

# PROPELLANT GAUGING FOR EXPLORATION

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## ABSTRACT

This paper presents a brief overview of propellant gauging needs and requirements in the context of lunar exploration missions defined by the Exploration Systems Architecture Study (ESAS) report. A timeline for the development and testing of gauging technologies, and a few key design review dates are presented. A lunar exploration mission scenario is discussed which aids in defining the propellant gauging needs. The fleet of new exploration vehicles includes the Ares I and Ares V launch vehicles, Earth Departure Stage (EDS), Lunar Surface Access Module (LSAM) ascent and descent stages, and the Orion Crew Exploration Vehicle (CEV). The liquid propellant choices are currently oxygen - hydrogen for the launch vehicles, the EDS, and LSAM descent module; oxygen - methane for LSAM ascent module; and monomethylhydrazine – nitrogen tetroxide (MMH-NTO) for the CEV. Estimated tank sizes, temperatures, pressures, and storage durations are presented. A baseline propellant gauging system is proposed that is based on high Technology Readiness Level (TRL) gauging technologies. In order to be considered for use on the new exploration vehicles, any new gauging technologies will have to show a clear benefit over the baseline methods in terms of performance and/or cost.

## INTRODUCTION

The Vision for Space Exploration, announced by President Bush in 2004, calls for returning to the Moon by 2020 and thus requires a whole new fleet of vehicles to carry out the exploration missions. The Exploration Systems Architecture Study (ESAS) Final Report<sup>1</sup>, released in 2005, assessed and defined top-level requirements for the exploration vehicles, and identified several key technologies required to enable and enhance the exploration systems. Low-gravity mass gauging is one of several propulsion technologies that the ESAS report identified as a technology development need. A propellant gauging technology that functions in low-gravity (independent of fluid orientation) would eliminate the need for settling burns by spacecraft, which consumes propellant. Furthermore, even if settled gauging technologies are used, the exploration program may benefit from new gauging technologies provided they offer some performance benefit. NASA's Propulsion and Cryogenic Advanced Development (PCAD) program is supporting propellant mass gauging technology development and testing to reduce risks associated with gauging for the new exploration vehicles.

The purpose of this paper is to present the propellant gauging needs that are required to successfully carry out the exploration program. Just as different rockets have different engine designs, so too it may be with propellant tank gauges for the various new exploration vehicles. The new fleet of vehicles presently calls for five different liquids (hydrogen, oxygen, methane, MMH, and NTO), at least twelve different tank/fluid combinations, post-launch storage times ranging from minutes to months, and a wide range of nominal operating environments (temperature, pressure, gravity-level, vibration, sloshing, and space radiation). Several different gauging technologies will likely be needed to satisfy the various gauging requirements.

The rest of the paper is organized as follows: A notional lunar mission scenario is borrowed from the ESAS report which helps to define the gauging needs. Next, the liquid propellant tanks of the various vehicles are presented, which again are borrowed from the ESAS report but with some changes noted. Other changes may occur in the future; these remain notional designs until hardware designs are finalized. Two key vehicle design review dates listed are the Preliminary Design Review (PDR) and Critical Design Review (CDR). The vehicle tank subsections list the fluids, tank size and geometry, quantity of propellant (total of fuel and oxidizer mass), the duration of time over which the tanks will need to be gauged (even if gauged intermittently) starting with launch from Earth as a  $t = 0$  reference, and the critical burn periods for the vehicle. A “baseline gauge” scenario is proposed for each vehicle, which is not meant to define what gauging technologies should be used, but instead to propose relatively high TRL methods that *could* be used in the absence of something better. The proposed baseline gauging methods are not without risk, however, as some methods have had problems, others may be at a lower TRL (e.g., a methane tank has never been gauged in space) and some may carry relatively high gauging uncertainties.

### REFERENCE MISSION

The ESAS reference mission “Lunar Sortie with Crew and Cargo” is chosen here to illustrate the propellant gauging needs. The architecture is illustrated in Figure 1, and is referred to in the ESAS report as the “1.5-launch EOR – LOR” (Earth orbit rendezvous – Lunar orbit rendezvous). The gauging operations described here are a notional idea of what might be done.

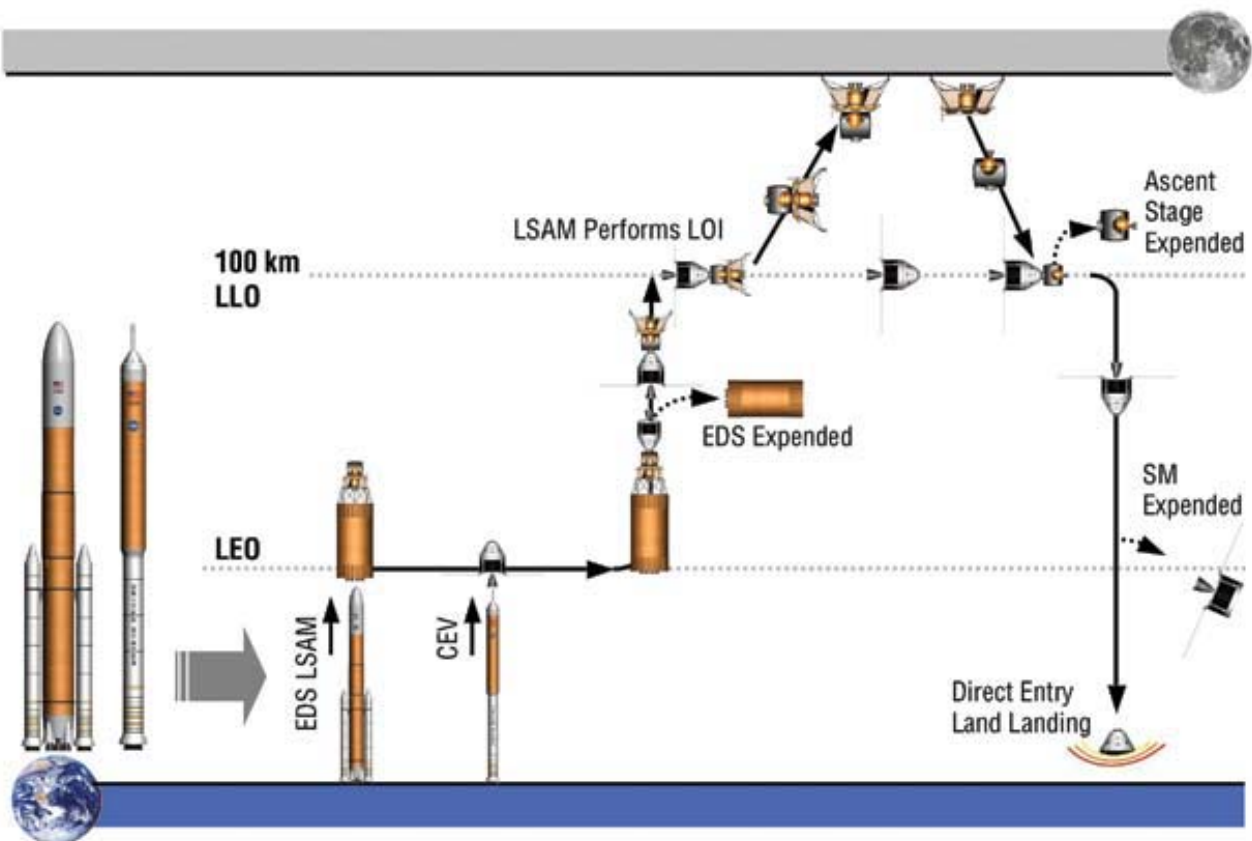


Figure 1. The ESAS Lunar Sortie mission architecture concept.

A heavy-lift launch vehicle carries the EDS and LSAM to a sub-orbital altitude using a liquid oxygen / liquid hydrogen (LOX-H<sub>2</sub>) core first stage vehicle with solid rockets. Within minutes after launch, the EDS acts as the second stage, providing the needed boost to LEO and which consumes about half of the EDS supply of LOX-H<sub>2</sub>.

While loitering in LEO, the LSAM tanks remain full (~ 95% capacity). The approximately half-full EDS tanks would likely be gauged using a level sensor just before orbit insertion while there is vehicle thrust. Once in LEO, however, further gauging of the EDS and LSAM tanks presents some challenges. Settling the tanks using small-thruster firings may be sufficient to settle the fluid, but slow slosh dynamics may hinder accurate readings. Further analysis is needed to investigate these effects in more detail, but an accurate low-gravity gauging method would certainly be valuable.

Next, the CEV is launched on the Ares I and is placed in LEO using the Ares I LOX-H<sub>2</sub> upper stage. Gauging the propellant in the Ares I upper stage could be done in the same manner as currently accomplished on the Centaur upper stage, using a  $\Delta P$  (differential pressure) sensor. The duration of use of the upper stage is only a matter of minutes before reaching LEO, then the CEV separates from the upper stage and rendezvous and docks with the EDS-LSAM vehicle.

The EDS then performs the trans-lunar injection (TLI) burn, during which level sensor readings on LSAM, EDS, and CEV could potentially be obtained. The CEV-LSAM separates from the EDS and coasts toward the Moon. The LSAM LOX-H<sub>2</sub> descent stage performs the lunar orbit injection burn, offering another opportunity for a settled gauging measurement.

Once in lunar orbit, the CEV and LSAM separate, and the LSAM descent stage takes the crew, cargo, and LSAM vehicle to the lunar surface while the CEV remains in lunar orbit.

LSAM descent stage gauging is critical during descent and landing, and may have to deal with multiple maneuvers, changing gravity-vectors and liquid slosh. Likewise, although the LOX - methane ascent stage tanks will be easily gauged while resting on the Moon and during ascent, multiple maneuvers during rendezvous and docking with the CEV could give erratic level sensor readings. During these periods of sloshing, the gauging may have to rely on a burn-time integration reading, referenced from an accurate settled-gauging measurement.

Since boil-off and venting is not a problem with CEV Service Module MMH-NTO tanks, they could be gauged in low lunar orbit (LLO) by monitoring the tank pressures (PVT method). In addition, one could implement the thermal Propellant Gauging System<sup>2</sup> as a redundant low-gravity gauge. The CEV Service Module tanks may require heaters to keep the propellant from freezing, so this may offer an opportunity to incorporate this method.

The LSAM ascent stage is expended after docking with the CEV, and the CEV performs the trans-Earth injection (TEI) burn during which a level sensor measurement would likely be used for gauging.

## VEHICLE TANKS

This section presents the notional design and size of the vehicle tanks, together with a proposed baseline gauging method which is based on methods currently used in space vehicles<sup>3</sup>. Tank pressures range from 20-35 psi for pump fed tanks, to ~300 psi for pressure fed tanks. The cryogenic tank temperatures are typically within a few degrees of the normal boiling point (20 K, hydrogen; 90 K, oxygen; 112 K, methane) and the MMH-NTO tanks must be kept above their freezing points (221 K, 262 K respectively).

## Ares I Upper Stage

The Ares I launch vehicle first-stage is a Reuseable Solid Rocket Booster, the upper stage will deliver the Crew Exploration Vehicle to LEO. The ESAS concept for the Ares I upper stage did not have the common bulkhead between tanks; this concept has changed in more recent documents<sup>4</sup>.

<b>PDR:</b>	May 2008
<b>CDR:</b>	November 2009
<b>Propellants:</b>	Liquid Hydrogen / Liquid Oxygen; pump fed
<b>Tank geometry:</b>	Cylindrical, domed ends; 16.4 ft. diameter; common bulkhead.
<b>Quantity:</b>	~ 360,000 lbm
<b>Duration:</b>	minutes
<b>Critical burn:</b>	Second stage burn to deliver CEV to LEO.
<b>Baseline gauge:</b>	$\Delta$ P level sensor, burn-time integration

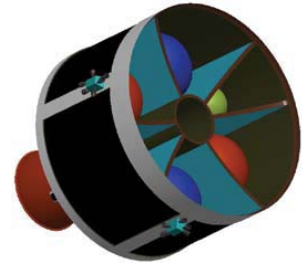
Although larger, the Ares I Upper Stage is otherwise very similar to the Centaur Upper Stage, so it is reasonable to assume that the gauging method will be similar. The short duration of use and constant thrust make a level sensor and burn-time integration a practical choice for a gauge.



## Crew Exploration Vehicle – Service Module

The Service Module provides the main power and propulsion system for the CEV. The ESAS report recommended LOX/methane for the main propulsion system, but this has been changed to MMH / NTO to reduce development risks.

<b>PDR:</b>	June 2008
<b>CDR:</b>	July 2009
<b>Propellants:</b>	MMH / NTO; pressure fed
<b>Tank Geometry:</b>	Cylindrical, domed ends. For reference, the Shuttle Orbital Maneuvering System (OMS) tanks are 4 ft. x 8 ft. and the four tanks hold 25,000 lbm of MMH / NTO (Ref. 5).
<b>Quantity:</b>	> 20,000 lbm. Since MMH / NTO is a lower performance propellant combination than LOX/methane, the quantity required is likely higher than the ESAS LOX/methane mass estimate.
<b>Duration:</b>	Weeks – months
<b>Critical burns:</b>	Rendezvous and docking with LSAM in LEO and LLO; TEI; disposal
<b>Baseline gauge:</b>	Capacitance probe level sensor, burn-time integration, PVT, thermal PGS.



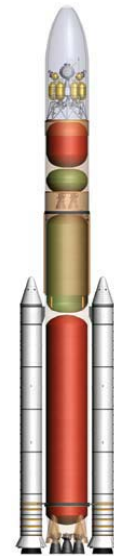
There have been some reliability issues with the capacitance probes in the Shuttle OMS tanks<sup>6</sup>. PVT can be accurate but would not be reliable in the event of a leak. Burn-time integration is reliable but the gauging uncertainty accumulates with burn-time. The thermal Propellant Gauging System may offer a method to gauge the Service Module tanks while in LLO.

### Ares V Core Stage

The Ares V launch vehicle is comprised of a pair of solid rocket boosters and a liquid propulsion core stage. The Ares V lifts the EDS and LSAM to a sub-orbital altitude.

<b>PDR:</b>	TBD
<b>CDR:</b>	TBD
<b>Propellants:</b>	Liquid Hydrogen / Liquid Oxygen; pump fed
<b>Tank Geometry:</b>	Cylindrical, ellipsoidal domes; 27.5 ft. diameter.
<b>Quantity:</b>	2.2 M lbm
<b>Duration:</b>	minutes
<b>Critical burn:</b>	Launch
<b>Baseline gauge:</b>	Burn-time integration; Main engine cut-off (MECO) sensors

There have been some reliability problems in the recent past with the hydrogen MECO sensors on the Space Shuttle External Tank<sup>7</sup>, which has led to scrubbed launches.



### Earth Departure Stage

The Earth Departure Stage, which carries the LSAM at launch, acts as the upper stage for Ares V, providing the boost from a sub-orbital altitude to LEO. After parking in LEO, it awaits arrival and docking of the CEV then provides the TLI burn.

<b>PDR:</b>	TBD
<b>CDR:</b>	TBD
<b>Propellants:</b>	Liquid Hydrogen / Liquid Oxygen; pump fed
<b>Tank Geometry:</b>	Cylindrical, ellipsoidal domes. 27.5 ft. diameter.
<b>Quantity:</b>	~ 490,000 lbm at launch ~ 220,000 lbm in LEO
<b>Duration:</b>	weeks-months
<b>Critical burns:</b>	Insertion into LEO; LEO circularization; Trans-lunar injection.
<b>Baseline gauge:</b>	Level sensor, burn-time integration



Upon reaching LEO, the EDS will have less than half of its original propellant load. The duration spent in LEO will depend on launch of the Ares I /CEV. Launch delays of the CEV could result in LEO loitering times of months, during which boil-off losses in the hydrogen tank could become significant. Before launch of the CEV, one would presumably want to gauge the EDS and LSAM propellant tanks, but in the absence of a low-gravity mass gauge this would require a settling burn. LEO stationkeeping burns, which compensate for orbital decay from atmospheric drag, may be sufficient to settle the fluid. The type of level sensor that might be implemented on the EDS is not clear. The small acceleration levels of a station-keeping burn might not produce sufficient pressure head for an accurate  $\Delta P$  measurement. A capacitance probe would have to extend to the center of the tank. Some method of low-gravity gauging is desirable.

### Lunar Surface Access Module – Descent Stage

The LSAM descent stage performs the LOI burn, and together with the ascent stage undocks from CEV and takes crew and cargo to the lunar surface.

<b>PDR:</b>	September 2011
<b>CDR:</b>	September 2013
<b>Propellants:</b>	Liquid Hydrogen / Liquid Oxygen; pump-fed
<b>Tank Geometry:</b>	Cylindrical, domed ends, ~ 7 ft. diameter. 6 LH2 tanks, 2 LOX tanks
<b>Quantity:</b>	~ 55,000 lbm
<b>Duration:</b>	one week – months (depending on CEV launch delay)
<b>Critical burns:</b>	Lunar orbit injection; descent and landing
<b>Baseline gauge:</b>	Capacitance probe level sensors, burn-time integration

As with the EDS, the LSAM tanks will likely need to be gauged with certainty before launch of the CEV. Gauging uncertainties due to liquid sloshing may be unacceptably high.

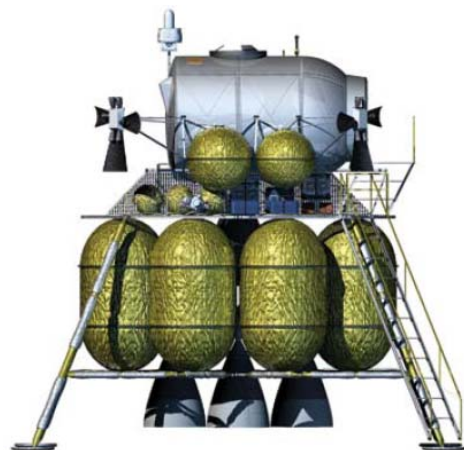
### Lunar Surface Access Module – Ascent Stage

The LSAM ascent stage transports the crew back to the CEV in LLO. The ascent stage also houses the Reaction Control System (RCS) thrusters used during descent, ascent and LOR.

<b>PDR:</b>	September 2011
<b>CDR:</b>	September 2013
<b>Propellants:</b>	Liquid Methane / Liquid Oxygen; pressure fed
<b>Tank Geometry:</b>	Spherical, ~ 5 ft. diameter. Only two tanks may be required in the minimal ascent stage design (one methane, one oxygen)
<b>Quantity:</b>	~ 7800 lbm, minimal ascent ESAS design
<b>Duration:</b>	weeks - months
<b>Critical burns:</b>	RCS maneuvers during descent; ascent from lunar surface; rendezvous and docking with CEV; disposal
<b>Baseline gauge:</b>	Capacitance probe level sensors, PVT, burn-time integration

Settled gauging for the ascent stage is certainly appropriate while on the lunar surface, but the possibility of long durations in space, the harsh environment, a new fuel, and the criticality of gauging the ascent tanks makes gauging the ascent tanks a higher risk.

The cost of gauging uncertainties comes at a high price. *Carrying an extra 1% of propellant margin to cover a 1% uncertainty in the LSAM propellant mass translates to over 600 lbm of reduced payload delivered to the lunar surface.*



## SETTLED VS. LOW-GRAVITY GAUGING

Although there are opportunities for settled gauging in a lunar exploration mission, a low-gravity gauging technology could offer performance benefits if it proves to save propellant and reduce gauging uncertainties at critical times. The settled-gauging uncertainties are likely to be highest when the EDS-LSAM is in LEO and an accurate measurement is needed before launching the CEV, and also during LSAM landing and ascent stage docking with CEV. These periods are all likely to have propellant sloshing which could give erratic level sensor readings. Furthermore, there could be situations where it is desirable to obtain an accurate propellant quantity measurement without performing a settling burn.

While the EDS-LSAM vehicles are in LEO, the atmospheric drag on the vehicle will require small station-keeping burns to maintain the proper orbit. Suppose it is desired to obtain a settled-liquid gauging measurement during such a thrust maneuver. With effective tank baffling in place to dampen the slosh waves, it may be possible to obtain a rough measurement of propellant level within four slosh periods. Assuming a net 400 lbf (1780 N) of thrust, and a combined vehicle mass of 364,000 lbm (165 mT), the resulting vehicle acceleration is  $a = 0.011 \text{ m/s}^2$ . The lowest-mode slosh frequencies of the tanks can be calculated from reference 8. For the EDS tanks, which are slightly less than half full, the lowest slosh frequencies are estimated to be approximately 0.01 Hz. Assuming the LSAM tanks are nearly 95% full, the lowest slosh frequencies are estimated to be 0.027 Hz for the descent stage tanks and 0.036 Hz for the ascent stage tanks. Thus, in this example, waiting four slosh periods would require  $\sim 400 \text{ s}$  to gauge the EDS tanks, and  $\sim 150 \text{ s}$  to gauge the LSAM tanks. The  $\Delta v$  (velocity change) resulting from 400 s of such a thrust is 4 m/s, compared to a typical average annual budget of  $\sim 25 \text{ m/s}$  for atmospheric drag compensation in LEO. Thus, the amount of propellant used to settle the tanks may not be much different than normal station-keeping propellant budgets, but the uncertainty associated with the measurements needs to be analyzed. Obviously, the LEO propellant-settling problem needs to be investigated in much more detail. Inertial effects have been neglected and will play a significant role in the fluid dynamics, and realistic station-keeping operations need to be included in the model.

## CONCLUSIONS

The fleet of new exploration vehicles and mission architectures presents new challenges and opportunities for propellant gauging. It is very likely that many of the gauging technologies that have been used in past will be implemented on the new vehicles unless new technologies can demonstrate a performance benefit. Low-gravity propellant gauging technologies are desired to reduce uncertainties at critical times, and to eliminate the need for settling. However, there is no easy solution to the low-g gauging problem. More work is needed to analyze the prospects of settled gauging in LEO, and also to analyze the consequences of gauging uncertainties.

## ACKNOWLEDGEMENTS

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