CONFERS Document # xxxxx

CONFERS Recommendations for
Prepared In-Space (Re)Fueling Systems for Storable Propellants

Contents

Introduction

This document provides the current industry best practices for development of prepared interfaces for in-space (re)fueling for Storable Propellants. It is intended to provide guidance to developers and operators of both the servicing vehicles and the client vehicles.

This document builds upon the foundation of other CONFERS documents including the CONFERS Guiding Principles, the CONFERS Recommended Design and Operational Practices, and CONFERS On-Orbit Servicing (OOS) Mission Phases (Figure 1) which are the foundation of an international standard (ISO 24330 Space Systems – Rendezvous and Proximity Operations and On-Orbit Servicing Programmatic Principles and Practices). The scope of this document is within the context of services for #9 in Figure 1.

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There are no patent licensing issues associated with the content of these recommendations.

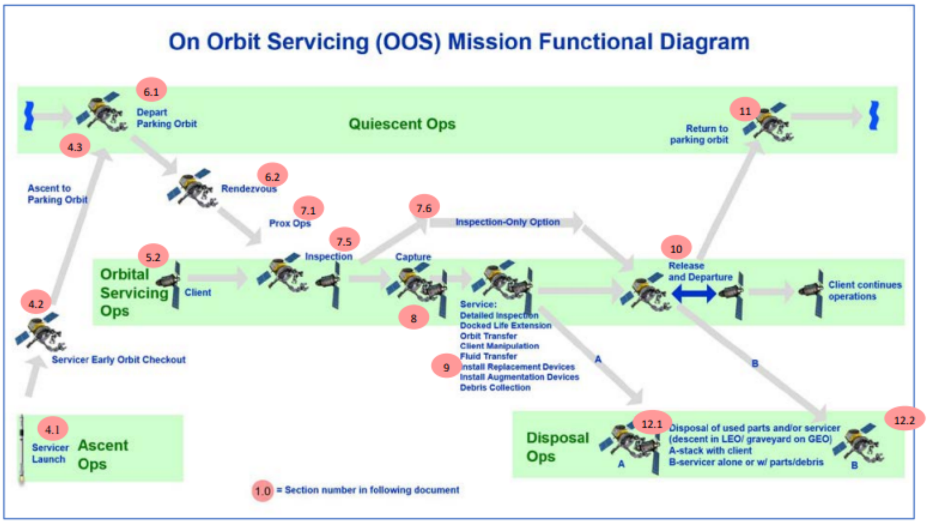


Figure 1 – OOS Mission Functional Diagram

Recommendations for Prepared In-Space (Re)Fueling Systems for Storable Propellants

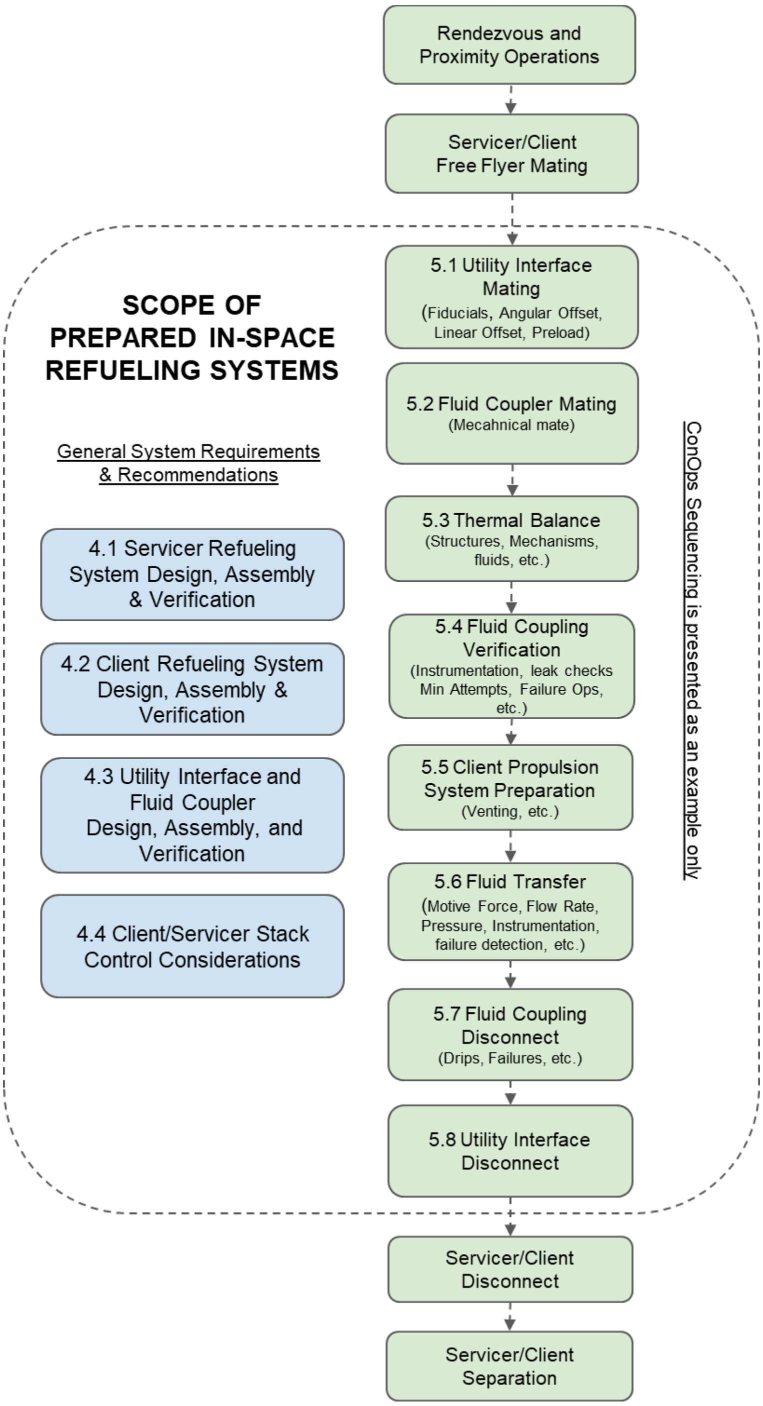
1 Scope

This document defines best practices and requirement for the design, testing and operation of "prepared spacecraft" in-space (re)fueling systems. The term "prepared spacecraft" describes a spacecraft that includes interfaces and accommodations intentionally designed to enable safe and efficient servicing. This document includes requirements and recommendations for both servicer and client spacecraft. At present the recommendations' scope is limited to storable (non-cryogenic) propellants and pressurants. These recommendations could easily be extended to other storable non-propellant fluids. The standards and recommendations collected here are informed by years of engineering development experience garnered through work with NASA on in-space (re)fueling technology development programs augmented by relevant commercial industry experience.

The recommendations in this document are a collection of best practices that should be considered in the development of any prepared refueling systems, interfaces, and operations. Figure 2 illustrates the concept of operations for prepared in-space (re)fueling operations and outlines the scope for an interface standard. This documents focus is on the design, qualification, and operations of the fluid coupling interface rather than the servicer to client capture. Within this document, the servicer to client free-flyer mating interface standards are limited to interactions between this interface and the fluid transfer systems interface only.

Due to the early stage in commercializing in-space (re)fueling systems, this document does not specify a particular form factor of such an interface. Furthermore, the intent is to leverage existing standards to maximum extent practical. The intent is to promote progress, safety, capability, reliability and capacity while not hindering innovation or specific mission requirements. Any successful (re)fueling interface hardware that 1) completes successful qualification and 2) becomes widely adopted could form the basis of a future fluid coupling and utility mating standard interface. Content of this document intends to inform an "interface standard," whereas normative statements for form, fit, and function would be addressed in specific "standard interface" specifications.

While the initial scope is limited to storable propellants on spacecraft in-space, future versions could be expanded / tailored to include cryogenic (re)fueling and (re)fueling operations on planetary surfaces. It should also be made clear that this document focuses on the "in-space" (re)fueling. While the same interface may be used for ground fueling, requirements for such features/capabilities are not considered within the scope of this document as specific requirements and guidelines appliable to use for ground re(fueling) are contained within AFSPCMAN91-710V3: Range Safety User Requirements Manual.



Rendezvous and Proximity Operations
Servicer/Client Free Flyer Mating
SCOPE OF PREPARED IN-SPACE REFUELING SYSTEMS
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5.7 Fluid Coupling Disconnect (Drips, Failures, etc.)
5.8 Utility Interface Disconnect
ConOps Sequencing is presented as an example only
Servicer/Client Disconnect
Servicer/Client Separation

Figure 2 – ConOps and Scope for Prepare In-Space Refueling Operations

2 Normative References

The following documents, as applicable to specific concept /architecture, are references of other existing standards that should be applied as appropriate to the in-space (re)fueling systems or an equivalent existing Aerospace standard proposed by the developing authority.

2.1 ISO 24330 Space Systems – Rendezvous and Proximity Operations (RPO) and On-Orbit Servicing (OOS) Programmatic Principles and Practices

2.2 NASA STD 5017A Design and Development Requirements for Mechanisms

2.3 International Deep Space Interoperability Standards

2.4 NASA Artemis Accords

2.5 CONFERS inputs to Spacecraft Fiducials for Rendezvous and Proximity Operations

2.6 AIAA S-080, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components

2.7 NASA Materials and Processes Technical Information System(MAPTIS)

2.8 ASNT SNT-TC-1A, Recommended Practice for Personnel Qualification and Certification in Non-Destructive Testing

2.9 AWS D17.1/D17.1M, Specification for Fusion Welding for Aerospace Application

2.10 ISO 14952, Space systems — Surface cleanliness of fluid systems

2.11 GEVS-STD-7000, General Environmental Verification Standard (GEVS) for GSFC Flight Programs

2.12 GSFC-EEE-INST-002, Instructions for EEE Parts Selection, Screening, Qualification, and Derating

2.13 MIL-STD-130, Identification Marking of US Military Equipment

2.14 NASA-STD-8739 series -for applicable to flight article general & electrical workmanship and software standards and qualification

2.15 SAE AS9100, Aerospace Basic Quality System Standard

2.16 AFSPCMAN91-710V3, *AIR FORCE SPACE COMMAND MANUAL 91-710, VOLUME 3, RANGE SAFETY USER REQUIREMENTS MANUAL VOLUME 3 – LAUNCH VEHICLES, PAYLOADS, AND GROUND SUPPORT SYSTEMS REQUIREMENTS*

2.17 AIAA S-XXX Spacecraft Fiducial Markers

2.18 Bonding and grounding per_____

Commented [ATJ(1]: Suggest adding some ref existing MIL_STD or ISO STD as bonding grounding considerations are referenced in text.

3 Terms and Definitions

For the purposes of this document, the terms and definitions in the CONFERS Lexicon document apply, noting the following terms and definitions.

Free Flyer Mating Operations: A subset of proximity operations where the servicer spacecraft (and potentially client spacecraft) intentionally perform mutually agreed maneuvers and take actions to make and maintain physical contact.

Mate: When two objects or interfaces make and maintain an intentional physical connection. Mate, Dock, Berth, Grapple, and Capture are all terms which are related, and often used interchangeably.

Utility Interface: The interface that contains the utility that is to be shared between the two sides. The utility interface provides for (initial) alignment, the structural connection and preload required to maintain connection between the two sides of the utility coupler (i.e. a fluid coupler, power coupler, data coupler, etc).

Active (Re)Fueling Utility Interface: The side of the (re)fueling utility interface that 'controls' the refueling process, from guiding the fluid coupling, verifying interface connections, commanding valve openings and closings, and transferring fluids. The Active Interface is typically resident on Servicer Satellite and Depots.

Passive (Re)Fueling Utility Interface: The side of the (re)fueling interface that is mostly inactive in the (re)fueling process. Typically, this is present on the Client Satellite being refueled and is the side of the interface that receives fluids.

Fluid Coupler: A two sided reversible mechanism that when successfully coupled will allow for the safe transfer of fluid from one side to the other.

Prepared Spacecraft: spacecraft with interfaces and accommodations intentionally designed to enable safe and efficient in-space servicing.

4 General System Requirements and Recommendations

This section provides best practices, requirements, and considerations for the design of:

1) the refueling system on the Servicer spacecraft,
2) the propulsion system on the client spacecraft,
3) the utility interface and fluid coupling through which the fuel is transferred.

4.1 Servicer Refueling System Design, Assembly, Verification

Servicer spacecraft (re)fueling system shall be compatible with the Client spacecraft (re)fueling system.

Cleanliness and contamination of the Servicer Spacecraft (re)fueling system must be carefully controlled per standard propulsion system design for each commodity and propulsion subsystem design requirements. (ref ISO_14592)

Servicing features of the Servicing Spacecraft shall not impose Foreign Object Debris (FOD) or contamination risk to the primary mission of the Client or Servicer Spacecraft (e.g. feature(s) will be captive/FOD will be captured).

The servicer refueling system shall have means to enable onboard fluid transfer metering (e.g. fluid mass flow measurement) of the expendable commodity being transferred.

A means to manage and measure the Servicer Spacecraft fluid transfer system pressure and temperature differentials shall be provided to ensure that pressure and temperatures are within the limits allowed for the specific fluid commodity prior to the start of fluid transfer.

Consideration for thermal control of the Servicer Spacecraft fluid transfer system is required to prevent freezing and/or over-temperature protection of any trapped residuals or in-hold phase fluid transfer operations

4.2 Client Spacecraft (Re)Fueling System Design, Assembly, Verification

Client spacecraft (re)fueling system shall be compatible with the Servicer spacecraft (re)fueling system.

The Client Spacecraft shall have a dedicated Fluid Coupler for (re)fueling of each fluid or gas to be transferred that are not compatible.

The Client Spacecraft's commodity tanks shall be capable of being refilled or partial refilled a number of times consistent with the expectations of the mission.

The client spacecraft Fluid Coupler shall have means of thermal control that allows easy access to the valve by a Servicer Spacecraft.

The Client Spacecraft propulsion system shall be designed to support the (re)fueling (e.g. venting, interface valves with easily removable covers, check valves, key tank press and temp feedback, Fill/Drain Valves heater controls and feedback, etc).

4.2.1 Thermal Control

A means to manage and measure the Client Spacecraft fluid transfer system temperature differentials shall be provided to ensure that temperatures are within the limits allowed for the specific fluid commodity prior to the start of fluid transfer.

Consideration for thermal control of the Client Spacecraft fluid transfer system is required to prevent freezing and/or over-temperature protection of any trapped residuals or in-hold phase fluid transfer operations.

4.2.2 Venting

Specific provisions for safe client tank venting should be considered for timely and high percentage refill of PMD type or pressure regulated diaphragm tanks.

Specific system level provisions for a safe vent and re-capture for use of valuable commodity to be vented is the recommended method where possible versus direct vent to space.

For a pressurized and closed client spacecraft propulsions system, provisions for safe venting (no impacts to client or servicer) through servicer vent system may be required. Consideration for dispersion pattern and commodity compatibility with surfaces of possible impingement are required.

4.2.3 Cleanliness and Foreign Object Debris (FOD)

Cleanliness and contamination of the Client Spacecraft (re)fueling system must be carefully controlled per standard propulsion system design for each commodity and propulsion subsystem design requirements. (ref ISO_14592)

Serviceable Client Spacecraft features shall not impose foreign object debris (FOD) risk to the primary mission of the Client or Servicer Spacecraft (e.g. feature(s) will be captive).

4.2.4 Documentation, Fiducials, and Access

All mating and (re)fueling servicing worksites of the Client Spacecraft shall be photographed prior to launch. A distance/length scale measurement/reference should be included, as should a reference to the most current CAD revision if available and any known discrepancies with flight hardware.

Client Spacecraft system documentation shall reflect final as-built configurations to the greatest extent possible.

The Client Spacecraft shall provide reasonable access volumes near mating and (re)fueling worksites of interest where the servicer can operate to perform servicing tasks.

The Client Spacecraft shall have unique fiducial markers for each (re)fueling interface that can clearly be seen by a Servicer Spacecraft. (Ref AIAA S-XXX Spacecraft Fiducial Markers)

4.2.5 Client Spacecraft Testing of Refueling System

The refueling mechanism functionality shall be verified by test with a realistic (actual or mockup) servicer spacecraft test device once the spacecraft is assembled.

4.3 Utility Interface and Fluid Coupling Considerations

4.3.1 Mating and Alignment

The Servicer and Client Spacecraft shall be connected by means of free-flyer mating, independent from the Fluid Coupler.

The fluid coupling design should incorporate methods to accurately mate with compliance across interfaces and compliance across multiple ports.

There shall be absolute separation of the seal engagement sequence from the fluid coupling alignment sequence (“scoop-proof” design in electrical parlance).

The utility interface shall have the means to accommodate angular and linear offsets at the initiation of mating and preload upon ridgidization.

The Utility Interface shall be designed to accommodate expected impact forces

No sealing feature should be used as an alignment feature.

If the fluid coupling design incorporates preloading features, they should be designed to not over constrain the seal’s ability to self-align at the instance of engagement.

The fluid coupling should be able to accommodate a small amount of misalignment as it engages. A misalignment budget must be provided to specify the 6-DOF limits under which the couplings would be expected to mate.

4.3.2 Accommodating Pressures

The Utility Interface and Fluid Coupler should accommodate all anticipated dynamic and static pressures with safe minimum margin per applicable design standards referenced in specific commodity design sections.

Where a Utility Interface is used with high pressure fluid couplings, the design should incorporate a feature to absolve the utility interface actuator from bearing the loads of the high-pressure Fluid Coupler and disconnection.

(Re)fueling Coupler design should have predictable pressure drops and system performance including uncertainty values.

Special consideration and features are required for non-vented systems requiring mate at pressures above minor levels (includes evaluation of residual commodity vapor pressure at temperature for transfer).

Analysis or testing of the specific fluid commodity shall be performed for surge pressure protection and any catastrophic hazards such as adiabatic compression.

4.3.3 Other Design Features

If the (Re)fueling Coupling design utilizes balanced springs, the springs must follow strict requirements for verification of all control elements.

Where springs are used, they should be redundant, captive, full-length-guided, and jam-proof in the failure case.

O-Rings (soft good materials) are not recommended for repetitive use dynamic applications in oxidizer applications such as NTO.

A Fluid Coupler should meet all fluid transfer requirements when flowing in either direction.

A means of launch restraint/attenuation of launch loads is required to prevent chattering of compliance features against their hard stops

Ideally, for maximum commonality, all elements of the Fluid Coupler should be compatible with all the fluids in the Fluid Compatibility table in Appendix A.

Wetted volume should not include potential entrapped volumes unless bleed passages are provided. An active purge and venting system may be required such that at disconnect only trace vapors remain in coupling system protecting adjacent surfaces from contact with any incompatible fluid commodity dispersions.

4.3.4 Thermal and Electrical Considerations

Electrical Bonding provisions of the interface need to be present throughout mating and combined operations.

Consideration for thermal isolation (with ground / bonding enabled) from flight attach structure is required.

A means to manage and measure the system temperature differentials shall be provided to ensure that temperatures are within the limits allowed for the specific fluid commodity prior to the start of fluid transfer.

Consideration for thermal control of the fluid coupler is required to prevent freezing and/or over-temperature protection of any trapped residuals or in-hold phase fluid transfer operations.

4.3.5 Cleanliness, FOD, and Interface Protection

Precision cleanliness levels should meet ISO 14952, Space systems — Surface cleanliness of fluid systems, minimum to ISO Level00A.

Cleanliness and contamination of the fluid coupling must be carefully controlled per standard propulsion system design for each commodity and propulsion subsystem design requirements. (ref ISO_14592)

The Fluid Coupler shall incorporate features to prevent generation of, and tolerate budgeted levels of, FOD on seals and sealing surfaces.

The Utility Interface and Fluid Coupling shall not impose Foreign Object Debris (FOD) risk to the primary mission of the Client or Servicer Spacecraft (e.g. feature(s) will be captive/FOD will be captured).

Any Utility Interface or Fluid Coupler with a view to space should possess a means to protect seals and sealing surfaces, and to obscure energetic particle line-of-sight to polymer seal materials for all planned mission operations and planned mission life duration.

Coverings may be required to protect cleanliness of couplers. Such coverings will need to withstand the rapid ascent depressurization rate at launch or be designed to hold at atmospheric to vacuum delta pressure change.

4.3.6 Lifetime Qualification

The Fluid Coupler should have a qualification level of at least 3 times the minimum cycle-life-use-margin.

The Fluid Coupler shall be tested for life span with specific commodity.

Testing and qualification of the Fluid Coupler shall confirm the level of FOD generation meets requirements.

The Fluid Coupler function and performance should comply with GEVS-STD-7000, General Environmental Verification Standard (GEVS) for GSFC Flight Programs and Projects.

4.3.7 Mission Safety and Reliability

(Re)fueling Coupling should not create a single point failure that prevents separation of the servicing vehicle from the client.

Servicing stack should not have single failure points that would cause a client/servicer stack disconnect during refuel operations.

All systems shall be designed to tolerate a minimum number of credible failures. The number of designs inhibits required to prevent an overall system failure or mishap is based on the failure or mishap result. Specific inhibit requirements are addressed in the design criteria for each of the systems / subsystems.

Those systems that do not have specific design criteria or systems not addressed in this Standard shall be designed, where possible, to the following general criteria:

a. The system shall be dual fault tolerant to any credible catastrophic hazard (on-orbit explosion of servicer or client or both).
b. The system shall be single fault tolerant to any credible critical hazard (loss of mission transfer operational capability).
c. The system may have no fault tolerance to any marginal hazard.
d. Probabilities of hazard occurrence shall be taken into consideration when determining the level of fault tolerance. Where determined as non-credible or extremely highly unlikely by design, qualification or test, the documented risk may be accepted. (reference, "Acceptability Guidelines Complex Hazard Consequences and Probability Categories.")

For interface features that will have frequent re-use and subject to wear, consideration shall be made for use of replenishable connector savers in design / ConOPS to ensure reliability if not able to qualify for 3x planned mission use life use factor at high reliability

The (re)fueling Coupling should provide (x) redundant seals for external leakage paths in all configurations.

Any use of soft goods for seal surfaces must be protected from radiation degradation over time (or tested /rated for lifetime exposure and life cycles) and any contamination degradation from launch processing through inflight use cases.

The maximum leakage rate of the fluid coupler shall be no greater than10-4 scc/s Ghe throughout the life cycle.

A means shall be available to determine a leak in the fluid transfer system prior fluid transfer with a sensitivity of at least 10^{-4} scc/s Ghe as goal (e.g. bubble tight leak level).

A means shall be available to determine a leak in the fluid transfer system during fluid transfer with a sensitivity of at least 10^{-1} scc/s Ghe as goal (e.g. visual camera monitored leak level).

The Fluid Coupler design should be nearly zero-spill (level to be established per commodity and contamination requirements), or system level operational constraints and provisions exist to evacuate system prior to de-mate.

5 In-Space (Re)Fueling ConOps

This section addresses operations and design considerations of the (re)fueling operations at each major phase of the notional Concept of Operations.

5.1 Utility Interface Mating

The Active Utility Interface, located on the Servicer Spacecraft, , performs the Utility Interface mating which aligns the Fluid Coupler, and provides any necessary preload prior to engagement of the Fluid Coupler.

5.2 Fluid Coupler Mating

5.3 Thermal Balance

Prior to start of fluid transfer or venting operations, the fluid transfer system temperature differentials shall be verified to be within the limits allowed for the specific fluid commodity.

5.4 Fluid Coupling Verification

Following successful Fluid Coupler mating and thermal balance, and prior to the start of fluid transfer, the combined fluid transfer system shall be validated to be sealed with leakage rates of no greater than 10-4 scc/s Ghe.

If initial attempt results in leakage levels exceeding allowables, a repeated disconnect and reconnect attempt followed by leak test may proceed. Consideration in design to replace seal(s) or use of specialty adapter (or new connector saver) should also be evaluated in overall system architecture.

5.5 Client Propulsion System Preparation

5.6 Fluid Transfer

During fluid transfer, the combined fluid transfer system shall be validated to be sealed with leakage rates of no greater than 10-1 scc/s Ghe.

5.7 Fluid Coupling Disconnect

5.8 Utility Interface Disconnect

Appendix A – Design/ Development Guides

Below table is typical commodity and inflight mission use variables required for passive mechanical interfaces, but may be tailored based on mission specific needs or type of specific components utilized for interface transfer. Detail design parameters ad test/qual levels are covered in AIAA S-080, Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components and specific allowable materials are covered in NASA Materials and Processes Technical Information System (MAPTIS)

Fluid	**Pressurant (Nitrogen, Helium)**	**Hydrazine**	**MMH**	**NTO (MON-3)**	**Xenon**
State	Gas	Liquid	Liquid	Liquid	Supercritical
Maximum Design Pressure	3000 psia	1000 psia	1000 psia	1000 psia	3000 psia
Minimum Fluid Temp	-10°C	+10°C	-10°C	-10°C	-10°C
Maximum Fluid Temp	+75°C	+40°C	+75°C	+75°C	+75°C
Maximum Internal Mated Leak Rate at MEOP	1xe-**3** scc/s gHE	1xe-4 scc/s gHE	1xe-4 scc/s gHE	1xe-4 scc/s gHE	1xe-**3** scc/s gHE
Maximum Un- Mated Leak Rate at MEOP	1xe-4 scc/s gHE	1xe-4 scc/s gHE	1xe-4 scc/s gHE	1xe-4 scc/s gHE	1xe-4 scc/s gHE
MDP Multiplication Factor, Qualification Proof Test	2.5	2.5	2.5	2.5	2.5
MDP Multiplication Factor, Acceptance Proof Test	1.5	1.5	1.5	1.5	1.5