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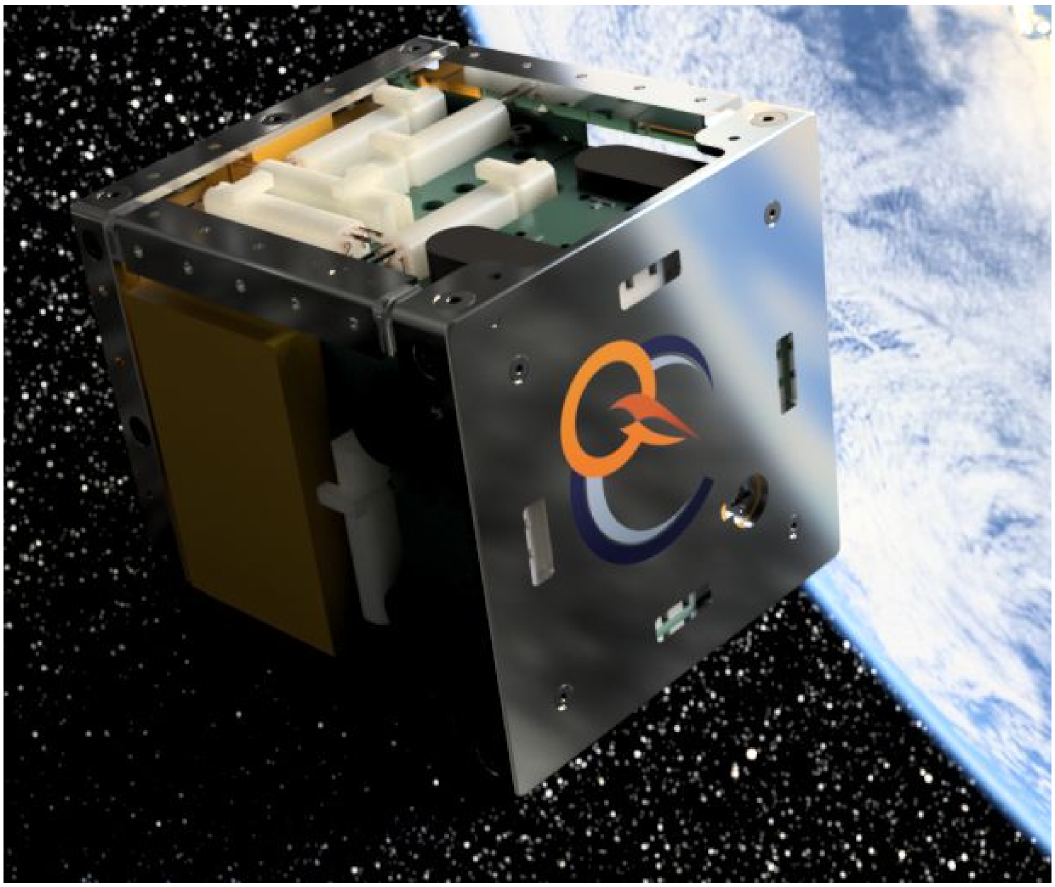
ConstantQ™
Propulsion
Technology

M1.4 Thruster Interfaces & User Manual

Document Version 1.1
by Miles Space, Inc.



Version History

Version Number	Description
1.1	Internal version.
1.0	Initial version.

Table of Contents

1 Introduction

This document describes the interfaces and operation of the M1.4 device. Interfaces include mounting, electrical cabling, sensor communication, valve control, and refueling.

The M1.4 device uses ConstantQ™ propulsion technology, converting electricity and water vapor into thrust. Thrust is derived from electrostatic acceleration of separated ions and electrons using a combination of classic collisionless flow and electrohydrodynamic (EHD) regimes, all working in a cycle determined by propellant temperature, input power, and device geometry. The operating cycle is self stabilizing and does not require real time active control once initiated, though altering temperature and/or power will alter delivered thrust. The process is self neutralizing and does not require a neutralizer device. Pressures throughout the system generate water vapor through sublimation, avoiding the need for water to boil and tolerating frozen ice as the propellant.

Temperature management is achieved with a high-density flat heater on the tank, a valve self-heating feature, and routing of electronics waste heat to minimize freezing of water vapor. Thrust is attained with a wide range of temperatures, including a tank full of frozen water ice.

Water vapor, not liquid water, reaches the thrust heads and is converted into plasma and thrust. Should liquid water get near the thrust heads, it would rapidly sublimate into vapor due to vacuum exposure.

The M1.4 device is useful for orbit changes, desaturating reaction wheels, coarse attitude control (such as RF antenna pointing), collision avoidance, course adjustments, and deorbiting. Due to variation in the operating cycle timing, impulse bits are not well suited for fine attitude control needed for camera pointing.

2 Conventions

This document adopts common USA formats for numbers. To express a numeric value, a period (".") separates the integer and fractional components. A comma (",") is used between groupings of 3 integer digits. For example, the numeric value of the fraction 100025/100 is written as "1,000.25" in this document. Common European formatting would write the value as "1.000,25" or "1 000,25".

Where possible, this document identifies the units of measurement for any number. The default unit for distance is millimeter, abbreviated "mm" in this document.

Bolt sizes are a mixture of metric and UNC threads.

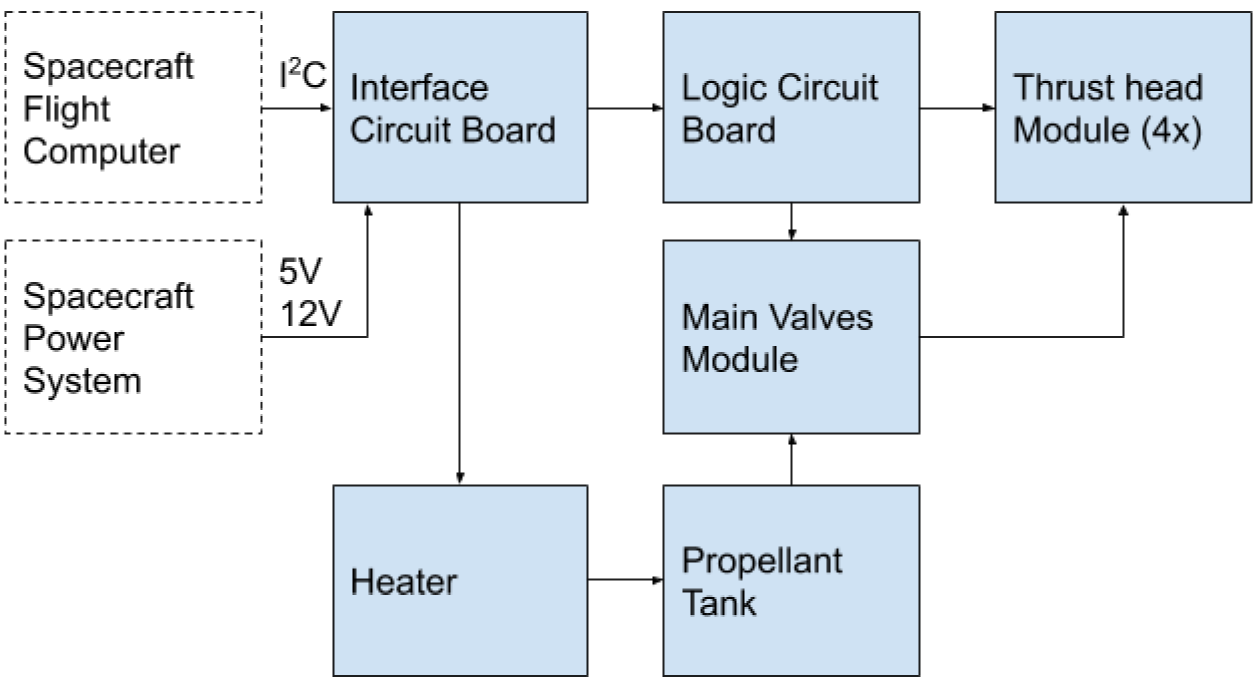
3 Overview and Identification of Components

The M1.4 device contains 4 thrust heads, 1 propellant tank with heater, 4 main valves, and associated sensors and power distribution components. Each thrust head contains high voltage generation electronics, a valve, a temperature sensor, and, of course, components to generate, separate, and accelerate plasma. Any combination of the 4 thrusters, including all 4, can be operated simultaneously.

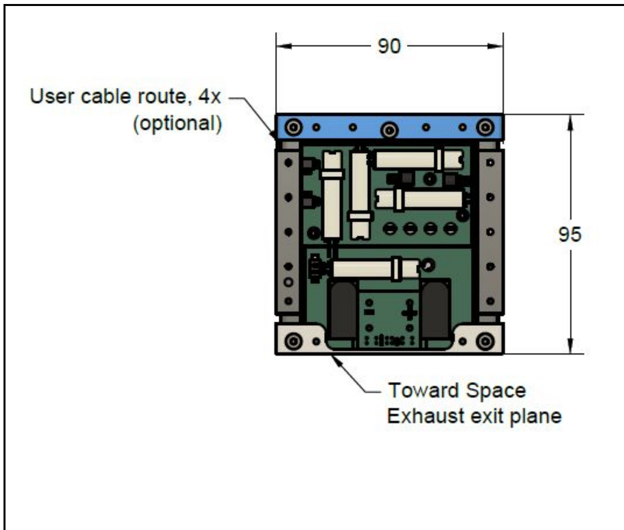
The propellant tank holds 250 grams of pure liquid water (H2O) and includes enough volume and design features to tolerate freezing the water into solid ice yet still generate thrust. The M1.4 device's propellant can be refilled by the end user.

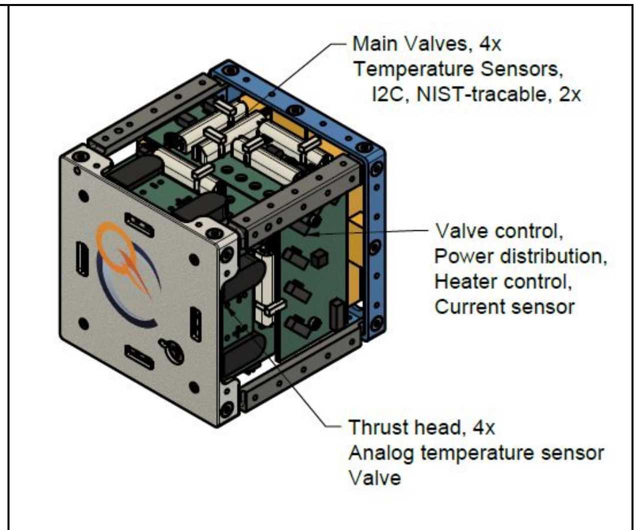
The M1.4 device does not contain an embedded computer, a mass flow sensor, or a mass flow controller. (Note: Accessories are planned for these features.)

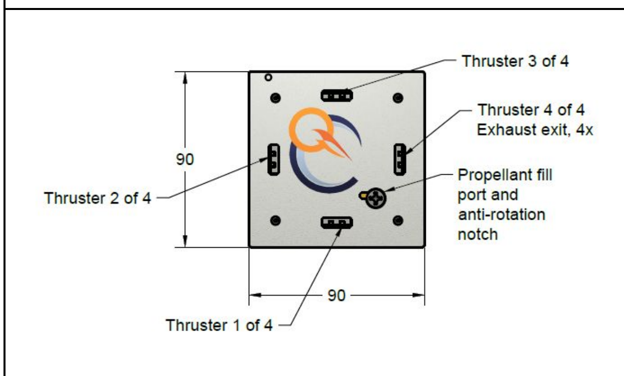
A functional block diagram of the principal components of a M1.4 is below:

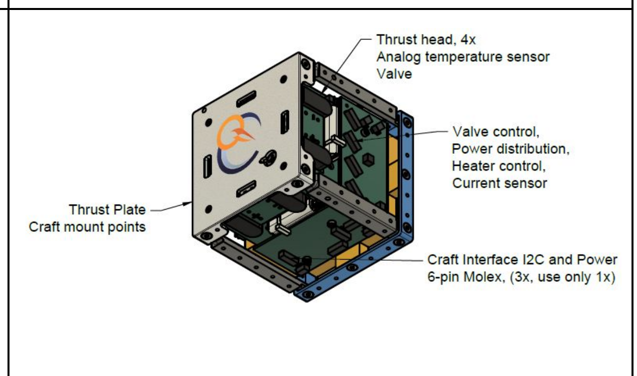


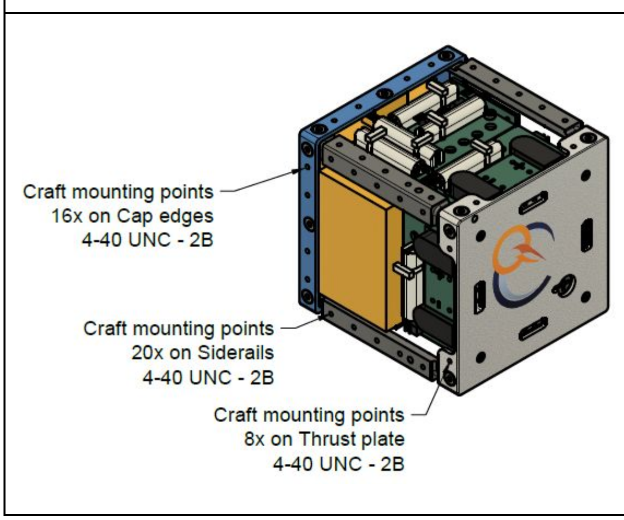
The following images show the device from many viewpoints, highlighting components and features. The images use false color to aid in component identification. Dimensions are millimeters (mm).

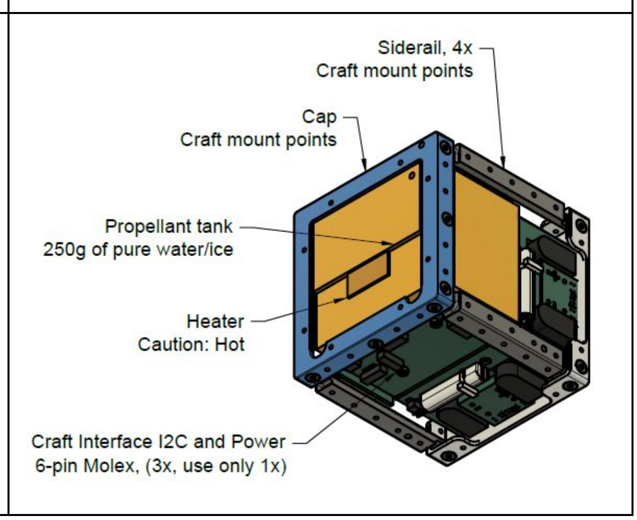

90
95
User cable route, 4x
(optional)
Toward Space
Exhaust exit plane


Main Valves, 4x
Temperature Sensors,
I2C, NIST-tracable, 2x
Valve control,
Power distribution,
Heater control,
Current sensor
Thrust head, 4x
Analog temperature sensor
Valve


Thruster 3 of 4
Thruster 4 of 4
Exhaust exit, 4x
90
Thruster 2 of 4
Propellant fill
port and
anti-rotation
notch
90
Thruster 1 of 4


Thrust head, 4x
Analog temperature sensor
Valve
Valve control,
Power distribution,
Heater control,
Current sensor
Thrust Plate
Craft mount points
Craft Interface I2C and Power
6-pin Molex, (3x, use only 1x)


Craft mounting points
16x on Cap edges
4-40 UNC - 2B
Craft mounting points
20x on Siderails
4-40 UNC - 2B
Craft mounting points
8x on Thrust plate
4-40 UNC - 2B


Siderail, 4x
Craft mount points
Cap
Craft mount points
Propellant tank
250g of pure water/ice
Heater
Caution: Hot
Craft Interface I2C and Power
6-pin Molex, (3x, use only 1x)

Each thrust head contains an analog temperature sensor (a LM235 device). This sensor is read using an analog-to-digital converter (an ADS7828 device on the I^2C bus). The sensor is placed so that flowing water vapor will change the temperature reading.

The main valves module contains two digital temperature sensors (STS35-DIS devices on the I^2C bus). These devices are placed so that flowing water vapor will change their temperature readings. These devices are high precision with NIST-traceable calibration.

The main valves module contains 4 valves, arranged in 2 sets of 2 valves, denoted the “Horizontal” and “Vertical” valves. In each set, both valves are actuated simultaneously.

All 12V power is routed through a Hall Effect-based current sensor (an ACS723 device). The sensor’s analog output is read by the analog-to-digital converter.

The M1.4 contains a digital I/O expander (a PCA3535A device on the I^2C bus). This device creates all of the on/off signals needed internally. The M1.4 is controlled by commanding this device to alter its output bit values.

The M1.4 contains an analog-to-digital converter (an ADS7828 device on the I^2C bus). This sensor reads the 5V input line (as a general system check), the current draw on the 12V line (to measure heater or thruster high voltage power consumption), and thrust head analog temperatures.

4 Operation Overview

Water vapor is passively generated via sublimation of liquid water or solid ice. Sublimation occurs when system pressure is less than the propellant vapor pressure, which varies with temperature.

The main valves provide a safety system that prevents propellant leakage during storage and launch.

When the water vapor reaches a thrust head, it is made into plasma via a high voltage spark, then accelerated by high voltage fields. The amount of thrust generated depends upon the propellant temperature and technically upon the voltage actually provided on the 12V input line. Given sufficient mass flow, the spark and acceleration cycle occurs on its own when high voltage is enabled.

Warning: When propellant flow drops too low (or technically becomes too high, which is far less likely), plasma cannot be formed and the high voltage system must be quickly shut down by the flight computer. It is strongly recommended that lab testing of the M1.4 include a current limited power supply on the 12V feed set to 0.2 Amps. Note that even with a current limited power supply, high voltage supplies must be commanded to shutdown within 250ms of no spark formation.

Valves are controlled in a two step process. First, the valve direction must be established. Second, the desired valve must be actuated by briefly connecting it to the valve direction power lines. The valve will open or close depending upon its physical configuration and the valve direction setting. The main valves open with opposite polarity than the thrust head valves.

Operation of thrusters is done by the craft's flight computer as it commands the M1.4's I^2C-based devices to:

- Heat the propellant tank
- Measure temperature with and without flowing propellant.
- Set valve actuation direction.
- Actuate valves.
- Enable/disable high voltage.

Thrust is achieved when the flight computer performs the following steps:

1. Instruct the craft EPS to deliver 5V and 12V power to the M1.4 device.
2. Record internal temperatures before propellant begins flowing.

   a. Record the temperature of the main valves by reading both I^2C-based main valve temperature sensors in high precision mode.
   b. Record the temperature of each thrust head that will be used by reading the I^2C-based analog-to-digital converter connected to the thrust head analog temperature sensor.
3. Open the main valves.
   a. Instruct the M1.4’s I^2C-based digital I/O expander to set the valve direction to 0 (zero).
   b. Instruct the M1.4’s digital I/O expander to actuate the Horizontal main valves.
   c. Wait 10ms.
   d. Instruct the M1.4’s digital I/O expander to stop actuating the Horizontal main valves.
   e. Instruct the M1.4’s digital I/O expander to actuate the Vertical main valves.
   f. Wait 10ms.
   g. Instruct the M1.4’s digital I/O expander to stop actuating the Vertical main valves.
4. Open a thrust head valve.
   a. Instruct the M1.4’s digital I/O expander to set the valve direction to 1 (one).
   b. Instruct the M1.4’s digital I/O expander to actuate the required thrust head valve.
   c. Wait 10ms.
   d. Instruct the M1.4’s digital I/O expander to stop actuating the thrust head valve.
   e. Repeat for each thrust head needed.
5. Wait for temperature change to indicate propellant flow. Use the recorded temperatures as comparison.
6. Energize high voltage, which creates thrust, stopping if too little propellant is available.
   a. Record the idle current on the 12V line by reading the I^2C-based analog-to-digital converter connected to the current sensor on the 12V line.
   b. Instruct the M1.4’s digital I/O expander to enable high voltage for the desired thrust head.
   c. Read the current on the 12V line, subtracting the idle current.
   d. Immediately stop power, either through craft EPS or by commanding the M1.4’s digital I/O expander, if the 12V current draw exceeds 0.2 Amps per thrust head. This indicates there is not enough propellant available.
   e. After 250ms of providing power to the high voltage system, stop power if current draw is not at least 0.05 Amps per thrust head. This indicates there is not enough propellant available.

Proper shutdown of a thrust head follows these steps, which ensure there is no trapped vapor that can become ice crystals:

1. Instruct the M1.4’s I^2C-based digital I/O expander to disable high voltage for the desired thrust head.

2. Wait 250ms. This allows internal capacitors to discharge before propellant flow is stopped.
3. Close the main valves.
    a. Instruct the M1.4’s digital I/O expander to set the valve direction to 1 (one).
    b. Instruct the M1.4’s digital I/O expander to actuate the Horizontal main valves.
    c. Wait 10ms.
    d. Instruct the M1.4’s digital I/O expander to stop actuating the Horizontal main valves.
    e. Instruct the M1.4’s digital I/O expander to actuate the Vertical main valves.
    f. Wait 10ms.
    g. Instruct the M1.4’s digital I/O expander to stop actuating the Vertical main valves.
4. Wait 1 second. This allows vapor between the main valves and the thrust head to vent to space.
5. Close the thrust head valve.
    a. Instruct the M1.4’s digital I/O expander to set the valve direction to 0 (zero).
    b. Instruct the M1.4’s digital I/O expander to actuate the required thrust head valve.
    c. Wait 10ms.
    d. Instruct the M1.4’s digital I/O expander to stop actuating the thrust head valve.

During normal operation, the temperature of a thrust head is expected to increase as waste heat of the high voltage system warms nearby material. Little to no effect is expected on the temperature readings at the main valves though due to the location of the high voltage components.

5 Envelope, Mass, Temperature, Power, Materials

The mechanical envelope of the M1.4 device is 90x90x95 mm. The mass of a M1.4 is:

M1.4 Dry Mass	953 grams
Propellant, pure H_2O water	250 grams
M1.4 Wet Mass	703 grams

M1.4 temperature ranges are:

Case	Min	Max
Storage, fueled	-40C / -40F	49C / 120F
Storage, unfueled	-40C / -40F	80C / 176F
Operation, fueled	-25C / -13F Valves heated to 4C / 39F	49C / 120F

Power draw varies by load scenario as shown below:

Case	5 Volt Power	12 Volt Power	Total Power
Storage or Inactive during Flight	0 Watts	0 Watts	0 Watts
Thermal preventative maintenance: Heater only, no active sensors.	0 Watts	Nominal: 11.5 Watts, 0.96 Amps, 12 Volt. Range: 10.6 - 12.0 Watts over 11.0 - 12.5 Volts.	Nominal: 11.5 Watts Range: 10.6 - 12.0 Watts
Standby: Sensors only, no heater.	Nominal: 0.18 Watts, 0.035 Amps, 5 Volt. Range: 0.16 to 0.19 Watts over 4.7 - 5.3 Volts.	Nominal: 0.1 Watts, 0.008 Amps, 12 Volt. Range: 0.08 - 0.11 Watts over 11.0 - 12.5 Volts.	Nominal: 0.27 Watts Range: 0.25 - 0.29 Watts
Setup or shutdown of thrust: Sensors and valve actuation, no heater, 10ms duration.	Nominal: 0.72 Watts, 0.144 Amps, 5 Volt. Range: 0.64 - 0.80 Watts over 4.7 - 5.3 Volts.	Nominal: 0.1 Watts, 0.008 Amps, 12 Volt. Range: 0.08 - 0.11 Watts over 11.0 - 12.5 Volts.	Nominal: 0.81 Watts Range: 0.73 - 0.90 Watts

Attitude control: Sensors, one thrust head, no heater.	Nominal: 0.18 Watts, 0.035 Amps, 5 Volt. Range: 0.16 to 0.19 Watts over 4.7 - 5.3 Volts.	Nominal: 1.90 Watts, 0.158 Amps, 12 Volt. Range: 1.59 - 2.06 Watts over 11.0 - 12.5 Volts.	Nominal: 2.07 Watts Range: 1.76 - 2.24 Watts
Propulsive maneuver: Sensors, all 4 thrust heads, no heater.	Nominal: 0.18 Watts, 0.035 Amps, 5 Volt. Range: 0.16 to 0.19 Watts over 4.7 - 5.3 Volts.	Nominal: 7.30 Watts, 0.608 Amps, 12 Volt. Range: 6.13 - 7.92 Watts over 11.0 - 12.5 Volts.	Nominal: 7.48 Watts Range: 6.30 - 8.10 Watts

For outgassing and launch safety purposes, the material quantities used in a fueled M1.4 device are:

Material	Mass (g)
Water	250.0
ABS-like SLA resin	171.8
Aluminum 6061-T6	129.7
Mixture of electronics and epoxy	104.0
PCB electronics with ceramic, plastic, and metal	73.1
FR4 circuit board with solder mask and copper traces	64.7
Epoxy	45.0
18-8 Stainless Steel	35.3
PTFE Teflon	35.1
Nylon plastic	14.0
Silicone, flexible	14.0
316 Stainless Steel	12.1
Loctite thread locker	4.0

6 Mechanical Interfaces

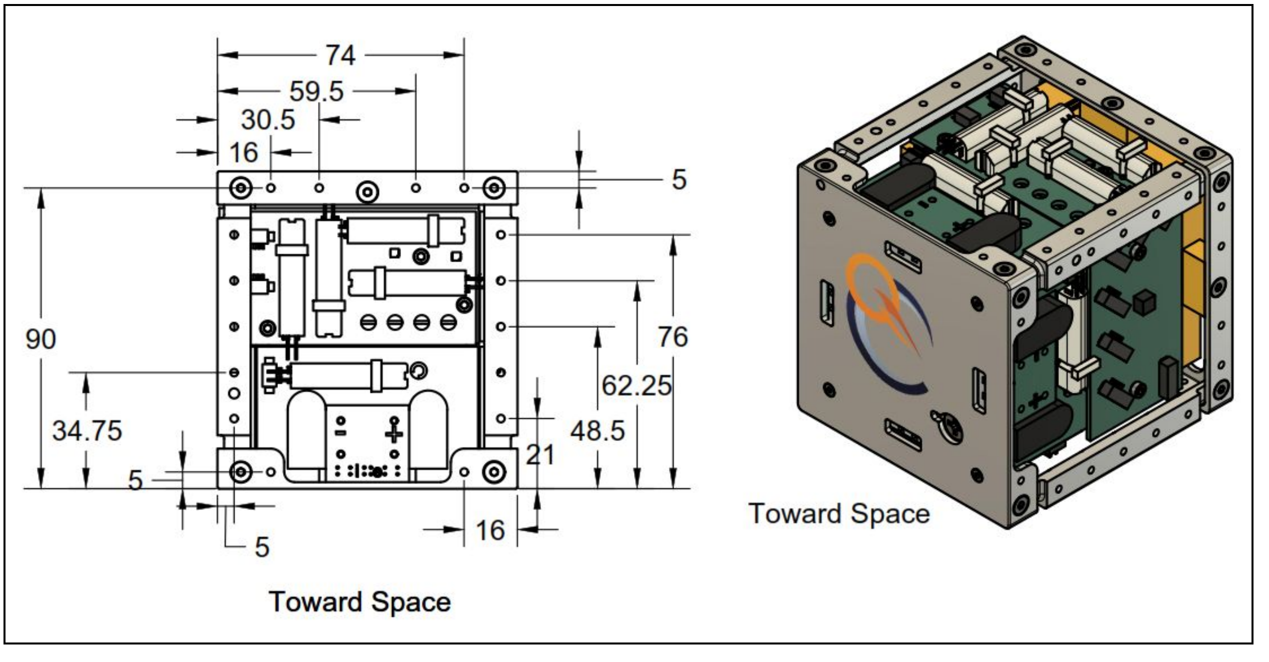
6.1 Mounting Points

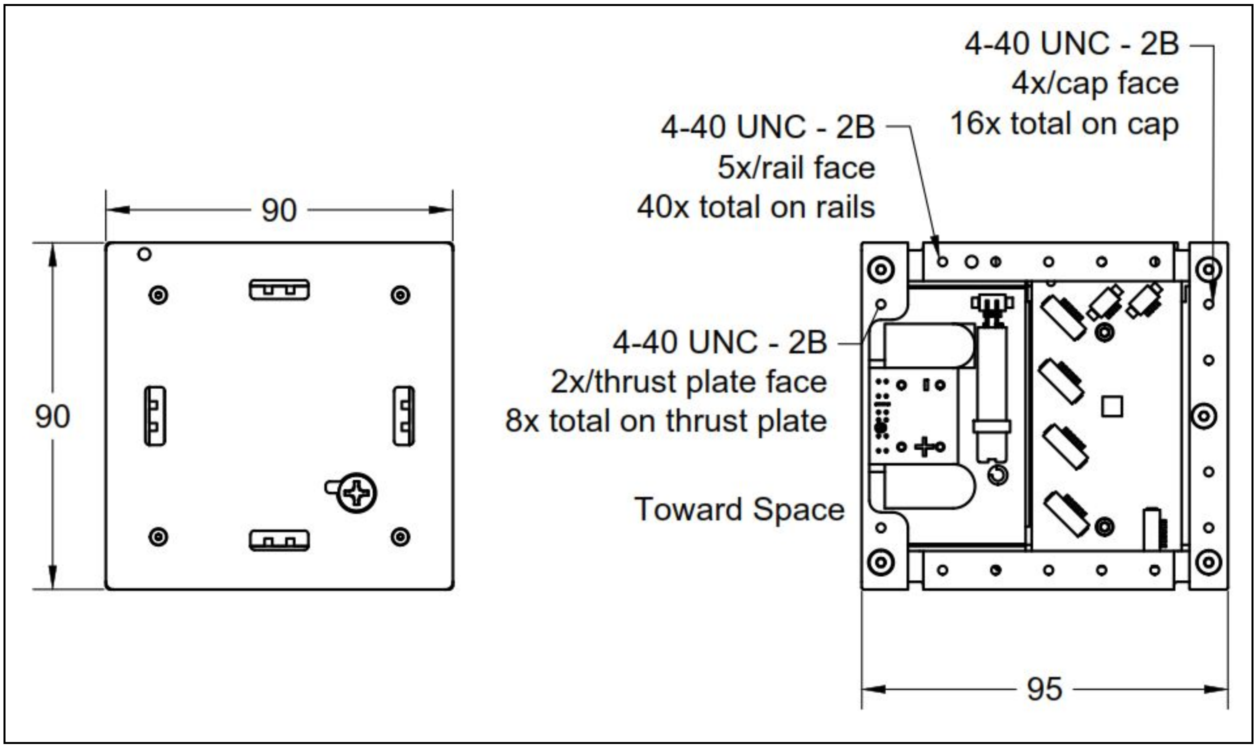
There are many attachment points available to mount the M1.4 device to a craft. The thrust plate, which is exposed to space, contains 8 threaded bolt holes on its interior faces. The cap, most distant from the thrust plate, contains 16 threaded bolt holes on its side faces. The side rails each contain 10 threaded bolt holes, 5 per face, for a total of 40 on the side rails. Attachment point geometry is identical on all 4 interior sides.

All craft mounting points are tapped with 4-40 UNC-2B threads into Aluminum alloy 6061-T6. Threadlocker should be used to secure attachment bolts.

It is recommended that craft attachments include holes from the thrust plate, the cap, and at least one side rail.

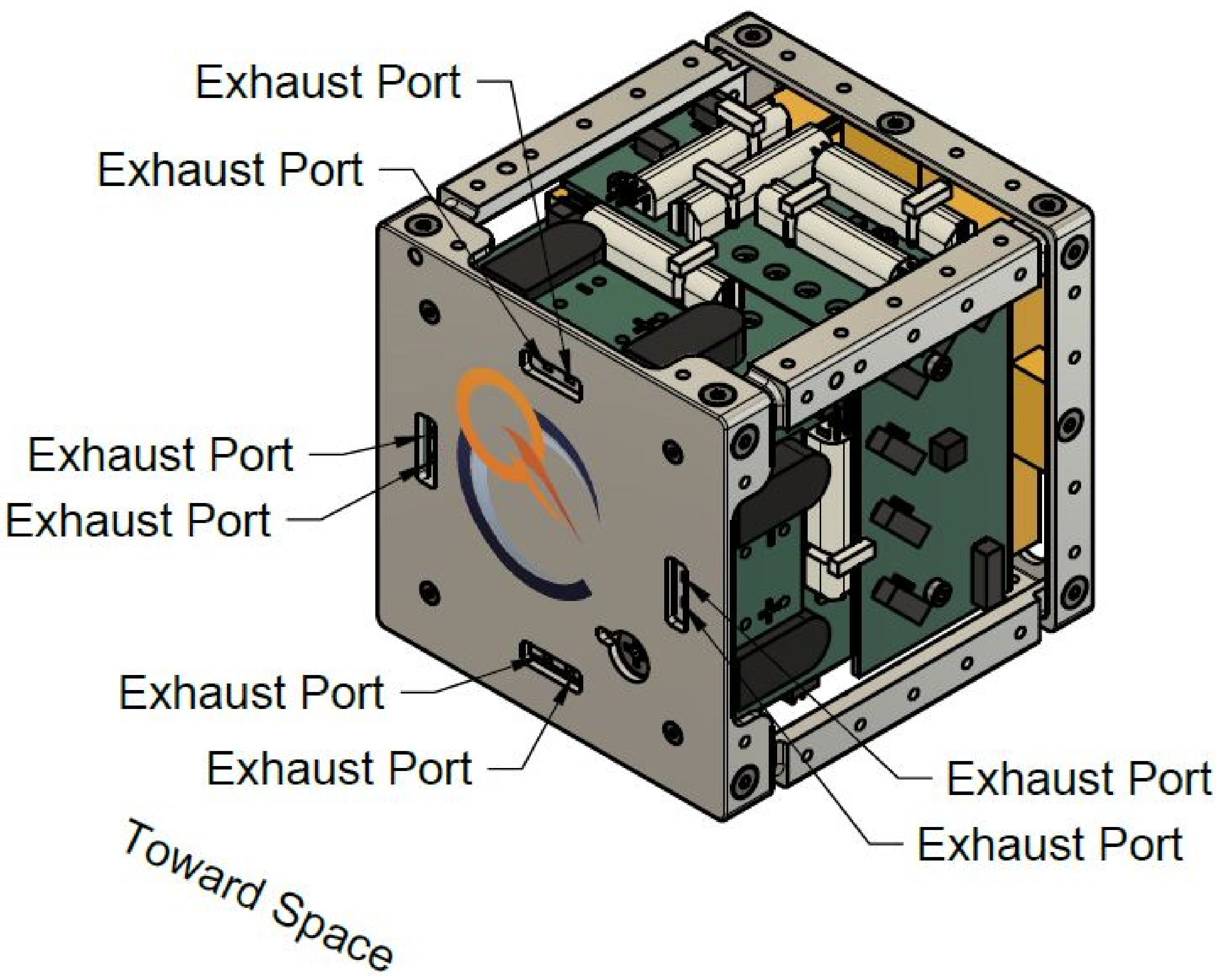
The locations of mounting holes are shown below:



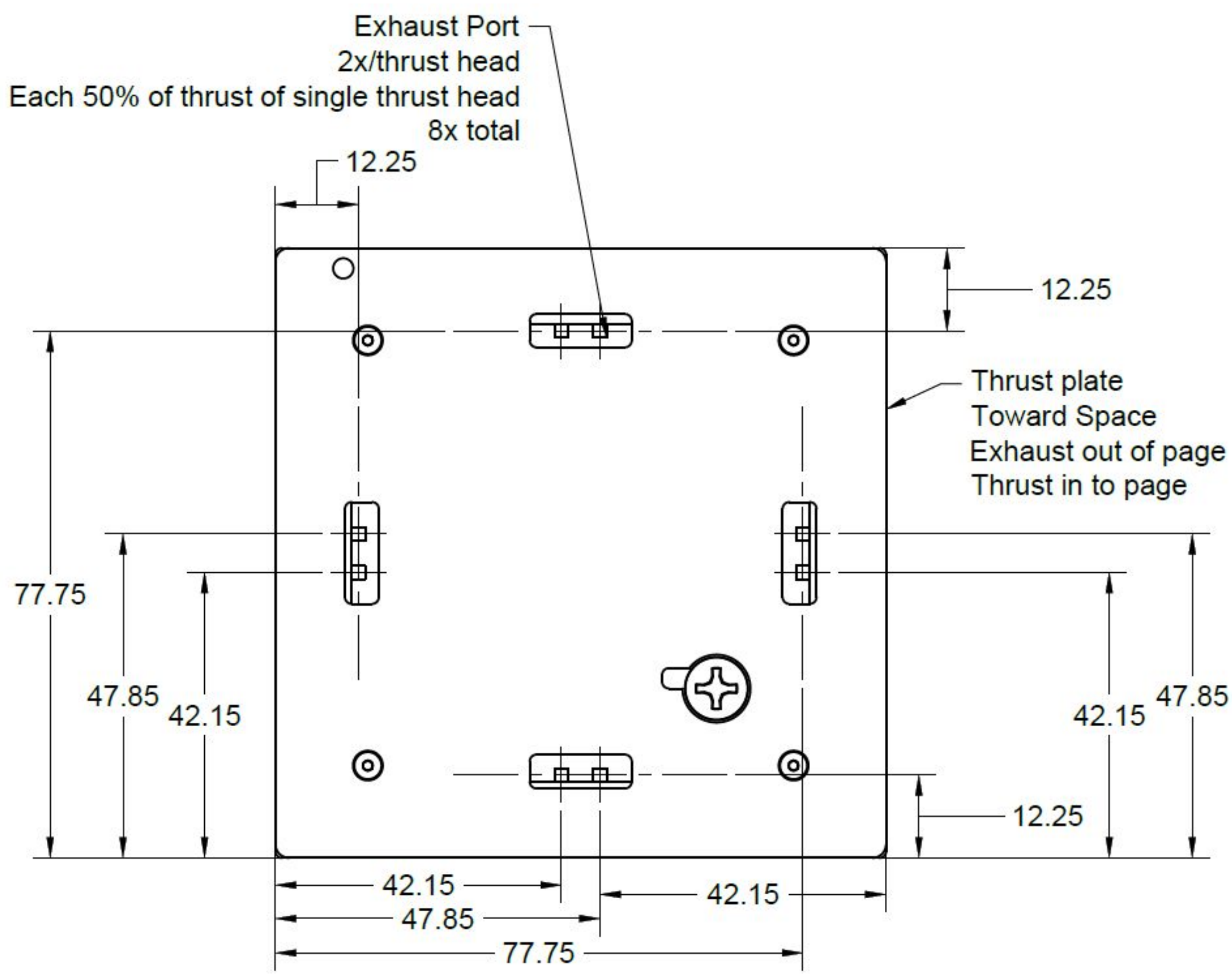

90
90
4-40 UNC - 2B
4x/cap face
16x total on cap
4-40 UNC - 2B
5x/rail face
40x total on rails
4-40 UNC - 2B
2x/thrust plate face
8x total on thrust plate
Toward Space
95

6.2 Thrust Vectors

The M1.4 device has 4 thrust heads. Each contains 2 exhaust ports. In all, there are 8 exhaust ports. Each exhaust port is responsible for 50% of the thrust of its thrust head. Both exhaust ports effectively operate simultaneously when a thrust head is activated. The exhaust follows the face normal of the thrust plate exposed to space. Thrust is directed into the M1.4 from the exhaust ports, occurring 5 mm into the device.



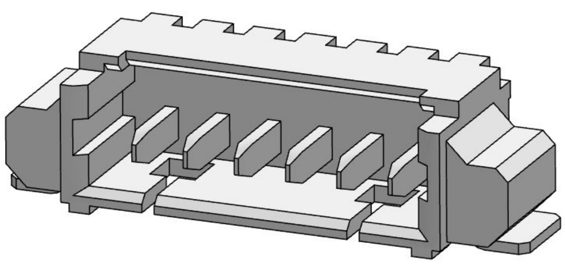
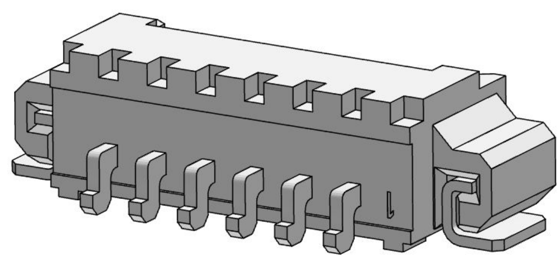
Looking at the thrust plate that faces space, the locations of each exhaust port are shown below, with all dimensions in millimeters. Exhaust comes out of the page and thrust in to the page.



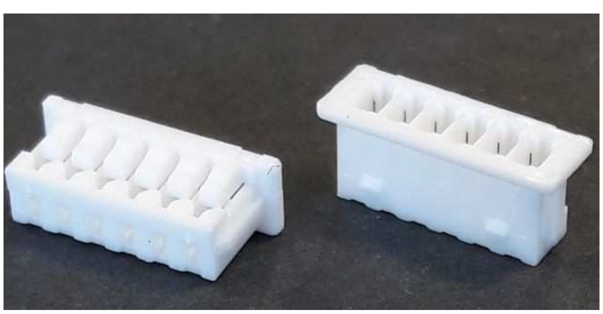
7 Electrical Interfaces

7.1 Connectors and Wire

Connections to the spacecraft are made using PicoBlade-style Molex connectors and 26 AWG wire. The Interface board contains 3x Molex 532617006 headers (https://www.molex.com/molex/products/part-detail/pcb_headers/0532617006). These are 6 circuits, 1.25mm pitch, single row, surface mount, gold plated, friction lock devices. All 3 headers are wired in parallel. One or more may be used simultaneously. The 3 headers differ only in physical orientation, permitting wire routing options to the craft designer.

	
Molex 532617006 front	Molex 532617006 rear. Note the location of Pin 1.

The spacecraft must connect a wire harness to one or more of the Interface board's 3x Molex 532617006 headers. The wire harness should terminate in a Molex 510210600 receptacle crimp housing. These devices house 6 wires, each terminated with a Molex 500798000 female crimp terminal. Alignment tabs ensure correct polarity during connection.

	
Molex 510210600 receptacle crimp housing	Molex 500798000 female crimp terminals

The wire harness should use 26 AWG wire. Molex makes pre-crimped wires that can be used, such as Molex part 797580014 which is a Pre-Crimped Lead PicoBlade Female-to-PicoBlade Female, Tin (Sn) Plating, 300.00mm Length, 26 AWG, Black wire.

⚠	**Warning:** The datasheet for the Molex 532617006 header states it can be used 10 times. Avoid excessive attachment and detachment of wire harnesses during testing and integration. Before launch, use epoxy to stake the wire harness(es) to the M1.4. Verify electrical connectivity after staking by reading registers from I^2C devices.

7.2 I^2C Connection

All commands and sensor readings needed to control the M1.4 device, including initiating thrust and valve actuation, are done using I^2C data packets to the individual devices on the M1.4 I^2C network. All devices use 5 Volt I^2C, with a typical range of 4.7-5.3 Volts being acceptable. If 3.3 Volts is needed, the craft must supply a level shifter. A bus speed of 100KHz is recommended as it is the most used speed during factory testing.

Every I^2C bus needs pullup resistors at some point on the bus. The M1.4 device does not contain any I^2C pullup resistors. The craft must incorporate pullup resistors into its connection.

In “I2C Bus Pullup Resistor Calculation” (https://www.ti.com/lit/an/slva689/slva689.pdf), Texas Instruments describes the calculation of typical resistor ranges. For a 5 Volt I2C bus with 400 pF capacitance in Standard Mode (100KHz), the pullup resistor range is 1.5K to 2.9K Ohms. If capacitance were down to 100 pF, the range is 1.5K to 11.8K Ohms. 2.2K Ohm resistors have been used successfully during factory testing. Cable length, bus speed, and use of level shifters will impact the pullup resistor choice.

7.3 Pinout and Power

Each of the 3x Molex 532617006 headers for craft connections have the same pinout, shown below:

Pin	Signal	Description	Current
1	5 Volt nominal 4.7 - 5.3 Volt range	Supply for digital electronics and valve actuation. Varies with sensor usage, such as the high speed of the temperature sensors.	35 mA (0.035 Amp) idle Plus 10-20 mA to actuate or heat a valve.
2	12 Volt nominal 11.0 - 12.5 Volt range	Supply for high voltage, heater, and analog temperature sensors on each thrust head. Can be disconnected until needed by the craft.	960 mA (0.96 Amp) during heater operation. 150 mA (0.150 Amp) per thrust head during thrust production (600 mA max with all thrusters operating).
3	Ground, 0 V	Ground for all power (1 of 2 redundant lines).	35 mA (0.035 Amp) idle. 1.0 A during heater operation. 150 mA (0.150 Amp) (plus sensor idle power) per thrust head during thrust production (635 mA max with all thrusters operating).
4	SDA, 5 V nominal +/- 0.3 V from 5 V line range	I^2C serial data line	5 mA or less
5	SCL, 5 V nominal +/- 0.3 V from 5 V line range	I^2C serial clock line	5 mA or less
6	Ground, 0 V	Ground for all power (2 of 2 redundant lines).	See Pin #3 Ground.

Pins 3 and 6 are redundant Ground lines. It is recommended that the craft connect to both pins 3 and 6 as doing so reduces cable heating that would change ground potential of the M1.4.

8 Software Interfaces

8.1 I²C Notes

Thrust is generated by enabling high voltage while propellant is flowing (which is known by monitoring temperature changes after opening valves), then monitoring current consumption, shutting down if current consumption goes too low or too high. This process requires coordination of digital I/O to actuate valves, reading digital temperatures, reading analog temperatures, and reading an analog current sensor - all using I²C components.

I²C devices are addressed with a 7 bit address followed by a read/write flag in the least significant bit. Some of the bits are fixed by the component manufacturer, others are varied during circuit design. In a typical datasheet, the address is presented as:

7.4.1 Address Byte

The address byte is the first byte received following the Start condition from the master device (see Figure 15). The first five bits (MSBs) of the slave address are factory pre-set to 10010. The next two bits of the address byte are the device select bits, A1 and A0. Input pins (A1-A0) on the ADS7828 determine these two bits of the device address for a particular ADS7828. A maximum of four devices with the same pre-set code can therefore be connected on the same bus at one time.

Figure 15. Address Byte

MSB	6	5	4	3	2	1	LSB
1	0	0	1	0	A1	A0	R/$\overline{W}$

The A1 and A0 address inputs can be connected to V_{DD} or digital ground. The device address is set by the state of these pins upon power-up.

The last bit of the address byte (R/$\overline{W}$) defines the operation to be performed. When set to a 1, a read operation is selected; when set to a 0, a write operation is selected. Following the Start condition, the ADS7828 monitors the SDA bus, checking the device type identifier being transmitted. Upon receiving the 10010 code, the appropriate device select bits, and the R/$\overline{W}$ bit, the slave device outputs an acknowledge signal on the SDA line.

Excerpt from ADS7828 datasheet.

Some I²C interface software accepts 8 bit addresses, spanning bits 7-0, and alters the LSB read/write flag. Some software expects 7 bit addresses, spanning bits 6-0, then appends a read/write flag bit. It is important to know the expectation of your I²C interface software. Addresses in this document are presented as 8 bits in hexadecimal notation, with a 0 for the LSB read/write flag.

It is recommended to operate the M1.4 I²C bus at 100KHz. This is the speed used during factory testing. Bear in mind that I²C is a serial bus, often without checksums, and some bad bits do occur. More likely are entirely empty response blocks. Determine the error behavior of your interface software, which may include returning registers with all bits set to 0 or 1, and include error checks and retry logic.

8.2 Digital Temperature Sensors

A M1.4 device contains 2 digital temperature sensors. These are STS35-DIS devices by Sensiron. The STS35-DIS devices are high accuracy temperature sensors with NIST traceable calibration done by the component manufacturer. All of the device's operating modes are supported. It is recommended to use the High Repeatability mode without clock stretching.

Temperature Sensor #1 is at I^2C address 0x4A (STS35-DIS address with ADDR pin=Low).
Temperature Sensor #2 is at address 0x4B (STS35-DIS address with ADDR pin=High).

Temperature Sensor #1 measures the temperature nearest the outlet of the tank into the main valves. This temperature will change when the tank is heated due to heated vapor. This temperature will change when the valves open allowing vapor to move and transport heat.

Temperature Sensor #2 measures the temperature between the first and second main valve. This temperature will change slowly when the tank is heated as no vapor reaches this location when valves are closed. When valves open, this temperature will change as flowing vapor transports heat.

Changes in temperature that are correlated with valve actuation and not heater actuation indicate propellant is flowing.

The STS35-DIS datasheet can be found online at:
https://www.sensirion.com/en/environmental-sensors/temperature-sensors/
Or directly at:
https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/3_Temperature_Sensors/Datasheets/Sensirion_Temperature_Sensors_STS3x_Datasheet.pdf

8.3 Analog Digital Converter

A M1.4 device contains 1 analog to digital converter (ADC). This is an ADS7828E/2K5 device by Texas Instruments (Mouser part number 595-ADS7828E/2K5). The device is configured for 8 single ended, 12 bit channels with a 5 volt reference. The device's internal reference defaults to Off at startup and should not be used with the 5 Volt-based signals being sensed.

All of the device's measurement modes are supported, though it's High-Speed (HS) mode requires clock stretching which can complicate interface programming, especially error checks and timeouts.

The ADC is at I^2C address 0x90 (ADS7828 address with A0 pin=Low and A1 pin=Low).

Device input CH0 (device pin 1) senses the 5 Volt input. This is used as a health check as it should read near the high end of the sensing range.

Device input CH1 (device pin 2) senses the temperature of Thrust Head 1's LM235 analog temperature sensor. Refer to section "3 Overview and Identification of Components" for the placement of Thrust Head 1. Refer to section "8.4 Analog Temperature Sensors" for more information on the sensors and their placement. It is recommended to heavily denoise this and the other analog temperature sensor inputs by using a moving average and discarding extreme, brief outliers so as not to falsely move the average.

Device input CH2 (device pin 3) senses the temperature of Thrust Head 2's LM235 analog temperature sensor.

Device input CH3 (device pin 4) senses the temperature of Thrust Head 3's LM235 analog temperature sensor.

Device input CH4 (device pin 5) senses the temperature of Thrust Head 4's LM235 analog temperature sensor.

Device input CH5 (device pin 6) senses the current flowing in the 12 Volt supply via an ACS723 current sensor. The voltage reading is proportional to the amount of current flowing through the high-side of the 12 V input that supplies the heater, thrust head high voltage systems, and thrust head analog temperature sensors. 12 V current should never be zero due to the small draw of the analog temperature sensors. It should increase predictably and stably as each thrust head comes online. Stability is the key measurement of the current reading. It is recommended to monitor the moving average and variance of a window of 0.1 seconds of current readings.

Device inputs CH6 and CH7 (device pins 7 and 8) are unconnected. At the M1.4 factory, these are used experimentally to check for aberrant EM emissions during thruster operation and as health checks since they should read near the low end of the sensing range.

The ADS7828E/2K5 datasheet can be found online at:
https://www.ti.com/lit/ds/symlink/ads7828.pdf

8.4 Analog Temperature Sensors

Each of the M1.4's 4 thrust heads contains a temperature sensor. These are LM235Z devices by STMicroelectronics (Mouser part number 511-LM235Z) in a TO-92 package. Each LM235Z output voltage is sensed by the M1.4's analog to digital converter. See section "8.3 Analog Digital Converter" for more information.

A LM235Z device operates as a 2-terminal Zener diode with a breakdown voltage that is directly proportional to the absolute temperature at 10 mV/K. For example, at an absolute temperature of 293 Kelvin, the device has a breakdown voltage of 2.930 Volts and 2.930 volts would be sensed by the ADC. At the manufacturer, the device is calibrated at 25C and has an error of less than 1C over a 100C temperature range. Output is linear over all temperatures.

The device is operated at 2 mA. Some self heating is inevitable. Monitor the temperature during idle periods with closed valves to understand the baseline response. It is important to distinguish temperature change due to self heating from change due to propellant flow. Interface software may elect to wait for a steady state response or work from a projected temperature/time curve in a 1-5 minute window.

Each LM235Z device is arranged near its thrust head's valve inlet. The device will change temperature slowly when the thrust head valve is closed and the main valves are open as propellant diffuses through the distribution tubes. The device will change temperature faster when the thrust head valve opens and the flowing propellant changes the temperature of the surrounding material. A change in temperature correlated with valve actuation is the indication of propellant availability.

On the emulator circuit board, each LM235Z is placed near a resistor that heats when the emulated high voltage system is activated. Temperature on the emulator should rise with operation duration.

The LM235Z datasheet can be found online at:
https://www.mouser.com/datasheet/2/389/lm135-1849523.pdf

8.5 Current Sensing

A M1.4 device contains 1 current sensor. This is an ACS723LLCTR-05AB-T device by Allegra MicroSystems (DigiKey part number 620-1641-1-ND). The current sensor uses the Hall Effect to measure current and includes internal temperature compensation. The device is configured for low-noise 20KHz bandwidth operation.

The current sensor's reading is read by the ADC on ADC input CH5.

The current sensor has a nominal sensitivity of 400 mV/Amp. At 0 current, output is 2.5 Volts (5 V VCC * 0.5). When viewing the datasheet, be certain to view the section pertaining to the 05AB device variant because sensitivity varies with model number.

The current sensor is tied to the 12V input to the M1.4 and measures all 12V power consumption. This includes the 4 temperature sensors (one per thrust head), the heater, and each thruster's high voltage system. The temperature sensors draw 8 mA total (3.2 mV response), whereas the heater draws nearly 1Amp (400 mV response) and thrust heads can draw up to 150 mA each (60 mV response, 240 mV response for all thrust heads active at once).

The ACS723LLCTR-05AB-T datasheet can be found online at:
https://www.allegromicro.com/~/media/Files/Datasheets/ACS723-Datasheet.ashx

8.6 Digital Outputs and Valve Directions

A M1.4 device contains 1 digital I/O expander. This is a PCA9535APW,118 device by NXP Semiconductors (Mouser part number 771-PCA9535APW,118). The device provides 16 digital outputs under I^2C control.

The digital I/O expander is at I^2C address 0x40 (PCA9535 address with A0 pin=Low, A1 pin=Low, and A2 pin=Low).

After powerup, the I/O expander must be configured for use. The device boots with all pins set to high-impedance inputs and all output registers set to 1/High, even though all pins are inputs. All pins are connected to pull-down resistors on their external circuits, so leaving the pins as high-impedance inputs will have no effect. Therefore, it is not timing critical to configure the device. Merely, it must be configured before usage.

Before usage, the device output register must be cleared to all 0/Low values then all pins configured as outputs. The steps are:

1. Set all outputs to 0/Low, so when set to be an output instead of an input, nothing will be activated.
    a. Write the value 0x00 to output port 0 register 0x02.
    b. Write the value 0x00 to output port 1 register 0x03.
2. Set polarity to normal, minimizing chances of misreading documentation.
    a. Write the value 0x00 to polarity inversion port 0 register 0x04.
    b. Write the value 0x00 to polarity inversion port 0 register 0x05.

3. Set all pins as outputs.
    a. Write the value 0x00 to configuration port 0 register 0x06.
    b. Write the value 0x00 to configuration port 1 register 0x07.

The output port registers 0x02 and 0x03 should then be manipulated to accomplish control of the M1.4.

From the PCA9535 datasheet, the outputs are identified with identifiers such as “O0.7”, indicating bit 7 of output port 0:

6.2.3 Output port register pair (02h, 03h)

The Output port registers (registers 2 and 3) show the outgoing logic levels of the pins defined as outputs by the Configuration register. Bit values in these registers have no effect on pins defined as inputs. In turn, reads from these registers reflect the value that was written to these registers, **not** the actual pin value. A register pair write is described in Section 7.1 and a register pair read is described in Section 7.2.

Table 7. Output port 0 register (address 02h)

Bit	7	6	5	4	3	2	1	0
Symbol	O0.7	O0.6	O0.5	O0.4	O0.3	O0.2	O0.1	O0.0
Default	1	1	1	1	1	1	1	1

Table 8. Output port 1 register (address 03h)

Bit	7	6	5	4	3	2	1	0
Symbol	O1.7	O1.6	O1.5	O1.4	O1.3	O1.2	O1.1	O1.0
Default	1	1	1	1	1	1	1	1

The connections of the PCA9535 to the M1.4 features are:

PCA9535 Output Name	PCA9535 Output Port	PCA9535 Output Bit	M1.4 Signal Name	Description
O0.0	0	0	ValveDir	Valve direction, sets voltage polarity for actuated valves, if any.
O0.1	0	1	SVHoriz	“Horizontal” main valves actuation, actuate when 1. Open when ValveDir=0, Close when ValveDir=1.

O0.2	0	2	SVVert	"Vertical" main valves actuation, actuate when 1. Open when ValveDir=0, Close when ValveDir=1.
O0.3	0	3	HeatCtl	Heater, enable when 1.
O0.4	0	4	n/a	n/a
O0.5	0	5	n/a	n/a
O0.6	0	6	n/a	n/a
O0.7	0	7	n/a	n/a
O1.0	1	0	T1Valve	Thrust head 1 valve actuation, actuate when 1. Open when ValveDir=1, Close when ValveDir=0.
O1.1	1	1	T1HV	Thrust head 1 high voltage, enable when 1.
O1.2	1	2	T2Valve	Thrust head 2 valve actuation, actuate when 1. Open when ValveDir=1, Close when ValveDir=0.
O1.3	1	3	T2HV	Thrust head 2 high voltage, enable when 1.
O1.4	1	4	T3Valve	Thrust head 3 valve actuation, actuate when 1. Open when ValveDir=1, Close when ValveDir=0.
O1.5	1	5	T3HV	Thrust head 3 high voltage, enable when 1.
O1.6	1	6	T4Valve	Thrust head 4 valve actuation, actuate when 1. Open when ValveDir=1, Close when ValveDir=0.
O1.7	1	7	T4HV	Thrust head 4 high voltage, enable when 1.

To set a valve, first set ValveDir then briefly actuate the valve. With all valve actuation outputs set to 0, no valve will change direction when ValveDir is changed. Do not set ValveDir and enable valves in the same operation. Rather, set ValveDir then wait a few milliseconds before enabling valves (i.e. opening or closing valves depending upon their relationship to ValveDir).

The PCA9535 datasheet can be found online at:
https://www.mouser.com/datasheet/2/302/PCA9535A-1127607.pdf

9 Heater Control

The tank heater is enabled by setting all thruster high voltage outputs to 0 then setting the HeatCtl digital output to 1. See section "8.6 Digital Outputs and Valve Directions" for details on setting digital outputs.

If at all possible, proactively run the heater. It can take some time for heat to spread, so factor in a long lag into any PID temperature control loop.

While the heater is operating, monitor temperatures. With all valves closed, it is expected that thrust head temperatures will rise more slowly than the main valve temperature sensors. Main valve temperature sensor #1 is the most important to watch as it most closely measures propellant vapor temperature. See section "8.2 Digital Temperature Sensors" for details on the main valve temperature sensors. See section "8.4 Analog Temperature Sensors" for details on the thrust head temperature sensors.

⚠	**Warning:** The heater and thruster high voltage should not be operated simultaneously. Valves can be actuated while the heater is enabled.

10 Valve Operation

10.1 Valve Actuation

Valves are actuated by setting the ValveDir digital output then pulsing the valve's digital output to 1 for 10-30 ms. The value to set ValveDir depends upon which valve is being opened or closed.

The main valves are opened when actuated while the digital I/O signal ValveDir is 0, closed when ValveDir is 1. The 4 main valves are arranged in 2 groups of 2, denoted the “Horizontal” and “Vertical” main valves. All 4 main valves must be open for propellant to reach the thrust heads, where the thrust head’s individual valve must also be open to produce thrust.

Each thruster valve is opened when actuated while ValveDir is 1, closed when ValveDir is 0.

10.2 Maximizing Mission Lifetime by Minimizing Leakage

Every type of valve leaks a little, even those on the M1.4. The leakage rate depends on pressure differences, getting larger with increased pressure differences on each side of the valve. After achieving orbit, leakage is minimized by venting the propellant tank. Once in orbit, pressure difference is 1 atmosphere or less, with atmospheric gases trapped during fueling slowly leaking into vacuum. Opening all valves will vent this comparatively high pressure gas. Once closed, the system pressure will be the vapor pressure of the propellant, 1 to 30 Torr typically, greatly reducing leakage rate and extending mission lifespan.

For comparison, a 760 Torr (1 atmosphere) tank in orbit will leak 10% of its contents in 3 months. A 30 Torr tank in orbit, which is achieved by venting the stored atmosphere, will leak 10% in 5 years. A 760 Torr (1 atmosphere) tank on the ground does not have a constant pressure differential and has even lower leakage than the 30 Torr tank in orbit.

Note: Leakage data is preliminary. It is based upon valve data from The Lee Company. A conservative scenario is presented that neglects the beneficial cascade effect of 5 valves in series that must be passed for vapor to leak.

10.3 Valve Heating

Valves must be at least 4C in order to operate. The temperature sensors will give a good indication of conditions. However, in borderline cases or in the event a frozen valve is suspected, the valve can be heated.

A valve draws 550 mW of power when energized. Normally, this is applied for 10 ms to change the valve position. When applied for a longer duration, either by changing the valve position or by maintaining an existing position, the valve will heat up. In air at 22C, the valve will reach 74C within a few seconds. A cold valve should be heated by energizing it so as to maintain valve position, then deenergized briefly to allow heat to spread to any trapped water or ice, then the process repeated several times before energizing the valve to change direction.

Valve heating is done by setting a valve's output bit to 1 without altering the valve direction, so as to leave the valve in its current position. When heated, set the valve's output bit to 0.

Don't actuate a valve for more than 2 seconds continuously or more than a 50% duty cycle over a 4 second window. This rule prevents excessive heating and gives time for the valve's heat to spread to nearby temperature sensors.

11 Enable High-Voltage To Create Thrust

Thrust is generated by enabling high voltage while propellant is flowing (which is known by monitoring temperature changes after opening valves), then monitoring current consumption, shutting down if current consumption goes too low or too high.

When the water vapor reaches a thrust head, it is made into plasma via a high voltage spark, then accelerated by high voltage fields. The amount of thrust generated depends upon the propellant temperature and technically upon the voltage actually provided on the 12V input line. Given sufficient mass flow, the spark and acceleration cycle occurs on its own when high voltage is enabled.

When propellant flow drops too low (or technically becomes too high, which is far less likely), plasma cannot be formed and the high voltage system must be quickly shut down by the flight computer. When high voltage is enabled yet current does not indicate a spark is being formed, the high voltage system must be disabled within 250 ms of no spark formation. Therefore, it recommended that the flight software distinguish the state of "high voltage enabled" from a state of "ignition", relying upon current readings not just the high voltage enable flags to register state.

Immediately stop power, either through craft EPS or by commanding the M1.4's digital I/O expander, if the 12V current draw exceeds 0.2 Amps per thrust head. This indicates there is not enough propellant available.

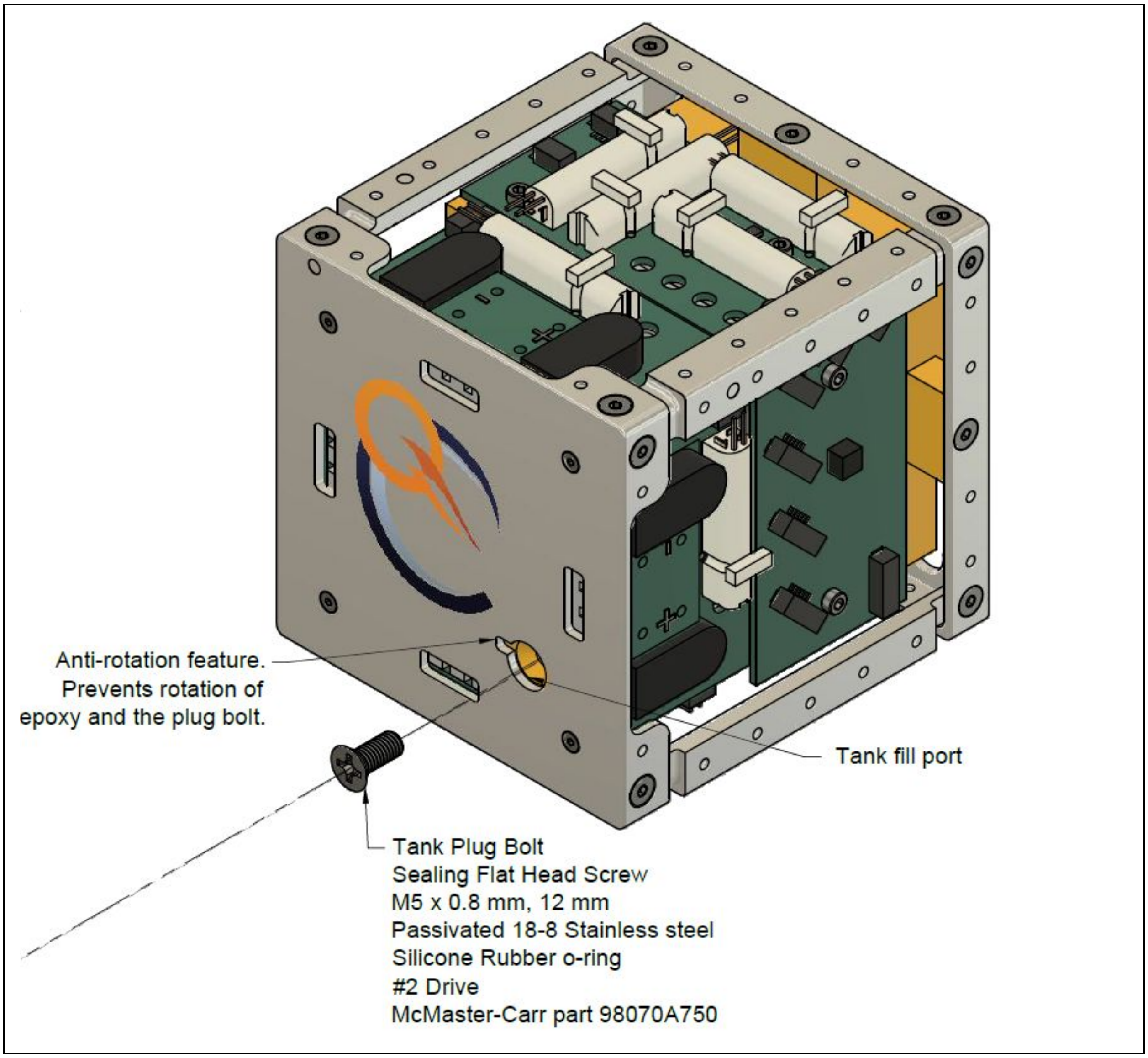
After 250ms of providing power to the high voltage system, stop power if current draw is not at least 0.05 Amps per thrust head. This indicates there is not enough propellant available.

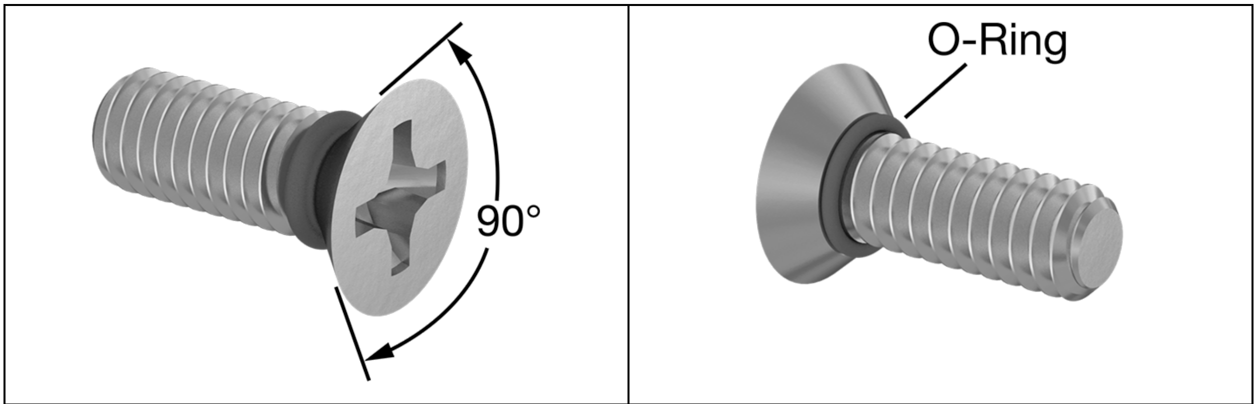
Current draw of 0.15 Amps per thrust head is nominal during factory testing at room temperature.

If a shutdown of any one thrust head is performed due to an out of range current, it is recommended to shutdown all thrust heads at once. During operation, a possible course of action is to disable one thrust head and close its valve, increasing propellant flow to the remaining thrust heads. Doing so is not likely to increase flow soon enough to be a viable recovery method though.

12 Refueling before Launch

The propellant tank has a single port for refueling with pure liquid water (H_2O). It is on the thrust plate face of the device, exposed to space and accessible after thruster integration. The propellant tank is sealed with a countersunk bolt with integral o-ring, known as the plug bolt. Prior to launch, an epoxy coating on the plug bolt must be provided by the end user. The epoxy binds the plug bolt to the tank and thrust plate as well as prevents rotation of the plug bolt. The components are identified in the graphics below:





Closeup of the tank plug bolt (McMaster-Carr part 98070A750)

The tank plug bolt is a sealing flat head screw of size M5x0.8, 12mm long. It is made of 18-8 stainless steel with a passivated coating. The bolt includes an integrated silicone rubber o-ring. Use a #2 drive to install and release the bolt. The bolt is available from McMaster-Carr under part number 98070A750.

Should the fill port threads on the tank become damaged, the fill port can be drilled and tapped as M6 and a suitable replacement bolt with integrated o-ring provided by the end user.

During fueling with pure liquid water (H_2O), a small amount of atmospheric gas is trapped in the tank. If the water were to freeze into ice, the expanded ice will cause the trapped gas to become compressed. The fill method outlined below minimizes the trapped gas pressure by freezing the water before sealing the tank. The fill method can be streamlined by the end user for situations where freezing will not occur before the next fueling.

Refueling requires several items. Gather these before proceeding:

- A scale with 0.5 grams or better accuracy and accepting up to 1300 grams mass
- A freezer
- A M1.4 device
- A tank plug bolt (may already be installed in the M1.4 device)
- 300 grams of degassed, pure, liquid water (H_2O). (250 grams is needed, however spillage can occur so 300 grams is a safe amount that avoids rework.)
- A small funnel with end roughy 3-4mm OD
- Thin pipette or thin, long necked dropper for removing water from the tank, 3-4mm OD
- A #2 screwdriver
- A pan and jig for capturing drain water from the M1.4 and allowing the M1.4 to remain stationary for extended periods
- An electrical interface wire harness to power and command the M1.4
- Software to open and close all valves individually on the M1.4

- A 5V power supply
- Approximately 3 mL of 2 part structural epoxy, mixed at the final step

To refuel a M1.4 device, follow these steps:

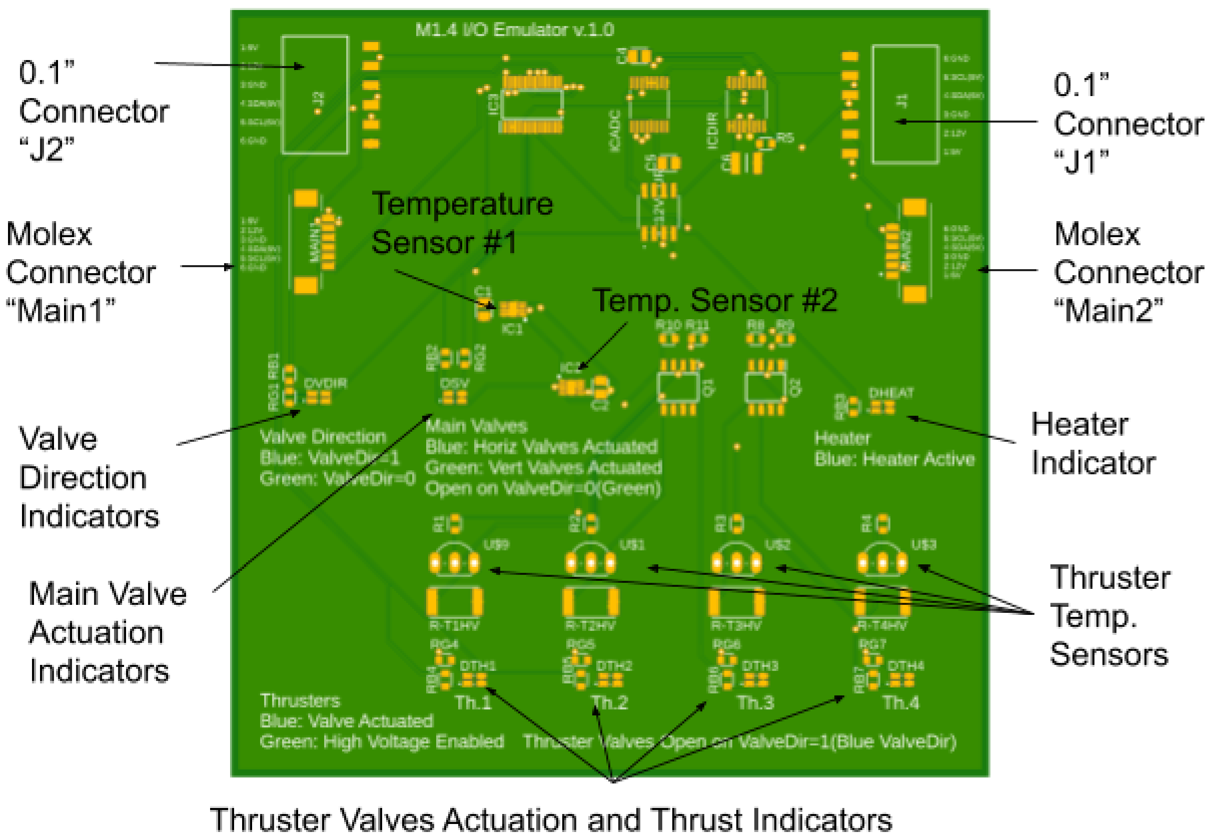
1. Start with a M1.4 device that is partially fueled or was previously fueled. The tank plug bolt must be installed.
2. Close all valves. This requires use of the 5V power supply, the interface wire harness, and valve control software.
3. Orient the M1.4 so the tank fill hole, currently filled with the tank plug bolt, is upward.
4. Remove the tank plug bolt. Use the #2 screwdriver.
5. Inspect the tank plug bolt for thread damage, damage to the o-ring, or damage to the drive slots. Discard and acquire another tank plug bolt if damaged.
6. Weigh the tank plug bolt.
7. Set aside the tank plug bolt.
8. Weigh the M1.4, taking care to factor in the mass of the interface cable. It is recommended that the interface cable remain attached to the M1.4 and be disconnected from the other side and the cable mass included in the weighing.
9. Place the M1.4 so the fill hole is downward and water, if any, in the tank can drain. This requires use of the pan and jig to allow draining.
10. Allow water to drain for 5 minutes. This step ensures the tank water level is far lower than the exit point near the main valves.
11. Open all valves.
12. Wait 8 hours. Doing so allows water droplets in the propellant delivery lines to evaporate.
13. Close all valves.
14. Orient the M1.4 so the tank fill hole, currently open, is upward.
15. Weigh the M1.4, taking care to factor in the mass of the interface cable. The difference between this weight and the previous weight is the mass of water that remained in the unit.
16. With the M1.4 and interface cable still on the scale, insert the funnel into the fill hole.
17. Record the weight of the assembly.
18. Carefully add 250 grams of pure, degassed, liquid water (H_2O). 250 grams is nominal. Under 251 grams is acceptable. **Do not supply more than 251 grams of room temperature water liquid water when the device may freeze after refueling, including before turning over the spacecraft for launch integration.**
19. Record the weight of the assembly, ensuring the correct amount of propellant was added.
20. Place the fueled M1.4, without the tank fill plug, into the freezer, oriented with the tank fill port upward.
21. Let freeze.
22. Remove the assembly from the freezer.

23. Install the tank plug bolt while the water is still frozen. Use the #2 screwdriver. This step traps a small amount of room temperature air in the tank.
24. Weigh the assembly. Check the weight for reasonableness knowing the total weight before the assembly went into the freezer and the weight of the tank plug bolt. Calculate and document the mass of water now sealed in the tank.
25. Let the assembly thaw and remove any condensation before connecting electrical power.
26. If ready for launch, seal the tank for launch by mixing and applying a structural epoxy to the tank plug bolt (now installed into the tank), ensuring the epoxy flows both into the plug bolt's drive slots and into the anti-rotation slot on the thrust plate. Reserve the remaining epoxy as a witness sample, checking it for hardness. Let the epoxy cure before moving the M1.4 so the epoxy does not flow onto the thrust plate's exterior face.

13 Emulator Usage

The M1.4 emulator is a circuit board that contains all I^2C devices and sensors present on the actual M1.4 device. The emulator allows "flatsat" development of flight software without risk to the flight unit. LED indicators show valve actuation, valve direction, and heater activation. Thruster activation is sensed via current sensor readings. Temperature sensors are exposed so users can warm them separately to confirm correct addressing. Thruster temperature sensors are nearby load resistors so as to show change when current is flowing. No high voltage components are present on the emulator.

M1.4 I/O Emulator



Observe correct polarity on all connectors. Do not place the emulator on a conductive surface, ideally avoiding antistatic materials as they are slightly conductive and could short exposed solder points.

Multiple connectors are provided for interfacing with the flight computer. 2 are flight-like Molex 6-pin connectors. 2 are typical prototype connectors with 0.1" socket spacing. All provided connectors are in parallel so any combination of them can be used. The pin out of the connectors is shown below, preserving the top-to-bottom orientation of the emulator circuit board.

Connector J2

Pin	Description
1	5 V
2	12 V
3	Ground
4	SDA (5 V)
5	SCL (5 V)
6	Ground

Connector J1

Pin	Description
6	Ground
5	SCL (5 V)
4	SDA (5 V)
3	Ground
2	12 V
1	5 V

Connector Main1

Pin	Description
1	5 V
2	12 V
3	Ground
4	SDA (5 V)
5	SCL (5 V)
6	Ground

Connector Main2

Pin	Description
6	Ground
5	SCL (5 V)
4	SDA (5 V)
3	Ground
2	12 V
1	5 V

Valve actuation events are intentionally short duration, 10-30 ms ideally. These will appear as short flashes on the indicator lamps. Should a valve actuation indicator be lit for longer, verify the control software is intentionally performing a valve heating operation.

The heater and thrusters should not be operated simultaneously. Verify the indicators for the heater and any thruster high voltage operation are never lit concurrently.

The valve direction indicator is blue when the digital I/O signal ValveDir is 1 (High). Green is shown when it is 0 (Low).

The main valves are opened when actuated while ValveDir is 0 (Green), closed when ValveDir is 1 (Blue). The main valve actuation indicator is blue when the two valves denoted the “Horizontal” main valves are actuated (either open or closed). Green is shown for “Vertical” main valve actuation.

Each thruster valve is opened when actuated while ValveDir is 1 (Blue), closed when ValveDir is 0 (Green). Each of the 4 thruster valve actuation indicators shows blue when the valve is actuated.

Each of the 4 thruster high voltage enable indicators shows green when the corresponding digital I/O signal is set to 1 (High), unlit when set to 0 (Low).

14 Vapor Pressure of Water and Ice

From "Water Vapor Pressure Calculator - Antoine Equation" (https://www.watervaporpressure.com/) the vapor pressure of water and ice is given by:

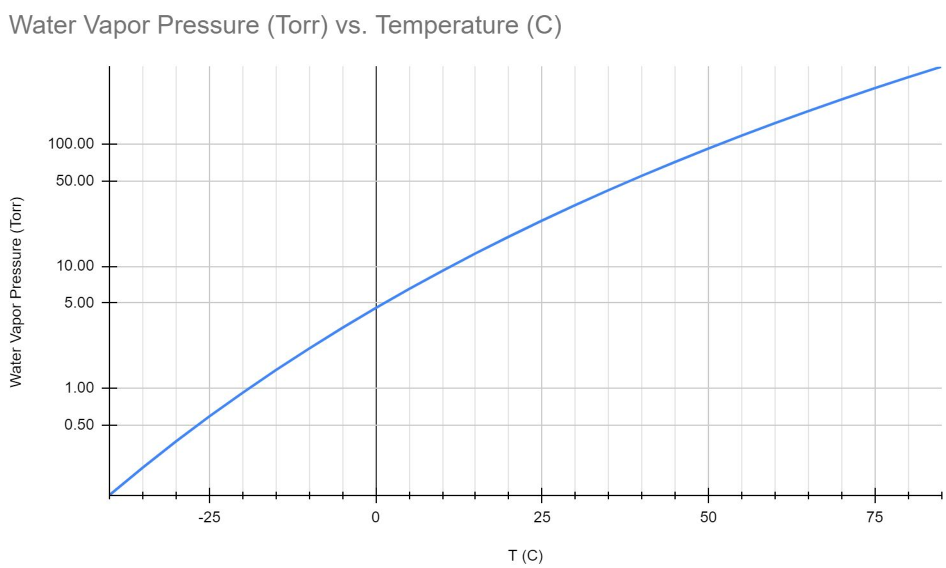
$$P = 10^{\left(8.07131 - \left(\frac{1730.63}{233.246 + T}\right)\right)}$$

where:

- P is water vapor pressure (mmHg)
- T is water temperature (C)

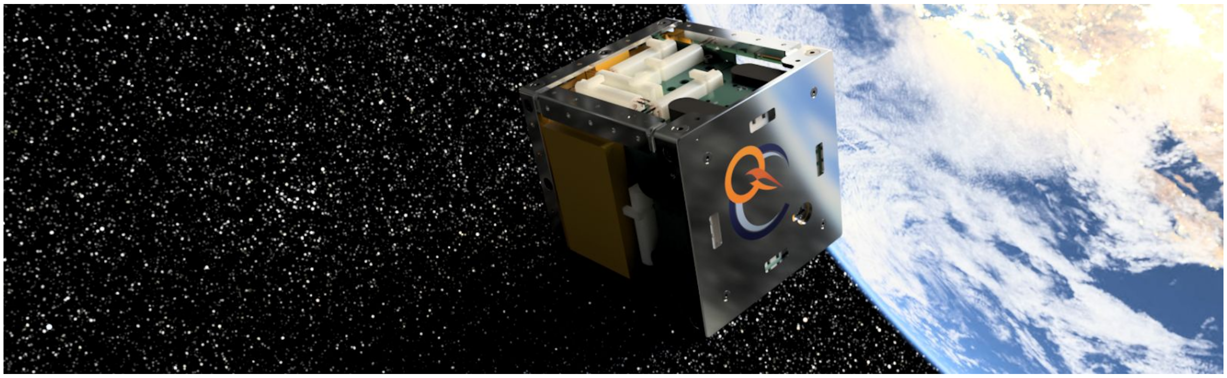
Pressure is 4.5 Torr maximum for ice, dropping to 0.92 Torr at -20C. Water creates 17.4 Torr vapor at room temperature.

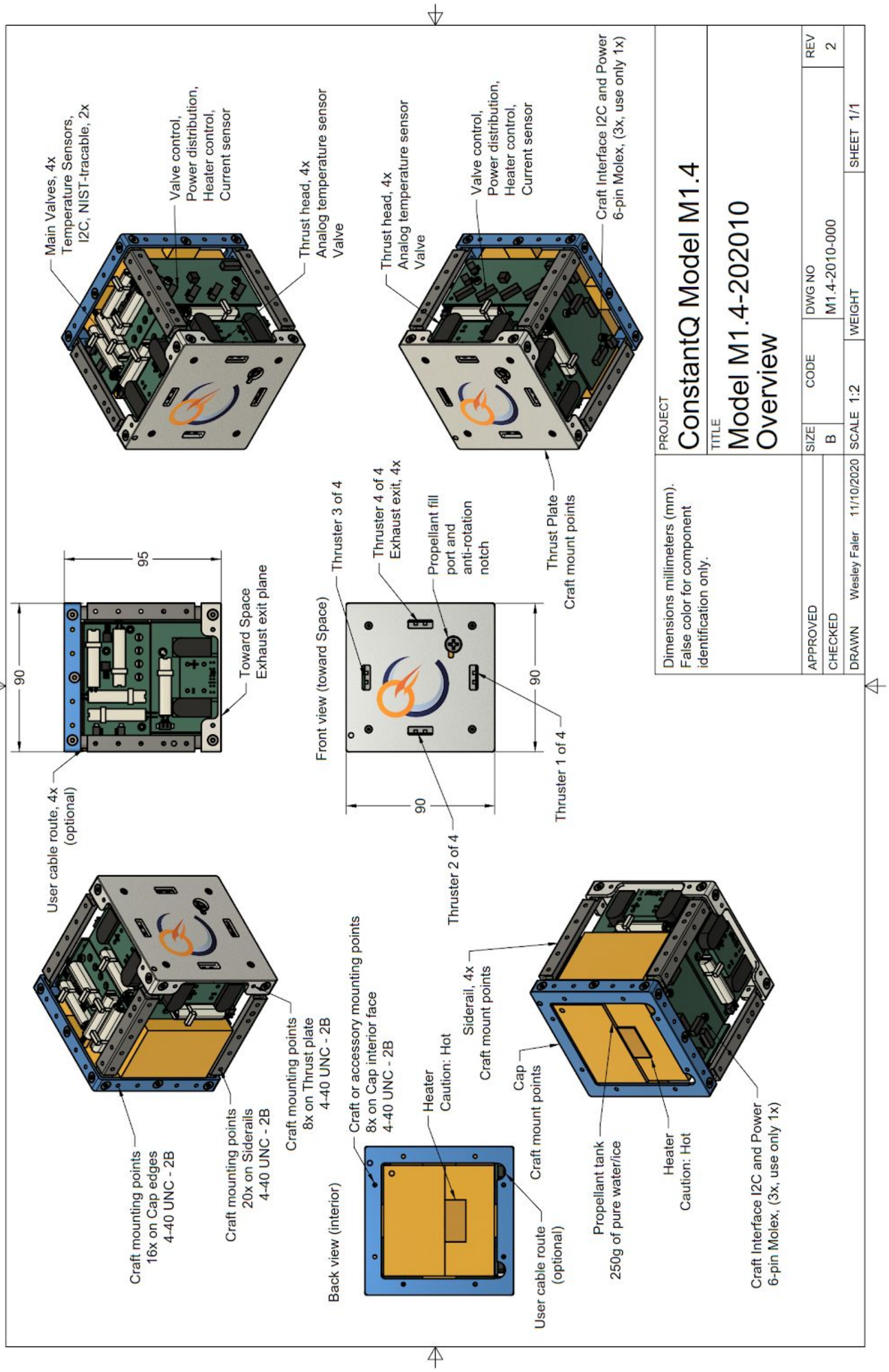
Temperature (C)	**Water Vapor Pressure (Torr)**
-20	0.92
0	4.54
10	9.16
20	17.47
30	31.74
50	92.30

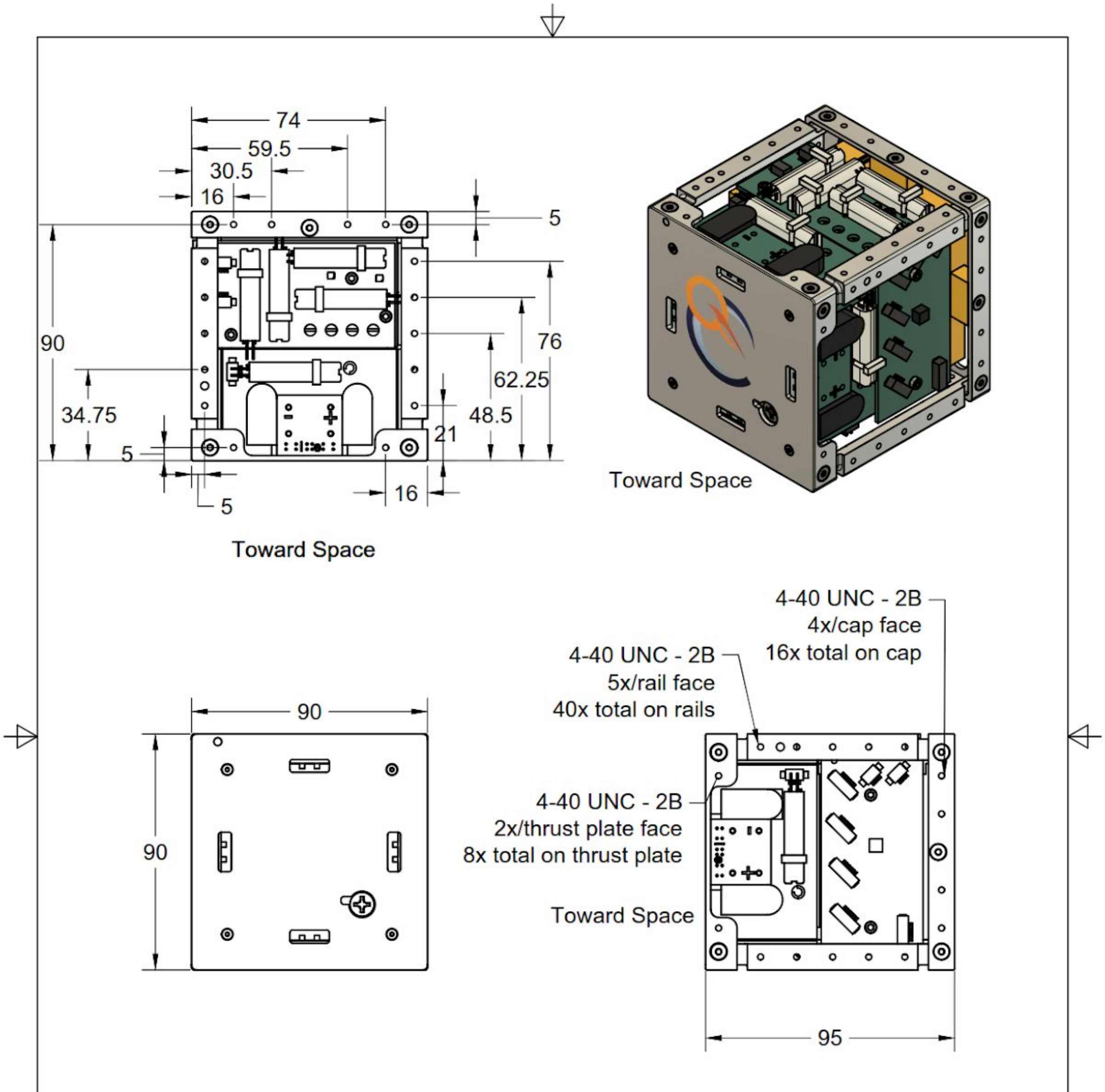


15 Performance Given Temperature and Power

Appendix: Drawings & Quick Reference




Main Valves, 4x
Temperature Sensors,
I2C, NIST-tracable, 2x
Valve control,
Power distribution,
Heater control,
Current sensor
Thrust head, 4x
Analog temperature sensor
Valve
Thrust head, 4x
Analog temperature sensor
Valve
Valve control,
Power distribution,
Heater control,
Current sensor
Craft Interface I2C and Power
6-pin Molex, (3x, use only 1x)
90
95
Toward Space
Exhaust exit plane
User cable route, 4x
(optional)
Front view (toward Space)
Thruster 3 of 4
Thruster 4 of 4
Exhaust exit, 4x
Propellant fill
port and
anti-rotation
notch
Thrust Plate
Craft mount points
90
90
Thruster 1 of 4
Thruster 2 of 4
Craft mounting points
16x on Cap edges
4-40 UNC - 2B
Craft mounting points
20x on Siderails
4-40 UNC - 2B
Craft mounting points
8x on Thrust plate
4-40 UNC - 2B
Craft or accessory mounting points
8x on Cap interior face
4-40 UNC - 2B
Heater
Caution: Hot
Siderail, 4x
Craft mount points
Back view (interior)
Cap
Craft mount points
User cable route
(optional)
Propellant tank
250g of pure water/ice
Heater
Caution: Hot
Craft Interface I2C and Power
6-pin Molex, (3x, use only 1x)
Dimensions millimeters (mm).
False color for component
identification only.
PROJECT
ConstantQ Model M1.4
TITLE
Model M1.4-202010
Overview
APPROVED
CHECKED
DRAWN Wesley Faler 11/10/2020
SIZE B
CODE
DWG NO M1.4-2010-000
REV 2
SCALE 1:2
WEIGHT
SHEET 1/1

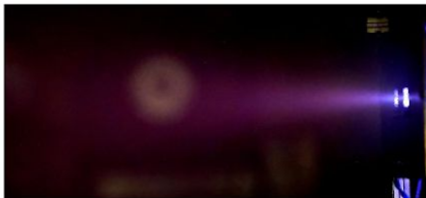


Dimensions millimeters (mm).
False color for component identification only.
Mounting holes tapped 4-40 UNC-2B in Aluminum 6061-T6.

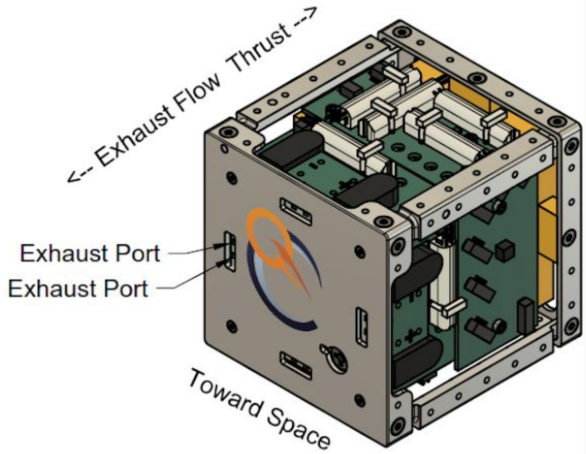
PROJECT
ConstantQ Model M1.4

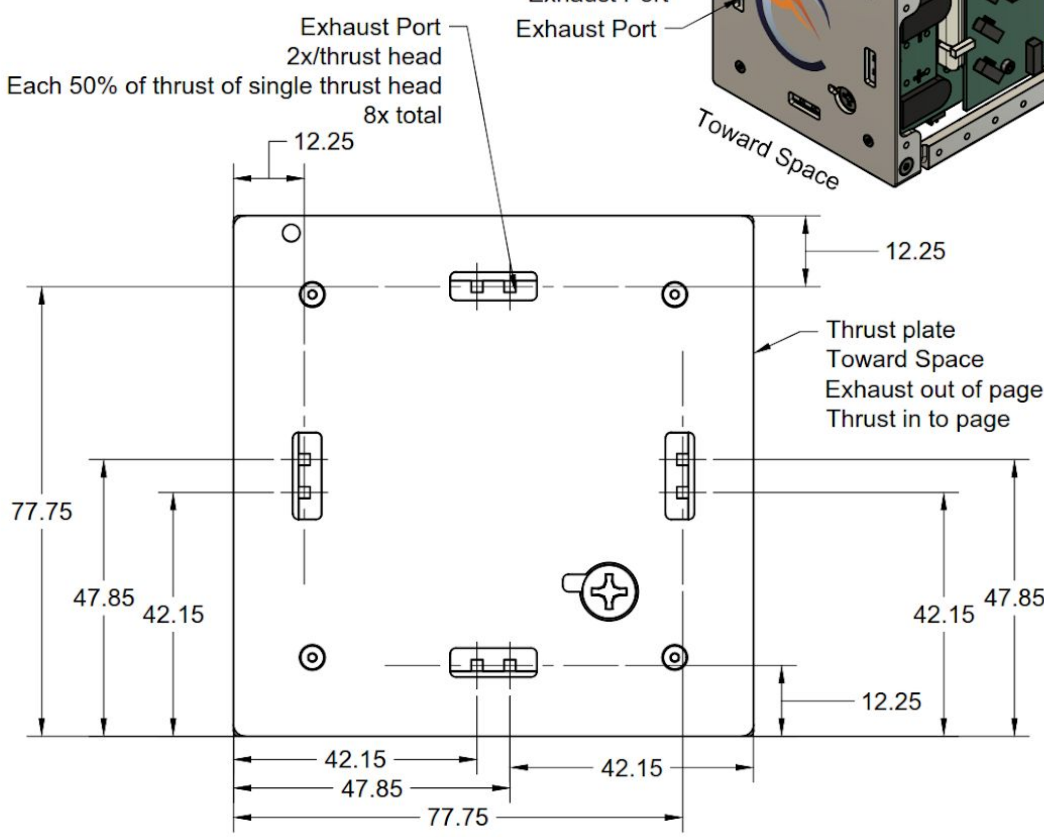
TITLE
Model M1.4-202010 Mounting Holes

APPROVED		SIZE	CODE	DWG NO		REV
CHECKED		A		M1.4-2010-010		1
DRAWN	Wesley Faler 12/17/2020	SCALE 1:2		WEIGHT	SHEET 1/1	

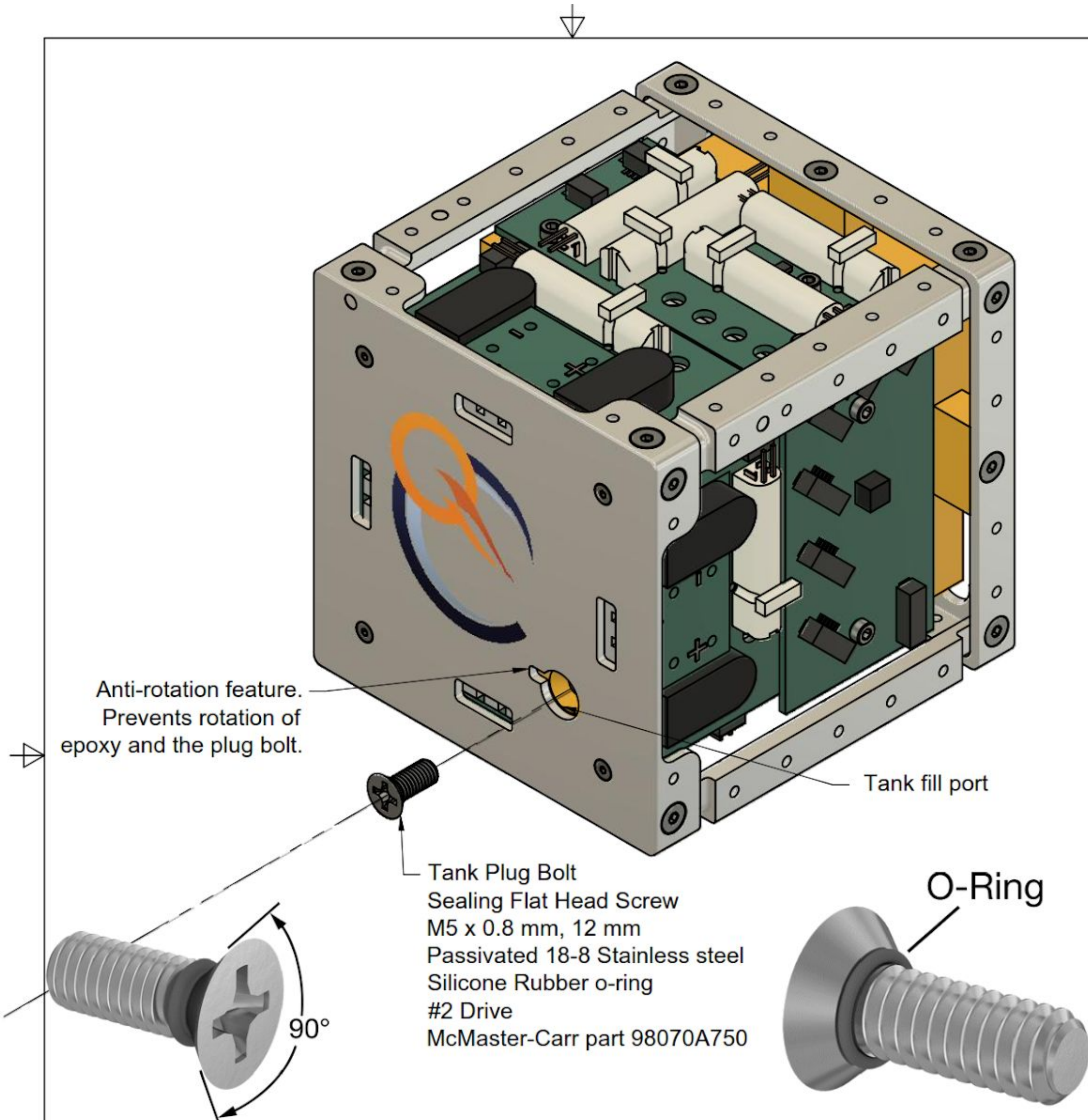


<- Exhaust Flow Thrust ->
Exhaust plume during test firing.





Dimensions millimeters (mm). False color for component identification only.	PROJECT ConstantQ Model M1.4			
	TITLE Model M1.4-202010 Thrust Points			
APPROVED	SIZE A	CODE	DWG NO M1.4-2010-020	REV 1
CHECKED				
DRAWN Wesley Faler 12/17/2020	SCALE 1:2	WEIGHT		SHEET 1/1



False color for component identification only.

PROJECT

ConstantQ Model M1.4

TITLE

Model M1.4-202010 Propellant Fill Features

APPROVED	SIZE	CODE	DWG NO	REV
CHECKED	A		M1.4-2010-025	1
DRAWN Wesley Faler 12/22/2020	SCALE 1:1		WEIGHT	SHEET 1/1

PCA9535 Signals and Valve Directions

PCA9535 Output Name	M1.4 Signal Name	Description
O0.0	ValveDir	Valve direction, sets voltage polarity for actuated valves.
O0.1	SVHoriz	"Horizontal" main valves actuation, actuate when 1. Open when ValveDir=0.
O0.2	SVVert	"Vertical" main valves actuation, actuate when 1. Open when ValveDir=0.
O0.3	HeatCtl	Heater, enable when 1.
O0.4-7	n/c	n/c
O1.0	T1Valve	Thrust head 1 valve actuation, actuate when 1. Open when ValveDir=1.
O1.1	T1HV	Thrust head 1 high voltage, enable when 1.
O1.2	T2Valve	Thrust head 2 valve actuation, actuate when 1. Open when ValveDir=1.
O1.3	T2HV	Thrust head 2 high voltage, enable when 1.
O1.4	T3Valve	Thrust head 3 valve actuation, actuate when 1. Open when ValveDir=1.
O1.5	T3HV	Thrust head 3 high voltage, enable when 1.
O1.6	T4Valve	Thrust head 4 valve actuation, actuate when 1. Open when ValveDir=1.
O1.7	T4HV	Thrust head 4 high voltage, enable when 1.

To set a valve, first set ValveDir then briefly actuate the valve. With all valve actuation outputs set to 0, no valve will change direction when ValveDir is changed. Do not set ValveDir and enable valves in the same operation. Rather, set ValveDir then wait a few milliseconds before enabling valves (i.e. opening or closing valves depending upon their relationship to ValveDir) for 10-30 ms.