

Ventilation Heat Exchanger/Flow Meter for xPLSS

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The flow meter/heat exchanger (FMHX) in the ventilation loop of the exploration EMU cools the ventilation gas and measures the ventilation flow rate. The heat exchanger transfers heat from the ventilation gas to the thermal control loop via a miniature shell-and-tube heat exchanger. The flow meter calculates the flow rate of gas through the ventilation loop based on the pressure drop across the heat exchanger core. Creare has delivered four design validation test (DVT) heat exchangers and five DVT flow meters to NASA JSC to support development of the exploration portable life support system (xPLSS). This paper describes the design and performance of the DVT units. The heat exchangers are designed to cool the ventilation gas to a specified temperature with low pressure losses under the most challenging operating conditions. The measured performance of the DVT heat exchangers agrees well with design models and meets all performance requirements. The flow meters use a MEMS thermal flow sensor to produce a signal that is proportional to a small bypass flow around the heat exchanger core. They are designed to achieve high measurement accuracy across the full range of xPLSS operating conditions. We calibrated the flow meters in a special-purpose flow facility that simulates operation in the xPLSS ventilation loop. Calibration testing shows that DVT flow meters produce digital output for vent loop mass flow that meets NASA's accuracy requirements across the range of xPLSS operating conditions. A DVT FMHX has been installed in the xPLSS and operated as part of the validation test program for the second build. Preliminary data agree well with calibration results from initial lab calibration tests and validation flow rate measurements made in conjunction with the xPLSS tests. This paper reviews the design of the heat exchangers and flow meters and presents data from the final flow meter calibration testing, heat exchanger performance validation, and initial ground testing in NASA's xPLSS.

Nomenclature

<i>ACFM</i>	=	actual cubic feet per minute
<i>ADC</i>	=	analog-to-digital converter
<i>xPLSS</i>	=	exploration portable life support system
<i>FMHX</i>	=	flow meter/heat exchanger (same as HX/FM)
<i>DVT</i>	=	design validation test
<i>DV_{TP}</i>	=	differential voltage generated by thermal flow sensor (V)
<i>EVA</i>	=	extra-vehicular activity
<i>GN₂</i>	=	gaseous nitrogen
<i>JSC</i>	=	NASA Lyndon B. Johnson Space Center
<i>MEMS</i>	=	micro electromechanical system
<i>PIA</i>	=	Pre-Installation Acceptance
<i>xPLSS</i>	=	exploration portable life support system

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I. Introduction

IN 2022, Creare delivered four ventilation loop heat exchangers (HX-340) and five ventilation loop flow meters (FM-321) to NASA JSC for design validation testing as part of the development of the exploration portable life support system (xPLSS). Although the flow meter is a replaceable unit, the heat exchanger and flow meter comprise an integral system because the heat exchanger generates a pressure drop in the ventilation flow that is essential for the flow meter's sensing function.

In the xPLSS, HX-340 cools the ventilation gas between the RCA beds and the fresh oxygen injection tee by rejecting heat to water in the thermal control loop just downstream of the circulating pump. FM-320 is a compact gas flow meter that uses a MEMS thermal flow sensor to generate an electronic signal that depends on the pressure drop across the heat exchanger core. The sensor includes an integrated microprocessor that uses only local measurements to produce a digital output expressing the mass flow rate of ventilation gas in engineering units.

The HX-340/FM-321 package was designed, built, and validated to meet demanding standards for use in a space life support system that runs with pure oxygen. Because the system interacts with the ventilation loop, thermal control loop, and ventilation loop controller, the hardware design and performance specifications deal with materials compatibility, structural integrity, thermal and flow performance, measurement accuracy, space environmental requirements for electronic parts, and software reliability. The entire package must fit within a compact size and shape that conforms to the space available in the tightly packed xPLSS assembly.

This report documents the design, requirements, and validation testing of the design validation test (DVT) versions of HX-340/FM-321. We will review key requirements, describe critical tests and analysis included as part of the xPLSS, and document lessons learned. Because the heat exchanger design and performance has been reported extensively in prior papers (ICES-2020-083¹ and ICES-2021-213),² most of this paper focuses on the flow sensor, flow sensor electronics, flow sensor calibration, and validation tests of the FMHX in the xPLSS.

II. Description of the Ventilation Heat Exchanger/Flow Meter

The ventilation loop heat exchanger is a miniature shell-and-tube heat exchanger (Figure 1). Ventilation gas flows through the tubes and water flows through the shell side, crossing the tubes in a four-pass, counter-crossflow configuration (Figure 2). The ventilation loop flow meter comprises an electronics enclosure that bolts on to the body of the heat exchanger and makes fluid connections with the gas inlet and exit plena. The pressure difference across the tube bundle drives a small bypass flow of gas through the flow meter and across a MEMS thermal flow sensor. Output from this sensor is processed by onboard electronics to produce digital output to the CON-350 ventilation loop controller. The output includes the mass flow rate of ventilation gas in engineering units.

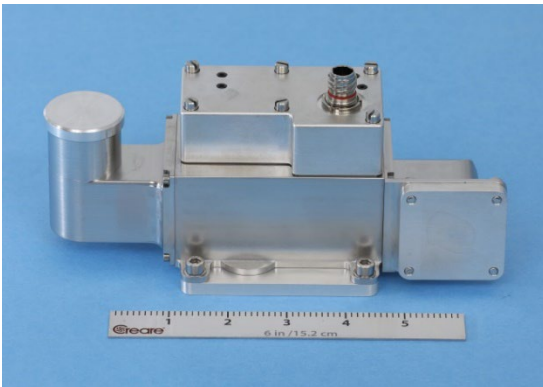


Figure 1. Ventilation loop heat exchanger and flow meter for xPLSS.

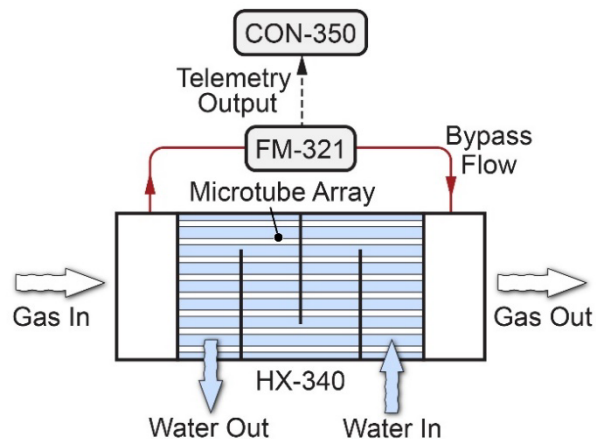


Figure 2. Schematic of HX-340 and FM-321 components.

A. Ventilation Loop Heat Exchanger Design

Configuration. Figure 3 shows the overall design of the heat exchanger. Gas enters the elbow on the left, flows through the tube side of the heat exchanger, and then leaves from the elbow on the right. The heat exchanger core is roughly 2.5 in. long and assembled from 679 microtubes. The overall length of the heat exchanger (measured between center points of the gas inlet and exit ports) is about 6.3 in. Key features in the heat exchanger are as follows:

- A honeycomb element straightens the gas flow and eliminates secondary flows that could interfere with accurate measurement of the flow rate. The honeycomb is located between the gas inlet elbow and the heat exchanger core.
- The heat exchanger core is a microtube bundle installed inside the heat exchanger housing. Flow baffles are built into the tube bundle to force cooling water to make multiple passes across the tubes.
- Dual O-rings are built into the tube sheets on either end of the tube bundle. The dual O-rings make a reliable seal between the ventilation loop and the cooling water on the shell side of the heat exchanger.
- Small gas ports are drilled into the upper surface of the heat exchanger just upstream and just downstream of the tube bundle. These ports couple to flow passages inside the flow meter and allow a small amount of vent gas to bypass the heat exchanger core.
- Inlet and exit ports for cooling water are located on the bottom face of the heat exchanger. These ports are also sealed with dual O-rings that are compressed against the surface of the xPLSS backplate.

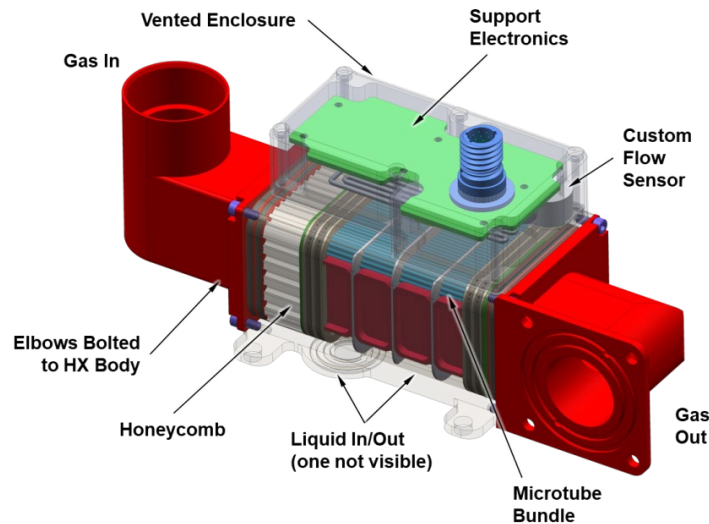


Figure 3. Mechanical layout design of the HX-340/FM-321.

Thermal Design. Early in the design process, simple physical models are most useful for estimating performance and assessing design trade-offs. Consequently, we sized the heat exchanger core using the effectiveness/NTU method for a multi-pass, crossflow shell and tube heat exchanger. Heat transfer coefficients for the gas side are calculated based on analytic expressions for laminar flow through tubes. Heat transfer coefficients for the water side are based on empirical correlations for flow across tube arrays. These methods were validated by comparing performance of the heat exchanger with analysis predictions (documented in ICES-2018-192).³

Fluid Design. Because of the complex geometry of the heat exchanger and the Reynolds numbers that lie within the transition region, correlations were more useful for predicting the overall flow/pressure drop performance than analytical models, particularly for the water side of the heat exchanger. Our main source for pressure loss estimations for the gas and water loops was the Handbook of Hydraulic Resistance. The pressure drop analysis includes not only the heat exchanger core but also the inlet elbow, honeycomb, and exit elbow. These methods were also validated by comparing actual pressure losses through heat exchanger with analysis predictions (also documented in ICES-2018-192).

Another key element of the flow design is to ensure uniform flow of ventilation gas through the heat exchanger. Without uniform flow, some of the tubes will receive little gas flow and the effective heat transfer area will be less than the nominal tube area. This issue is challenging because the heat exchanger must fit into a highly constrained volume, so the inlet elbow has a very small turning radius and is located very close to the heat exchanger core. To ensure uniform flow, we formulated a CFD model for the heat exchanger using ANSYS Fluent® as documented in a prior paper (ICES-2018-192).⁵ The predicted flow through the core varies by only ~5.5% around the mean value. This

⁵ CFD calculations use detailed models of the flow geometry and are typically time consuming to set up and run. As a result, they are useful primarily for analysis later in the design process when major decisions about overall core configuration have already been made. This is why the pressure drop analysis used to design the heat exchanger relied on analytical models and empirical correlations.

relatively small variation is not large enough to significantly affect the heat exchanger sizing calculations, as validated by comparing the actual versus predicted heat transfer performance.

Structural Design. The heat exchanger must be designed to accommodate all static and dynamic structural loads without exceeding allowable stresses. We used ANSYS to calculate stresses for limiting static pressure loads and under vibration conditions specified by NASA to simulate the spacecraft launch environment.

Materials. The materials of construction must meet requirements for service in the ventilation loop and/or thermal loop (depending on what fluids they contact), as well as general requirements for service in a space life support system. When possible, materials were selected from lists of preapproved materials from CTSD-ADV-1456. Remaining materials were selected in close consultation with NASA to meet requirements for oxygen safety and materials compatibility with other components in the system.

Method of Construction. Three assembly processes are used to build the HX/FM:

1. *Automated, precision laser welding.* The heat exchanger core (Figure 4) is assembled by welding the tubes to the tube sheets using an automated laser welding process. The entire process for each core is documented by video and photography and qualified through inspection and helium leak checks. The welding process parameters are qualified using small weld samples produced along with the production cores. These samples are used for destructive pull tests to measure weld strength and for sectioning and metallography to measure weld penetration.
2. *Electron beam welding.* The flow sensor housing is sealed by welding in two plugs to seal drilled flow passages and a plate to cover and seal the cavity that houses the flow sensor and associated hardware. The plugs and plate are sealed to the housing by electron beam welding. The welds were qualified by fabricating a dummy part that was then sectioned to inspect the weld penetration depth. Welds in the production housings are qualified by pressure and leak checks.
3. *Mechanical fasteners.* The main components are assembled using mechanical fasteners according to standard NASA-STD-5020. The flow sensor enclosure is attached to the heat exchanger body using captive fasteners specified by NASA.

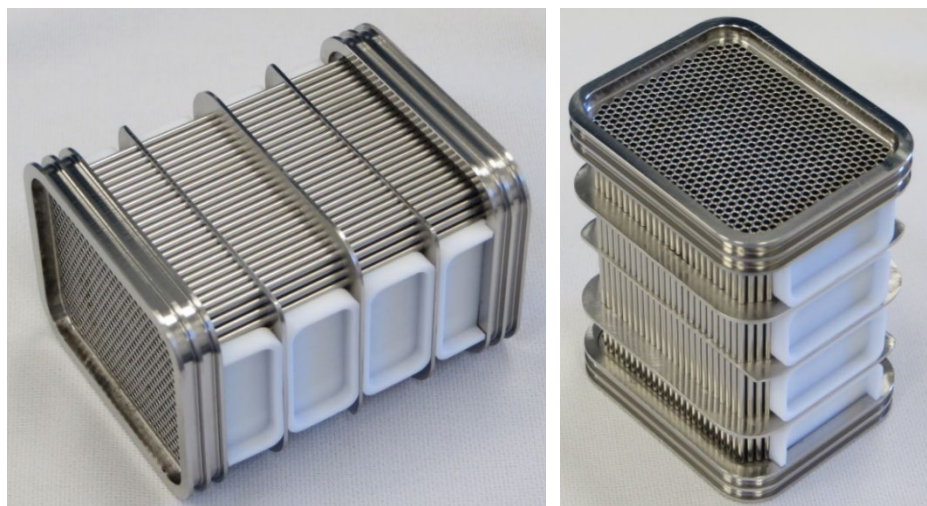


Figure 4. All-welded microtube core built from Inconel 625. Photo shows microtube array, inlet and exit tube sheets, water flow baffles, and Teflon flow blockers.

B. Ventilation Loop Flow Meter (FM-321)

The flow meter uses a miniature, MEMS thermal mass flow sensor to produce an electronic signal that is primarily a function of the mass flow rate of gas that bypasses the HX core (Figure 2). Since the bypass flow depends on the pressure drop due to flow through the HX core, the output from the flow sensor can be used to calculate the mass flow rate of the ventilation gas. The flow meter electronics comprise subsystems that control the flow sensor, interface properly with the xPLSS power and control systems, correct the measurement for temperature and supply voltage, and generate digital output for the CON-350 controller.

Thermal Flow Sensor. The MEMS flow sensor (Figure 5) operates on a thermal mass flow principle, in which the fluid is heated by a polysilicon resistive heater and the resulting temperature gradients upstream and downstream from the heater are monitored by thermopile sensors. The thermopiles consist of multiple aluminum-polysilicon

thermocouple junctions that are fabricated in series to increase the voltage generated for a given temperature gradient. The heater and “warm junctions” of the thermopiles are fabricated on a porous silicon substrate, which provides improved thermal isolation compared to normal silicon. A multilayer silicon carbide/silicon nitride and glass coating protects the active face of the flow sensor.

The DVT flow meter uses a Renesas FS1010-C01 die-level flow sensor (bottom of Figure 5) that has been packaged on a ceramic carrier (top of Figure 5). The carrier provides six bonding pads for connecting the die-level sensor to the rest of the sensor electronics. The pads are connected to the die-level sensor by wire bonds inside a “glob-top” of protective epoxy.

With heater power applied and no flow, the temperature field across the sensor is dominated by conduction and will be symmetrical on either side of the heater (subject to small variations in device symmetry). Thus, in an ideal device at no flow, the thermopile temperature gradients on either side of the heater are identical and the thermopiles generate the same voltage. For 5 V applied to the heater of the FS1010-C01, the thermopiles generate ~120 mV each. When gas flows across the sensor face, the temperature distribution is modified by the forced convection and the temperature field skews away from the upstream thermopile (i.e., the upstream sensor is cooled), resulting in a voltage difference between the thermopiles. It is possible to use a single thermopile to sense flow in a similar way, but the differential measurement between the upstream and downstream thermopiles provides some inherent compensation for device temperature.⁴ The fundamental output of the device is the difference between the upstream and downstream thermopiles (ΔV_{TP}). Referring to the bonding pads shown in Figure 5, $\Delta V_{TP} = (TP2^+ - TP2^-) - (TP1^+ - TP1^-)$, this voltage difference is proportional to the mass flow rate of gas across the face of the heater.

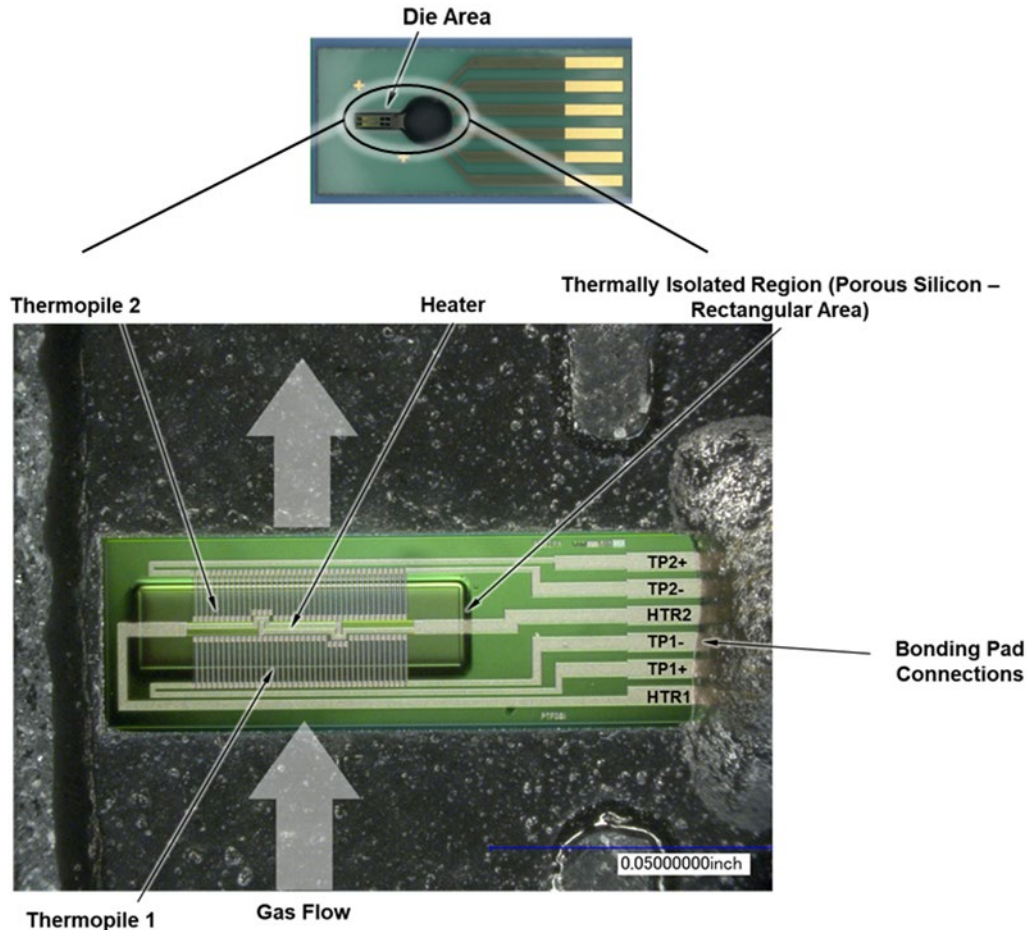


Figure 5. Image of Renesas FS1010-C01 die-level flow sensor (top) with enlargement to show details of the sensing element (bottom).

The sensor is coupled to the ventilation flow using a custom flow sensor housing (Figure 6). The flow sensor is mounted inside a flow shaper element that provides a very narrow passage for the bypass gas flow across the top of the flow sensor. The flow shaper, in turn, is installed in a metal housing that provides a gas flow passage that couples to the heat exchanger just upstream and downstream from the microtube core. The housing also provides a port that fits an electronic feedthrough for coupling the flow sensor to the flow sensor electronics. During assembly, the feedthrough is soldered into the housing to make a hermetic seal and the leads are soldered to the bonding pads on the ceramic carrier.

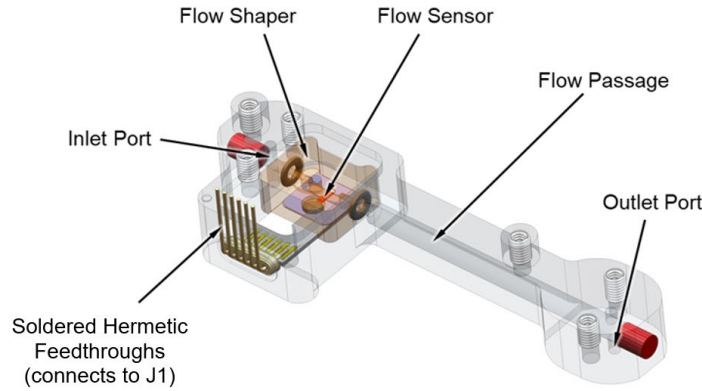
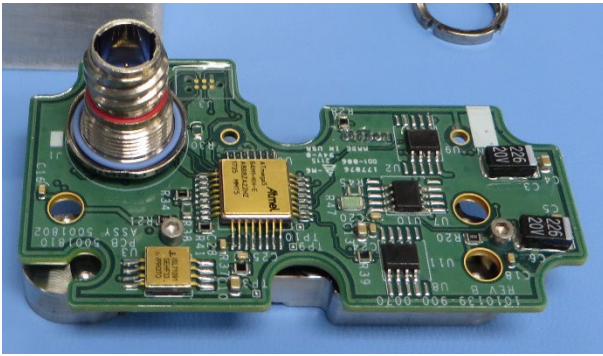
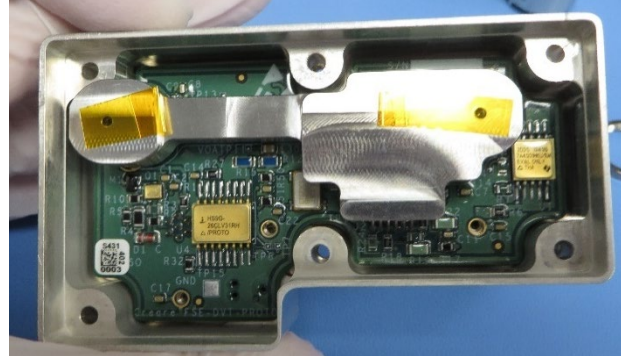


Figure 6. FM-321 custom flow sensor based on the FS1010-C01.

Flow Sensor Electronics. Figure 7 shows the flow meter components during final assembly. All the electronic circuitry needed to power the sensor, meet integration requirements, and process the sensor output is built onto the single miniature circuit board shown in the photo. The gas ports that allow a small amount of ventilation gas to bypass the core are visible in the right-hand photo, covered by Kapton tape. The connector in the left-hand photo couples the sensor to the CON-350 system.



(a) Top Side (away from HX-321)



(b) Bottom Side (toward HX-321) Inside Enclosure

Figure 7. FM-321 during final assembly.

Calibration. Each thermal flow sensor generates a unique voltage output, DV_{TP} , as a function of the bypass mass flow rate, board temperature, and input voltage. As a result, each sensor must be calibrated against an independent measurement of the ventilation gas flow rate. The calibration procedure calls for a series of tests that span (1) the entire pressure and temperature operating range of the ventilation loop, as well as (2) the operating range of the sensor voltage supply and sensor board temperature, which are key inputs that affect the sensor response. We use the data measured in the calibration tests to calculate the calibration function for the sensor. Inputs to this function are DV_{TP} , the temperature measured on the circuit board, and the voltage supplied to the circuit from the xPLSS power system. The output of the calibration function is the mass flow rate of ventilation gas through the heat exchanger. We calculate the accuracy of the sensor by comparing values of the calibration function with the flow rate measured by the independent sensor during the calibration tests.

Firmware. The calibration function is used by the sensor's microprocessor (an ATmegaS64M1) to calculate the mass flow rate of ventilation gas. The microprocessor uses an integral analog-to-digital converter (ADC) to convert the amplified thermopile voltage to a digital signal (a number of ADC counts), then operates on the digitized signal with the calibration function to generate a digital value for the mass flow rate. The calibration function is written into firmware code, which is then programmed into the microprocessor by accessing programming pins on the circuit board through a small port in the electronics enclosure.

Note that the calibration function is not known during calibration tests. During calibration, the microprocessor uses an interim version of the firmware that reports the ADC counts corresponding to the amplified voltage difference between the thermopiles. The resulting data set (independently measured flow rate vs. ADC counts) is used to generate the calibration function, which is then programmed into the microprocessor.

III. Requirements

The HX/FM operates in a manned space flight oxygen system. To meet its thermal, flow, and measurement requirements, the FMHX comprises heat transfer and flow elements, analog and digital electronics, and software. As a result, the system must meet an extensive set of requirements related to materials, design, performance, and component selection.

Requirements Documentation. The technical requirements for HX-340/FM-321 are specified in NASA's end item specification document (CTSD-ADV-1081), the DVT compliance matrix supplied by NASA, and the outer mold line and mechanical interfaces that are defined in NASA's source control drawing.

Critical Requirements. The complete set of requirements is extensive and documented in the end item specification. The requirements that played the most important role in the DVT unit design were as follows:

- *Materials safety and compatibility.* Materials in contact with the ventilation loop must meet strict standards for oxygen safety. Materials used in the thermal control loop must be compatible with the coolant and avoid corrosive interactions with other materials in the loop.
- *Ventilation gas cooling.* The heat exchanger must reduce the ventilation gas temperature to acceptable levels across all operating conditions. Specific cooling requirements were documented in a prior paper (ICES-2021-213). This paper also shows that the heat exchanger met all cooling requirements.
- *Low pressure losses.* Pressure losses on the oxygen and water sides of the heat exchanger must be below specified limits. Specific requirements for pressure drop on the oxygen and water sides of the heat exchanger were documented in a prior paper (ICES-2021-213). This paper also presents data showing that the heat exchanger met all pressure drop requirements.
- *Form factor and mechanical interfaces.* The xPLSS is a highly integrated, compact system, and the FMHX must fit within the allocated space and interface with the oxygen and water loops at precisely specified locations. The source control drawing defines the outer mold line for the system and key details of the mechanical interface with the xPLSS.
- *Measurement accuracy.* The flow meter will be used as part of the overall design validation testing of the entire xPLSS, and the ventilation flow rate will be critical data for evaluating performance of other components and the entire system. The flow meter is therefore required to measure the flow rate within 3% of full scale across the entire expected range of temperatures, pressures, and input power conditions.
- *High-reliability electronics.* The electronics design and components must be selected to satisfy the flow measurement accuracy requirements for the life of the unit, accounting for all space environmental effects, including ionizing radiation, electromagnetic environment, and ordinary drift. These requirements limit selection of components to those that are available with suitable spaceflight qualifications. Methods of assembly must also be suitable for high-reliability flight electronics.

IV. Flow Meter Testing and Validation

Each of the five FM-321 DVT flow meters was operated across its operating range to generate a flow calibration curve, which is used by the flow meter's controller to convert the digitized flow sensor output to a mass flow rate in engineering units (lb_m/hr). The digitized flow sensor output is generated by the microcontroller's onboard analog-to-digital converter (ADC), which accepts as input an amplified flow sensor signal and produces as output a number of ADC counts. The flow sensors were assembled onto their corresponding HX-340 heat exchanger in the benchtop flow test facility using standard test procedures developed for the DVT FMHX. For each flow test, we collected several steady state flow rate, temperature, and voltage conditions (outlined in Table 1), with approximately constant and distinct flow rates collected over the range specified. The test facility voltage, gas temperature, and gas flow rate were

held within the specified tolerance during each test, and data were collected for one minute at that condition. The calibration test facility has been described in a prior paper (ICES-2021-213).

Table 1. FM-321/HX-340 Calibration Test Conditions						
	AA	AB	AC	AD	AE	Tolerance
Pressure, P2 (psia)	4.3	4.3	4.3	25	3.1	± 0.1
Gas Inlet Temp, T1 (°C)	15.6	51.7	6	15.6	15.6	± 0.2
Flow rates, FM1 (ACFM)	0 to 7.5	0 to 7.5	0 to 7.5	0 to 7.5	0 to 7.5	± 0.1
Flow rates, FM1 (std L/min) ⁶	0 to 64	0 to 57	0 to 66	0 to 373	0 to 46	-
Flow rates (lb _m /hr)	0 to 9.7	0 to 8.6	0 to 10.1	0 to 56.5	0 to 7.0	-
Input Voltage (V)	4.9, 5.05, 5.2	4.9, 5.05, 5.2	4.9, 5.05, 5.2	5.05	4.9, 5.05, 5.2	± 0.01

Since the incoming supply voltage to the flow sensor heater is unregulated (5.0 $\pm$ 0.1 V), variations in the supply voltage were controlled and recorded during testing since the voltage affects the power to the resistance heater (Figure 5). The flow meter control electronics contain an ADC voltage measurement; this value is reported as part of the ADC output data and is corrected in the calibration data reduction. To vary the voltage in the test setup, we simply changed the voltage in the power supply to the flow meter.

The high-accuracy calibration flow rate measurements were made based on actual ft³/min (ACFM) and were measured by a calibrated laminar flow meter. These were compared to the flow rate counts reported by the FM-321 for calibration.

During testing, two separate file sets were created: (1) raw data capturing the full data collection including intervals between calibration data points, and (2) the “on-point” single-minute recordings of steady state data to be used for calibration. The latter data set was plotted to accent trends and anomalies. Figure 8 shows an example of the volumetric flow rate (ACFM) vs. flow counts for all data. Figure 9 shows the same data plotted using the corresponding mass flow rate; this figure demonstrates how the various data sets collapse to a nearly a single curve on a mass flow rate (or std L/min = slpm) basis. The horizontal spread in counts at some flow rates is due to the variation in input voltage.

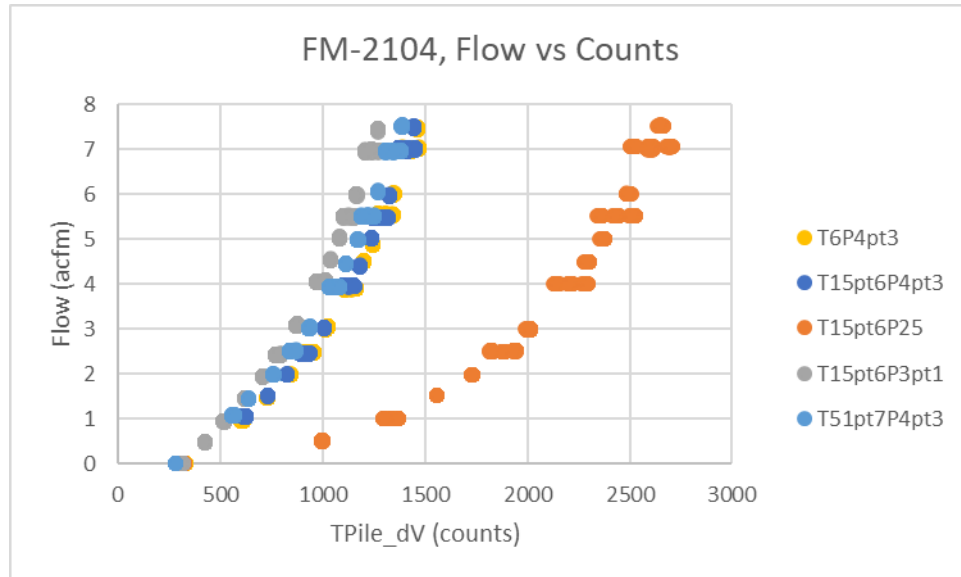


Figure 8. Flow sensor calibration data plotted on an ACFM basis. FM-1002 shown as an example. Test conditions ($T = x^{\circ}\text{C}$, $P = y.z \text{ psia}$) are indicated by labels TxPyptz.

⁶ The ventilation loop is designed to provide a required, actual volumetric flow rate under all operating conditions. This is why the ACFM specifications are the same for all test pressures. The mass flow rates in std L/min or lb_m/hr vary at each point because the gas density increases with pressure.

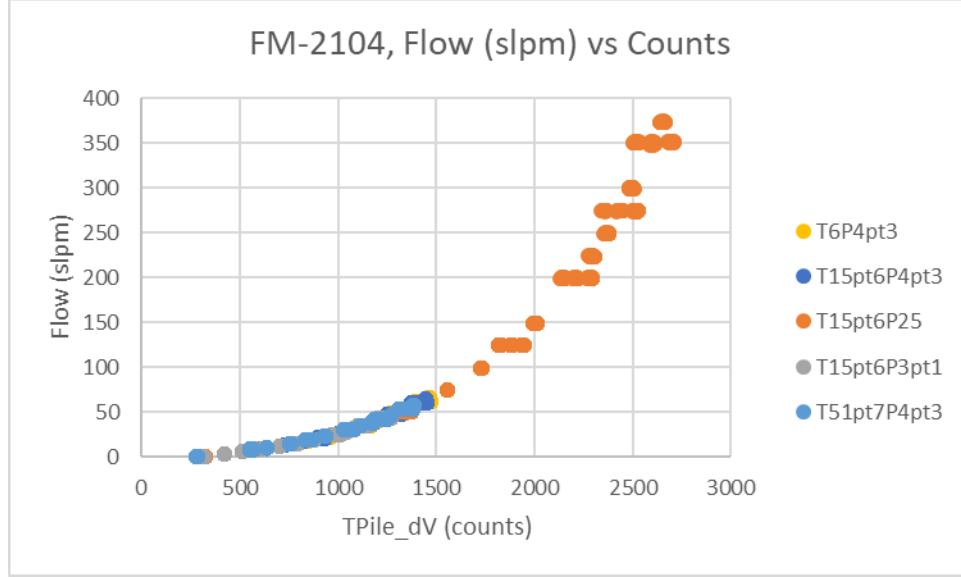


Figure 9. Flow sensor calibration data plotted on a mass flow rate basis. As expected, the data collapse to a single curve. Horizontal spread in the data at a single flow rate is due to the range of input voltage. FM-1002 shown as an example. Test conditions ($T = x^{\circ}\text{C}$, $P = y.z \text{ psia}$) are indicated by labels TxPyptz.

V. Flow Meter Output Data Reduction and Calibration

We used the calibration data to generate a set of best-fit calibration curves. The calibration includes corrections for input voltage and temperature across the collected data range to improve flow meter accuracy.

Basis. Flow sensing is based on a physical process in which the resistive heater (Figure 5) changes the temperature distribution in the gas that flows across the sensor. These changes in gas temperature cause the upstream and downstream thermopiles to generate voltages that depend on the heater power and the mass flow rate of gas. In the ideal case, the heater would generate a constant thermal power and there would be a one-to-one correspondence between the mass flow rate across the sensor and the difference in thermopile voltages. Since the mass flow rate across the sensor is driven by the pressure drop across the heat exchanger (Figure 2), which in turn is proportional to the mass flow rate through the heat exchanger, the voltage signal generated by the sensor should ideally be a function only of the mass flow rate of ventilation gas through the heat exchanger.

In practice, this measurement approach does not yield high-accuracy measurements because the power generated by the heater is affected by additional variables. The main source of inaccuracy is the voltage that drives current through the heater, which is not regulated to high accuracy. The specified $5.0 \pm 0.1 \text{ VDC}$ can cause the heater power to vary by $\pm 2\%$, which is very large compared to the sensor accuracy requirement. The heater power also depends on the electrical resistance of the heater, which in turn depends on the heater temperature. The temperature of the flow sensor in the DVT unit varies with environmental conditions, and we have found that the internal temperature inside the flow sensor enclosure has a secondary but significant effect on sensor output as well.

To improve sensor accuracy despite variations in voltage and temperature, we formulated a calibration approach that accounts for these variables. Measurements for voltage and temperature are available to the onboard microprocessor: Voltage is measured directly from the power-to-ground pins in the connector, and temperature is measured by a temperature sensor on the circuit board. Based on the calibration data (sensor ΔV , supply voltage, and temperature), we deduce linear corrections that account for input voltage and temperature. These corrections reduce all the calibration data to a single curve. We then identify a curve fit to calculate ventilation flow rate with high accuracy from the corrected sensor output. Figure 10 plots the same data as Figure 9 after correcting for voltage and temperature. The figure also shows the curve fit for the corrected data, which predicts the data with high accuracy within NASA's specified error bounds.

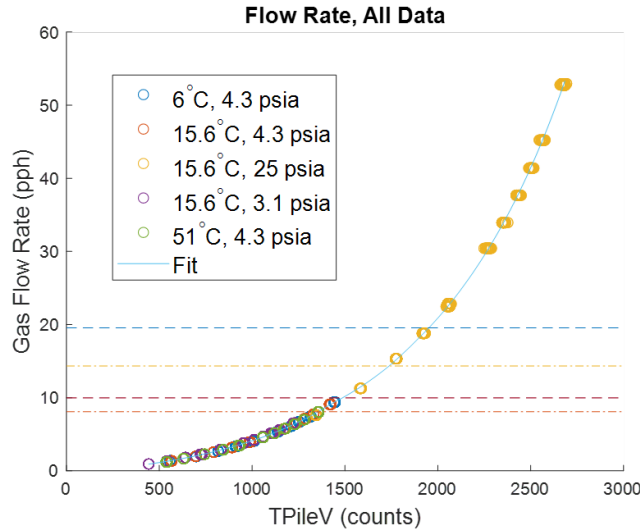


Figure 10. Flow sensor calibration curve with regions boundary lines. FM-1002 as an example.

The results of the calibration for all five of the DVT units are shown in Table 2. The table shows that all of the units met the calibration accuracy requirement (within $\pm 3\%$ of full-scale flow, with “full scale” defined based on the 7 ACFM flow rate at a given pressure).

Table 2. DVT Flow Meter Calibration Accuracy Results		
Serial Number	Low-Pressure Error (< 10 psia)	High-Pressure Error (> 10 psia)
FM-1003 (Creare FM-2101)	2.32%	1.57%
FM-1004 (Creare FM-2102)	0.83%	1.52%
FM-1005 (Creare FM-2103)	0.86%	1.55%
FM-1006 (Creare FM-2104)	0.88%	1.68%
FM-1007 (Creare FM-2105)	1.37%	1.26%

The FM-321 microcontroller is programed with firmware to read flow sensor measurements, convert the measured values into engineering units, calculate the mass flow rate based on the converted measurements, and report data using an RS-485 serial bus following xPLSS specification requirements. The FM-321 firmware was designed to run on the ATmegaS64M1 microcontroller, which has a space-qualified version available.

The FM-321 firmware samples ADC measurements of the thermopile voltage difference, the heater voltage, the heater current, and an onboard temperature sensor. FM-321 uses the 10-bit ADC that is integrated into the ATmegaS64M1. The firmware transmits serial data to the CON-350 system according to a telemetry frame defined by NASA specifications. The calibration constants that correspond to a specific flow sensor are stored in that sensor’s EEPROM. On start-up, the values from the EEPROM are loaded into RAM for use by the microcontroller.

VI. Heat Exchanger and Flow Meter Validation in xPLSS

The xPLSS DVT assembly has been undergoing Pre-Installation Acceptance (PIA) functional testing at JSC in both the lab ambient and vacuum environments. In the lab ambient PIA tests, the xPLSS is in a closed-loop configuration to test basic component functionality. To minimize risk to the system and personnel, all oxygen and ventilation loop tests are completed using GN₂ as the test fluid during the DVT phase. The lab ambient test stand includes a variety of pressure, temperature, and flow sensors to independently verify functionality and accuracy of the xPLSS components. In addition to pressure integrity and leakage tests for the oxygen, ventilation, and thermal loops, each component is individually assessed. The FMHX performance was verified as part of two separate procedures: the FM-321 verification occurred in the same test series as the Fan verification, while the HX-340 verification occurred with the CO₂ scrubber verification test.

In the fan verification test series, the xPLSS primary or secondary fan provided a minimum of 6.0 ACFM of flow through the ventilation loop, while a throttling valve on the test system was adjusted to achieve varying head rise values that correspond to suit pressure design points. Additional test points to verify the FM-321's functionality at lower flow rates were achieved by using the test system's gas pressurization panel to introduce flow to the ventilation loop via a test loop entry port. The test system includes a volumetric flow meter (VL-FM-301) to both confirm adequate flow through the ventilation loop during each test series and to verify FM-321 outputs.

Figure 11 compares the flow measurement from FM-340 with the test system's volumetric flow meter. Agreement between the two flow meters is generally within a few percent except at very low flow rates. Since the temperatures of the two sensors are not the same, we expect some differences between the actual volumetric flows.

In the HX-340 functional test, cool water was introduced to the thermal loop via a chiller in the test system to simulate loop cooling that would be accomplished during EVA operations by the suit water membrane evaporator. Simultaneously, the temperature of GN2 flow at 7.5 ACFM through the ventilation loop was monitored via TS-320, which is the temperature sensor located at the suit helmet inlet in the ventilation loop. As the water temperature was reduced from an initial lab ambient value of 70°F to 50°F, the TS-320 and secondary test system temperature sensor (VL-TS-301) confirmed that the HX-340 was functioning as the ventilation gas temperature was reduced from approximately 73°F to 62°F. Figure 12 shows data from this test.

The xPLSS DVT unit is slated for continued functional testing in 2023, including a thermal vacuum chamber test series to demonstrate system functionality in a realistic environment. This test series will also include test segments for airlock/pre-EVA open loop configurations as well as simulated EVA metabolic rate profiles for verification of xPLSS functionality in all expected operating conditions.

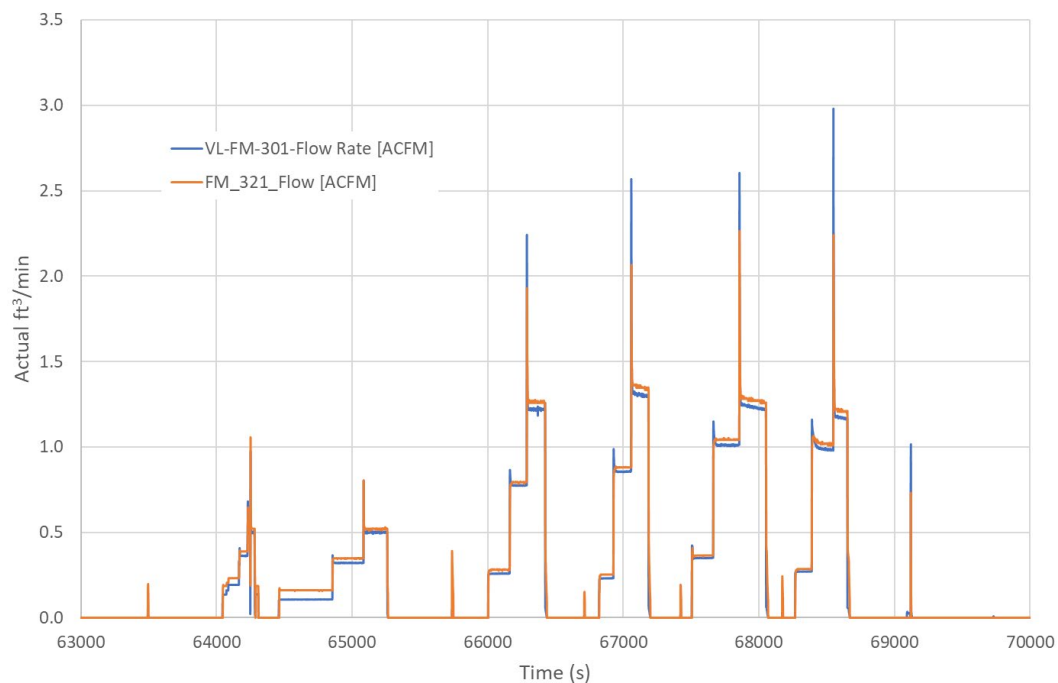


Figure 11. FM-320 output compared to system volumetric flow meter (VL-FM-301). *Small differences in actual volumetric flow may be due to different temperatures in the two sensors.*

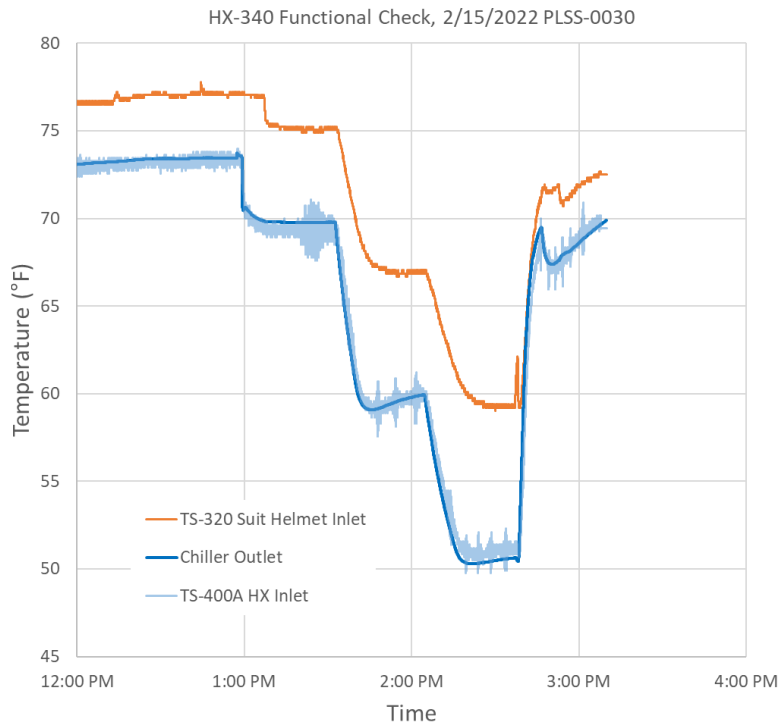


Figure 12. Results of HX-340 functional test. *Helmet inlet temperature responds as expected when the heat exchanger inlet temperature changes.*

VII. Lessons Learned

An extensive list of lessons learned was initiated and maintained during the development and testing of the DVT units. These lessons will be incorporated into the design of future flight units as well as updates to test and manufacturing procedures. Most of the lessons learned concern small details of fabrication and assembly; however, there were several significant issues or opportunities for improvement that are noted below.

1. Prescreen temperature sensor chips during burn-in. During development of the DVT units, we developed a test fixture that enabled flow testing of an individual sensor before integration with the sensor electronics and heat exchanger. A similar test rig could be used to identify sensor chips that have high sensitivity to flow during the burn-in procedure. Using only chips with the highest sensitivity would increase flow measurement accuracy.
2. Thermal analysis and design of the electronics enclosure. Future units should consider a more comprehensive thermal analysis of the flow sensor housing, circuit board, and electronics enclosure. This analysis could enable redesign of some elements of the electronics assembly that will lead to better control and measurement of the sensor temperature.
3. Improved thermal coupling between flow sensor, circuit board, and cooling water. Part of the thermal redesign should include consideration of better coupling between the sensor and electronics components and the cooling water temperature. Better coupling would make the electronics temperatures and performance less sensitive to environmental conditions.
4. Make lifetime buy of Ultem material to qualify for flight. We found that the Ultem (polyetherimide) material used to build the gas flow passages inside the flow sensor housing is not available with material certifications that are appropriate for flight hardware. The approach for flight units will be to purchase a relatively large quantity of Ultem from a single production lot, qualify the material by test for service in the ventilation loop, and use this material for all subsequent flight units.

Conclusion

Under Contract No. 80JSC018P0097, Creare designed, built, calibrated and delivered to NASA four HX-340 heat exchangers and five FM-321 flow meters for design validation testing. These units were designed to meet extensive

requirements for service in the xPLSS based on NASA's end item specification, source control drawing, and a compliance matrix that specified how to determine compliance with each specification. DVT units were extensively tested and calibrated as individual components on the lab bench, then installed in the xPLSS for verification testing. Preliminary data from functional tests of both the flow meter and heat exchanger as part of PIA testing show that both the flow meter and heat exchanger are performing as intended.

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