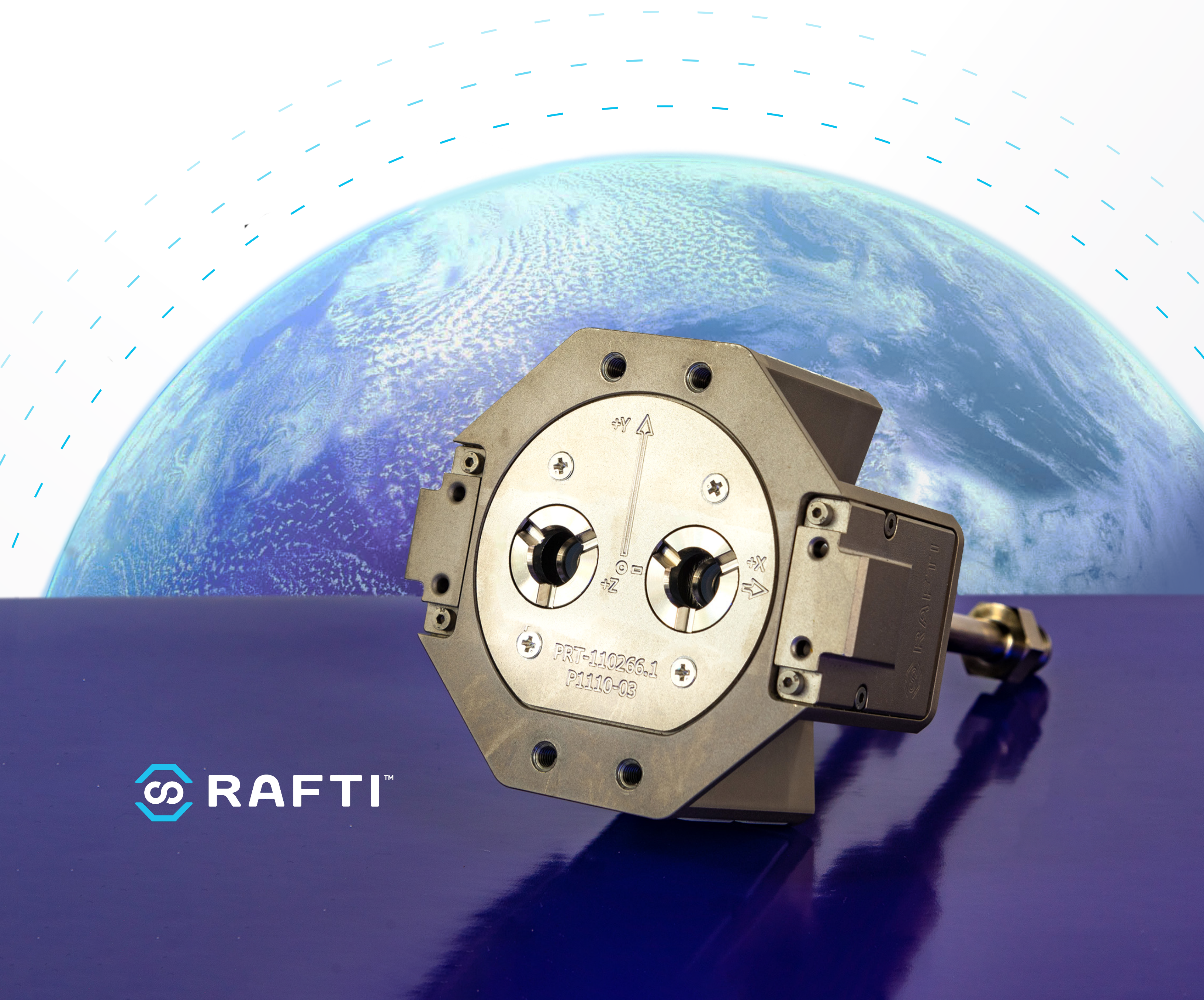
ORBITFAB
Gas Stations in Space™

RAFTI™ User Guide

Refuelable Spacecraft Requirements Specification



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Refuelable Spacecraft Requirements Specification

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Change Log	
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1. Introduction

Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI) extends operational life and increases operational flexibility of your spacecraft by equipping it with an on-orbit refueling capability. Spacecraft can now make frequent orbit changes without concerns for on-board propellant margin. High-value assets can be retasked to serve new purposes or extend current missions. They also gain a defensive capability with additional maneuverability. By integrating RAFTI, your spacecraft becomes designed with docking and refueling activities in mind. As an added benefit, during ground operations the RAFTI Service Valve doubles as a reliable, cost effective fill/drain valve for your propulsion system.
After navigating to the client vehicle location, Orbit Fab's Fuel Shuttle handles soft capture and hard latch of the client vehicle (see Figure 1). Your spacecraft participates in the docking process by maintaining pointing and sharing state information. The RAFTI refueling interface allows reliable propellant transfers in the harshest space environments, making it ideal for mission operations from LEO to GEO, and in cislunar space.

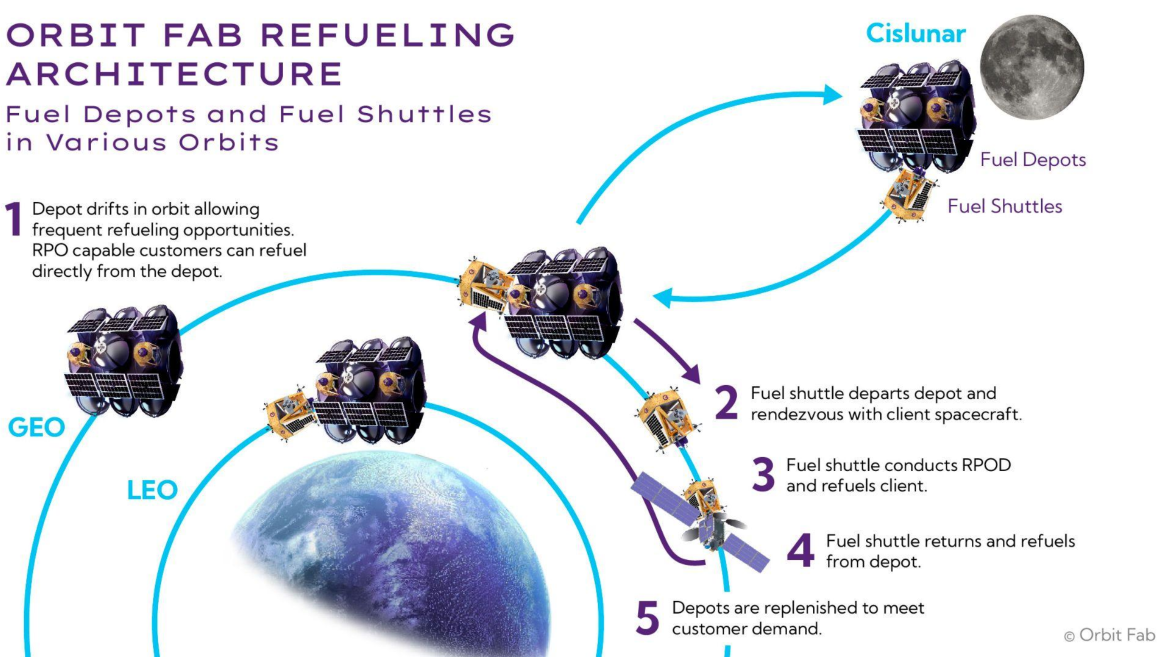


Figure 1: Orbit Fab's Shuttle-Depot architecture for on-orbit fuel delivery

1.1 Purpose

The purpose of this User Guide/ICD is to provide spacecraft designers with sufficient information to integrate the RAFTI refueling capability into their vehicles.

1.2 Scope

This document contains interface specifications for the Rapidly Attachable Fluid Transfer Interface (RAFTI) system. This document is primarily intended as a User's Guide to be used by propulsion system manufacturers and spacecraft integrators to properly mount and correctly operate the RAFTI Service Valve (RSV) and alignment markers on a client vehicle. The document also serves as a guide for mission planners, system engineers, and software engineers.

Servicing operations include three categories of interfaces: docking, utility, and fluid transfer. The docking interface joins two space vehicles together with a rigid attachment. The utility interface provides the alignment and preload for the fluid transfer interface. The fluid transfer interface makes a viable fluid coupling. It should be noted that the RAFTI Service Valve can be used strictly as a fluid transfer interface, it can be used as a fluid transfer interface and a utility interface, or it can be used to provide all three interface functions: fluid transfer, utility and docking. This document provides specifications and requirements which can be used to implement any of the three scenarios described above. It also contains interface specifications and requirements for operation with the active half of the refueling interface, the Grappling Resupply Interface for Products, (GRIP).

The RAFTI Open Interface does not currently define all interfaces required for prepared, cooperative spacecraft docking. In addition to the mechanical and electrical interfaces described herein, the docking interface would define navigational aids, like fiducials, and control algorithms for the client and refueling vehicles. This document currently provides a placeholder for those specifications and requirements. Details will be added to this document as they become available. The addition of security features that prohibit docking or fluid transfer activities has been anticipated and will also be added in future versions.

The open nature of this specification is intended to foster a thriving space economy. Orbit Fab developed this technology in coordination with its government and commercial partners. Orbit Fab maintains this document and continually solicits industry input to improve its content.

In what follows:

"Shall"	implies a strict requirement.
"Should"	implies a desire.
"TBD"	means "To Be Determined."
"TBC"	means "To Be Confirmed."

1.3 Related Documents

The following documents are referenced herein and intended to accompany this Interface Control Document:

Specification / Document	**Title**
NASA-STD-5017	NASA Technical Standard: Design And Development Requirements For Mechanisms
NASA-STD-5020	Requirements For Threaded Fastening Systems In Spaceflight Hardware
MSFC-STD-3029 Table 1	MSFC Technical Standard: Multiprogram/Project Common-Use Document - Guidelines For The Selection Of Metallic Materials For Stress Corrosion Cracking Resistance In Sodium Chloride Environments
MMPDS-15	Metallic Materials Properties Development And Standardization (Mmpds) Handbook
AFSPCMAN 91-710	Range Safety User Rqmts Manual Volume 3 - Launch Vehicles, Payloads, And Ground Support Systems Requirements
GSFC-STD-8009	Goddard Space Flight Center (Gsfc) Wallops Flight Facility Range Safety Manual (Rsm)
DOI: 10.1109/ICCV.2015.239	CV-HAZOP: Introducing Test Data Validation for Computer Vision
GSFC-STD-7000 (GEVS)	Goddard Technical Standard: General Environmental Verification Standard (Gevs) For Gsfc Flight Programs And Projects

SMC-S-016	Test Requirements For Launch, Upper-Stage And Space Vehicles
NASA-HDBK-4001	Electrical Grounding Architecture for Unmanned Spacecraft
MIL-STD-681	Color Code Designators for Wire

1.4 Interface Control Drawings

Specification / Document	**Title**
ICD-00001	RAFTI SV, CLASS 2 INTERFACE CONTROL DRAWING

1.5 Acronyms and Abbreviations

Acronyms and abbreviations used in this document are listed in this section.

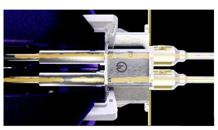
ACS	Attitude Control System
ADCS	Attitude Determination and Control Subsystem
CAD	Computer Aided Design
CAN	Controller Area Network
CG	Center of Gravity
ConOps	Concept of Operations
CV	Client Vehicle
Cv	Flow Coefficient
EICD	Electrical Interface Control Drawing
EPS	Electrical Power Subsystem
FOD	Foreign Object Debris
g	Grams
G	G forces
GEO	Geosynchronous
GRIP	Grappling and Resupply Interface for Products
HTP	High Test Peroxide

ICD	Interface Control Document
ISS	International Space Station
LEO	low Earth orbit
MEOP	Maximum Expected Operating Pressure
MICD	Mechanical Interface Control Drawing
N	Newtons
PPS	Pulse Per Second
PWM	Pulse Width Modulation
RAFTI	Rapidly Attachable Fluid Transfer Interface
RPOD	Rendezvous Proximity Operations and Docking
RSV	RAFTI Service Valve
RTS/CTS	Request To Send/Clear to Send
S/C	Spacecraft
SV	Service Vehicle
TBR	To Be Reviewed
TBC	To Be Confirmed
TBD	To Be Determined
TBS	To Be Supplied
TVAC	Thermal Vacuum
UMPIRE	Universal Mission Planner to Investigate Refueling Effectiveness
V	Volts
VDC	Volts, Direct Current

1.6 Engineering Units of Measure

This document uses US customary units as its primary unit system. All other units presented in parentheses are provided for reference only. Contact Orbit Fab with any questions regarding units of measurement and/or conversions.

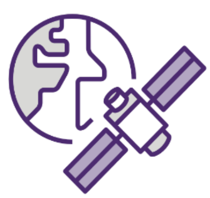
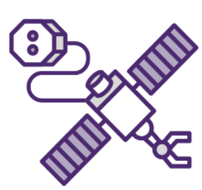
1.7 Definitions

	**Client Vehicle**	Space asset being refueled by the servicing vehicle.
	**Servicing Vehicle**	Spacecraft that is performing the fuel servicing operation on the client vehicle.
	**Fuel Depot**	A cache of propellant that is placed in orbit around Earth or another body to allow spacecraft to be fueled in space.
	**Fuel Shuttles**	Vehicles that transport fuel from a depot to a customer vehicle on orbit.
	**RAFTI Active Coupling**	The activity of docking a servicing vehicle to a client vehicle and engaging the RAFTI Active Valve Cores on the servicing side to participate in the fuel transfer.
	**GRIP**	A mechanism that implements the RAFTI Active Coupling specification.

2. Refuelable Spacecraft Overview

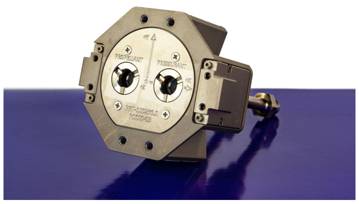
2.1 Benefits of Refueling

Creating a refuelable spacecraft allows the spacecraft to be refueled on orbit with only minor modifications using the RAFTI system. Making a spacecraft refuelable enables increased revenue potential, enhanced mobility, novel operations, and new business models. Orbit Fab's UMPIRE Mission Analysis software can further assist in refueling mission planning – available upon request.

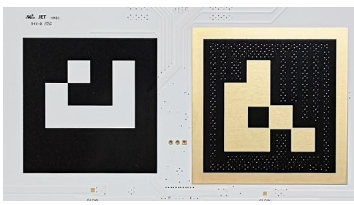
Table 2.1.1 Refueling Benefits	
 **Increase Revenue Potential**	• Extend spacecraft lifetime • Trade fuel mass for payload mass • Enable faster asset deployment • Realize direct cost savings
 **Enhance Mobility**	• Reposition assets • Negate mission life reduction caused by collision avoidance maneuvers • Enable on-demand retasking • Correct orbital insertion inaccuracies
 **Enable New Operations & Business Models**	• Perform secondary missions • Offer unique capability to clients • Enable access to novel maneuvers, orbits, spacecraft designs, and constellation architectures

2.1 Refuelable Spacecraft Components

Upgrading a spacecraft/vehicle to be refueling capable requires minor modifications and requirements analysis outlined in this document. A refuelable spacecraft consists of the below components:

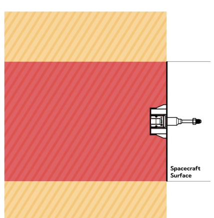


RAFTI Service Valve – Passive service valve that enables docking & fluid transfer.
See Section 3 for details.

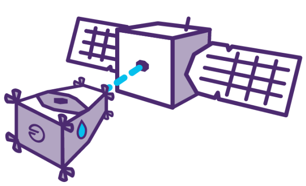


Alignment Markers – Alignment markers enable RPOD with Orbit Fab shuttles and depots.
See Section 4 for details.

Propulsion System Accommodations – Enable RPOD as well as refueling connections with our active coupling half (GRIP).
See Section 5 for more information.

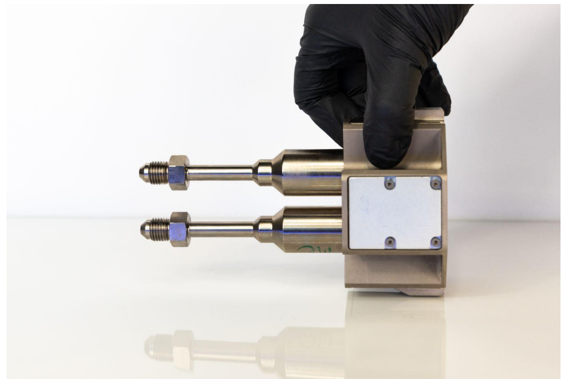


Keep Out Zones – Are areas near RAFTI & alignment markers that need to be free of other items that could inhibit RPOD operations.
See Section 3 for details.



Client GNC – Further enable RPOD.
See Section 6 for more information.

3. RAFTI Service Valve



3.1 RAFTI Service Valve Overview

The RAFTI Service Valve (RSV) is a passive fluid transfer interface that also enables cooperative docking. It consists of an octagonal grapple fixture and two valve cores. A single RSV supports the transfer of two independent fluids, for example propellant and pressurant. The RAFTI Service Valve is designed to support three major functions to the spacecraft on which it is installed:

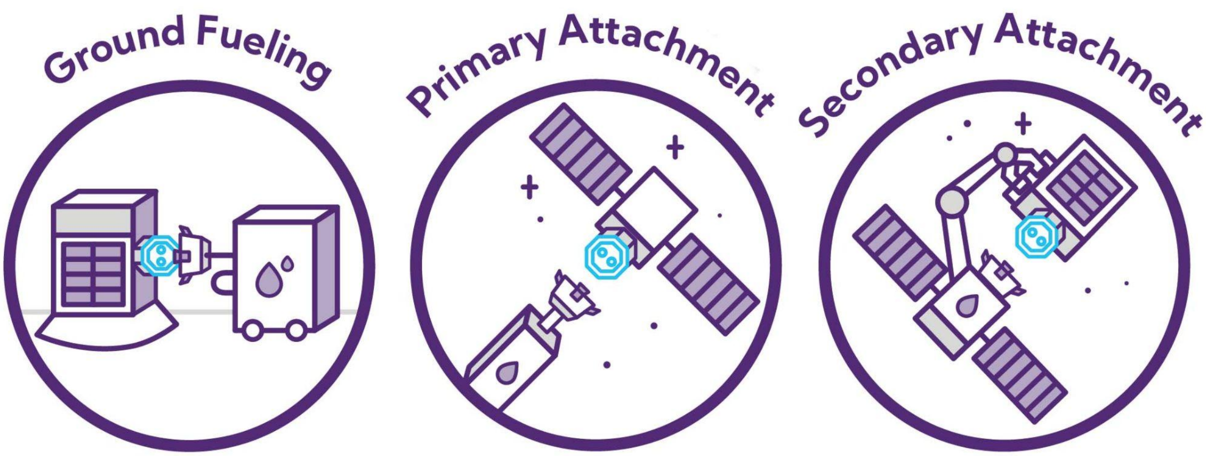


Figure 3.1.1 RSV Major Functions

1. Fill and drain functions for the propulsion system during ground operations.
2. A prepared spacecraft docking interface for primary docking attachments, and/or a utility interface for secondary attachments, providing the alignment and preload to the fluid transfer interface.
3. Fluid transfer functions during in-space fueling operations.

The RAFTI Service Valve acts as the passive fluid transfer interface. It is present on any vehicle intended to be refueled or from which fuel could be extracted, including client vehicles, fuel shuttles, and fuel depots.

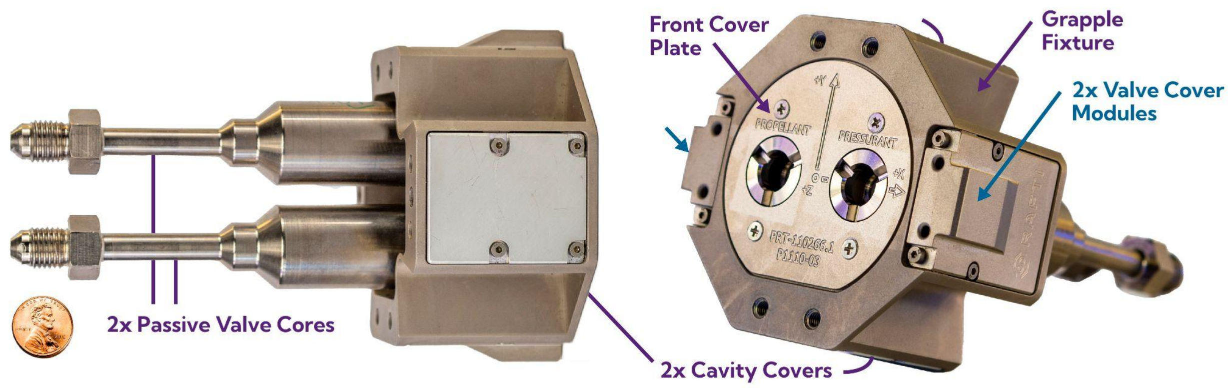


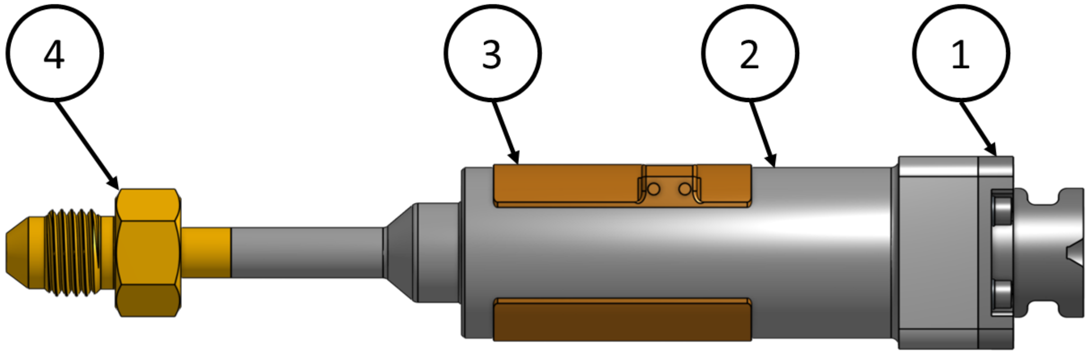
Figure 3.1.2 The RAFTI Service Valve (RSV)

The RAFTI Service Valve comprises three primary parts and assemblies:

1. Grapple Fixture
2. Passive Valve Cores
3. Cover Closeout Assembly

The Grapple Fixture may be used as a docking interface to mate two spacecraft together. It may also be used in conjunction with another docking interface, strictly as a utility interface, to provide alignment and preload to the mating valve cores.

The RSV contains Passive Valve Cores (see Figure 3.1.2), which define the fluid transfer interface. RAFTI uses a pintle valve design, where the pintle in RSV is actuated via the active coupling half within the Orbit Fab GRIP system. Valve cores come in multiple variations to account for two pressure ratings and material compatibility with various fluids. The Valve Cores use elastomeric o-rings for static sealing and energized seals for dynamic sealing applications. See Table 3.3.1 for material specifications. The Cover Closeout Assembly mechanisms are included on the RAFTI Service Valve and actuated passively during mating when a utility connection is established.



Item number	Description
1	Alignment cap
2	Valve core body
3	Heater with integrated thermistor
4	AN fitting (optional; tube stub can be shorter upon request) Other fitting types available upon request

Figure 3.1.3 RAFTI Passive Valve Core on the RAFTI Service Valve

3.2 Mechanical Configuration

The RAFTI Service Valve is available in multiple configurations designated by Class. The class designation has two components, 1) a number and 2) a letter, as in "Class 2A."

The RAFTI Class Number designates the mounting interface and mechanical envelope per the Mechanical Interface Control Drawings (MICDs) – See Table 3.2.1. As of Jan 1, 2022, Class 1 RAFTI has been deprecated and replaced with Class 2. The RAFTI Class Letter designates the number of valve cores, pressure rating, and wetted materials. All requirements and specifications not specifically addressed in the Class designation apply to all RAFTI Classes.

Table 3.2.1 below shows the class designations of the RAFTI products.

Table 3.2.1 RAFTI Service Valve Class 2 Designations

CLASS	VALVE CORE QTY	MEOP (psig)	MASS (kg/lb)	EXAMPLE PROPELLANT
Class 2A	2	650	0.52 / 1.15 (TBC)	Hydrazine
Class 2B	2	650 (TBC)	TBD	H_2O_2
Class 2C	2	650 (TBC)	TBD	ASCENT
Class 2D	2	3000 (TBC)	TBD	Xenon

3.2.1 Mechanical ICD

Reference Appendix A for full RAFTI Mechanical ICD including envelope dimensions & mounting interface hole locations.

Table 3.2.1.1 Mechanical ICDs for RAFTI Classes	
Class 1	DEPRECATED
Class 2	ICD-00001

3.3 Material Compatibility

RAFTI Class 2A material compatibility is defined in the wetted material list below. Future RAFTI Classes (B–D) will be available upon release.

Table 3.3.1 RAFTI Class 2A Wetted Material List

Wetted Material	Finish	Notes
304 SS per ASTM-276	Electroless Nickel Plate per AMS-2404 Class 2	
304 SS per ASTM-276	Passivate per ASTM A967 Nitric 3 then electroless nickel plate per AMS-2404 Class 2	Performed in this order so masked surfaces are passivated and unmasked features are plated
304 SS per ASTM-276	Passivate per ASTM A967 Nitric 3	
Fluoroloy A02	None	Cleaned to IEST-STD-CC1246E 100R1. Modified PTFE
302 SS per ASTM A313 Class 1	Passivate per ASTM A967 Nitric 3	Cleaned to IEST-STD-CC1246E 100R1
304 SS per MSD2007-04	Passivate per ASTM A967 Nitric 3	Cleaned to IEST-STD-CC1246E 100R1
EPDM E0540-80	None	
Krytox 240 AC	N/A; lubricant	

3.4 Thermal Operating Limits

Thermal operating limits are dependent on propellant media and outlined in the table below:

Table 3.4.1 Thermal Operating Limits

	Propellant	Water	H_2O_2	Hydrazine	MMH	NTO (MON-3)	Pressurant (He)	Xenon
	State	Liquid	Liquid	Liquid	Liquid	Liquid	Gas	Supercritical
Temp.	Minimum Fluid Temp	5 ºC	0 ºC	10 ºC	–10 ºC	–10 ºC	–10 ºC	–10 ºC
	Maximum Fluid Temp	75 ºC	75 ºC	40 ºC	75 ºC	75 ºC	75 ºC	75 ºC
	Hardware Operating	–40 to 80 ºC (unwetted)						
	Hardware Survival	–60 to 100 ºC (unwetted)						

3.5 Component Body Axes

The RAFTI primary components use a local coordinate system in which the origin is located on the plane which defines the hard stop when an RSV and a GRIP or RGC are clamped.

See Appendix A for the full description of the RAFTI coordinate system.

3.6 Mounting Requirements

RAFTI needs to be mounted to the spacecraft surface. See ICD in Appendix A for specific mounting hole configurations. The fasteners attaching RAFTI to the customer's interface shall have a minimum preload of 786 lbf applied.

3.7 Docking and Utility Interfaces

The RAFTI Service Valve contains a grapple fixture which serves as the passive docking and/or utility interface. A docking interface brings two spacecraft together and a utility interface aligns and preloads a specific utility connection.

The RAFTI Service Valve may be used as a direct docking interface for two vehicles. A soft capture can be achieved when the two vehicles have the following sizes and alignments. Soft capture is followed by hard latch. The RAFTI grapple fixture may be used to achieve both states.

Table 3.7.1 Docking Sizes

PARAMETER	VALUE
Direct Docking Vehicle Size	Assuming RAFTI alignment is within the specified center of gravity offsets, up to 1,000kg *equivalent mass*. *Equivalent mass* = $m_1m_2/(m_1+m_2)$. For example: ● Assuming vehicles of the same mass, two up to 2,000kg vehicles can dock ● Assuming one is smaller, an up to 1,000kg vehicle can dock with any more massive vehicle These mass classes have so far been rated for final relative docking velocities up to 25mm/s.
Docking/Utility Misalignment to GRIP	± 10mm in X & Y Axes ±5 degrees in X,Y, & Z Axes

The momentum transferred when the servicer and client spacecraft contact is a function of their equivalent mass (reduced mass) and relative velocity. In this case equivalent mass is given by the equation: $m_1m_2/(m_1+m_2)$, where m_1 and m_2 can be either the mass of the chaser or the client, as the contact dynamics are symmetric. This means that the rating of the RAFTI Service Valve is expressed only in terms of relative velocity between the two objects regardless of orbital direction.

The graph below further shows the relationship between chaser mass (here set at 1,000kg) and client mass (ranging from 1 to 1 million kg), showing that as one of the spacecraft masses approaches infinity, the equivalent mass of the system approaches the mass of the smaller spacecraft. In this case, above 1,000kg is the chaser vehicle and below 1,000kg is the client vehicle.

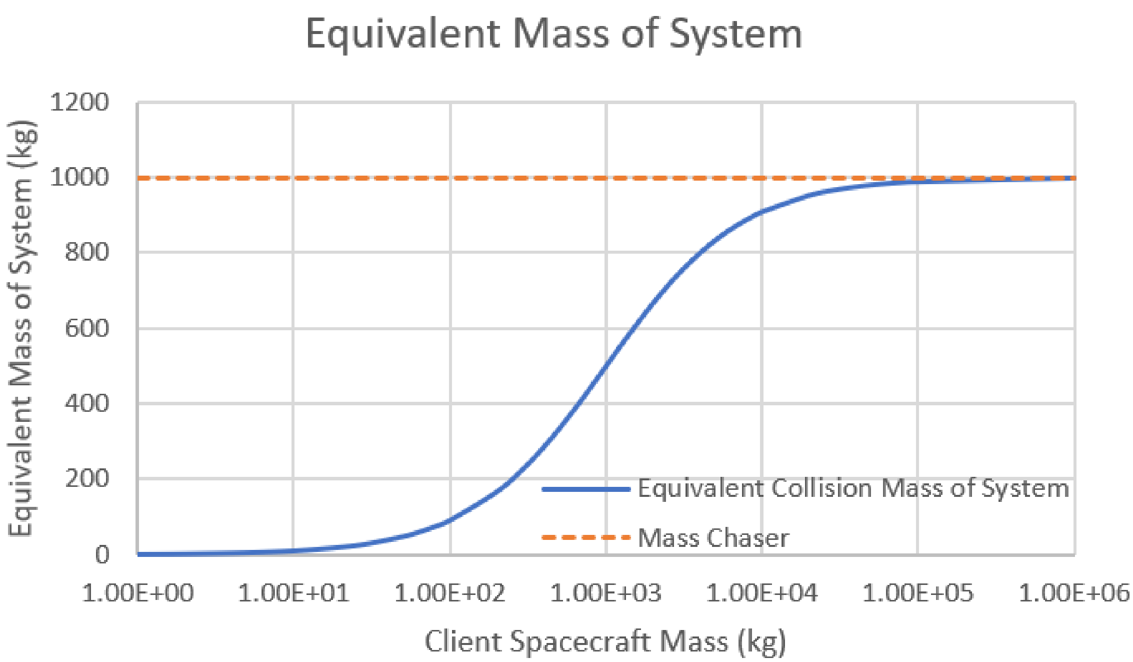


Figure 3.6.2 Equivalent Mass when Docking

The RAFTI Service Valve has been rated for use up to an equivalent mass of 1,000kg at approach velocities ranging from 0 to 25mm/s. This means that for those velocities, a spacecraft 1,000kg or less could dock to a spacecraft of up to effectively unlimited mass or vice versa. If both objects are above 1,000kg, the maximum permissible mass for two vehicles of equal mass is 2,000kg each, resulting in a 1,000kg equivalent mass.

3.8 Utility Alignment and Preload

The grapple fixture of the RAFTI Service Valve supports a hard latch state in coordination with an active grapple mechanism. Together they provide the following utility interface capabilities. The utility interface defines the preload and alignment required to open the Valve Covers and to establish and maintain a fluid connection between mating Valve Cores.

Table 3.8.1 Preload Requirements	
PARAMETER	**VALUE**
Docking/Utility Minimum Preload:	2 kN of clamping force
Utility Misalignment Limit:	± 1mm in X & Y Axes ± 2 deg in Z Axis

3.9 Clearances

When used as a Docking Interface, the Client Vehicle shall mount the RAFTI Service Valve according to interface specifications in the MICD and provide for a keep out zone as indicated in Figure 3.9.2. This keep out area should be kept free of all spacecraft features such as solar panels, antennas, and radiators. Insulation in this region should follow the guidelines listed in Section 4 for thermal considerations.

All areas beyond the plane defined by the plate RAFTI is attached to and outside the keep out zone are strongly discouraged for spacecraft features. Spacecraft features in this region create technical complexities involving more complicated collision avoidance, plume impingement analysis, and shadowing of fiducials. Some of these issues may not be able to be resolved, will involve client cost for consideration, and will increase the schedule time in order to prepare for the first refueling. Please contact Orbit Fab early should your mission require spacecraft features placed in this region.

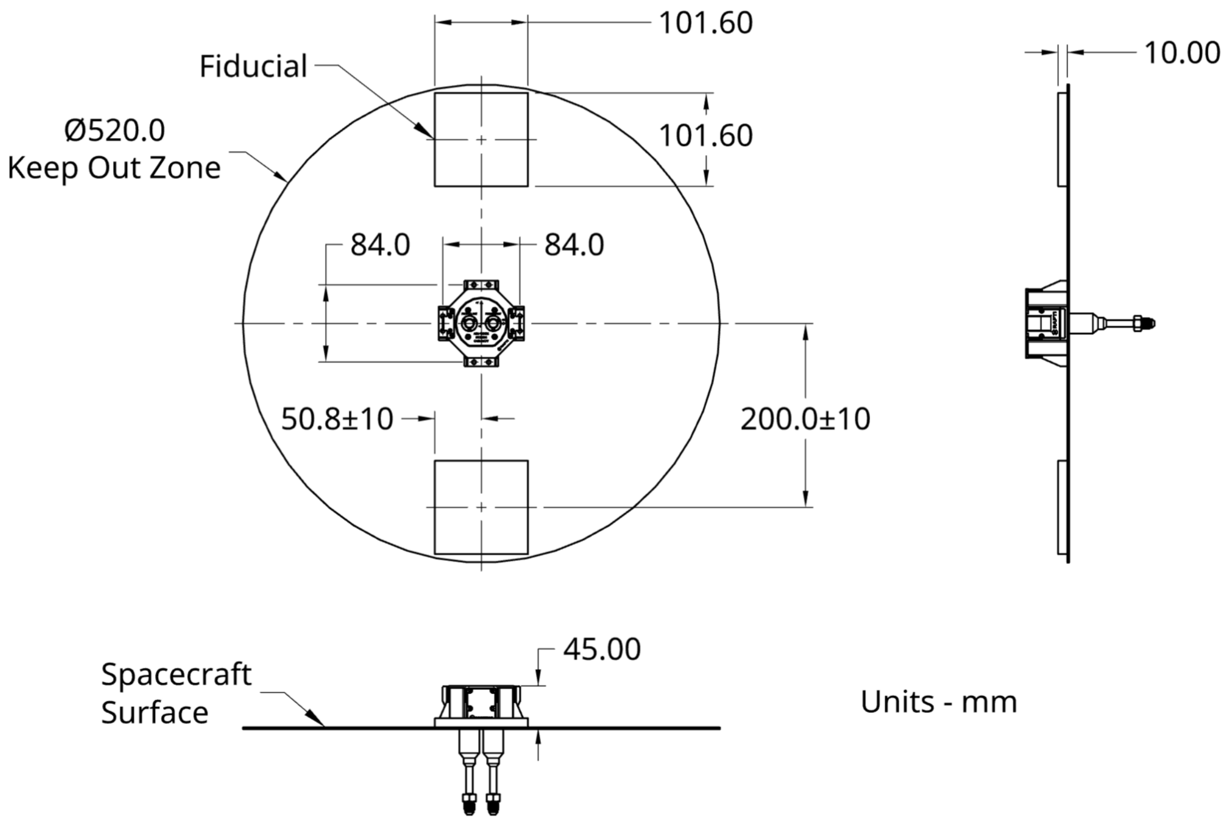


Figure 3.9.1 Client Vehicle Keepout Zone for Mounting RAFTI Service Valve

See Section 3.9 for Details

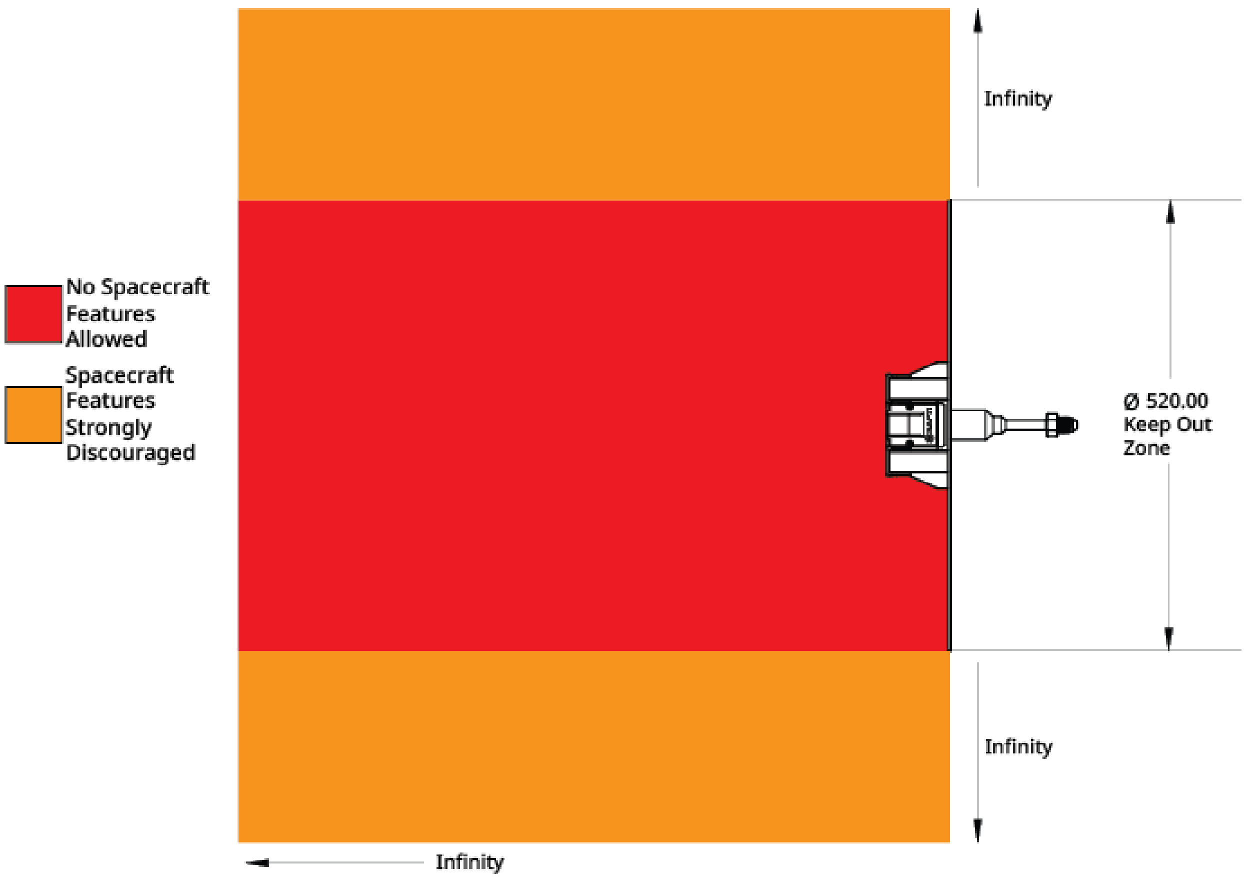


Figure 3.9.2 RAFTI Keep Out Zone

3.10 Positioning

While it is ideal to mount RAFTI Service Valve along the CG axis, this serves as a general rule of thumb for small and large spacecraft, but requires a case by case analysis to verify, accounting for differences in spacecraft body and keep out zones. Figure 3.10.1 and Table 3.10.2 show initial analysis for allowable mounting offset from the CG. This CG shall be defined at the propellant fill fraction expected during a refueling operation to accommodate for the CG shifting as propellant is expelled through the satellite's life.

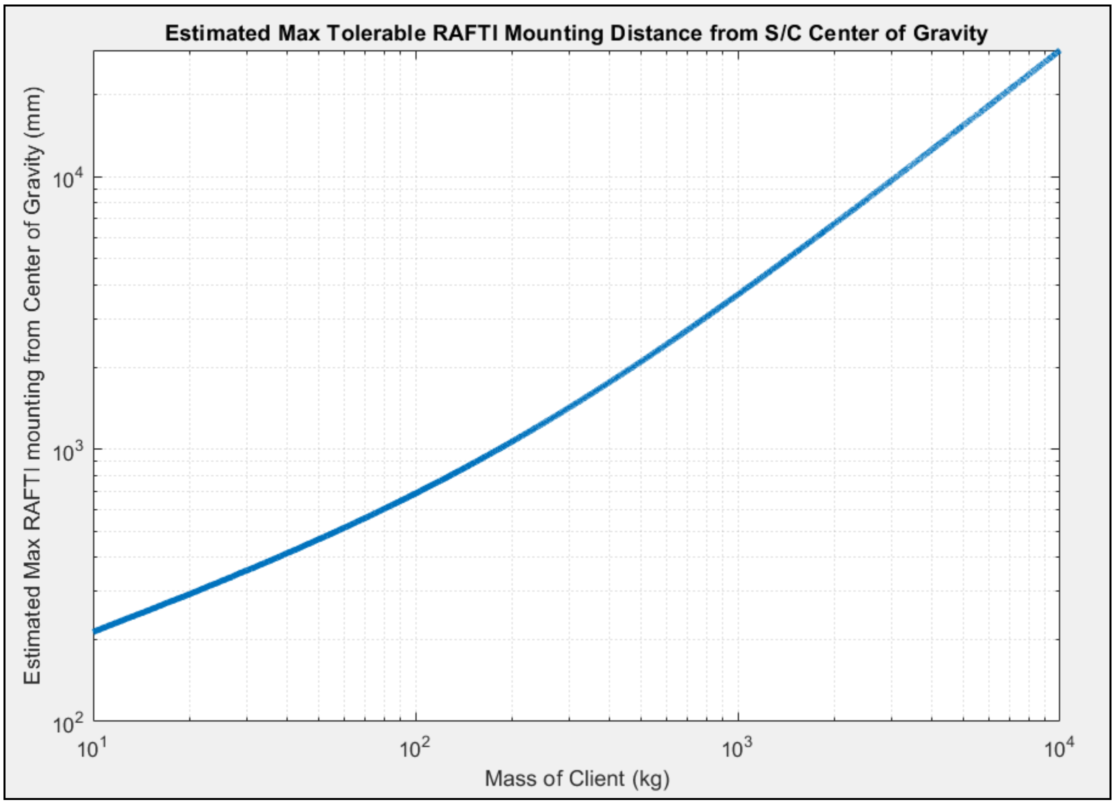


Figure 3.10.1 Max RAFTI Mounting Distance from Spacecraft CG

On the lower end of the client mass spectrum, the reduced mass which governs the momentum exchanged upon collision and is calculated by the formula: $m_1m_2/(m_1+m_2)$, is very low. This means that it takes quite a bit of rotation on top of the body's rebounding velocity to exceed the reach of GRIP, resulting in a large maximum radius which can exceed the normal form factor of the client spacecraft's standard body. This would suggest that towards these maximum bounds, it is especially relevant to rerun these cases with client specific MOI, but for these generalized purposes this approximation serves well.

Table 3.10.2 Client Vehicle Max Allowable CG Offsets	
Client Vehicle Mass Range (kg)	**Max allowable CG Offset (mm)**
<10	210*
10–100	680*
101–200	1,070
201–500	2,100
501–1,000	3,700
1,000+	3,700+

**At the lower mass range, spacecraft MOI may greatly vary CG Offset*

3.11 Mechanical Interface Loads

The RAFTI Service Valve shall enforce various loading cases through its mounting interface to the spacecraft structure below. The Client Vehicle shall use the following loading cases for design and verification.

Table 3.11.1 Client Vehicle Loading Specifications	
LOAD CASE	**VALUES (N)**
Contact:	11600 (9.31 MPa [1.35 ksi] @ Mounting Interface) (TBS)
Grappling:	2000 (TBS)
Docked:	TBD
Push Off:	TBD

3.12 Electrical Grounding

Grounding of the RAFTI Service Valve shall comply with NASA-HDBK-4001, *Electrical Grounding Architecture for Unmanned Spacecraft* and does not impinge on the ability of the Client Vehicle to adhere to this standard

3.13 Electrostatic Discharge

GRIP shall manage all design considerations to handle/mitigate ESD.

3.14 Separation

The RAFTI Service Valve and keep out zone is designed for a separation velocity of 25 mm/s for the largest spacecraft (1000 kg equivalent mass). No part of the Service Valve inhibits release by the RAFTI Active Coupling in the case of a power failure or other single fault.

3.15 Failure Modes Analysis

TBD

3.16 Marking Options

The RAFTI Valve cores shall be marked with 'Port A' and 'Port B'.

3.17 Security

On-orbit security concerns are addressed in several ways. Clients that are concerned about an unauthorized space vehicle using the RAFTI Service Valve to add or remove fluids, should implement an isolation valve between the propulsion system and the RAFTI Service Valve. In this way, fluid transfer can only occur when the client vehicle allows it.

Client vehicles will also want to entirely prohibit other space vehicles from docking with the RAFTI Service Valve. Future versions of the RAFTI Open ICD will define a lockout mechanism which would allow docking only through an unlocking action. The ICD will include protocols for a communication handshake allowing for the authentication of refueling vehicles.

3.18 Operational Life

The RAFTI Service Valve shall be capable of operating for 15 years in low Earth and geosynchronous orbits.

3.19 Storage Life

The RAFTI Service Valve shall be capable of being stored for a minimum of three years without requiring maintenance or repair at the end of storage.

3.20 Environments and Lifetime

The RAFTI Service Valve is designed to be functional after being exposed to shock, vibration and TVAC levels per GSFC-STD-7000 (GEVS).

3.21 Cleanliness

Table 3.21.1 Cleanliness Specifications

PARAMETER	VALUE
Externally Exposed Surfaces:	Visible Cleanliness II levels (VC-II) per NASA Contractor Report 4740.
Wetted Valve Core Surfaces:	100R1 per IEST-STD-CC1246E cleanliness standard.

3.22 Venting

The RAFTI Service Valve structure is vented such that all non-fluid-path, enclosed volumes can reach vacuum during the launch ascent.

3.23 Thermal Interface

All parts of the RAFTI Service Valve have been designed to the following thermal specifications. With mounting as required in the RAFTI ICD, when mounted to a client vehicle, the mounting interface has a thermal conduction under 7.0 W/℃.

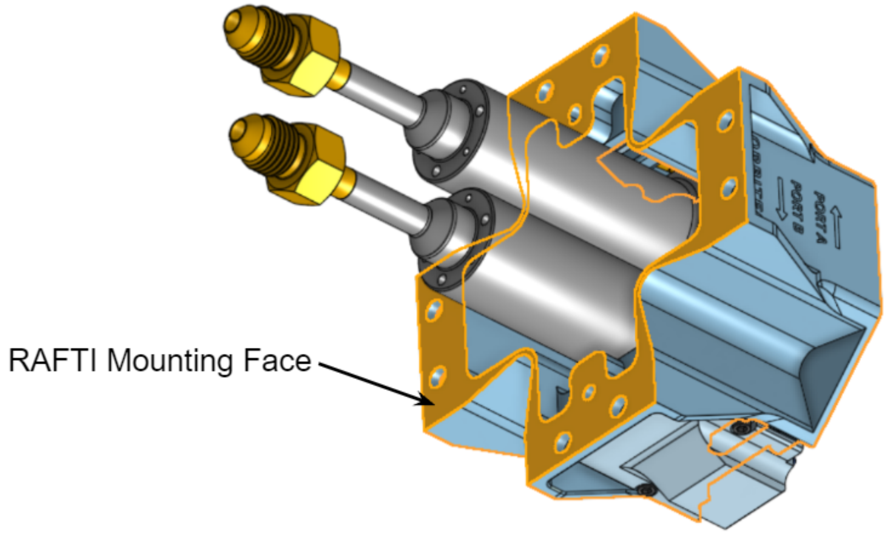


Figure 3.23.1 RAFTI Mounting Face

3.24 Electrical Interfaces

The electrical interface of the RAFTI Service Valve provides power to heaters and receives signals from unconditioned thermistors (leads only, no additional electronics). These interfaces are defined as the electrical connections necessary for operation and instrumentation. The RAFTI Service Valve includes integrated heaters which are powered by an EPS PWM (Pulse Width Modulation) switching interface from the Client Vehicle power system.

The power system bus voltage is determined by the spacecraft design. A RAFTI Service Valve may be operated on multiple spacecraft bus voltages, with a preference for 12VDC and 28VDC busses. The RAFTI Service Valve shall be delivered to the end user with datasheet specifications for the specific integrated heaters and thermistors selected. A RAFTI Service Valve may have one or two RAFTI Valve Cores, designated Valve Core A and Valve Core B. Each Valve Core will have two heaters and two thermistors. The electrical interface will consist of wired pigtails using the following labeling convention.

Table 3.24.1 Wire Out Specification

WIRE	LABEL	NOMINAL DESCRIPTION	RANGE AND DERIVED	MIL-STD-681 DES	BASE COLOR	1ST STRIPE
1	SV_Heater_A1	Heater A1 PWM Control	12-28V DC	0	Black	None
2	SV_Heater_A2	Heater A2 PWM Control	12-28V DC	1	Brown	None

3	SV_Heater_B1	Heater B1 PWM Control	12-28V DC	2	Red	None
4	SV_Heater_B2	Heater B2 PWM Control	12-28V DC	3	Orange	None
5	SV_Heater Return_A1	Heater A1 Return	GND	4	Yellow	None
6	SV_HeaterReturn _A2	Heater A2 Return	GND	5	Green	None
7	SV_HeaterReturn _B1	Heater B1 Return	GND	6	Blue	None
8	SV_HeaterReturn _B2	Heater B2 Return	GND	7	Violet	None
9	SV_Thermistor_A 1+	Thermistor A1 Differential Positive	+/- 3.3V Analog Differential	8	Gray	None
10	SV_Thermistor_A 2+	Thermistor A2 Differential Positive	+/- 3.3V Analog Differential	9	White	None
11	SV_Thermistor_B 1+	Thermistor B1 Differential Positive	+/- 3.3V Analog Differential	90	White	Black
12	SV_Thermistor_B 2+	Thermistor B2 Differential Positive	+/- 3.3V Analog Differential	91	White	Brown
13	SV_Thermistor_A 1-	Thermistor A1 Differential Negative	+/- 3.3V Analog Differential	92	White	Red
14	SV_Thermistor_A 2-	Thermistor A2 Differential Negative	+/- 3.3V Analog Differential	93	White	Orange
15	SV_Thermistor_B 1-	Thermistor B1 Differential Negative	+/- 3.3V Analog Differential	94	White	Yellow
16	SV_Thermistor_B 2-	Thermistor B2 Differential Negative	+/- 3.3V Analog Differential	95	White	Green

3.25 Thermistor Monitoring

3.25.1 Thermistor characteristics

The thermistors integrated onto RAFTI shall be TBD. More information will be included in this document as the design is finalized.

3.25.2 Monitoring rates

The thermistors should be monitored at 0.016 Hz (once per minute).

3.26 Heater Control

The RAFTI Electrical System is controlled via an external bus-level control system. High-side PWM switching control of the heaters with PWM is rate controlled by thermistor feedback. Either bang-bang or proportional heater control can be used, although other control methods which maintain RAFTI thermal requirements are also acceptable. Thermistors are recommended to be read differentially for minimum noise via conditioned analog input to the bus. Additional testing is planned at Orbit Fab to fully characterize the heater control system.

3.27 Software Requirements

The RAFTI Customer will integrate software designed and tested by Orbit Fab to operate heaters in compliance with thermal specifications in Section 3.26.

3.28 Test & Validation Requirements

RAFTI Test and Validation requirements are key to ensure all RAFTI systems are consistent and will function properly for docking and refueling. The tables below outline Orbit Fab RAFTI Requirements.

Table 3.28.1 Qualification Test Requirements	
MAIT Flow	**Test Requirements**
Proof	1.5 x MEOP x ECF* for a duration of 5 mins ● MEOP=650 psig ● ECF=1.09 (Assuming max operating temp. of 81°C) *ECF=Environmental Correction Factor
Flow rate test	Validation of the valve flow coefficient (Cv) for specific unit
Helium leak test	Validation of leak rates per a low pressure (15 psig) and high pressure (650 psig) helium leak test ● Leakage of less than 1e-4 sccs of helium at 15 psig and MEOP while in the unmated state. ● Leakage of less than 1e-4 sccs of helium at 15 psig and MEOP while pre-mated. ● Leakage of less than 1e-4 sccs of helium at 15 psig and MEOP while mated.
Valve opening force test	Measurement of the force required to actuate the valve core

<table>
<tr><th colspan="2">Table 3.28.1 Qualification Test Requirements</th></tr>
<tr><th>MAIT Flow</th><th>Test Requirements</th></tr>
<tr><td>Shock test</td><td>
<table>
<tr><th>Frequency (Hz)</th><th>MPE SRS (g's)</th><th>Qualification SRS (g's)</th></tr>
<tr><td>10</td><td>30</td><td>60</td></tr>
<tr><td>1000</td><td>1000</td><td>2000</td></tr>
<tr><td>10000</td><td>1000</td><td>2000</td></tr>
<tr><td colspan="3">Q=10; three shocks per axis</td></tr>
</table>
</td></tr>
<tr><td>Vibration</td><td>
<table>
<tr><th>Frequency (Hz)</th><th>ASD Level (g^2/Hz)</th></tr>
<tr><td>20</td><td>0.026</td></tr>
<tr><td>20-50</td><td>+6 dB/oct</td></tr>
<tr><td>50-800</td><td>0.16</td></tr>
<tr><td>800-2000</td><td>-6 dB/oct</td></tr>
<tr><td>2000</td><td>0.026</td></tr>
<tr><td>Overall</td><td>14.1 gRMS</td></tr>
<tr><td>Duration</td><td>3 min/axis</td></tr>
</table>
</td></tr>
<tr><td>Thermal vacuum</td><td>TBD</td></tr>
<tr><td>Burst test</td><td>2.5 x MEOP x ECF*
● MEOP=650 psig
● ECF=1.18 (Assuming max operating temp. of 81°C)
*ECF=Environmental Correction Factor</td></tr>
<tr><td>Life test</td><td>TBD</td></tr>
</table>

<table>
<tr><th colspan="2">3.28.2 Acceptance Test Requirements</th></tr>
<tr><th>MAIT Flow</th><th>Test Requirements</th></tr>
<tr><td>Proof</td><td>Hydrostatic pressurization:
1.5 x MEOP x ECF* for a duration of 5 mins
● MEOP=650 psi
● ECF=1.09 (Assuming max operating temp. of 81°C)
*ECF=Environmental Correction Factor</td></tr>
<tr><td>Flow rate test</td><td>Validation of the valve flow coefficient (Cv) for specific unit</td></tr>
</table>

<table>
<tr><th colspan="2">3.28.2 Acceptance Test Requirements</th></tr>
<tr><th>MAIT Flow</th><th>Test Requirements</th></tr>
<tr><td>Helium leak test</td><td>Validation of leak rates per a low pressure (15 psig) and high pressure (650 psig) helium leak test
Leakage of less than 1e-4 sccs of helium at 15 psig and MEOP while in the unmated state. RSV side is pressurized
Leakage of less than 1e-4 sccs of helium at 15 psig and MEOP while pre-mated. RGC is pressurized, RSV is unpressurized
Leakage of less than 1e-4 sccs of helium at 15 psig and MEOP while mated. RSV and RGC pressurized</td></tr>
<tr><td>Valve opening force test</td><td>Measurement of the force required to actuate the valve core</td></tr>
<tr><td>Vibration</td><td><table>
<tr><th>Frequency (Hz)</th><th>ASD Level (g^2/Hz)</th></tr>
<tr><td>20</td><td>0.013</td></tr>
<tr><td>20-50</td><td>+6 dB/oct</td></tr>
<tr><td>50-800</td><td>0.08</td></tr>
<tr><td>800-2000</td><td>-6 dB/oct</td></tr>
<tr><td>2000</td><td>0.013</td></tr>
<tr><td>Overall</td><td>10.0 gRMS</td></tr>
<tr><td>Duration</td><td>1 min/axis</td></tr>
</table></td></tr>
<tr><td>Thermal cycle</td><td><table>
<tr><th rowspan="2">Thermal Cycle</th><th colspan="3">Survival Temps</th><th colspan="3">Operational Temps*</th><th rowspan="2"># Cycles (acceptance)</th></tr>
<tr><th>Cold</th><th>Hot</th><th>Soak</th><th>Cold</th><th>Hot</th><th>Soak</th></tr>
<tr><td>First</td><td>-60°C</td><td>100°C</td><td>6 hours</td><td>-31°C</td><td>71°C</td><td>6 hours</td><td>1</td></tr>
<tr><td>Last</td><td>-</td><td>-</td><td>-</td><td>-31°C</td><td>71°C</td><td>6 hours</td><td>1</td></tr>
</table></td></tr>
</table>

3.28.3 Dimensional Validation Requirements

Please reference Appendix A for the dimensional requirements noted on the ICD. This will allow for confirmation that a GRIP & RGC can mate to the completed RAFTI once installed.

3.28.4 Test Matrix

The Manufacturing, Assembly, Integration and Test (MAIT) flows will differ between Qual, Acceptance & EDU RAFTI units per SMC-S-016 requirements, section 6.3 Test Program for Units. The matrix below summarizes the differentiation between the units, requirements, and test flow process

Table 3.28.4.1 RAFTI MAIT Flow Requirements

MAIT FLOW	QUAL (Burst)	QUAL (Life)	Acceptance (Flight)	EDU (Non flight)
Assembly	✔	✔	✔	✔
Inspection	✔	✔	✔	✔
Proof Test	✔	✔	✔	✔
Functional	✔	✔	✔	✔
Shock	✔	✔		
Functional	✔	✔		
Vibration	✔	✔	✔	
Functional	✔	✔		
Thermal vacuum	✔ (12x)	✔ (8x)		
Thermal cycle			✔ (2x)	
Functional	✔	✔	✔	
Cleanliness			✔	
Burst	✔			
Life (in TVAC)		✔		
Functional		✔		
Inspection	✔	✔	✔	✔

4. Alignment Marker Module

4.1 Fiducials

A minimum of three fiducials are necessary to do prepared, cooperative docking. In order to minimize the impacts of shadows on our computer vision algorithms, all three fiducials shall not be collinear. Fiducials beyond the minimum of three increases the robustness of the RPOD system to shadows. The fiducial center should be placed following the diagram in the figure below. The misalignment between the X and Y axis of each fiducial and the X and Y axis of RAFTI may be no greater than 5 degrees.

A larger Whycon marker may be used to encircle the entire keep out zone if needed for robustness.

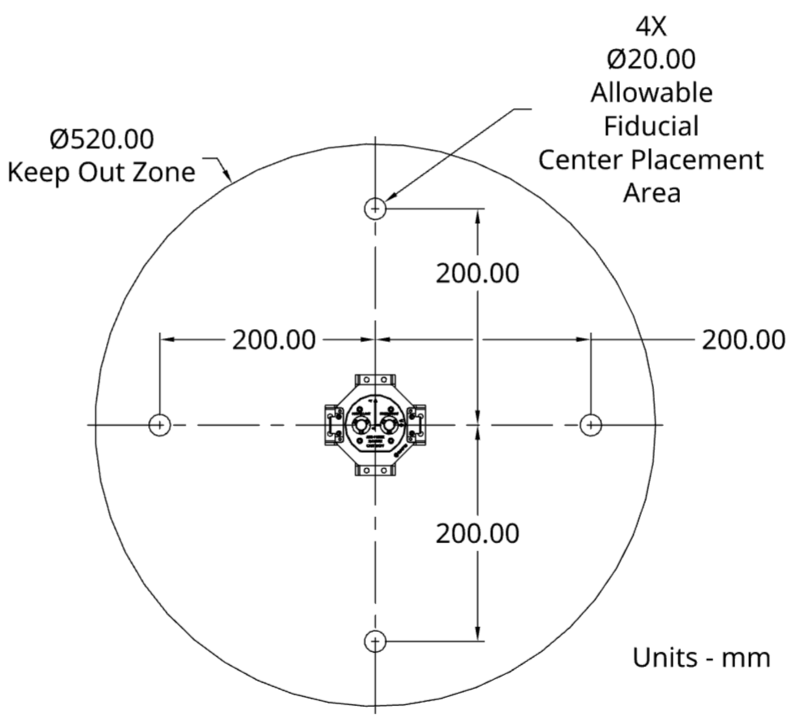


Figure 4.1.1 Fiducial Mounting Locations

Please refer to the Spacecraft Appearance Considerations in Section 6.4 for more information on using fiducials.

4.1.2 Surveying of Fiducial Placement

Errors between the actual position of fiducials and the expected position of the fiducials are a known hazard to computer vision algorithms. The same applies to fiducial size (See CV-HAZOP IDs 316 and 574).

To guard against the hazard from incorrectly sized fiducials, only use Orbit Fab provided fiducials. These fiducials have been characterized after manufacturing to ensure that their errors are within specifications. If Orbit Fab provided fiducials can not be used, please reach out to Orbit Fab to discuss options.

To guard against the hazard from differences in expected position and actual placement, clients must characterize the location of the Fine Alignment Markers with respect to RAFTI within 0.1 mm in all 3 axes, and 0.1 deg angular alignment with respect to RAFTI.

4.2 Thermal Considerations

The Orbit Fab system uses Long Wave Infrared accessible ArUco markers. Thus, there are some points clients must consider when integrating a RAFTI into their spacecraft. The fiducials should be maintained near bulk spacecraft temperatures during all RPOD phases. The purpose of this is to ensure the fiducials are emitting radiation in the wavelengths detected by LWIR cameras.

The fiducials shall have a temperature of between -20°C [TBC] and 80°C [TBC] while in operation during the RPOD mode of refueling. Fiducials shall remain detectable as an LWIR Aruco fiducial at the time of integration and when the spacecraft is placed into the RPOD mode. Detectible is defined as a 0.1% false negative rate when a LWIR camera is pointed at the target from 30 meters away. LWIR camera is defined as the FLIR Tau 2 640 with a [TBD] degree FOV lens

5. Client Propulsion System

5.1 Fluid Interface

5.1.1 Pressures & Flow Rates

The RAFTI Service Valve includes one or two Valve Cores specified in the Class Rating. Each valve core is capable of survival and operation at a MEOP defined by the Class Rating of the Valve. There are currently two variants of operating pressure, generally described as Low Pressure and High Pressure. The values for these pressures are indicated below.

Table 5.1.1.1 Pressure Variants	
Low Pressure MEOP:	4.48 Mpa (650 psig) TBS
High Pressure MEOP:	20.68 Mpa (3000 psig) TBS

Table 5.1.1.2 Pressure Specifications	
PARAMETER	**VALUE**
Valve Core MEOP:	Based on Class Rating. See Table 3.2.1
Proof Pressure:	1.5 x MEOP x ECF* for a duration of 5 mins ● MEOP=650 psig ● ECF=1.09 (Assuming max operating temp. of 81°C) *ECF=Environmental Correction Factor
Burst Pressure:	2.5 x MEOP x ECF* ● MEOP=650 psig ● ECF=1.18 (Assuming max operating temp. of 81°C) *ECF=Environmental Correction Factor

The RAFTI Service Valve is capable of the following minimum flow rates, depending on pressure variant.

Table 5.1.1.3 Fluid Transfer Specifications	
PARAMETER	**VALUE**
Low Pressure Variant:	TBD
High Pressure Variant:	TBD

5.2 Fluid System Integration

The following diagram illustrates an example of integrating RAFTI into a spacecraft propulsion system.

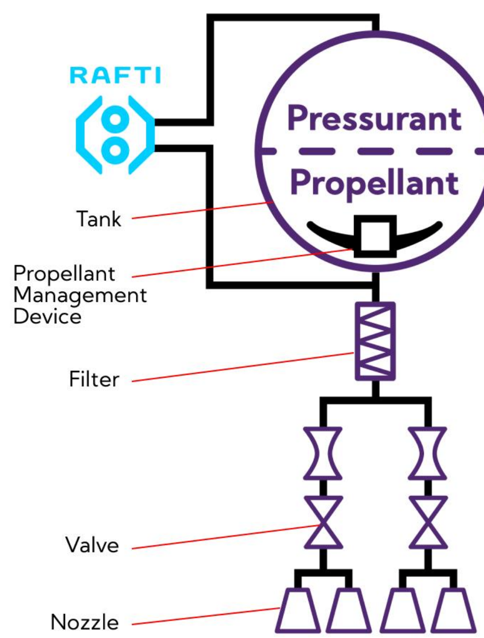


Figure 5.2.1 Integration of RAFTI with a spacecraft propulsion system

5.3 Inhibits to Leak and Drip at Disconnect

The RAFTI Valve Cores have three (3) inhibits to leak during ground and on-orbit operations and meet AFSPCMAN 91-710 safety requirements of three independent seals to provide dual-fault tolerance against inadvertent actuations (including leakage) which would cause a catastrophic failure. Leak rates are limited to the values found in the following table.

Table 5.3.1 Maximum Fluid Leak Rates	
PARAMETER	**VALUE**
Unmated	External leakage rate no greater than 1e-4 scc/s GHe
Mated	External leakage rate no greater than 1e-4 scc/s GHe

TBR - Fluid drip fault management steps and assumptions.

6. Client Spacecraft Systems

6.1 Client GNC

Orbit Fab's on-orbit refueling service offering includes assistance with mission planning, client spacecraft design accommodations (mechanical, thermal, electrical, software, attitude control, communications), safety, mission assurance and security. The following sections describe high level considerations when planning for on-orbit refueling.

6.1.1 Orbits

Orbit Fab plans to service spacecraft in low Earth orbit (LEO), Geosynchronous (GEO) and Cislunar Orbit.

TBS - Potential constraints (Lighting, SAA Avoidance in LEO, etc.)

6.1.2 Pointing and Stability

Client Vehicle pointing and stability requirements flow from various factors such as fiducial detection by imaging components on the service vehicle.

- The client shall hold RAFTI in line with the velocity vector within 4 degrees.
- The client attitude control stability shall be less than 0.1 degrees over 1 second, 1 sigma.

When docked, the Attitude Control Systems (ACS) on the two space vehicles may interact and "fight" each other, causing instabilities. Therefore it is necessary to place one space vehicle into a passive mode in which thrusters are disabled and reaction or torque wheels hold their current speed. Typically, the active participant (service vehicle) will retain active mode and therefore control the attitude of both vehicles, however the passive participant may take this role if it is of significantly greater mass than the active participant.

6.1.3 Mechanical Accommodations

See Section 3 for details on mechanical accommodations for the RAFTI Service Valve.

6.1.4 Power and Thermal Management

In current architectures, the service valves are typically placed under Multi Layer Insulation (MLI). Placement of the RAFTI Service Valve in a location accessible for a docking and refueling operation requires that it is outside the MLI. Therefore thermal analysis is necessary to ensure that the propellant residual in the RAFTI fuel lines does not freeze or boil (or is tolerant of freezing and boiling).

6.2 Client/Servicer Communications

TBS - Client/Servicer Communications requirements and implications.

6.3 Design Documentation Requirements

The following client spacecraft design data shall be provided to the Servicer Company prior to refueling:

1. Docking ICD defining placement of Fiducials relative to RAFTI origin.
2. 3D geometry models with TBD fidelity
3. Mass and moment of inertia

6.4 Spacecraft Appearance Considerations

Unexpected fiducials seen by the shuttle camera are a known mode of potential failure in computer vision algorithms (See CV-HAZOP ID 283). Therefore, RAFTI users are required to inform Orbit Fab about non-RAFTI fiducial markers on the client spacecraft. It is preferred that non-RAFTI fiducials are placed on a different spacecraft face than the RAFTI system fiducials. However, if this isn't feasible, the shuttle will take precautions to ignore non-RAFTI fiducials. The client shall not use ArUco 4 by 4 markers with the same marker ID numbers as the supplied ArUco markers. These ID numbers will be specified at purchase.

Reflections from an object are a known mode of potential failure in computer vision algorithms (See CV-HAZOP IDs 4, 5, 59, 482, 706, 707, 478, 481, 482). Therefore, RAFTI users are required to inform Orbit Fab about surfaces which are either specularly reflective (that is to say mirrored) or diffusely reflective with an albedo greater than 0.2 at the start of the satellite's life. RAFTI users are also required to inform Orbit Fab about the LWIR reflectivity and emissivity. These values will be used to do analysis to determine hazardous moments during vehicle approach for refueling due to glare. If available, these values should also be provided for end of life, however Orbit Fab can do additional analysis should these values be unavailable for the satellite's end of life. In addition, Orbit Fab requests photos and CAD models for plume analysis.

Do not point visible spectrum or LWIR spectrum illuminators at the Orbit Fab refueling spacecraft.

6.5 Client Assembly, Integration and Test

TBS – AI&T workflow diagram.

6.6 Verification and Validation Plan

TBS – Verification and Validation Plan

6.7 Licensing

TBS – Licensing Requirements

7. Ground Operations

7.1 RAFTI Ground Coupling

The RAFTI Ground Coupling (RGC) enables ground operations for spacecraft with the RAFTI Service Valve. The design allows customers to flow fluid through each of the RSV valve cores independently and has visual indicators that will show the current engagement state of the assembly. RGC will function in standard laboratory & integration settings. RGC has a fully enclosed chassis to keep foreign debris out of the assembly and away from the RAFTI unit. Wiper seals are integrated into the probe assembly to further mitigate risk of FOD. Figure below shows the RGC attached to RSV.

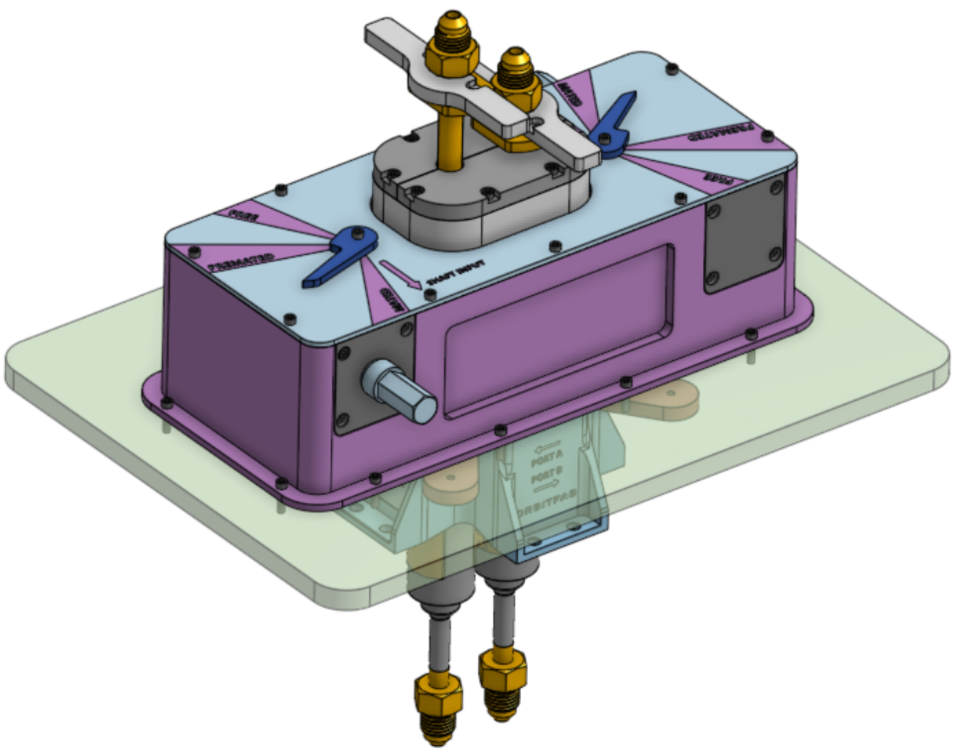


Figure 7.1.1 RGC attached to RSV

7.2 Range Safety

TBS – Range Safety considerations and advice on integration.

7.3 Ground Fueling CONOPS

TBS – Ground Fueling CONOPS

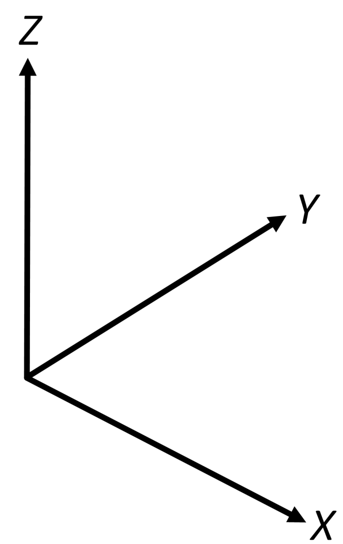
APPENDIX

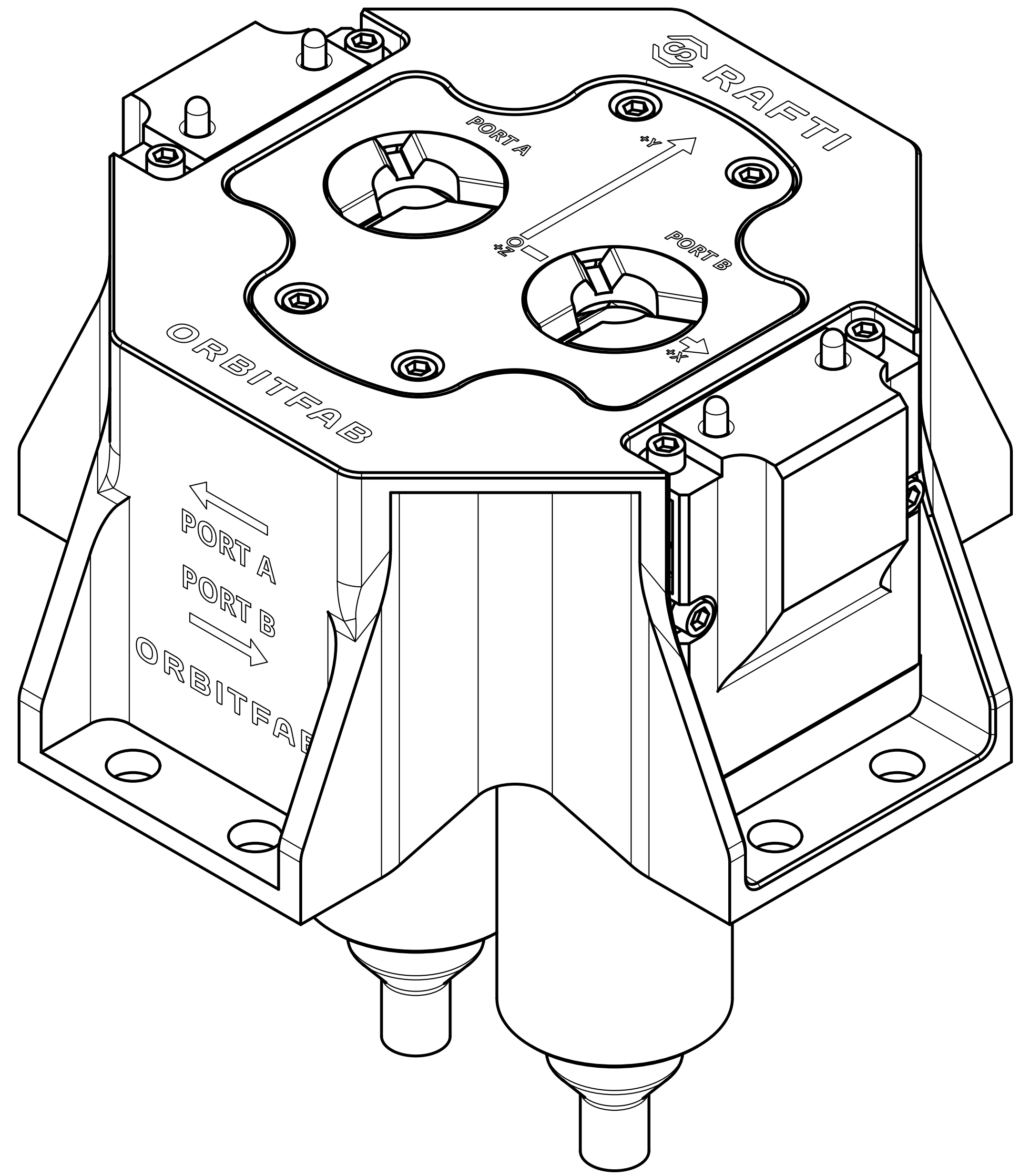
Appendix A RAFTI Mechanical ICD

NOTES	
1	TUBE STUB FLUID CONNECTION PROVIDED UNLESS OTHERWISE SPECIFIED. CONTACT PRODUCT MANAGER FOR OPTIONS
2	USE #8 NAS1351 OR NAS1352 FASTENERS, OR EQUIVALENT. FASTENERS PROVIDED BY ORBIT FAB UPON REQUEST
3	USE PIN MS16555-625 OR EQUIVALENT. PINS PROVIDED BY ORBIT FAB UPON REQUEST
4	IF USING WASHERS, USE NAS620 #8 WASHER (REDUCED OD) OR EQUIVALENT. WASHERS PROVIDED BY ORBIT FAB UPON REQUEST

REVISIONS			
REVISION	DESCRIPTION	DATE	APPROVER
A	INITIAL RELEASE	10/28/2022	TAK

RAFTI CSYS





ISOMETRIC (REFERENCE)

UNLESS OTHERWISE SPECIFIED, TOLERANCE AND VALUES ARE LISTED BELOW AND IN INCHES.
.XXX = ± .005
.XX = ± .01
.X = ± .05
ANGULAR = ± 1°
SURFACE 32

EDGE BREAK: .005 MIN .020 MAX
INTERNAL EDGE: R.020 MAX

BREAK ALL SHARP EDGES AND REMOVE BURRS

THIRD ANGLE PROJECTION

PRT NO.	ICD-00001	
CAGE CODE	81CP7	
MATERIAL	SEE NOTE 3	
FINISH	SEE NOTE 4	
	BY	DATE
DRAWN	DJK	2022-10-14
CHECKED		
APPROVED	TAK	2022-10-28

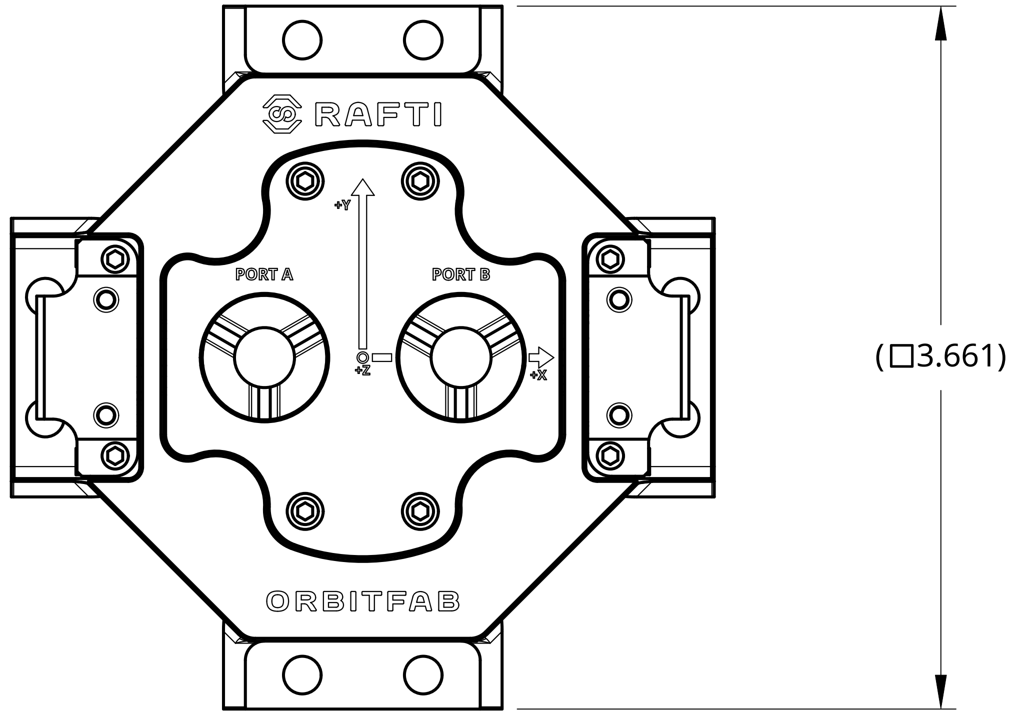
ORBIT FAB, INC.
1460 OVERLOOK DR
LAFAYETTE, CO 80026

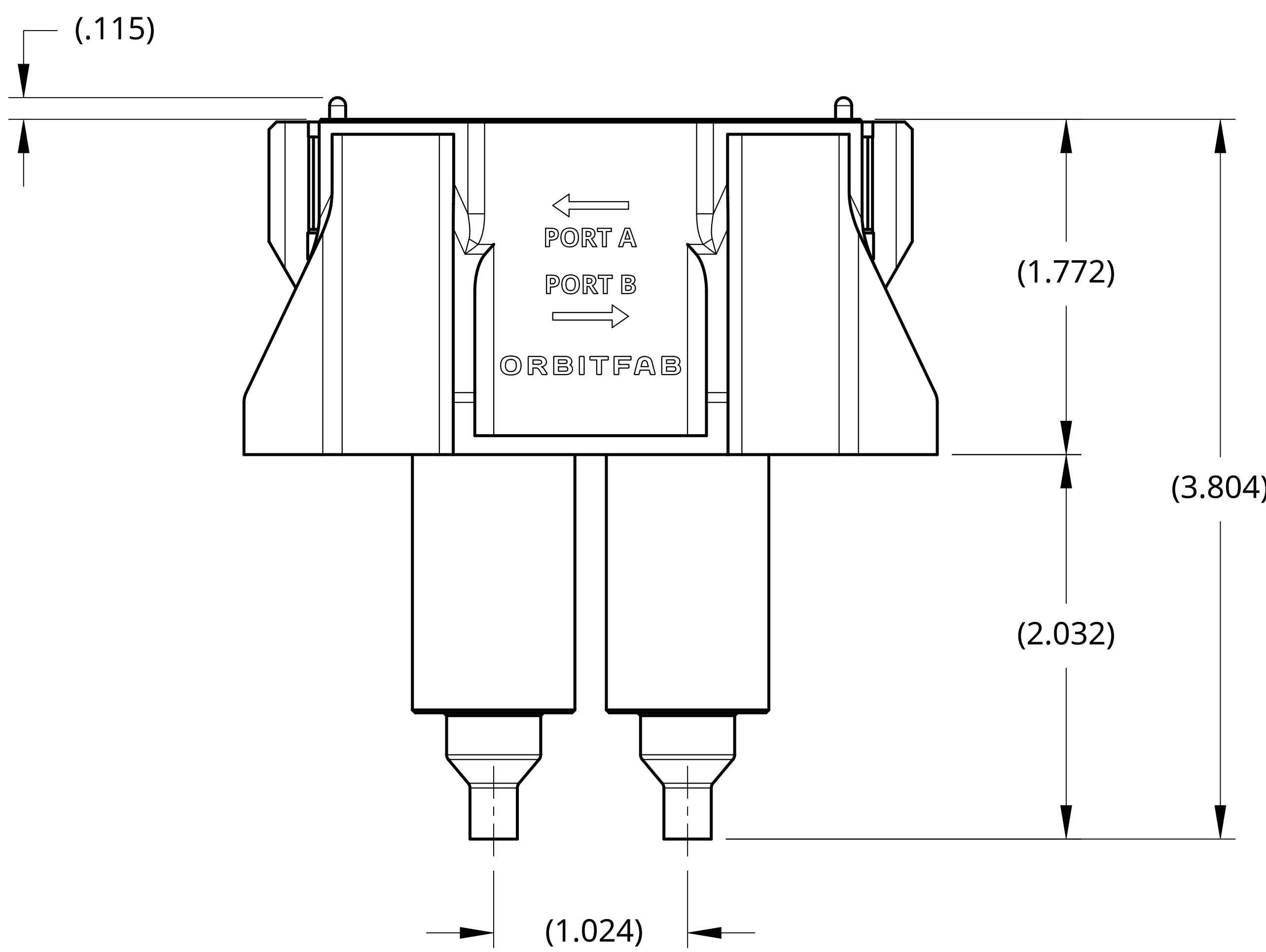
TITLE
RAFTI SV, CLASS 2
INTERFACE CONTROL DRAWING

SIZE	DWG NO.	REV.
B	ICD-00001	A

APPLICABILITY	REF WEIGHT	SCALE	SHEET
		3:2	1 of 5

REVISIONS
SEE SHEET 1





CONTAINS PROPRIETARY INFORMATION
USE OR DISCLOSURE OF DATA CONTAINED ON THIS PAGE IS SUBJECT TO THE RESTRICTIONS ON SHEET 1.

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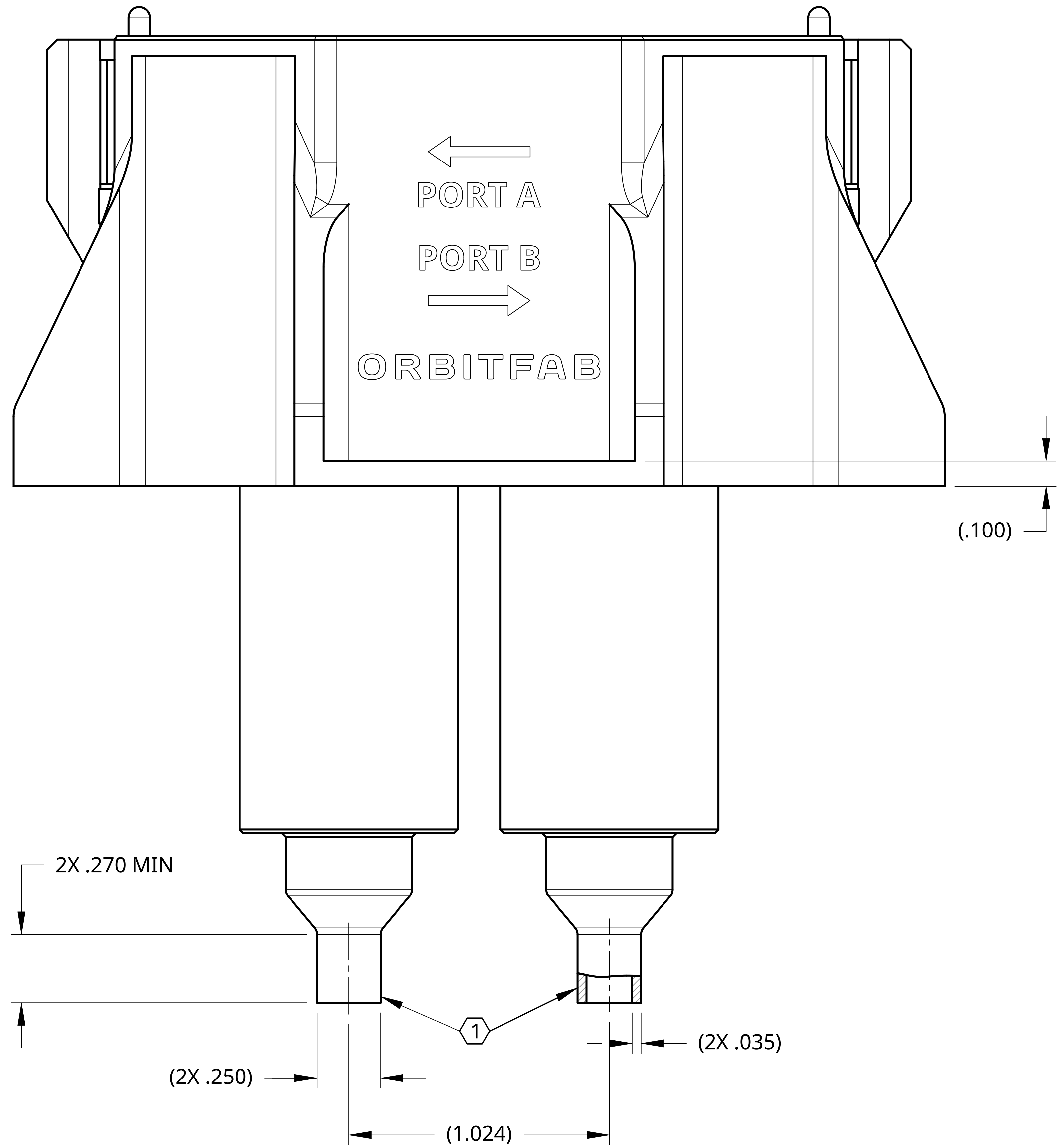
REVISIONS
SEE SHEET 1



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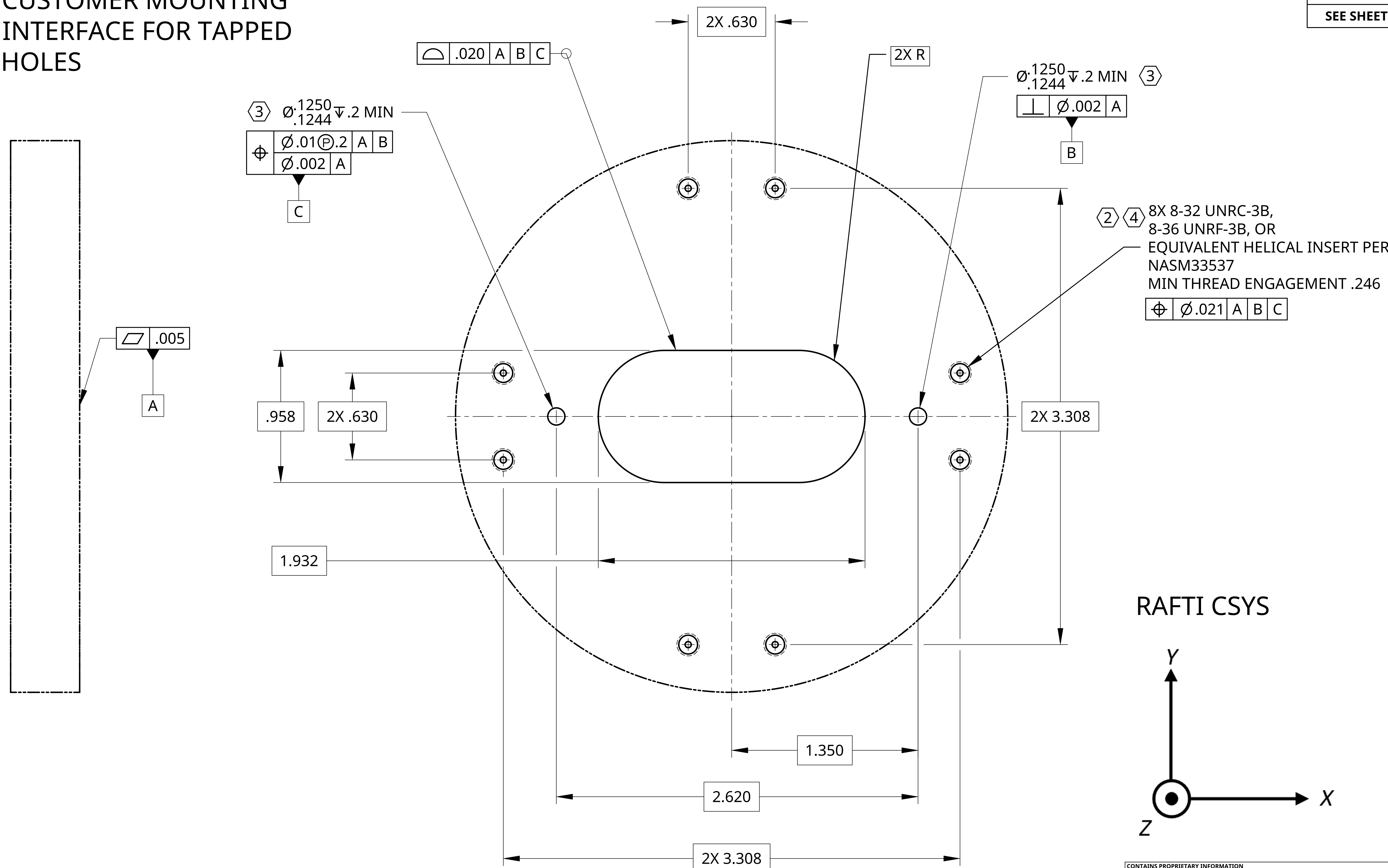
CUSTOMER MOUNTING INTERFACE FOR TAPPED HOLES

REVISIONS
SEE SHEET 1



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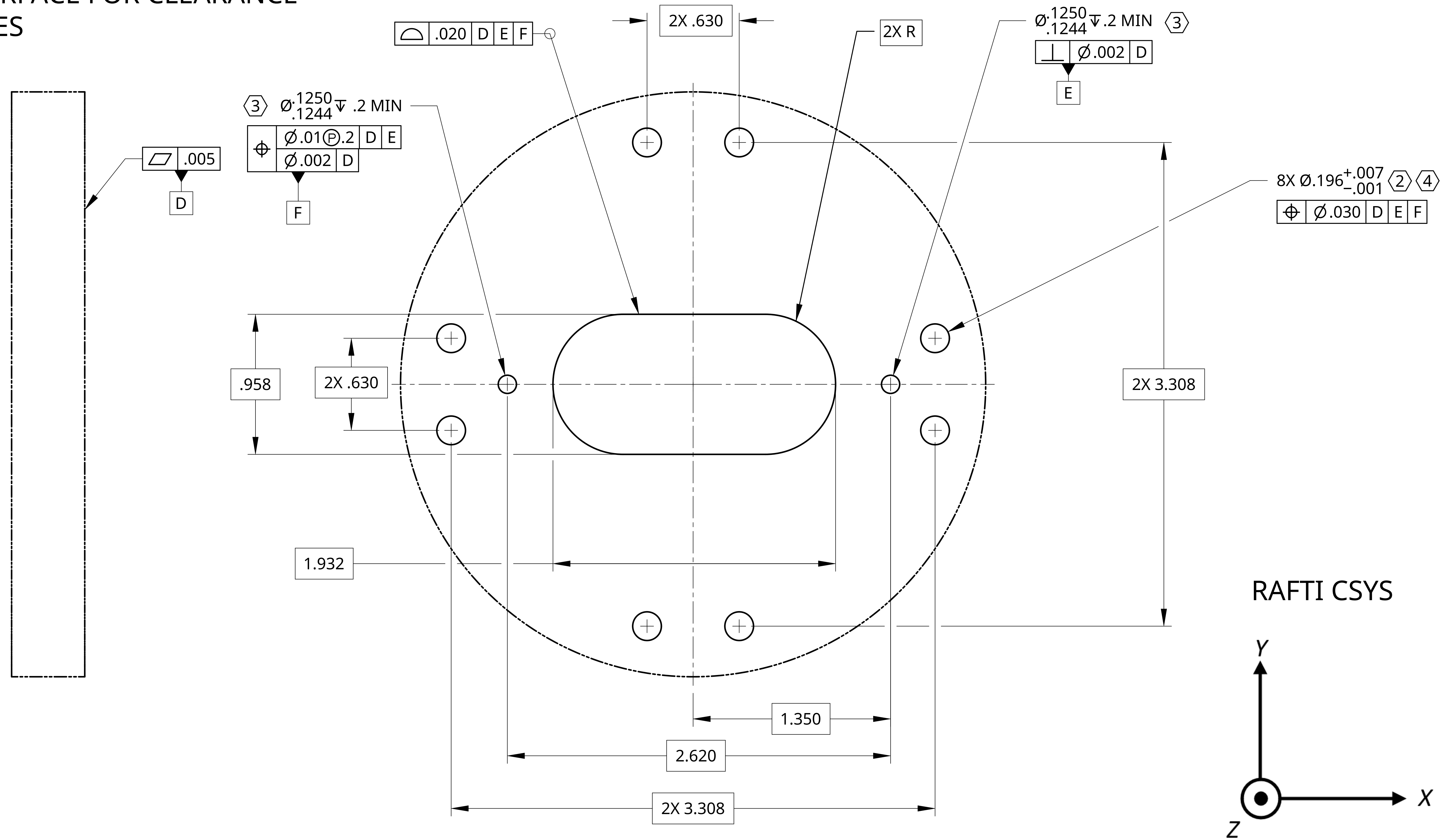
DWG NO. ICD-00001	SIZE B	SCALE 3:2	SHEET 4 of 5	REV. A

REVISIONS
SEE SHEET 1

CUSTOMER MOUNTING INTERFACE FOR CLEARANCE HOLES



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