Tempest: Crew Exploration Vehicle Concept

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Tempest is a reusable crew exploration vehicle (CEV) for transferring crew from the Earth to the lunar surface and back. Tempest serves as a crew transfer module that supports a 4-person crew for a mission duration of 18 days, which consists of 8 days total transit duration and 10-day surface duration. Primary electrical power generation and on-orbit maneuvering for Tempest is provided by an attached Power and Propulsion Module (PPM). Hydrogen (H2)/oxygen (O2) fuel cells and a high energy-density matter (HEDM)/liquid oxygen (LOX) propellant reaction control system (RCS) provide power and reaction control respectively during Tempest's separation from the PPM. Tempest is designed for a lifting entry and is equipped with parachutes for a soft landing.

Tempest is part of an overall lunar transportation architecture. The 60,731 lbs combination of Tempest and the PPM are launched atop the notional Centurion C-1 heavy-lift launch vehicle (HLLV) and delivered to a 162 nmi, 28.5° circular orbit. After separating from the C-1 upper stage, the Tempest/PPM autonomously rendezvous with Manticore, an expendable trans-lunar injection (TLI) stage pre-positioned in the current orbit, and transfer to a lunar trajectory. After entering a 54 nmi polar circular lunar orbit, the Tempest/PPM separate from Manticore. Tempest separates from the PPM and is ferried to/from the lunar surface by Artemis, a reusable lunar lander. Upon return from the lunar surface, Tempest reconnects with the PPM, and the PPM provides the trans-earth injection (TEI) burn required to return to low earth orbit (LEO). Prior to atmospheric entry, Tempest separates from the PPM and subsequently executes a lifting entry trajectory. Crushable thermal foam attached to the lower surface of Tempest serves as an ablative thermal protection system (TPS) and the impact absorber of the parachute landing.

Details of the conceptual design process used for Tempest are included in this paper. The disciplines used in the design include: configuration, aerodynamics, propulsion, trajectory, mass properties, environmental control life support system (ECLSS), entry aeroheating and TPS, terminal landing system (TLS), cost, operations, and reliability & safety. Each of these disciplines was computed using a conceptual design tool similar to that used in industry. These disciplines were then combined and optimized for the minimum gross weight of the Tempest CEV. The total development cost including the design, development, testing and evaluation (DDT&E) cost was determined to be $2.9 B FY'04. The theoretical first unit (TFU) cost for the Tempest CEV was $479 M FY'04. A summary of design disciplines as well as the economic results are included.

Nomenclature

CEV = crew exploration vehicle
CER = cost estimating relationship

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DDT&E = design, development, testing & evaluation
ECLSS = environmental control life support system
HEDM = high energy-density matter
HLLV = heavy lift launch vehicle
LEO = low earth orbit
LLO = low lunar orbit
LRU = line replacement unit
MER = mass estimating relationship
PPM = power and propulsion module
RCS = reaction control system
TEI = trans-earth injection
TFU = theoretical first unit
TLI = trans-lunar injection
TLS = terminal landing system
TPS = thermal protection system
UTTR = Utah Test & Training Range

I. Introduction

NASA's Constellation Systems is responsible for the development of the Crew Exploration Vehicle (CEV) and related exploration architecture systems required to transport astronauts to the Moon and form the basis for exploration missions to other destinations. Constellation Systems Exploration Spiral 1 will develop and test the crew transportation and lunar exploration elements while Spiral 2 will conduct human exploration missions to the lunar surface by 2020. The third spiral is the establishment of the capability to conduct routine human long-duration missions at a lunar base to test technologies and operational techniques that enable sustainable human and robotic exploration.[1]

Spiral 2 human exploration missions on the lunar surface are conducted without pre-positioned surface infrastructure. The lack of infrastructure requires the lunar lander and/or CEV (for CEV-to-surface architecture) to provide support for crew habitation throughout the mission duration. A fully reusable system would seem idea for this type of mission, but due to the complexity involved with sizing architectural elements to satisfy mission requirements along with launch vehicle payload weight constraints, an expendable architecture is more plausible. Developers are also prohibited from utilizing various advanced technologies that could relax some of the CEV weight/volumetric constraints because of the failure of these potential technologies to reach full maturity for the 2014-2020 timeframe. The premise of an established lunar infrastructure and utilization of advanced technologies beyond the 2014-2020 timeframe allows for the development of a more advanced Spiral 3 CEV that provides more reusability than its Spiral 2 predecessor.

Tempest is a new fully reusable crew exploration vehicle concept designed to comply with the crew transportation segment of NASA's Exploration Spiral 3 development for lunar exploration. Tempest is designed to use much of the same technology as currently used in human space transportation system design. The main technologies assumed are high energy density matter (HEDM) propellants, crushable thermal foam thermal protection system (TPS), and a morphable tail surface/body. Tempest serves as a crew transfer module that supports a 4-person crew for a mission duration of 18 days, which consists of 8 days total transit duration from Earth to the lunar surface and back and 10-day surface duration. Primary electrical power generation and on-orbit maneuvering for Tempest is provided by an attached expendable Power and Propulsion Module (PPM). The 60,731 lbs combination of Tempest and the PPM are launched atop the notional Centurion C-1[2] heavy-lift launch vehicle (HLLV) and delivered to a 162 nmi, 28.5º circular orbit. Upon reaching this orbit, Tempest/PPM autonomously rendezvous with the Manticore expendable trans-lunar injection (TLI) stage and transfers to lunar orbit.

Figure 1. Tempest CEV in Orbit.

In addition to transferring crew from Earth to lunar orbit, Tempest also serves as the descent/ascent habitat from lunar orbit to the lunar surface. Tempest is ferried to/from the lunar surface by Artemis[3], a reusable lander stationed in LLO. After reaching the lunar surface and the crew exits the vehicle, Tempest powers down to standby mode until the crew returns to travel back to LLO. Returning to lunar orbit from the surface of the moon, Tempest reconnects with the PPM, and the PPM provides the trans-earth injection (TEI) burn required to return to low earth orbit (LEO). Prior to atmospheric entry, Tempest separates from the PPM and subsequently executes a lifting entry trajectory. Crushable thermal foam attached to the lower surface of Tempest serves as an ablative thermal protection system (TPS) and the impact absorber of the parachute landing.

A full multi-disciplinary conceptual design process was performed for the development of the Tempest CEV concept. This design process was completed using a disciplinary design tool for each of the following disciplines: external and internal configuration with the solid modeling tool Pro/ENGINEER, aerodynamic analysis with APAS[4], propulsion analysis with GTHEDM, ascent/entry trajectory optimization using POST[5], in-space trajectory optimization using IPREP[6], power systems and environmental control life support system (ECLSS) sizing using historical data and NASA estimates[7], TPS and terminal landing system (TLS) sizing using an MS Excel spreadsheet model, vehicle ground operations analysis using AATe[8], safety and reliability analysis using Relex[9], and vehicle non-recurring cost estimation using TRANSCOST[10] and NAFCOM derived cost estimating relationships (CERs). Mass estimation was conducted using industry standard mass estimating relationships (MERs) and empirical calculations within spreadsheet models to size the primary vehicle subsystems and components. Each of these tools was used to analyze their respective disciplines and develop the Tempest design.

II. Tempest Overview

Tempest is a new fully reusable CEV concept designed for transferring crew from Earth to the lunar surface and back. Tempest serves as a crew transfer module that supports a 4-person crew for a mission duration of 18 days, which consists of 8 days total transit duration and 10-day surface duration. Tempest also serves as the descent/ascent habitat from lunar orbit to the lunar surface. The Tempest pressurized crew cabin provides a large habitable volume that accommodates mission task and personal needs of the crew with minimum impairment throughout the transit duration. Since it serves primarily as a habitat module, Tempest's propulsive capability is limited to 32 reaction control system (RCS) motors on the vehicle. Primary electrical power generation and on-orbit maneuvering are provided by an expendable PPM attached to the rear of Tempest. The crushable thermal foam heat shield attached to the lower surface of Tempest for TPS/impact absorption is replaced after each mission.

Tempest is a part of an overall lunar transportation architecture with elements for post-2025 lunar operations. The development of this architecture concept assumes the design of a new HLLV to satisfy NASA's manned and cargo requirements for lunar missions and a reusable lunar lander stationed in LLO to support the Spiral 3 lunar infrastructure. Georgia Tech Space System Design Lab's Centurion C-1 HLLV[2] and Artemis lunar lander[3] served as their respective elements in the architecture for this study. The Tempest/PPM combination are launched atop the notional C-1 HLLV and delivered to a 162 nmi, 28.5º circular orbit. After separating from the C-1 upper stage, the Tempest/PPM autonomously rendezvous with Manticore, an expendable trans-lunar injection (TLI) stage pre-positioned in the current orbit, and transfer to a lunar trajectory. After entering a 54 nmi polar circular lunar orbit, the Tempest/PPM separate from Manticore. Tempest separates from the PPM and is ferried to/from the lunar surface by Artemis.

Upon return from the lunar surface, Tempest reconnects with the PPM, and the PPM provides the trans-earth injection (TEI) burn required to return to low earth orbit (LEO). Prior to atmospheric entry, Tempest separates from the PPM and subsequently executes a lifting entry trajectory. The shape of the airframe provides a high hypersonic lift-to-drag ratio (L/D) greater than 1.2 for large crossrange and downrange capability during entry. After atmospheric entry at high altitudes, the five round parachutes release to provide a soft ground landing at the landing site on the Utah Test & Training Range (UTTR). Crushable thermal foam heat shield attached to the lower surface of Tempest serves as an ablative TPS and the impact absorber of the parachute landing. The heat shield is replaced after each mission.

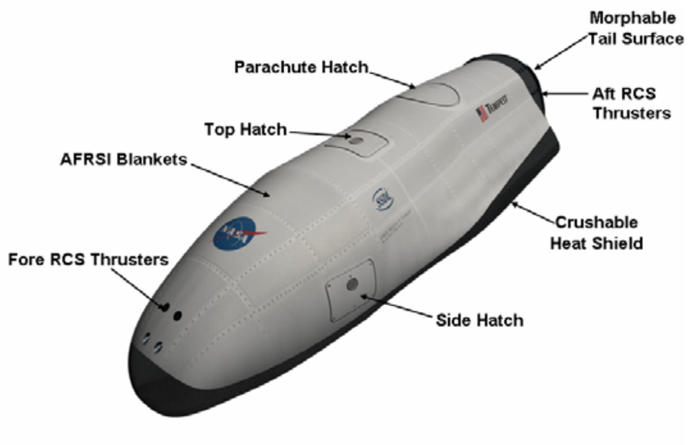


Figure 2. Tempest Concept.

Reliability and safety are main concerns for manned vehicles. For ascent reliability, the Centurion C-1 is designed to meet the reference

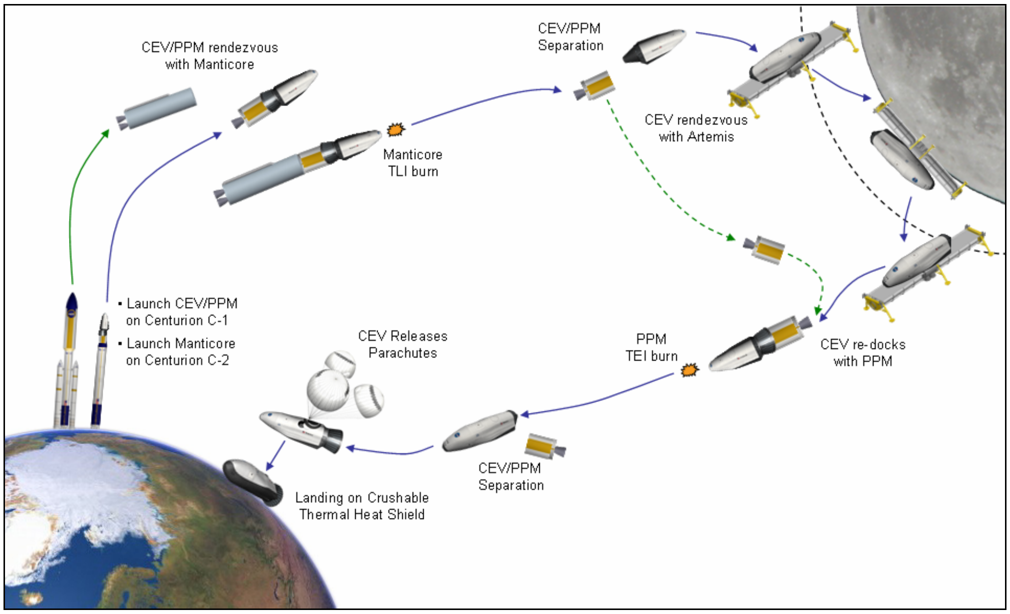


Figure 3. Tempest Mission Profile.

mission with an engine failure on both the first and second stages in the same flight. Also Tempest is equipped with a crew escape system (CES) that provides abort capability from the pad until main engine cut-off (MECO) of the C-1 booster. Tempest includes redundant avionics and communication systems to increase reliability during cis-lunar operations. The terminal landing system is also designed to provide a soft landing with a parachute failure during entry.

Some advanced technologies were assumed in the design of Tempest concept. Quadricyclane, a high energy density matter (HEDM) propellant was used for the Tempest RCS and PPM propulsion system due to its storability, increased specific impulse (Isp), and non-toxic properties. The double-duty crushable thermal foam heat shield serves as an ablator as well as impact attenuation for Tempest. This alternative reduces the weight and complexity of utilizing two separate systems for thermal and impact protection. Tempest utilizes the morphable tail surface/body flap for lightweight flexible roll and pitch control during entry. The airframe and pressurized crew cabin structure are composed of a lightweight aluminum-lithium metal alloy to decrease weight as compared to typical aluminum structures.

III. Multidisciplinary Design Process

The conceptual design process involves the integration of many design disciplines. These disciplines are highly coupled with one another. Figure 4 is a design structure matrix (DSM) for the Tempest conceptual design process.

A DSM provides a very concise, structured means of representing the disciplines involved and the inter-dependencies between disciplines. The links between the discipline boxes represent data flow from one discipline to another. Links in the upper right represent data flow downstream while the links in the lower left represent the data flow upstream. Upstream data flow requires iteration in order to converge the design. The conceptual vehicle design has one main iteration loops: between propulsion, trajectory, weights & sizing, ECLSS/power/avionics, and TLS/Aeroheating. This iteration loop converges the performance aspects of the vehicle. Each discipline has one or more conceptual design tools associated with it. Table 1 provides a listing of each discipline and its associated design tool or tools.

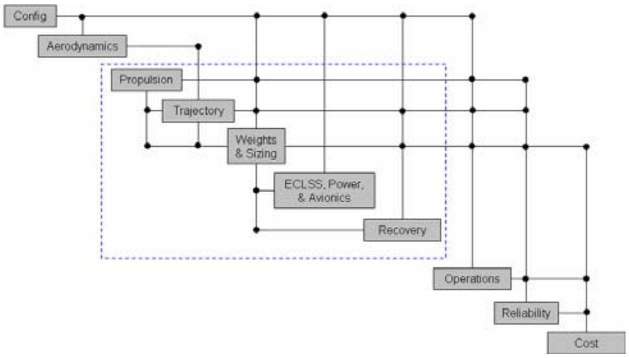


Figure 4. Tempest Design Structure Matrix.

Table 1. Tempest Disciplinary Design Tools.

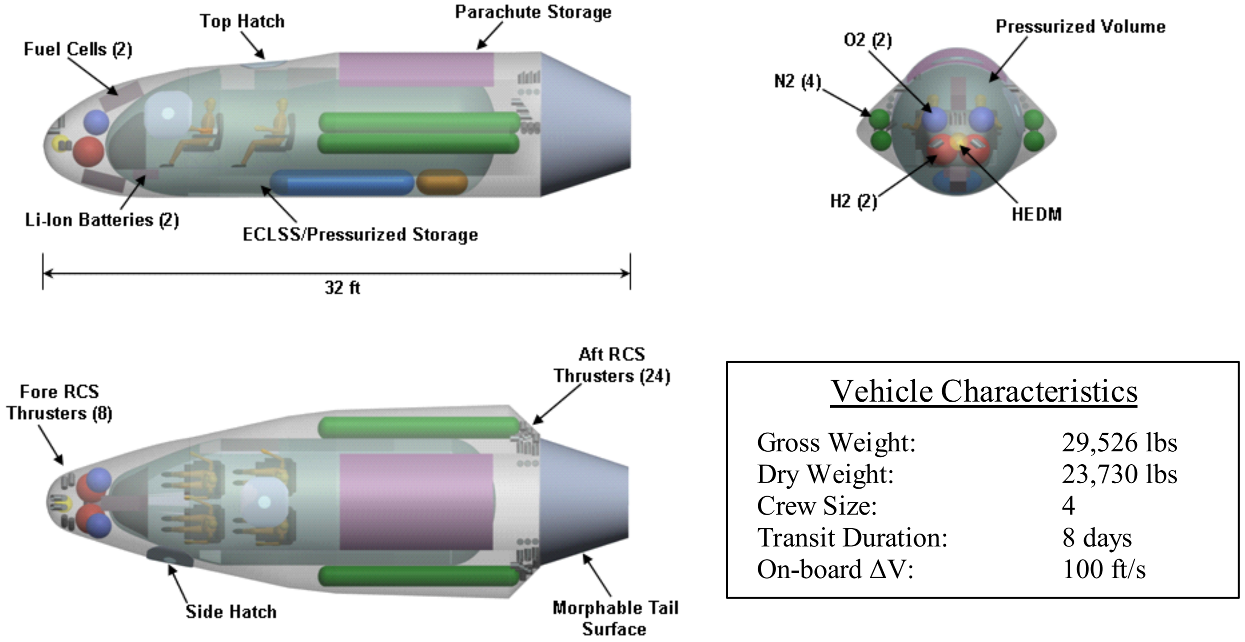
Discipline	*Analysis Tool*
Configuration	Pro/ENGINEER
Aerodynamics	APAS (HABP)
Propulsion	GT-HEDM, MS Excel
Ascent, Entry Trajectory	POST-3D
In-space Trajectory	IPREP
Weights & Sizing	MS Excel
ECLSS, Power	MS Excel
Avionics	SESAW, MASS
Thermal Protection System	MS Excel
Terminal Landing System	MS Excel
Operations	AATe
Reliability	Relex
Costs	TRANSCOST, NAFCOM-99

IV. Baseline Design Results

A. Internal Configuration and Layout (CAD)

The total length of the Tempest baseline configuration, including the morphable body flap is 32 ft. The maximum vehicle width is 12.7 ft with a maximum height, including the crushable heat shield, of 11.3 ft. The total pressurized volume of the crew cabin is 1,130 ft^3. Propellant tanks, ECLSS, TLS, RCS, power systems, and the pressurized crew cabin are packaged using Pro/ENGINEER, a solid modeling Computer Aided Design (CAD) package. Internal views of Tempest are shown in Figure 5.

All pressure vessels (tanks) and airframe structure are made of aluminum-lithium. The non-integral cylindrical nitrogen (N2) pressurant tanks are located in the chines of the airframe. Nitrogen within these tanks serves as the pressurant for the RCS thrusters and the primary gas for the air supply managed by the ECLSS. The spherical HEDM propellant tank for the RCS is located within the vehicle nose. The two spherical hydrogen (H2) tanks, which contain the reactant for the H2-O2 fuel cells, are also located within the vehicle nose. The two spherical oxygen (O2) propellant tanks located in the vehicle nose provide oxygen for both the RCS and the fuel cells. Oxygen within the tanks are stored as a cryogenic liquid with a density of 71.3 lb/ft^3. The RCS uses the oxygen



Vehicle Characteristics

Gross Weight:	29,526 lbs
Dry Weight:	23,730 lbs
Crew Size:	4
Transit Duration:	8 days
On-board ΔV:	100 ft/s

Figure 5. Tempest Internal Configuration.

directly in its liquid form, but the oxygen is transformed to gaseous O2 by a converter to be used with the fuel cells and ECLSS. Parachutes and other elements of the TLS are stored in the raised compartment above the crew cabin. Hatches at the top and on the left side of the vehicle allow passengers to ingress/egress the vehicle. ECLSS, power systems, and avionics are located within pressurized storage under the crew cabin floor. The remaining internal components shown in the Tempest CAD model are the 32 RCS thrusters. The arrangement of the eight fore RCS thrusters located in the nose and the remaining 24 thrusters positioned about the aft of the vehicle provide thrust for attitude and translation maneuvers.

The internal volume of the vehicle is dominated by the pressurized crew cabin. The large volume of the crew cabin is to provide a comfortable confinement during transit and allow enough room for the crew to put on their spacesuits. NASA research has demonstrated that the mission duration has an effect on the required habitable volume within the space module.[11,12] As the mission duration increases, a greater physical envelope is required to accommodate mission tasks and crew personal needs.[11] According to guidelines for habitable volume values within references 12, the required habitable volume for a person to be comfortable and also be able to perform their required duties with minimum impairment for a 4 day mission is 70 ft^3/person. Habitable volume is considered the free/unobstructed volume used by the person. Translation of this habitable volume to include the equipment and accommodations within the pressurized volume yields a total pressurized unit volume of 282 ft^3/person for the comfortable conditions for the 4 day mission. For a 4-person crew, the total pressurized volume is 1,130 ft^3.

Because Tempest does not posses an airlock, the crew cabin is depressurized/pressurized whenever the crew exits/enters the vehicle. Crew members are required to don/doff their spacesuits within the pressurized volume due to the depressurization/pressurization. The minimum volume and height requirements to don/doff the MK III spacesuit are 114 ft^3 and 7.4 ft, respectively.[13] The large available volume within the pressurized cabin accommodates the volumetric requirement, but the 6.4 ft height from the cabin floor to the ceiling restricts the crewman from donning the suit while standing. Therefore the spacesuits are donned/doffed in a microgravity environment, allowing more efficient use of the cabin space. To aid in this task, the crew chairs are collapsible and are easily stored within the pressurized storage under the cabin floor.

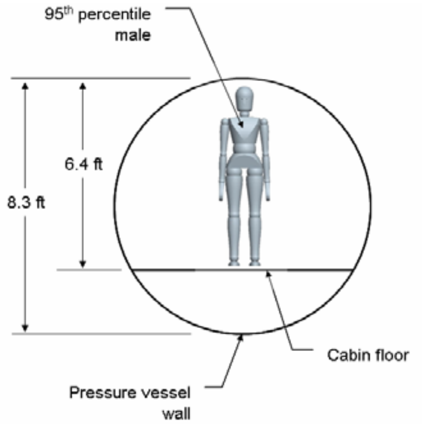


Figure 6. Tempest Don/Doff Height.

B. Aerodynamics

Tempest is designed for a lifting entry trajectory. The airframe shape blends from the blunt conical nose around the varying elliptical chines to the morphable body flap, giving it a form characteristic of a lifting body. Instead of relying on wings, Tempest uses the combination of outboard chines and the morphable body flap to provide lift and stability for the vehicle. Outboard chines along the side of the airframe are designed to allow enough volume for the N2 pressurant tanks and instrumentation while also providing majority of the lift to satisfy the trajectory. The morphable tail surface/body flap is the lightweight solution for flexible roll and pitch control during entry. The flap has similar flexible motion to 2-D vectoring nozzles and convergent-divergent ejector nozzles used on fighter aircraft. The high-temperature carbon mesh surface and variable actuator rods operate the motion of body flap/tail surface, allowing it to expand, collapse, and change shape within the maximum diameter of 11.3 ft throughout entry.

Hypersonic aerodynamic analysis of the vehicle during entry for Mach 3-20 was conducted using the APAS aerodynamic software.[4] The baseline configuration has a theoretical cross-sectional area (S_{ref}) of 54.9 ft^2. The maximum L/D is 1.33 at an angle-of-attack (α) of 23°. The location of the center of gravity (c.g.) for the trimmed configuration is 18.6 ft from the nose along the longitudinal centerline of the vehicle. APAS creates tables of lift and drag coefficients as a function of Mach number and angle of attack. This aerodynamic data is formatted for use in the POST 3-D trajectory analysis program.

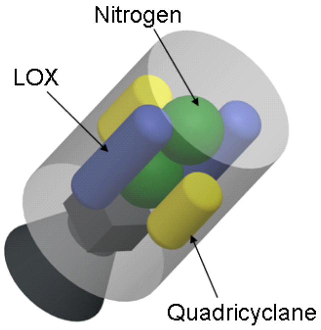
C. Propulsion

Power and Propulsion Module (PPM)

Primary power and on-orbit propulsive capability for Tempest is provided by the attached PPM. The PPM is used for trans-earth injection (TEI) and some rendezvous operations. Though the PPM is not the focus of this design study, estimating its performance and size is essential to accurately design the CEV to satisfy the mission requirements for the architecture in its entirety.

The PPM is designed to use much of the same technology as currently used in in-space vehicle design. The primary structure and non-integral propellant tanks for the PPM are constructed of graphite-epoxy, and the power is generated using H2-O2 fuel cells. The main technology assumed is the use of the HEDM propellant Quadricyclane for the PPM main propulsion system. The higher specific impulse (Isp) and density of HEDM propellants in comparison to conventional in-space propellants results in an increase in propellant performance and storability, respectively.

The PPM is sized to provide the TEI burn for a ΔV of 3,280 ft/s, which includes transfer from LLO to LEO in 3 days as determined by IPREP and required rendezvous operations. The HEDM propellant properties were calculated using an in-house Georgia Tech conceptual design tool known as GT-HEDM. GT-HEDM is a conceptual chemical rocket design tool that calculates engine performance parameters based upon initial condition inputs. GT-HEDM estimates the Isp and density of quadricyclane as 356 seconds and 61.8 lb/ft^3, respectively. A notional pressure-fed engine is also designed for the LOX/Quadricyclane propellant combination with the PPM using GT-HEDM. The mass estimation and sizing of the PPM is composed of a series of empirical relationships based on mission and performance inputs that are summarized and internally closed in a MS Excel workbook. A summary of the PPM is included as Figure 7.



PPM Characteristics

Gross Weight:	24,466 lbs
Dry Weight:	10,103 lbs
Propellant Weight:	13,675 lbs
Length:	34.25 ft
Diameter:	12.74 ft
Isp:	356 s
Propellant:	LOX/Quadricyclane
O/F Ratio:	2.28
$(T/W)_{vehicle}$:	0.25
On-board ΔV:	3,280 ft/s

Figure 7. Power and Propulsion Module.

Reaction Control System (RCS)

Similar to the PPM main propulsion system, the PPM/CEV RCS utilize the LOX/Quadricyclane propellant combination. Since the PPM provides the primary propulsion requirement, Tempest's propulsive capability is limited to the 32 RCS thrusters. The RCS thrusters provide the thrust for attitude (rotational) maneuvers and for small velocity changes along the CEV axis for rendezvous with the PPM/lunar lander and entry trajectory alignment.

Each CEV RCS thruster is sized to produce a single newton (0.22 lbf) of thrust. The total propulsive capability for the RCS system is 100 ft/s; 75 ft/s for on-orbit maneuvering and 25 ft/s for entry alignment. Mass estimation and sizing of the Tempest RCS is based upon a series of propulsion system relationships[14] and historical RCS performance data that is also summarized in a MS Excel worksheet. The RCS for the PPM is sized within the PPM spreadsheet model.

Crew Escape System (CES)

The purpose of the CES is to separate the Tempest CEV from the launch stack (C-1 and PPM) in the case of catastrophic launch failure from the launch pad until MECO. The required ΔV of 1,394 ft/s for the worst case abort scenario calculated by POST is provided by three solid rocket motors attached to the nose of the vehicle. In the event of a successful launch, the tractor solids are ejected at the C-1 MECO. The solid rocket motors are designed using historical estimates of the performance and structure of CES and summarized in a MS Excel worksheet. A summary of the performance of the CES is included in Figure 8.

D. Performance

Ascent and Abort

The ascent trajectory for the notional Centurion C-1 HLLV to LEO is optimized using a three degree of freedom trajectory simulation code known as the Program to Optimize Simulated Trajectories (POST 3-D).[5] The Centurion C-1 is originally designed to carry 77,162 lbs to a highly elliptical 162 nmi x 540 nmi orbit with engine out capability on both booster and upper stages.[2] Placement of the payload into this highly elliptical orbit requires a large ΔV increase by the upper stage at the perigee. The 162 nmi circular orbit of the reference mission for the Tempest CEV concept architecture allows the C-1 to carry a larger payload while remaining at an orbit that provides access for lunar missions and return to LEO in the occurrence of a CEV/PPM failure. Re-optimizing the trajectory to minimize the C-1 gross weight subject to the constraints on the final orbit (162 nmi x 28.5°) and ascent accelerations (3 g's) results in the final payload capability of 92,594 lbs.

CES Characteristics	
Thrust of CES:	63,000 lbs
Burn Time:	2 s
CES System Mass:	6,737 lbs
CES Propellant Mass:	6,064 lbs
Isp:	285 s

Figure 8. Tempest Crew Escape System.

Abort scenarios were examined for the separation of the Tempest CEV from the launch stack in the case of failure from launch until C-1 MECO. Three solid rocket motors attached to the nose of the CEV pull the vehicle away from the launch stack. A few seconds after separation, the abort rockets are ejected and the parachutes are released to allow for a soft landing on land. The required ability to abort from the launch stack on the pad is used to size the crew escape system, while the downrange, acceleration profiles, and abort windows are calculated at other intervals in the trajectory using the sized system. Outputs from the optimized POST 3-D C-1 trajectory in conjunction with a MS Excel workbook is used to size the CES and determine the abort scenario parameters using the following assumptions: 11,500 ft minimum altitude for 0/0 abort, 330 ft minimum separation at 2 seconds after booster failure, the g forces for the abort must not be greater than 9 g's.

In-Space

The In-space trajectory for the Tempest CEV/PPM is optimized using a three dimensional patch conic method simulation program called Interplanetary Preprocessor (IPREP).[6] As noted earlier in this paper, the Manticore propulsive module provides the trans-lunar injection from the initial parking orbit (162 nmi x 28.5°) to the final lunar orbit (54 nmi x 90° circular). After the lunar surface duration, the PPM provides the trans-earth injection burn to return to low earth orbit.

IPREP calculates the required ΔV for each stage of the in-space trajectory based on the departure date from the initial parking orbit in LEO. From calculations of the velocity requirements for day-by-day departure dates within a timeframe, the average, minimum, and maximum ΔV are determined. Assumptions for the velocity requirements are: 2025 mission launch date, a 3.5 time of flight (TOF) required to reach the lunar sphere of influence (SOI) from the initial parking orbit, and ten days between the lunar orbit injection (LOI) and the TEI. A summary of the IPREP ΔV results for TLI and LOI/TEI stages of the trajectory are provided in Table 2. The variation in the velocity requirements for the total in-space flight burns (TLI, LOI, TEI) are presented in Figure 9.

Entry

After arrival to LEO, Tempest separates from the PPM and subsequently executes a lifting entry trajectory. Tempest's atmospheric entry trajectory was also optimized using POST-3D. The Tempest entry trajectory is optimized by minimizing the peak convective heat rate by varying the entry velocity, angle, and corridor width for the descent. The trajectory is constrained by a peak deceleration limit of 5 g's. The resulting optimized maximum convective heat rate and total heat load experienced by the vehicle for the trajectory are 551 BTU/ft^2-s and 1.51x10^5 BTU/ft^2, respectively. The large heating values for Tempest are attributed to the large entry corridor width concluded from the analysis. Narrowing the corridor with a higher fidelity analysis of the vehicle entry will result in heating values that are more reasonable to lifting entry trajectories. The altitude profile of the relative velocity and convective heat rate are illustrated in Figures 10 and 11, respectively. A summary of the entry trajectory results are provided in Table 3.

Table 2. Required Velocity Calculated by IPREP.

Level	TLI ΔV	LOI/TEI ΔV	Total ΔV
Average	10,203 ft/s	2,635 ft/s	15,463 ft/s
Minimum	10,167 ft/s	2,588 ft/s	15,400 ft/s
Maximum	10,217 ft/s	2,697 ft/s	15,525 ft/s

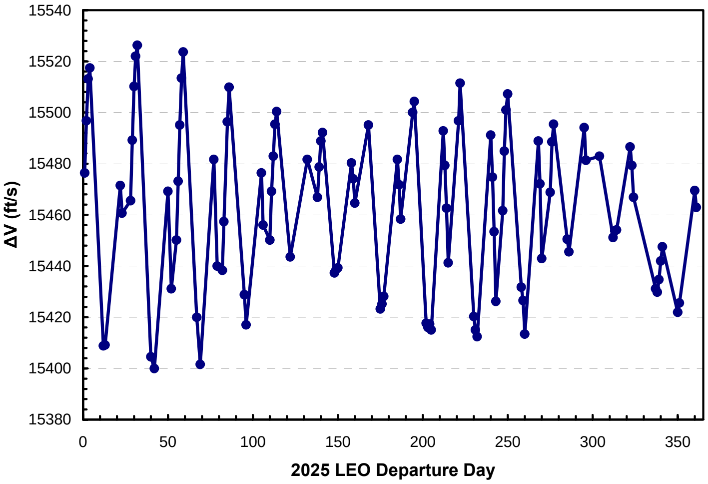


Figure 9. Variation in Total Required Velocity.

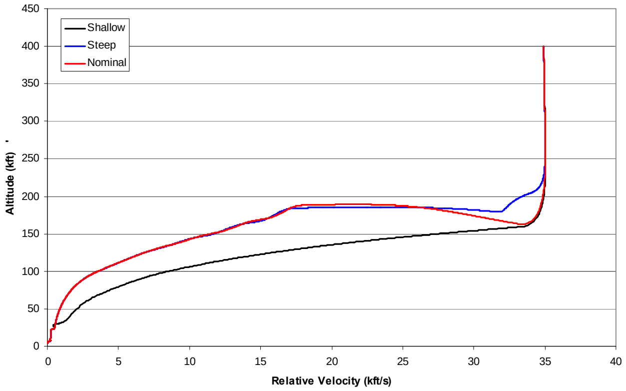


Figure 10. Relative Velocity Altitude Profile.

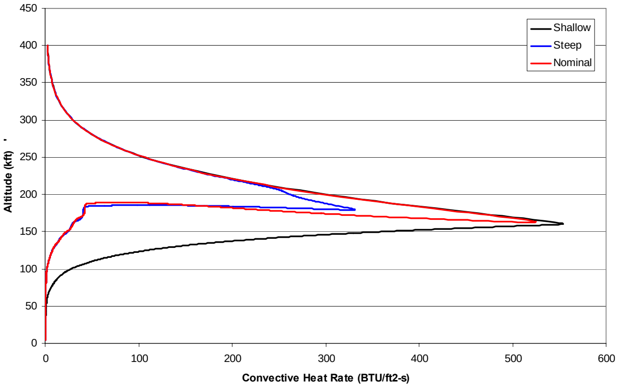


Figure 11. Convective Heat Rate Altitude Profile.

Table 3. Tempest Entry Trajectory Summary.

Entry Speed:	36,090 ft/s
Peak Deceleration:	5 g's
Maximum Crossrange:	2,320 nmi
Downrange:	min: 1,130 nmi max: 10,260 nmi
Corridor Width:	2.26°
Max Peak Convective Heat Rate:	551 BTU/ft^2-s
Max Total Heat Load:	1.51x10^5 BTU/ft^2

The high hypersonic lift-to-drag ratio (L/D) provided by Tempest's airframe shape yields large crossrange and downrange capability during entry. The maximum cross-range distance is 2,320 nmi while the minimum and maximum downrange distance are 1,130 nmi and 10,260 nmi, respectively. These large values form a large landing footprint, which gives Tempest the ability to land at various locations if there are any problems during entry.

E. Recovery

The thermal protection system for Tempest is constructed of AFRSI Blankets that cover the upper surface of the vehicle and a crushable thermal heat shield attached to the lower surface that serves as the primary thermal protection during the atmospheric entry trajectory and impact attenuation for the ground landing. The upper layer of the heat shield composition is a thin layer of fiberglass/foam composite that allows for simple application of the heat shield and provides insulation to the lower surface of the vehicle. The core material of the heat shield is a low density carbon foam with a graphite epoxy honeycomb matrix. The foam provides a lightweight alternative to absorption of energy from impact, and it is currently under development at NASA Langley Research Center for an Earth entry vehicle for Mars sample return.[15] The amount of relative energy absorbed by the foam is determined by the foam thickness. A 2.69-ft foam thickness is sized for the lower surface of Tempest to withstand the impact energy associated with the 5-g landing deceleration determined from the optimized entry trajectory.

The outer surface of the low density foam is covered with an ablator to provide thermal protection. As heat is absorbed during entry, the ablative material vaporizes. Ablative properties of the ablator applied to the foam surface are very similar to Phenolic Impregnated Carbon Ablator (PICA), a lightweight ceramic ablator highly used for planetary entry capsule thermal protection. The thickness of the ablator is sized for the peak heat rate and total heat load determined from the trajectory discipline. A summary of the thermal protection system is provided in Figure 12.

Crushable Heat Shield Characteristics

Foam Thickness:	2.69 ft
Ablative Section Thickness:	0.164 ft
Landing Deceleration:	5 g's
AFRSI Blanket Unit Weight:	1.67 lbs/ft^2
Foam Unit Weight:	0.961 lbs/ft^2
Ablator Unit Weight:	2.147 lbs/ft^2
Heat of Ablation:	1.9x10^8 BTU/lbs

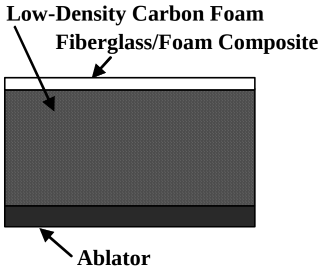


Figure 12. Thermal Protection System Summary.

The terminal landing system consist of a drogue chute to slow down the vehicle after atmospheric entry at high altitudes and five round parachutes to provide a soft ground landing. The TLS is designed to provide a safe landing with a single parachute failure. The diameter of the four main parachutes is sized to provide enough drag force to reduce the descent rate to 24.6 ft/s or 16.77 mph at impact. An additional parachute of the same diameter is added to the TLS to increase the landing reliability of the mission.

Tempest's TLS is derived from current developments of recovery systems for evolved expendable launch vehicles[16] (EELVs) and preliminary sizing relationships for parachute recovery systems that are summarized in a spreadsheet model. The TLS spreadsheet adjusts the diameter and weight of the parachutes to match the drag force necessary to land the vehicle weight at the predetermined descent rate. As the required vehicle landed weight increases the spreadsheet increases the TLS weight by sizing the parachutes to match the new required drag force. The parachutes and landed weight are then iterated on between the recovery and weights disciplines until the design is closed. A summary of the terminal landing system is provided in Table 4.

Table 4. Tempest Terminal Landing System Summary.

# of Parachutes:	5
Chute Diameter:	160.9 ft
Descent Rate:	24.6 ft/s
Drag Coefficient (c_d):	0.55
Total Main Parachute Weight*:	2,875 lbs
Drogue Chute Weight$^+$:	239 lbs

*includes canopy, lines, reefing system; $^+$includes mortar

F. Vehicle Subsystem Sizing

Tempest's on-board avionics, power, and environmental control and life support systems (ECLSS) utilize current subsystem technology for man-rated transport vehicles, such as the Space Shuttle. Each of these subsystems is sized to ensure proper vehicle operation and provide/satisfy resources for all crew needs and activities during the mission.

The ECLSS system manages the nitrogen-oxygen (N2-O2) atmosphere within the 1,130 ft3 vehicle pressurized cabin at a pressure of 1 atm (14.7 psia). The two gas mixture (79% nitrogen, 21% oxygen) maintain the physiological requirements for respiration and perspiration while reducing the risk of a flammable atmosphere. The tanks for the air supply are sized for the 8-day total transit duration and two cabin depressurizations. Since Tempest doesn't posses an airlock, the entire cabin is depressurized before the crew exits to the lunar habitat and pressurized upon the crew's return. One contingency depressurization is also included within the system sizing for emergency extra-vehicular activities (EVAs) during the transit duration.

In addition to atmosphere management, the ECLSS also manages the contaminants removal, water supply, waste, and food provisions. Lithium hydroxide (LiOH) canisters provide air revitalization by chemically absorbing CO2 and trace contaminate from the air. Prepackaged food for the entire mission duration and an initial supply of water are provided and stored prior to launch. During the mission the primary source of water on the vehicle is provided as the products of the H2-O2 fuel cells and stored within the H_2O tank. The total amount of water produced during the entire mission is 183.5 gallons. Due to the shorter mission duration, all solid waste is collected, and stored in canisters for the entire mission. Design and sizing of all ECLSS elements are based upon historical data and NASA estimates of crew support systems for lunar missions[7] and summarized in a MS Excel worksheet.

Though the PPM serves as the primary power generation for Tempest, an additional on-board power system is required to provide power for the CEV during phases of the mission where it is not connected to the PPM, such as docking, crew excursion, and entry. About 30% of the mission power requirements are supplied by Tempest's H2-O2 fuel cells, which are built upon the same fuel cell technology used on the Space Shuttle. In addition to fuel cells, Tempest also utilizes lithium ion (Li-Ion) batteries to sustain power during dormant vehicle operation while on the lunar surface and in the case of primary power source failure. A summary of the power system is provided in Table 5.

Tempest utilizes redundant and lightweight avionics and communications systems. Avionics subsystems considered for Tempest consisted of the following: navigation and guidance, communications, data storage and processing, vehicle health and monitoring, and crew interface (displays, interfaces, crew input). The avionics subsystems were sized using two avionic conceptual estimation tools: Spaceworks Engineering's SESAW[17] and NASA JSC's MASS. SESAW and MASS are conceptual design sizing and mass estimation tools which predict the avionics subsystem weight based upon vehicle parameters along with mission inputs and timeframe. At least double redundancy is included in the sizing of every subsystem. A summary of the avionics is provided in Table 6.

Table 5. Tempest Power System Summary.

Power Subsystem	*Mass/Value*
# of Fuel Cells	2
Fuel Cell Mass	401 lbs
Batteries Mass	259 lbs
PMAD Mass	147 lbs
Mass of Power O2 Consumable	425 lbs
Mass of Power H2 Consumable	54 lbs

Table 6. Tempest Avionics Subsystem Summary.

Avionics Subsystem	*Mass*
Navigation and Guidance	192 lbs
Communications	43 lbs
Data Storage and Processing	285 lbs
Vehicle Health and Monitoring	295 lbs
Wiring	441 lbs
Crew Interface	330 lbs

G. Mass Properties

Mass properties for Tempest were computed from parametric MERs and system calculations for the primary subsystems of the vehicle. The vehicle weights are broken down into a 28 category, 7 level weight breakdown structure (WBS). The MERs and system calculations are parametric equations that take in some related sizing, performance, and/or mission input(s) and compute the weight of the component. The series of MERs and system calculations for each primary subsystem are summarized and internally closed in an MS Excel workbook. Each dry weight component includes a 20% growth margin to take into account the likelihood of weight increases as the design matures. Table 7 provides summary items from the full WBS for the vehicle. The full WBS is not included in this paper for brevity.

Table 7. Tempest Mass Summary.

Dry CEV		**Gross Stack**	
WBS Item	*Mass*	*WBS Item*	*Mass*
Airframe	9,606.6 lbs	Dry Mass	23,730.1 lbs
TPS	2,407.9 lbs	Crew & Gear	3,318.0 lbs
Propulsion (RCS)	60.4 lbs	Cargo	500.0 lbs
Primary Power	659.8 lbs	Consumables	1,680.4 lbs
Electrical Conversion & Distribution	147.5 lbs	Propellants	297.6 lbs
Surface Control and Actuators	193.1 lbs	HEDM	90.6 lbs
Avionics	1,379.7 lbs	LOX	207.0 lbs
ECLSS	1,670.9 lbs	PPM Dry Mass	10,103.8 lbs
Personnel Equipment	408.5 lbs	PPM Propellants	13,675.6 lbs
Recovery & Auxiliary	3,240.8 lbs	HEDM	4,377.9 lbs
Margin	3,955.1 lbs	LOX	9,297.7 lbs
Dry Mass	**23,730.1 lbs**	Crew Escape System (CES)	6,737.4 lbs
		Gross Mass (with PPM/CES)	**60,730.6 lbs**

As seen in Table 7, the gross weight of the Tempest CEV is 29,526 lbs, with a total dry weight of 23,730 lbs. The total gross mass of Tempest with the PPM and CES is 60,731 lbs. The gross mass of the total system (CEV/CES/PPM) is well under the 92,594 lbs limit of the C-1 HLLV to the initial orbit. The vehicle length is 32 ft from nose to end of morphable cone.

H. Ground Operations

The Tempest CEV is designed to be a highly reusable crew transportation system. Ground operations analysis is conducted using the Architectural Assessment Tool – enhanced (AATe) developed by NASA KSC. AATe assess all of the elements for the Tempest CEV concept for its operational impacts, which are primarily recurring costs and ground cycle times.[8] The time spent at each facility is predicted by AATe from quantitative inputs and qualitative order of magnitude comparisons of Tempest to the Space Shuttle. Quantitative inputs include overall vehicle reliability, orbital duration, dry weight, and vehicle dimensions. Outputs include ground cycle time, facilities cost, labor costs, and LRU costs.

Tempest utilizes various technologies and techniques to reduce cycle time and operating costs. Tempest is equipped with integrated vehicle health monitoring systems that prevent subsystem operation failure through early detection of problematic symptoms, which require less inspection. LOX/HEDM propellant combination is used for the RCS engines to avoid the handling concerns with hypergolic propellants and toxic fluids. Easy access and a minimal number of propellant tanks within the CEV and PPM reduces the time required for maintenance and refueling.

Launch operations for Tempest are assumed to take place at KSC while the landing operations are managed on-site at UTTR. A mobile station is required for immediate vehicle post flight checkout after landing due to the lack of facilities available to NASA on the test range. Tempest is transported from the landing site to KSC via NASA's Super Guppy transport aircraft. After arrival at KSC, vehicle processing for turnaround takes place in one of the three orbiter processing facilities (OPFs). Assembly and integration of Tempest, PPM, and C-1 occur in the Vehicle Assembly Building (VAB) so that the vehicle has the shortest pad time possible. The total CEV specific turnaround time, from landing to launch, takes approximately 22 days. The entire processing schedule is displayed in Figure 13.

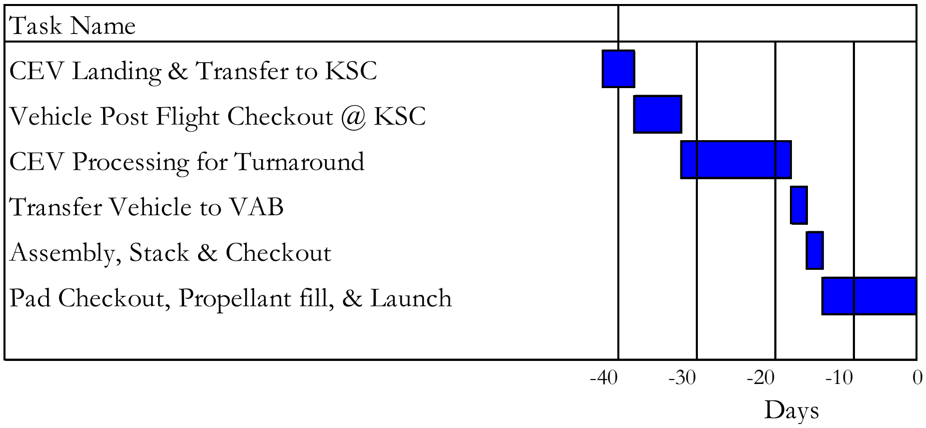
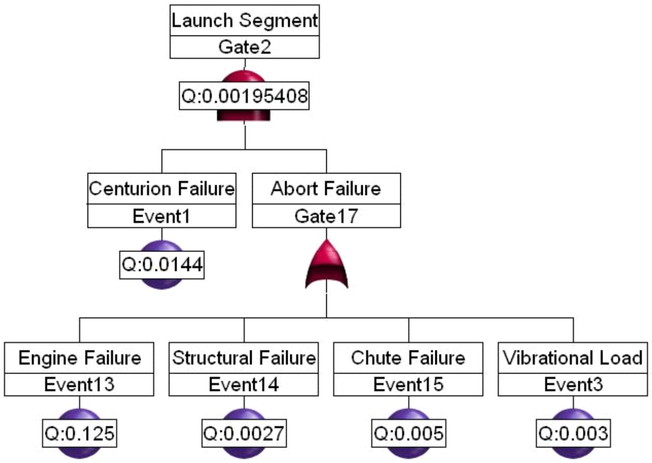


Figure 13. Tempest Processing Schedule.

I. Safety & Reliability

All elements of the Tempest crew transportation concept are designed to be highly safe and reliable. Tempest's safety and reliability analysis was conducted using Relex[9], a fault tree analysis software. The reliability of each subsystem for each segment of the mission serves as input into the program and the output is the resulting reliability of the entire system. This reliability analysis involves all elements of the lunar mission architecture, including C-1, Manticore, PPM, and Artemis. The reliability for Centurion[2], Manticore, and Artemis[3] are already determined and serve as inputs into Relex, while assumptions are made for the reliability of the CEV and PPM. For this analysis, a range of failure rates for each mission phase are assumed. The results of the Relex are included as Figure 14.



Assumptions

Mission Phases	*Failures/Flights*
Launch	1/265 – 1/510
Abort	1/4 – 1/8
Cis-Lunar	1/55 – 1/200
Entry	1/100 – 1/200
Landing	1/200 – 1/500

Results*

Parameter	*Failures/Flights*
Loss of Mission (LOM)	1/20 – 1/50
Loss of Crew (LOC)	1/35 – 1/80
Loss of Vehicle (LOV)	1/35 – 1/80

**Results very dependant upon other element assumptions*

Figure 14. Tempest Reliability Analysis with Relex.

Results of the analysis show that the overall reliability for loss of crew and loss of vehicle ranges from one failure in 35 flights (0.971 reliability) to one failure in 80 flights (0.9875 reliability). The additions of the abort system and parachute-out capability improve the reliability of the launch and entry mission phases respectively, but the low reliability of the Cis-Lunar phase reduces the overall reliability tremendously. The drivers for the Cis-Lunar reliability are the multiple in-space rendezvous and potential operation failures with Manticore, PPM, and Artemis. The mission primary propulsive capability is provided by the PPM and Manticore. Rendezvous failure results in the loss of mission (LOM), but the CEV has the capability to return to Earth from LEO and descend upon the Artemis lander to the lunar surface. Operation failure of Manticore during the TLI burn and PPM during the TEI burn can place the CEV into a high orbital trajectory around Earth. Failure of Artemis during ascent/descent can result in being stranded in LLO or landing failure.

The resulting overall mission reliability is not reflective of the reliability of the CEV. The launch and landing phases of the mission have high reliability due to the abort and parachute-out capability of the CEV.

J. Cost and Economics

Cost estimation for the development and production cost of the Tempest CEV concept is calculated using the NASA-Air Force Cost Model (NAFCOM-99) and data from the TRANSCOST[10] model. These models contain a set of subsystem cost estimating relationships (CERs) for vehicle component groups and also include programming cost estimation for systems test hardware, integration, assembly & checkout, system test operations, ground support equipment, systems engineering & integration, and program management.[18] Operation costs estimation is computed by AATe. These costs include facilities cost, labor costs, and line replacement unit (LRU) costs.[18] A summary of the design, development, testing, and evaluation (DDT&E) costs along with production costs for each segment of the Tempest concept is included in Table 8 (all values are presented in FY 2004 dollars).

Cost analysis of the CEV and PPM was conducted with NAFCOM-99 while the CES was conducted using TRANSCOST. Though many of the CEV subsystems are based on current space habitat technology, the development of the crushable thermal heat shield and morphable body flap/surface for the vehicle airframe are the drivers for its high DDT&E value. The discrepancy in development costs between the CEV and PPM/CES is that the CEV is the only reusable element within the architecture. An inflation rate of 2.1% is used for this economic analysis. A cost margin of 20% of the total vehicle costs is also included in the cost estimation to account for unexpected costs increase during development and production.

Facilities acquisition for CEV integration facility and VAB modifications will be approximately one billion dollars, while ground support equipment unique to the Tempest CEV mission will cost close to $300 M.

Table 8. Tempest Non-Recurring Cost Summary

Item	*Costs*
DDT&E – CEV	$2,859 M
DDT&E – PPM	$573 M
DDT&E – CES	$207 M
Total DDT&E	**$3,639 M**
TFU – CEV	$479 M
TFU – PPM	$61.6 M
TFU – CES	$3.6 M
Total TFU	**$544.2 M**
Facilities/GSE Acquisition	$1,300 M
Total for First Vehicle	**$5,483 M**

As seen in Table 8, the total cost from the start of the program until acquisition of the first vehicle is $5.48 B. This cost is divided into $1.3 B for facilities/GSE acquisition, $3.64 B for DDT&E, and $544.2 M for production of the theoretical first units (TFU). There will be a total of 3 CEVs produced for a total CEV lifetime production cost of $1.257 B.

The program starts in 2018 with initial operating capability (IOC) in 2025. The recurring costs are calculated based upon the steady state flight rate of 12 flights per year with also considering the maximum steady flight rate of Centurion, which is 6 flights per year.[2] Recurring costs include labor and materials costs required to sustain and operate the vehicle along with propellant costs.[18] Labor costs involve the cost of employing people to work on a variety of vehicle operations including vehicle processing, launch and landing, integration, support, logistics, and management.[8] Materials costs include the cost required for routine replacement of vehicle components or LRUs.[18] Propellant costs are calculated for the four main propellants used on the CEV and PPM: hydrogen, oxygen, nitrogen, and quadricyclane (HEDM). Recurring cost for the CEV, PPM, and CES are summarized in Table 9. Including all of these items, Tempest's total recurring costs per flight is $55.83 M.

Table 9. Tempest Recurring Cost Summary

Item	*Value*
Fixed Ground Operations Cost Per Year	$348 M
Variable Ground Operations Cost Per Flight	$19 M
Fixed Flight Operations Cost Per Year	$34 M
Variable Flight Operations Cost Per Flight	$5.0 M
PPM Average Production Costs	$43.8 M / unit
CES Average Production Costs	$2.5 M / unit
Total Recurring Cost Per Flight	**$55.83 M**

V. Trade Studies

After the completion of the baseline design for Tempest, trade studies were conducted. A sensitivity assessment was preformed on the effects of the unit volume on the vehicle dry weight and DDT&E. The assessment involved the variation of the crew cabin comfort accommodations level from comfortable to cramped and spacious conditions. Changing the cabin comfort level would result in a change in the vehicle physical size and dry weight due to the variation in the total pressurized unit volume. Because the development and production costs are based on vehicle subsystem component weight, the trend in the vehicle dry weight is also reflected in the vehicle DDT&E.

As mentioned earlier in the paper, the required total pressurized unit volume for a person to be comfortable and be able to successfully perform their required duties with minimum impairment for a 4 day mission is 282 ft^3/person. Cramped conditions refer to a notable impairment in the crew's ability to perform their required task due to lack of habitable volume, whereas spacious conditions means that the crew has no impairment in performance because of the large habitable volume provided. The total pressurized unit volume for cramped and spacious conditions are 141 ft^3/person and 353 ft^3/person, respectively. Since the unit volume value for the spacious condition can be infinitely large, the lower bound volume is used to allow for a more comparable trade study.

A summary of the variation in dry weight and DDT&E due to the pressurized unit volume is provided in Figure 15. As the cabin conditions increase from cramped to spacious the dry weight and DDT&E of the vehicle also increases. The cramped condition version of Tempest is 2.01 meters shorter than the baseline version, and the spacious version is 0.753 meter longer. The increase in vehicle dry weight is reflective of the increase in the physical size of the crew cabin and airframe due to the change in unit volume, as well as the larger subsystems required to support the crew in the larger volume for the mission duration. Because the development and production costs are based on vehicle subsystem component weight, the increasing trend in the vehicle dry weight is also reflected in the vehicle DDT&E.

By exploring the variations in the crew cabin comfort conditions, the Tempest CEV concept can be considered for missions that require shorter/longer durations or extra storage space. Using a CEV that is sized for cramped conditions may be useful for a shorter duration mission that does not require the crew to perform many task while a spacious condition may be necessary to provide crewman with adequate space for longer duration missions. The results of the trade study show that the variation in the crew cabin volume largely affects the vehicle weight and costs.

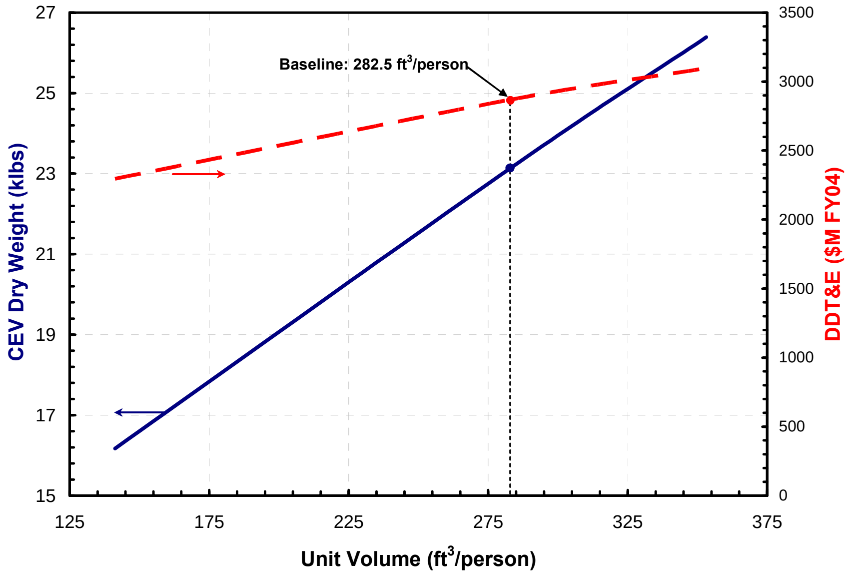


Figure 15. Sensitivity Assessment of Tempest Crew Cabin Unit Volume

VI. Conclusion

Tempest is a post-2025 fully reusable CEV concept designed for transferring crew from Earth to the lunar surface and back. Tempest serves as a crew transfer module that supports a 4-person crew for a mission duration of 18 days, which consists of 8 days total transit duration and 10-day surface duration. Tempest also serves as the descent/ascent habitat from lunar orbit to the lunar surface. The Tempest pressurized crew cabin provides a large habitable volume that accommodates mission task and personal needs of the crew with minimum impairment throughout the transit duration. Tempest utilizes heritage technologies for human space transportation in addition to advanced propulsion and thermal protection technologies that reduce the vehicle weight and system complexity.

The dependence of Tempest on the Spiral 3 lunar infrastructure and other architecture elements to complete the mission reduces vehicle weight along with launch/landing ground operations. The low vehicle turn around time allows for maximum usage of the vehicle. With the CES abort and TLS chute-out capabilities, the reliability of the vehicle during launch and landing is increased vastly in comparison to modern crew space transportation. Though the CEV possesses a high reliability by itself, its reliability with respect to the mission and crew survivability is highly dependent upon the performance and reliability of the other architecture elements.

The economic results for Tempest indicate that the initial investment will be over $5 B dollars, which is largely due to the development of the crushable heat shield and morphable body flap/tail surface. Based on the assumed flight rate, the total recurring cost is about $56 M for each flight. These recurring costs can be further reduced with an increase in annual flight rate, but with this architecture the flight rate is solely dependent upon the flight rate of the Centurion C-1.

The pressurized volume of the crew cabin largely affects the vehicle weight and development costs. Variation of the crew cabin comfort accommodations results in a change in the vehicle physical size and dry weight, along with development and production costs. The design of the Tempest CEV concept has been optimized to perform the lunar mission using the prescribed architecture. Smaller volume conditions decrease the vehicle costs, but also reduce the crew performance capability during the mission. Larger volume conditions condense the impairment on the crew's performance and comfort, but can also potentially increase the CEV/PPM/CES launch stack mass beyond payload capability of the C-1 HLLV and Artemis lunar lander.

Acknowledgments

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