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What if Titan Dragonfly had a fusion engine?

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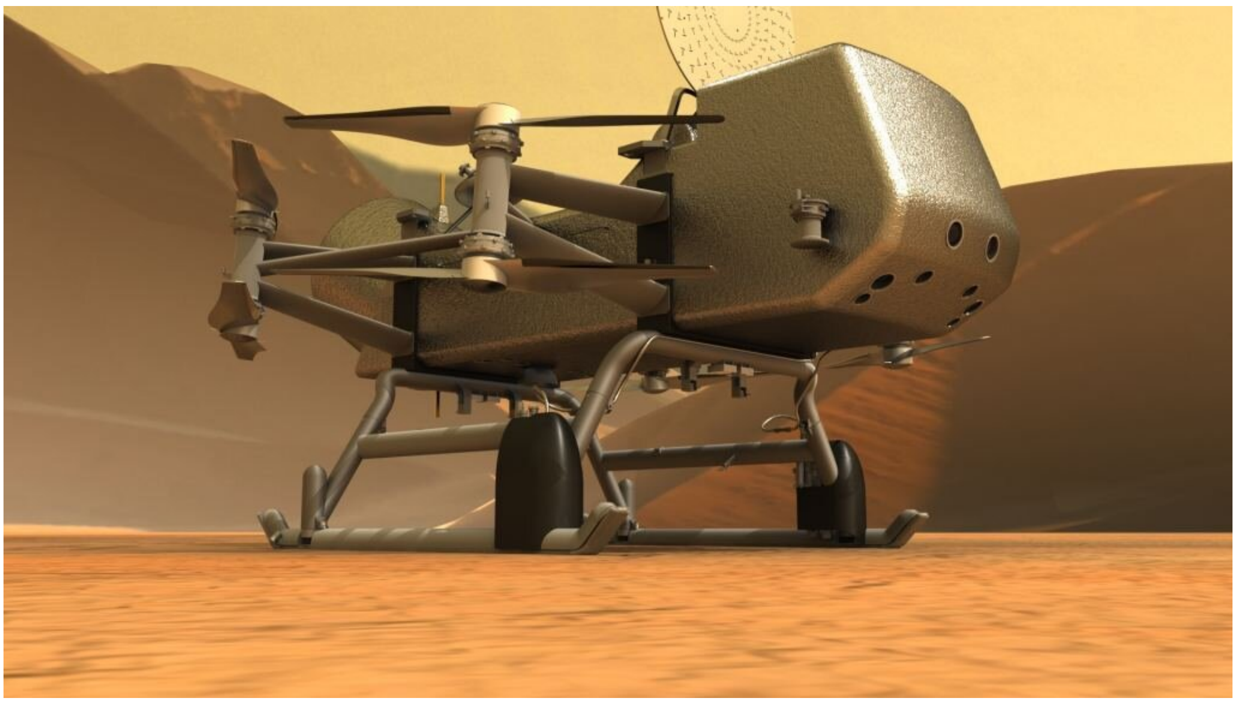

Artist's Impression of Dragonfly on Titan's surface. Credit: NASA/Johns Hopkins APL

In a little over four years, NASA's Dragonfly mission will launch into space and begin its long journey towards Titan, Saturn's largest moon. As part of the New Frontiers program, this quadcopter will explore Titan's atmosphere, surface, and methane lakes for possible indications of life (aka. biosignatures).

This will commence in 2034, with a science phase lasting for three years and three and a half months. The robotic explorer will rely on a nuclear battery—a Multi-Mission Radioisotope Thermal Generator (MMRTG)—to ensure its longevity.

But what if Dragonfly were equipped with a next-generation fusion power system? In a recent mission study paper, a team of researchers from Princeton Satellite Systems demonstrated how a direct fusion drive (DFD) could greatly enhance a mission to Titan. This New Jersey-based aerospace company is developing fusion systems that rely on the Princeton Field-Reversed Configuration (PFRC).

This research could lead to compact fusion reactors that could lead to rapid transits, longer-duration missions, and miniature nuclear reactors here on Earth.

The research team was led by Michael Paluszek, the president of Princeton Satellite Systems (PSS) and an aeronautic and astronautical engineer with a long history of experience in space systems and the commercial space industry. He was joined by multiple colleagues from PSS, the Princeton Plasma Physics Laboratory (PPPL), the Air Force Institute of Technology at Wright-Patterson AFB, and Princeton and Stanford University. Their mission study, "Nuclear fusion powered Titan aircraft," recently appeared in *Acta Astronautica*.

The concept of nuclear propulsion goes back to the early Space Age when NASA and the Soviet space program sought to develop reactors to power future missions beyond the Earth-moon system. Between 1964 and 1969, their efforts led to the Nuclear Engine for Rocket Vehicle Application (NERVA), a solid-core reactor that relies on the slow-decay of highly-enriched uranium (235U) to power a nuclear-thermal propulsion (NTP) or nuclear-electric propulsion (NEP) system.

The former relies on a reactor to heat deuterium (2H) and liquid oxygen (LOX) propellant, which is then directed through nozzles to generate thrust. The latter involves a reactor providing electricity to a Hall-Effect thruster or ion engine that relies on electromagnetic fields to ionize an inert gas (like xenon) that is directed through nozzles for thrust. In contrast to these traditional nuclear engines, the direct fusion drive (DFD) calls for a nuclear-fusion rocket engine that would produce both thrust and electric power for an interplanetary spacecraft.

In a previous study, an international research team proposed how a spacecraft equipped with a 2-megawatt (MW) DFD could transport a 1000 kg (2200 lbs) payload to Titan in less than 2.6 years (~31 months). This is over twice the mass of the Dragonfly mission, which is (relatively speaking) a featherweight by comparison—450 kg (990 lbs). A transit time of 2.6 years is also significantly less than the seven years the Dragonfly's spacecraft will take to reach Titan.

In their paper, Paluszek and his colleagues extended this work to include an aircraft as the payload, which would explore Titan's atmosphere and surface for years. And unlike the Dragonfly's quadcopter design, their Titan aircraft would be a fixed-wing robotic explorer. As Paluszek told Universe Today via email, the key to this spacecraft concept is the PFRC reactor concept developed by researchers at the PPPL:

"The Princeton Field Reversed Configuration is a magnetic topology in which fields, produced by antennas, close the field lines within a magnetic mirror. The antennas produce what is called a rotating magnetic field (RMF). Fusion takes place in this closed field region. Additional lower-temperature plasma streams around the fusion region to produce an exhaust stream with the best exhaust velocity and thrust for a given mission."

According to their paper, a DFD propulsive engine could transport a sizable spacecraft to Titan in less than two years. A second fusion reactor would power the Titan spacecraft as a closed-loop electrical power generator. Both reactors would be based on the PFRC concept and rely on a novel radio-frequency plasma heating system and deuterium/helium-3 ($^2H/^3He$) fuel. This would give the Titan aircraft significantly more power (by several orders of magnitude) and greatly extend the life of the mission. Said Paluszek:

"The Titan aircraft is much larger. It provides over 100 kW for experiments. Dragonfly supplies about 70 W. More power means faster data transfer to Earth and a whole new class of high-power instruments. The NASA Jupiter Icy moon Orbiter mission had a similar amount of power, and many novel instruments that required kWs of power were planned."

Utilizing nuclear power to advance space exploration is something that space agencies have been investigating since the dawn of the Space Age. With the Artemis Program and the return to the moon in this decade, and missions to Mars and other deep-space destinations in the next, NASA and other space agencies are once again considering potential applications. These include bimodal nuclear spacecraft equipped with an NTP and NEP system that could reduce transits to Mars to 100 days (it currently takes six to nine months for spacecraft to travel there).

An NTP system was recently selected for Phase I development as part of the 2023 NASA Innovative Advanced Concepts (NIAC) program that could reduce transit times to as little as 45 days. In addition, NASA has contracted with DARPA to test an NTP prototype—the Demonstration Rocket for Agile Cislunar Operations (DRACO)—in orbit by 2027. There are also efforts to develop small, lightweight fission systems through NASA's Fission Surface Power (FSP) project to continuously provide up to 10 kilowatts (kW) of power for at least ten years.

These latter efforts build on NASA's Kilopower project, which led to the Kilopower Reactor Using Stirling TechnologY (KRUSTY) demonstrator. As Paluszek explained, a DFD that relies on the PFRC reactor design could drastically improve on these proposals. What's more, the technology has significant implications for space exploration and terrestrial applications as well:

"A key number is the ratio of power to power plant mass. DFD should be around 1 kW/kg. NEP is about 0.02 kW/kg. This tech could be used for portable power for emergencies or for the military. It could power remote towns that don't have a grid-tie [and] for industrial applications where a grid-tie is not available. It could power ships and very long-endurance drone aircraft. It could also be used for modular power plants, much like wind turbines and solar. Another application is peaking power."

This is not the first time that Paluszek and his colleagues at the PPPL and Princeton Satellite Systems have proposed DFD technology to advance space exploration. In 2014, as part of the 65th International Astronautical Congress (IAC), they recommended a DFD spacecraft for a crewed orbital mission to Mars. In 2016, they proposed how a DFD-equipped orbiter and lander would facilitate a mission to Pluto, which was selected for Phase I and Phase II development by the NIAC.

In the coming decade, nuclear propulsion and nuclear power systems will likely become regular mission features. This will likely include miniature fusion reactors that provide power for facilities that support exploration and development on the lunar surface. It could also provide for rapid transportation and power systems on Mars and astrobiology missions to Europa, Ganymede, Titan, Enceladus, and other ocean worlds in the outer solar system. In summary, fission and fusion power are a vital part of humanity's efforts to go further into space and stay there long-term.

More information: Michael Paluszek et al, Nuclear fusion powered Titan aircraft, *Acta Astronautica* (2023). DOI: 10.1016/j.actaastro.2023.04.029

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