International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2020): 7.803

Uses of Advanced Spacecraft Propulsion Systems for in-Space and Deep-Space Applications

Kaushik Deo[1], **C. Srinidhi**[2]

Department of Mechanical Engineering, PVG COET, Pune-30, India

Professor, Department of Mechanical Engineering, PVG COET, Pune-30, India

Abstract: ***Space technology is one of the biggest feat mankind has achieved in the past 5 decades. These technologies have enabled humans to send satellites and even humans to outer space and even various planets in our solar systems. But the technology used in these endeavors is showing its age. The chemical propulsion systems used in these applications are very expensive and not at all efficient. This has given rise to various advanced space propulsion systems. In this paper, we discuss the Nuclear Thermal Propulsion System, Xenon Ion Propulsion System, and Solar Sails Propulsion as part of the advanced propulsion systems. We discuss the past usage of these systems; their possible future uses for in-space and deep-space applications and how these can advance the exploration of space further.***

Keywords: Propulsion, Nuclear thermal propulsion, Xenon Ion Propulsion system, Solar Sails, History, Applications, Current Research

1. Introduction

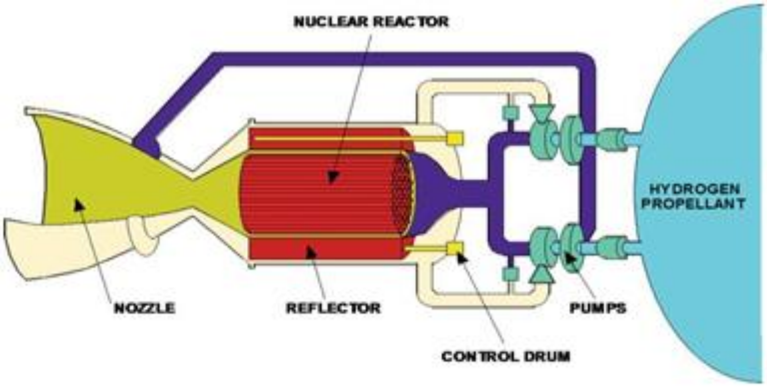
1.1 Current Space Propulsion Systems

When space exploration began in the 1950s, the technology of chemical propulsion was introduced. These consisted of solid and liquid propulsion systems.

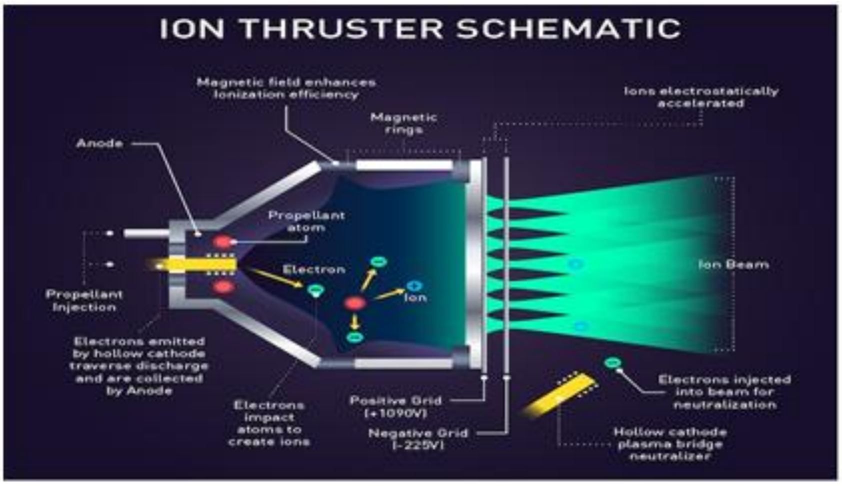
- **Solid Propellant Rockets** work by burning solid fuel such as gun powder, zinc sulfur propellants, and candy propellants (consists of potassium nitrate and sucrose/dextrose). These fuels provide the thrust required to move the spacecraft.
- **Liquid Propellant Rockets** work by mixing fuel (mostly kerosene) and an oxidizer (mostly liquid oxygen) in a combustion chamber at extremely high pressure and temperature and is expelled out of the nozzle to create thrust.
- These technologies kept getting more and more refined but the system itself was never changed as it proved to be sufficient for space exploration during those times. One of the most important factors for space propulsion systems is **Specific Impulse (I_{sp})**. Specific impulse is the measure of efficiency of the engine. It can be thought of as “how many seconds the propellant can accelerate its starting mass by 1 g”. The chemically propelled rockets to date have been tested to give a maximum I_{sp} of 500-550 seconds. As the times are changing and we are hoping to explore our neighboring planets and study the asteroids, these systems are proving to be extremely costly and also very inefficient. That’s why new propulsion systems such as Nuclear thermal Propulsion, Xenon Ion Propulsion, and Solar Sail Propulsion were introduced.

Advanced Space Propulsion Systems

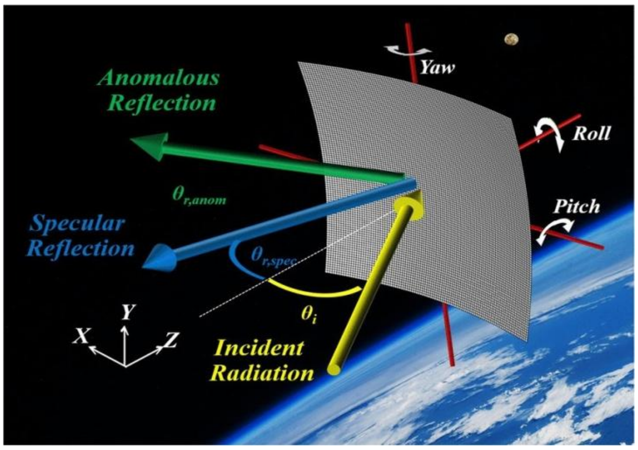
- **Nuclear Thermal Propulsion** works in the same ways as the nuclear reactors work on Earth, that is nuclear fission. The reactor core is made of enriched uranium carbide which undergoes nuclear fission to produce tremendous amounts of heat (range of 2500K to 3000K). A fuel such as liquid hydrogen is passed through the channels provided in the core. The core heats the fuel at high temperatures and is expelled out through the nozzle at very high speeds.



- **Xenon Ion Propulsion System** works on the principle of accelerating positive xenon ions through an accelerating grid at extremely high speeds. These positive ions are produced by bombarding a xenon ion with an electron which makes it electropositive. This positively charged ion is then accelerated through an accelerating grid which is negatively charged. The electrons emitted during this are expelled out through a separate chamber which then mixes again with the electropositive ions to make them neutral. Ion propulsion systems are the most efficient systems ever developed which is capable of producing an I_{sp} of 4000-5000 seconds.



- **Solar Sails** work on the same principle as wind sails work on Earth. It was proven that the sun exerts radiation pressure on objects in space which makes them move in space. This phenomenon was used for the development of solar sails. These have no working fuel hence have infinite I_{sp}. The most common material used in designs is a thin layer of aluminum coating on a polymer sheet, such as aluminized 2 µm Kapton film. The polymer provides mechanical support as well as flexibility, while the thin metal layer provides reflectivity. Such material resists the heat of a pass close to the Sun and remains reasonably strong.



In-space and Deep-space regions

2. Theory

Generally, space technology categorizes space according to the regions. These are distinguished as 'in-space', 'deep-space'.

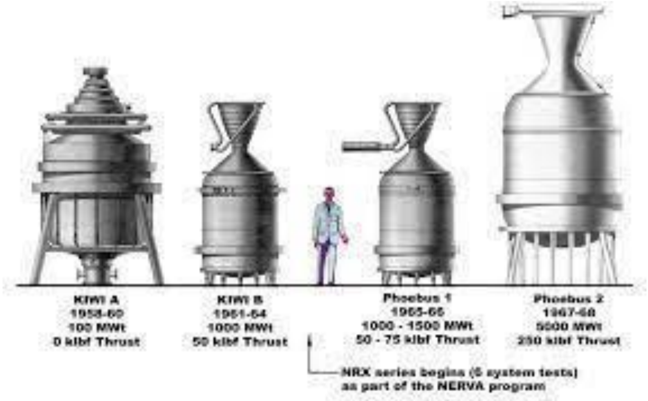
- The region above the Earth's gravitational influence, the Geostationary Earth Orbit that is 35.786 km above the Earth's surface up to the Moon's orbit is called "in-space". It contains every activity such as Earth monitoring systems like weather satellites, GPS satellites, communication satellites, surveillance satellites, etc.
- The region outside of the Moon's orbit is called as "deep-space" region. It contains all the interplanetary, interstellar, and intergalactic space.

3. History and Applications of Nuclear Thermal Propulsion Systems

3.1 History

In 1961 NASA and the former Atomic Energy Commission started the Nuclear Engine for Rocket Vehicle Application (NERVA) program. NASA's director of time Werner Von Braun proposed a mission of sending a dozen astronauts to Mars aboard two rockets. Each rocket was supposed to be powered by 3 NERVA engines. The expected mission was supposed to take place in 1981. But due to budget constraints and the commitment of landing humans on the moon, the project was suspended.

Tested engines included Kiwi, Phoebus, NRX/EST, NRX/XE, Pewee, Pewee 2, and the Nuclear Furnace. During the program, NERVA accumulated over 2 hours of run time including running the engine for 28 minutes at full power.

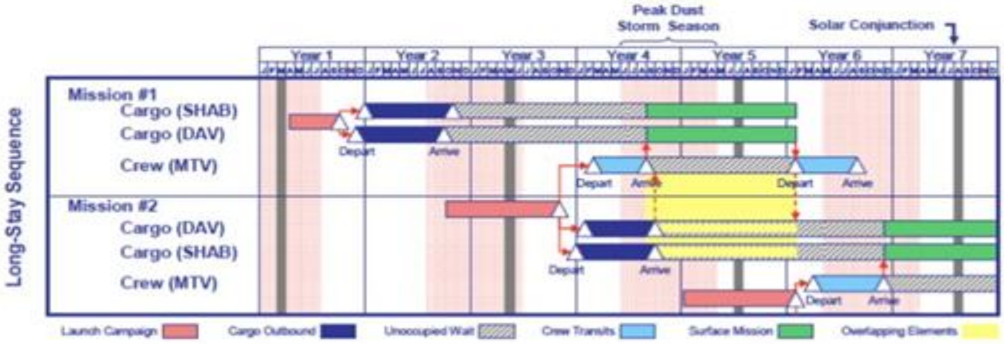


3.2 Current Research

As of 2013 an NTR for Earth-Mars travel was studied. The NERVA program proved that the NTR's were at least twice as efficient as the most advanced chemical rockets. Using these rockets will reduce the time of travel to Mars at the same time reducing the exposure of astronauts to space radiation which can be harmful. In 2017 NASA, with a 3-year $18.8 million contract, continued the study of nuclear thermal propulsion. In 2019 NASA was funded $125 million for the research of NTR's including a flight demonstration by 2024.

3.3 Future Applications

The main application of Nuclear Thermal Propulsion is to be used for interplanetary space travel. These rockets can provide an I_{SP} of 850-1000 seconds which is extremely useful for long-distance travel. One of the missions described is "Human Exploration of Mars Design Reference Architecture 5.0" also known as DRA5.0. The mission will contain a round trip crewed mission preceded by two one-way cargo delivery missions which would be flown in parallel. One of the cargo missions would deliver the Surface Habitat (SHAB) for the crew to stay in once they arrive on Mars. The second cargo mission would deliver the ascent/descent vehicle to mars for the crew to take to land on Mars. The crew would leave Earth orbit and enter Mars orbit once the cargo missions are completed. The overall mission including all the crew flights and cargo deliveries is supposed to last for 6 years and is supposed to be a part of the 2 mission scenario.



Each of the cargo missions would just 1 full power NTP reactor. The total engine burn time for each cargo mission is supposed to be for 39 minutes. The crewed mission is supposed to consist of 3 NTP reactor burns, one for trans Mars injection for 55 minutes, one for Mars orbit capture for 15 minutes, and one for trans Earth injection for 10 minutes. Each cargo mission is supposed to take 350 days to reach Mars. The crewed mission is supposed to take about 180 days to reach Mars, followed by 500 days of Mars habitat and 180 days to return to Earth.

4. History and Application of Xenon Ion Propulsion System (XIPS)

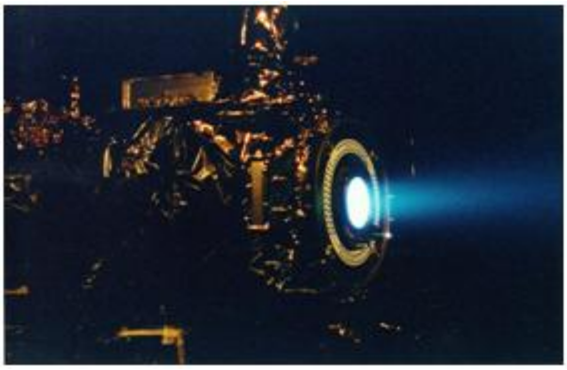
4.1 History

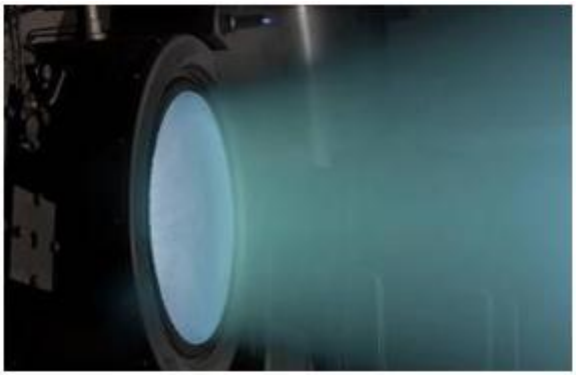
An ion thruster was first built in 1959 by Harold R. Kaufman at NASA. It was similar to the gridded electrostatic ion thruster and used mercury as a propellant. Suborbital tests were conducted during the 1960s. It ran successfully for 31 minutes before falling to Earth. An alternate form of ion propulsion, the Hall Effect Thruster was studied in the USA and the Soviet Union in the 1950s and 1960s. Hall effect thrusters operated on Soviet satellites from 1972 until the late 1990's mainly used for satellite stabilization.

4.2 Current Research and Applications

These are the current Xenon Ion Propulsion Systems in research and some of them are in orbit.

- SpaceX's Starlink satellites use ion propulsion systems having krypton as the propellant to raise and lower the orbits.
- European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) was launched in 2009. It used ion propulsion for its 20-month mission to combat the air drag it experienced in its low orbit.
- NASA developed the NSTAR ion engine for use in interplanetary science missions beginning in the late-1990s. It was space-tested in the highly successful space probe Deep Space 1, launched in 1998. This was the first use of electric propulsion as the interplanetary propulsion system on a science mission. Based on the NASA design criteria, Hughes Research Labs developed the Xenon Ion Propulsion System (XIPS) for performing station keeping on geosynchronous satellites.
- Dawn launched on 27 September 2007, to explore the asteroid Vesta and the dwarf planet Ceres. It used 3 Deep Space 1's xenon ion thrusters (firing one at a time). Its ion drive is capable of accelerating from 0 to 97 km/h (60 mph) in 4 days of continuous firing.
- The Japanese Aerospace Exploration Agency's Hayabusa space probe was launched in 2003 and successfully reached the asteroid 25143 Itokawa. It was powered by four xenon ion engines, which used microwave electron cyclotron resonance to ionize the propellant and an erosion-resistant carbon/carbon-composite material for its acceleration grid.





4.3 Future Missions and Applications

- The Power and Propulsion Element (PPE) is a module on the Lunar Gateway that provides power generation and propulsion capabilities It is targeting launch on a commercial vehicle in January 2024. It would use the 50 kW Advanced Electric Propulsion System (AEPS) under development at NASA Glenn Research Center and Aerojet Rocketdyne.
- The MARS-CAT (Mars Array of ionospheric Research Satellites using the CubeSat Ambipolar Thruster) mission is a two 6U CubeSat concept mission to study Mars' ionosphere. The mission would investigate its plasma and magnetic structure, including transient plasma structures, magnetic field structure, magnetic activity, and correlation with solar wind drivers.
- In early 2015, NASA initiated the NextSTEP program in which private companies are funded to develop next-generation propulsion technologies. The funding that goes to Ad-Astra, MSNW, and Aerojet will support technology that eventually will purportedly mature to electric thrusters that serve very high-power far–future endeavors at power levels of well above 100-kW.
- The NASA Evolutionary Xenon Thruster (NEXT) qualification involved the operation of the thruster under strict laboratory conditions for about 5 years. Now, the NEXT has an easier path to be used for commercial purposes in addition to interplanetary missions.

5. History and Applications of Solar Sails Propulsion

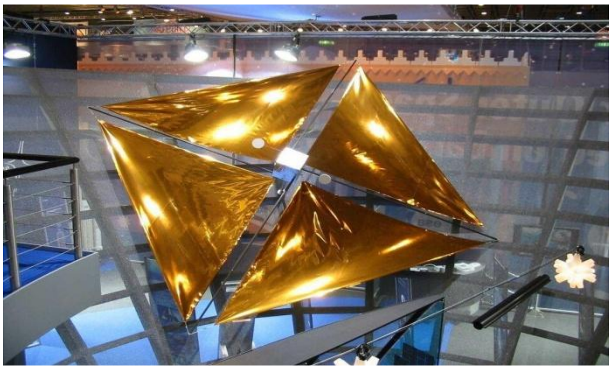
5.1 History

In 1974 the Mariner 10 satellite was on a mission to Mercury when it ran low on attitude control gas. The scientists had an idea; they angled the solar panels of the satellite in such a way that they could use the solar radiation pressure for attitude control. Though this was not a solar sail mission, it proved the concept of solar sailing.

Solar sails were used on India's INSAT 2A and 3A communications satellites, in 1992 and 2003. The satellites utilized a 4-panel solar array on one side. A solar sail was mounted on the north side of the satellite to balance the torque resulting from the solar pressure.

5.2 Current Research and Applications

- On 21 May 2010, Japan Aerospace Exploration Agency launched the world's first interplanetary solar sail called "IKAROS" (Interplanetary Kite-craft Accelerated by Radiation of the Sun) to Venus. Using a new solar-photon propulsion method, it was the first true solar sail spacecraft fully propelled by sunlight and was the first spacecraft to succeed in solar sail flight.
- NanoSail-D2, also sometimes called simply NanoSail-D, was launched on November 19, 2010, becoming NASA's first solar sail deployed in low earth orbit. The goals of the mission were to test sail deployment technologies and to gather data about the use of solar sails as a simple mean of de-orbiting dead satellites and space debris.
- In August 2019, NASA awarded the Solar Cruiser team $400,000 for nine-month mission concept studies. The spacecraft would have a 1,672 m^2 (18,000 sq ft) solar sail and would orbit the Sun in a polar orbit, while the coronagraph instrument would enable simultaneous measurements of the Sun's magnetic field structure and velocity of the coronal mass ejections. If selected for development, the launch would take place in 2024.
- As of December 2013, the European Space Agency (ESA) has a proposed deorbit sail, named "Gossamer", that would be intended to be used to accelerate the deorbiting of small (less than 700 kilograms (1,500 lb.)) artificial satellites from low Earth orbits. The launch mass is 2 kilograms (4.4 lb.) with a launch volume of only 15×15×25 cm (0.49×0.49×0.82 ft). Once deployed, the sail would expand to 5x5 m (16 ft × 16 ft) and would use a combination of solar pressure on the sail and increased atmospheric drag to accelerate satellite reentry.



6. Future Missions and Applications

- For the Non-Keplerian orbit applications, two applications were proposed, namely, Geostorm and Polesitter. The Geostorm mission concept provides real-time monitoring of solar activity. Another application concept was Statite, which would use a high-power solar sail to directly balance the solar sail to hover over the poles of the Sun.
- For Inner solar system applications include docking with asteroids or comets, specifically excluding bodies that are, in effect, part of the Jupiter system, for example, the Hilda and Jupiter Trojan asteroids.
- A sequence of assessment studies was previously conducted by the Authors and Hughes looking at solar sail sample return missions to Mars, Venus, Mercury, and a small-body, with the specific objective of enabling a system-level trade on the propulsion selection criteria within each mission. Within each of these, a complete system-level analysis was performed, considering a range of mission architectures, attempting to define the most preferential solar sail architecture.
- The use of solar sails for outer solar system rendezvous missions has been long discussed. Furthermore, an assessment study was previously conducted by the authors and Hughes looking at a range of solar sail Jupiter missions, including concepts for exploration of the Galilean moons.
- A Jupiter atmospheric probe mission was considered by the Authors and Hughes as a potential Jupiter flyby mission. As the distance from the sun increases, the difficulty of using chemical or solar propulsion goes on increasing. Hence, being very cost-effective solar sails gain a lot of attraction for missions further away from the sun.
- A significant quantity of work in the past decade has been performed to assess the problem of trajectory and system design of a solar sail mission beyond Neptune. It has been shown that solar sail propulsion offers significant benefits to missions' concepts which aim to deliver a spacecraft beyond Neptune, for either a Kuiper Belt or Interstellar Heliopause (at approximately 200 au) mission.

7. Conclusion

Space technology has opened up space as we have only dreamed about. The technologies that started space exploration have started to show their age. These technologies sure got us as far we have reached but the future applications seem farfetched. That’s why the advanced space propulsion systems discussed are the way to the future. These systems are safe to use, long-lasting, and most importantly very economical. Humanity can reach many different star systems in their lifetime, we could develop satellites that harvest the total power of the Sun, we could develop extreme technology, all that, and much more while being economical. The power of these systems is still in its infantry and with proper development and advancements, these can surely be the go-to propulsion systems of the future.

References

[1] Andrew C. Clein, Allen Camp, Patrick McClure, Susan Voss (January 2021). “Operational Considerations for Fission Reactors Utilized on Nuclear Thermal Propulsion Missions to Mars”, NASA, https://fas.org/nuke/space/opcon-ntp.pdf

[2] Dunbar, Brian. “Ion Propulsion.” NASA, NASA, 18 Aug. 2015, www.nasa.gov/centers/glenn/about/fs21grc.html.

[3] Dauna Coulter, “A Brief History of Solar Sails” July 2008, NASA, https://science.nasa.gov/science-news/science-at-nasa/2008/31jul_solarsails

[4] Macdonald, Malcolm. (2011). Solar Sailing: Applications and Technology Advancement. 10.5772/13614. https://www.researchgate.net/publication/221910806_Solar_Sailing_Applications_and_Technology_Advancement Please note down your paper reference number : IJSTR-0621-45677