Development of a Lunar Consumables Storage and Distribution Depot

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Abstract

NASA is in the preliminary planning stages for a future lunar base as a response to President George W. Bush's recent announcement of a new sustained exploration program beyond low earth orbit. Kennedy Space Center engineers are supporting this program by utilizing experience in Spaceport system design and operations to help develop a Lunar Consumables Depot. This depot will store propellants, life support fluids, and other consumables either transported from Earth or manufactured from In Situ resources. The depot will distribute these consumables in an energy efficient manner to end users including spacecraft, habitation modules, and rovers. This paper addresses some of the changes to lunar base architecture design as a result of advances in knowledge of lunar resources over the past 35 years, as well as technology advances in the area of In Situ Resource Utilization and consumable storage and distribution. A general system level description of the depot will be presented, including overall design philosophy and high level requirements. Finally, specific subsystem technologies that have been or will be developed by KSC will be addressed. Examples of these technologies are automated umbilicals, cryogenic refrigerators, novel storage vessels, advanced heat switches and heat exchangers, and self healing gaskets and wires.

Introduction

On January 14, 2004, President George W. Bush announced his administration's vision for the future of space exploration for the United States. Among other things, one key element of the plan is a strategy of lunar exploration, beginning with robotic missions starting in 2008 and continuing with human expeditions in the timeframe of 2015 to 2020. In addition to scientific exploration the NASA Level 0 Exploration Requirement (1.3)[1].states that "NASA shall conduct human lunar expeditions to further science, and to develop and test new exploration approaches, technologies, and systems, including the use of lunar and other space resources to support sustained human space exploration to Mars and other destinations". While the details of the plan are still being developed, NASA is starting to implement this policy by creating the new Office of Exploration Systems (Code T), and a Presidential Commission on Implementation of US Space Exploration Policy has been formed. While waiting for these organizations to formulate detailed policy, managers and engineers at Kennedy Space Center are beginning to plan on utilizing expertise gained by years of spacecraft processing operations to assist the agency in creating a operations friendly lunar base.

Much has changed since the United States last set off on a path of lunar exploration. While several different rationales were given as reason for the Apollo program, from enhancing the nations technology base, encouraging students to pursue fields of study in science and engineering, and exploring the Moon to discover its history and origins, it is no secret the driving force behind the program was to win the "Space Race" against our cold war rivals, the Soviet Union. This political reality drove the mission architecture to being a "flags and footprints" mission, with strict constraints on mission mass and duration. This mass limit also led to constraints on total Δ Velocity allowed, which limited the landings to within 30 degrees of the equator. No plans were seriously considered that allowed for a permanent presence on the lunar surface, and lack of knowledge of surface composition contributed to an absence of any In Situ Resource Utilization (ISRU). The current vision calls for a long-term human presence on the lunar surface, with extended mobility options, greater science capabilities, and the goal of leveraging off lunar experience and resources to enable further exploration of the solar system. Clearly these goals cannot be realized by using the same architectural elements as the Apollo program. Although heavy lift transportation options from the Earth's surface are needed, utilizing resources found on the lunar surface will still be necessary to minimize transportation costs. The lunar surface has the possibility of providing both fuels and oxidizers for primary and secondary propulsion systems, life support gasses for atmospheric revitalization, numerous metals for future manufacturing, regolith for radiation protection and insulation, and possibly water for cooling systems, human consumption and propellant. The early robotic phases of this exploration vision will help provide more information on exact resource availability, but there is much we currently know about the make-up of the lunar surface.

Prior to the Space Age, all the information we had about the moon was derived from Earth based telescopes. In the late 1950's and early 1960's both the United States and the Soviet Union sent a number of probes to the Moon, with mixed success. The first US flyby was achieved by Pioneer 4 in 1959, but little scientific data was collected. In 1962, Ranger 3 and 5 collected measurements of lunar radiation levels. The first major American successes were Rangers 7, 8, and 9, which collected thousands of detailed pictures of the lunar surface prior to hard impact on the surface. Meanwhile the Soviets were compiling a number of successful missions including the first flyby (Luna 1), the first hard landing (Luna 2) and the first pictures of the far side (Luna 3). Lunar 1 also discovered the Moon had no magnetic field. In 1966, Luna 9 achieved the first soft landing on the moon, and Luna 10 become the first man made object to orbit the moon. Important data on the near lunar gravitational field was collected during the mission. In the1960's, the American space program had a number of successes with the Surveyor and Lunar Orbiter series of spacecraft. Scientific data gathered included soil sample analysis, surface radar and thermal reflectivity, and descent and landing dynamics of soft landings [2]. By the late 1960's, the American space program acquired, via these robotic explorers, all the data necessary to attempt the manned Apollo missions.

The six successful Apollo landings provided a wealth of further information on the history and current character of the Moon.[3] Based on these missions, current theory is the Moon was formed as the result of a collision between Earth and another planetary body about 2.5 million years ago, which destroyed the other body and sent large quantities of material into orbit around the Earth. This material eventually condensed and formed the Moon. The Moon is an evolved terrestrial planet with internal zones similar to earth. It is lifeless, with no evidence of organisms, fossils, or native organic compounds. Moon rocks fall into three distinct categories; Basalts which are similar to lavas on the Earth, Anorthosites, which are light rocks from the ancient highlands, and Breccias, composite rocks formed by crushing, mixing or melting during meteorite impacts. All are formed from high temperature processes, with no involvement with water, unlike shales or limestones found on Earth. Regolith, powdery dust formed from eons of meteorite bombardment covers most of the surface. Mean grain sizes range from 45 to 100 microns, and grains are sharp and glassy. Electrostatic charges may generate in the regolith due to low electrical conductivity and dielectric losses. The chemical makeup of the rocks vary depending on location, with highlands being rich in calcium and aluminum, and maria rich in iron and titanium. Regolith in both areas is rich in silicon, sulfur, magnesium, manganese, and nickel. Most of these elements are found in oxides. The Moon is seismically stable, with fewer than 500 moonquakes per year averaging between 1 and 2 on the Richter scale. The atmosphere is so weak, it can barely be approached by the best vacuum chambers on Earth.

Based on information gathered during the Apollo program, future mission architectures can design missions to take advantage of lunar resources and properties. The moon provides an ideal platform for the observation of our universe, due to its lack of atmosphere, low level of seismic activity, low rotation rate, and lack of electromagnetic radiation interference from the earth on the far side. In addition, some sites near the poles have extremely low and stable temperatures. A variety of other scientific investigations could be undertaken that capitalize on the high vacuum and high surface stability, such as particle physics, solar wind characterization, and basic materials research. Such basic research can lead to applied materials processing studies, which will focus on how to best utilize lunar resources to minimize the amount of mass to be imported from Earth. This initial ISRU will probably provide only propellant and life support consumables, although future activities will require locally derived metals and semiconductors to allow for large scale expansion. Most of the post-Apollo studies concentrated on extracting oxygen that is chemically bound in the lunar rocks, due to the total absence of water in any of the Apollo samples. However, the Lunar Prospector orbiter in 1996 detected the presence of hydrogen in some of the permanently shaded areas of the south pole. There is speculation that this hydrogen is in the form of water ice that has been deposited from comet flybys and due to the cold temperatures is not volatile. If this is true, and early robotic missions will be designed to verify and quantify this presence, mission architectures will probably be based on south pole bases and water electrolysis processes. The advantages of this ISRU option include the fact that it provides water, hydrogen and oxygen, as opposed to only oxygen from the soil, the simplicity and reliability of electrolysis processes, and the requirement for less energy as opposed to energy intensive processes that break down the oxides in rocks and soils.

The large amount of information we have gathered on the Moon over the past 45 years will be studied and analyzed by mission planners. Even so, final base siting will not be decided until the end of another period of robotic probes explore various sites on the planet, and test critical technologies for local production of resources. For purposes of this paper, assumptions must be made on the result of these robotic missions, as well as assumptions regarding mission requirements

Conceptual Base Design Requirements

The first sustained human presence Lunar Base can be conceptualized by extrapolating from a notional mission architecture derived from the NASA Level 0 requirements and the Level I Exploration Objectives [1.1]. The siting of the Lunar Base will be driven by the objectives of the mission and there will be a variety of choices due to the diverse nature of possible missions as mentioned above. The site selection will be driven by a balance of science, resources, operations and strategic purpose objectives. For the purposes of this paper it will be assumed that the mission architecture will be aimed at exploring regions of the Moon's South pole in an effort to utilize the speculated water resources that may be available. The operationally desirable surface topography for a lunar base should be as flat as possible to allow landing and launch activities as well as deployment of surface infrastructure and mobile surface support equipment. The mobile equipment would be used to access the craters in which it is suspected that H2O resources exist.

For a sustained series of repeated 30 day stays on the Moon, with different crews, some infrastructure will be required which may be pre-deployed and robotically activated.

At a minimum, Lunar Base element requirements will consist of a launch / landing pad, Lunar Lander/Ascent vehicle, a habitat element, a power source, a radiation shelter, transportation equipment and other Surface Support Equipment (SSE) which includes a lunar consumables and storage depot.

Although it is too early to identify specific requirements it is highly likely that the mass benefits of In-Situ Resource Utilization (ISRU) will justify the use of this type of equipment. It is likely that lunar regolith and water ice (if found) will provide raw materials for mining and chemical processing which will in turn supply the consumables and propellant for a lunar base. Using these raw materials would reduce the total mass required for transportation from Earth.

All of this equipment will be required to operate in a highly challenging extreme environment on the Moon with extreme temperature swings from a mean day surface temperature of 107 C to a night temperature of -153 C with other factors such as lunar dust which compromises the operation of mechanisms and other moving parts unless protected. This equipment must have minimized mass and power requirements, and high safety, reliability and maintainability. All interfaces must be simplified and standardized to the highest extent possible since astronaut Extra Vehicular Activity (EVA) must be minimized for crew safety. The quantities of regolith, propellants, life support and purge gases will be highly dependent on the actual design and specific requirements of the lunar mission.

Kennedy Space Center Systems Developments

In order to enable in-situ surface operations and science on the moon, a variety of Surface Support Equipment (SSE) will be required to allow safe and efficient deployment, construction, use, and de-commissioning of mission components and equipment throughout their life cycles. This would include design, operations, maintenance, training, manufacture or acquisition, and disposal of various items. The specifics of this SSE will depend on mission architectures and detailed mission objectives, but will deal with issues such as:

Access/Handling Equipment
Transportation Equipment
Surface Preparation
Launch Site Preparation
Infrastructure Development
Vehicle Configuration and Checkout
Maintenance and Repair
Hazardous Materials Handling and Waste Disposal
In-Situ Umbilicals
Inspection Technology
Cable Management
Deployable Devices and structures

Since Kennedy Space Center has extensive experience in many issues related to ground based operations of Spaceport technology and launching spacecraft and their payloads it is a natural evolution of KSC's capabilities to provide SSE which will meet all mission requirements for surface operations. Technology activities that are recognized as areas to pursue are listed below.

<u>Access and Handling Surface Support Equipment</u>
A variety of Access and Handling Support Equipment will be required In-Situ to off-load equipment from the space craft and deploy it on the surface. Even with reduced gravity, Extra Vehicular Activity (EVA) operations will be constrained by Extra- Vehicular Manned Unit (EMU) mobility restrictions for the astronauts which will require additional EVA tools and ISE. KSC has extensive experience in developing, designing and operating Earth based access and handling equipment for the Gemini, Apollo, Shuttle, Space Station and Expendable Launch Vehicle (ELV) programs over the last 40 years. By applying new extra-terrestrial design requirements, this knowledge can be leveraged in an operations

savvy manner in order to produce the best SSE possible. Working with other EVA system designers at other centers and agencies will ensure the development of a suite of surface items that function together smoothly.

Access Equipment

Access equipment must be developed that will allow astronauts and equipment access to remote locations either on the Spacecraft or in the field. Such equipment may be simple in nature or may involve robotic / autonomous capabilities depending on the nature of the task. Examples of typical access equipment that may be required are:

- Personnel-lifts (universal)
- Stands
- Scaffolding
- Borescope visualization and inspection
- Internal inspection micro-robots and plumbing pigs
- In-Situ Replaceable Unit installation access equipment
- Harnesses
- EVA steep terrain access/climbing/rappelling equipment
- Lightweight folding ladders
- Re-configurable structural element kit
- Rope deployment device (pole assisted, catapult, sling shot, ballistic)
- Lightweight bridge devices
- Winches
- Telescoping deployment mechanisms for remote camera inspections
- EVA traverse equipment
- Anchoring devices

Handling and Lifting Equipment

A variety of Field Replaceable units (FRU), Base Camp Infrastructure components and field science equipment will be too heavy for an EVA astronaut to safely lift and handle. Equipment will be required to lift and handle items such as drilling assemblies, power plants, pressurized rover deployment, power cable deployment and other construction and field work related tasks. Examples of typical handling equipment that may be required are:

- Jib hoists
- Inflatable Actuators/jacks
- Lightweight deployable cranes
- Self-deploying guy derricks
- Utility carts for heavy equipment
- Robotic end effectors for tele-operated rovers
- Exoskeletons for astronauts
- Come-along devices (lightweight)
- Maintenance lifting jacks for rovers, space vehicle and other equipment
- Cable-activated regolith collection scoop buckets (lunar hydrogen)
- LRU handling equipment
- Inertia-reel devices

In-Situ Transportation Equipment

Transportation equipment will be required for astronaut EVA's, autonomous robot scouts and repair agents, as well as spacecraft and related launching infrastructure deployment and configuration. KSC is responsible for terrestrial transportation of critical spacecraft, related systems and payloads. This knowledge and experience can be applied to extra-terrestrial transportation requirements in co-operation with other centers that have prior experience in extra-terrestrial environments. Examples of typical In-Situ Transportation Equipment that may be required are:

- Automated mobile umbilical devices
- Crawler transporters
- Un-pressurized autonomous rovers
- Pressurized utility rovers
- EVA "mule" rovers
- Regolith moving equipment
- Autonomous rover "scouts"
- Rail and monorail systems for transporting material
- Spacecraft re-positioning systems

Surface and Launch Site Preparation

Any landing site chosen will require some form of surface preparation in order to support infrastructure needs such as building berms, solar radiation and cosmic ray protection shelters, habitats, access ways and other In-Situ activities using local resources. In addition the Spacecraft launch site may require preparation to enable a successful launch. Such activities might include the following:

- End effectors for rover (eg. Backhoe, dozer blade, crushers, compactors, forms, pneumatic hammers, grading equipment, regolith moving equipment)
- Berm building devices (autonomous)
- Solar radiation and cosmic ray protection shelters
- In-situ habitats using local materials
- Access way construction
- Flame deflector construction
- Foundation consolidation
- Debris removal from landing sites
- Foundation preparation

Infrastructure deployment and configuration

Launching vehicles on the moon will require a consumables storage and distribution depot with associated infrastructure such as dewars, cryo-coolers, In-Situ Propellant Production Plants, Power generation systems, plumbing, pump stations, control systems, purge systems, blast protection and other related systems. The infrastructure may be located on the surface or on the vehicle and will require EVA or autonomous deployment, assembly, configuration, checkout and operation.

Vehicle Configuration and Checkout

Prior to launching, all Spacecraft require configuration and checkout, and after landing, safing and post landing operations are required. Configuration control and safe methodical systems engineering methods must be employed to ensure an efficient and timely work flow process. Extensive scheduling, co-ordination and logistics functions must be performed to allow for un-interrupted operations. Typical operations required may be maintenance, vacuum line verification, purging, propellant conditioning, pyrotechnic systems activation, main propulsion system check-outs, thermal conditioning, blast protection configuration, loading fuel, tank pressurization and other related activities. Typical products might include scheduling software, work control software, configuration control software, logistics tracking software and artificial intelligence control agents.

Maintenance and Repair

Maintenance and repair will be an unavoidable facet of space exploration in the Solar System. By designing for operational and logistical synergy, it will be possible to reduce the mass and volume of spares as well as allowing for efficient Field Replaceable Unit (FRU) and Line Replaceable Unit (LRU) as well as component level repair. EVA operations will necessitate FRU design for human or robotic repair missions. Equipment, tools and operational methods will be required to ensure a successful recovery from a system or component level failure. The current plans are for KSC to prepare the Failure Effects Modes and Analysis (FEMA) investigations for Surface Hardware and develop procedures, tools and materials that will be required to make most envisioned repairs.

Hazardous Materials Handling and Waste Disposal

Chemical systems, nuclear systems, biological systems, life support systems and other undefined systems requirements will require the handling of sensitive materials, hazardous materials, radioactive materials and waste disposal. Human tended or autonomous methods must be developed to ensure the safety of the crew while working with hazardous and radioactive materials. Waste disposal must be addressed in order to comply with planetary contamination treaties, international laws and other safety issues. Examples of such undertakings are quarantine methods, sterilization, isolation, packaging, automated maintenance robots, sealed waste disposal land fills, hazardous materials storage areas, radioactive materials storage areas and other required methods, facilities and devices. KSC would develop methods and containment supplies to safely dispose of known hazardous materials as well as investigate the use of a multi-purpose vehicle to assist with the disposal (bury waste).

In-situ Umbilicals

Multiple elements will have interfaces that will require the transfer of commodities between them to allow for integrated systems operations. These commodities will typically be electrical power, data, communication, pneumatics, coolant fluids, cryogenic fuel and oxidizer, and other systems related commodities as required. Since missions beyond Earth orbit will have total masses that are beyond a single lift capability by a heavy lift launch vehicle, multiple launches of multiple vehicle elements will be required in any such undertaking. This will require Low Earth Orbit (LEO) rendezvous and assembly and possible interconnection of pre-deployed assets on a distant solar system body. Umbilicals are mechanisms that enable these connections between multiple elements and can be manually operated or autonomous. Depending on the specific operation, both manual and automated umbilicals will be required to enable deployment and operation of space based equipment, In-Situ Production facilities and habitation modules.

Cryogenic Umbilicals

Cryogenic Fuel and oxidizer will be required for efficient launch vehicle propulsion systems and sufficient specific impulses (Isp's). In-Situ production of these commodities will require cryogenic umbilicals for the transfer of fuel and oxidizer to the launch vehicle from the In-Situ Production Plant (ISPP). In addition cryogenic hydrogen feedstock will be a likely consumable that must be transported from Earth in order to facilitate the production of Methane fuel and water for life support from In-Situ resources. Fuel cells may also be used to power rover vehicles that will also require re-fueling with cryogenic commodities. Astronaut EVA excursions will require a Primary Life Support System (PLSS) recharging capability. These are some examples of cryogenic umbilicals that must be developed to enable long duration missions to other solar system bodies.

Automated Umbilicals

Pre-deployed assets and EVA minimization will require automated umbilicals that are either tele-operated or autonomous. Launch vehicles that are Earth based or space based may also benefit from automated umbilicals by reducing the umbilicals mating and configuration timelines and allowing for quick turn around and re-fueling between launches.

Electrical Umbilicals

Unique umbilicals required for the connections of pre-deployed nuclear power plants have been identified. Inter-connection of subsequent mission elements (cargo and habitats) will also be required to provide a power grid and a modular growth strategy. Each element will require an electrical/data umbilical connection that may be autonomous or tele-operated. A nuclear power plant would also require a tele-operated or autonomous umbilical device in order to cross-strap multiple power plants for increased redundancy and reliability.

Inspection Technology

Remote and manual photography/TV, Non-destructive visual inspection sensor (shearography) – local and remote. and a variety of other non destructive technologies (NDT) will be required to assess and repair space craft and supporting infrastructure.

Cable Management

In-Situ Surface applications will require a variety of cable management techniques and equipment in order to transport, manage, deploy, protect and utilize power and data transmission cables. These cables may have to be deployed across long distances of several kilometers and will require the appropriate equipment.

Kennedy Space Center Specific Technology Development Examples

The Mars Umbilical Technology Demonstrator (MUTD) is a robotic teleoperated automated umbilical designed a s a "proof of Concept" technology demonstrator designed in 1999 by KSC for NASA Johnson Space Center (JSC) in order to validate the concept of automatically connecting a power cable from a Mars Crew Lander to a pre-deployed Power source module, therefore providing power to the Crew Lander so that the astronauts would have time to re-habilitate in 1/3 G prior to their first EVA.. NASA KSC designed and built the MUTD and successfully tested it by deploying a 100 foot cable and mating the electrical connector to a simulated power module. The demonstration validated several aspects of JSC's Mars Architecture plans and showcased KSC's automated umbilical capabilities.

Deployable mechanisms, structures and equipment are required for packaging purposes during transportation to the Moon, and KSC has been taking preliminary steps to develop a capability for implementing the use of deployment methods for the SSE that was mentioned above. Deployable truss structures are an example of deployable elements that can be configured in a variety of methods to support the lunar SSE requirements.

Modular SSE that can be reconfigured for multiple uses would be very beneficial to a lunar base capability since this would minimize mass and maximize functionality. The conceptual development of such a kit of modular SSE has been initiated in the form of a Utility Support Equipment (USE) Kit design. This design uses a variety of modular structural elements and actuators that can be reconfigured to provide access, handling, lifting and jacking capabilities.

Assuming hydrogen and oxygen will be manufactured In Situ on the lunar surface, a storage and distribution system will be needed to contain and control these commodities for distribution to end users. In most cases these commodities will be stored as cryogenic liquids, since mass and volume constraints limit their use as gasses. By nature, cryogenic processes are very energy intensive due to the low temperatures required, especially for liquid hydrogen. This poses a problem for space missions as high power requirements imply high mass requirements for both the power supply and the thermal control systems. Depending on the mission architecture, the use of In Situ produced cryogens may require so much mass it creates some high level requirements, such as the need for nuclear power on Mars. On Earth, Kennedy Space Center engineers have been working on the idea of energy efficient cryogenics, which promotes active and passive means to minimize losses in production, storage and distribution systems for liquid oxygen and hydrogen. This concept is even more important for space missions due to limited mass and volume allowed, where any product losses are magnified in effect.

KSC efforts at producing passive thermal control systems for cryogens have been performed at the Cryogenic Testbed since 1999. Several cryostats have been used to evaluate advanced insulation systems for a wide range of ambient pressures. Early work focused on developing alternatives to multi-layer insulation (MLI) for cryogen storage on Mars. Properly applied, MLI is the most effective insulation currently in use in the cryogenic industry, however there is a large mass penalty as it depends on a vacuum jacketed tank and good internal vacuum to minimize convective heat transfer losses. This convection heat transfer would dominate in a Martian atmosphere of 7 Torr, so alternatives were investigated. KSC cryogenics engineers developed a layered composite insulation that was more effective than MLI at those pressures, eliminating the need for a 2 walled vessel [X]. For cryogenic storage tanks that are filled on the Moon, the ultra high vacuum present will eliminate any convective heat transfer, so MLI systems are a good candidate for use. However, such systems are delicate without the surrounding vacuum shell and will need to be protected from launch, landing and handling forces. In addition, concepts for expandable or deployable tanks (to be discussed later) have issues with insulation systems. One promising alternative is using the regolith as an insulating blanket. This eliminated the need for bringing insulation from earth, allowed for tanks to be deployed as needed, and takes advantage of insulating properties of the lunar soil and vacuum. While some thermal properties of the regolith have been studied, no tests results have been published for thermal conductivity in the cryogenic temperature range. KSC engineers are ordering bulk samples of lunar soil simulant for this testing to be performed in the cryogenic testbed in 2004. Some combination of shielding from solar radiation (such as permanently shadowed areas near the poles) and blanketing with regolith will probably be useful as a highly effective insulation candidate for cryogenic storage vessels on the Moon.

Developing an energy efficient cryogenic system will also depend on using active components to manage the heat flow into and out of the system. No matter how well insulated a tank is, if the ambient temperature is above the fluid storage temperature, heat will leak into the tanks and create boil off that must be managed. Considering the amount of energy required to extract the water from the regolith, electrolyze it into hydrogen and oxygen, than liquefy the product, any boil off that gets vented to space will be an economic loss. It is more energy efficient to eliminate that heat leak by providing active refrigeration in the storage vessel, creating a zero boil off (ZBO) condition. This ZBO refrigerator may also be combined with the refrigeration system required for liquefaction of the product gasses to increase refrigeration capacity and efficiency and minimize mass requirements. In addition, this refrigerator can also be used to densify, or subcool, the propellant, allowing for higher density mass storage and providing a temporary thermal energy storage for transient situations. This type of integrated refrigeration/storage system for liquefaction, ZBO, and densification has been developed by a partnership between KSC and the Florida Solar Energy Center for liquid hydrogen storage[x]. Testing using liquid nitrogen has proven the feasibility of such a system, and testing using liquid hydrogen is scheduled to begin in May 2004.

Although the above program for hydrogen testing will prove the feasibility of refrigerated storage system for liquefaction, ZBO, and densification from a thermodynamic storage standpoint, the prototype in use is unsuitable for actual space use. The refrigerator is an off the shelf Gifford McMahon cryocooler, which is too large and inefficient for space applications. KSC has been actively pursuing advances in cryocooler technology for several years, with the goal of increasing efficiency and decreasing mass of the system. KSC is funding development of a Brayton cycle cryocooler and related components with the University of Central Florida. Specifically, miniaturization of recuperative heat exchangers while maintaining effectiveness would help reduce system mass, and UCF is currently fabricating a polymer derived ceramic recuperator with microchannels in the range of 100 microns diameter. Fabrication of the entire heat exchanger is scheduled to be complete in April 2004, followed by performance and reliability testing. Another phase involves development of a two stage brayton cycle cryocoolers, and current emphasis is in developing the first stage compressor. The compressor is designed to turn at 150,000 rpm, but initial tests were successful up to 100,000 rpm before shaft misalignment with the motor aborted the test. Data gathered up to that point showed the compressor delivered the designed amount of mass flow and compression, validating the design of the turbine wheel. A custom designed motor is in work to replace the off the shelf model used for initial tests, and this is expected to eliminate the misalignment. Other cryocooler work currently underway at KSC includes development of advanced regenerative heat exchanger materials for low temperature AC cycle systems. Heat capacity of most materials decreases rapidly as temperatures approach 20K, making liquid hydrogen temperature pulse tubes inefficient. Using rare earth materials to form cold stage regenerators offers promise to dramatically increase efficiency of these devices.

Innovative storage vessels can be used to minimize the volume per unit mass stored ratio to help increase packaging efficiency in launch vehicles. Launching empty tanks for use on the Moon will require a lot of room in the launch vehicle payload fairing, so finding other ways of packaging these systems is necessary. One option is to use existing propellant tanks that will be empty upon arrival. If this method is not feasible, another option is the development of collapsible cryogenic tanks. Analysis performed at KSC over the last several years has indicated this approach may be possible. Several different configurations, including telescoping tanks, bellows expansions, and bladders were studied to determine their suitability. Factors considered were thermal performance, operational complexity, mass per unit volume, cryogenic compatibility, and safety and reliability. The most advantageous system for use on the surface of Mars was determined to be a Teflon inner liner with a Kevlar outer containment for strength. The tank would arrive deflated and be pressurized with gaseous oxygen upon arrival. Once inflated and rigidized, the tank could then be filled with liquid oxygen. Testing of such a configuration with water at KSC in 2002 resulted in a premature burst at 60 psig, due to a failure in the outer support jacket. This failure was attributed to a poor seam fabrication, and better workmanship should result in higher allowable pressures. Further analysis and testing of this concept should be considered with the Moon as the chosen application.

Other specific component development work that has potential Lunar applications has also been supported by KSC. Spaceport Technology Directorate engineers are partnering with Big Horn Valve Inc., Sierra Lobo and the FSU Magnetic Laboratory to prototype and test an axially operated, high efficiency, low mass cryogenic valve. This valve design innovation, termed Venturi Off-Set Technology (VOST), addresses four critical needs for effective storage, transfer and use of cryogens in space applications. These needs are: thermal isolation to minimize heat leakage, low pressure drop to accommodate high flows without cavitation, minimal mass and space requirement due to low profile, and adaptability to electromechanical actuation (see Figure 1). Existing cryogenic valves require elaborate insulation measures to mitigate heat leakage through actuator stems, they are also characterized by high pressure drop at high flows, large mass to envelope ratio, and high actuation torques. VOST™ valves eliminate actuator contact with internal wetted parts, improving thermal and fluid containment characteristics necessary for cryogenic propellants while maintaining high flow. The high fluid flow with minimal pressure drop characteristic coupled with the axial design envelope is unique and significant among cryogenic valves. The VOST design will eliminate perpendicular actuation devices that are known significant heat leak sources, reduce device mass and enable a device envelope that is suited for superior insulation and electromechanical actuation. Currently available cryogenic valves require complex and bulky insulation strategies to maintain safe and predictable fluid conditions such as warm gas barriers required for effective stem seal operations. VOST™ valves are ideally suited for electromechanical actuation due to low torque requirements required to open and close. These features combine to improve valve safety and reliability necessary for use of cryogens in extra-terrestrial environments.

KSC is partnering with the University of Central Florida to develop thermal and fluid management devices based on shape memory alloys. Shape memory alloys are a class of metals that remember their original shape after undergoing a phase transformation. Heating or cooling the alloys beyond the transition temperature results in a reversible phase transformation, and the reverse transformation is followed by recovery of all the accumulated strain. This strain recovery can take place against large forces, resulting in their application as actuators. This unique relationship allows the SMA's to serve the function as both a sensor and actuator, resulting in a simpler and more reliable device. They function in a clean, debris free, spark free manner, and have high power to weight ratios. Two aspects of shape memory alloys are currently under investigation; materials properties and device development. The material properties research focuses on developing unique alloy compositions to meet user requirements. Depending on composition and the materials processing such as history of cold working or heat treatment, the phase transformations exhibit complicated behavior. Efforts are underway to understand this behavior and develop alloys with transition temperatures in the 118 K (liquid methane), 90 K (liquid oxygen) and 20 K (liquid hydrogen) range. Other work is in progress to minimize the hysteresis associated with these phase transformations. In addition, basic materials properties in the microscopic scale are being investigated using neutron diffraction at Los Alamos National Lab, which allows researchers to measure strains in the atomic scale. The materials development work will be coupled with specific device development to allow for reliable operation of cryogenic thermal and fluid control systems. Heat switches can control the refrigeration to cryogenic tanks by closing to provide cooling only when necessary, and when the switch opens the heat leak into the tank can be eliminated. Similar switches can control heat flow to radiators during transient day/night cycles. Thermal mixing valves utilizing SMA's can control outlet temperatures by regulating the amount of warm or cold inlet streams allowed to flow. Cryogenic couplings are being designed to use SMA's to provide additional sealing force when temperatures drop, which helps mitigate the effect of thermal contraction of materials during cooling. This may also lead to the development of self healing cryogenic seals and gaskets.

Conclusions

As the Kennedy Space Center transitions to a stronger developmental role with the research and development activities being performed by the civil service workforce and partners, future exploration needs offer exciting opportunities for our developers. KSC is engaged in several research and technology development activities in support of the Exploration effort while also conforming to the direction of the Center. Kennedy Space Center is focusing its research and development efforts to become "recognized as the world's pre-eminent source of information and technologies for systems used to process, launch, land and recover vehicles and payloads from spaceports on the Earth, Moon, Mars and beyond."[1] This concept has been termed "Spaceport Technology Center (STC)" and all exploration efforts will adhere to this concept.

There are many similarities in the tasks that need to be performed to launch a spacecraft, whether it is on the Earth or on the Moon or other planetary surfaces. Although the specifics and details of the implementation will vary, the basic needs of the launch vehicle and crew remain the same. Kennedy Space Center has extensive experience in launch vehicle processing, launch and landing that can be applied to innovative solutions in the development, design, construction and operation of a Lunar Consumables Storage and Distribution Depot.

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