Next-generation Cryogenic Transfer and Autonomous Refueling (NeCTAR)

AggieSat Laboratory

Texas A&M University

Kamalika Bose, Thomas Lopez, Kai Elmore, Ryan Chacko, Miguel Cunanan, Arnav Shah, Gage Wallace, Sri Dhriti Kuram, Jaret Pinkerton, Siquan (Cindy) Qiu, Pallavi Gokul, Melanie Fuentes, Colter Swim, Vincent Guerrero, Ikaika Mendoza, Arthur Nguyen, Poorvi Parikh

Advisor: John F. Connolly, P.E.

Introduction

Cryogenic fuel transfer in space presents critical engineering challenges due to the extreme properties of cryogens and the complexity of operating in microgravity. Without gravitational stratification, liquid propellants tend to float freely or cling to tank walls via surface tension, destabilizing flow and compromising transfer reliability [1].

Materials exposed to cryogens must be capable of enduring intense thermal cycling, which can cause brittleness, cracking, or vapor lock. These effects are amplified by environmental risks such as leaks, pressure spikes, and contamination from lunar regolith introduced by plume-surface interactions (PSI) [1].

To enable sustainable lunar and Martian exploration, autonomous systems must overcome these hazards with robust thermal control, material resilience, and reliable docking.

Objectives and Solution Overview

NeCTAR aims to enable autonomous, reliable cryogenic fuel transfer on the lunar surface.

Primary Objectives

- Achieve stable, bidirectional cryogenic transfer in low gravity
- Mitigate contamination from PSI and lunar regolith
- Maintain thermal and structural integrity through extreme cycles
- Operate autonomously with onboard fault detection and recovery

Secondary Objectives

- Interface with various lander architectures
- Support autonomous docking and sealing
- Withstand extended mechanical cycling for multi-mission use

NeCTAR integrates a vacuum-jacketed pipe, recessed TZM flange, cryo-rated actuators, and full FSM-controlled autonomy.

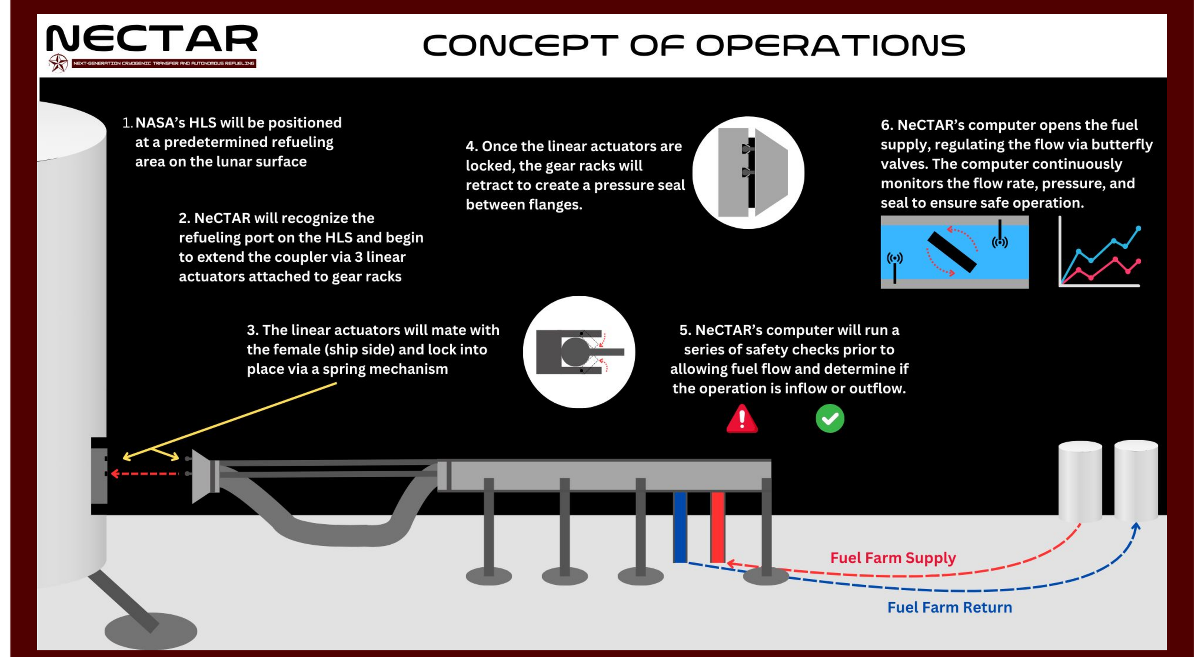


Figure 1. CONOPS of NeCTAR

System Design and Operations

Thermal, Mechanics, and Structures (TMS)

NeCTAR is a compact cryogenic transfer system built around a vacuum-jacketed 316L pipe, a recessed 37.5° TZM flange, and spring-energized PTFE/Elgiloy seals rated for 10,000+ cycles. Bidirectional transfer is handled by dual ¼-turn butterfly valves with non-concurrent sequencing. Cryo-rated Maraging Steel actuators ensure precise force and repeatability, with CDH-monitored drift and limit-switch homing. Dust protection includes an iris shutter, electrostatic rings, and YBCO-based repulsion. Fully autonomous, NeCTAR supports retry logic, leak-before-burst safety, and redundant lockouts for robust lunar surface reliability.

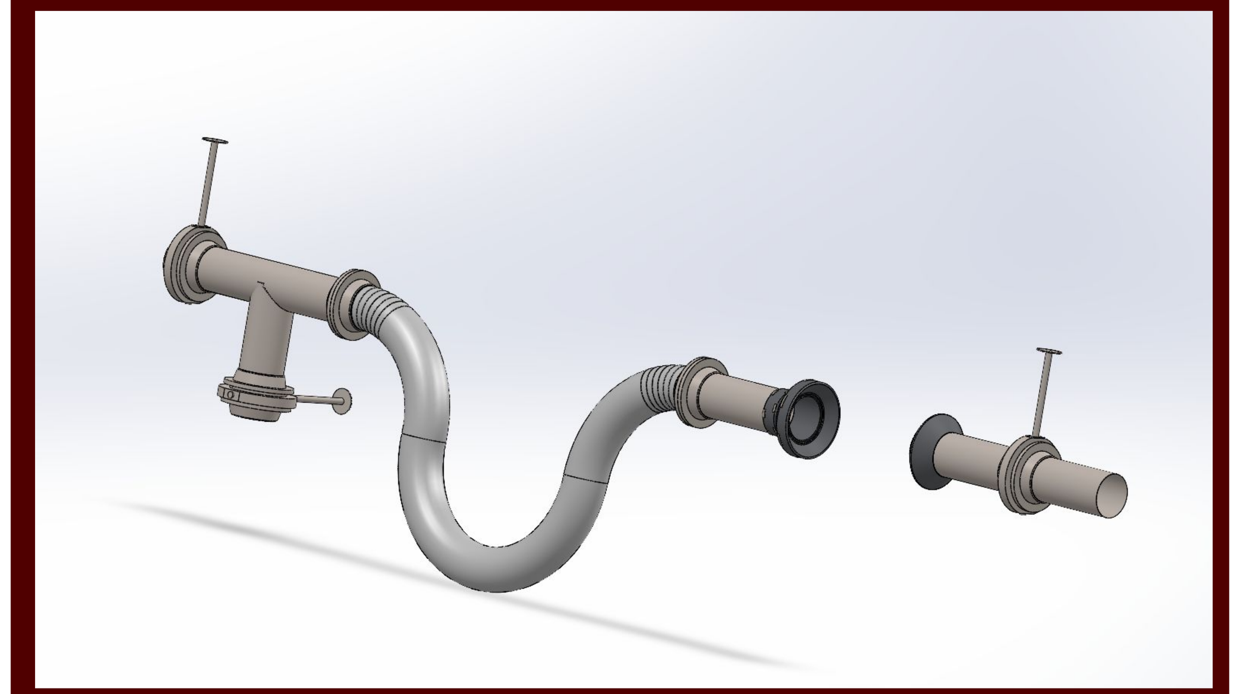
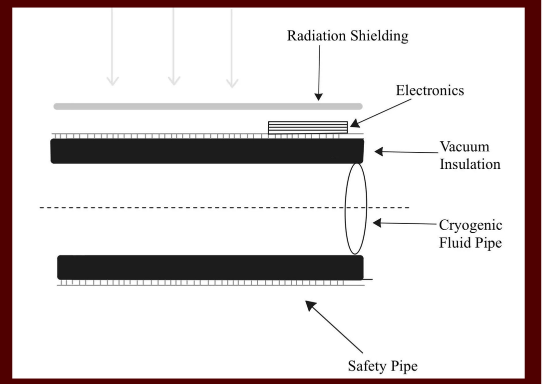


Figure 2. 3D Model of interior NeCTAR pipe-coupler system, to scale.

Dynamics (DYN)

DYN is responsible for the characteristics and behaviors surrounding the flow of cryogenic fluids, working closely with TMS to focus on their primary objectives: to maintain an optimal cryogenic environment in the system, develop a flow path capable of bidirectional flow while ensuring no backflow may occur, and ensure the coupler system may attach and detach in a simple and repeatable manner for the onboard computer.



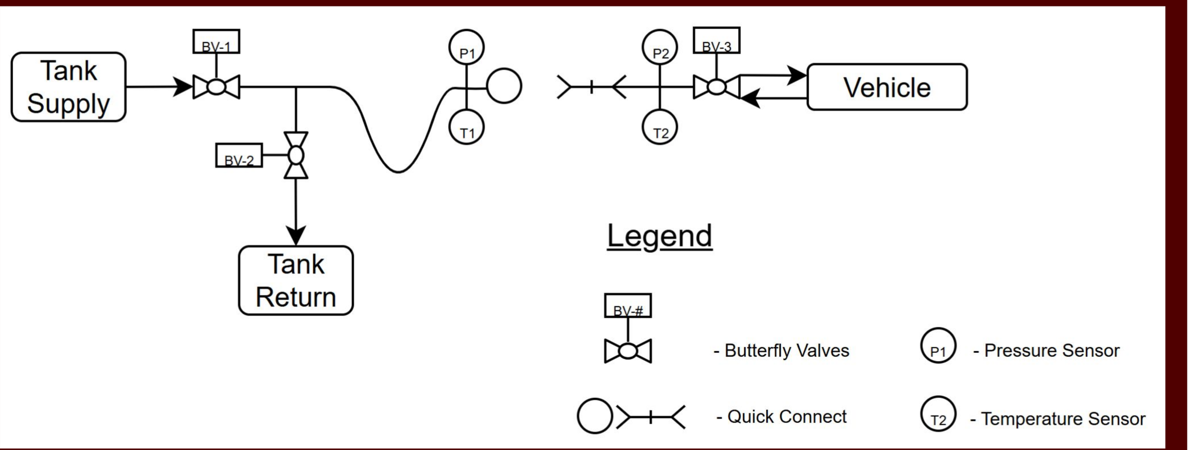


Figure 3. NeCTAR's Piping and Instrumentation Diagram

System Design and Operations (cont.)

Electrical Power Subsystem (EPS)

The EPS provides power generation, storage, and management to NeCTAR. NeCTAR employs thirteen 7-cell lithium-ion batteries for power, and has a sensor suite consisting of temperature sensors, pressure sensors, limit switches, linear actuators, and a dust shield. These, with the rest of the system, result in an estimated power budget of 3.286 kW at its maximum.

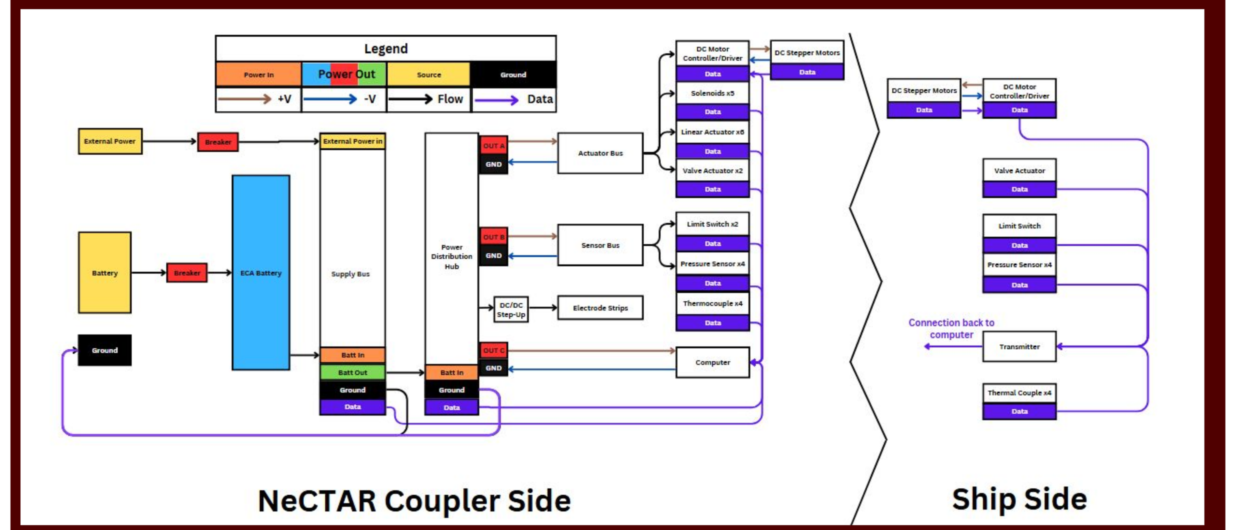


Figure 4. EPS functional block diagram NeCTAR.

Command and Data Handling (CDH)

The CDH subsystem uses a 5 state system architecture that incorporates all subsystems associated with NeCTAR to perform all necessary operations. NeCTAR's CDH also incorporates a variety of failsafes and aborts that prevent system failure and damage to the coupler itself and/or the spacecraft. Logical checks are implemented throughout the architecture to ensure that the system knows which variables are present at all times. The mainstages embedded in NeCTAR's architecture are as follows:

Mainstage 1: Attach

- Performs initial motion towards the HLS to line up and connect to the refueling port, initializing the fuel transfer process.

Mainstage 2: Outflow

- Option to move fuel from the HLS to a dedicated fuel storage tank. Performs constant state checks and implements the respective failsafe or abort in accordance to system condition.

Mainstage 3: Inflow

- Option to move fuel from a dedicated fuel storage tank to the HLS. Performs constant state checks and implements the respective failsafe or abort in accordance to system condition.

Mainstage 4: Purge Coupler

- Implemented whenever the system is done with the fueling process. A pressure differential will purge the system to remove any residual fuel from the system to present exposure to the lunar environment.

Mainstage 5: Detach

- Retracts the arm from the HLS to finalize the refueling process. Returns the system to a standby state and allows for the refueling process to be repeated at multiple iterations for multiple vehicles.

System Merit and Recommendations

System Merit

- Performance: NeCTAR adheres to HuLC constraints and guidelines. NeCTAR also applies an innovative approach towards current refueling processes to reduce risk and increase efficiency.
- Technology Readiness: NeCTAR will support a TRL 6 at its system level testing completion and a TRL 7 at its complete system validation.
- Risk: NeCTAR is a low-risk solution providing enhanced safety with the elimination of human error, with remaining risks shown below in Figure 7.
- Programmatic Implementation: NeCTAR provides a standardized refueling process applicable to NASA's HLS intended for long term usage on the lunar surface, intended to be implemented with pre-existing lunar infrastructure to include fuel storage, pipelines, and a dedicated refueling location on the lunar surface.
- Cost: From NASA's PCEC software, NeCTAR is estimated to have a total program cost of $59.63M FY2025.

NECTAR System Risk Matrix		Severity				
		Insignificant	Minor	Moderate	Major	Severe
Likelihood	Almost Certain					
	Likely					
	Possible			2		
	Unlikely		4		3	1
	Rare					5

Figure 5. Risk matrix of NeCTAR's five most critical issues with values after mitigation.

1: Ruptured fuel line
2: Misaligned coupling
3: Seized valve
4: Seal degradation
5: Vapor lock

References

[1] Hensley, M., Bhimji, W., and Cirillo, W., "A Review of In-Space Propellant Transfer Capabilities and Challenges for Missions Involving Propellant Resupply," NASA Technical Report NASA/TM-2020-5007997, 2020.

NECTAR

NEXT-GENERATION CRYOGENIC TRANSFER AND AUTONOMOUS REFUELING