CREATING A SPACETUG FOR SPACE EXPLORATION BY MODIFYING THE ULA COMMON CENTAUR UPPER STAGE: M. E. Evans[1] and L. D. Graham[1], [1]NASA Johnson Space Center, Astromaterials Research and Exploration Science (ARES) Division, michael.e.evans@nasa.gov, lee.d.graham@nasa.gov

Introduction: Space exploration requires the movement of materials from Earth to remote destinations, but reliance on large, Heavy Lift Vehicles (HLVs) limits access for many projects. The recent growth of (relatively) inexpensive Commercial Launch Vehicles (CLVs) capable of delivering 15-20 metric tonnes of payload to Low Earth Orbit (LEO) opens the need for a transfer vehicle to deliver these payloads to interplanetary trajectories. Modification of existing, mature, commercial Upper Stage Vehicles (USV) into a transfer vehicle is appealing from a cost, schedule, and reliability aspect. This project selects the United Launch Alliance (ULA) "Common Centaur" to create a "SpaceTug" with high efficiency propellants of Liquid Oxygen (LOX) and Liquid Hydrogen (LH_2) as a transfer vehicle for payloads to/from LEO.

Background: The Centaur program has a long and successful history of flying since 1958. The Common Centaur evolved from the Atlas IIIB program, and was first launched in February 2002 [1]. The Centaur family now includes both the single-engine common Centaur and a double engine variant [1]. Both versions are available on the current Atlas 5 rocket. The single engine Common Centaur is a more flexible USV since it could be flown within the existing diameter of available 4.2m CLV fairings on ULA and SpaceX, or on the European Space Agency (ESA) Arianne 5 [2]. Discussions at SpaceX are underway to use larger fairings for future military contracts [3].

Concept of Operations: Conceptually, the SpaceTug is launched on a CLV near the same time as its intended payload (which is launched on a separate CLV). The SpaceTug conducts an autonomous rendezvous in LEO and mates with the payload. The SpaceTug then provides the necessary change in velocity (ΔV) to achieve the desired payload trajectory.

Vehicle Specifications: The proposed SpaceTug dry mass is 2.75 mt (adding 0.5 mt for vehicle modifications to the Common Centaur) with the same Centaur-III propellant load of 20.83 mt (total mass = 23.6 mt). The SpaceTug is designed to stack together in LEO to become a 2-stage vehicle for pushing heavy payloads from LEO to TLI and beyond. As shown in Figure 1, a single SpaceTug has the ability to deliver nearly as much mass from a 400 km circular 28.5° LEO to TLI (16.2 mt) as a SpaceX Falcon Heavy (predicted 16 mt) [4]. A double SpaceTug can deliver significantly more more payload from LEO to TLI (34.3 mt) than a SLS Block 1 using the Interim Cyrogenic Propulsion Stage (ICPS) (predicted 27.5 mt) [5].

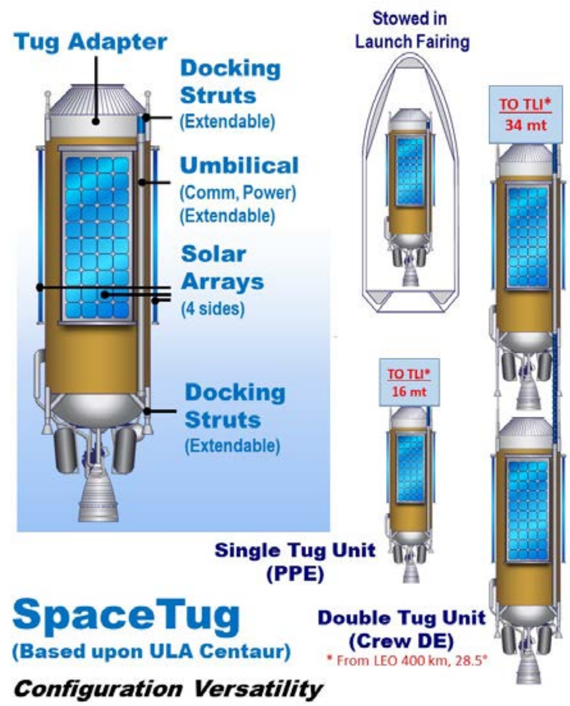

Figure 1: SpaceTug Configurations

Minimizing Cryogenic Propellant Boil-off: To support SpaceTug loiter time on-orbit, the boil-off of cryogenic LOX/LH_2 must be minimized. The original Titan/Centaur was designed to support an eight-hour mission with a boil-off rate of 2%/day [6]. ULA has developed and patented numerous concepts to store propellant on-orbit [7, 8]. The SpaceTug requires the ULA Integrated Vehicle Fluids (IVF) technology developed for the new Advanced Crtyogenic Evolved Stage (ACEs). ACES is planned to fly on the ULA Vulcan rocket beginning in 2021 [9] to re-pressurize the system and provide power to the vehicle [10]. This also removes the need for Hydrazine or Helium as tank pressurizers, or heavy batteries for electrical energy storage. An alternative design, using the Centaur USV as a secondary tank - called the CRYogenic Orbital Test (CRYOTE) concept - has been conceived with up to 1 year of storage of cryogenic propellants on-orbit [11, 12]. Building on CRYOTE tests, a follow-on ULA concept uses a "Drop Tank" which waits in LEO for "days, weeks, or even months" to refill a Centaur USV launched on a subsequent mission [6]. The Drop Tank remains attached to its depleted USV and spins slowly (1°/sec) to provide centrifugal acceleration that settles the cryogenic fluids. The Drop Tank design includes features to minimize boil-off with insulated blankets, lightweight materials, a vacuum insulated common bulkhead and low conductivity struts. The expected boil-off is under 0.1%/day of the total propellant load. Studies with “Zero-Boil-Off” (ZBO) systems show that spacecraft with proper insulation, and/or small cryocooling systems, could provide for months of liquid hydrogen storage without evaporation [13, 14]. The anticipated result is an expectation that the daily boil-off rate for the SpaceTug is < 0.5%/day of cryogenic propellants.

Other Modifications: A new Tug Adaptor (TA), replacing the Common Centaur Payload Adaptor atop the LH_2 tank, , provides the electronics and re-pressurization system components for the SpaceTug. The TA also houses the retractable docking struts and umbilical connections for mating the SpaceTug to other vehicles (including other SpaceTugs). Additional electrical power is provided to the SpaceTug with solar arrays affixed on each side, which cover Multi-Layer-Insulation (MLI) blankets to reduce solar heating into the propellant tanks. The power generated by the SpaceTug creates a robust, independent vehicle capable of precision maneuvering and longer mission durations. The SpaceTug is an autonomous vehicle that operates independently or collaboratively when stacked with other SpaceTugs.

On-orbit Fluid Transfer: The SpaceTug includes umbilical connections for cryogenic transfer on-orbit. A challenge of this transfer is evolved gas release during the fill process. “No-vent-fill” designs, tested by NASA in the 1990s ([15, 16], used cold-liquid thermodynamic properties to condense the vapor in the tank [6]. NASA and Yetispace have conducted tests on Earth demonstrating successful liquid nitrogen transfer under flight-like conditions [17]. Additionally, in 2019 a company built an experiment “Furphy” on the ISS that successfully demonstrated the transfer of water on-orbit [18]. The technology gap must be closed to support long-term harvesting of planetary resources to fuel space vehicles. The on-orbit transfer of LOX/LH_2 is also enabling for future Mars and asteroid exploration.

Enhanced Capabilities: Future adaptations to the SpaceTug could enable landing on other worlds. The propellant tanks could then be refilled with LOX/LH_2 harvested from insitu regolith or water ice. The SpaceTug provides both a storage system and a transportation engine for a fuel depot. Numerous lunar studies have been published detailing the necessary technology and infrastructure requirements for this capability [19-22]. ULA has developed a concept to transform an ACES into a horizontal lander. Called the XEUS, it provides a novel design to deliver crew and cargo to the lunar surface [10]. The SpaceTug would require additional structural components and attitude control systems for descent, hover, and touch-down.

An additional concept for future SpaceTug design is aerocapture. Rather than have a nearly-empty vehicle de-orbit directly to Earth after delivering components from elsewhere, the needed deceleration could be performed with an inflatable shield that would slow the SpaceTug to Earth orbit velocities [21]. The SpaceTug could then rendezvous with ISS (or other Earth orbiting vehicles) for reuse.

The SpaceTug could be human rated to support crew transport beyond LEO. This could enable deep space exploration with commercial crew vehicles.

Summary: The proven ULA Common Centaur could be modified to become a SpaceTug capable of delivering payloads, reboosting platforms, storing and transferring propellants to other vehicles, conducting independent science missions, or transporting crew beyond LEO. The SpaceTug reduces dependency on large, expensive HLVs by adding transfer capability to payloads delivered to LEO by relatively inexpensive CLVs.

References: [1] Rudman, T.J. and K.L. Austad (2002), *4th IAC on Launcher Technology*. [2] Kyle, E. (2019), https://www.spacelaunchreport.com/. [3] Ralph, E (2019), https://www.teslarati.com/spacex-agreement-ruag-bigger-falcon-fairings/ [4] Tito, D.A., (2013) *IEEE Aerospace Conference*. [5] Donahue, B. and S. Sigmon (2019) *IEEE Aerospace Conference.* [6] Kutter, B.F. (2015), *AIAA SPACE 2015 Conference and Exposition*. [7] Kutter, B.F., F.C. Zegler, and M.R. Ragab, (2012), *Google Patents*. [8] Zegler, F.C., (2017), *Google Patents*. [9] Alliance, U.L. (2019), https://www.ulalaunch.com/about/news/2019/08/14/snc-selects-ula-for-dream-chaser-spacecraft-launches [10] Barr, J. (2015), *AIAA SPACE 2015 Conference and Exposition*. [11] McLean, C., (2011), *2011 Aerospace Conference*. [12] Gravlee, M., (2012), *Cryogenics*, 52(4-6), 231-235. [13] Sun, X.-w., Z.-y. Guo, and W. Huang, (2015), International Journal of Hydrogen Energy, 40(30), 9347-9351. [14] Plachta, D.W., W.L. Johnson, and J.R. Feller (2016), *Cryogenics*, 74, 88-94. [15] Taylor, W. and D. Chato (1992), *28th Joint Propulsion Conference and Exhibit*. [16] Chato, D.J., et al. (2002), *IAC-02 V*, 5(05). [17] Stephens, J., et al. (2019), *NASA Technical Reports Server*. [18] Foust, J (2019), https://spacenews.com/orbit-fab-demonstrates-satellite-refueling-technology-on-iss/. [19] NASA (1988), *The Second Conference on Lunar Bases and Space Activities of the 21st Century*. [20] Eckart, P. and B. Aldrin (1999), *The Lunar Base Handbook, An Introduction to Lunar Base Design. Development, and Operations.* [21] Oeftering, R. A (2011), *AIAA SPACE 2011 Conference & Exposition*. [22] Spudis, P.D. (2016) *The Value of the Moon: How to Explore, Live, and Prosper in Space Using the Moon's Resources*.