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Centurion: A Heavy-Lift Launch Vehicle Family for Cis-Lunar Exploration

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Centurion is an expendable heavy lift launch vehicle (HLLV) family for launching lunar exploration missions. Each vehicle in the family is built around a common two-stage core. The first stage of the core uses kerosene (RP-1) fuel and utilizes four staged-combustion RD-180 rocket engines. The upper stages consist of liquid oxygen (LOX)/liquid hydrogen (LH2) propellant with three 220,000 lb thrust-class expander rocket engines. The larger variants in the Centurion family will also use either one or two pairs of five-segment solid rocket motors which are now being developed by ATK Thiokol.

The Centurion family consists of three vehicles denoted as C-1, C-2, and C-3. The first vehicle (C-1) is a four RD-180 core with a LOX/LH2 upper stage. The C-1 is designed to deliver a 35 metric ton (MT) CEV to a 300 km X 1000 km highly elliptical orbit (HEO). This HEO allows the CEV to more easily transfer to a lunar trajectory, while still having the ability to abort after one revolution. The C-1 also is designed to meet mission requirements with a failure of both one RD-180 and one upper stage engine. The C-2 and C-3 Centurions are both cargo carrying variants which carry 100 MT and 142 MT of cargo to a 407 km low earth orbit (LEO) respectively. The C-2 utilizes two five-segment solid rocket boosters (SRB), while the C-3 uses four SRBs.

Details of the conceptual design process used for Centurion are included in this paper. The disciplines used in the design include configuration, aerodynamics, propulsion design and selection, trajectory, mass properties, structural design, aeroheating and thermal protection systems (TPS), cost, operations, and reliability and safety. Each of these disciplines was computed using a conceptual design tool similar to that used in industry. These disciplines were then combined into an integrated design team process and used to minimize the gross weight of the C-1 variant. The C-2 and C-3 variants were simulated using the C-1 optimized core with different configurations of SRBs. Each of the variants recurring and non-recurring costs were computed. The total development cost including the design, development, testing and evaluation (DDT&E) cost and a new launch pad at Kennedy Space Center (KSC), was $7.98 B FY'04. The theoretical first unit (TFU) cost for the C-2 variant was $532 M FY'04. A summary of design disciplines as well as the economic results are included.

Nomenclature

Al-Li	=	Aluminum- Lithium
CAD	=	computer aided design
CER	=	cost estimating relationship

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CEV = crew exploration vehicle
COF = construction of facilities
DDT&E = design, development, test, & evaluation
DSM = design structure matrix
ELV = expendable launch vehicle
ETO = Earth to orbit
GLOW = gross lift-off weight
HEO = highly elliptical orbit
HLLV = heavy lift launch vehicle
Isp = specific impulse, sec
KSC = Kennedy space center
LCC = life cycle cost
LEO = low earth orbit
LH2 = liquid hydrogen
LOX = liquid oxygen
MECO = main engine cutoff
MER = mass estimating relationship
MR = mass ratio (gross weight / burnout weight)
OEI = one engine inoperative
RP-1 = rocket propellant 1 (kerosene)
SRB = solid rocket booster
STS = shuttle transportation system
TFU = theoretical first unit
TPS = thermal protection system

I. Introduction

Centurion is a new heavy lift launch vehicle designed to meet NASA's needs for a heavy lift launch vehicle for the new lunar initiative. Centurion consists of a family of launch vehicles designed to satisfy the manned and cargo needs for a new lunar mission. Centurion builds on current propulsion technology such as the RD-180 and the five-segment SRBs, but is designed to carry a far greater payload than the current launch vehicle fleet. Centurion is designed to use much of the same technology as currently used in launch vehicle design. The main technologies assumed were aluminum-lithium tanks, lightweight avionics, and a lightweight composite fairing and intertank. The only "new" piece of hardware, which has not already been proven, is the new expendable upper stage engine. This engine is necessary since the current engine market does not provide a high thrust, high altitude engine that is cheap enough to be expended, yet still provides the adequate performance.

Centurion solves the heavy lift problem by approaching it as most expendable launch vehicles do, with a family of designs built around common or shared elements. Centurion differs from these current launch vehicles by starting with a much larger vehicle. The C-1, or the manned variant of Centurion, is designed to carry a 35 MT CEV to a 300 km X 1000 km highly elliptical orbit. This orbit allows the CEV to reach a lunar trajectory with a shorter burn than a traditional circular orbit, while still providing the abort ability comparable with a smaller circular staging orbit. The C-1 is also designed to complete the mission with an engine failure on both the first and second stages. This inherent engine out capability allows the C-1 design to have a much higher reliability (0.986) than the reliability demonstrated by existing expendable launch vehicles (ELVs).

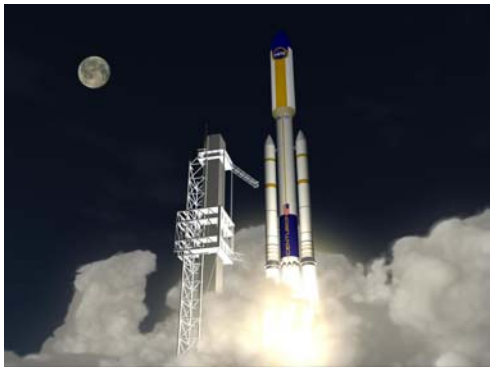


Figure 1. Centurion C-2 Launch.

The Centurion C-2 and C-3 cargo variants utilize the same central core as the C-1. The main difference between these cargo versions and the C-1 is the five-segment reusable solid rocket boosters which are attached in pairs. The

C-2 utilizes a single pair of SRBs (much like the STS program), while the C-3 uses two pairs of SRBs. These cargo variants can carry 100 MT, and 142 MT of payload to a 407 km circular orbit. This is well above the draft NASA exploration design requirements of 80 MT for lunar exploration missions[1].

A multi-disciplinary conceptual design process is used to create the Centurion design. This design process was completed using a disciplinary design tool for each of the following disciplines: external configuration and CAD was completed using ProEngineer, aerodynamic analysis was conducted with APAS[2], propulsion design and selection was completed using REDTOP[3], trajectory optimization used POST[4], mass estimation and sizing was completed using mass estimating relationships[5] (MERs), a structural analysis was completed using GT STRESS[6], aeroheating and TPS design was completed using Miniver[7], Cost estimating was conducted using TRANSCOST[8] cost estimating relationships (CERs), and reliability was completed using Relex[9]. Each of these tools was used to analyze their respective disciplines and was iterated to close each of the Centurion variants.

II. Centurion Overview

A. Centurion C-1

The Centurion C-1 is the man-rated version of the Centurion family. The C-1 is a typical in-line two stage expendable launch vehicle. The first stage is designed to use four staged-combustion RD-180 engines, which are already flight proven on current expendable launch vehicles. The second stage requires larger engines than any current ELV employs. This large second stage is necessary because the first and second stage split is designed to give the lowest overall vehicle gross weight. This large second stage requires engines that provide the necessary thrust to propel such a large stage, but also provides the high efficiency (Isp) and low cost. A new engine is designed to be a LOX/LH2 propelled expander-cycle engine. An expander-cycle engine is chosen to be cost effective due to simplicity of design yet still providing the necessary performance. This engine's thrust-class is chosen to be near the upper limits of what propellant experts believe possible for expander cycles, while still providing multiple engines for redundancy.

The Centurion C-1 is designed to carry 35 MT to a highly elliptical 300 km X 1000 km orbit. The payload class has been determined by choosing a representative size of a crew excursion vehicle, with margin for a propulsion module, and crew escape system. The orbit of the reference mission has been chosen to provide a stepping stone to lunar missions (high apogee provides lower ΔV than circular orbits), while still allowing a return to low earth orbit if a CEV propulsion failure occurs.

Reliability and safety is a main concern for manned vehicles. The Centurion C-1 is designed to meet the reference mission with an engine failure on both the first and second stages in the same flight. The C-1 includes redundant avionics and communication systems. The large reference payload also allows for an increase in reliability through a robust CEV design, since a typical CEV will require less than 35 MT of lifting capacity. This extra payload margin can be used to provide a more capable crew escape system. This redundancy and margin allows the reliability of the C-1 to be significantly higher than typical ELVs currently in use by launch services.

In the design of the C-1 some advanced technologies were assumed. The C-1 also utilizes lightweight avionics and power systems to increase payload capacity. The tanks of the C-1 are assumed to be composed of a lightweight aluminum-lithium metal alloy to decrease weight as compared to typical aluminum structures. As noted, C-1 takes advantage of current propulsion developments such as the RD-180 staged-combustion engine.

B. Centurion C-2 & C-3

The Centurion cargo versions are the C-2 and the C-3. The C-2 is a single C-1 with two five-segment solid rocket boosters. The C-3 is a single C-1 with four five segment solid rocket boosters. Both the C-2 and C-3 utilize the same 30 m long, 8 m in diameter composite payload fairing. This fairing is designed to meet draft NASA exploration requirements[1] (Table 1).

The Centurion C-2 and C-3 are designed to carry as much payload as possible using the C-1 core with existing combinations of STS SRBs. The C-2 is capable of lifting just over 100 MT to a 407 km (220 nmi), 28.5° circular orbit. The C-3 (with four SRBs) is capable

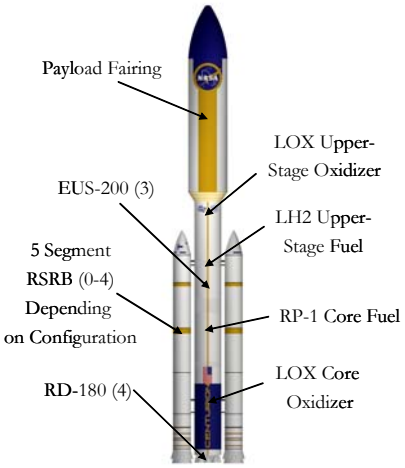


Figure 2. Centurion C-2 Configuration.

of lifting over 142 MT to the same 407 km (220 nmi), 28.5° circular orbit. The solid rocket boosters are not reused due to the low flight rates assumed for Centurion, this reusability issue is addressed in Section V.

The designs of the C-2 and C-3 use the same technology subsets used in the C-1 design. The only added technology is that of the composite payload fairing. The use of this lightweight composite fairing is especially advantageous due to the large size of the payload fairing (30 m long, 8 m in diameter). The C-2 and C-3 also use the five-segment solid rocket boosters. These SRBs have already been ground tested and are approaching flight certification.

C. Centurion Family

As previously mentioned, the Centurion family is designed to meet NASA exploration requirements. These requirements are included as Table 1. As these requirements show, the Centurion family of launch vehicles can meet all of these requirements with the defined family of vehicles. The Centurion C-2 meets all of the cargo requirements for both the exploration ETO missions as well as the deep space human exploration missions. The Centurion C-3 design further enhances the Centurion family's ability to meet the deep space human exploration throughput requirement with the increased payload of 142 MT. The Centurion family can meet this requirement in just four launches (two C-2 and two C-3 launches per year).

Table 1. Draft Exploration Design Requirements[1].

Mission Type	Cargo to 407 km, 28.5° inclination	Throughput	Fairing Volume	Target Reliability	Number of Crew per Launch
Exploration Earth to Orbit Missions	80 MT	220 MT in 10 month period	8 m diameter, 30 m length	0.997	6
Deep Space Human Exploration Missions	100 MT	450 MT in 20 month period	8 m diameter, 30 m length	0.997	N/A

The family of Centurion launch vehicles is included as Figure 3. As this figure shows the Centurion family consists of three vehicles, the GLOW of the heaviest vehicle (C-3) is over 4200 MT. The engine configuration for each of the Centurion variants is also included. The arrangement of the two nozzle RD-180s is particularly difficult. This configuration of RD-180s is chosen so that control can be maintained if one engine fails in the C-1.

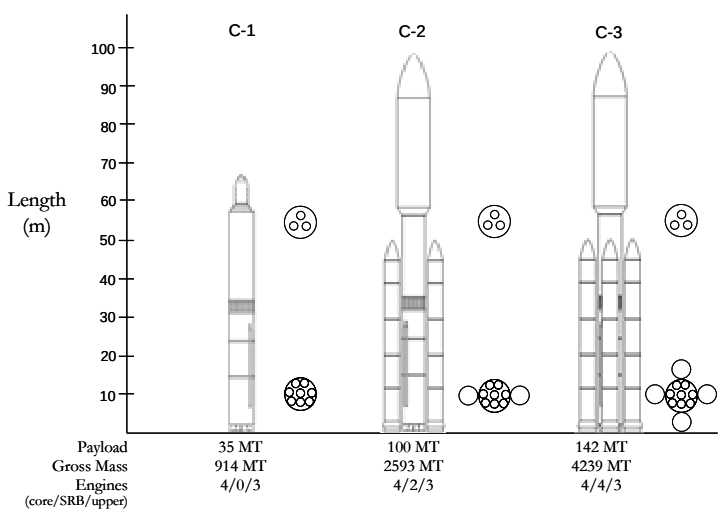


Figure 3. Centurion Family.

The Centurion family is comparable in size to past HLLVs. The Centurion family is significantly larger that the Titan IV HLV. The Titan IV has the largest payload capacity of any US HLLV and is close to retirement. The Centurions are similar in height to the Saturn V launch vehicle. The Saturn V is between the Centurion C-2 and C-3 in both payload mass and gross mass. The Centurion C-3 is almost 50 percent heavier, yet is shorter than the Saturn V. This is due to the fact that the Centurion's SRBs have a lower efficiency (Isp), yet a higher density that the Saturn V's RP fueled first stage. The Centurions are capable of launching anything from an Apollo style return mission (Saturn V sized) to the larger payload requirements necessary for more permanent lunar missions.

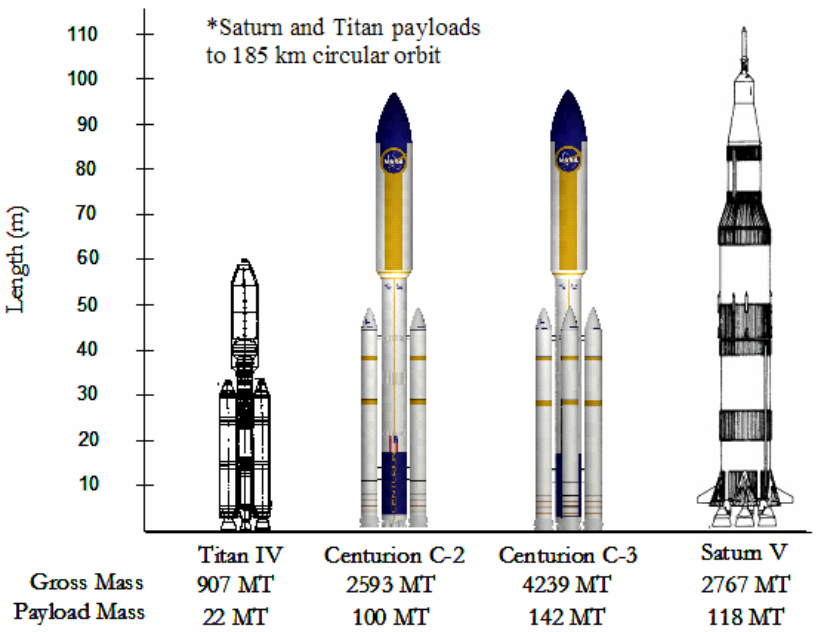


Figure 4. Comparison of Cargo Heavy Lift Vehicles.

III. Multidisciplinary Design Process

The conceptual design process involves the combination of many different design disciplines. These disciplines are treated as individual contributing analyses to the entire vehicle design. Each of these contributing analyses are coupled which makes a difficult design problem. This coupling requires iteration between the disciplines to close the vehicle design. This coupling is graphically represented as a design structure matrix (DSM). Each of the contributing analyses (design disciplines) is represented as a box in the DSM and the links between the boxes are the coupling variables that are passed between the disciplines. Links leaving the right hand side of the boxes represent data that is passed downstream, while links leaving the left hand side represent information that is required upstream in the design process.

The DSM for the Centurion design involves two different iteration loops. The first iteration loop is between the propulsion, trajectory, aeroheating, and weights and sizing disciplines. This iteration loop closes the performance aspects of the vehicle. The second iteration loop is between operations, reliability, and cost. This loop uses the converged physical design and creates the operations, reliability, and costs of the closed design.

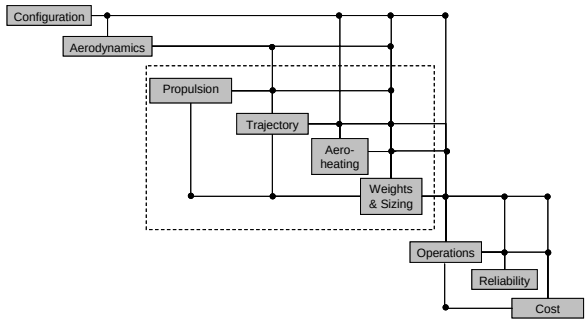


Figure 5. DSM for Centurion Design.

Table 2. Centurion Design Tools.

Discipline	*Analysis Tool*
Configuration	Pro/E
Aerodynamics	APAS (HABP)
Propulsion Design	REDTOP
Trajectory	POST 3-D
Weights & Sizing	MS Excel
Structures	GT-STRESS
Aeroheating	Miniver
Reliability	Relex
Operations	Historical Estimates
Cost	TRANSCOST

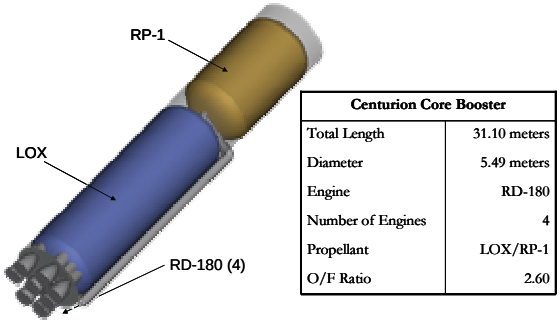
Each discipline has its own conceptual design tools associated with it. Table 2 provides a listing of each discipline and its associated design tool or tools. Configuration, aerodynamics, propulsion, trajectory, structural design, aeroheating, and reliability are all analyzed with their respective disciplinary tool. Weights and sizing is composed of a series of MERs that are summarized and internally closed in an MS Excel workbook. Operational data is based on historical estimates of the cost of a new launch pad at KSC, as well as operating costs derived from the STS program. Cost CERs are based upon TRANSCOST and are also summarized in a MS Excel workbook.

IV. Centurion C-2 Closure Results

Each of the design disciplines depicted in Figure 5 are explained below in this section. Each of the design disciplines are then iterated and closed to get the Centurion design. Each of the Centurion vehicles was closed using the same procedure. For brevity only the C-2 variant closure results are presented.

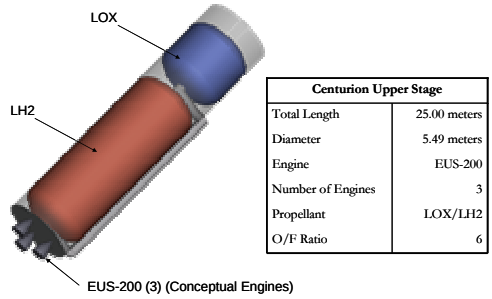
A. Internal Configuration and Layout (CAD)

The Centurion C-2 architecture consists of three separate flight segments (core 1st stage, core 2nd stage, SRBs). The assembled Centurion is approximately 97 meters tall and just under 6 meters in diameter. The Centurion payload fairing has a 30 meter long, 8 meter in diameter cylindrical section with an 11 m tall cone. The five segment SRBs are 47 meters tall and 3.6 meters in diameter. A summary of the individual components that comprise the core are provided as Figure 6 (core 1st stage) and Figure 7 (core 2nd stage).



Centurion Core Booster	
Total Length	31.10 meters
Diameter	5.49 meters
Engine	RD-180
Number of Engines	4
Propellant	LOX/RP-1
O/F Ratio	2.60

Figure 6.Core 1st Stage Configuration.



Centurion Upper Stage	
Total Length	25.00 meters
Diameter	5.49 meters
Engine	EUS-200
Number of Engines	3
Propellant	LOX/LH2
O/F Ratio	6

Figure 7. Core 2nd Stage Configuration.

As noted the first stage consists of four RD-180s with RP-1 fuel and LOX. The upper stage consists of LOX/LH2 propellant. The second stage length is very close to the first stage length (25 meters for the second stage, 31 meters for the first stage). The large relative size of the second stage is due to a combination of the low density of the hydrogen propellant (compared with the higher density RP-1) and the high ΔV that the second stage provides.

The second stage provides over 65% of the available ΔV in the core. The O/F ratio of the different fuels also plays a role in the overall size. The O/F ratio of the first stage (2.6) drives the stage to be more compact than the O/F ratio of the second stage (6.0). This lower O/F ratio combined with the higher density fuel (in both cases the LOX is more dense than the fuel) results in a smaller package (physical size vs. ΔV provided) than the upper stage.

Engine arrangement is also a problem in the RD-180 configuration. The RD-180s are two nozzled engines, which will be discussed in more detail in the Propulsion Design section of this paper. To keep the one engine out capability on the C-1 variant, it is necessary to have four RD-180s on the first stage. Due to the shear size and unusual two nozzle layout it is difficult to arrange the engines symmetrically. The final engine configuration has been chosen as a compromise between the C-1 and C-3 variants. For the C-1, it was required that the engines be centered as much as possible to help sustain proper control if an engine failed, for the C-3 it was necessary to keep one engine centered since it would be the only engine functioning during liftoff (the other three RD-180s are air-started). The final engine configuration resulted in one centerline engine with the remaining three surrounding the first. This first engine would act as the ground started engine at take-off of the C-3. The arrangement also allows for the greatest nozzle rotation freedom to help control the C-1 during an engine failure. A picture of the engine configuration is provided as Figure 8.

Figure 8. C-2 End View.

B. Propulsion Design

The Centurion family uses three types of propulsion elements. The first stage uses Russian-designed staged-combustion RD-180s, while the second stage uses a new conceptual LOX/LH2 220,000 lb thrust expander-cycle engine. The cargo variants of Centurion also use solid rocket boosters that are ATK Thiokol five-segment solid rocket boosters. The RD-180 performance characteristics are taken from flight RD-180s, while the SRB performance is taken from a ground test firing of a preliminary five-segment SRB. A summary of the performance characteristics of the RD-180 (Figure 9) and SRB (Figure 10) are shown below.

- Staged-Combustion Cycle
- LOX/RP-1 Propellant
- T_{vac}= 3830 kN
- $T_{s/l}$ = 2890 kN
- Isp_{vac}= 338 s
- $Isp_{s/l}$ = 311 s
- $Weight_{Installed}$ = 5300 kg
- $Area_{exit}$ = 3.20 m^2
- Expansion Ratio = 36.4
- O/F Ratio = 2.6
- Throttle Range = 50% or 100%
- $P_{chamber}$ = 25.7 MPa

Photo courtesy of:
http://spaceflightnow.com/news/n0201/29rd180

Figure 9. RD-180 Engine Design Specifications.

- Five-Segment SRB
- HTPB Propellant
- T_{vac}= 17.8 MN
- Isp_{vac}= 264 s
- $Area_{exit}$ = 5.7 m^2
- Weight Empty = 85 MT

Figure 10. Core 2nd Stage Configuration.

The new upper stage engine is designed using REDTOP[3] , a conceptual chemical rocket design tool. The new engine is designed to propel the relatively large second stage of Centurion with a T/W of approximately 1 at staging. The engine was chosen to be an expander cycle to keep the design simple and relatively inexpensive. The thrust class was set by the approximate scaling limits of the expander cycle. There had to be enough engines to satisfy the one engine out capability of the C-1, yet keep the number of engines small enough for the design to remain simple for production and operations. A summary of the EUS-200 (expendable upper stage-200,000 lb thrust class) is included as Figure 11.

- Expander Cycle
- LOX/LH2 Propellant
- T_{vac}= 978 kN
- Isp_{vac}= 442 s
- $Weight_{Installed}$ = 1425 kg
- $Area_{exit}$ = 4.53 m^2
- Expansion Ratio = 60
- O/F Ratio = 6
- Throttle Range = 30%-100%
- $P_{chamber}$ = 6.9 MPa
- Re-starts = 3

Photo courtesy of: http://www.spaceandtech.com/spacedata/engines/rl50_sum.shtml

Figure 11. EUS-200 Engine Design.

This new conceptual engine is designed to be restartable as well as throttleable. This design feature is necessary to reduce the thrust when all engines are operating, while allowing the engines to provide an insertion into an eliptical orbit and restarting the engine to fire the circularization burn at apogee of the coast.

The upper stage engine design could also be used in other high thrust in-space applications. In-space transportation vehicles for lunar transits will require high thrust, high efficiency engines. High payload lunar landers could also use this engine as a high thrust alternative to RL-10s for large payload lunar landings, which will be necessary for future lunar missions.

C. Performance

The trajectory of the Centurion family is optimized using a three degree of freedom trajectory simulation code called the Program to Optimize Simulated Trajectories (POST 3-D)[4]. As noted earlier in this paper the C-1 payload requirement of 35 MT is used to size the core of the Centurion family, while the payload for the cargo variants are calculated after optimizing the trajectory with different combinations of SRBs.

The C-1 trajectory is optimized to minimize the gross weight of the C-1 by changing the pitch angles during the ascent. The constraints on the trajectory are: the final orbit (after coast and circularization burn) must be a 300 km x 1000 km highly elliptical orbit, the g forces for the ascent must not be greater than 3 g's for the C-1, and the final payload must be 35 MT. The staging ΔV between the first and second stages is optimized to produce the lowest gross weight vehicle.

The C-2 and C-3 trajectories are simulated by adding the SRBs to the static C-1 core and increasing the acceleration limit to 6 g's. It was found during the simulation that the C-2 and C-3 violated the acceleration constraints on the trajectory. This was solved by air-starting some of the RD-180 core engines. This solution has two benefits. The first benefit is that air-starting reduces the acceleration sensed by the payload during the boost phase. The second benefit is that air-starting the engine reduces the propellant consumption during the boost phase and in effect adds propellant for the post boost phase. The C-2 air-starts two of the four RD-180s while the C-3 air-starts three of the four.

As shown in Figure 12, the C-2 trajectory has three different segments. The first segment is the boost phase, where the SRBs and RD-180s are firing. The second segment is when the SRBs are extinguished and the core is flying on four RD-180s. The third segment is the firing of the three EUS-200 engines including a coast phase and circularization. The thrust and resulting Isp of the combination of engines are also included as Figure 13.

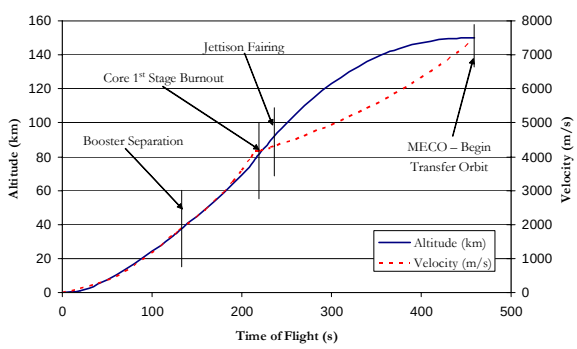


Figure 12. Altitude and Velocity vs. Time.

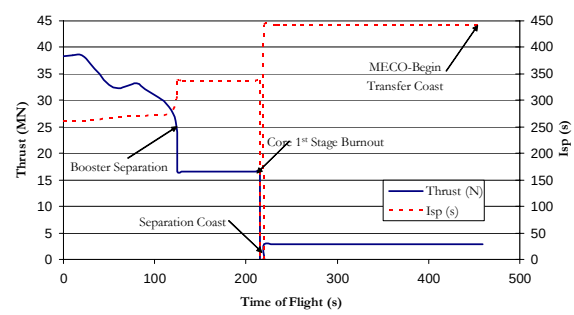


Figure 13. Thrust and Isp vs. Time.

These figures show the powered phase of flight for the Centurion C-2. The end of the powered phase begins at perigee of a 150 km x 407 km transfer orbit. At apogee of the transfer orbit there is a short circularization burn which is accounted for in the weights and sizing discipline. A summary of the propellant weights for the C-2 is provided below in Table 3. As this table shows, most of the C-2 propellant weight (65%) is composed of the solid

rocket propellant. The C-3 variant has twice as much solid rocket propellant as the C-2 with the same size core propellant.

Table 3. C-2 Propellant Breakdown.

Fuel	*Value*
HTPB	1,431 MT
First Stage LOX	451 MT
First Stage RP-1	173 MT
Second Stage LOX	139 MT
Second Stage LH2	23 MT

D. Mass Estimation & Structural Design

Mass estimation is computed using MERs for each of the stages in the core with static sizes for the five SRBs. The vehicle weight is broken into thirteen categories for each of the stages, resulting in 26 categories. The MERs are based upon the required volume for propellants as well as tank and structural weights. The structure weights were computed using an in-house Georgia Tech conceptual design tool known as GT-STRESS[6]. GT-STRESS is a conceptual design weight estimator which calculates the dry weights of the vehicle based upon trajectory load inputs.

The mass properties spreadsheet adjusts the size and weight of the vehicle to match the propellant output from the trajectory analysis. As the required propellant increases the spreadsheet increases dry weight of the vehicle by sizing the tanks to match the new required propellant load. The subsystems and interstages also parametrically scale with the dry weight. The propellant and dry weight are then iterated on between the trajectory and weights disciplines until the design is closed. A summary of the closed weights for the first and second stages of the Centurion C-2 design are included as Table 4 and Table 5.

Table 4. First Stage Mass Summary.

Weight Breakdown Structure	*Mass*
Body/Structure	15.6 MT
Propulsion	29.5 MT
Subsystems	3.9 MT
Growth Margin	7.3 MT
Dry Weight	**56.3 MT**
2nd Stage	295.8 MT
Propellant	623.0 MT
SRBs	1600.3 MT
Gross Weight	**2593 MT**

Table 5. Second Stage Mass Summary.

Weight Breakdown Structure	*Mass*
Body/Structure	17.5 MT
Propulsion	5.4 MT
Subsystems	2.2 MT
Growth Margin	3.8 MT
Dry Weight	**28.9 MT**
Payload	99.9 MT
Propellant	162.3 MT
Gross Weight	**295.8 MT**

As shown in these tables the gross weight of the C-2 is 2593 MT, with a dry core weight of 85.2 MT. The first stage dry weight is 56.3 MT, while the second stage dry weight is 28.9 MT. This dry weight difference is mainly due to the difference in weight of the two sets of main propulsion. The first stage has four RD-180s which weighs 29.5 MT (including feed systems); while the second stage's three EUS-200s weigh only 5.4 MT (including feed systems). The entire C-2 is 97 meters tall, with the first stage being 31 meters, the second stage (including interstage) is 25 meters, and the payload fairing is 41 meters.

E. Reliability

The Centurion family's reliability is calculated using Relex[9], a fault tree analysis software product. The reliability of each of the subsystems is inputted into Relex and the resulting reliability of the system can be obtained. For this analysis, an improvement in the historic reliability of ELV subsystems as well as hydraulic systems, payload fairings, and SRBs is assumed. It is also assumed that the RD-180 has a reliability of 1 failure in 3000 starts, while the new EUS-200 has a reliability of 1 failure in 5000 starts. A summary of the Relex analysis is included as Figure 14.

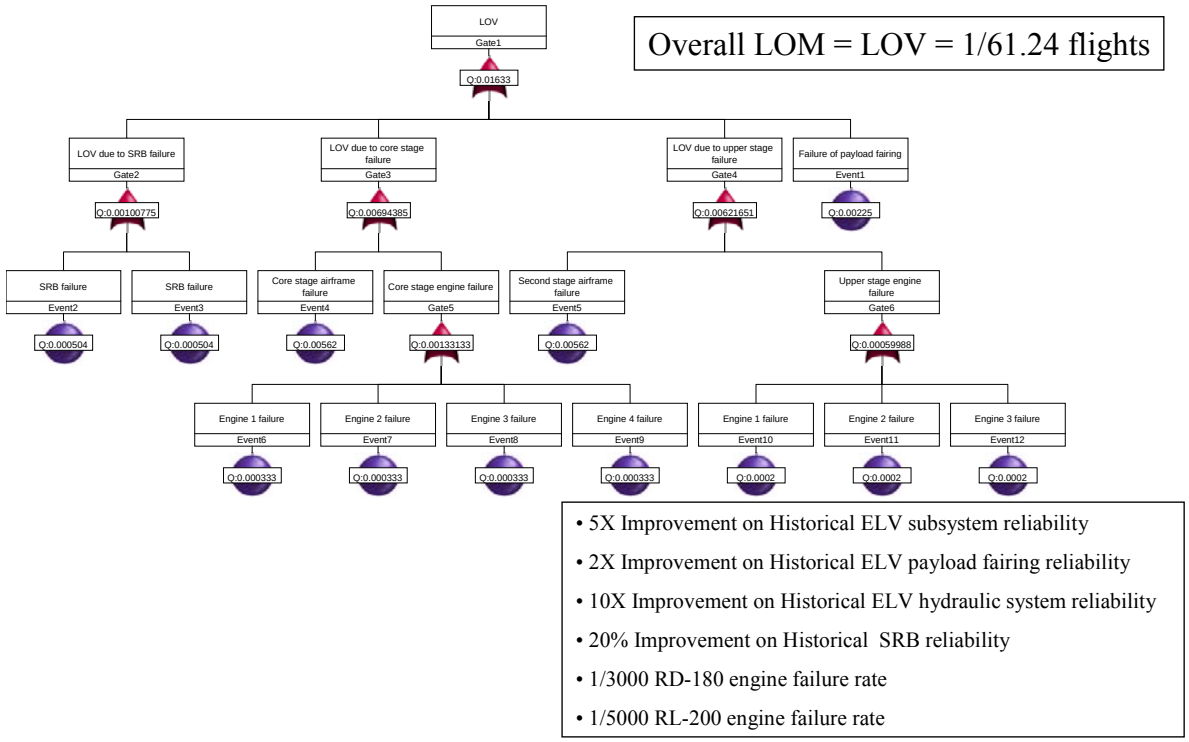


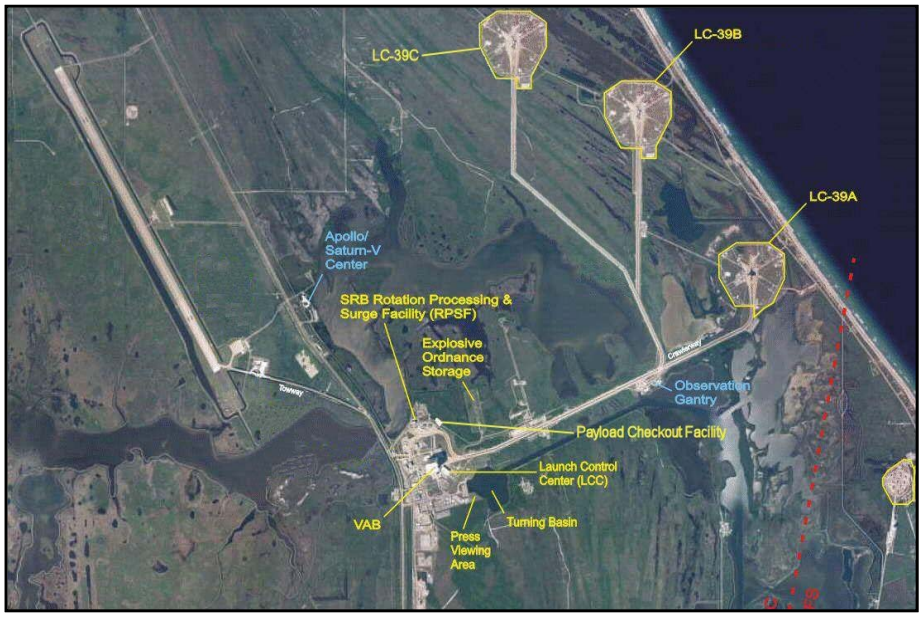
Figure 14. Reliability Analysis with Relex.

As this analysis shows even with the improvements on historical ELV subsystems and engine components the overall reliability of the C-2 design is still one failure in 62 flights or a 0.984 reliability. This is well below the target of 0.997 for the design requirements. This additional reliability is deemed unreachable with current technology for a cargo HLV. For a manned version the reliability goal was taken not as a loss of mission, but as a loss of crew. To reach the 0.997 survivability the manned version of the Centurion family will have to carry a crew escape system. This crew escape system will be designed to help increase the survivability of the crew to 0.997 to account for a catastrophic failure in the launch vehicle.

F. Operations

The operations of the Centurion family are calculated using historical estimates derived from the STS program. Although some of the shuttle architecture will be reused, major changes are necessary to the infrastructure at KSC before the first Centurion can lift-off. The first major change is that a new launch pad will have to be constructed.

Pads 39 A and B are not designed for the loads that will occur when the C-3 lifts off with four SRBs firing. This new pad will be in the same area as the two shuttle pads, just to the north and west of 39 B (Figure 15).



Original Photo courtesy of www.cryptome2.org//ksc-eyeball.htm

Figure 15. KSC layout for Centurion processing and launch.

A new payload checkout facility will also be constructed to reduce the checkout times and therefore reduce overall launch times. Engines, payload, and the upper stage will all arrive by aircraft, which will land on the KSC runway. The SRBs will continue to arrive by rail, and the first stage will be delivered by barge, much like the STS external tank. It is also necessary to improve the STS crawler to carry the increased weight of the C-3 variant to the pad.

All of these considerations (arrival and processing times) are taken into account and a processing schedule is calculated (Figure 16). As this schedule shows, the vehicle and payload are fully integrated in the Vehicle Assembly Building (VAB) so that the launch vehicle has the shortest pad time possible. This short pad time is necessary to reduce the effect of the elements on the launch vehicle. Up to four Centurions can be processed in the VAB at the same time, but the single processing time for a C-2 is shown below. The VAB vehicle integration does require the crawler to take the entire stack (four SRBs, fully assembled core, with 142 MT payload) to the pad. This fully assembled vehicle weight requires the crawler to be redesigned to meet its new payload requirement. The entire processing schedule, from the arrival of the first components to launch, takes approximately 110 days.

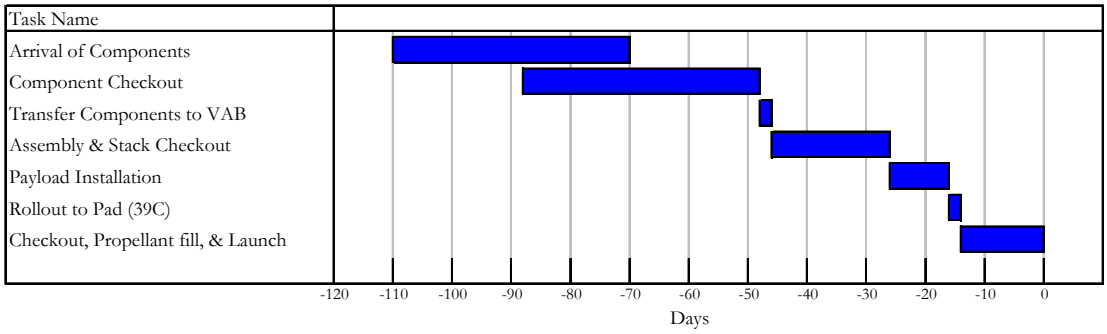


Figure 16. KSC layout for Centurion processing and launch.

G. Cost and Economics

The cost estimating for the Centurion design is calculated using weight-based cost estimating relationships (CERs). These CERs are used to estimate the development and production costs for each of the items in the weight breakdown structure. These CERs are based upon data from the TRANSCOST[8] model for cost estimating. Construction of new facilities as well as operational labor costs is estimated from historical programs such as the STS program. A summary of the design, development, testing and evaluation costs (DDT&E) as well as the production costs for each of the segments of the C-2 are included as Table 6 (All costs presented in FY 2004 dollars).

The DDT&E for the SRBs and the RD-180 is assumed to be zero since each of these propulsion components has already been developed. It is also assumed that the SRBs, although theoretically reusable, are expended after every mission. This is due to the fact that the flight rates for the cargo variants of the Centurion family are assumed to fly at a low flight rate (two a year). This low flight rate does not justify the infrastructure necessary to reuse the boosters. The existing RD-180s are taken to be a flat cost from the manufacturer of $8 M per engine. There is also a cost margin built into the cost estimating model. This margin is 20% of the total vehicle costs and is used to approximate for unforeseen cost overruns.

Table 6: Cost Breakdown for C-2.

	Facilities		$2,000
Core	DDT&E		
		Airframe	$2,178
		RD-180	$0*
	Production		
		Airframe	$130
		RD-180 (4)	$32
Booster	DDT&E		
		SRB-5	$0*
	Production		
		SRB-5 (2)	$35**
Upper Stage	DDT&E		
		Airframe	$1,852
		Engine	$1,953
	Production		
		Airframe	$134
		Engine Set (3)	$74
	Margin (20%)		$1,714

* Assumed to be prior developed/ Existing Hardware
** Flight rate too low to justify reusability

It is assumed that the construction of a new pad at KSC will be close to one billion dollars, while the entire construction of facilities (new payload integration facility, VAB modifications, new roads, etc.) will raise the construction costs to approximately two billion dollars.

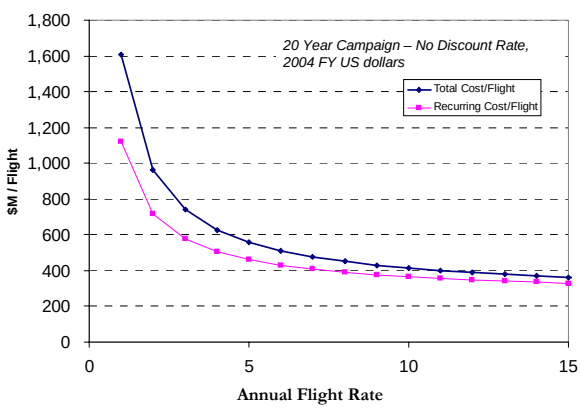


Figure 17. C-2 Cost Sensitivity to Flight Rate.

The total DDT&E, TFU, and construction of new facilities cost is $10.2 B. This can be divided into $2 B for construction of facilities, $5.98 B for DDT&E, and $532 M for production of the theoretical first unit (TFU).

The life cycle cost (LCC) for the Centurion family is calculated based upon the flight rate assumed Figure 17. The LCC includes the initial investment (DDT&E and construction of facilities), the production and integration of airframe and engines, as well as the operations and maintenance of the launch facility. The initial investment of $10.2 B is spread evenly over the twenty year life of the program. The production of the airframe and the new upper stage engines are subjected to an 85 % Crawford learning curve and averaged over the life of the program. The operations are assumed to be comprised of a fixed cost per year of $750 M with a variable cost of $100 M per flight. The total LCC is calculated as equation 1.

$$\text{LCC/Flt} = \frac{\text{DDT \& E} + \text{COF}}{\text{Flts/Yr} * \text{Years_Program}} + \frac{\text{FixedOps/yr}}{\text{Flts/yr}} + \text{VariableOps/Flt} + \text{Production/Flt} \tag{1}$$

$$\text{Production/Flt} = \frac{\text{Total_Production_Cost}}{\text{Flts/Yr} * \text{Years_Program}} \tag{2}$$

The total undiscounted cost per flight is approximately $961 M for the flight rate of two flights per year. As the flight rate increases the costs drop significantly as the initial investment is spread over all of the flights. The cost asymptote at about $360 M as the flight rate approaches 15 flights per year. A max shuttle flight rate (one pad) is probably the best indication for the maximum flight rate attainable by the Centurion which is approximately 6 flights a year. This rate results in a total cost of $511 M per flight.

V. Trade Studies

Once the baseline design for the Centurion family was completed trade studies were conducted. The major trade study performed involves a change of first stage propulsion from the RP-1 based RD-180s to the LOX/LH2 based RS-68s. The change of first stage propulsion would result in a larger (physical size) vehicle due to the LH2 density, but it should also provide a lighter vehicle due to the higher Isp of the RS-68. The RS-68 Centurion design methodology will be the same as the RD-180 variant. The C-1 will first be optimized to carry the 35 MT payload with one engine out on both the first and second stages, and the C-2 and C-3 variants will be optimized to have the same core with different combinations of SRBs (two and four SRBs respectively).

- Gas Generator Cycle
- LH2/LOX Propellant
- T_{vac}= 3315 kN
- $T_{s/l}$ = 2890 kN
- Isp_{vac}= 410 s
- $Isp_{s/l}$ = 365 s
- $Weight_{Installed}$ = 6600 kg
- $Area_{exit}$ = 4.17 m^2
- Expansion Ratio = 21.5
- O/F Ratio = 6.0
- Throttle Range = 60% or 100%
- $P_{chamber}$ = 9.72 MPa

Photo courtesy of: http://www.boeing.com/defense-space/space/propul/RS68.html

Figure 18. RS-68 Engine Specifications.

The RS-68 is a LOX/LH2 based gas generator rocket engine currently used on EELVs. The RS-68s provide less thrust per engine than the RD-180s, but provide a much higher Isp. A summary of the RS-68 is included as Figure 18. The RS-68 has an Isp in vacuum of 410 seconds. This is 72 seconds more efficient than the RD-180. Unfortunately the lower thrust of the RS-68 requires five RS-68s versus the four RD-180s. The extra engine provides more engine weight and therefore a heavier overall engine structure than the RD-180. This, combined with the larger tanks required for the LH2, results in an overall larger and heavier (dry) vehicle for the same payload performance. A summary of the RS-68 family of Centurions is included as Figure 19.

The RS-68 version of Centurion is 6 meters higher and 1.2 meters wider than the RD-180 version (Figure 19). The gross weight of the C-1 version is 110 MT lighter than the RD-180 version (again due to the higher Isp of the engines). The C-2 and C-3 variants with RS-68s can actually carry more payload than the C-2 and C-3 variants with RD-180s. This is due to the lighter overall gross weight of the core. A lighter core with the same SRBs attached can carry more payload than the heavier core. The RS-68 can carry five more metric tons of cargo for the C-2 and six more for the C-3.

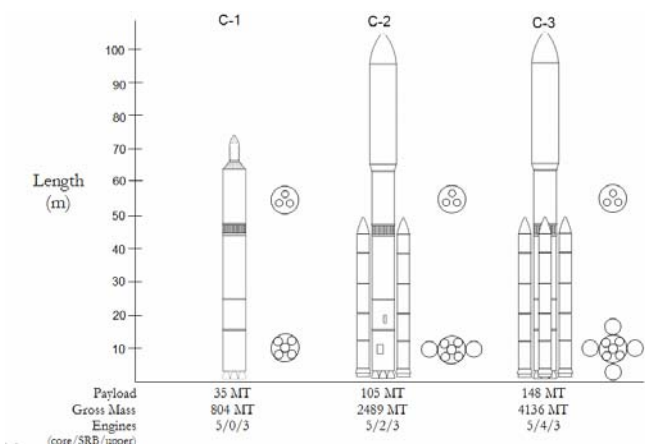


Figure 20. Centurion Family with RS-68 Family.7

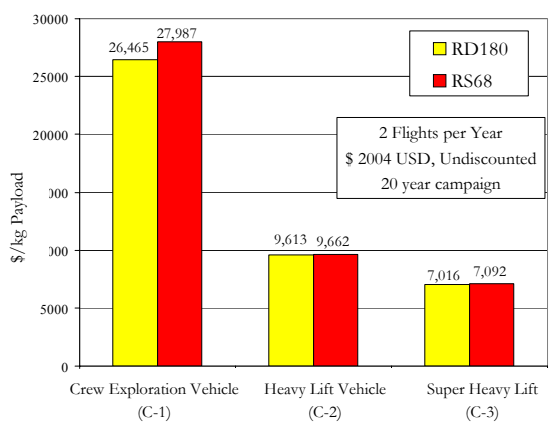


Figure 19. Cost Comparison Centurion Versions.

The main distinction between the RS-68 and the RD-180 versions of Centurion is not measured in payload, since both variants have practically the same payload capacities. Instead the distinction is made by comparing cost per kg of payload to orbit. A comparison of the cost per kg of payload for both versions is included as Figure 20.

The RD-180 version of Centurion is cheaper ($/kg) than the RS-68 version. This is due to the lighter and therefore cheaper structure of the RD-180 version as well as the need for one fewer engine on the RD-180 version. The larger payload capacity closes the cost per kg gap on cargo variants; however the RD-180 version still is less

expensive. It should be noted that the costs are very close for both the RS-68 and the RD-180 variants. For this study the RD-180 was chosen for the Centurion design due to the marginal improvement in cost. Other reasons (political or operation) are not considered and may drive the design in one direction.

VI. Conclusions

Centurion is a new family of HLLV designed to be used in lunar exploration mission. The Centurion family consists of three vehicles. The C-1 is a single core, two-stage, all liquid rocket using four RD-180s for main propulsion and three conceptual EUS-200 engines for the upper stage. The C-1 is mainly designed to carry a 35 MT CEV to a 300 km X 1000 km highly elliptical orbit. The C-2 and C-3 are the cargo carrying versions in the Centurion family. The C-2 and C-3 use the same C-1 core with two or four STS 5 segment SRBs for added performance. The C-2 carries 100 MT of payload to a 407 km x 407 km x 28.5° circular orbit. The C-3 version can carry up to 142 MT of cargo to the same 407 km x 407 km x 28.5° circular orbit. Centurion utilizes mainly ELV heritage technologies with improvements assumed for reliability of the ELV components.

The economic results for Centurion indicate that the initial investment for Centurion will be over $10 B dollars, even though STS infrastructure was used whenever possible. The low flight rates assumed for Centurion result in a launch cost of $961 M per flight (C-2). This can be reduced by launching more flights per year until the infrastructure becomes saturated at approximately the max STS flight rate per pad of 6 flights per year. At this max flight rate, the Centurion costs drop to about $511 M per flight.

The Centurion family was evaluated using either RD-180 LOX/RP-1 engines or RS-68 LOX/LH2 engines on the core booster stage. The payload capacity of the two different versions of Centurion was found to be very close. The C-1 versions were designed to carry 35 MT, while the C-2 and C-3 payload capacities did change significantly due to different core weights. Since the performance of the two versions was approximately the same, economics was chosen to be the determining factor in deciding the final configuration. The cost per kg of the RD-180 version was found to be slightly lower than the RS-68 version and therefore the RD-180 version was chosen as the baseline engine.

Acknowledgments

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