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Swamp Works: A New Approach to Develop Space Mining and Resource Extraction Technologies at the National Aeronautics & Space Administration (NASA) Kennedy Space Center (KSC)

Prospecting, Excavation, Load, Haul, & Dump for In-Situ Resource Utilization (ISRU)

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ABSTRACT

The first steps for *In Situ* Resource Utilization (ISRU) on target bodies such as the Moon, Mars and Near Earth Asteroids (NEA), and even comets, involve the same sequence of steps as in the terrestrial mining of resources. First exploration including prospecting must occur, and then the resource must be acquired through excavation methods if it is of value. Subsequently a load, haul and dump sequence of events occurs, followed by processing of the resource in an ISRU plant, to produce useful commodities.

While these technologies and related supporting operations are mature in terrestrial applications, they will be different in space since the environment and indigenous materials are different than on Earth. In addition, the equipment must be highly automated, since for the majority of the production cycle time, there will be no humans present to assist or intervene. This space mining equipment must withstand a harsh environment which includes vacuum, radical temperature swing cycles, highly abrasive lofted dust, electrostatic effects, van der Waals forces effects, galactic cosmic radiation, solar particle events, high thermal gradients when spanning sunlight terminators, steep slopes into craters / lava tubes and cryogenic temperatures as low as 40 K in permanently shadowed regions. In addition the equipment must be tele-operated from Earth or a local base where the crew is sheltered. If the tele-operation occurs from Earth then significant communications latency effects mandate the use of autonomous control systems in the mining equipment. While this is an extremely challenging engineering design scenario, it is also an opportunity, since the technologies developed in this endeavor could be used in the next generations of terrestrial mining equipment, in order to mine deeper, safer, more economical and with a higher degree of flexibility. New space technologies could precipitate new mining solutions here on Earth.

The NASA KSC Swamp Works is an innovation environment and methodology, with associated laboratories that uses lean development methods and creativity-enhancing processes to invent and develop new solutions for space exploration. This paper will discuss the Swamp Works approach to developing space mining and resource extraction systems and the vision of space development it serves. The ultimate goal of the Swamp Works is to expand human civilization into the solar system via the use of local resources utilization. By mining and using the local resources *in situ*, it is conceivable that one day the logistics supply train from Earth can be eliminated and Earth independence of a space-based community will be enabled.

INTRODUCTION

Resource materials in space are primarily contained in the regolith of target bodies such as asteroids, comets, Mars, Mars moons, and lunar cold traps. Following remote sensing data collection, then a sample must be obtained for “ground truth” characterization. Science and *In Situ* Resource Utilization (ISRU) customers need proven technologies and devices for regolith and volatiles sample acquisition in very challenging environmental conditions such as micro-gravity (1/1000th G), low temperatures (40 K) and dusty environments (< 100 μm particles). These samples will help us to better understand the solar system and assess the value of resources for human and robotic exploration purposes. NASA’s Lunar Resource Prospector Mission planned for 2020 is focused on a lunar south pole exploration by a rover near the impact site of the recent Lunar CRater Observation and Sensing Satellite (LCROSS) mission in order to obtain ground truth on the lunar surface. However, the Resource Prospector mission is limited in its ability to sample the cryogenic cold traps (~ 40 K) in the crater’s permanently shadowed regions for power and mobility reasons, so new technologies and prospecting devices will be required for future missions to access and sample similar deposits of interest. Other target bodies such as asteroids and Mars moons will also need prospecting and characterization. When NASA relocates a fragment of a NEA in a stable orbit around the Moon with the Asteroid Re-direct Mission (ARM) the object will be in position for repeated ISRU demonstrations in lunar orbit. Sampling devices will be needed to prospect the asteroid for useful resources, such as water on a carbonaceous chondrite and this technology development will benefit robotic missions to other NEAs or other target bodies in the asteroid belt. The Mars moons and Mars itself, are also of interest for ISRU purposes and will require efficient technology combinations to assess subsurface mineral and water deposits on a larger scale to support extended human presence with robotic devices or by human crews to follow-up on remote sensing data.

NASA’s Evolvable Mars Campaign is a comprehensive study currently underway on the wide array of technologies and engineering needs required to establish a human-tended Mars Exploration site with the goal of achieving logistical near-independence from Earth during extended surface stays of 500 days; this goal requires ISRU. In parallel, private investments in space resources discovery and exploitation are beginning, spurred by early start-ups that provide the necessary public-private synergy to advance the possibility of permanent human presence in space by enabling its pioneering. The development of needed technologies must begin now and progress in an evolutionary way through testing in space under most relevant conditions while serving mission objectives.

The range of functionalities and uniqueness of the ISRU space equipment require an approach to R&D that emphasizes rapid concept-design-test cycle with immediate exposure to regolith as the most challenging medium: the Swamp Works approach.

SWAMP WORKS LABORATORIES: LEAN DEVELOPMENT OF NEW SPACE EQUIPMENT

The Swamp Works is a new KSC facility established in 2013 with the strong heritage of several laboratory groups as a lean development environment to provide rapid, innovative and cost effective exploration mission solutions for NASA and commercial space industry with the vision of being the premiere U.S. government laboratory for development of surface systems at any space destination. Our mission is to provide government and commercial space ventures with the technologies they need for working and living on the surfaces of the Moon, planets, and other bodies in our solar system with a particular emphasis on finding and exploiting local resources.

Firmly rooted in the rich history of successful methodologies developed by the National Advisory Committee for Aeronautics (NACA) and early NASA, the research and development philosophy put in practice at KSC Swamp Works is aligned with those used in Kelly Johnson's Skunk Works and Werner von Braun's development shops. At its core, the Swamp Works approach promotes early hands-on concept development by highly competent small teams focused on executing an iterative design-build-test cycle over short periods of performance. Swamp Works teams leverage existing and new partnerships across NASA, industry and academia to achieve the synergy of complementary expertise in order to achieve meaningful testing as early as possible during which failures are openly allowed to drive designs forward. This emphasis on early solution finding through rapid test/learn iterations is best served through the practice of Agile methods of project management in contrast with the traditional methodology practiced by large design teams. The adoption of an Agile approach yields many tangible and less tangible improvements in performance: design sprints and regular short peer-reviews during design and test phases enable strong schedule control while energizing team collaboration; exposing young engineers to all faces of the project within a short time, regular brainstorming sessions on far-reaching concepts in positive open forum atmosphere and conducting technical work on different projects in a large viewable space contribute strongly to team cohesion, buy-in, self-motivation and retaining highly skilled personnel.

The centerpiece of the physical workspace is a high-bay space hosting most of the projects conducted by the Granular Mechanics and Regolith Operations (GMRO) laboratory including NASA's largest Regolith Test Bed (8 m X 8 m X 1.5 m deep) enclosed in a dust-sealed and air-flow controlled transparent chamber enabling repeated hardware testing in regolith at relevant scales (Fig. 1.) In its totality, Swamp Works world-class laboratories cover 900 m^2 that also include three wet laboratories. In addition to GMRO, the main laboratories are the Applied Chemistry Lab focused on analysis and chemical processing of space resources, the Electrostatics and Surface Physics laboratory focused on static and dynamic electrical phenomena and energy storage in space environments, and the Advanced Life Support laboratory focused on next generation support for deep space crews including the technologies food production using local planetary resources.

The "Innovation SPACE" on mezzanine is a unique, reconfigurable meeting space overlooking the GMRO high bay to foster collaborative innovation through ideas generation, brainstorming operational concepts, peer-review sessions, and daily project management activities.

Critical Needs of Deep Space Sustainability

The NASA Evolvable Mars Campaign (EMC) is developing the plans and systems needed for a robust, evolutionary strategy to explore cis-lunar space, the Mars sphere of influence (including the moons of Mars), and the surface of Mars (Bobskill et al, 2015.) Recently, the emphasis of NASA's plans has changed to focus on the prolonged pioneering of space, rather than focusing on a limited number of exploratory crewed missions as the ultimate goal. A sustainable, pioneering vision of space would include *in situ* resource utilization (ISRU) in multiple forms and at multiple destinations such as atmospheric capture of Mars CO_2 and/or volatiles for consumables and propellants, regolith for bulk use and extracted materials, and *in situ* manufacturing at Mars, and other bodies. The utilization of these resources as an integral piece of the space exploration architecture would greatly enable a reduction in the logistical needs from Earth for future missions, thus preparing the way for a sustained presence on Mars. Although the EMC initially relies only on

ISRU for propellant production for the Mars ascent vehicle to launch the crew off the Mars surface for their journey back home, one of its primary objectives is to prospect at every EMC destination to understand the potential for ISRU; this will permit true pioneering to be enabled after the first crew arrives at Mars.

Mars is a deep space destination beyond the Moon where humans can aspire both to survive and to settle. The relative positions of Earth and Mars and associated orbital mechanics make the journey to Mars and back orders of magnitude longer than the ones made to the Moon; thus, the technical requirements and constraints, as well as the risks, are orders of magnitude greater. The achievement of a sustained and safe presence of humans on a planet months away of travel from Earth is more likely to succeed if the crew is equipped with the technical ability and know-how to become self-reliant. In pioneering situations on Earth, the knowledge and tools to access local resources and transform them into needed consumables or items has often made the difference between a thriving endeavor and its demise. Since other planets are not readily habitable and humans are not physiologically adapted to space environments, this need for self-reliance becomes even more important.

The quest to discover, assess and eventually acquire valuable mineral-based resources in space has received great attention in the past decade and been joined by many new institutions pursuing various goals and interests. The major governmental space agencies of Europe (ESA, DLR, CNES), Japan (JAXA), China (CNSA), India (ISRO), and Russia (Roscosmos) all have at least plans to investigate and explore space resources in the coming decades. On par with NASA, ESA and its national partner space agencies CNES (France), DLR (Germany) have developed and are conducting deep space missions to perform preliminary resource assessment of comets (Rosetta mission) and asteroids (Asteroid Impact and Deflection Assessment mission in planning with NASA). Similarly, NASA is conducting investigations of several asteroids and their resources with deep space missions such as the Dawn mission to protoplanets Vesta and Ceres in the asteroid belt between Mars and Jupiter orbits, and the upcoming OSIRIS-ReX mission to the volatile-rich carbonaceous asteroid Bennu. NASA is preparing a Resource Prospector mission to a lunar polar region for 2020 where it will drill and process subsurface samples thought to contain several percent by weight of water ice. China’s CNSA has announced plans to conduct a similar mission. Meanwhile, India’s ISRO has performed a lunar mineralogical mapping mission with Chandrayaan-1 and JAXA has also achieved detailed terrain and mineralogical mapping of the Moon with its Kaguya (Selene-1) mission. All these government actors have so far all announced, developed or conducted their plans as part of international scientific missions that widely share the data collected and analysed by scientists.

More recently, private corporations have been created to pursue the direct commercial exploration of mineral resources on other planetary bodies. Backed at various levels by private investors, these companies have targeted asteroids and the Moon as exploratory locations for resources such as water and platinum-group metals (PGM). Planetary Resources, Inc. and Deep Space Industries, Inc. are currently developing early versions of specialized space telescopes for resource detection of distant asteroids to catalogue these objects in privately owned databases. Moon Express and Shackleton Energy are developing moon landers designed for the rapid evaluation of water and minerals of interest in the lunar subsurface.

The current global picture depicts national space agencies and a few new private start-up corporations all announcing plans and intentions and some investing in the early stages of space resources exploration. While data on specific governmental and private investments in the exploration phases are not readily available, we estimate the range of global current annual investments to be around $150–250M. In addition, investments are being made in technologies enabling the processing of space resources ranging from drilling and mining to chemical reactors for extraction. In western countries, these investments are estimated to be on the order of $70–120M annually, mostly in government-funded programs.

This emerging landscape of a possible new space-based industry is characterized by modest investments so far but is also populated by very motivated actors pursuing very specific goals. It is also characterized by rapid development of critical technologies generating important intellectual property for the future. In the absence of an international framework on space resources property rights, it is also clear that the institutions involved are positioning themselves to have a voice on future negotiations by proving themselves in space itself. The realization that the technological advances make new concepts feasible has emboldened both space agencies (e.g. NASA’s ARM, OSIRIS-ReX and ESA’s Rosetta missions) and private entrepreneurs to shift to a new gear in the search and use of space resources.

Projects focused on confronting the harshest challenges

Excavation and regolith transport

Swamp Works projects are focused on finding pragmatic solutions for the acquisition of mineral resources in space by including the critical space-constrained design variables at the onset of concept evolution. The immediate use of relevant simulant mineral materials and the awareness of the level of gravity force in the design constrain the outcome of the engineering to viable solutions that warrant early testing. The development of the counter-rotating Regolith Advanced Surface Systems Operational Robot (RASSOR) excavator is a prime example (Fig.2.) In the face of very low or micro-level gravity forces on the Moon (1/6 G) and asteroids (1/1000th to micro-G), the US-patented RASSOR design provide the necessary traction and reaction force during excavation by using the resulting force applied to the surface by the counter-rotating bladed drums that collect regolith material for transport (Mueller et al, 2013.) Reversal of the drum rotation allows the dumping of the material for processing or berm erection. The excavation of icy regolith containing varying amounts of bound ice is also a priority in various environments. The challenge was confronted in the VIPER project in which a series of percussive actuated blade concepts were tested from a stationary platform in materials simulating lunar basalts mixed with ice (Fig. 3.) The test data informed the development of RASSOR and provide the engineering team the opportunity to build experience with ice-regolith mixtures and their characteristics through many attempts at creating them and shaping them with hand tools. Pneumatic transport of regolith has also received much attention with the goal of rapidly transferring excavated regolith into hoppers feeding extraction reactors.

Launch and Landing Pads on Other Planets

Spacecraft launching and landing on unprepared soils and regolith expose these granular materials to high velocity hot gas flows and eject particles of wide range of sizes by cratering or surface scoring. Recent studies of these phenomena based on previously unnoticed evidence of ejecta damage during past lunar missions (Immer et al. 2011) have led to careful monitoring of the landing of the Mars rover Curiosity that revealed dust-induced vision obstruction of the landing zone and damage on sensors during landing (Vizcaino et al, 2015).

The Swamp Works labs approach this problem on several fronts. The one-of-a-kind large test enclosure for regolith operations (aka. Big Bin) enables the creation of calibrated dust environments with metered dust flows for operational testing of various sensor technologies. The dimensions of the facility make possible a wide range of evaluations and investigation at near and mid-ranges of detection and the simultaneous testing of multiple technologies configured together as in real-world applications. Low-pressure or evacuated enclosures can be set-up inside the Big Bin for the creation of in-space conditions during landings on different planetary or asteroid locations for repeated measurements and variation of operating conditions and configurations. These investigations enable early proof-of-concept of new sensor technologies with rapid test cycles because of the closed-loop dust control system of the Big Bin and the large space offered for test operations.

The ejection of regolith particles of varying sizes during landings poses major risks to infrastructure previously deployed at the site and to the landing spacecraft itself. The problem is seen as critical to solve for the future human Mars landings that will occur at sites with pre-deployed spacecraft for return to Earth and habitats. Current estimates of material ejecta under martian conditions recommend a safe zone between 700 m and 1 km for a human-class lander under consideration for the Evolvable Mars Campaign. The protection of the surface elements in the vicinity of a landing site may come from several solutions or their combinations: provide adequate shielding, and distribute elements across the landscape at adequate distances. As the number of missions increases that carry supplies, hardware elements, and crew so does the number of landings and the requirement on minimum distances demands the transport of large hardware over terrain and long distances or selecting new landing sites away from the settlement. Such strategy involves complex and time-consuming logistical transports with the risk they pose to mission assurance on another planet and may ultimately require the addition of mass-intensive transport solution such as rail to build the Mars base away from landing sites. Providing shielding offers a more flexible operational solution that can be adapted to the mass-constrained Mars missions. Shielding can be designed in each element such as habitat, crewed rover, return spacecraft and resource processing plants; this solution can provide high flexibility to move elements anywhere at the Mars site by relying on their individual protection shields but it adds mass to each element that must be launched from Earth and thus imposes large mass penalties across the Mars campaign that may translate into additional launches.

Swamp Works has a series of projects underway to provide solutions for protection of spacecraft and surrounding hardware during launch and landing on planetary surfaces. The concept of shielding of Mars site infrastructure elements is being investigated as a combination of mitigating the creation of high-velocity ejecta and using local regolith materials to erect berms, expanding natural shield features and movable impact shield structures. Lightweight composite blades have been designed with quick attach mounts for use by heavy transporters conceived to carry large hardware on Mars. Recent integrated tests conducted at Desert Rats campaigns have shown superior performance in efficient soil moving for surface work and berm erection in normal gravity (Fig. 4.) The combination of excavators such as RASSOR for trenching and regolith-moving equipment are one solution to create and position shielding berms surrounding landing / launch sites and near habitat and other stationary assets as well as to create emergency shelters for crews during outside operations. Techniques of consolidation of the regolith are under development that use little or no ligand materials that would be imported from Earth; such advances are sought to provide landing / launch pads that minimizes the creation of ejecta when exposed to rocket exhausts. Basalt sintering and net-shape casting as well as extrusion of concrete mixtures using only indigenous materials are among the approaches for *in situ*-built pads structures under development and tests under rocket-propelled vehicles (Fig. 5 and Fig. 6.)

Regolith Operations and Advanced Concepts

The Swamp Works approach of rapid concept-to-test cycling yields both design validation information and operational data and experience during integrated testing with other technologies in analogue sites that reproduce major characteristics of relevant environments. Each technology matures from concept research to become a working prototype in a laboratory that typically achieves a specific function such as crushing regolith or extracting volatile components from it. The technology is then subjected to "field tests" during which it must operate in an environment selected to simulate stress and constraints similar to some of what is encountered during a planetary surface mission in space. Both the operators and the hardware are taken out of the familiar lab environment and face the challenges of a remote location: operations beyond line-of-sight by telecommunications, remote diagnostics and troubleshooting, thermal and dust invasion issues, constraints of schedule and data bandwidth, etc...

As the technologies mature, they are integrated with each other with the goal of "Closing the Loops" and achieve the field demonstrations of a system. Figure 5 depicts the notional Space Resource Processing Cycle and how ISRU processes and technologies work together and interface with other mission elements to deliver their products. Taken out of the laboratory development environment, ISRU technologies and systems are tested during field campaigns dedicated to ISRU during which the focus is on evaluating mission relevant hardware in an analogue environment (Sanders and Larson, 2015.) In recent years, such tests hardware and integrated systems have taken place at a test site on Mauna Kea, Hawaii in 2008, 2010, and 2012 (Fig. 7.)

SPACE MINING IN AN AGE OF EXPLORATION: CHALLENGES AND OPPORTUNITIES

Regolith in space: what is my ore?

The broad field of *In Situ* Resource Utilization encompasses all prospecting, assessment and processing functions and activities that ultimately deliver valuable products from resources found in space. To date, the use of solar radiation to provide onboard electrical power remains the sole application of a space resource that has been exploited to sustain exploration missions. Even if one includes vacuum and the thermal sink offered by interplanetary space as exploited resources, our fleet of spacecraft has always been designed to operate in space environments without tapping their vast potentials. In broad terms, the material resources encountered in space are found in planetary atmospheres, large liquid reservoirs, and planetary regolith. While atmospheric resources such as carbon dioxide are of high value on Mars, Venus, and on moons of the giant planets (nitrogen), the mineral resources and volatile compounds associated with them are present on far more planetary bodies throughout the solar system. Volatile solids occur naturally on most planetary bodies including the Moon, Mars, asteroids and comets. Carbon dioxide and water ices have been detected remotely at high latitudes and in polar caps on Mars (Rummel et al, 2014) and in permanently shadowed polar craters on the Moon. Comets consist mostly of ice (>85% of mass), and some asteroids also contain solid ices in various amounts. In the outer Solar System, moons of the giant planets host the same resources; Ganymede, Europa and Callisto are composed of silicate rock and water ice to varying degrees, and the Cassini-Huygens probe has revealed methane snow and water ice crusts on Titan.

Recent studies suggest that water, oxygen, and metal resources on the Moon, NEA's, and Mars are critical for achieving NASA's long-term goal of Earth independence for human exploration of our solar system as well as commercial transportation and construction in space (Spudis and Lavoie, 2011; Lewis, 1997). The NASA Resource Prospector (RP) mission currently planned for 2020 is likely to *find water ice and other volatiles at the Moon's poles.* When it does, the next logical questions involve, how to mine and extract the resources, and how this will benefit future exploration of the Moon and beyond. Following the *in situ* scientific study of the relocated NEA to lunar orbit to understand the history and development of our solar system, *the next logical activity is for resource extraction to advance sustainable human exploration and economic development in space*.

In the 21st century, water has become the prime commodity of choice targeted for extraction in government-funded studies as well as private business plans. The last two decades of scientific exploration of our solar system have indeed heralded the era of ubiquitous water that is changing our paradigm of a quasi-sterile ensemble of planets into an exciting vision of ice-filled worlds potentially harbouring microbial life in several locations. Ice deposits on the Moon, ice and hydrated minerals covering wide regions of Mars and volatile-rich carbonaceous asteroids are now part of our new knowledge and have opened the possibilities of water as the first "ore" that may both support space exploration and a new emerging space resource-based economy. The triple use of water in space as a source of oxygen for life-support and rocket propellant and as the essential compound for human and plant life sustenance create its value at least on paper. On Mars, water extracted from the subsurface also provides the needed hydrogen that, when reacted with atmospheric carbon dioxide makes methane as the propellant fuel in rocket engines. Concentrations of water-bearing minerals ranging from 2 wt.% to near 10 wt.% in water and pure ice deposits have been confirmed by remote sensing on Mars and in the various planetary bodies and have prompted renewed efforts for better resource exploration techniques on the scale of asteroids, and planetary regions. We know little of the accessibility of such water deposits since the surface prospecting era is only beginning in the wake of the data gleaned by remote sensing probes.

The concept of a valued resource in deep space is more multi-dimensional than the terrestrial concepts. Solar energy and temperature gradients are abundant and of great value for a mission that uses them for energy generation, storage and thermal management. An accessible water source can become key to the survival of a crew facing a failure of a closed-loop life-support system and a metal feedstock may be of critical importance to a crew having to replace a simple part by additive manufacturing. Placed in a different mission context, the same resources can reveal their strong monetary value. Water extracted from regolith and processed to provide oxygen and methane as rocket engine propellants for a spacecraft to return to Earth has a measurable value in reducing the initial mass launched into space or even the number of launches. The same propellants can be part of commercial trade between space producers and satellite operators interested in the ability to refuel their spacecraft to extend their operational life.

Space Resources Exploitation: Pioneers and Partners

The establishment of a resource exploitation site through mining in space is an entreprise that will require adopting the best practices of both the mining and the aerospace sectors in close collaboration. Current efforts focus on the discovery and prospecting phase of the resources of value in the inner solar system and these efforts are primarily carried out by government space agencies. In the case of asteroids, several companies such as Planetary Resources Inc. and Deep Space Industries, Inc. recently formed are aiming to launch and operate their own specialized space telescopes to gather data they need to identify Near Earth objects of potential value. These actors develop their technologies for prospecting and sampling using a combination of private investments and U.S. government funding for small businesses. As a partner, the government is interested in seeing such technologies be developed to enable a larger future space infrastructure that will benefit both space exploration and future economic activity in space. It is also interested in purchasing the data that will be generated about these resources for science and future planning. Through this synergy, these corporations can further their ambitions to develop mining spacecraft of their own to mine water, gases, and valuable metals such as platinum-group metals for in-space customers or use on Earth when their import from space makes economic sense.

The private-public collaboration for planetary resource mining also occurs in the planning phases and involves international partners. In the case of Mars, recent analysis by the ISRU and Civil Engineering Working Group has yielded engineering constraints, based on ISRU, that impact the evaluation of landing sites for missions to the surface of Mars. The terrain of a particular site must be sufficiently flat to permit ISRU systems, as well as ancillary systems such as power and propellant storage tanks, to be landed, moved into position, set up, and operated. Water must be accessible in a form that can be acquired via excavation and other forms of mining, in quantities that align with demands. The chosen method of acquiring and processing water should align with the available resources at a particular site, and that site must have sufficient quantities to meet the requirements (based on crew consumables and propellant demands). Lower altitude landing sites are preferred, as the increase in atmospheric density can facilitate both landings and the acquisition of carbon dioxide from the atmosphere for propellants manufacturing. Another preference is for sites with a greater ability to move regolith for civil engineering purposes; for example, this would be conducive to both bulk regolith uses (such as the manufacture of berms), and processed regolith uses (such as microwave sintering). NASA has recently invited interested individuals and institutions from around the world to propose potential sites and zones of interest for future human missions to Mars and engage in developing plans for resource exploitation at these locations (NASA, 2015). This type of opportunity opens specific avenues of collaboration between the mining sector, planetary scientists and space technology developers to work together on balancing the multi-disciplinary requirements of many stakeholders.

CONCLUSIONS

The realization of a sustainable Mars human outpost or a mining operation on an asteroid near or beyond the Moon will not be accomplished solely by the insertion of a few well-choreographed tasks on deep space missions; instead it will be born from the heritage of crews well practiced in the new paradigm of self-reliance in space that result from years of missions during which they developed, tested and relied on the processing and utilization of the resources found in space. Such a well-steeped culture of knowing a planetary environment and possessing the tools and techniques to create survival solutions from the available environment will equip the crews with the creative mindset and psychological assurance that will prove critical for safe long stays away from Earth and open the door to sustained off-Earth mining. This culture will be the result of an evolutionary development strategy of ISRU technologies that start in development centers such as Swamp Works and mature during proving ground missions in cis-lunar space that will involve fully autonomous, adaptable robotic machines and crew interaction via tele-operation.

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FIGURE CAPTIONS

FIG 1 – The Swamp Works High Bay space for rapid research and development of planetary surface systems at Kennedy Space Center, FL (USA).

FIG 2 – Regolith Advanced Surface Systems Operational Robot (RASSOR) with Gravity Offload System.

FIG 3 – Vibratory Impacting Percussive Excavator for Regolith (VIPER) Testing in Icy Regolith Simulant.

FIG 4 – Quick attach mount in front of multi-purpose surface transport during tests at Desert Rats.

FIG 5 – Regolith-based pad under tests during Morpheus Vertical Take Off Vertical Landing (VTVL).

FIG 6 – Regolith-based pad with trench under tests during Morpheus vertical take-off at NASA Kennedy Space Center.

FIG 7 – Space Resource Processing Cycle and Integration with Surface Elements.

TABLE CAPTIONS

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TABLE 2

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FIGURES

Note: only high quality, high resolution images are acceptable. Original graphics files (tifs, jpgs, etc) are preferred.

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FIG 5 – Regolith-based pad under tests during Morpheus Vertical Take Off Vertical Landing (VTVL)

FIG 6 – Regolith-based pad with trench under tests during Morpheus vertical take-off at NASA Kennedy Space Center.

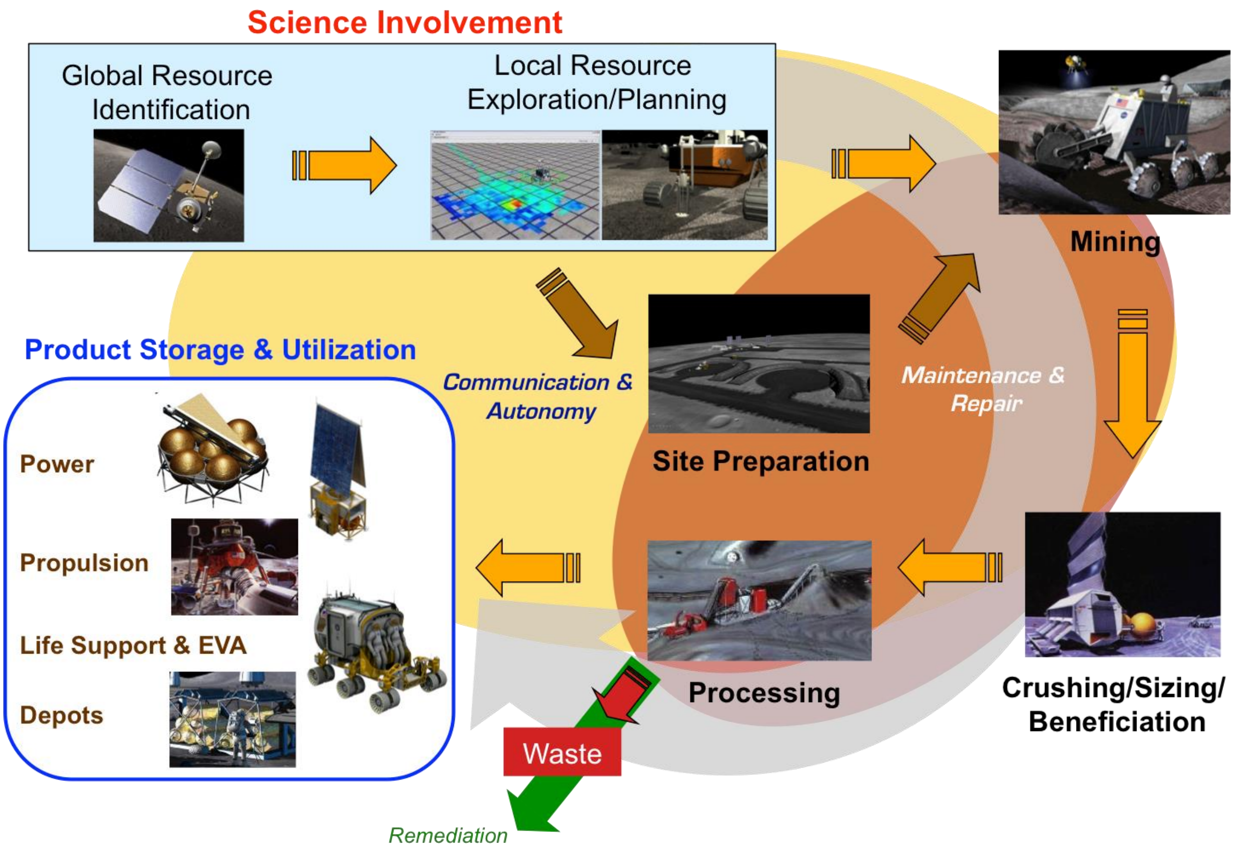

FIG 7 – Space Resource Processing Cycle and Integration with Surface Elements.

TABLES

TABLE 1

Caption here.

Column 1 (Use 'Table text header row' style)	Column 2	Column 3
X (Use 'Table text' style')	10	50
Y	20	55
Z	30	62
X	40	50
Y	60	50
Z	20	35
x	15	10

Note: Tables should be editable (ie – not graphics, we must be able to access individual data cells). They will be recreated by AusIMM desktop publishing staff in the correct formatting for production.

TABLE 2

Caption here.

…and so on.