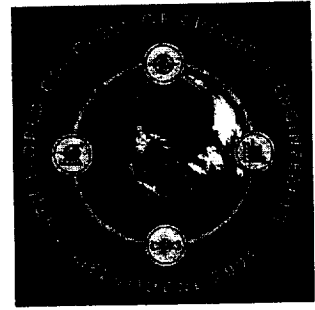


Chemical Engineering in Space

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The aerospace industry has long been perceived as the domain of both physicists and mechanical engineers. This perception has endured even though the primary method of providing the thrust necessary to launch a rocket into space is chemical in nature. The chemical engineering and chemistry personnel behind the systems that provide access to space have labored in the shadows of the physicists and mechanical engineers. As exploration into the cosmos moves farther away from Earth, there is a very distinct need for new chemical processes to help provide the means for advanced space exploration. The state of the art in launch systems uses chemical propulsion systems, primarily liquid hydrogen and liquid oxygen, to provide the energy necessary to achieve orbit. As we move away from Earth, there are additional options for propulsion. Unfortunately, few of these options can compare to the speed or ease of use provided by the chemical propulsion agents.

It is with great care and significant cost that gaseous compounds such as hydrogen and oxygen are liquefied and become dense enough to use for rocket fuel. These low-temperature liquids fall within a specialty area known as cryogenics. Cryogenics, the science and art of producing cold operating conditions for use on Earth, in orbit, or on some other nonterrestrial body, has become increasingly important to our ability to travel within our solar system. The production of cryogenic fuels and the long-term storage of these fluids are necessary for travel.

As our explorations move farther away from Earth, we need to address how to produce the necessary fuels to make a round-trip. The cost and the size of these expeditions are extreme at best. If we take everything necessary for our survival for the round-trip, we invalidate any chance of travel in the near future. As with the early explorers on Earth, we need to harvest much of our energy and our life support from the celestial bodies. The in situ production of these energy sources is paramount to success. We are currently working on several processes to produce the propellants that would allow us to visit and explore the surface of Mars.

The capabilities currently at our disposal for launching and delivering equipment to another planet or satellite dictate that the size and scale of any hardware must be extremely small. The miniaturization of the processes needed to prepare the in situ propellants and life support commodities is a real challenge. Chemical engineers are faced with the prospect of reproducing an entire production facility in miniature so the complex can be lifted into space and delivered to our destination.

Another area that does not normally concern chemical engineers is the extreme physical aspects payloads are subjected to with the launch of a spacecraft. Extreme accelerations followed by the sudden loss of nearly all gravitational forces are well outside normal equipment design conditions. If the equipment cannot survive the overall trip, then it obviously will not be able to yield the needed products upon arrival. These launch constraints must be taken into account.

Finally, we must consider both the effectiveness and efficiencies of the processes. A facility located on the Moon or Mars will not have an unlimited supply of power or other ancillary utilities. For a Mars expedition, the available electric power is severely limited. The design of both the processes and the equipment must be considered. With these constraints in mind, only the most efficient designs will be viable.

Cryogenics, in situ resource utilization, miniaturization, launchability, and power/process efficiencies are only a few of the areas that chemical engineers provide support and expertise for the exploration of space.

INTRODUCTION

Chemical engineering is applying chemistry to industrial processes. Sometimes within the aerospace industry the processes we apply the principals of chemistry to are unusual. These processes include very low-temperature fluids or cryogenics, novel uses of long-standing chemical reactions for the production of fuels and oxidizers, high-pressure gases, along with new and unusual materials of construction. In essence, we still apply the same principals, whether the industrial process occurs on Earth, in space, or on another planet.

CRYOGENICS

Both Science and Art

Cryogenics is both the science and art of producing cold. This should be qualified by saying that you are producing extreme cold. Another popular description of cryogenics is the low-temperature physics and chemistry associated with materials, especially liquids at or below 125 kelvin. "Cryogenics is a very diverse supporting technology, a means to an end and not an end in itself." [1] Cryogenics is an industry and area of technology that provides the necessary commodities to allow reasonable access to space and space technologies.

Principal Cryogens for Aerospace

One area of cryogenics that has extensive aerospace applications is liquid cryogens. There are four principal cryogens utilized in, on, and around space vehicles – hydrogen, oxygen, nitrogen, and helium. Hydrogen and oxygen are primarily used for propulsion. The liquid hydrogen and liquid oxygen provide the highest impulse power of any liquid fuel available at this time. Hydrogen and oxygen are also clean burning and environmentally friendly. Current work in the propulsion community is focused on the densification of these two liquids to enable increased quantities of propellants to be loaded onto a spacecraft.

Nitrogen is primarily used as an inert fluid. The liquid nitrogen can be used as a test fluid for safely simulating liquid oxygen within systems and support operations. Gaseous nitrogen is used in large quantities for purging, inerting, and pressurizing innumerable systems, including the liquid oxygen tanks. NASA uses gaseous nitrogen for many things, from drying to fire fighting. Liquid nitrogen is also used for many things, from supplying clean gas to freezing hydraulic fluids.

Helium is used as a purge and pressurant gas for liquid hydrogen storage tanks as well as a leak detection fluid. The use of the helium in leak detection can be found in nearly every aspect of the space program. Helium fluid cryocoolers are used extensively in spacecraft to provide the cooling necessary for superconducting sensors and electronics.

Production and Storage on Earth

The production of cryogenic fluids is primarily accomplished through refrigeration either by the Carnot or the Joule-Thomson processes. These processes are energy intensive and are therefore extremely focused on energy recovery systems. The low-temperature compressor-expanders (companders) utilized in standard air separation facilities are extremely efficient, with thermal efficiencies on the order of 90 percent. Storage of liquefied cryogens is both an art and a science. The primary means of storing liquids is by the time-honored vacuum-insulated vessel or dewar. The choice of insulation materials used within the vacuum annulus is highly dependent upon the cost and critical storage times required. In larger vessels the use of low-cost materials (such as perlite or other calcined materials) is quite common. In smaller or more critical applications, the insulation of choice is a multilayer composite system (MLI) using alternating layers of a paper or fiber material with a reflective foil or metallized Mylar. The choice of insulating materials is primarily driven by economics. Some newer materials being developed are starting to minimize the difference between the highly efficient (i.e., expensive) MLI and the less efficient (i.e., inexpensive) perlite. Some of the newer materials are the aerogels or similar silica-based products. These products show promise especially in the area of moderate vacuum levels. [2] A large part of the cost of storing cryogens is the maintenance of the vacuum space between the inner and outer tank. Small reductions in the required vacuum levels can translate into very large labor savings.

Production and Storage on Orbit

Production of cryogens while on-orbit is not envisioned in the near future. However, storage of cryogens aboard spacecraft while orbiting Earth or any other planet is of extreme interest within the aerospace communities. Orbiting instrumentation platforms are becoming more and more complex and high tech. A large number of sensors, instruments, signal processing equipment, communications amplifiers, etc., require part if not all of the system to operate in a superconducting manner. Most of the current systems qualified for flight utilize low-temperature superconducting materials and require temperatures of 15 kelvin or less.

The cost and the weight penalty associated with providing liquid helium to cool these devices have spawned an entire industry designing and building cryocoolers. Cryocoolers provide a mechanical means of delivering low-temperature refrigeration for long durations without any external intervention. Cryocoolers

transitioned from the laboratory to the space industry very easily. Only the space industry was able to afford the relatively high cost of cryocooler construction initially. The reliability of the devices versus a liquid storage (one-time use) system is obvious. Cryocoolers have transitioned to Earth-based operations and are in use in many of the wireless telephone base stations around the world. As the cost decreases and the robustness of the units increases, additional markets and applications are being found daily.

Production and Storage Off-World

The need for efficient storage of cryogenic liquids on other planets or celestial bodies such as the Moon and Mars is paramount for the successful exploration of our solar system. Initially we will have to transport at least part if not all of our fuel for survival and return to these off-world locations. The cryogenic losses that occur during the transportation to or while on the surface of another planet simply increase the quantities that must be boosted into orbit and then transported with the mission.

Additionally, the equipment that stores the cryogenes carries a significant penalty with regard to the overall cost of the mission and ability to get the equipment into space. The current launch system economics dictate that each pound of material put into orbit costs \$10,000. Once in orbit it must reach its destination and land safely. This cost is currently estimated at \$10,000 per pound. [3] In order for a mission profile to be within the cost constraints of expected funding availability, the costs need to be less than \$2,200 per pound. [4] The need for reducing this cost as well as reducing the weight of the equipment becomes paramount.

IN SITU RESOURCE UTILIZATION (ISRU)

Background

The effective exploration of Mars is dependent on being able to utilize the available resources to produce propellants from the Martian atmosphere. The propellants could be utilized in two areas: (1) as fuel and oxidizer for the return trip to Earth and (2) as a backup component for life-support systems. The In Situ Propellant Production (ISPP) component of ISRU is the enabling technology to allow humans to realize the goal of performing meaningful work while on the surface of Mars. [5]

Commodities Required

The commodities required to make the ISPP a reality are carbon, oxygen, and hydrogen.

Available Commodities

Since the hydrogen component of the propellant mix is very light, a spacecraft can bring it directly from Earth. The remaining required raw materials, carbon and oxygen, can be found in abundance in the Martian atmosphere in the form of carbon dioxide. The Martian atmosphere is composed of approximately 95% carbon dioxide, with small amounts of other components such as nitrogen and argon.

Instead of using a pump to collect the carbon dioxide from the atmosphere for use in propellant production, a sorbent bed (made up of material such as activated carbon) will be constructed. This material would be used to adsorb or soak up the carbon dioxide during the cold Martian nights, where temperatures can be as low as -90 degrees Celsius (°C). Warming of the sorbent bed during the day would easily release the trapped gas, thus making it available for processing. This type of cyclic process is very simple and reliable and it requires very little power.

Chemistry

The chemistry necessary to convert the "raw" materials from the carbon dioxide and hydrogen to a usable fuel and oxidizer is relatively simple using either the Sabatier Reaction or Reverse Water Gas Shift (RWGS) reaction.

Sabatier Reaction

This reaction is very well known and has routinely been used to produce methane and water from carbon dioxide and hydrogen as follows:



This reaction releases heat and occurs spontaneously in the presence of a catalyst. Routine yields of greater than 95 percent have been observed with one pass through a reactor. This reaction was evaluated for

potential use on the International Space Station (ISS). The methane produced by this reaction can be stored cryogenically for later use as fuel for the spacecraft return trip.

The water produced in reaction (1) can easily be pumped into an electrolysis cell and split into the basic components of hydrogen and oxygen as shown in equation (2):



The oxygen produced in equation (2) is stored, while the hydrogen is recycled back into reaction (1), the Sabatier Reaction.

Reverse Water Gas Shift (RWGS) Reaction

A secondary reaction that helps generate the proper ratio of methane and oxygen for the bi-propellant mixture is the RWGS shown in equation (3):



This reaction occurs well within the temperature range of the Sabatier Reaction. The low equilibrium constant for this reaction necessitates having a condenser to remove water from the reactor on a constant basis.

Hardware/Controls

Several prototype ISPP systems have been constructed. They were proof-of-concept systems designed to demonstrate functionality. The hardware utilized for the RWGS Reaction consists of several modules including reactor, condenser assembly, separation membrane, and electrolysis cell. These hardware modules are designed to work together to optimize the efficiency of the RWGS Reaction (3).

The reactor itself is key to the initial reaction of carbon dioxide from the Martian atmosphere and the hydrogen transported from Earth. The products from this reactor include carbon monoxide and water along with unreacted carbon dioxide and hydrogen. The function of the condenser assembly is to separate out the water and allow the remaining gasses to pass into a separation membrane. The electrolysis cell takes input water from the condenser assembly and breaks it down into hydrogen and oxygen. The separation membrane is designed to recycle the unused hydrogen and carbon dioxide back into the reactor.

Overall Flowchart for ISPP

The ISPP processes are relatively straightforward regarding the actual chemical processes. The challenge is to integrate all the processes for successful flight. An overview of one of the proposed complete operations that would be sent to Mars follows.

MINIATURIZATION

Scale Down

While the processes and chemistry are straightforward and well understood, the scale of the processes and equipment allowed to fly is not fully understood. The entire package for one of the proposed demonstration plants was set at a total of 48 kilograms. This included all pumps, fans, compressors, reactors, and any associated piping and controls. This puts the actual "plant" size on the scale of a small laboratory apparatus setup.

Manufacturability/Maintainability

This small-scale requirement drives many of the manufacturing and maintenance requirements. The machinery included in the equipment must be lightweight and small enough to fit into the overall scheme, yet it must also be robust enough to operate unattended.

Ease of Assembly/Integration

Once the process is proven, the follow-on missions will undoubtedly get a little larger; however, they will also be subject to some very extreme size and weight requirements. The ability of robots and/or space-suited astronauts to assemble the facilities on the planet will play a large role in the design of the equipment. The entire facility that will house, feed, and sustain the future Mars inhabitants will once again need to operate independently and reliably for long durations without human intervention.

LAUNCHABILITY

We will utilize the phrase "launchability" to encompass an entire range of requirements that any system or apparatus must meet to enable it to reach Earth orbit or an off-world site. The process of accelerating an object from a low-energy position, such as the Kennedy Space Center, to a velocity that will allow the object to either achieve an orbit around the Earth or to break the bonds of Earth and travel to the Moon or beyond is very difficult and strenuous. Some of the areas the designer must address if that process is to be capable of operation once it arrives at its destination include the following.

Launch Forces

The most obvious area includes the forces applied to the equipment during the actual launch from Earth. For our purposes, the launch is considered the entire trip from Earth up to low Earth orbit.

Standing Conditions

The equipment placed aboard any spacecraft will undergo a great deal of unusual handling, packaging, and perhaps cleaning. Each payload placed upon a vehicle (i.e., a rocket) must be balanced and packaged so the vehicle is stable and controllable throughout the entire flight. This includes balance and center of gravity as well as undergoing a number of "spin" tests to verify the payload is stable.

Sudden Conditions (at Launch)

At the time of launch the forces applied to the payload and the vehicle become extreme. For the expendable launch vehicles, the acceleration forces are on the order of 3 to 5 g's. Additionally, shortly after launch, the vehicle rotates or rolls to provide the correct orientation for the flight through the lower atmosphere. The pressure and temperature at launch also affect rapid changes. The vehicle and payloads are usually purged with inert gases and/or provided with conditioned gases while awaiting the launch. Once the vehicle leaves the launch pad these groundside systems are no longer available.

In-Flight Forces

Somewhat less obvious are the in-flight forces that the payloads and the vehicles must undergo. Once on orbit the acceleration stops, and the vehicles and systems are subjected to zero gravity. Standard designs for equipment are generally intended to overcome the gravity of Earth. Bearings, supports, and other mechanical designs that we take for granted must be rethought due to the lack of gravity during the flight.

Free-Flight Conditions

During a long flight there will be long periods of zero-gravity flight or very low-level accelerations. The equipment and systems must be designed to survive these periods of weightlessness.

Course Corrections

Another area of concern will be the necessary course corrections required during the long transit times. Each course correction will require the vehicle and the payloads to be subjected to an acceleration or artificial gravity for a period of time. These short-duration accelerations may be significant enough to unbalance the payload and/or any internal bearing surfaces.

Flight Termination

At the end of the flight the vehicle and its payload must somehow come to a stop. On Earth, this is currently done one of two ways. The Space Shuttle glides to Earth and lands like an airplane. Other manned vehicles float to Earth using a parachute arrangement. On the Moon there is insufficient atmosphere to support either the gliding or the floating arrangements. In the case of lunar insertion, the vehicles will require a powered deceleration and landing procedure. The current design for Mars calls for a combination of gliding, floating, and perhaps bouncing to achieve final stop.

Each of these scenarios requires that the payload undergo significant acceleration or deceleration forces. All of the process equipment required for the survival of humans or of a return vehicle to the earth must be designed for these forces.

Packaging

The payloads or the process equipment for the production and liquefaction equipment must be packaged to make it easy to disassemble and reassemble once it arrives at the final destination. The packaging must provide the support and protection necessary to ensure the equipment arrives in working order. An additional constraint is the need to be as light as possible so the packaging does not reduce the effectiveness of the mission.

Dry/Purged

The payloads that will be launched to the Moon and Mars will undergo strenuous testing and preparations. One area of particular concern for the cryogenics is the drying and purging of the components. Cryogenic systems are unable to handle any significant amounts of moisture or other condensable materials within.

LONG-TERM STORAGE

One of the most critical requirements at this time for a return mission from another celestial body is the long-term storage of liquid hydrogen and other cryogenic fluids.

Time

The duration of the storage required for an extraterrestrial mission is on the order of years. During a Mars mission, for example, the duration of storage requirements are from three to four years. Significant losses of the cryogens while in storage are unacceptable. The Mars Reference Mission describes a duration of 888 to 924 days. [4]

Temperature

The temperature requirements necessary to maintain the liquid cryogens are relatively straightforward. The spacecraft and the liquid dewars must maintain the fluids at or below the boiling points of the contained liquids, for liquid hydrogen that is 43 kelvin. During the flight from Earth to Mars or the Moon there is very little heat input due to convection or conduction to the surrounding space. The heat gains and losses are primarily due to radiation effects. The sun and the planets radiate energy out into space where the spacecraft must then either absorb and reradiate or reflect much of the energy. The sun acts like a black body radiating at a temperature of 5760 kelvin, while the earth can be approximated by a black body at 254 kelvin which effectively adds heat to the spacecraft. [6] Additionally, the majority of space is absorbing heat from the spacecraft at an effective temperature of 3 kelvin. Therefore the insulation systems utilized will need to protect against these heat inputs. Thermal stability for the spacecraft itself is usually a controlling factor, and the cryogenic storage system can utilize the cold of space to enhance the long-term storage ability. Once on a planet surface the heat transfer equations are more involved as the convective and conductive terms become significant and must be considered. For our purposes, the average temperature of Mars is estimated to be 210 kelvin. [7]

POWER/PROCESS EFFICIENCIES

Power and Ancillary Utilities

The power available to operate the equipment and systems while on the surface of another celestial body is severely limited. In the case of Mars, the solar incidence on the surface of the planet is 43 percent of Earth's. This means the use of photovoltaic electricity is limited. Any alternate designs for supplying electricity would have associated weight and transport penalties.

Steam and cooling water services will also not be available. The local environment will be utilized in alternative ways to provide any of these other services.

Efficiency of Process

Processes need to be efficient and effective. While individual processes will not carry severe penalties, the overall efficiencies of the entire complex need to be in excess of 90 percent. The products/byproducts of the various systems and processes must be recycled and reused whenever possible.

SUMMARY

Chemical engineers are significantly involved in the process of achieving space exploration. Our expertise and ingenuity are necessary and required to maintain the integrity of space missions from liftoff to landing. In addition, we are now involved in the processes needed to allow missions to extend beyond Earth.

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