Atlas Centaur Extensibility to Long-Duration In-Space Applications

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Lockheed Martin is pursuing Centaur derivatives that will provide a common-stage supporting launch vehicle, upper-stage-applications, and the in-space/ascent/descent long-duration needs. Lockheed Martin's common-stage concept would provide efficient, robust in-space transportation, and take advantage of the high-mass fraction that is enabled by Centaur's moncoque design and its common bulkhead to minimize combined LO_2/LH_2 boil off. Lunar exploration missions that take advantage of the high Specific Impulse (sec) (ISP) of LO_2/LH_2 propulsion for in-space transportation have initial mass-to-orbit launch requirements less than half of those using traditional storable propulsion stages. Therefore, the application of long-duration LO_2/LH_2 in-space propulsion technology will result in significant launch cost savings for space exploration. We would achieve passive long-duration capability by implementing cross cutting Cryogenic Operation for Long Duration (COLD) technologies, and improve cryogenic storage capability by more than two orders of magnitude compared to existing large-scale flight-proven systems. Using a common stage for launch-vehicle upper stage and in-space operations reduces development and recurring costs while providing the high-flight rate needed to achieve the demonstrated high reliability required for crewed space exploration.

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Acronyms

CATS	Centaur Aft Thrust Structure
CEV	Crew Exploration Vehicle
COLD	Cryogenic Operation for Long Duration
EDS	Earth Departure Stage
g	Earth's Gravity
GSO	Geo-Stationary Orbit
GTO	Geosynchronous Transfer Orbit
ICES	Integrated Cryogenic Evolved Stage
IMLEO	Initial Mass in Low Earth Orbit
ISP	Specific Impulse (sec)
ISRU	In situ Resource Utilization
LAD	Liquid Acquisition Device
LEO	Low Earth Orbit
LOI	Lunar Orbit Insertion
LSAM	Lunar Surface Ascent Module
MF	Mass Fraction
M_f	Final Mass
M_i	Initial Mass
MLI	Multi Layer Insulation
MPK	Mission Peculiar Kit
M_s	Stage Mass
M_{pl}	Payload Mass
M_{prop}	Propellant Mass
PMD	Propellant Management Device
PPMS	Propellant Positional Management System
SM	Service Module
SS	Sun Shield
TEI	Trans Earth Injection
VCP	Vapor Cooled Point
VDMLI	Variable Density Multilayer Insulation
VIP	Vacuum Insulation Panels
VJ	Vacuum Jacket
ΔV	Change in Velocity

I. Space Exploration Transportation Requirements

Exploration of the Moon, Mars, and beyond will require multiple in-space transportation components. The Apollo program used the following five distinct in-space stages to send humans to the moon, (fig. 1).

1) Saturn S2 (upper stage)
2) Saturn S4B (Earth Departure Stage)
3) Service Module (lunar Orbit insertion)
4) Lunar descent module
5) Lunar ascent module
6) Service module (Trans Earth injection).

Each of these stages was unique, requiring its own development, support, and infrastructure. Uniquely designed to support the Apollo mission, none of these stages were suited to support other missions, such as Earth to orbit, or mid-latitude lunar exploration; let alone missions to Mars.

Over the course of the Apollo program's seven lunar missions, a total of approximately 10 to 20 of each of the stages were built, including development launches. Developing the large infrastructure required for each of the stages, and supporting this extremely limited production run resulted in exceedingly high-unit costs.

A. Sustainable Exploration Requires a Common In-Space Transportation Approach

For the present Space Exploration program to be sustainable and extensible[8] to NASA's exploration goals, NASA must diverge from Apollo's dedicated mission-specific design approach. A robust exploration program requires a transportation system that is flexible enough to accommodate wide-ranging mission requirements.

A common in-space transportation stage that can fulfill most, if not all of the exploration mission needs, (fig. 2), will significantly reduce the cost of exploration. Developing a single, common-exploration stage reduces the required near-term investment by eliminating five of the potential six-stage development programs. At the cost of more than $1 billion per stage development, this common stage has the opportunity to reduce NASA's near-term transportation investment by many billions of dollars. This will enable NASA to dedicate more investment on the unique, lunar science and exploration aspects of the nation's vision.

Commonality of the in-space stage with the upper stage of a launch vehicle launching other NASA, DoD, and commercial payloads can result in stage-production rates of approximately 25 units per year, (fig. 3). This high-production rate provides for efficient low-cost production, and allows the fixed costs to be spread across numerous users, thus benefiting the entire user community. This large user base also provides NASA the flexibility to accommodate changing priorities without being anchored to a NASA-only transportation system that may not meet changing mission priorities.

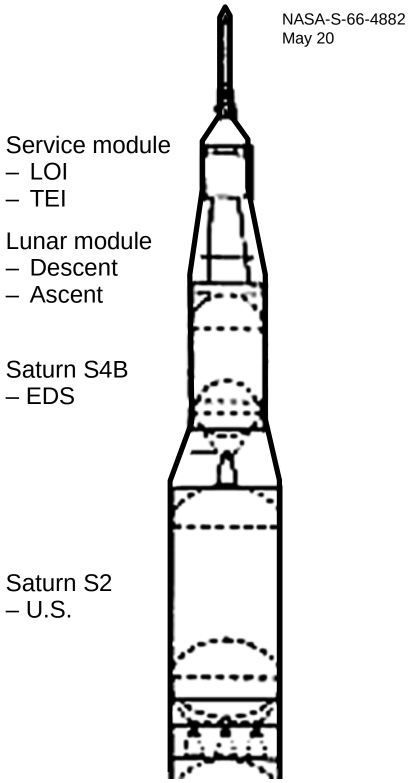

Figure 1. The Apollo program required six distinct transportation elements to send humans to the Moon. Credit: NASA

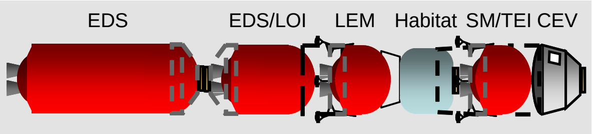

Figure 2. Common propulsion stage elements support all lunar exploration requirements.

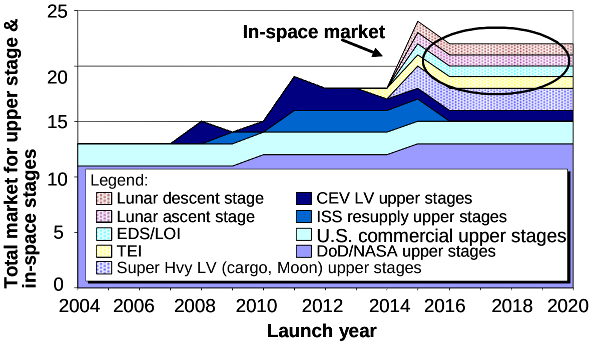

Figure 3. The combined stage market results in a high-production rate.

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[8] President Bush's stated objective of the Space Exploration mission is to be both sustainable and extensible.

Just as important, commonality provides the large-flight rate required to provide demonstrated reliability, (fig. 4), allowing NASA to not rely on questionable analytical reliability calculations. All flights, exploration or other, will provide further insight into this common stage that allows continuous improvement, increasing mission capability, and reliability.

B. LO_2/LH_2 Propulsion Enables Efficient, Sustainable Space Exploration

It is useful to examine the relationship between propellant, payload, stage mass, and Isp as given by the rocket equation, Reference 1:

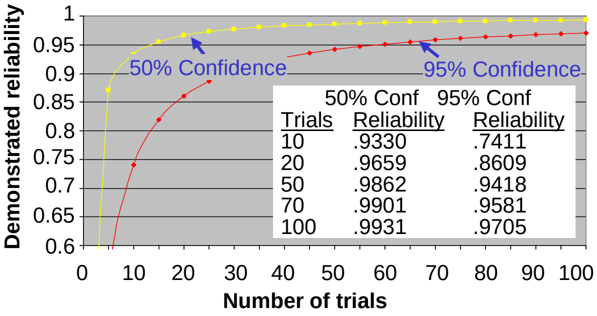

Figure 4. Achieving flight-demonstrated reliability requires a large number of missions.

$$\Delta V = g \, Isp \ln ((M_s + M_{pl} + M_{prop}) / (M_s + M_{pl}))$$

or

$$(M_s + M_{pl}) + M_{prop} = (M_s + M_{pl}) \, e^{(\Delta V/(g^* Isp))} \qquad (1)$$

As indicated in reference 1, this equation shows payload sensitivity to changes in Isp. This equation shows that Isp has a significant nonlinear impact on system payload capability. Not as obvious is that the stage mass also grows with decreasing Isp due to the required increase in propellant load, (fig. 5).

Indeed, Lockheed Martin's analysis indicates that the currently envisioned lunar-exploration missions using heritage storable propulsion systems (Isp~320 sec) require more than 250 metric tons (mT) initial mass in Low Earth Orbit (LEO). This same analysis shows high Isp (~460 sec) LO_2/LH_2 propulsion reduces initial mass to LEO by more than 45% to around 140 mT, (fig. 6), for the same mission capability. This mass reduction reduces the Earth-to-orbit launch cost by more than $1 billion per lunar mission. The efficiency offered by LO_2/LH_2 propulsion offers even greater savings for Mars and outer planet missions.

To realize the benefits enabled through the use of high Isp LO_2/LH_2 propulsion one must be able to efficiently store the cryogens for long durations. The required storage duration is driven by a combination of the planned mission duration and for multilaunch missions, the time required to assemble the mission components in orbit. Although multiple launches can be accomplished in weeks, delays for weather, anomalies, or failures could easily require many months of on-orbit storage in addition to the actual mission duration.

The short-duration lunar exploration missions envisioned in spiral 2 (~two weeks on lunar surface) could easily require cryogenic storage durations of three to six months, (fig. 7). Based on boil-off losses and mission performance partials, spiral 2 mission requirements can

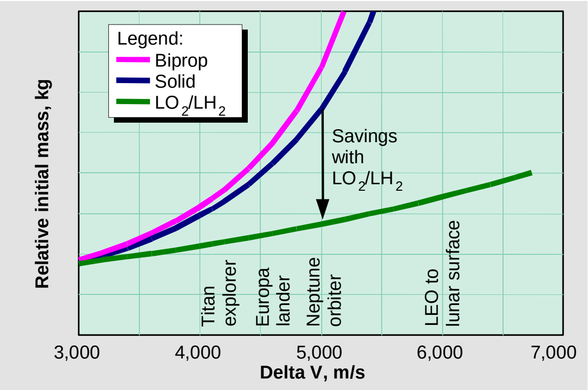

Figure 5. LO_2/LH_2 propulsion can support high-energy missions for which storable propulsion is not practical.

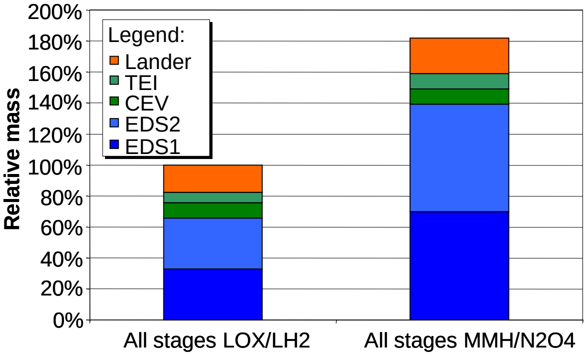

Figure 6. The use of LO_2/LH_2 propulsion for the entire lunar exploration mission provides a ~45% reduction in IMLEO relative to storable systems.

efficiently be accommodated with a combined LO_2/LH_2 boil-off rate of less than ~0.05%/day, (fig. 8). For the long-duration lunar exploration of spiral 3 that consists of multiple months on the lunar surface, cryogenic storage of up to one year may be required. This mission duration drives required boil-off rates down to ~ 0.02%/day for passive-cryo storage.

As discussed above, to truly benefit from the high Isp of LO_2/LH_2, the cryo stage must be mass efficient. This mass consists of the large tanks required for LH_2 storage, the thermal insulation, power and radiator (for active cooling), and boil-off mass. The existing Centaur provides the highest mass fraction of any LO_2/LH_2 stage, (fig. 9), and provides an ideal point-of-departure for any future long-duration LO_2/LH_2 stage.

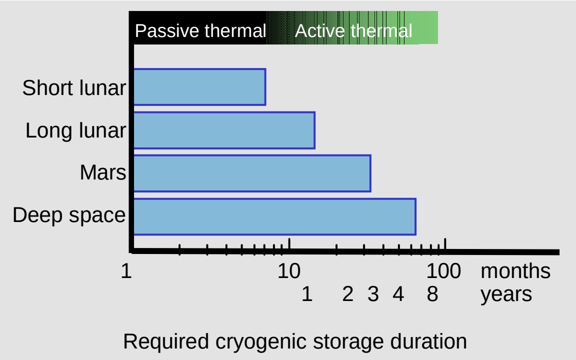

Figure 7. Near-term exploration requirements are satisfied with passive cryo storage that is enabled by the COLD technologies.

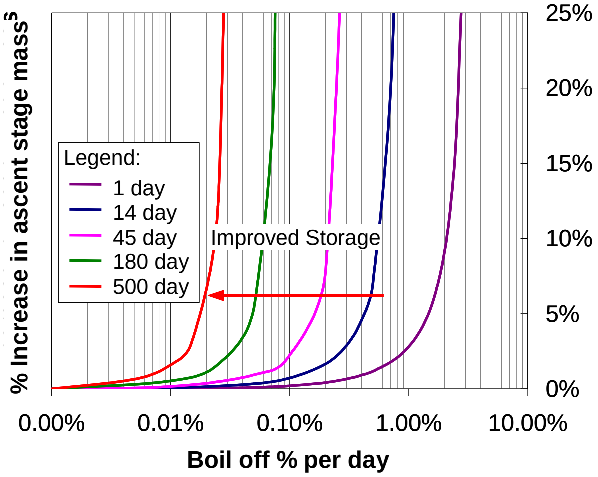

Figure 8. The required passive boil-off rate depends on the mission-duration requirement.

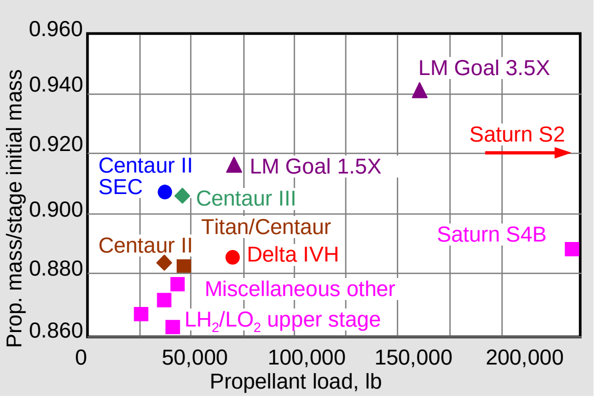

Figure 9. Centaur's unique monocoque, common bulkhead design provides the most efficient LO_2/LH_2 stage available.

II. Centaur Provides a History To Develop an Integrated Cryogenic Stage

Centaur provides an ideal foundation to evolve future in-space high-energy stages. The Centaur upper stage has been the mainstay for high-energy missions for over four decades, (fig. 10). Overall, there have been 159 successful Centaur missions—including such notable exploration missions as Mariner, Viking, Voyager, Cassini, and SOHO.

The key to successful usage of the high-energy LO_2/LH_2 propellants for upper stages is cryogenic propellant management, especially for missions requiring long-coast durations between burns, and multiple-burn missions. Fundamental to flying these missions is a thorough understanding of the nonequilibrium cryogenic thermodynamics and low- and zero-gravity behavior. Centaur is the only cryogenic stage that has repeatedly demonstrated this long-coast capability, both with 10-foot and 14-foot diameter configurations. LH_2 and LO_2 both have unique behaviors in low gravity, and a detailed understanding of the complex interaction of the fluid dynamics of the propellant on the tank thermodynamics is required for system-thermal management. Pressure control during the coast is critical to minimize vented-propellant, efficient use of the reaction control propellant, and to ensure that the engine conditions are met for each burn. Through regular flights, the Centaur team has accumulated more in-space LO_2/LH_2 flight experience than anyone else worldwide, (fig. 11).

Achieving the reliability, affordability, and cryo storage goals requires a synthesis of system design and technology maturation. Lockheed Martin's unique Centaur upper-stage integrated thermal/structural design approach has demonstrated the highest mass fraction in the world at commercially competitive prices. Lockheed Martin will leverage extensive cryogenic systems expertise to develop an integrated solution for long-duration storage of cryogens in direct support of NASA's goal to develop an affordable, reliable, and highly efficient cryogenic propulsion system. The existing Centaur also offers the unique potential for in-flight technology demonstrations (nominally, six flights/year) that provide a low-risk

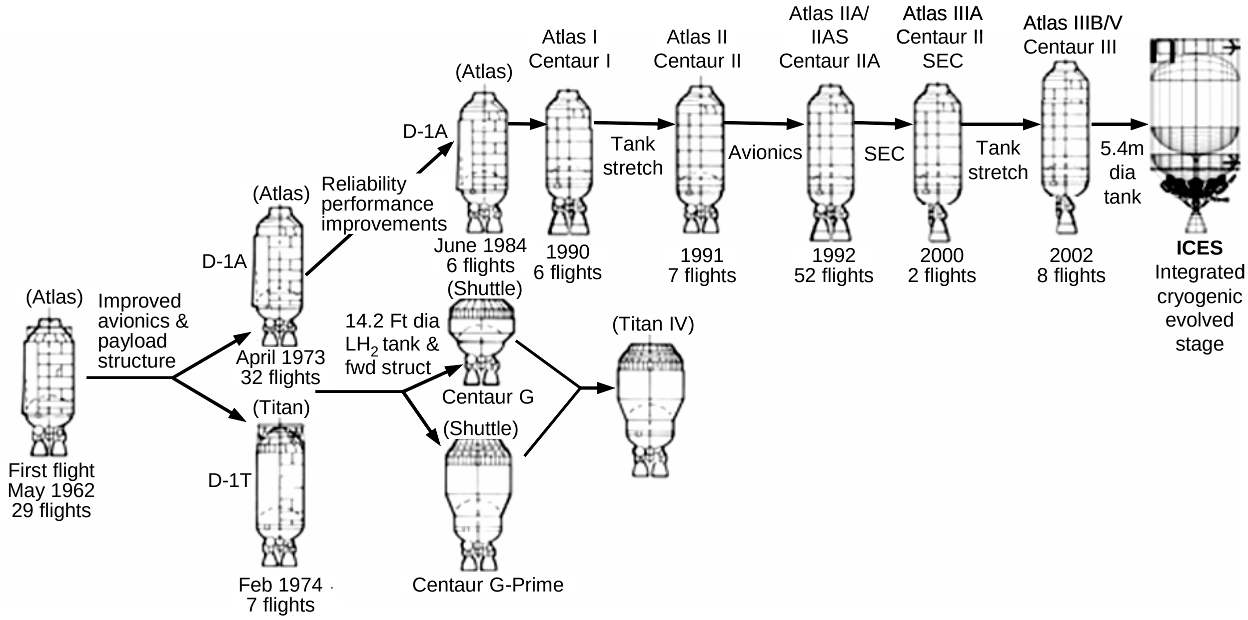

Figure 10. Centaur's 40+ year history provides a successful, solid foundation to build the Space Exploration's Common In-Space Transportation Stage.

evolutionary approach to long-duration missions.

For the Centaur program, the understanding of the detailed thermodynamics involved with LO_2/LH_2 management began with several full-duration firing tests in NASA's Plumbrook vacuum chamber in the early 1970s. For these tests, arrays of specially designed temperature sensors were installed inside the liquid hydrogen tank. This allowed that the extent of stratification near the liquid-vapor interface could be properly characterized while realizing that a miss prediction would result in either excessive pressurant usage, or dropping below the minimum net positive-suction pressure required by the RL10 engine. These data were further anchored to flight when two Centaurs were flown during the mid-1970s with this same complement of internal temperature sensors. One of these Centaurs demonstrated seven burns, including one that occurred following a 5.25-hour coast. These missions provided critical data that are still used today to assess the nonequilibrium conditions that exist during the mission. Centaur continues this learning tradition by regularly flying additional instrumentation and unique sequences to provide a continuous, evolutionary learning environment of the complex thermodynamic inter play of LO_2 and LH_2 in the space environment. Many of the phenomena that occur during the low-G periods still elude classical equilibrium thermodynamic modeling. Thus, semi-empirical models anchored to the Plumbrook testing, the fully instrumented missions of the 1970s, and updated with the large amount of recurring flight data and the multitude of recent flight demonstrations are critical to continued successful flight.

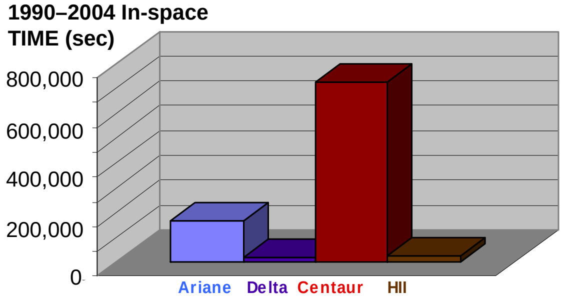

Figure 11. Centaur's long history, high-flight rate, and long-mission capability results in unparalleled cryo-fluid management experience for the existing Centaur team.

III. Integrated Common Evolved Stage (ICES) Enables Sustainable, Extensible Transportation for Space Exploration

To satisfy NASA's exploration needs for a cross cutting, extensible LO_2/LH_2 stage, Lockheed Martin is developing the Integrated Common Evolved Stage (ICES), (fig. 12). The ICES is designed to provide an efficient, common platform that is extensible to all transportation aspects of the exploration mission. The ICES is specifically designed to cross cut to nonexploration applications, and to provide improved support for existing NASA, DoD, and commercial launch requirements.

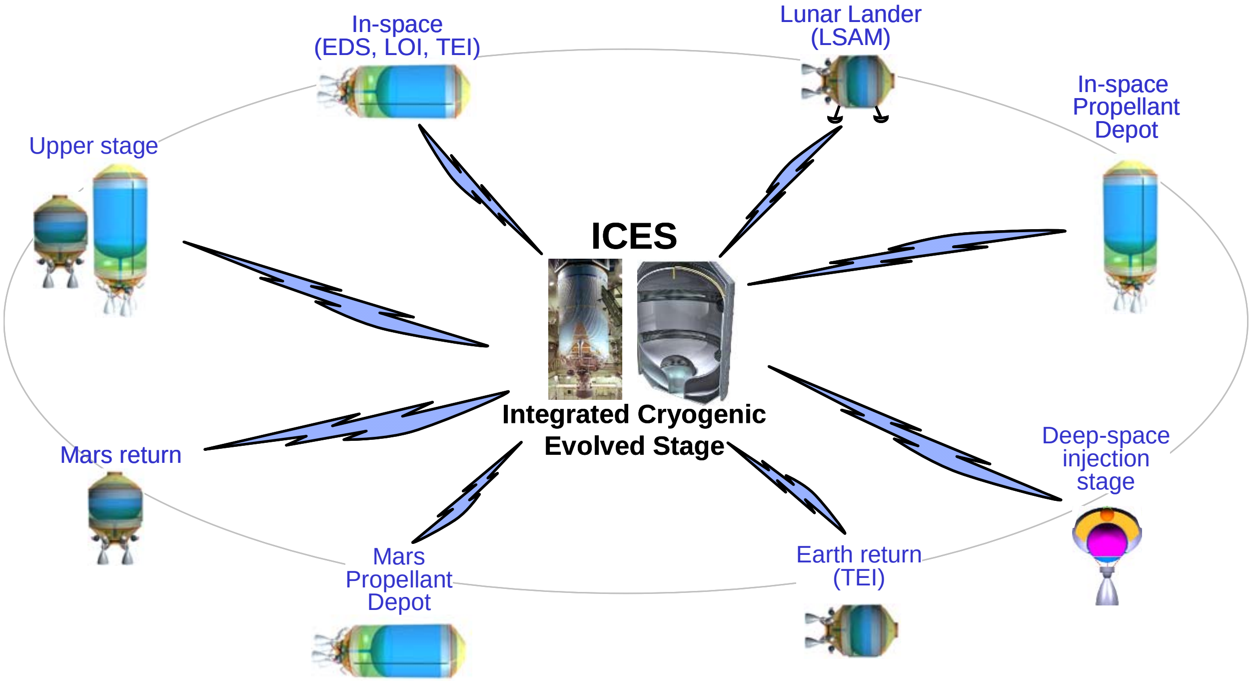

Figure 12. ICES is a flexible, modular in-space stage capable of supporting all of the lunar exploration transportation needs while being extensible to Mars and beyond.

The ICES concept will enable NASA to meet the strategic technical challenges that support a sustainable exploration program. Cross-program commonality is the key to enable a robust, reliable, and sustainable exploration program. Commonality spreads the nonrecurring and infrastructure costs between multiple users to reduce the cost for everyone.

The ICES development is planned as the first phase of any future Atlas evolution and is composed of a larger volume Centaur. This is achieved through significantly increasing stage diameter while maintaining successful Centaur heritage design concepts. The ICES is intended to become the foundation for a modular system of stages to satisfy a wide variety of uses for space exploration from upper stages to in-space stages to propellant depots. The ICES places the tremendous efficiencies of cryogenic propellants into the hands of the Moon and Mars mission architects. This allows a significant reduction in launch mass relative to Saturn, which primarily relied on the much lower efficiency of storable propellants.

The ICES is based on a simple modular design as shown in fig. 13. Common domes are joined to barrel panels through the friction-stir welding process. The barrel panels come in multiple segments that allow stages of variable propellant capacity. The common-thrust structure accommodates either 1, 2, 4, or 6 RL-10 engines. The longer ICES versions with four or six engines are suitable for upper stage and Earth-departure stage (EDS) applications that carry very heavy payloads. Shorter ICES versions with one or two engines would be used for traditional Geosynchronous Transfer Orbit (GTO) missions, interplanetary missions, or in-space stages such as lunar orbit insertion (LOI), trans-earth injection (TEI), or lunar descent stage.

ICES will take advantage of the existing Centaur subsystems such as avionics, pneumatic, and propulsion elements. The majority of these subsystems are directly applicable with little or no changes required. The primary hurdle to enabling long duration for ICES is cryo-fluid management.

IV. Cryogenic Fluid Management Is the Key to Enabling ICES

The ICES design is optimized with long-duration cryogenic applications in mind. A number of passive-thermal management features have been incorporated into the stage at the system level, (fig. 14). The tank geometry is designed to minimize the exposed surface area. The number of conduction paths into the tank has been minimized by placing all propulsion and avionics hardware onto the thermally isolated Centaur aft thrust structure (CATS). Vapor-cooling paths, where vented hydrogen is used to intercept the remaining high-load heat paths, are integrated into the tank structure.

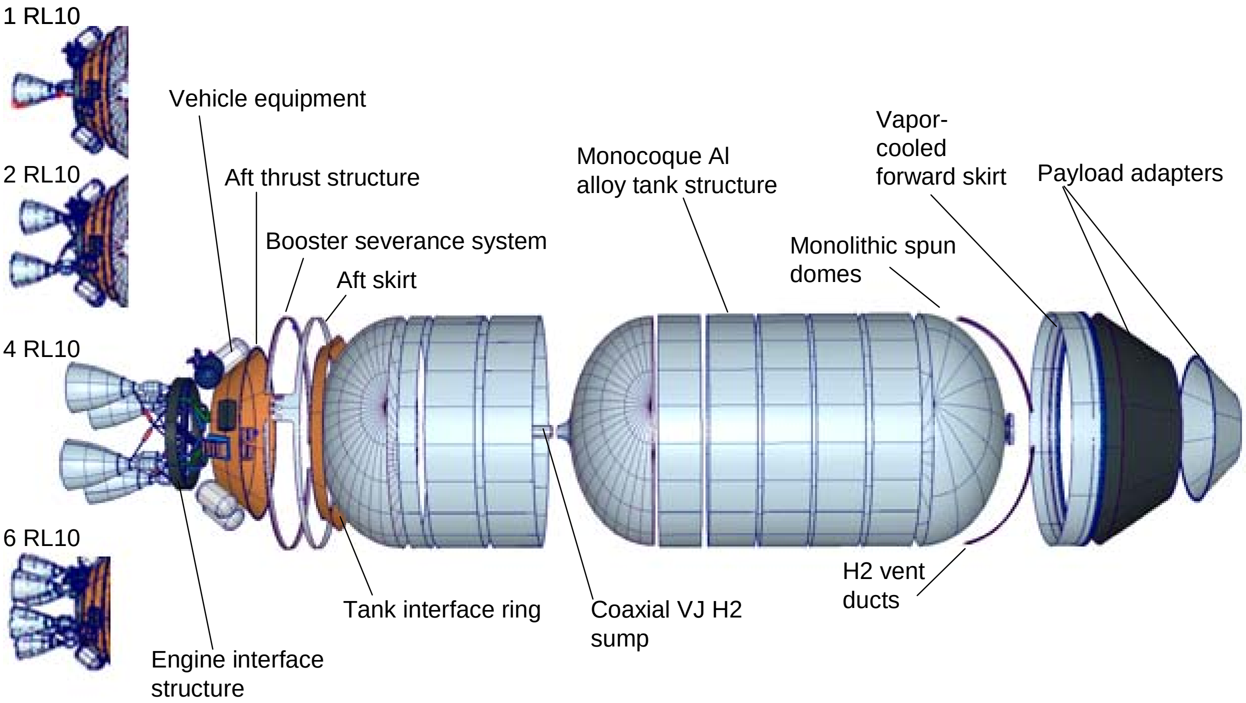

Figure 13. The ICES modular design provides flexibility to support a wide range of missions.

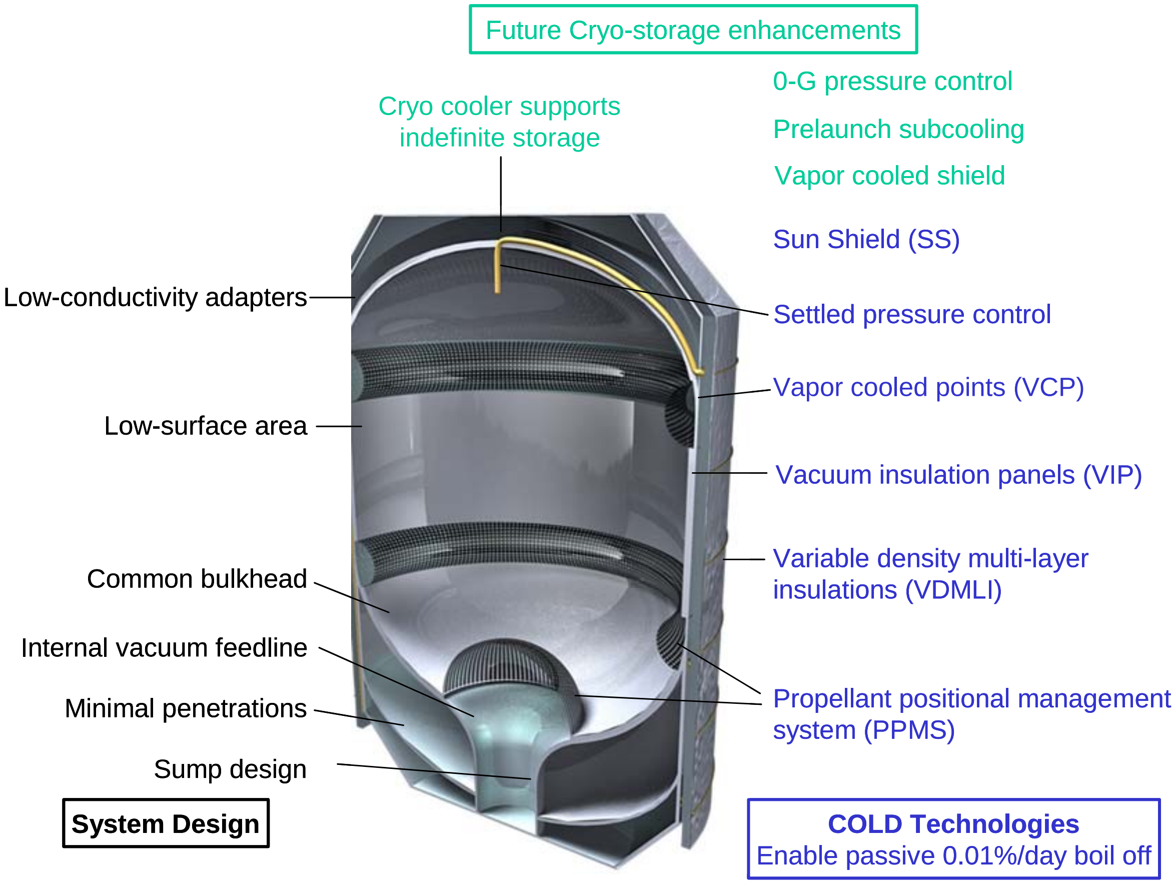

Figure 14. Six design elements and six COLD technologies enable passive extended LO2/LH2 missions.

Perhaps most important is the common bulkhead; a feature of all Centaur tanks and carried over to the ICES. Due to inherent thermodynamic properties, it is two to 10 times more efficient to vent hydrogen in terms of amount of heat removed per pound than oxygen, (table 1). The common bulkhead provides an extremely efficient and reliable method to direct all stage heating to the LH2 tank, where the energy can be efficiently removed via H2 venting to allow zero O_2 boil off.

Table 1. Venting GH_2 provides 2 to 10 times the thermal efficiency as venting GO_2.

Thermal attribute	LO_2	LH_2	Benefit
Heat of formation KJ/Kg (BTU/lb)	205 (88)	428 (184)	H_2 2 times better than O_2
Change in enthalpy from liquid to 400 R KJ/Kg (BTU/lb)	335 (140)	3,256 (1,400)	H_2 10 times better than O_2

This inherently structurally and thermally efficient design will reduce the system boil off to 0.1%/day for the baseline ICES compared to the current Titan Centaur ~2%/day. This low boil off provides a common stage that is ideally suited for standard Low Earth Orbit (LEO), Geosynchronous Transfer Orbit (GTO), and Geo-stationary Orbit (GSO) missions with mission durations up to 24 hours and provides the foundation for much longer missions.

C. Long-Duration Cryo-Fluid Management Mission-Peculiar Kit

For long-duration missions (~ one year), additional passive-thermal management features can be incorporated via mission-peculiar kits. These features include: enhanced vacuum insulation panels (VIP); variable density multilayer shields (VDMLI); propellant positional management devices (PPMD); sun shields (SS); and zero-G pressure control features (fig. 15). Taken together, these long-duration mission-peculiar kit technologies make up the cryogenic operation for the long-duration (COLD) system.

These mission-peculiar kit items can be developed and implemented as the mission needs dictate, (table 2). Initially, the technologies required to support mission durations of weeks will be implemented and directly support NASA's Spiral 1 exploration needs. These missions will develop early confidence in the COLD system. Additional capability will be added as future mission needs demand. This will allow NASA to focus its near-term limited budget on technology needed to satisfy NASA's near-term exploration goals. Through flight experience and on-going development, continuous improvement can be made to each individual technology and the system as a whole. Through this evolutionary, continuous product improvement process, ICES will advance the state-of-the-art large-scale cryo storage from the current Titan Centaur system boiloff rate of ~2%/day to the ICES goal of 0.01%/day.

Most of the COLD technologies required to meet the ICES cryo-storage goals have been developed across

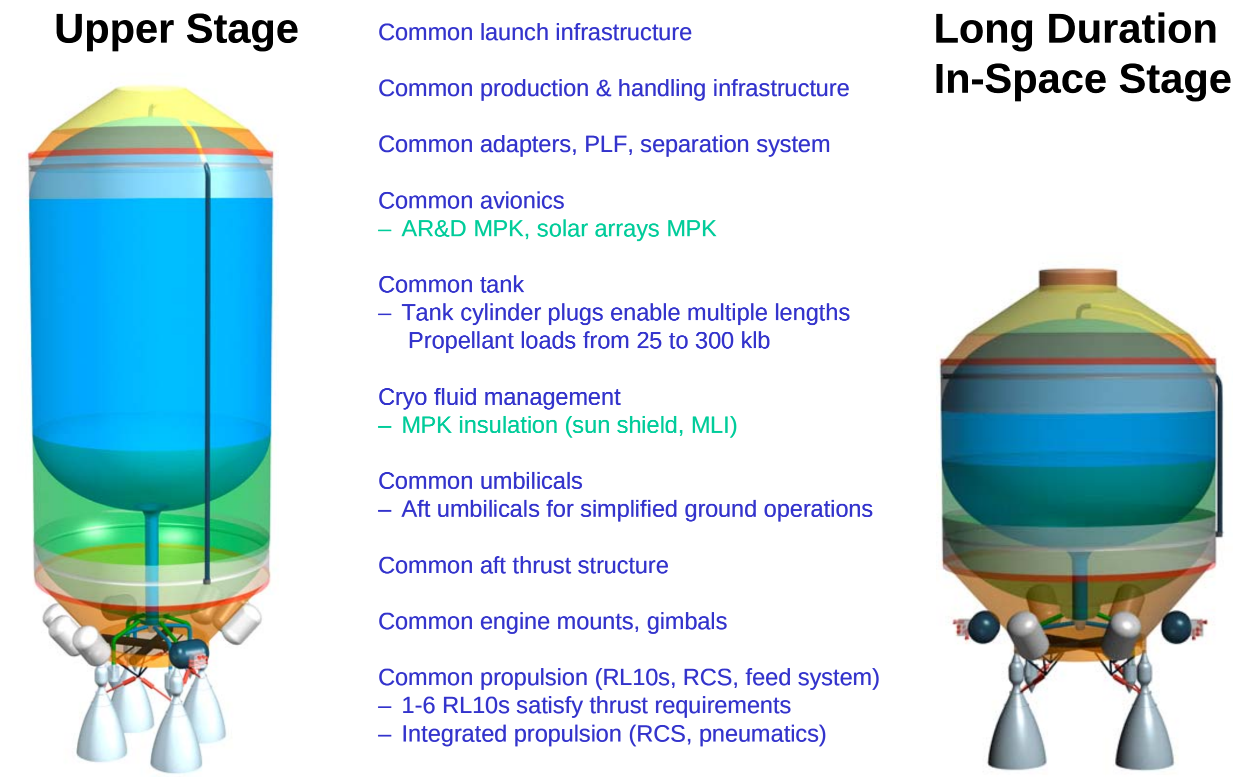

Figure 15. Through the addition of mission-peculiar kits, the baseline ICES can be enhanced to support very long-duration missions.

Lockheed Martin, at NASA, and in industry, but these technologies need to be efficiently combined in a large-scale system.

Table 2. The COLD technologies inserted into ICES will parallel the mission-duration needs.

	Mission duration				
COLD technologies	Days	Weeks	Months	Year	>Year
Vacuum panel insulation	🟩	🟩	🟩	🟩	🟩
Settled pressure control	🟩	🟩	🟩	🟩	🟩
Vapor-cooled points	🟦	🟩	🟩	🟩	🟩
Variable density MLI	🟦	🟦	🟩	🟩	🟩
Propellant position management system	🟦	🟦	🟩	🟩	🟩
Sun shield	🟦	🟦	🟩	🟩	🟩
Enhanced technologies					
Prelaunch subcooling			🟦	🟩	🟩
0-G pressure control			🟦	🟦	🟩
Cryocooler			🟦	🟦	🟩

🟩 Mandatory
🟦 Helpful

D. Passive vs Active Cooling

The purely passive COLD technologies are particularly attractive for early-lunar exploration missions allowing NASA to delay investment in large-scale active cooling systems. Passive systems are expected to be substantially more affordable and more reliable than active systems that require continuous power and complex radiator systems. For the longest mission durations, actively cooled systems will significantly benefit from the COLD technologies developed for the passive systems.

V. Exploration Systems Impact

The ICES development cross cuts many elements of the nation's exploration program, including orbital assembly, in-space stages, ISRU, ascent/descent vehicles, and launch systems.

E. Launch Systems and Trans-Planetary Transportation

The technology encompassed in ICES enabling light-weight, long-duration cryogenic missions is directly applicable to evolutionary enhancements of existing upper stages such as Centaur and the Delta IV. Use of the COLD technologies on existing upper stages provides an early application of the technology for enhanced near-term mission capability. These near-term missions can demonstrate the effectiveness, and develop operational experience on repeated commercial and government launches before the first use for exploration.

The use of cryogens in the trans-lunar injection and lunar-orbit insertion stage(s) provides greater mass-reduction benefits than any other architecture element. The COLD technologies are also critical to allowing on orbit rendezvous of cryo stages.

F. Descent/Ascent Vehicles

The COLD technologies in this project will enable practical cryogenic descent and ascent stages. Storable-propellant alternatives are approximately 20% heavier in gross mass than LO_2/LH_2 for a lunar-surface-to-orbit ascent module (the difference is greater for surface-to-L_1 vehicles). A COLD-based boil-off rate of approximately 0.1%/day is sufficient for lunar-mission durations of about 45 days, while the planned 0.01% rate enables very long-duration lunar and Mars missions.

G. Planetary Missions

Planetary missions currently rely on solid or storable propellant propulsion modules, or aero capture to achieve orbital insertion at another planet and have the following limitations:

- Low Isp of ~325 sec for storable liquid or ~290 sec for solids (single burn only).
- Lack of 3-axis stabilization places additional requirements on spacecraft.
- Low thrust for storable liquid systems delays final orbit insertion by several weeks.
- Aero capture limited to bodies with substantial atmospheres and detailed knowledge of the atmospheric altitude-density profile and requires an extremely precise entry trajectory.

The COLD technologies enable small cryogenic propulsion modules that mitigate the limitations of current planetary insertion options, (fig. 16). A small cryogenic propulsion module with common elements to the ICES could have multi-burn capability enabling supplemental Earth-escape burn, large-scale mid-course burns, propulsive planetary fly bys, planetary injection, and in- system maneuvers.

VI. Flight Demonstration

The COLD technologies embedded in the ICES project will significantly benefit from opportunities to flight demonstrate the individual technologies in the 0-G space environment. The existing Atlas® V/Centaur provides the ideal, near-term, low-cost access to the space environment. With nominally six missions per year and frequently hundreds to thousands of pounds of excess propellant, Atlas V/Centaur missions provide an opportunity to gain confidence in the emerging COLD technologies.

Simple flight-software changes and the addition of instrumentation allow on-orbit demonstration of the COLD technologies, (fig. 17). Additionally, feed-line instrumentation allows demonstration of enhanced propellant-transfer sequences. Flight data enables optimization of vent-system designs that are critical to the overall system efficiency and reliability.

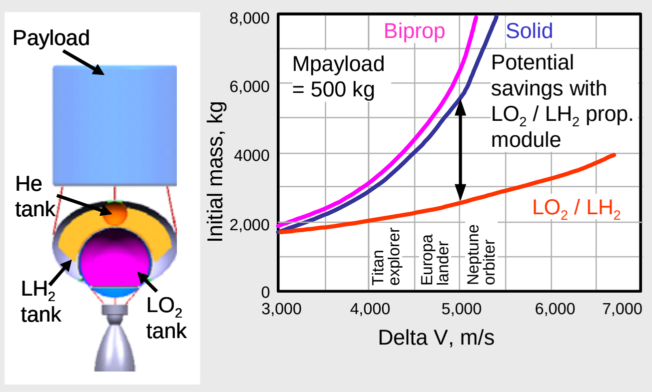

Figure 16. Miniature LO2/LH2 propulsion module with elements common to ICES enhances robotic exploration.

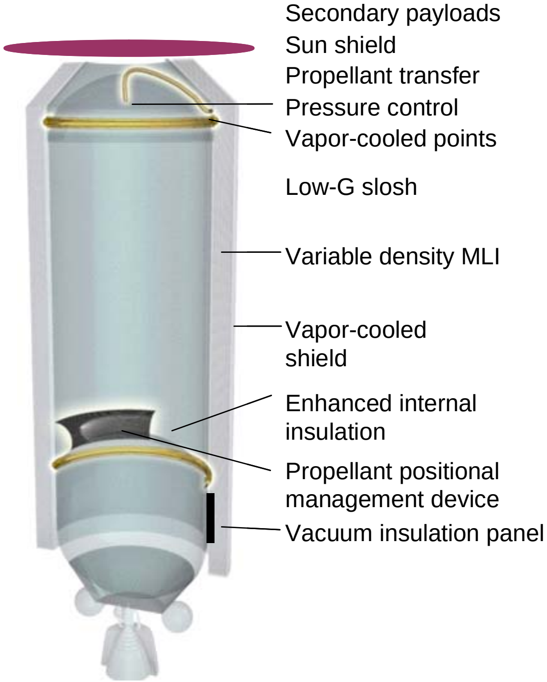

Figure 17. Centaur provides numerous launch opportunities to demonstrate cryo-fluid management technologies.

VII. Conclusion

Use of LO_2/LH_2 propulsion, vs storable propulsion, reduces initial mass in low Earth orbit (IMLEO) by more than 45% for lunar exploration. The performance benefit pays off in three ways:

- Total system mass can be reduced, lowering launch cost more than 45%.
- Increased payload and mission capability for the same total mass.
- Mission margins can be increased, allowing safer operations.

Despite the potential benefits, cryogenic in-space propulsion has traditionally been hindered by two difficulties: the expense of developing new cryogenic stages, and the challenge of storing the propellant for long durations.

Development of ICES provides a robust, flexible solution to most of NASA’s space exploration transportation requirements. ICES builds on the 40 years of successful Centaur flight history. ICES improves on the extremely high-mass fraction currently offered by Centaur to provide an effective, affordable, and reliable long-duration in-space cryogenic transfer stage. The ICES design accomplishes this through improvements to all aspects of the propulsion stage, including propulsion system, structure, thermal systems, and avionics. System development to date indicates that the ICES mass fraction accounting for the long-duration mission-peculiar kit will significantly exceed 0.9.

ICES will implement the foundation for efficient cryo-fluid management in the baseline vehicle designed to satisfy NASA, DoD, and commercial customer requirements for Earth to orbit. Inclusion of the mission-peculiar kit COLD technologies enables passive-mission duration of months to years.

References

[1] Griffen, M. D., and French, J. R., “Space Vehicle Design,” AIAA Education Series, Second Printing (1991), P. 187.