Centaur Extensibility For Long Duration

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ABSTRACT: The Centaur LOX/LH2 cryogenic stage has been used as an upper-stage for most of the deep space missions because of its high ISP. Now with the advent of Lunar and Mars initiatives, Centaur-like vehicles are being considered for trans-Lunar, Earth-return, and Mars missions with quiescent coast durations lasting from a month, up to one year.

This paper reviews the results of a funded study by NASA/KSC NAS10-00-060 done by Lockheed Martin Space Systems titled: **Advanced Cryogenic Evolutionary Stage (ACES).** This study is an assessment of the Centaur integrated with new technologies in an effort to accommodate these longer duration missions.

Study specifics include: avionics, environmental effects, attitude controls, active/passive thermal controls, passive thermal Vacuum Insulation Panel applications, advanced MLI, sun-shield, RL10 engine (cold-soak, restart and long duration effects), and operations.

WHY A CRYO STAGE FOR LONG DURATION?

A Cryogenic stage consists of LOX/LH2. A nominal mission today would be complete with a second or third burn after 8 or 10 hours. It is desired to support stays of several months in Lunar orbit or Mars Missions that extend for a year in transit.

What are the benefits of utilizing a cryogenic-stage for long in-space durations? LOX/LH2 have high ISP and are thus more efficient than storables. As a result a Cryo stage can support higher energy missions that would not be practical with storable systems, see Fig-1.

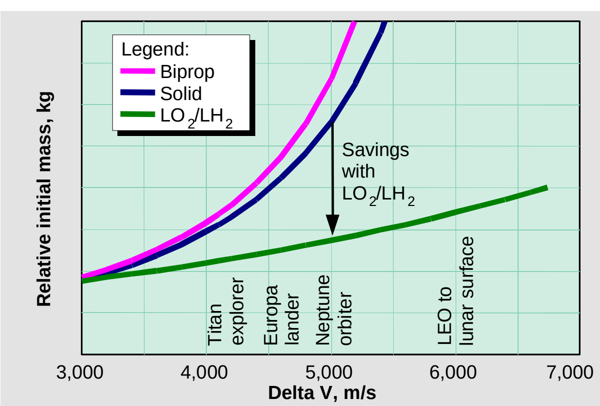

Figure-1, Relative Propellant Performance

The applicability of a Cryo Stage is still viable to CEV for Trans-Lunar Insertion (TLI), Trans-Earth Insertion (TEI), or a Lunar lander.

WHAT PROBLEMS FACE CRYO STORAGE?

The principal problem of a cryo stage is boiloff of the propellants. The present day Centaur vehicle looses upwards of 17-20 % lbm of Hydrogen per day (Ref: <u>Centaur Upper Stage Applicability for Several-Day Mission Durations with Minor Insulation Modifications</u>, by Jeffery DeKruif, AIAA Space 2006.). Hydrogen is the deciding factor since it is harder to adequately insulate the LH2 tank than the LOX. To limit the LH2 boiloff the heat sources must be removed and these include: the Sun, the avionics, structure, and most important the LOX. The LOX is considered a heat source since it is normally 140 degrees warmer than the LH2 at 40 deg. R. This presents another potential problem in that the LOX and other on-board fluids may need protection from getting too cold and freezing.

Other problems regardless of the stage, exist that must be resolved for a long-duration environment. Any solution must be in the context of a total system solution since perturbations can have cross-correlating effects.

One such problem is the avionics - specifically thermal protection and power, and to a lesser degree, navigation, telemetry, up/down link margin, and electronics reliability.

The second problem is attitude control. Traditional Hydrazine is fine but you have to take it with you. There must be a sufficient supply of propellant for attitude control to last throughout the mission. What do you use? How much can you store, and where? And are there any other alternatives?

PRIOR STATUS LEADING UP TO ACES

We had done selected studies and IRADs directed to expanding the use of Centaur for some time. These included the NASA BAA "Friction Stir Welding of Thin Sheet Metallic Alloys for Ultra Lightweight Cryogenic Tanks" (NASA BAA *NNM05AB11C*). This study had as a goal the reduction of structural mass by a factor of 2 using Friction Stir Welding (FSW) with thin materials, explosive bonding of metal joints, and Spin forming of cryo tanks domes.

Other IRADs included: the analysis of the Centaur Wide Body: common intermediate bulkhead, reduction of penetrations, and the central sump thru the LOX tank for better thermal control of the LH2 heating.

THE ACES STUDY

The Advanced Cryogenic Evolutionary Stage (ACES) Study was funded by NASA/KSC to evaluate new technologies applied to the Centaur Cryo Stage specifically to access the potential of adapting such a stage for missions of from 1 month to 1 year duration. The goal was to reduce the projected model of LH2 boiloff to less than 0.1 %lbm/day. This is an improvement of a factor of 20 or more over today's vehicle characteristics.

The study has three primary areas of focus: cryo management using thermal insulation, long-duration engine effects, and long-duration system impacts. A summary of these initiatives is shown in Fig-2.

Figure-2, ACES Initiative for Long Duration Missions

THE LONG-DURATION STUDY PLAN

The first area focused on cryo-thermal management looking at direct approaches to the problem of boiloff. The most promising were Passive Systems. MLI blankets of various thickness can be used for cutting the Sun energy input. Second, Vacuum Insulation Panels (VIP) can be used to separate the heat flow from the LOX to the LH2. The VIP investigation considered the type of material to use, the effects of the cladding materials, and the manufacturing and logistical considerations involved in actual application. Finally, Sun-shades were studied as a more elaborate means of cutting off Sun and Earth heating effects, while allowing RCS attitude control thruster actuation.

Passive cooling can be used to extract heat from the system. The cold vapor is available to intercept heat from flowing into the LH2 tank from the LO2 tank. Vapor cooling channels using the vented LH2 gas can intercept the heat from the LOX to the LH2 that passes thru the metal common bulkhead and up the side walls.

Active cryo-thermal management systems were also studied but were found to be more difficult to implement, as they require additional engineering, the consumption of electrical power, large radiators, and active management. Cryo-coolers use energy to literally pump the heat out of the cryogen and dump the heat overboard.

A separately funded portion of the study, performed by Pratt & Whitney (P&W), assessed the ability of the RL10 Engine to survive extended time in a dormant coast-mode and have a successful restart. The specifics of the study focused on the materials aspect related to cold-soak for long duration and the necessary conditions and probability of a successful restart.

The third leg of the study was a review and identification of total-system impacts and assessment of mitigating approaches that can enable the long-duration Centaur missions utilizing the current Centaur vehicle as the baseline. The Avionics is of importance because the high-energy ions can cause electronics integrated circuit (IC) upsets and mortality. Guidance is of concern from the accumulation of errors over time (~5 deg. over a 4-5 day flight to the moon). Power systems had to be investigated because the current battery configuration will not go further than 24 hrs, even when draining the redundant battery bank. Attitude controls presented a problem in that the usage was limiting and the current thermal venting system (TVS) causes an imbalance that perturbs the vehicle. Telemetry was another item. The current vehicle does not have an uplink capability. Further the existing antenna system is not positioned to accommodate the vehicle turned to face broadside to the sun with a role and the antenna gain is insufficient for missions beyond GSO.

CRYO-MANAGEMENT RESULTS - BLANKETS

The most significant result from the study is that the use of MLI insulative blankets can cut the boiloff rate significantly. The 16-layer MLI suggested, results in a theoretical <u>total system</u> loss of <u>4 %lbm/day</u>. Even greater saving can be realized with thicker blankets of 45- layer variable density MLI. These thicker blankets have more logistical problems of greater thickness (1.5 in.) and greater hanging weight.

Less useful is the application of cryo-coolers. Their energy input is hard to justify the thermal savings. Although thermally promising, sub-cooling poses significant challenges to the current Centaur and ground infrastructures. These difficulties appear to limit sub-cooling to the future very long duration missions. Vapor cooling channels on the other hand are more promising for longer duration missions (greater than a month) and are easily implemented. The thermal savings can be justified vs the weight and cost penalty. The Vapor cooling channel in combination with a balanced Thermal Vent System (TVS) can be engineered with very low risk and the implementation eliminates the current unbalanced vent system to better conserve reaction control system (RCS) propellants.

Sun-shields using 16-layer MLI have aa high a probability to cut the heat flux into the vehicle system as the 45-layer MLI blanket. There are existing shield-deployment concepts that have flown on deep-space spacecraft missions in the past. The application of a sun-shield or MLI blanket on a 5-meter fairing class mission is certainly possible. With a 4-meter fairing the Centaur is not covered, therefore, you have the problem of the sun-shield or MLI blanket being exposed during the ascent. Another potential problem culminates from the RCS impacting on the shield surface. Implementing a deployment scheme, in the case of the 4-meter fairing, that drapes the Centaur (either an umbrella or shower-certain effect) after ascent would appear to be one solution. In addition, having the blanket or shield short enough to avoid the RCS plumb or positioning the RCS thrusters out and away from the sun-shield, would be another potential answer.

Figure 3 gives a summary of the Cryo-thermal study results.

CRYO-MANAGEMENT RESULTS - VIP

Various Vacuum Insulation Panel (VIP) materials were considered as an insulation and cladding for the intermediate bulkhead between the LOX/LH2 tanks, Fig 4.

- **Active & Passive Systems**
  - MLI (sidewall & fwd bulkhead) can reduce boiloff rates /day

Flown vehicle data	LO2	2.2>2.6%	LH2	13>17%
3-Layer MLI model		1.5		4>5%
16-Layer MLI model		**0.8**		**2.5**

  - Cryo-Coolers currently work on small scale and require significant power > not workable in the near future.
  - Vapor Cooling Channels very promising to cut off thermal leakage from LO2 to LH2 thru side walls. A single -pass 4" duct using Hydrogen vent gas (2 lbm/hr) results in **51% heat reduction**.
  - Thermodynamic Vent System (TVS) > gas only – **low risk**.
  - Sun Shields studies found that the full skirt cone configuration **Reduces heat flux to 10%**
  - Pre-Lnch Sub-cooled LH2 problems outweigh benefits, not for Earth-Moon missions

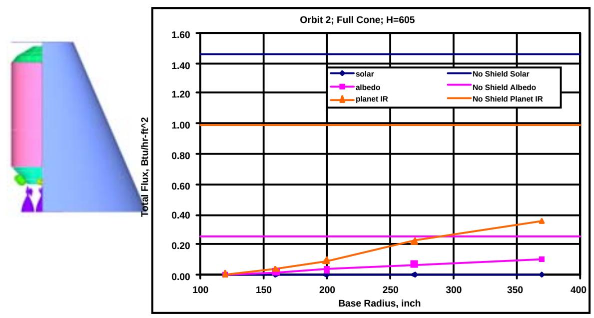

Figure-3, Cryo Thermal Study Results

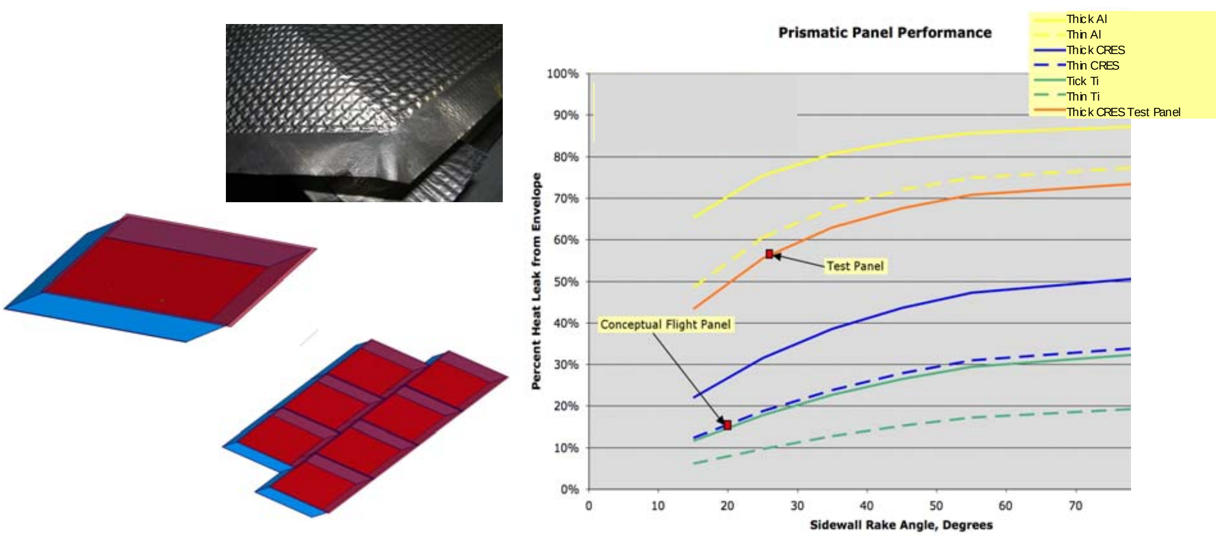

Figure 4, Vacuum Insulation Panel for the Intermediate Bulkhead

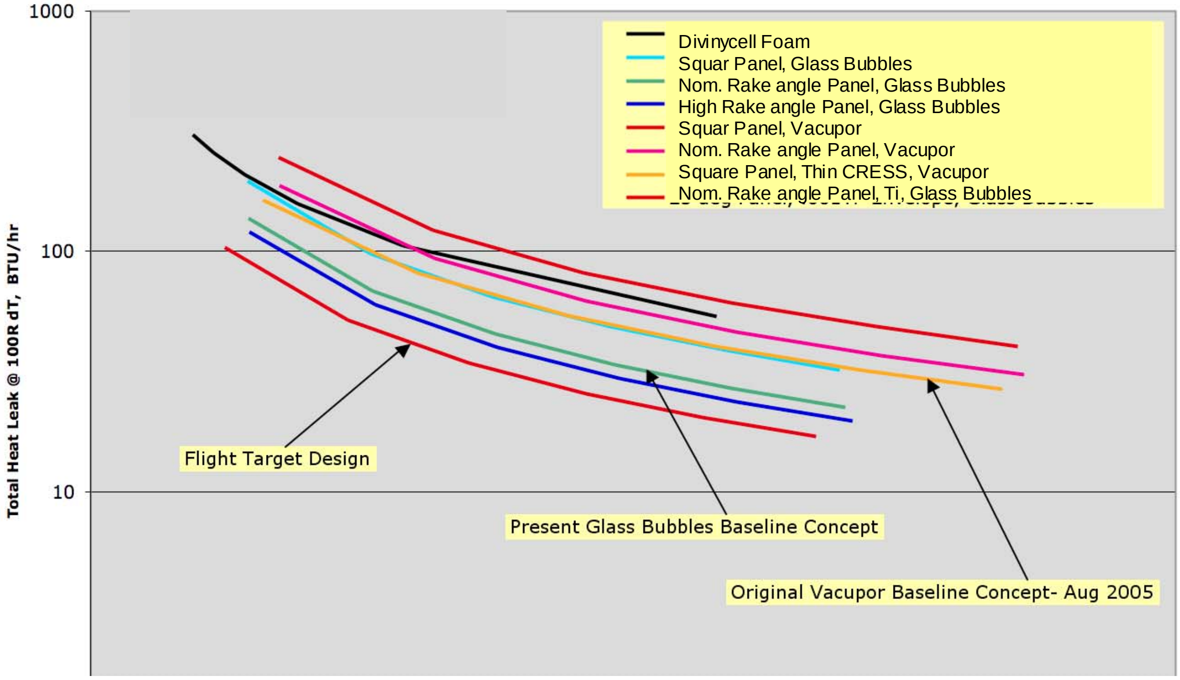

Figure 5, Vacuum Insulation Panel Materials

If insulation panels are used they must be tiled into place on the bulkhead. The overlapping of the tiles, the angle of the sides (or rake angle) turned out to be significant to the thermal insulation results. The thermal stress the cladding is a prime problem. Various thicknesses of cladding material were investigated, but the material selected must be compatible with the laser welding. The use of different cryo-compatible polymer materials were also considered, including the Vectra Resin. The study was not able to test these types of cladding materials in the time allotted

The study proved interesting results, concluding that the thickness of the cladding material and the rake angle had greater effects on the thermal short-circuit. The sensitivity is shown on the graph in Fig. 5. The mathematical model predicted that a rake angle could be optimized for decreasing the thermal short-circuit.

The fabrication process shown in the pictures, Fig. 4, used this wedge shaped for the cladding pans. Some thermal tests had being conducted on these VIP vacuum seals at the time of this writing, but had failed thermal cycling. Further tests on the pan laser welding revealed that the flanges used in the weld assembly were contaminated over long sections by the insulation material. It is assumed that sealing the pans prior to introducing the filler material to the panel will simplify the fabrication. A successful panel would then be filled thought the filling tube opening with the insulative materials by simply pouring the material into it. Further fabrication experimentation using this and other pan materials and thermal testing is needed to define an approach.

For the insulation, the table in Fig 5, shows the predicted difference between using the Divinycell foam vs the VIP using filler materials. The glass bubbles or a combination of aerogel and glass bubbles are predictably better than Divinycell and these are a great improvement over the currently used felt covering.

RL-10 ENGINE LONG-DURATION STUDY

The P&W study included a material study that reviewed the long-duration cold soak effects. The conclusion of the investigation was that there was no degradation over an extended period in full shade. They did recommend that some of the seals may indicate a further review and testing to be completely definitive.

Regarding engine re-start, they saw no problems with multiple engine re-start even after a long-duration cold soak so long as the pre-start conditions were met by turning the engines into the sun to warm back into spec levels. In fact the re-start has been demonstrated on prior flights but for shorter durations.

The question of the mixture ratio (MR) was of interest for Lunar lander missions. A minor mod would accommodate a change to the MR range from 4.0 to 6.3 if a smaller PU restrictor orifice is used.

LONG DURATION SYSTEM IMPACTS

Regarding the Avionics, the Centaur is now flying the Fault-tolerant Inertial Navigation Unit (FTINU). Currently there is a guidance drift over a period of a few days. If the mission is of a few-day duration as in a lunar mission demonstrator, this may be acceptable, especially if a telemetry uplink is made available for a guidance update. If the mission is of longer duration, a different type of avionics that already includes the deep-space communications, star-tracker etc. would be more applicable. This type of avionics has flown on satellite systems and is already radiation hardened, is commercially available, and consumes 1/3 of the power of the FTINU set.

The current Centaur power is based upon batteries that are redundant and provide 800 watts of service for the nominal mission of 8 hrs. If the batteries are allowed to run dry and effort is made to reduce power, a life of 24 hrs is possible. Additional batteries can be added with the associated weight penalty to extend the life up to 3 days. However, if the mission requires more time then a switch to a rechargeable system is recommended. Such a system may have to accommodate a shadow period in a Lunar orbit. Commercially qualified 40 amp-hr batteries are available for such an application. Two such batteries (for redundancy) would accommodate the nominal Centaur launch prior to a necessary charging cycle.

For the few-days mission, a RCS system could be accommodated with the addition of one extra hydrazine bottle. This is assuming that the role would be at a slow rate and that the role-reversals (for guidance error rate reduction) would be kept to a minimum (2/day). For longer missions, the Hydrazine would become an issue. The Cryogenic High-Pressure Storage (CHPS) would be a better solution. The CHPS system utilizes the vented LOX / LH2 gasses as the fuel for the RCS. However, there are problems that still need to be resolved with CHPS. The primary one is the line temperatures and the ignition system reliability. More research and testing will be needed to resolve these problems.

FUTURE RISK REDUCTION ACTIVITIES

Additional work would include:

- Continued investigation of the VIP materials and testing in the LH2 environment.
- System engineering for the wide-body Centaur with the central sump.
- Testing the CHPS RCS system in flight.
- Cryo transfer technologies needed for a future propellant depot services.
- A flight demonstration of technologies and the understanding of long duration effects.

A proposed Mission Kit for such a demonstration might include mods to the Avionics, thermal vent system, MLI blanketing, Sun shield, and necessary pneumatics and structures. The total mass of this Centaur Mission Kit would amount to 800 Kg.

SUMMARY

Fig 6 shows that significant progress can be made by implementing the results from this study to the Centaur baseline vehicle of today. It is feasible to achieve a long-duration cryogenic stage that can sustain itself in a ready state for weeks, months and potentially up to a year in an autonomous coast mode to serve an exploration crew for a return home. Fig 7 shows the concept of a Wide-Body Centaur modified for long duration.

In conclusion the study proved :

- Significant accomplishments in thermal insulation for the evolution of long duration Centaur, along with the identification of system level impacts and opportunities.
- Opportunities for synergy with Space Exploration development efforts and other needs.

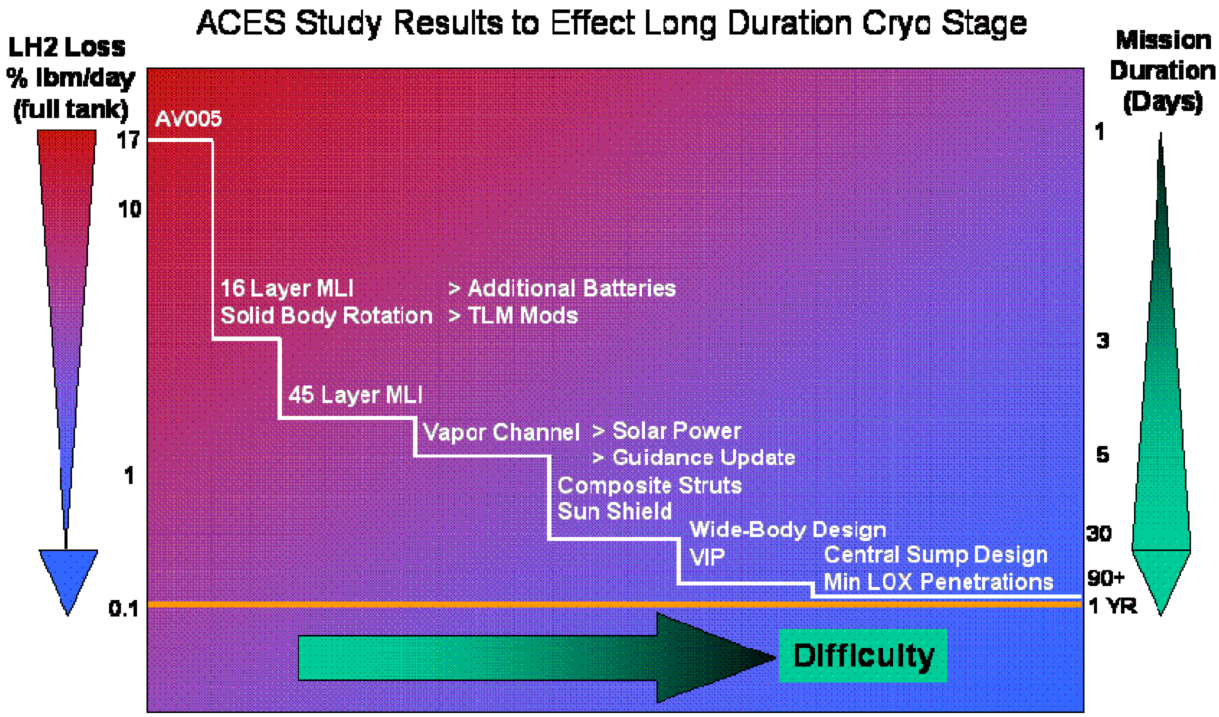

Figure 6, Long Duration Advanced Cryogenic Evolved Stage

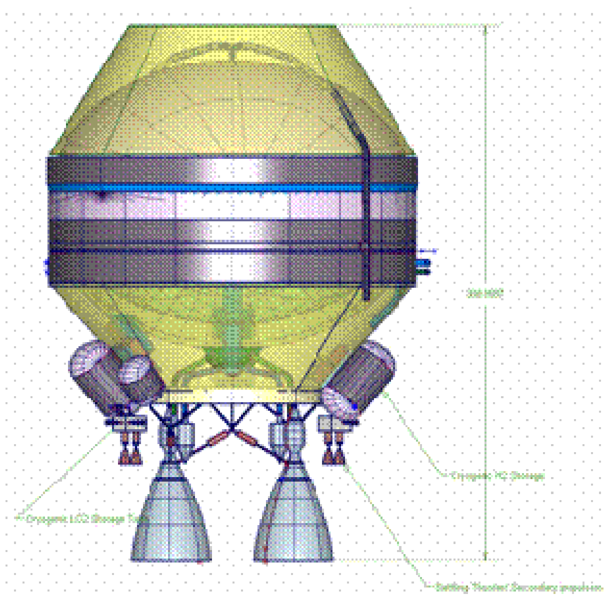

Figure-7, Wide-Body Centaur Concept

ACRONYMS

ACES	Advanced Cryogenic Evolutionary Stage
AV	Atlas Vehicle
CEV	Crew Exploration Vehicle
CHPS	Cryogenic High-Pressure Storage
FSW	Friction Stir Welding
FTINU	Fault Tolerant Inertial Navigation Unit
GSO	Geo-Synchronous Orbit
IRAD	Internal Research and Development
ISP	Specific Impulse
KSC	Kennedy Space Center
LH2	Liquid Hydrogen
LM	Lockheed Martin
LOX	Liquid Oxygen
MLI	Multi-Layer Insulation
MR	Mixture Ratio
P&W	Pratt and Whitney
S/C	Spacecraft
RCS	Reaction Control System
TEI	Trans-Earth Insertion
TLI	Trans-Lunar Insertion
TVS	Thermal Vent System
VIP	Vacuum Insulation Panel