cost of integration of multiple stages. From Koelle's handbook, the value of f_0 is computed as:

$$f_0 = (1.04)^n$$

where n represents the number of stages being integrated. For this system, n = 4 (first stage, second stage, spaceplane, cargo container) and $f_0 = 1.17$.

The factor f_6 is the cost growth due to the development program being executed with a schedule that deviates from the optimum. Attempts to speed up a program—a "crash" program, for example—forces normally sequential work to be performed concurrently, requires extra resources, etc., which have an economic cost. Stretching a program, due to constraints on funding or "critical path" resources, also ends up costing more. In this cost estimate, the program is assumed to be executed at the "optimum" balanced-resource schedule and f_6 is set at a value of 1.0. This assumes the availability of adequate resources, both funding and industrial, to avoid non-optimum schedule costs. With a shrinking industrial base, resource constraints may impose added costs. This important issue will require careful consideration and planning.

The factor f_7 represents cost growth by using the government as the integrating contractor rather than having a lead contractor. The intent is to use commercial-like acquisition of these systems relying upon a lead contractor for each reusable space access system. The value of this factor is set at 1.0.

With these factors being defined, the total estimate of the BAU ROM development cost for the two systems in 2005 $, is:

Configuration 1 BAU dev cost = (165,000 work-years)(1.17)(1.0)(1.0)

= (193,000 work-years)($250,000/yr)

= **$48.25 billion** (in 2005 $)

Configuration 3 BAU dev cost = (174,000 work-years)(1.17)(1.0)(1.0)

= (204,000 work-years)($250,000/yr)

= **$51.0 billion** (in 2005 $)

These costs are strikingly large and indicate why applying the principles of cost engineering are very important. For example, these projected BAU development costs would be higher if a specific TRL<6 technology was directed by the government, as this would cause the f_1 and f_3 factors to increase.

One important fact to note about these BAU costs is that they are based on historical government program costs that reflect a typical 15-20 percent cost growth for unanticipated technical or programmatic problems. *Hence, these estimates reflect a program "should cost" estimate with a 15-20 percent management reserve***—that is if these were undertaken as typical government procurement programs emphasizing advanced technologies and government directed solutions.***

Koelle argues that appropriate reductions in the BAU development cost can be achieved through prudent "cost engineering" reductions. Examples are:

- Engine development cost reduction due to normal maximum operating thrust between 90-95%;
- Use of current or derivative subsystems and manufacturing technologies with TRL 6-9;
- Use of existing or derivative engines (possible with use of RD-180 and SSME derivative engines);
- Use of commercial computer-aided design and verification methodology and virtual prototyping (now standard in the aerospace industry with remarkable cost and schedule benefits being reported);
- Reduced contractor reporting consistent with a TRL 6-9 technology risk level program; and,
- Schedule shrinkage due to a new optimal schedule consistent with improved design and fabrication productivity.

Koelle predicts a 40-50 percent reduction from the BAU estimate with the potential for a further 10-20 percent reduction using a strict commercial contract. Using the lesser 40 percent reduction, the *cost engineered* near-term, two-stage, fully-reusable space access system development cost estimates, *for each of the two system types*, are:

Configuration 1 dev cost = (\$48.25 billion)(1-0.4) = **\$28.95 billion**

\$28.95 billion = \$24.6 billion pgm cost + \$4.3 billion (15% reserve)

Configuration 3 dev cost = (\$51.0 billion)(1-0.4) = **\$30.6 billion**

\$30.6 billion = \$26.0 billion pgm cost + \$4.6 billion (15% reserve)

Production CERs and ROM Cost Estimates

The production CERs used for the reusable space access system are shown in Figure 13. The component production CER, while similar to the development CER, includes terms for the number of systems being produced and provides an adjustment for the influence of the production learning curve.

Using these production CERs, the ASC/EN weights, and the production quantities discussed earlier in the list of assumptions, Table 5 shows the BAU production cost estimates. The total BAU production cost estimate is the sum of the individual elements adjusted with the f_0 integration factor. f_0 has a value of 1.02 while the number of stages, *N*, is four.

Configuration 1 BAU prod cost = (31,000 work-years)$(1.02)^4$
= (33,600 work-years)(\$250,000/yr)
= \$8.4 billion (in 2005 \$)

Individual Component Production CER Form

$$F = a\ n\ M^x\ f_4$$

F – individual component production cost in work years
a – system-specific constant from regression fit of historic data
n – number of systems being produced
M – system empty mass (kg) with or without engines as specified for each component
x – system-specific cost-to-mass sensitivity factor from regression fit of historic data
f_4 – Production cost reduction factor tied to the "learning curve"

Total System Production CER Form

$$C_P = (F_{V1} + F_{V2} + F_{VS} + F_{CC} + F_{E1} + F_{E2} + F_{E3})\, f_0^N$$

C_P – Production cost expressed in work years
F – Component production effort in work years
- V1 – 1st stage or booster
- V2 – 2nd stage or orbiter
- VS – passenger spaceplane
- CC – cargo container
- E1 – 1st stage engines
- E2 – 2nd stage engines
- E3 – spaceplane engine

f_0 – Integration factor
N – Number of stages

Figure 13. Production cost estimating relationships. (Source: Koelle's handbook)

Near-Term TSTO Reusable Space Access System w/ 4 Std RD-180-equivalent First Stage Engines - Payload = 37,000 lb

	a	n	M (lb)	x	f_4	BAU Work-Years
First stage w/ engine	0.367	5	180,200	0.747	0.93	7,973
Second stage w/o engine	3.750	5	63,000	0.650	0.93	13,735
Passenger spaceplane w/o engine	0.160	3	23,000	0.980	0.94	3,911
Cargo container	0.367	7	9,300	0.747	0.93	1,219
New first stage engine	1.900	14	13,300	0.535	0.95	2,662
New second stage engine	1.900	14	3,200	0.535	0.95	1,242
New spaceplane engine	1.900	7	270	0.535	0.96	167
					Total =	**30,910**

Near-Term TSTO Reusable Space Access System w/ 4 120% RD-180-equivalent First Stage Engines - Payload = 50,400 lb

	a		M (lb)	x	f_1	BAU Work-Years
First stage w/ engine	0.367	5	234,700	0.747	0.93	9,713
Second stage w/o engine	3.750	5	54,500	0.650	0.93	12,500
Passenger spaceplane w/o engine	0.160	3	30,000	0.980	0.94	5,075
Cargo container	0.367	7	12,600	0.747	0.93	1,530
New first stage engine	1.900	14	15,960	0.535	0.95	2,934
New second stage engine	1.900	14	3,200	0.535	0.95	1,242
New spaceplane engine	1.900	7	270	0.535	0.96	167
					Total =	**33,162**

Table 5. "Business as usual" ROM production cost estimates for Configuration 1 (top) and Configuration 3 (bottom) using Koelle's methodology.

Configuration 3 BAU prod cost = (33,000 work-years)$(1.02)^4$

= (35,700 work-years)($250,000/yr)

= $8.9 billion (in 2005 $)

Cost engineering, through the use of TRL 6-9 technologies, coupled with advancements in production technologies now evident in the aerospace industry, should enable the same 40 percent reduction to be applied to the BAU ROM production costs.

Configuration 1 production cost = ($8.4 billion)(1-0.4) = $5 billion

Configuration 3 production cost = ($8.9 billion)(1-0.4) = $5.4 billion

The total ROM estimate of the combined development and production costs, using cost engineering principles, are:

Configuration 1 = $29 billion (dev) + $5 billion (prod) = $34 billion

Configuration 3 = $30.6 billion (dev) + $5.4 billion (prod) = $36 billion

Note that this is for a single system. To provide assured space access to support responsive space operations, two systems will need to be developed. These costs would be doubled:

2 x Configuration 1 = $34 billion x 2 = $68 billion

2 x Configuration 3 = $36 billion = $72 billion

Key points from this assessment of near-term, two-stage, fully-reusable space access system development and production costs are:

- As with most infrastructure, the cost to deploy the new infrastructure capabilities is high. The key question is: how does the life-cycle cost compare with a continuation of current space access costs and what additional national benefit would be accrued through the use of these systems?
- The estimated program development and production combined cost for the Configuration 1 ($68 billion) and Configuration 3 ($72.8 billion) systems represent an end-of-program cost including a 15-20 percent management reserve.
- These cost estimates do not address secondary costs such as establishing terrestrial space launch and payload handling facility costs.

Projected Operational Capabilities

An estimate of the operational capabilities of the two fleets of fully-reusable space access systems can be projected based on the number of operational systems produced and other assumptions listed previously. Assumptions regarding the following four operational capabilities are depicted graphically in the next series of Figures.

Figure 14: This figure depicts the fleet's annual flight capacity using the flight rate model above. Recall that two types of reusable systems, with three operational flight articles per type, are fielded to achieve assured space access. For the first type of reusable system, its three flight articles are bought into operation in years 1, 3, and 4. For the second type, its three operational flights systems are brought into operation in years 3, 5, and 6. The two year gap between the introduction of the first and second type of flight systems is intended to help balance demand on supporting resources such as engine test facilities.

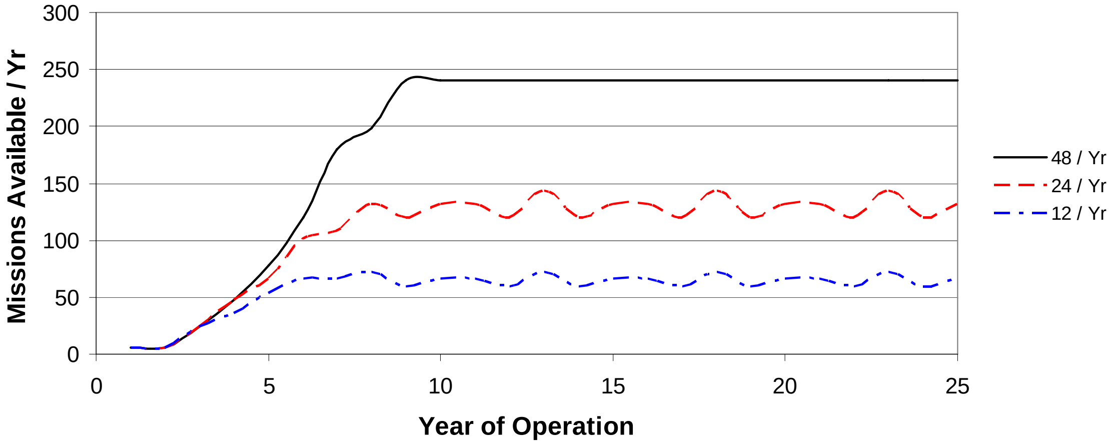


Figure 14. Annual fleet capacity for six operational systems.

Figure 15: This is the assumed annual flight rate used for *each flight system* for the three cases modeled: 12 flights per year per system where each system flies every four weeks; 24 flights per year per system where each system flies every two weeks; and 48 flights per year per system where each system flies about every week. After a ramp-up period for each new production flight system, the system is assumed to operate at the assumed flights per year until a six-month long phase inspection is undertaken. For the 12 and 24 flights per year case, the phase inspection is assumed to take place about every 5 years. For the 48 flights per year rate, the inspection is assumed to take place about every 100 missions. The reduction in flight operations during the phase inspection accounts for the dip in the annual flight rate. Engine change-out takes place as needed. For the 12 and 24 flights per year case, this occurs during the normal flight preparation. For the 48 flights per year, four weeks per year are scheduled for engine change-out while still enabling an approximate flight rate of once per week.

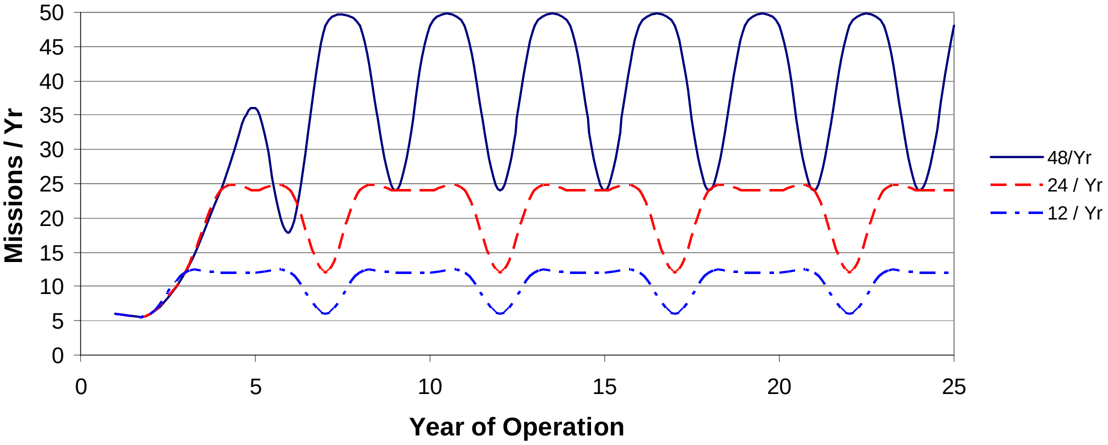


Figure 15. Flight rate model for each flight system.

Figure 16: This figure shows the possible total missions available for the initial fleet of six operational systems (both types combined) as a function of the average flight rate. This information is useful in projecting the operational life of the reusable space access system's airframe, propellant tanks, thermal protection system, etc. An initial objective of 1,000 flights per system would provide a factor of 2 margin on the average actual system usage of 500 total missions when flying every two weeks for 20 years. If the systems are capable of flying every week, then a life extension program, as is done with aircraft, could extend this useful life to approximately 2,000 missions. Again, this would provide a factor of 2 on the average actual usage of 1,000 total missions when flying every week for 20 years. Commercial airliners and military transports are typically designed for over 20,000 takeoff and landing cycles.

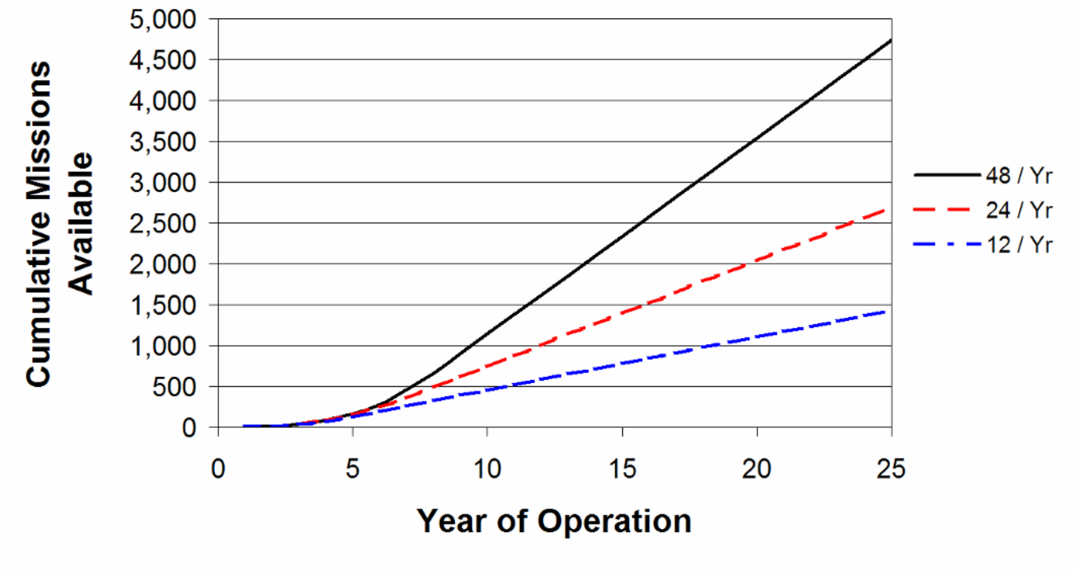


Figure 16. Cumulative missions available as a function of the number of missions per flight system per year.

Figure 17: This figure shows the days between missions at the maximum flight rate. The initial fleet of six flight systems would provide the ability to sustain reasonably high flight rates of one flight every six days for a four-week turn-around time, every three days for a two-week turn-around time, and every day and a half for a one-week turn-around time.

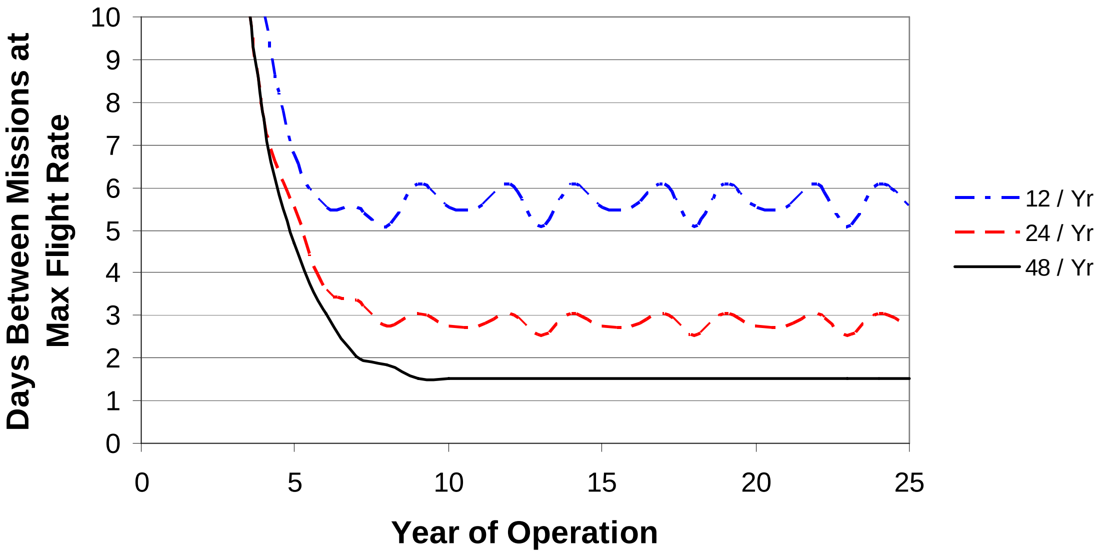


Figure 17. Sustained available sortie rate as function of number of missions per flight system per year.

Figure 17 reflects days between missions when the fleet of first-generation reusable space access systems is already operating at the maximum flight rate. As this would be unusual, several systems prepped for flight would normally be readied for launch.

Should a need arise for a quick response spacelift mission, such as launching a spare satellite or an emergency space part for an orbiting space station, then it may be expected that a launch could be executed within 24 hours. This assumes the payload is available.

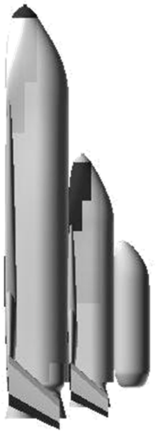
Configurations 1 and 3 Recurring Operational ROM Cost Estimates

The key expected benefit of a fully-reusable space access system, besides the increase in safety, is a reduction in the recurring operational costs. The following describes the ROM cost estimation methodology used to estimate the recurring operational costs for the two near-term reusable space access systems.

ASC/EN, working with historical information provided by the NASA Kennedy Space Center, developed a conceptual recurring support work-hours model for the Configuration 1 reusable space access system. [5] In these calculations, it is assumed that the delivered payload weight is 25,000 lb (11,300 kg) out of the 27,700 lb (12,600 kg) net cargo weight.

Figure 18 lists the breakdown of the estimated touch labor support for the two-stage flight system. Accepting that these are likely to be conservative, based on continued reductions in aerospace system support requirements since the Orbiter was designed, these support requirements are used in the following calculations to estimate the direct recurring support costs for Configuration 1. These calculations are summarized in Table 6.

Configuration 1 recurring cost calculations:



Configuration 1	*1st Stage*	*2nd Stage*
TPS	8500	12000
Structures/Mech	5000	5000
Reaction Control System	1200	3700
Avionics/Electric	2500	2500
Main engines	2500	2300
Hydraulic	2000	2000
Other	2000	2000
Payload	0	1000
Total Wk-hrs	**23700**	**30500**

Resource assumptions

- 2-8 hr shifts
- 5 day work week
- Work crew size = 100 / shift
    - 12 inspection techs
    - 30 engine techs
    - 50 TPS techs
    - 8 waterproof techs
- No cross-training of techs

Figure 18. Configuration 1 IOC work-hour support required per mission (Source: ASC/EN).

- Assuming 46 work weeks per calendar year, the number of hours per work-year is 46 x 40 = 1,840 hours.
- At $250,000 per aerospace work-year, the cost per hour is:
  $250,000 / 1,840 = $136 / hour

- From Figure 18, the total required support per mission is:
  23,700 + 30,500 = 54,200 hours
  or 54,200 hours / 1,840 hours per year = 29.5 work-years
- The cost of direct support per mission is:
  54,200 hours x $136 / hr = $7.36 million
- The direct support cost per pound of delivered payload is:
  $7.36 million / 25,000 lb = ~$300 / lb ($130 / kg)
- Assume the indirect support labor is equal to the direct support labor:
  Total support cost = 2 x $7.36 million = **$14.7 million ···(1)**
  Total support cost per lb = 2 x $300 = $600 / lb
- Assume the spaceplane requires the same level of support as the second stage:
  Direct support = 30,500 hr x $136 / hr = $4.1 million
  Total support = $4.1 million x 2 = **$8.2 million ··········· (5)**
- From Table 5, the total BAU production cost of 14 first stage RD-180 equivalent engines is 2,662 work-years.
- The cost engineered production cost of the 14 RD-180 equivalent engines is = 2,662 work-years x (1-0.4) = 1,597 work-years
- The IOC cost of the replacement first stage engines is:
  1,597 work-years / 14 x $250,000 = $28.5 million
- IOC cost for four 1st stage engines = 4 x $28.5 million = $114 million
- The first stage engines are assumed to be replaced every 10 missions:
  Apportioned IOC 1st stage engine cost / mission =
  $114 million / 10 = **$11.4 million ··················· (2)**
  IOC 1st stage engine cost per pound of payload =
  $11.4 million / 25,000 lb = ~$460 / lb
- From Table 5, the total BAU production cost of the 14 second stage RD-120 equivalent engines is 1,242 work-years.
- The cost engineered production cost of the 14 RD-120 equivalent engines is = 1,242 work-years x (1-0.4) = 745 work-years
- The IOC cost of the replacement second stage engines:
  745 work-years / 14 x $250,000 = $13.3 million
- IOC cost for four 2nd stage engines = 4 x $13.3 million = $53.2 million
- The second stage engines are assumed to be replaced every 10 missions:
  Apportioned IOC 2nd stage engine cost / mission
  = $53.2 million / 10 = **$5.3 million ················· (3)**
  IOC 2nd stage engine cost per pound of payload
  = $5.3 million / 25,000 lb = ~$210 / lb
- The spares and propellant per mission cost is assumed to be **$5 million ···· (4)** **—**about one percent of the non-propulsion unit cost of the Configuration 1 flight system.

- Total IOC recurring cost per mission for unmanned cargo delivery is the sum of items 1-4:
  = \$14.7 million for total support for both stages
  + \$11.4 million for 1st stage engine replacement
  + \$5.3 million for 2nd stage engine replacement
  + \$5 million for spares and propellants
  = **\$36.4 million / IOC mission ································ (6)**
- Total IOC recurring cost per pound = \$36.4 million / 25,000 lb
  = **~\$1,4600 / lb**
- The spaceplane spares per mission is assumed to be **\$2 million**. ·············· **(7)**
- Total IOC recurring cost per mission for a manned mission is the sum of items 5-7:
  = \$36.4 million + \$8.2 million for spaceplane support
  + \$2 million for spaceplane spares
  = \$**46.6 million / IOC mission**
- Total Configuration 1 IOC recurring cost per passenger per mission
  = \$46.6 million / 10 passengers
  = ~**\$5 million per passenger**

For the preparation of the estimate of the Configuration 1 FOC recurring operational costs, three changes to the IOC cost estimation methodology are made:

1. The engine replacement interval increases to 25 missions.
2. The production learning curve factor of (1-0.25) is applied to the replacement engine cost reflecting a higher engine production rate.
3. The support work-years are reduced 20 percent to account for learning curve effects and maturing flight systems.

- The total required support is: 54,200 x 0.8 = 43,400 hours or
  43,400 hours / 1,840 hours per year = 23.6 work-years
- The cost of direct support is 43,400 hours x \$136 / hr = \$5.9 million
- The direct support cost per pound of delivered payload:
  \$5.9 million / 25,000 lb = ~\$240 / lb (\$130 / kg)
- Assume the indirect support labor is equal to the direct support labor:
  Total support cost = 2 x \$5.9 million = **\$11.8 million ···· (8)**
  Total support cost per lb = 2 x \$240 = \$480 / lb
- Assume the spaceplane requires the same level of support as the second stage:
  Direct support = 30,500 hr x \$136 / hr x 0.8
  = \$3.3 million
  Total support = \$3.3 million x 2 = **\$6.6 million ·········· (12)**
- From Table 5, the total BAU production cost of 14 first stage RD-180 equivalent engines is 2,662 work-years.
- The cost engineered production cost of the 14 RD-180 equivalent engines is =
  2,662 work-years x (1-0.4) = 1,597 work-years

- The FOC cost of the replacement first stage engines:

  = 1,597 work-years/ 14 x $250,000 x (1-0.25)

  = $21.4 million

- FOC cost for four 1st stage engines = 4 x $21.4 million

  = $85.6 million

- The first stage engines are assumed to be replaced every 25 missions:

  Apportioned FOC 1st stage engine cost / mission =

  $85.6 million / 25 = **$3.4 million** ……………… **(9)**

  FOC 1st stage engine cost per pound of payload =

  $3.4 million / 25,000 lb = ~$140 / lb

- From Table 5, the total BAU production cost of the 14 second stage RD-120 equivalent engines is 1,242 work-years.
- The cost engineered production cost of the 14 RD-120 equivalent engines is =

  1,242 work-years x (1-0.4) = 745 work-years

- The FOC cost of the replacement second stage engines:

  745 work-years / 14 x $250,000 x (1-0.25)

  = $10 million

- FOC cost for four 2nd stage engines = 4 x $10 million

  = $40 million

- The second stage engines are assumed to be replaced every 25 missions:

  Apportioned FOC 2nd stage engine cost / mission

  = $40 million / 25 **= $1.6 million** ……………… **(10)**

  FOC 2nd stage cost per pound of payload

  = $1.6 million / 25,000 lb = ~$60 / lb

- The spares and propellant per mission cost is assumed to be **$5 million**. ·· **(11)**
- Total FOC recurring cost per mission for unmanned cargo delivery is the sum of items 8-11:

  = $11.8 million for total support

  + $3.4 million for 1st stage engine replacement

  + $1.6 million for 2nd stage engine replacement

  + $5 million for spares and propellants

  = **$21.8 million / FOC mission**………………………… **(13)**

- Total FOC recurring cost per pound = $21.8 million / 25,000 lb

  = **~$870 / lb**

- The spaceplane spares per mission is assumed to be $**2 million**. ………… **(14)**
- Total FOC recurring cost per mission for a manned mission is the sum of items 12-14:

  = $21.8 million + $6.6 million for spaceplane support

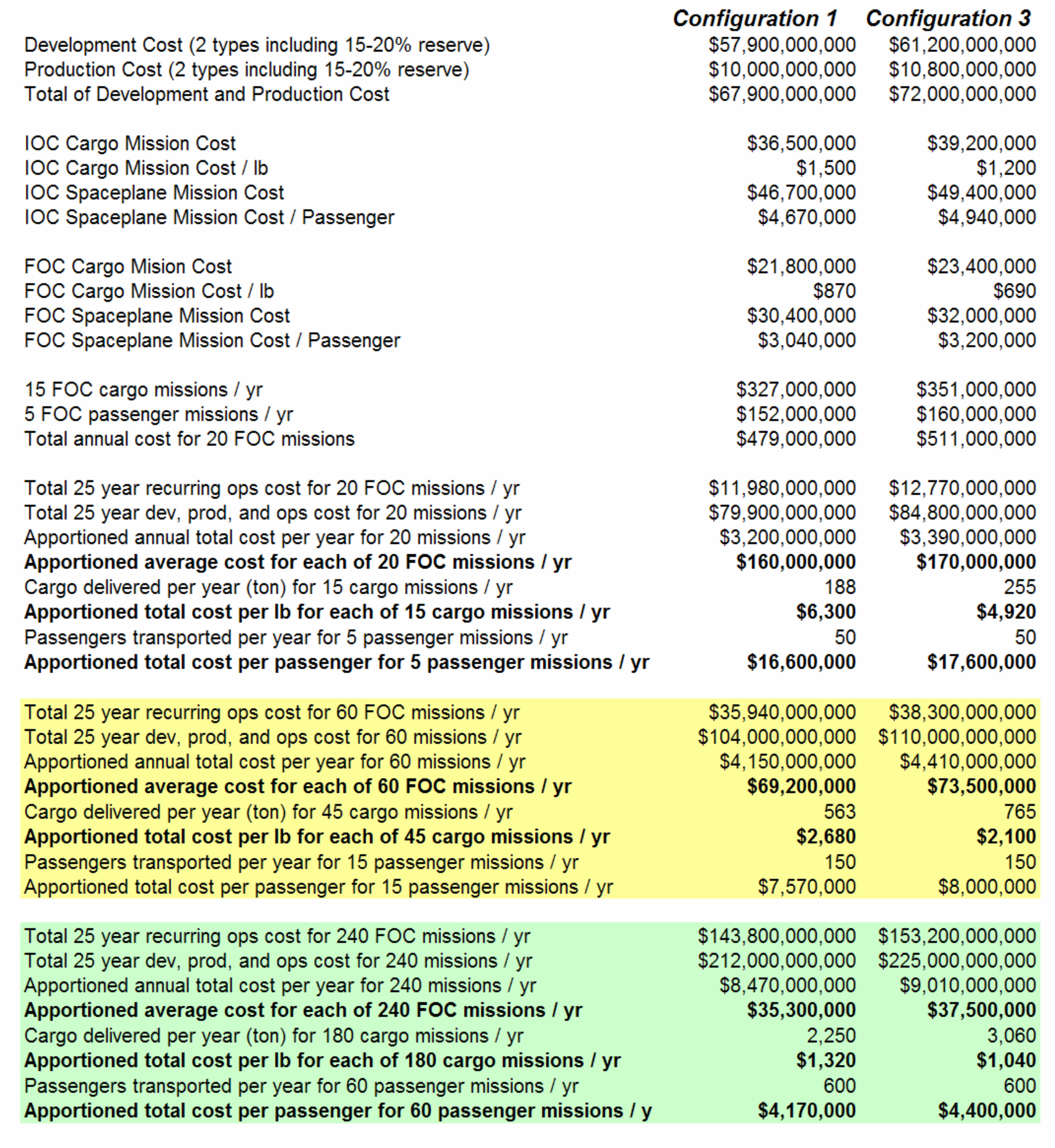
  + $2 million for spaceplane spares

  = **$30.4 million / FOC mission**

- Total Configuration 1 FOC recurring cost per passenger per mission

  = $30.4 million / 10 passengers

  = ~**$3 million per passenger**



	Configuration 1	*Configuration 3*
Development Cost (2 types including 15-20% reserve)	$57,900,000,000	$61,200,000,000
Production Cost (2 types including 15-20% reserve)	$10,000,000,000	$10,800,000,000
Total of Development and Production Cost	$67,900,000,000	$72,000,000,000
IOC Cargo Mission Cost	$36,500,000	$39,200,000
IOC Cargo Mission Cost / lb	$1,500	$1,200
IOC Spaceplane Mission Cost	$46,700,000	$49,400,000
IOC Spaceplane Mission Cost / Passenger	$4,670,000	$4,940,000
FOC Cargo Mision Cost	$21,800,000	$23,400,000
FOC Cargo Mission Cost / lb	$870	$690
FOC Spaceplane Mission Cost	$30,400,000	$32,000,000
FOC Spaceplane Mission Cost / Passenger	$3,040,000	$3,200,000
15 FOC cargo missions / yr	$327,000,000	$351,000,000
5 FOC passenger missions / yr	$152,000,000	$160,000,000
Total annual cost for 20 FOC missions	$479,000,000	$511,000,000
Total 25 year recurring ops cost for 20 FOC missions / yr	$11,980,000,000	$12,770,000,000
Total 25 year dev, prod, and ops cost for 20 missions / yr	$79,900,000,000	$84,800,000,000
Apportioned annual total cost per year for 20 missions / yr	$3,200,000,000	$3,390,000,000
Apportioned average cost for each of 20 FOC missions / yr	**$160,000,000**	**$170,000,000**
Cargo delivered per year (ton) for 15 cargo missions / yr	188	255
Apportioned total cost per lb for each of 15 cargo missions / yr	**$6,300**	**$4,920**
Passengers transported per year for 5 passenger missions / yr	50	50
Apportioned total cost per passenger for 5 passenger missions / yr	**$16,600,000**	**$17,600,000**
Total 25 year recurring ops cost for 60 FOC missions / yr	$35,940,000,000	$38,300,000,000
Total 25 year dev, prod, and ops cost for 60 missions / yr	$104,000,000,000	$110,000,000,000
Apportioned annual total cost per year for 60 missions / yr	$4,150,000,000	$4,410,000,000
Apportioned average cost for each of 60 FOC missions / yr	**$69,200,000**	**$73,500,000**
Cargo delivered per year (ton) for 45 cargo missions / yr	563	765
Apportioned total cost per lb for each of 45 cargo missions / yr	**$2,680**	**$2,100**
Passengers transported per year for 15 passenger missions / yr	150	150
Apportioned total cost per passenger for 15 passenger missions / yr	$7,570,000	$8,000,000
Total 25 year recurring ops cost for 240 FOC missions / yr	$143,800,000,000	$153,200,000,000
Total 25 year dev, prod, and ops cost for 240 missions / yr	$212,000,000,000	$225,000,000,000
Apportioned annual total cost per year for 240 missions / yr	$8,470,000,000	$9,010,000,000
Apportioned average cost for each of 240 FOC missions / yr	**$35,300,000**	**$37,500,000**
Cargo delivered per year (ton) for 180 cargo missions / yr	2,250	3,060
Apportioned total cost per lb for each of 180 cargo missions / yr	**$1,320**	**$1,040**
Passengers transported per year for 60 passenger missions / yr	600	600
Apportioned total cost per passenger for 60 passenger missions / y	**$4,170,000**	**$4,400,000**

Table 6. Summary of Configuration 1 and 3 near-term, fully-reusable space access system development, production, and operational ROM cost estimates (2005 $) for 20, 60, and 240 FOC missions per year.

For the estimates of the recurring operational costs of Configuration 3, the following changes were made:

1. The first stage engine BAU cost estimate was increased to account for the use of the 120 percent RD-180 engine.
2. The delivered payload was increased from 25,000 lb to 34,000 lb to account for the growth in gross weight of the cargo container increasing from 37,000 lb to 50,400 lb.
3. The first stage direct support was increased to 29,300 work-hours to account for the Configuration 3 first stage being larger and having more TPS area to maintain. The second stage size did not significantly change primarily because, in this conceptual design, the staging velocity where the second stage separates from the first stage increased. This resulted in a modest reduction in the Delta-V for the second stage that roughly offset the required increase in size due to the larger payload.

The ROM estimates of the Configuration 1 and 3 development, production, and recurring operational costs are summarized in Table 6. From these results, it is seen that the development and production costs of the larger Configuration 3 system do not scale linearly with the gross weight or payload. While the gross weight increased by approximately 25 percent, the development cost grew by only 6 percent and the production cost by 8 percent. It is also seen that the recurring operational cargo mission costs *per pound* declined by about 20 percent.

Comparison with Current Launch Costs

The United States government spends \$5-6 billion per year to annually launch between 10 and 20 unmanned and manned missions to LEO. This is a necessary expense if the nation is to maintain space access for undertaking critical and important national space operations. Using the development, production, and recurring operational ROM cost estimates for fully-reusable space access systems described above, an estimate can be made of the cost to replace these missions and to provide additional space access capacity. The larger Configuration 3 near-term reusable space access system is used in preparing this estimate.

Case 1 – Replacement for Current Government Launches

Twenty missions per year represents a flight rate that would approximately replace current government launches. Assuming 15 cargo and 5 passenger missions per year, the annual recurring launch cost of the larger Configuration 3 system, as seen in Table 6, is \$511 million. This is about 10 percent of the current annual space access cost. A total of 255 tons of cargo and 50 passengers would be transported to orbit each year using these government baseline missions. Using a period of 25 years of operation, the total annual apportioned cost of development, production, and operation for 20 missions per year is of the order of \$3.4 billion in current year dollars. Again for Configuration 3, the apportioned average mission cost is approximately \$170 million. At this flight rate, the apportioned total cost per pound of payload is approximately $5,000 ($11,000 per kg). The apportioned cost per passenger is approximately $18 million.

Case 2 – Minimum design flight rates for the near-term reusable space access systems

Sixty missions per year represents a conservative estimate of the annual flight capacity of a fleet of six operational flight systems with each flight system flying about once per month. For Configuration 3, the annual apportioned cost of development, production, and operation for 60 missions per year is of the order of $4.4 billion in current year dollars. This provides 45 cargo missions carrying 765 tons of cargo and 15 passenger missions carrying 150 passengers per year. Over the 25 years of operation, the fleet would fly about 1,400 missions carrying a total capacity of 18,000 tons and 3,500 passengers. The apportioned average mission cost is approximately $74 million. At this flight rate, the apportioned total cost per pound of payload is approximately $2,100 ($4,600 per kg). The apportioned cost per passenger is approximately $8 million.

Case 3 – Maximum design flight rates for the near-term reusable space access systems

Approximately 240 missions per year represents an optimistic estimate of the annual flight capacity of a fleet of six operational flight systems with each flight system flying about once per week. For Configuration 3, the annual apportioned cost of development, production, and operation for 240 missions per year is of the order of $9 billion in current year dollars. This provides 180 cargo missions carrying 3,000 tons of cargo and 60 passenger missions carrying 600 passengers per year. Over the 25 years of operation, the fleet would fly about 4,800 missions carrying a total capacity of 66,000 tons and 9,500 passengers. The apportioned average mission cost is approximately $38 million. At this flight rate, the apportioned total cost per pound of payload is approximately $1,000 ($2,200 per kg). The apportioned cost per passenger is

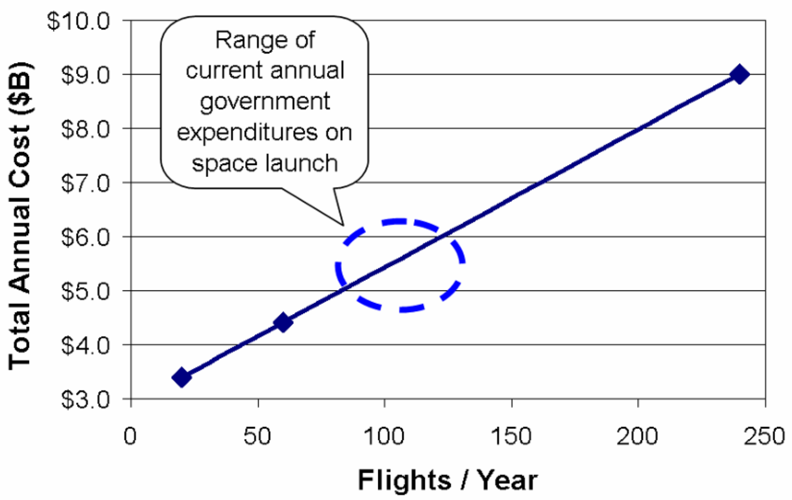


Figure 19. ROM estimate of Configuration 3's total annual cost (apportioned development and production costs over 25 years and recurring operations costs) vs. flight rate.

approximately $4.4 million.

Figure 19 plots these three cases as flights per year vs. the total annual apportioned cost of development, production, and operations. Recognizing that these are ROM estimates, it is seen that the current annual expenditures of $5-6 billion would cover the apportioned cost of development and production and pay for around 100 flights per year transporting 1,300 tons of cargo and 250 passengers without any "cost of money" taken into account.

Establishing Near-term Reusable Space Access Capabilities

One approach to establish aircraft-like reusable space access is to initiate new government programs, assigned to an existing federal organization, to develop, acquire, and operate these new systems. With this model, annual appropriations would be used to cover all costs. The obvious challenge of using this approach is to find sufficient new funds or to identify sufficient funding sources within existing program budgets to cover the new $72 billion costs for development and production. Capital-intensive development programs always face this problem and, outside of defense-related acquisitions, only rarely is direct annual appropriated funding made available to cover such large development and production costs.

Because of this situation, the traditional approach, stretching back to the Erie Canal of the early 19th century, has been to utilize government-backed bonds to raise the necessary capital for development and production and then to use fees, fares, excise taxes, special taxes, and/or long-term annual government appropriations to repay the bonds. Roads, bridges, schools, airports, etc., are built in this manner. Private industry uses comparable approaches to build new factories, office buildings, ships, airplanes, etc., with commercial revenue and, in some cases, government grants or tax abatements being used to repay the private debt. The key to using this funding approach is to establish a valid and sustainable need, identify a solution with acceptable technical and schedule risk, and identify an acceptable funding strategy.

Clear National Need for Improved Space Access

Since the mid-1980s, there has been a clear and broad understanding of the need for improved and assured space access. The National Aerospace Plane and the X-33 government programs to develop prototype single-stage reusable space access systems were undertaken because of this need. The Evolved Expendable Launch Vehicle program was initiated in the mid-1990s because of the need to update the U.S. commercial space access capability to compete with foreign suppliers of unmanned launch systems. The failures of the Space Shuttles *Challenger* and *Columbia* identified a need for improved space transportation of humans. Hence, having the ability to assure space access for unmanned missions and safer space transportation for humans may be expected to remain a clear national need that must be addressed.

Near-Term Technical Solution

As discussed at length in Reference 1, the particular circumstances of the last quarter century—including the operational consequences of the choice of the design of the Space Shuttle as a partially-reusable system, the inability of the NASP and X-33 programs to achieve a breakthrough in a single-stage reusable space access design, the loss of the *Challenger* and *Columbia*, and the slowing demand for unmanned U.S. civil space launch—has created the perception that significant further technological advancements are needed to achieve substantial improvements in safety and operability and reductions in the cost of operation of a new space access system. Reference 1 and this paper have addressed this perception by identifying near-term, two-stage, fully-reusable space access concepts, with aircraft-like safety and operability and lower recurring costs of operation, that are representative of what U.S. industry can build today using TRL 6-9 technologies.

Use of Infrastructure-Style Funding as a “New” Funding Strategy

Assuming that near-term reusable space access systems will not be developed as new weapon systems by the Department of Defense or new national space transportation systems by NASA, then the only remaining means to afford the $72 billion needed for their development and production is to fund them as public infrastructure. As has been pointed out previously, Congress has in recent decades provided annual appropriations of $5-6 billion (current dollars) for space access. For the purpose of argument, assume that, due to the importance of assuring and improving national space access, Congress would continue to approve appropriations of this magnitude for future assured government space access. Over the 25-year life of the new fully-reusable space access systems, roughly $125-150 billion (current dollars) would be available to pay off the bonds and cover the annual recurring operational costs of 20 missions per year to meet government space access needs. For this government investment, all government agencies would receive substantially improved space access capabilities, the incremental transportation mission cost of new missions would be substantially lowered, and the nation’s commercial space sector would have access to improved national space access capabilities. *It is important to note that this approach does not require an increase in federal appropriations either during the development of the system or during its operation.*

Conclusion

A true spacefaring nation must have aircraft-like access to space for passengers and cargo. This paper has addressed the three primary perceived obstacles to achieving this—the lack of sufficient technology maturity; unaffordable development, production, and operational costs; and, a lack of a federal government funding strategy to fund the development, production, and operation of new near-term, fully-reusable space access systems.

Addressing the perceived obstacle of lack of technology maturity, recent government and industry conceptual design studies of fully-reusable, two-stage-to-orbit space access systems were described that provided independently-developed government and industry examples of how closed conceptual designs, with appropriate design margins and acceptable performance and gross weights, could be achieved with TRL 6-9 technologies. Hence, fully-reusable space access is a near-term solution that can be pursued today.

On the perceived issue of unaffordable development, production, and operational costs, using the cost estimating methodology developed by Koelle for space transportation systems and the government's recent estimates of system weights and performance, this paper reported development, production, and operational ROM cost estimates for representative near-term, two-stage, fully-reusable space access systems. This paper discussed how, through the application of Koelle's space transportation system cost engineering principles, the development and production costs of these near-term systems can be substantially reduced. The ROM estimate for the combined development and production cost for two system types, each capable of transporting approximately 34,000 lb (15,400 kg) to LEO or 10 passengers, was $72 billion (current dollars, including a 15-20 percent management reserve). While this cost is high, it can be afforded using current government expenditures on space launch. This paper also developed ROM estimates of the recurring operational costs of these near-term, fully-reusable space access systems with the result that the estimated annual operational costs for 15 cargo missions (255 tons delivered) and 5 passenger transfer missions (50 passengers transported) was $511 million. This would represent a substantial reduction from current expenditures on government space access.

On the perceived issue of the lack of a suitable means to fund the development, production, and operation of two new types of fully-reusable space access systems, this paper noted that existing annual federal government expenditures on space launch were in the range of $5-6 billion. Over the 25-year life of the new reusable space access systems, a continuation of this level of funding would provide $125-150 billion (current dollars) in funding. Using the estimates of $72 billion for development and production of the two new reusable space access systems developed in this paper, this $125-150 billion in funding should be sufficient to pay off government-backed bonds used to raise the capital needed for development and production and to cover the annual recurring operational costs of approximately $500 million, or $13 billion over 25 years. This would provide baseline government space access capabilities of approximately 20 missions per year. This funding strategy does not impact funding for on-going space operations and should not require an increase in funding in future years.

From these results, no apparent obstacle—neither technical nor funding—appears to remain to prevent the United States from undertaking the development and introduction into routine operation of near-term, two-stage, fully-reusable space access systems providing aircraft-like passenger and cargo transportation to and from LEO.

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