ASTEROID PROVIDED IN-SITU SUPPLIES (APIS™): TECHNOLOGY AND MISSION ARCHITECTURE TO ENABLE AFFORDABLE HUMAN EXPLORATION AND INDUSTRIALIZATION OF SPACE, J. C. Sercel[1], A. Abbud-Madrid[2], C. B. Dreyer[3], J. R. French[4], and R. Jedicke[5]. [1]TransAstra Corporation (11404 Camaloa Avenue, Lake View Terrace, CA 91342, sercel@transastracorp.com), [2]Colorado School of Mines (Center for Space Resources, Golden, CO 80401, aabbudma@mines.edu), [3]Colorado School of Mines (Center for Space Resources, Golden, CO 80401, cdreyer@mines.edu), [4]JRF Aerospace Consulting LLC (3335 Punta Alta, Laguna Woods CA, frnchspace@aol.com), [5]University of Hawai`i (Institute for Astronomy, 2680 Woodlawn Dr., Honolulu, HI, 96822, jedicke@hawaii.edu).

Introduction: In the summer of 2014 the NASA Advisory Council issued a major recommendation to NASA indicating that the single largest issue faced by the agency is a "mismatch between NASA's aspirations for human spaceflight and its budget."[1]. Since that time TransAstra Corporation and its university and NASA partners have been working diligently on the Asteroid Provided In-Situ Supplies (Apis™) mission and system architecture. Apis is a breakthrough approach to cislunar and exolunar transportation in which reusable space tugs are supplied by propellant derived from Near Earth Objects (NEOs) and the Martian moons to eliminate the need for the launch of costly expendable upper stages or the transport or rocket propellant, mission consumables, and radiation shielding from the Earth. The goal of the Apis™ architecture is to save NASA enough money in terms of expendable upper stages and consumables to bridge the gap between NASA's aspirations for human space flight and its budget and to make profitable the concurrent industrialization and colonization of space.

TransAstra Corporation with its partners and coordinated related research efforts has accomplished the following:

- Performed a full-scale proof of concept demonstration of Optical Mining™, our innovative breakthrough method of solar thermal asteroid ISRU, which promises to allow extraction of tens of tons of water and carbon dioxide per week from 1,000 ton class asteroids based on a required plant mass of less than 2,000 kg.
- Invented and analyzed the performance of a new breakthrough propulsion technology called the Omnivore™ thruster which promises to use, concentrated solar power in conjunction with the raw, unprocessed effluents of Optical Mining™ to deliver thrust levels up to 100 times that of solar electric propulsion but without the need for large, costly solar electric power systems or tons of propellant launched from the Earth at high cost.
- Demonstrated a statistical method of analysis that allows the estimation of available asteroid ISRU resources as a function of return trip ΔV and trip time. Completed the conceptual design and performance analysis of the Apis reusable cis-lunar transportation architecture which is supplied from asteroid resources and which can be developed as a public-private partnership to reduce NASA's cost for human exploration while establishing a new commercially viable industry in space.
- Planned an integrated research and development roadmap to mature Apis™ component and systems level technologies based on rapid, agile ground based technology maturation concurrent with an innovative, early flight demonstration of Optical Mining™ technology on ISS followed quickly by a low-cost, subscale demonstration of the end-to-end Apis flight system technology in LEO concluding with a full scale demonstration mission to harvest up to 100 tons of ice from a NEO and return it to cis-lunar space with a trip time of about 3 years based on the launch of a single Falcon 9.

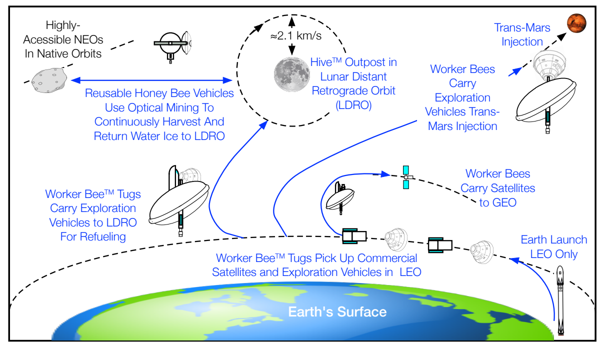

Figure 1 – Top-Level Diagram of Apis™ Architecture

Apis™ is named for the honeybee genus because like bees Apis efficiently gathers and returns useful resources and then utilizes those resources to perform useful work. In this case the resources are volatile materials from highly accessible asteroids and the useful work is transportation services for NASA's missions of human exploration of space. To do this, the Apis™ architecture comprises several elements including Honey Bee™ asteroid mining vehicles, Worker Bee™ reusable deep space tugs, and the Hive™ consumables depot and outpost in lunar distant retrograde orbit (LDRO) as shown in Figure 1. Together, these systems form a cost effective reusable cis-lunar transportation network supplied by asteroid resources which eliminate the need for launching large quantities of consumables to support human exploration of deep space beyond LEO. Lightweight, thin film solar concentrators,

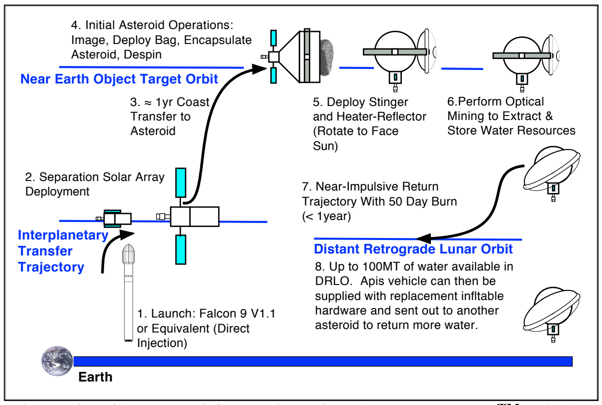

Figure 2 – Concept of Operations for First Honey Bee™ Mission

structures, and optical systems are key features of all elements of the Apis™ architecture which relies on raw solar thermal power in place of electrical power for all materials processing and propulsion functions.

We have created a concept-level design of a first full-scale project using the Apis™ architecture. In this first Honey Bee™ mission, a version 1.0 of the Apis™ architecture will enable a spacecraft launched on a single Falcon 9 class rocket to harvest and return to LDRO approximately 100 tons of water from an ARM-like NEO. Depicted conceptually in Figure 2, the first Honey Bee™ mission operations start with a Falcon 9 or equivalent launch to a low C3 transfer to a low ΔV volatile-rich NEO (step 1 in the figure). After launch, solar arrays are deployed and the Honey Bee™ vehicle performs a deep space cruise to the target. Once at the target (step 3), an inflatable capture system similar to that proposed for the Option "A" ARM mission, but designed to enclose the target with a nearly hermetic seal, is used to capture and control the asteroid. Note that NASA and JPL spent millions of dollars on this thin film inflatable capture mechanism and concluded that it was ready to be baselined on the ARM mission as documented in Wilcox 2015. JPL has published work showing extensive modeling, simulation, and engineering demonstrations of large scale hardware proving the feasibility of this approach at TRL-4. After the asteroid is encapsulated and the system de-spun (step 4), inflatable solar concentrators currently at TRL 3-4 provide direct solar thermal heat to the asteroid (step 5).

We have designed the Worker Bees™ transportation network to be confident of system performance and mass based on spacecraft scaling laws, physics-based estimates of the unproven technologies, and conservative margins. ΔVs and trip times have been estimated based on impulsive trajectory approximations with adjustments made for gravity loss and other factors. Figure 3 provides a parametric analysis of the effect of rendezvous altitude for cargo transfer between the injection orbit of a launch vehicle and LDRO. The OTVs are assumed to rendezvous with the launch vehicle payload and take it the rest of the way to LDRO. The apogee of the launch orbit is varied between 400 km (circular LEO) and 100,000 km to determine the optimum rendezvous altitude for payload transfer. Each Worker Bee is assumed to be able to complete the round trip 10 times prior to hardware retirement.

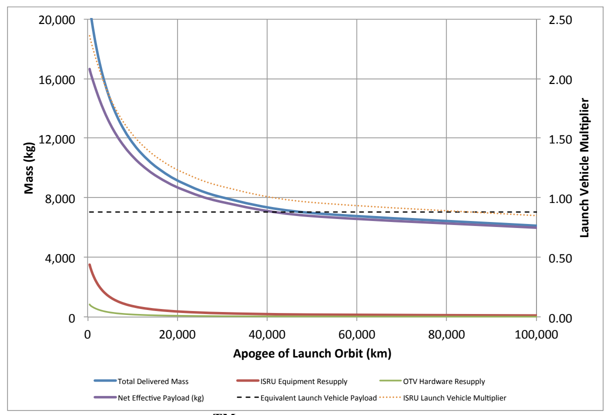

Figure 3 – Worker Bee™ Performance for LDRO Cargo Mission

Propellant for the Worker Bees is supplied from the Hive™ water depot in LDRO. The launch vehicle is modeled as a medium-heavy system based on LOX-RP1 with a LEO payload capability of 20,000 kg. For the comparison case without Worker Bees, the launch vehicle is assumed to use a LOX-LH2 high energy 3rd stage for direct delivery of cargo to LDRO. Worker Bees™ is penalized for ISRU equipment resupply and OTV equipment resupply in the purple line labeled "Net Effective Payload". The launch vehicle multiplier (read on the right-hand axis) is the ratio of the net effective payload with Work Bees to the payload of the launch vehicle with the expendable high energy upper stage. The results of this study show that:

i) the optimum altitude for Worker Bees to pickup payload for delivery to LDRO is LEO, and
ii) even without aerobraking, the net effective launch vehicle payload is more than doubled by the use of Worker Bees supplied from LDRO in place of rocket 3rd stages.

References:

[1] Squyres, Steven (2014) NASA Advisory Council Recommendation.