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Test Bed for Investigating Anomalous Pump Behavior in a Single Phase Mechanically Pumped Flow Loop and Lessons Learned

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NASA's Europa Clipper mission is tasked with investigating the habitability of this icy moon of Jupiter and determining if it is capable of supporting life. The suite of powerful instruments necessary for this mission, combined with the harsh environment, require an elaborate single phase, mechanically pumped flow loop (MPFL) to redistribute waste heat around the spacecraft, thus minimizing energy requirements and avoiding the need for constant heating of the propulsion tanks. At the heart of this MPFL is a pump which will circulate fluid for the entirety of the 12-year mission; however, during initial qualification testing, anomalous behavior raised serious concerns regarding the pump and system design. Due to the critical nature of the pump, a major investigation was launched to evaluate the pump, system design, and the testing methodology employed to investigate this anomaly. This investigation resulted in a highly detailed analysis of the test loop, revised procedures, and the isolation/removal of variables impacting the quality of the observed pump behavior. The resulting test loop permitted comprehensive monitoring of the pump in the MPFL, including: flow rate, inlet and outlet static pressures, temperature, power consumption, and pump speed. Additionally, the investigation of the anomaly revealed several key lessons learned and helped institute a new set of best practices for future MPFL tests.

Nomenclature

AFT = *Allowable Flight Temperature*
AU = *Astronomical Unit*
CFC-11 = *Trichlorofluoromethane (Freon)*
DAQ = *Data Acquisition Unit*
DMM = *Digital Multimeter*
GN_2 = *Gaseous Nitrogen*
HES = *Hall Effect Sensor*
HRS = *Heat Redistribution System*
HXR = *Heat Exchanger*
JPL = *Jet Propulsion Laboratory*
kPa = *Kilo Pascal*
LPM = *Liters per Minute*
MER = *Mars Exploration Rover*
MPFL = *Mechanically Pumped Fluid Loop*
MSL = *Mars Science Laboratory*
NVR = *Non-Volatile Residues*
OD = *Outer Diameter*
PLC = *Power Line Cycle*
PPM = *Parts per Million*
PS = *Power Supply*
PSIG = *Pound per Square Inch Gauge*
PSID = *Pound per Square Inch Differential*
PTFE = *Polytetrafluoroethylene*
RPM = *Revolutions per Minute*
TC = *Thermocouple*
TIM = *Thermal Interface Material*
VCR = *Metal Gasket Face Seal Fittings*
VI = *Virtual Instrument*
W = *Watts*
ΔP = *Pressure Drop*

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I. Introduction

DATA from previous missions indicates that a liquid water ocean could exist under the icy crust of Jupiter's fourth largest moon, Europa. On Earth, scientists have long established a link between the presence of liquid water and the potential for life, thus we are drawn to study this distant ocean world in the hopes of answering one of humanities' oldest questions: "Are we alone?"

The purpose of the mission is to study the Galilean moon Europa and determine if it is capable of supporting the essential ingredients necessary for life: water, chemistry, and energy. An advanced payload of nine NASA-selected science instruments is necessary to accomplish the three main science objectives studying: ice shell and ocean, composition, and geology. Europa lies in an extremely harsh radiation zone surrounding Jupiter, which presents significant challenges for the spacecraft and instrumentation operation; therefore, the mission plans to fly the spacecraft in long, looping orbits around Jupiter, with forty-five close fly-bys of the moon, with altitudes ranging from 25 to 2700 kilometers, to accomplish the science objectives and map the surface. During these fly-bys, the suite of science instruments will be in heavy use resulting in peak power demand. The Europa Clipper spacecraft employs a large solar array (90 m^2) to charge a 350A-hr battery, which will run all on-board instruments and systems. At a maximum distance of 5.6 AU from the sun during a mission powered by solar arrays, power is a precious resource. In addition to the science payload, avionics, telecommunications and engineering hardware all require power for mission success. At these extreme distances from the sun, the spacecraft has significant heat leaks from radiating surfaces and heaters are required to maintain systems within allowable flight temperature (AFT) ranges. All of these factors dictate a robust and carefully engineered thermal control architecture in order to accomplish mission objectives.

During conceptual planning for the mission, several trade studies were conducted to determine the optimal thermal architecture for the system, with the conclusion that an active thermal control architecture was better suited to this mission than the continued use of passive architecture as has been the case with all previous outer planet missions of this size flown by NASA: Juno, Cassini, and Galileo [1] [2]. Based on the findings of these trade studies, the use of an active Heat Redistribution System (HRS) was selected for the mission. This HRS employs a Mechanically Pumped Fluid Loop (MPFL) to pick up heat from sources (electronics boxes, instruments, etc.) and use this otherwise waste heat to keep the propellant tanks within the AFT range. This will be the furthest NASA mission to fly a MPFL, but recent success with MPFL systems on interplanetary missions provides confidence that this is the ideal choice given the mission requirements. Detailed discussion of the Europa Clipper HRS design and development can be found in previous literature [3] [4]; however, in order for the HRS to function properly for at least a twelve year mission, it must have a robust pump at the heart of the design.

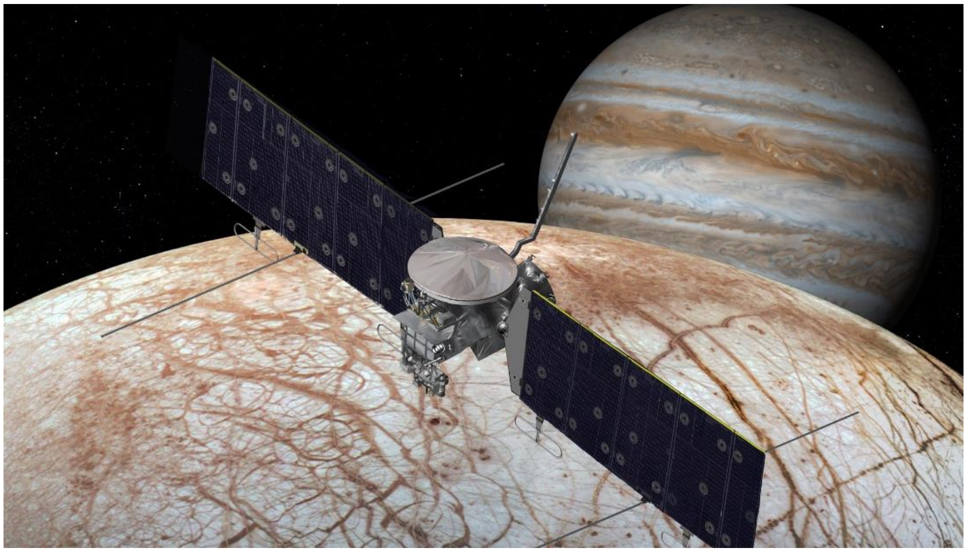

Figure 1. Rendering of the Europa Clipper spacecraft during a fly-by of Europa in the Jupiter system.

II. Pump Overview

Several previous missions developed by JPL have utilized MPFLs, which provides a strong heritage to build upon for the Europa Clipper mission (Pathfinder [5], MER [6], MSL [7], and Mars 2020). Due to the Europa Clipper mission requirements, the resulting HRS design necessitates a pump with a higher flowrate than those previously flown, but based on the extensive test data collected in long-duration life tests [8] and radiation impact life tests [9] of heritage model pumps, it was deemed best to modify the heritage design to accommodate a larger, single-shrouded impeller instead of the smaller, straight vane Barske impellers utilized in previous missions. Changing the impeller size and type allowed the flowrate and pressure head to be increased to sufficiently accommodate the HRS design for the spacecraft; however, these modifications changed the loading on the hydrodynamic bearings. This change required new qualification and characterization testing to evaluate the changes to the pump before flight.

The pump has a number of critical design points, as outlined in Table 1, which must be verified through testing. Early testing showed initial agreement with the design points, but as testing continued anomalous behavior presented and root cause could not be immediately identified. In order to trace the root cause of the anomaly, a rigorous test system and methodology were developed, which allowed the root cause to be determined.

Table 1. Nominal design point values for pump operation

Design Point	Nominal Value
Flow Rate	1.5 LPM
Pressure Head	≥ 22 PSID (152 kPa)
Speed	~10,500 RPM
Power Consumption	~30 W

III. Test Anomalies

During characterization testing of an engineering model unit for the new pump design, an anomaly presented in the form of undulating operating noise, the loss of one Hall effect sensor feedback signal, and a high-power draw during operation. This anomalous behavior was observed to be significant and repeatable, and thus an in-depth investigation was launched to find the root cause of the issue.

The investigation included the disassembly of the pump to establish the state of internal parts and components following the anomalous test behavior. This operation led to the discovery of visual wear in key areas and foreign particles within the pump. In addition to the presence of foreign particles, chlorides were detected, which confirmed corrosion of key surfaces. This corrosion was due to acid, which can form when CFC-11 breaks down due to high temperatures and/or high moisture content. The bearings were also noted to have been contaminated by amides. While these were key findings, they did not provide answers for the root cause in the occurrence of the anomaly. As root cause was not identified a major effort was launched to fully vet every aspect of the pump design, fabrication, assembly, installation, and testing.

IV. Pump Characterization Test Bed

The test bed is a MPFL used to simulate operation of the pump in the spacecraft HRS, which allows engineers to verify the pump design. Since many aspects of the pump design cannot be directly measured during operation, it is critical that the loop is carefully configured, such that pump operation is not adversely impacted by the loop. The core purpose of the test stand is to provide a means to characterize pump performance by obtaining pump curves (ΔP vs. flowrate) across a range of pump speeds and fluid temperatures. In order to comply with this, some fundamental components must be present to support the pump in the test loop: an accumulator, a fluid impedance control, and a heat exchanger. An accumulator is installed upstream of the pump to compensate loop pressure for thermal expansion of the incompressible working fluid. A means of controlling the loop impedance is essential for creating pump curves because, by varying the impedance at a given pump speed, the flowrate and corresponding ΔP for the loop will change. Finally, a heat exchanger is required for testing, since pump performance must be characterized across a wide range of operating temperatures and the working fluid temperatures need to be controlled during testing for consistency.

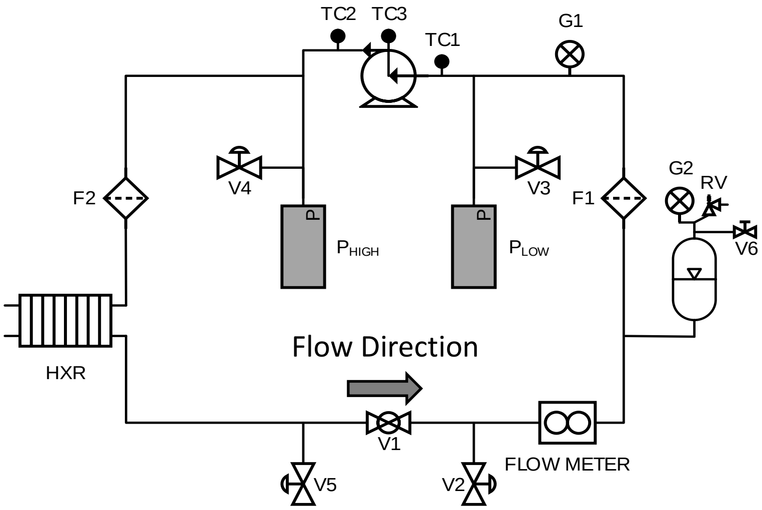

Figure 2. Schematic of test loop used to investigate pump anomaly, where G1 and G2 represent analog pressure gauges, F1 and F2 are inline filters, V1 is a ball valve, V2 – V6 are diaphragm valves, TC1 – TC3 are surface mount thermocouples, and RV is the pressure relief valve mounted on the gas side of the bellows accumulator. The heat exchanger (HXR) is connected to a recirculating chiller to control the temperature of the test loop working fluid.

A. Test Loop Overview

The Europa Clipper HRS utilizes trichlorofluoromethane (CFC-11) as the working fluid, which not only works well for the mission environment, but also has extensive heritage in MPFLs of previous missions and testing at JPL. A key factor during the design of this test system is to ensure material compatibility with the working fluid; thus, only select materials are allowed in wetted paths within the system, these include aluminum, stainless steel, PTFE, and Viton. This strict material control prevents the introduction of materials that are soluble or can break down in CFC-11, which would result in contamination - impacting pump performance. This requirement drives judicious selection of system components to comply with this allowable materials list, but additional attention must be paid to select components which can be adequately cleaned to avoid introduction of foreign particles and debris. An all stainless steel, edge welded bellows accumulator is employed instead of other operating designs or traditional steel housed models to avoid introduction of additional materials into the system. A stainless steel ball valve is selected for impedance control. This may seem like a strange choice and while something like a metering valve provides higher resolution for incremented flow control, it also impacts the loop by way of a much higher pressure drop. The amount of pressure drop added by such a valve would have resulted in the system being too close to the desired operating point and would not have permitted sufficient adjustment range for the test campaign. A stainless steel, stacked-plate heat exchanger was originally used in the system, but closer scrutiny following the anomaly revealed issues that needed to be addressed with this selection.

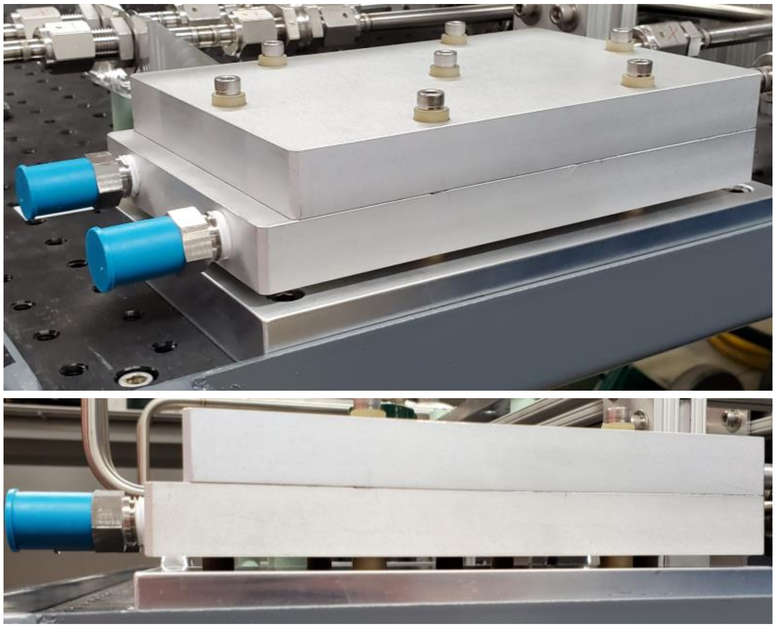

Figure 3. Stacked friction stir-welded cold plate heat exchanger. The top plate is for the CFC-11 working fluid and has welded fittings, while the bottom plate is supplied by a recirculating chiller. The plates are mounted with G10 thermal stand-offs for thermal isolation.

The types of particles discovered following the test anomaly lead to an investigation of the possible sources of these particles in the system. It was determined that the stainless steel, stacked-plate heat exchanger, in use at the time, in fact contained additional brazing alloys. In addition to the brazing alloys, the design for the stacked plate heat exchanger makes it very difficult to precision clean. The presence of corrosion after the anomaly led to concern that the heat exchanger could be a source of moisture introduction to the loop. In an effort to alleviate these concerns for future tests and improve the quality/serviceability of the loop, separate cold plates are employed for the working fluid and chiller loop, as shown in Figure 3. These cold plates are constructed solely from 6061 aluminum and friction stir-welded, resulting in the ability to operate at pressures many times that required for this test bed. The cold plate on the loop side has VCR fittings welded in place to reduce the possibility of leaks that would impact the working fluid. The plates are mounted together with a Grafoil TIM, then bolts and G10 thermal isolation standoffs are used to thermally decouple the loop from the mounting surface. Similar isolators are used at all mounting points for the loop. In addition to addressing the material compatibility concerns for the heat exchangers, these cold plates have very low pressure drops due to their internal design and are easy to precision clean.

B. Instrumentation

Although the accumulator, fluid impedance control, and heat exchanger are the primary loop elements necessary to operate the pump, without instrumentation, the test is of little use. During pump operation, many parameters must be closely monitored to ensure hardware safety and avoid extended operation outside of designated operating ranges.

System pressure is monitored by two pressure transducers, one tapping into the flow line at the inlet of the pump (P_{Low}) and the other at the outlet (P_{High}). The difference between these two transducers is the ΔP across the pump for the loop configuration. While a single standard pressure transducer and a differential pressure transducer could lower the uncertainty of the ΔP measurement, the combined maximum uncertainty for the current setup is ± 0.28 psid (2 kPa) and is acceptable. In addition to the pressure transducers, the loop includes two analog gauges, one for the liquid and one for the gas charge in the accumulator. These analog gauges are important for system safety checks and charging operations.

The flow rate of the pump is measured using an ultrasonic flow meter with two transducers mounted externally on the tubing. These transducers send signals back and forth between each other through the fluid and, based on the time of flight differences with the flow vs against the flow, the fluid speed can be accurately measured without a wetted component. This helps to reduce the risk of contamination inside the system. The flow meter is set up for the specific tubing material, outer diameter (OD), wall thickness, roughness, working fluid properties at operating temperature, and transducer mounting configuration. During steady operation of the pump at nominal flowrates, the uncertainty of the volumetric flow rate measurement is ±0.03 LPM.

Temperature of the pump and fluid are monitored throughout testing to ensure that excessive heating does not occur. Type E thermocouples are instrumented on the inlet, outlet, and surface of the pump body. These measurements help to identify if the power draw for the pump is causing it to heat up too much and thus increasing the fluid temperature across the pump.

Power for the pump is measured in two different ways. First, the average power from the power supply to the motor controller is monitored by measuring the output voltage in parallel and current in series from the power supply with a DAQ and DMM respectively. However, this only provides information on the average power supplied to the controller and does not reveal the actual power supplied to the motor windings of the pump alone. An overview of the instrumentation wiring connection scheme is depicted in Figure 4. A second method of power monitoring is employed to capture the actual power supplied to each winding. This is accomplished by using two oscilloscopes to monitor the power from the controller to the pump. The first oscilloscope monitors the winding voltages, while the second utilizes current probes to capture the current suppled to each winding. This provides valuable information about the waveforms supplied from the controller to the pump motor and can provide quick feedback on the proper operation of the pump during a test.

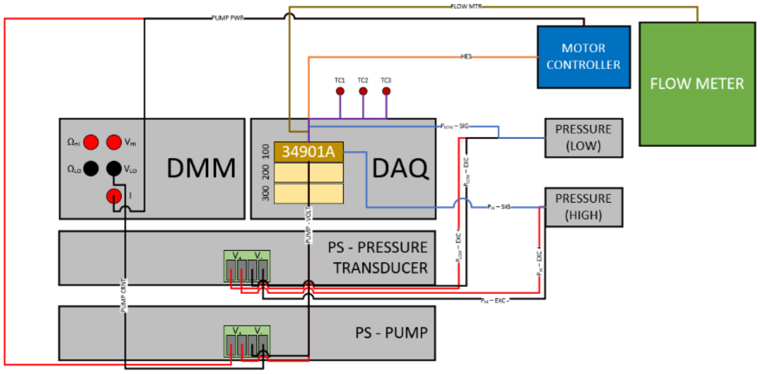

Figure 4. Wiring configuration for primary test bed instrumentation.

Much like power, the feedback signals from the Hall effect sensors (HES) are measured in two different manners. The first takes an average of the HES signal over 10 power line cycles (PLC) using a frequency counter in the DAQ to determine the average rotational speed of the pump; however, this value does not reveal information about the rotational direction or provide any other insight into the actual sequencing within the motor. In order to capture this data, a third oscilloscope is instrumented to capture the HES voltage waveforms. All three oscilloscopes are synchronously triggered from the same HES to allow post-processing of the waveforms and provide insight into the interaction between motor and controller. These waveforms are critical to diagnosing anomalies related to reverse drive or improper ordering of the winding excitation due to incorrect controller configuration.

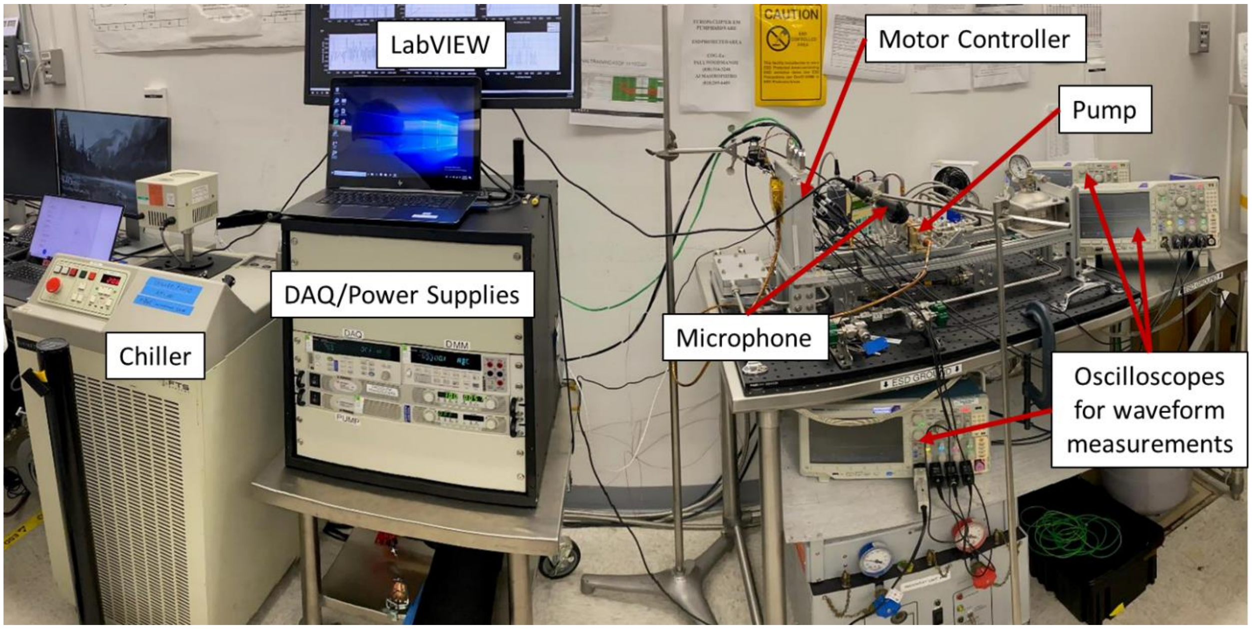

Figure 5. Overview of test bed system for characterization of pump performance.

All instrumentation is controlled and data is collected through a custom LabVIEW VI interface displaying all crucial test information in real time. This allows easy monitoring of the pump operation during testing and quick shut-down if operating values stray outside of allowable limits. A microphone is also utilized to record the operation of the pump and correlate any changes in audible operating frequency to data collected during the test.

C. Cleaning

As discussed in Section III, after the test anomaly, a number of foreign particles and substances were detected inside the pump, the presence of which can be detrimental to the operation of the pump if they are large enough. The allowable particulate size is calculated based upon the minimum flow path feature size within key areas of the pump architecture. There are three means of particle introduction to the pump:

1. Particles contained in the working fluid brought in during system charging
2. Particles generated by system components during the test.
3. Particles which remain in system components prior to the start of the test

The first means of particulate introduction can be addressed with chemical analysis of the source fluid to verify the particulate count, which was conducted along with tests for non-volatile residues (NVR) and moisture content. The CFC-11 working fluid passed all tests verifying that the source fluid for the test is clean. This eliminates option 1, but still leaves both 2 and 3 as possible avenues for particle contamination.

It is not uncommon for some level of particulate generation to occur during operation of MPFLs, but it is critical that any particle generation/shedding is minimized and these particles are prevented from continually circulating through the pump. This system utilizes two all-welded, pleated stainless steel, in-line filters on either side of the pump with different filter sizes: a 2 µm upstream and a 7 µm downstream. The purpose of these filters is to collect any particles that are generated during operation and prevent them from entering the pump during recirculation. A filter size of 2 µm is sufficient to catch any particles large enough to cause problems within the pump, while the 7 µm filter downstream of the pump is in place to catch any large particles prior to entering the heat exchanger. The driving reason to use this filter is to prevent large particles from lodging in hard to clean locations within the heat exchanger in the event of a test failure. In such a case, the in-line filters can be replaced with new filters and the loop can be cleaned appropriately without added complication.

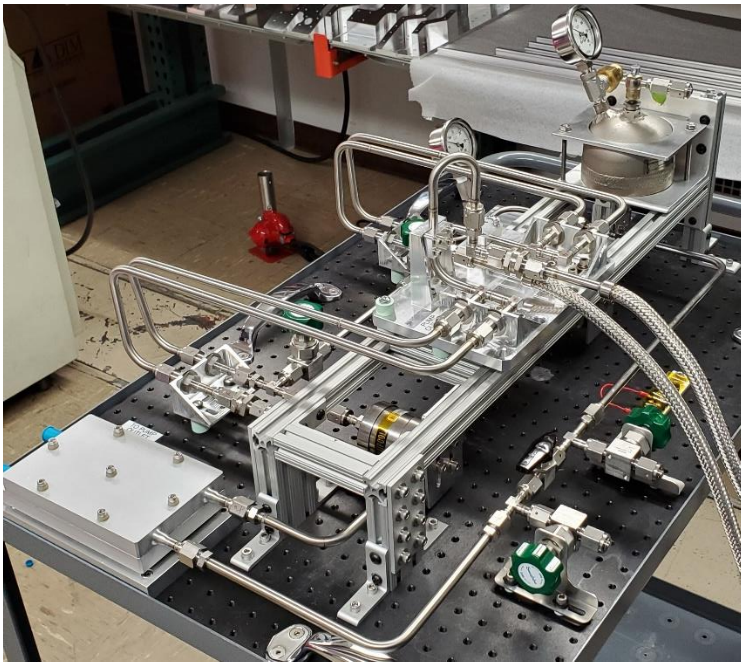

Figure 6. External recirculation cart connected for flow through cleaning of the test loop.

The issue of contamination from particles already present in the system or components is addressed through precision cleaning of the entire loop, all system components, the pump, and any wetted ancillary equipment or lines used during the test procedure. The entire system must be cleaned prior to installation of the pump to ensure that any particulates are removed before the pump is exposed as flow through cleaning cannot be accomplished with the pump in place. The pump is cleaned separately to avoid introduction of system contaminants. Cleaning the loop is accomplished using sacrificial in-line filters combined with an external 2 µm filter. An external recirculating cleaning cart flows heated CFC-11 through the system for a period of time sufficient to meet a cleanliness level of 100A per ISO 14952-2:2003(E). This is verified through samples processed by analytical chemistry to determine the particulate count, NVR, and water content (< 20 ppm) of the CFC-11 pulled from the loop. Once the loop has met this cleanliness level, both the in-line loop filters are replaced with new filters which have been precision cleaned to level 50A to minimize introduction of contaminants to the system. At this time, the pump can be installed into the clean system, but remaining checkouts are required prior to filling the system or operating the pump.

D. Procedures

The need for extensive procedural changes was identified while updating the test bed design. The main focus of all changes was to increase traceability of all steps of the investigation process and ensure that all actions can be tracked and witnessed by at least two people. This includes meticulous procedural check-outs of all cabling, fluid connections, valve positions, pressure levels, instrument settings, facilities verifications, and environmental conditions prior to every test. While the incorporation of these procedures adds time to testing, the information gleaned by them was key in putting together a story of what was occurring in the system after a test is completed and the data is being analyzed. Cleanliness certifications are required and tracked for each test when an external component (flex hose, valve, sample jar, etc.) was connected.

Since there is usually a time delay between cleaning of the loop and installation of the pump, the loop is stored under positive pressure of grade B GN_2 to avoid any contamination from the environment. After the pump installation, it is critical that the dryness of the loop be verified again prior to the CFC-11 fill. The system is purged with grade B GN_2 and a trace moisture analyzer is connected at the outlet to verify that the dew point of the system is < -55°C (< 20 ppm). At this point, the loop can be charged with CFC-11 and fluid samples are collected and archived from the loop sample port during this process. This provides a data point for the quality of the operating fluid and system prior to the start of the test. Similarly, fluid samples are collected and archived following each test when the pump is removed for inspection.

Following the comprehensive design reviews, extensive alterations, and new test methodologies implemented, the system provided a platform which was successfully used to vet performance of a new pump design. The well-characterized test bed enabled the isolation of any anomalous behavior during testing and provided the data and evidence necessary to focus attention on the key issues with the article under test.

V. Lessons Learned

During the in-depth treatment of the pump test bed and efforts to determine the root cause of the testing anomaly, a number of key lessons were learned that may prove useful as general guides in other systems. The most salient lesson is that routine cable inspections should be conducted prior to every test. The root cause of the initial anomaly was traced to a laceration in the jacket insulation of the pump cable caused by manipulation of the back shell after connection with the pump. This laceration occurred between the strain-relief back shell of the cable and a HES signal conductor, which shorted the signal to the ground of the pump chassis. This cable had been previously examined prior to the failure and was determined to be in good condition, but manipulation of the back shell after installation led to the creation of a small slit in the insulation, which was just enough for the signal to ground out. This cut was not visible without magnification, and all parts passed visual inspection. Given this, all testing now implements mandatory pin-to-pin and pin-to-ground buzz out inspections prior to every connection and power on for the system.

Cleaning procedures and protocols were also updated after the discovery of particles in the pump following the test anomaly. Since the cleaning of the loop prior to the test was not documented with full traceability, the exact state of the loop prior to the anomaly is not known. This makes it impossible to say with certainty if the particles existed before the test and contributed to damage or if they were created during the test as a result. The lesson learned is to fully establish the state of the loop and hardware cleanliness prior to any testing operation, even development tests, which allows full visibility and traceability for the conditions surrounding the test should an anomaly occur. The new standard practice with this test bed is to collect samples of the working fluid at the time the loop is charged and prior to recovering all fluid. This provides an archive of samples that can be analyzed if any suspect behavior presents, allowing a full before and after picture of the condition of the working fluid. Another outcome of the rigorous cleaning treatment was the discovery that some parts bags employed were treated with an amide coating on the inside to minimize the bag sticking to itself and make it easier to load. This coating was easily transferred to parts and can introduce unwanted material into the wetted flow path of the system.

Due to the large number of charging and recovery operations required for this test bed investigation, a new charging procedure was developed to eliminate the need for a non-condensable gas ullage when charging the loop with CFC-11. This gas ullage needs to be recovered any time the charging cylinder is refilled and can be time-consuming and difficult to properly recover due to the nature of a non-condensable gas and the limitations of the recovery equipment. A new charging procedure was created which eliminates the non-condensable gas ullage in the charging cylinder for pressurization, but instead uses a pure CFC-11, two phase charging cylinder and a heated jacket to increase the cylinder pressure. This provides an effective alternative to traditional charging methods without the need for elaborate recovery of the ullage gas.

A strange behavior presented during testing after the new test bed was constructed where the loop was losing pressure without any measurable external leak. This did not seem possible, and after extensive testing it was determined that an internal leak was present between the loop (the portion at a higher operating pressure) and the low-pressure charging cylinder that remained connected to minimize the volume of CFC-11 that must be recovered for every test. This leak was occurring internally across a diaphragm valve; thus, nothing was introduced to the atmosphere and was not measurable by external sniffing leak detectors. At the time of the discovery, leak checking across internal system valves was not part of the procedure, but following this discovery, all valves used to isolate large pressure differences are checked to verify leak levels. It was determined that the leak originated due to minor damage to the soft good seat of the valve caused by over-tightening of the valve during test operation. The leak was corrected, all test operators were briefed on the appropriate valve tightening procedure, and, where possible, all extraneous connections were removed from the system and sealed with a cap prior to testing.

During the investigation into the loss of a HES feedback signal during the initial anomaly, which was later attributed to the short stemming from the harness laceration, a detailed examination of HES failure mechanisms was conducted. As an added precaution against future anomalies, it was concluded that increased electrostatic discharge (ESD) precautions were necessary and should be enacted for the test bed. The HES components in use have a relatively low susceptibility to ESD (<500V), but added measures were enacted to fully protect the hardware. A grounding plug was fabricated to fully protect the pump HESs when not connected to the controller, permitting safe handling for inspection and disassembly/assembly operations. Wrist straps have always been utilized when handling the pump, but facilities surrounding the pump test loop operation were updated for ESD compliance, all test personnel received updated ESD training, and the system grounding was revised to achieve a single point grounding scheme, which has the added benefit of reducing signal noise for data acquisition.

Separating performance of the pump from possible impacts of the motor controller is vital to fully vetting the performance of the pump. In order to accomplish this decoupling, commercial motor controllers were first used to assess the baseline motor response, then subsequent performance testing can be conducted with the custom designed flight or flight-like controller. Commercial controllers can be configured for a wide range of motors, so configuration control of the controller is imperative and needs to be verified prior to connecting the pump under evaluation to avoid the possibility of damage. Configuration can be verified by the use of a benchtop motor stand to test proper wiring and settings in a similar fashion to that used in the pump. This wiring configuration can then be confirmed on previous generation pump motors in other test loops. While this will allow the bulk of the controller configuration to be verified, it cannot verify drive direction for the pump under test. Due to manufacturing differences between generations of motors, it is possible the controller could still drive the new motor in reverse even after these verification checks. Due to this possibility, it is critical that careful attention is paid during start-up of the motor. If the pump is found to experience high power draw but minimal flowrate and pressure head, then the pump should be shut-off and the controller configuration modified to reverse the drive direction.

VI. Conclusion

The meticulous process used in the development of the new test bed for pump characterization resulted in a system that is a fully capable platform for vetting new pump designs. Discoveries made and lessons learned along the path have enhanced the test planning process and provided greater insight into the impact of the system design on the pump during testing. As a result, well-vetted procedures and carefully planned test campaigns will facilitate rapid characterization of key pump hardware and will provide confidence in the performance of this hardware during future missions.

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