

The Safety and Hazard Process Followed During the Design of a 50kW-class Electric Propulsion Subsystem: PPE

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The Power and Propulsion Element (PPE) is the first piece of the Artemis Lunar Gateway. This spacecraft will host a 50kW-class state of the art electric propulsion subsystem, containing a combination of never-before-flown 6kW and 12kW thrusters, large Carbon Fiber Overwrapped Pressure Vessel Xenon tanks, and a refueling interface. The combination of the high degree of new hardware within the propulsion system, the inclusion of PPE within the larger human-rated Artemis Gateway, and the high level of Lanteris Space Systems heritage with the LS1300 platform required a tailored safety and hazard process for the program. This paper details the system safety and hazard analysis methods applied during the design phase, summarizes key hazard identification and mitigation activities, and discussed how these influenced the final architecture of the electric propulsion subsystem.

I. Introduction

THE Power and Propulsion Element (PPE) spacecraft is the first element of the Artemis lunar Gateway. Numerous studies have demonstrated that 40-60kW-class solar electric propulsion (SEP) capability can be enabling for both near term and future architectures and science missions [1,2]. In March of 2017, NASA announced its conceptual next steps for exploration of destinations beyond LEO. In order to move toward these next steps, the first phase of this exploration will involve the building of a Gateway in cislunar orbit, primarily in a Near Rectilinear Halo Orbit (NRHO). The Gateway is envisioned as an outpost for lunar exploration and for explorations further away from Earth and eventually to Mars. Key to the enabling of exploration in the vicinity of the Moon, the PPE spacecraft will be capable of transferring the entire Gateway stack between various cislunar orbits as well as capable of maintaining itself in the selected NRHO.

In order to provide the required thrust, while minimizing the propellant usage, to move a lunar spacecraft around, a high-power and highly-efficient electric propulsion system will be used. PPE is the first spacecraft developed to expand electric propulsion capability beyond the ~kW power levels used for commercial applications into this higher power regime. A notional NASA graphic of the lunar Gateway in the NRHO, can be seen in Figure 1. In this representative image, the notional lunar lander elements are attached at the top of the image, and an Orion piloted vehicle is shown approaching from the right to dock with the Gateway. A robust and comprehensive hazard and safety process has been implemented across all Lunar Gateway elements, including PPE. There was additional scrutiny on the electric propulsion system because of the degree of new hardware without flight heritage as well as the higher power environment compared to previous electric propulsion spacecraft.

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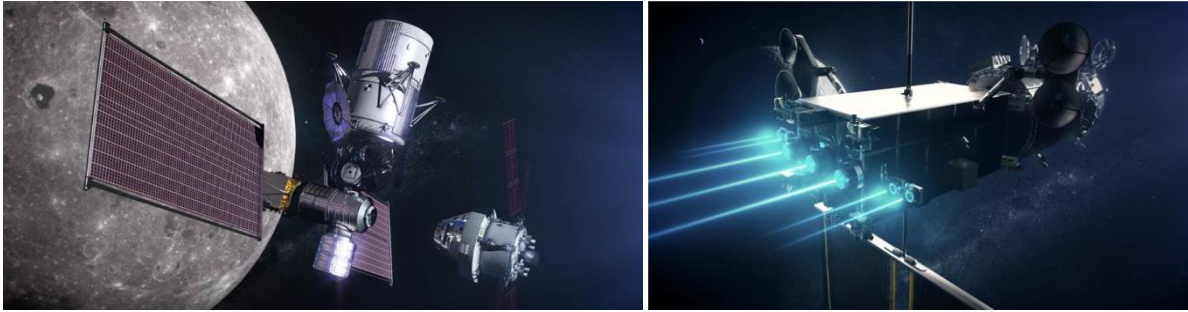


Figure 1. Lunar Gateway illustration showing the Power and Propulsion Element (PPE), Habitation and Logistics Outpost (HALO), Human Lunar Lander, and crewed Orion vehicle (left). Rendering of PPE spacecraft showing seven high-power EP thrusters operating (right).

II. Hazard and Safety Process Overview

In support of the PPE and Gateway programs, Lanteris Space Systems and NASA have used tools such as fault tree analyses and hazards analyses to identify potentially hazardous conditions initiated by, or affecting, the PPE Electric Propulsion System. The intent of the safety process is to identify hazardous conditions and their controls. Controls may be provided in the form of hardware features, autonomous isolation, or ground enabled operational procedures.

A. System Safety Fundamentals

System Safety is a systems engineering discipline with an emphasis on safety where the goal is to identify hazardous conditions, define requirements necessary to control those conditions, and ensure compliance with safety requirements to minimize the likelihood of a hazard manifesting on-orbit. NASA Systems Safety Handbook Volume 1 provides that, “System safety is the application of engineering and management principles, criteria, and techniques to optimize safety within the constraints of operational effectiveness, time, and cost throughout all phases of the system life cycle”. By conducting a functional decomposition of the PPE’s subsystems and Concept of Operations (CONOPS) and leveraging analysis tools, including Fault Tree Analyses (FTA), Failure Modes Effects and Criticality Analysis (FMECA), and Hazards Analysis, a thorough understanding of the PPE hazards is achieved. Although PPE will not host flight crews, failure of the PPE could impact human safety while crew is on-board the Gateway. The likelihood of a catastrophic hazard to both the system and Gateway flight crews is minimized by understanding spacecraft hazards and identifying necessary controls and mitigations.

The PPE program leveraged fundamentals and processes from ARP4761 [10], ARP4754 [9], Mil-STD-882E [11], as well as the NASA System Safety Handbooks Vol 1 and 2 [13, 14] to address system hazards for the spacecraft. Given their long-standing application in commercial aviation, these standards offer a well-established foundation for hazard analysis and risk management. Adapting them to spacecraft systems allowed the program to leverage proven processes while addressing unique spaceflight challenges. These challenges include, but are not limited to, ensuring the PPE does not experience an uncontrolled anomaly that results in loss of life or significant injury, demonstrating safe transfer of xenon from the Gateway to PPE, and establishing system robustness such that the PPE can maintain attitude and translational controllability in the event of a failure.

Both ARP4754 and ARP4761 provides a detailed methodology for understanding system failure modes and hazards through the application of FTAs and FMECAs and provides guidance for addressing hazards induced by failure of hardware, operating environment and the operational conditions of the system. These standards also provide guidance for integrating Safety in the Systems Engineering process. MIL-STD-882E [11] and the NASA System Safety Handbooks offers insight into managing safety for US Government customers. By adapting these standards, a comprehensive and robust process has been established that allows the System Safety engineer to thoroughly identify system level hazards and allocate verifiable controls and mitigations.

B. The PPE Program’s System Safety Process

The PPE systems safety process flowchart is shown in Fig. 2 below. This chart shows how the safety process begins at contract award in Phase 0, and continues through the CDR design in Phase2, and concludes with post-launch activities.

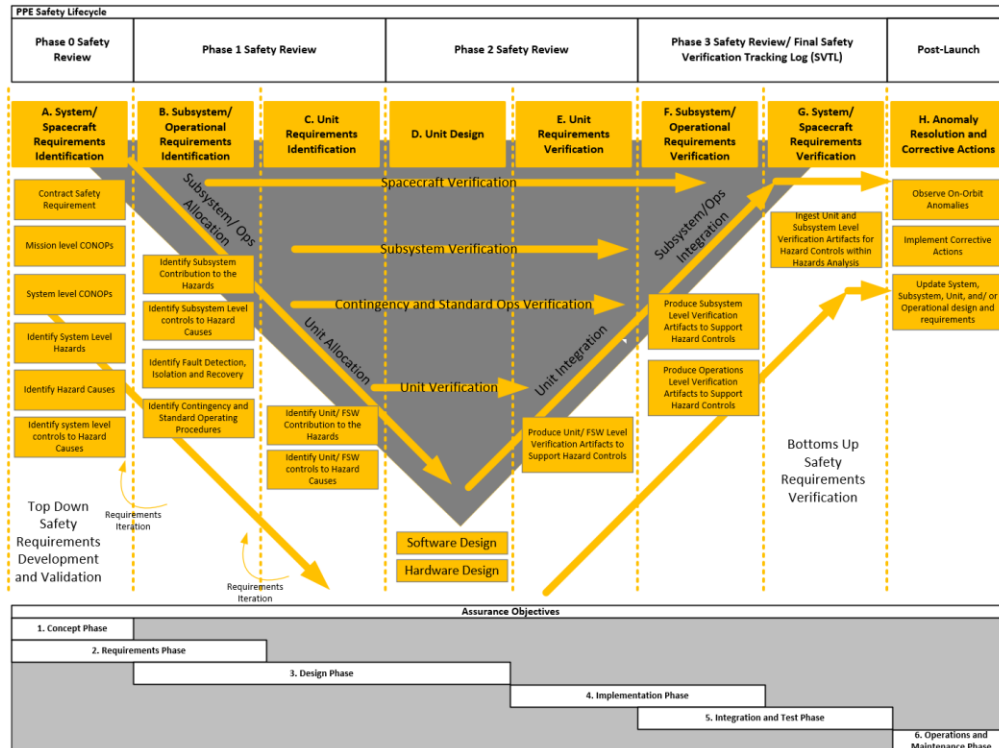


Figure 2. PPE systems safety lifecycle chart

1. Risk Criteria

Hazards on PPE were evaluated based on risk scores defined by NASA on a 5 by 5 risk matrix, where severity is defined on the X axis and likelihood on the Y axis. Fig. 3 describes the risk matrix employed on PPE.

Likelihood	Very High (5)					
	High (4)					
	Moderate (3)					
	Low (2)					
	Very Low (1)					
		Minor (1)	Moderate (2)	Severe (3)	Critical (4)	Catastrophic (5)
Severity						

Figure 3. PPE Safety Risk Matrix

Critical and catastrophic are the only two severity categories that are considered for the PPE program by Lanteris Space Systems per contract with NASA. Critical hazards include any condition which may cause loss of major Gateway element not in a critical path or major damage to other essential flight assets. Critical hazards do not require failure tolerance for human-rating, however, critical hazards can have a significant impact on Loss of Mission risk. Catastrophic hazards include any condition which may cause a permanently disabling or fatal personnel injury (loss of crew) or one of the following: loss of Gateway, loss of crew-carrying vehicle, or equipment damage that results in loss of the mission. Loss of the Gateway is defined as a condition resulting from failures or damage to Gateway elements that render the Gateway unusable for further operations. Loss can be defined as a failure that results in a Gateway condition that prevents further rendezvous and docking operations with visiting vehicles or elements.

2. Failure Tolerance

The PPE spacecraft is required to be single failure tolerant to any catastrophic hazard and zero failure tolerant to any critical hazard. In the context of the electric propulsion system the following types of failures have been considered:

- **Functional Failure:** Redundancy has been implemented and enabled by ground commanding or spacecraft Fault Detection, Isolation and Recovery (FDIR) software.
- **Anomalous Pressure:** FDIR, in coordination with ground troubleshooting, has been employed to isolate potential pressure anomalies.
- **Anomalous Temperature:** FDIR, in coordination with ground troubleshooting, has been employed to isolate potential temperature anomalies.
- **Thruster Arcing/ Sparking:** Sparking and arcing events from the electric thrusters, which may impact spacecraft health, has been observed in ground testing and on-orbit on other spacecraft [15]. A combination of operational changes, hardware implementations, and FDIR are being implemented to prevent thruster EMI/EMC events from damaging spacecraft hardware on-orbit.

3. Requirements Based Design

A requirements-based design approach allowed the PPE team to evaluate system level hazards and derive requirements which prescribe mitigations. Fault tree and hazard analyses are used to determine risks to the flight system which subsequently allowed for the development of requirements that prescribed mitigations. Risks include hazards that are intrinsic to subsystems and their interfaces or are initiated by environmental effects. Those requirements were then incorporated as part of PPE's system safety requirements specification. Subsystems decomposed the system safety requirements and generated verification artifacts which ensured implementation of the controls. Control verifications were produced, thus ensuring proof of the implementation of the control. As shown in Figure 2. PPE systems safety lifecycle chart depicts the process from requirement derivation to final verification artifact submission.

4. PPE Safety Phase

System Safety on the PPE program is addressed with a four phased approach:

- **Phase 0 (Concept Development):** System requirements are proposed. System Safety conducts a preliminary Fault Tree Analysis (FTA) and subsequently the preliminary hazards analyses. Initial hazardous conditions are defined.
- **Phase 1 (Preliminary Design):** Subsystem requirements become defined. System Safety refines the FTA with considerations of the preliminary system and subsystem architecture. The initial system and subsystem designs are functionally decomposed within the FTA, initial Failure Modes, Effects and Criticality Analyses (FMECA) are created. Initial controls and mitigations and risks are defined.
- **Phase 2 (Detailed Design):** Safety products are iterated upon given the updated system and subsystem designs. Verification activities for the implementation and effectiveness of the hazard controls are defined.
- **Phase 3 (Design Validation and Verification):** Safety product are finalized. Verification activities supporting the implementation and effectiveness of all hazard controls and mitigations are conducted and documented.

Spacecraft Safety Criteria "in a Nutshell"

Effects on spacecraft and/or occupants of the identified failure condition	Mil-Std-882E Definitions*	Could result in one or more of the following: injury or occupational illness not resulting in a lost work day, minimal environmental impact, or monetary loss less than \$100K.		Could result in one or more of the following: injury or occupational illness resulting in one or more lost work day(s), reversible moderate environmental impact, or monetary loss equal to or exceeding \$100K but less than \$1M.		Could result in one or more of the following: permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, reversible significant environmental impact, or monetary loss equal to or exceeding \$1M but less than \$10M.	Could result in one or more of the following: death, permanent total disability, irreversible significant environmental impact, or monetary loss equal to or exceeding \$10M.
Mil-Std-882E System Level Effect Category*		Minor		Major		Critical	Catastrophic
NPR 7150.2D Software Classifications		Class E		Class D	Class C	Class B	Class A
Mil-Std-882E Software Criticality Indices (SwCI)		SwCI5		SwCI4	SwCI3	SwCI2	SwCI1
Mil-Std- 882E Quantitative Probability Category*		Eliminated	Improbable	Remote	Occasional	Probable	Frequent
<u>System Validation Method</u> (Common cause hazards not conducive to numerical analysis, such as foreign object collision, human error, etc. may be analyzed primarily by Design Review.)		<u>Design Review</u> Design, functional separation, and implementation reviewed to ensure failures will only produce Minor effect.		<u>FMEA Review</u> Failure modes & effects analysis reviewed to ensure that failure effects of components involved in the function and failure rates are appropriate for Major category.		<u>Fault Tree Analysis</u> FMEA & FHA data combined in detailed fault tree analysis to validate that the system probability of hazard is Extremely Remote.	<u>Fault Tree Analysis</u> FMEA & FHA data combined in detailed fault tree analysis to validate that the system probability of hazard is Extremely Improbable.
Effect Category Validation		Where spacecraft functions are the same as previous systems, flight history should be reviewed and considered. Where available, unique conditions should be evaluated by tests. Tests include but are not limited to ground, flight, lab, and simulation tests. Failures affecting handling qualities should be evaluated in spacecraft simulation and/or spacecraft In-Orbit Test (IOT).					Specified Failure may be evaluated by spacecraft simulation as necessary if plausible.

*NASA Procedural Requirements (NPR) 8715.3C, NASA General Safety Program Requirements cites Mil-Std-882E for hazard definition, system level effect category and quantitative probability category

Figure 4. Spacecraft Safety Criteria

III. Electric Propulsion Subsystem Design Overview

The design of the electric propulsion system on the PPE spacecraft draws heavily on Lanteris's heritage 1300-series to leverage established reliability and lower program risk. Numerous Lanteris electric propulsion components which have flown successfully on GEO spacecraft since 2004 will also fly on PPE. Many of these components have undergone minor design iterations based on on-orbit lesson's learned, arguably increasing their TRL above the standard maximum of TRL9 [2]. This spacecraft will operate never-before-flown 6kW [18] and 12kW [19] thrusters, both operating at 600V – all of these values are higher and more challenging than previous on-orbit Hall Effect Thruster string operation. The spacecraft is required to be refueled on-orbit for both bipropellant and xenon propellants, which is needed to support the program 15-year orbit maintenance and cis-lunar transfers, as the initial lunar transit will consume ~90% of the xenon loaded at launch. A refuelable Gateway platform also provides significant long-term flexibility and the on-orbit refueling experience feeds forward into future exploration architectures. This will be the first on-orbit transfer of Xenon propellant in an electric propulsion spacecraft. A cartoon of the electric propulsion subsystem can be seen in Figure 5 below, and images of the spacecraft during the build phase can be seen in Figure 6.

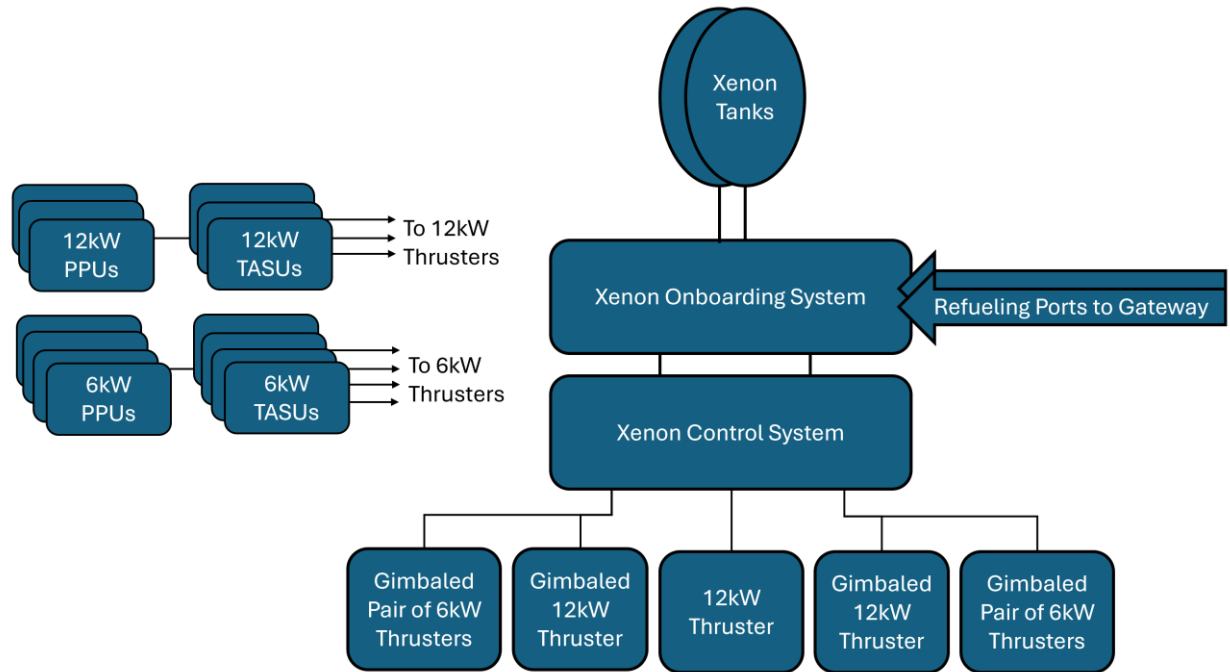


Figure 5. PPE electric propulsion subsystem cartoon



Figure 6. PPE electric propulsion build showing an 825L Xenon tank being installed [16] (left), and after the tanks have been installed [17] (right).

The PPE spacecraft has two propulsion systems onboard, a high-thrust chemical system with 22N bipropellant thrusters, and the lower-thrust / high-specific impulse electric system. As described in Table 1, the chemical system will generally be used for attitude control when time is critical or when power from the arrays can't be guaranteed. While the electric system will generally be used for deltaV maneuvers when minimizing propellant usage is of importance.

Table 1. Electric vs. chemical propulsion subsystem top-level operations [3].

	Electric Propulsion	Chemical Propulsion
Post-Launch		
Detumble		X
First Rev Activities		X
Electric Orbit Raising		
Primary Propulsion	X	
Momentum Management	(during maneuvers)	
Lunar Capture	X	(if needed)
Lunar Operations		
Orbit Transfers, Deorbit	X	X (if high moment of inertia or faster slews required)
Orbit Maintenance	X	
Momentum Management	(during maneuvers)	
NRHO Re-orientation		
Off-Nominal Scenarios		
Spacecraft Safing		X
Momentum Dumping		X

IV. Documented Hazards for the PPE Electric Propulsion Subsystem

The intent of the hazards process is to define the hazardous conditions that the PPE may experience on-orbit. This process serves to understand the potential risks involved in operating the vehicle given the operating configuration, environment, and Concept of Operations (CONOPS). The PPE program established their system safety process by adapting systems engineering and system safety guidelines from industry standards [9-14] as shown in Figure 2 as well as establishing spacecraft safety criteria based on existing industry standards [10-12] as shown by Figure 4. By adopting practices from these guidelines, PPE has established a robust process for addressing system safety for the spacecraft and the larger Artemis lunar Gateway.

A. Refueling Hazards

Refueling operations are novel for the PPE as it will be the first mission to refuel xenon propellants in orbit around the moon. There are both integrated risks and intrinsic risks to the PPE. These risks ultimately result in either a failure of the vehicle to refuel xenon propellants or damage to the PPE or integrated system. In terms of PPE intrinsic risks, anomalous temperatures and anomalous pressures are primarily considered.

1. Anomalous Pressure

As shown in Figure 5, the PPE is a complex interconnect of propellant lines and valves that enable the transfer of xenon from the Gateway to the PPE xenon propellant tanks. Anomalous pressure conditions could manifest rupture, leakage of propellant, or an inability to load propellant from the Gateway to the PPE. Using the failure tolerance capabilities described previously, PPE employs hardware, software and operational controls and mitigations to ensure that, if PPE observes these hazardous conditions on-orbit, the system is equipped to isolate and recover from the anomaly. Redundancy is employed via the primary and redundant refueling paths at the Gateway interface. Isolation is implemented via dissimilar series redundant valves between PE and Gateway.

FDIR has been implemented to detect anomalous pressure which may result in damage to components within the electric propulsion system. These FDIR are enabled via pressure transducers throughout the refueling manifold which provide the spacecraft flight software with pressure telemetry. When critical pressures have been detected by the pressure transducers the FDIR acts to halt the flow of xenon from the Gateway to the PPE allowing ground operators to troubleshoot.

Using isolation capabilities through the implementation of series and functional redundancy, FDIR and contingency operating procedures, the risk of anomalous pressure manifesting a catastrophic event on orbit is reduced.

2. *Anomalous Temperature*

Thermal models have been produced to determine the impact of environmental and integrated thermal elements on the PPE xenon refueling manifold. Inadequate thermal management is considered a risk driver in the inability of the PPE to transfer xenon propellants. A failure to maintain nominal temperature conditions could result in failure of the refueling manifolds latch valves to function or outboard leakage through the latch valve. The use of passive thermal control devices and redundant heating elements and controllers, enabled by majority voting thermistors, minimizes the likelihood of exceeding qualification temperatures of any single unit within the refueling manifold from both a failure of the PPE or the external environment.

Anomalous thermal conditions could also be initiated by the integrated Gateway system. In conjunction with the design of the thermal management system, PPE uses FDIR to detect and halt the flow of xenon into its tanks to allow ground operators to troubleshoot and recover the system to a safe operating mode prior to completing refueling operations.

3. *Joule-Thompson Cooling*

Joule-Thompson (JT) cooling across PPE components has been identified as a likely occurrence as xenon is transferred from the Gateway interface to the PPE at much higher flowrates than flowrates required for thruster operation. If left unmitigated, the JT cooling phenomena could cool the xenon valves beyond qualification limits and ultimately resulting in failure. Mitigation strategies include limiting the flowrate of the refueling transfer, increased heater setpoints, and onboard fault protection to pause refueling if low temperatures are reached.

4. *Locked Fluid Volumes*

Fluid locked volumes have been closely studied for propulsion systems for decades. Inherent to having multiple valves is the possibility for small volumes of the subsystem to have trapped fluid, which can see large pressure increases from small temperature increases. In implementing FDIR to isolate a failure and restrict the flow of xenon into the PPE tanks, the potential for the creation of a locked volume exists potentially having unintended consequences. Regions within the Xenon feed system have been identified as at-risk from locked volumes if valves are commanded in off-nominal ways. As such, constraints have been generated to restrict the system and operators from inadvertently forming these volumes. This concern of trapped fluid volumes dramatically increasing in pressure is a far larger concern for liquid chemical systems, however large temperature increases in the Xenon system could cause pressures to exceed allowable tested limits.

B. Thruster Operation Hazards

The PPE 6kW and 12kW systems provide Gateway translational and attitude controllability. Functionally, losing either system could impact the PPE's ability to conduct critical operations, such as Electric Orbit Raising (EOR), NRHO Insertion, or orbit maintenance maneuvers that are required to sustain orbit while in NRHO.

Ultimately, the impact of losing hardware capability within either of the 6kW or 12kW systems depends on the mission phase. The 12kW and 6kW thrusters do compliment each another for mission execution and maneuver planning, with the higher power of the 12kW thrusters capable of providing more thrust and the lower power of the 6kW thrusters providing lower thrust [29]. Because the technologies associated with the 6kW and 12kW systems are new, there is an elevated risk posture associated with them. To reduce the risk, a series of mitigations have been employed in order to ensure nominal behavior in flight. The PPE follows fail-safe design concepts and design principles as outlined in the Federal Aviation Administration's Advisory Circular AC No: 25.1309-1A [23]. In relation to those associated with the 6kW and 12kW systems, the order is as follows:

- Design
- Automation
- Operational

Where hazards could not be explicitly designed out of the system, risk reduction activities have been performed. In the context of the 6kW and 12kW systems, dissimilar redundancy has been employed. Both units have been provided by different manufacturers with their own manufacturing and assembly processes. The likelihood of common cause failures between these units is significantly diminished. Given that, if a single 12kW thruster fails during critical activities capability exists between the 6kW system to compensate for that loss [29]. Likewise, loss of a single 6kW thruster can be compensated by other 6kW thrusters or by a 12kW thruster [29]. Mitigation of failure is enabled by on-board Fault Detection, Isolation and Recovery (FDIR) which allows the system to terminate thruster firing in the event of observed anomalous thruster behavior. Operators are used to troubleshoot anomalies and place the system in a nominal operating configuration.

C. Thruster Arcing and Sparking

Hall Effect Thrusters (HET) exhibit a known sparking and arcing phenomenon [15, 20]. At high power, these sparking events pose risk to the operation of the thruster and to the electronics in which they interface by generating short duration high-voltage transients. During on-orbit operation [15, 27] and ground testing [20, 28] of previous Electric Propulsion Thrusters, sparking and arcing events have been observed. These events were identified as an electrical risk to spacecraft electronics through interfaces with the Hall Effect Thrusters. Mitigations against these electrical transients include a wide array of options: relay boxes, fast acting diodes, increased shielding around sensitive hardware, modified conops, and removal of non-necessary hardware. The two thrusters on PPE have different electrical configurations, which create unique challenges for each:

- The 6kW thrusters have electrically insulating pole covers, a cathode which floats from the spacecraft chassis, and a metallic thruster body electrically tied to the spacecraft chassis. [18, 26]
- The 12kW thrusters have graphite pole covers, a cathode which floats from the spacecraft chassis, the cathode is electrically tied to the metallic thruster body, and the thruster body electrically isolated from the thruster baseplate which is tied to the spacecraft chassis. [19, 24, 25]

D. Other considerations

Numerous “standard” propulsion system hazards were identified during the development of the PPE spacecraft. These include topics such as leakage, high-pressure rupture of tubing, high-pressure rupture of tanks, and cycle life of components. These hazards have been well studied and documented within NASA and industry standards and requirements for decades. The PPE spacecraft is following a tailored NASA-STD-8719.24 [21] and SSCMAN 91-710 [22] approach for compliance with these requirements. Integrated hazards between PPE and Gateway are considered but fall outside the scope of this paper. Integrated Gateway hazards are managed by the NASA Integrated Hazards Analysis team.

V. Conclusion

In the evaluation of PPE hazards analysis, special consideration and scrutiny has been given to the Electric Propulsion Subsystem. The electric propulsion system plays a critical role in the PPE program, where it provides propulsion, Δv , and controllability for the PPE. Failure of this system poses risk to PPE, the lunar Gateway, and humans onboard. Utilizing fault tree and hazards analyses and approaching system safety from a requirements based design, PPE’s electric propulsion hazards have been identified, understood, and mitigated such that the risk of catastrophic failure on-orbit has been minimized.

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