CHEMISTRY IN SPACE TECHNOLOGY

Chemistry plays a crucial role in various aspects of space applications, enabling space exploration, development of advanced technologies and advancing the understanding of the universe, supporting space exploration, and enabling human presence in space. Following topics are some key areas where chemistry is essential in space applications:

1. **Propellant and Rocketry:**
   - Liquid and solid propellants - chemical reactions, combustion and oxidation, to generate thrust - formulations for efficiency, stability, and safety.
2. **Materials Science:**
   - Materials and coatings to withstand extreme conditions - polymers and ceramic composites - strength, thermal protection, surface treatments –- chemical techniques to enhance durability and functionality.
3. **Energy Generation:**
   - Solar cells and energy storage (Battery and Supercapacitor), Fuel cells – electrical power for spacecrafts, launch vehicles, interplanetary and future space habitats (communication and navigation)
4. **Instrumentation and Analysis:**
   - Analytical techniques: chemical analysis, identification and quantification – Spectroscopy and instrumental techniques for ground and space missions.
   - Environmental Monitoring: Space, composition of Earth, atmospheric changes, ozone depletion - extraterrestrial materials, rocks, minerals, celestial bodies.
5. **Life Support Systems:**
   - air revitalization, water purification, and waste management.
   - filtration, adsorption, electrolysis, and catalysis are employed to recycle and regenerate essential resources for astronauts during extended space missions
6. **Planetary Exploration and Astrobiology**
   - presence of water, organic compounds and elements- habitability and geological history of planets - building blocks of life -biosignatures - life on other planets

CHEMISTRY IN SPACE TECHNOLGY

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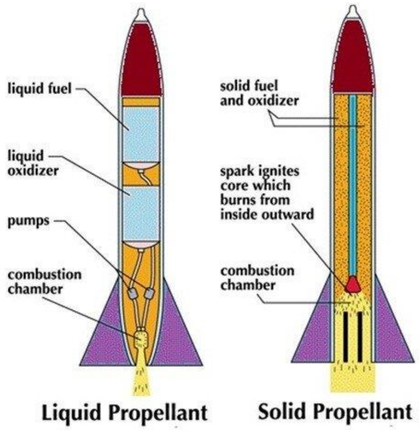
Chemical systems play a crucial role in various aspects of Launch vehicle applications from Propellants, Polymers, Chemicals, Materials, Energy Storage Systems to Analytical characterisation. Following topics are some key areas where chemical systems are essential.

1. Propellant and Rocketry

Chemical Propellants form the major reaction mass of a rocket. They play a critical role in rocketry to overcome Earth's gravity and propel the rocket into space. The rocket works on the principle of Newton's third law of motion. Propellants are substances that contain fuel and oxidizer mixed together (or in a single molecule) such that on ignition, they undergo combustion and burning (simultaneous oxidation & reduction) to release energy. As a result of combustion, the mass flow gets ejected at the highest achievable velocity from a rocket engine to produce thrust. The total thrust produced is directly proportional to the mass flow rate of the ejected combustion products and it greatly depends on the pressure, velocity, temperature and exit nozzle area of the motor. The chemistry of combustion is a complex phenomenon where in several interdependent factors namely decomposition, heat, diffusion, phase mixing, reaction kinetics etc. are considered.

There are three broad types of propellants used in rocketry called solid, liquid, and hybrid.

Solid propellants are the simplest type, basically the fuel and an oxidizer are combined in the solid state. The mixture typically includes powdered metal as fuel and ammonium perchlorate as oxidizer, along with binders and additives that control the burn rates and combustion characteristics. The propellant is cast into a specific shape, such as a cylindrical grain, and then ignited to produce thrust. They are commonly called as solid rocket boosters (SRBs). Solid propellants exhibit a high thrust-to-mass ratio and are relatively simple to store and handle while being reliable. However, they cannot be throttled or shut down once they are ignited.



Liquid propellants are typically a combination of a fuel and an oxidizer that are contained in separate tanks in liquid state. They offer number of advantages of higher specific impulse, precise control on flow and proportions and better throttling capabilities more complex than solid propellants. The most common liquid propellant combination is liquid oxygen (LOX) as the oxidizer and fuel such as liquid hydrogen (LH2) or hydrocarbon based. Hypergolic combinations such as hydrazine and nitrogen tetroxide ignite spontaneously upon contact, eliminating the need for an ignition system. Liquid propellants require complex plumbing and pumping systems, and the propellants need to be stored at low temperatures or under pressure.

Hybrid propellants combine the advantages of solid and liquid propellants. They consist of a solid fuel and an oxidizer as a liquid. The fuel is burned in the presence of the liquid oxidizer, and the exhaust gases are expelled from the rocket engine to produce thrust.

Hybrid propellants are easier to store and handle than liquid propellants, and they have a higher specific impulse than solid propellants.

Here are some of the factors that are considered when choosing a propellant for a rocket:

- **Thrust:** The thrust is the force that propels the rocket forward. The higher the thrust, the faster the rocket will get accelerated.
- **Specific impulse:** The ratio of the thrust to the weight of the propellant consumed per second is specific impulse. Higher value of specific means that the rocket is more efficient and will travel farther on a given amount of propellant.
- **Mass:** The mass of a rocket is a major factor in its overall performance. The lighter the rocket, the easier it is to launch and the more payload it can carry.
- **Storing and handling:** The propellant must be stable enough to store and handle.

The choice of propellant depends on number of factors such as desired thrust, specific impulse, and mass of the rocket, mission requirements, performance characteristics, safety considerations, and cost-effectiveness. Solid propellants are often used for launch vehicles, while liquid propellants are often used for upper stages and spacecraft. Hybrid propellants are a newer technology, but they are becoming increasingly popular.

Rocketry and propellants involve various other aspects such as engine design, combustion processes, nozzle configurations, and overall vehicle dynamics. Advances in propellant technology continue to shape the field of rocketry, aiming for improved efficiency, reliability, and sustainability in space transportation.

2. Materials Sciences

Materials sciences play vital role in developing polymers and ceramics for space applications. Polymers and ceramics offer unique properties and capabilities that are beneficial in the challenging conditions of space. Here's a closer look at their roles:

a. Polymeric Materials & Coatings

Polymeric systems play an important role by exhibiting thermal stability over wide temperature range (from 20 K to 1200 K) with adequate strength for Launch vehicle applications while meeting the extremely harsh space environment.

- Silicones are organic-inorganic hybrids, with wide operating temperature range and the thermal stability of the silicones can be further improved by the insertion of rigid groups into the chain backbone, where the rigid structures hinder the intra-chain rearrangements that cause polymer degradation at higher temperatures. Polymeric backbones/pendants can be suitably modified to impart specific properties. eg: phenyl modifications impart radiation resistance, high temp stability & low temp flexibility to siloxanes. Hyper branched silicone-based coatings have been successfully qualified as corrosion resistant coatings on metallic hardware of semicryo engine, with proven thermal cycling capability from 75K to 1000K.

- Polyimides are one of the potential candidates for cryo temperature applications, as it remains flexible due to chemical nature. However, its upper temperature capability is limited by Glass transition, and it can withstand high temperature for short excursions.

- Silicates are potential high temperature resistant inorganic polymers, which have proven capability upto 1400 K as base resins for coatings for thermal control purposes, especially for interplanetary/re-entry missions.
- Chemical surface treatment is a modification to provide surface finishing by using chemical processes techniques such as anodising, coating or adhesive applications. Reinforcement of the interfacial interaction between epoxy adhesives and metallic materials is a promising technique. Through the usage of suitable coupling agents such as epoxidised or aminosilanes, interfacial adhesion of low surface energy polymer like silicones can be improved. Polymer surface oxidation is also a promising approach to enhance the adhesion of plastics to metals.

Polymers have various applications in space missions. Some key uses include:

i. **Lightweight Structures:** Polymers offer excellent strength-to-weight ratios, making them suitable for lightweight structures in launch vehicles and spacecrafts. They are used in components such as panels, frames, and supports, to reduce overall mass and help increasing the payload capacity.

ii. **Thermal Protection:** Polymers with high-temperature resistance are used in heat shields, ablative materials, and thermal protection systems. They provide insulation and protect components from the heat generated during launch and re-entry.

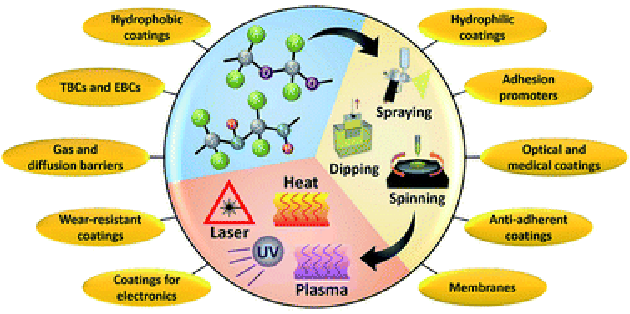
iii. **Flexible and Inflatable Structures:** Polymers can be engineered to be flexible and foldable, allowing for compact storage and deployment in space. Inflatable structures made from polymers are used in thermal screens, pressure testing, antennas etc.

iv. **Sealing and Adhesives:** Polymers with excellent sealing and adhesive properties are critical for joining and sealing components in space systems. They ensure leak-free connections, which are essential for maintaining pressure differentials and preventing gas or fluid leaks.

v. **Polymer coatings:** Polymers are employed to coat other structural materials, electronic components to improve their properties. Metallic surfaces are protected from corrosion, moisture etc. and well suited well-suited for use in the harsh environment of space.

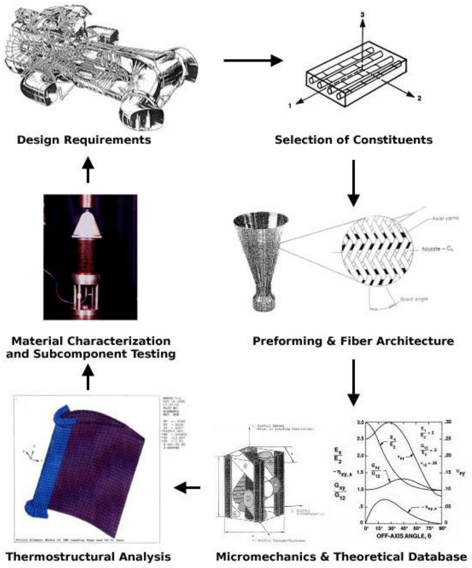
b. Polymer matrix composites

Polymer matrix composite (PMC) is comprised of a variety of short or continuous fibers bound together by an organic polymer matrix to provide high strength and stiffness. The PMC is designed in such a way that the applied mechanical load to structure is supported by the fibre reinforcement while the matrix is to bond the fibers together to transfer loads between them. This combination is the basis of their usefulness in launch vehicles & spacecrafts for challenging applications such as ablative materials, payload fairings, solar panels, thermal protection etc.



c. Ceramic matrix composites and coatings

Advanced ceramic materials are the main candidate for reusable launch vehicle (RLV) applications where high temperature stability, oxidation resistance, retention of strength at high temperature etc are the major requirements.



Ceramic Matrix Composites provides thermal protection of systems especially during reusable vehicles and hypersonic vehicles. Reentry of space vehicles faces high temperature (>2000 K) and severe thermo oxidative environment due to earth's atmosphere especially in the nose cap/cone area, wing leading edges and control surfaces. To withstand such harsh environment, carbide ceramic materials are only suitable over metallic structures. In order to improve the fracture toughness, ceramic materials are reinforced with ceramic particles, short or continuous fibers; and the resulting material are called ceramic matrix composites that exhibit good thermo-structural load bearing.

Ceramics, which are inorganic, non-metallic materials, find important applications in launch vehicle missions. Some significant uses include:

a. **Thermal Protection Systems (TPS):** Ceramics with high-temperature resistance, such as silica-based materials. They provide protection against the extreme heat encountered during atmospheric re-entry.

b. **Ceramic Coatings:** Ceramics can be used to coat metal surfaces to make them more resistant to heat and radiation.

c. **Electronic Components:** Ceramics with excellent electrical properties, thermal stability, and resistance to harsh environments are used in electronic components and circuitry. Ceramic capacitors, resistors, and substrates are common examples.

d. **Sensors and Instrumentation:** Ceramics are used in various sensors and instrumentation systems, such as accelerometers, gas and pressure sensors. They offer stability, durability, and compatibility with extreme temperature and vacuum conditions.

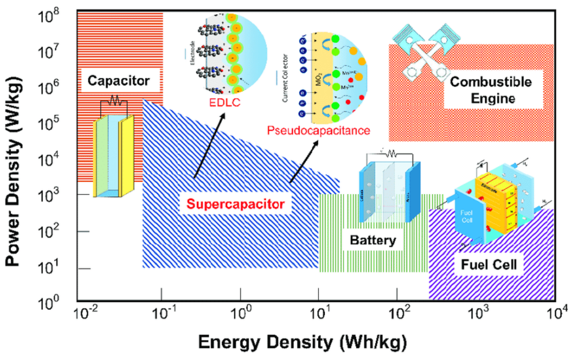
e. **Optics and Mirrors:** Certain ceramics, like silicon carbide, are used for high-precision optics and mirrors in space telescopes and imaging systems. They provide superior thermal stability and stiffness, allowing for precise focusing and imaging.

Polymers and ceramics are easy to process, well-suited for a wide variety of applications. Both polymers and ceramics undergo rigorous testing and qualification processes to ensure their reliability and performance in the extreme conditions of space, including vacuum, temperature variations, radiation exposure, and mechanical stress.

3. Energy Storage systems

Electrical Energy is very essential to power all the equipment onboard the launch vehicles to achieve the mission goals of all space operations. The amount of energy delivered often dictates the operational duration or mission life under harsh operating environments. Rechargeable energy storage systems with redundant units are implemented to ensure continuous supply of electricity.

Electrochemical energy storage devices such as rechargeable batteries, supercapacitors and fuel cells are in flight use as primary source of electricity. These systems are essential to power the pyro ignition, navigation / guidance systems (actuators), telemetry and tracking, instrumentation / on-board systems of launch vehicles, spacecrafts etc. Being life limiting component, the selection criteria of batteries for space applications including the following salient features (a) very high energy density (b) energy and power delivery over wide temperature ranges (c) long operating and calendar life (d) robust integrity to tolerate high shock, vibration, and radiation environments, (d) high reliability.



Advanced primary & secondary battery systems, Regenerative fuel cells etc. are being developed to cater the futuristic demands on interplanetary and exospheric missions. Supercapacitor and novel supercapattery (supercapacitor + battery) systems are the emerging choices to meet the high current pulse power needs of LV's / Spacecrafts along with energy density. Some of the advanced systems for future missions, which are being developed are as follows: Lithium primary batteries, Low temperature batteries (200 K), High temperature batteries (700 K for Venus missions), Lithium-ion cells with high energy anodes, Lithium-Sulphur cells (300 Wh/kg), All solid-state batteries (operating voltage: 5.0 V, high energy density: > 400 Wh/kg) etc. Advancements in energy storage technologies aim to improve efficiency, increase capacity, reduce costs, and enhance durability.

4. Instrumentation and Analysis

Chemical characterization plays a vital role in space research by the way of analysis and testing of chemicals and materials for launch vehicle structures, propellants, pyro techniques, adhesives, thermal protection systems, energy systems etc. Chemical analysis provides in depth understanding on the functional characteristics of materials with respect to acceptance and quality control aspects, evolving new combination of investigations and R & D, failure analysis in ground and post flight data analysis of material performance by both wet chemistry and instrumental analysis. Analytical techniques include spectroscopy, chemical, thermal, mechanical, microscopic and chromatographic characterization.

There are a wide variety of analysis and instrumentation techniques employed

- **Spectroscopy:** Spectroscopy is, based on interaction with matter, used to identify the composition of materials, functional groups, reaction intermediates etc.
- **Imaging:** Imaging is the process of capturing images of objects. It is mainly used to identify objects, measure their size and shape in microscopic levels.

- **Radiography:** Radiography is the measurement of electromagnetic radiation to map the bulk properties to verify the cracks, voids, delamination, and interior features.

  The development of new analysis and instrumentation techniques for space applications is an ongoing process. Researchers are constantly looking for ways to improve the performance and efficiency of these techniques.

5. Life Support Systems:

In human spaceflight, a life-support system is a group of devices that allows a human being to survive in outer space. The role of typical life-support system includes

- Environmental monitoring
- Atmosphere management
- Water and waste management

Components of the life-support system are life-critical and are designed and realized based on safety engineering principles. Chemistry plays a major role in the ECLSS.

Environmental monitoring:

Cabin air must be continuously monitored for the safety of astronauts. In addition to monitoring of the cabin environmental conditions like temperature, pressure etc. typical concentration of gases like oxygen, nitrogen, hydrogen, carbon dioxide, methane and water vapor content also must be measured on real time basis. A mass spectrometer is used for this purpose, which continuously measures the concentration of said gases and provide real time feedback to Life support systems like supply of oxygen, increase in CO_2 concentration etc.

Atmosphere management:

Air Revitalization System is one of the critical subsystems of ECLSS. Typical role of this system includes

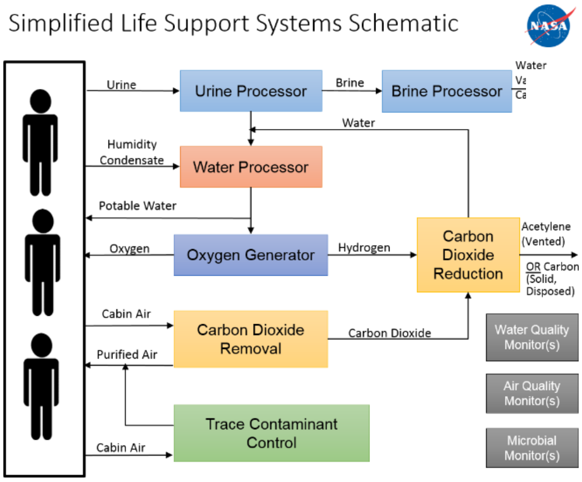
- Supply of oxygen (through water electrolysis in closed loop, Sabatier reaction)
- Crew-generated carbon dioxide is removed from atmosphere using sorbent beds [Adsorption over LiOH pellets or over solid amines in Carbon Dioxide Reduction Assembly (CDRA) based on mission duration).
- Trace Contaminant Control, which ensures that over 200 various trace chemical contaminants generated from material off-gassing and crew metabolic functions remain within allowable limits.

Water and waste management:

Ideally, life support systems need to recover close to 98% of the water that crews bring along at the start of a long journey. The space station's ECLSS recently demonstrated that it can achieve that significant goal.

- ECLSS includes a Water Recovery System.

- This system collects wastewater and sends it to the Water Processor Assembly (WPA), which produces drinkable water.



- One specialized component uses advanced dehumidifiers to capture moisture released into the cabin air from crew breath and sweat.
- All the collected water is treated by WPA - It uses a series of specialized filters, then a catalytic reactor that breaks down any trace contaminants that remain.
- Sensors check the water purity and unacceptable water is reprocessed. The system also adds iodine to the acceptable water to prevent microbial growth and stores it, ready for the crew to use.

Advances in life support system under study:

Plasma Pyrolysis for generation of Oxygen:

- Microwave-based plasma pyrolysis technology is being studied as a means of supporting oxygen recovery in future spacecraft life support systems.
- The process involves the conversion of methane produced from a Sabatier reactor to acetylene and hydrogen, with a small amount of solid carbon particulates generated as a byproduct.

Silver Biocide for Disinfection:

- Silver ions are highly toxic to all microorganisms, probably due to poisoning of the membrane respiratory electron transport chains and components of DNA replication.
- It proven shown that after Ag+ treatment, DNA loses its replication ability & proteins become inactivated.

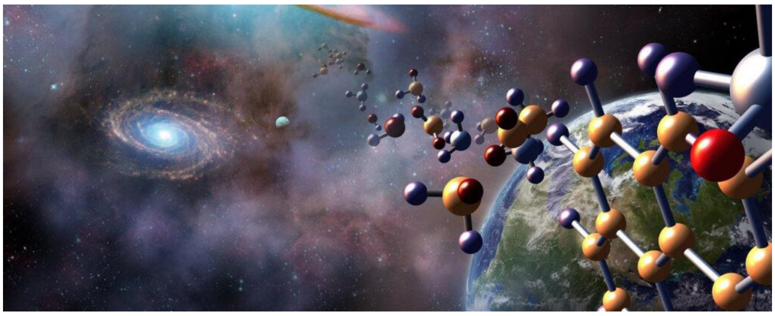
Urine pretreatment chemicals:

- This method combines solid phase acidification with two non-toxic biocides to prevent ammonia volatilization and microbial proliferation.
- The safe, non-oxidizing biocide combination consists of a quaternary amine and a food preservative.
- This combination has exhibited excellent stabilization of both acidified and unacidified urine.
- Urine processed in this manner remained microbially stable for over 57 days.

Role of chemistry and chemical technology is very vital for the life support systems to survive in space.

6. Planetary Exploration and Astrobiology

Astrobiology is a relatively new research area that addresses questions that have intrigued humans for a long time: "How did life originate?" "Are we alone in the Universe?" "What is the future of life on Earth and in the Universe?". Classical biological research has concentrated on the only example of "life" so far known – life on Earth, while astrobiology extends the boundaries of biological investigations beyond the Earth to other planets, comets, meteorites, and space at large. Major research areas focus on the different steps of the evolutionary pathways through cosmic history; it may be related to the origin, evolution, and distribution of life. Life as we know it is based on a complex chemistry involving highly sophisticated biological molecules such as proteins, ribonucleic acids (RNA), or deoxyribonucleic acids (DNA). Such elaborated structures result from a complex chemical evolution, starting with the simplest organic compounds. The chemical reactions that prevail on a prebiotic planet must lead to the generation of the molecules required for life or provide a fertile environment in which seeds of life from elsewhere might grow.



Prebiotic chemistry does not appear to last too long in the history of the Earth, perhaps only 500 million years, but in this time all the molecules must be made available for metabolism, propagation of information in an early gene and self-assembly into a membrane for a protocell. The two theories of endogenous or exogenous organic synthesis each require a chemical environment, which on a warm planet within a habitable zone would allow chemical reactions to occur on surfaces in the liquid phase as well as in the gas phase. Chemistry at liquid water temperatures is much more diverse; with the potential to harness energy from many sources, either external, such as lightening, impact heating and photochemical, or internal, such as volcanic activity or electrochemistry. The allowed set of chemical reactions is controlled by thermodynamics and kinetics, treating a prebiotic planet as an open system into which molecules and energy are continually being added.

This chemistry is controlled by thermodynamics producing local chemical equilibria based on temperature, pressure, and electrochemical gradient. The resulting combinations of molecules, or something like, produce life. Our mission is to explore the molecular universe with an understanding of all the local molecular environments and constrain possible chemical reactions using the concepts of chemistry.

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