Water Pump Development for the EVA PLSS

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Abstract

This paper describes the effort by the Texas Engineering Experiment Station (TEES) and Honeywell International for NASA to design, fabricate, and test a pre-flight prototype pump for use in the Extra-vehicular activity portable life support subsystem (PLSS). Major design decisions were driven by the need to reduce the pump's mass, power, and volume compared to the existing PLSS pump. In addition, the pump will accommodate a much wider range of abnormal conditions than the existing pump, including vapor/gas bubbles and increased pressure drop when employed to cool two suits simultaneously. A positive displacement, external gear type pump was selected because it offers the most compact and highest efficiency solution over the required range of flow rates and pressure drops. An additional benefit of selecting a gear pump design is that it is self priming, capable of ingesting non-condensable gas without becoming "air locked" and is highly tolerant to contamination.

The chosen pump design consists of a 28 V DC, brushless, sealless, permanent magnet motor driven, external lobe gear pump that utilizes a Honeywell development that eliminates the need for an inline magnetic coupling. Although the planned flight unit will use a sensorless motor with custom designed controller, the pre-flight prototype to be provided for this project incorporates Hall Effect sensors, allowing an interface with a readily available commercial motor controller. This design approach reduced the cost of this project and gives NASA more flexibility in future PLSS laboratory testing. The pump design was based on existing Honeywell designs, but incorporated features specifically for the PLSS application, including all of the key features of the flight pump.

Testing at TEES will simulate the vacuum environment in which the flight pump will operate. Testing will verify that the pump meets design requirements for range of flow rates, pressure rise, power consumption, working fluid temperature, operating time, and restart capability. Pump testing is currently scheduled for March, 2009, after which the pump will be delivered to NASA for further testing.

Introduction

NASA requires an improved portable life support subsystem (PLSS) water pump to support future missions. The current PLSS water pump is a centrifugal multi-vane type pump that operates at high speed (~20,200 rpm). This centrifugal pump is sensitive to gas bubbles and can require priming before extravehicular activity (EVA), lengthening EVA preparation time. To minimize outgassing and bubble formation during EVA, the current PLSS uses a special pressurizing system that maintains the water loop at 15 psi via a dedicated 15 psi oxygen regulator that provides backpressure to the feedwater tanks. In addition, the PLSS uses a gas trap and a centrifugal water separator to remove gas from the water loop. Despite these precautions, the current pump has experienced cavitation issues and has shown susceptibility to water impurities.

The current PLSS design goals for the Constellation Space Suit Element require the PLSS pump to use potable water from the vehicle or habitat that has been nominally delivered at 8 psi. NASA also desires to reduce the mass, volume, and power consumption of the pump in order to support longer duration EVAs.

As a result of the goals, and the deficiencies of the existing equipment, NASA contracted with TEES to design, build, and test a Custom Unit Pump (CUP) for future use in the PLSS. TEES in turn teamed with Honeywell on the basis of their experience and success with gear pump designs for spaceflight that could meet the requirements of the solicitation.

Requirements

The primary requirements for the CUP are derived from JSC-65685, Development Requirements for Waterpump in EVA Technology System (WETS), but are modified for the purposes of development testing. The primary requirement is to provide water flow for thermal regulation to a suited EVA crewmember's Liquid Cooling Garment and to spacesuit components during EVA in vacuum, Lunar, and Martian environments. EVA duration has been set at 8 hours, with an additional 2 hours of pump operation during EVA preparation, leading to a 10 hour continuous operation requirement. The design flow rate is 200 lbm/hr at 5 psid water loop pressure drop. The pump must be capable of operating from 40-240 lbm/hr at 5 psid and must be capable of providing 180 lbm/hr at 10 psid for emergency operations. Operating temperature, defined as the water temperature at the inlet of the pump, ranges from 35 to 100 ^{o}F. The pump must be capable of starting over this entire temperature range. The pump must accommodate water loop pressures at the inlet ranging from 3.3 to 10 psig. The pump may operate in ambient environments, but must be capable of operating in vacuum. Useful life is set at 2000 hours using potable water. Power consumption must not exceed 15 W +/- 10% at 28 VDC.

Pump Design

Approach

Our approach was to design an application specific pump that would meet all of the requirements of the flight PLSS Waterpump, then to fabricate a pre-flight prototype that contained the key design features of the flight pump using existing Honeywell designs that could be fabricated within program budgetary constraints. The features and materials of both flight and prototype are similar with the modifications resulting in larger size and different nominal operating speed.

Pump Type Selection

Prior work by NASA determined that the pump type would be positive displacement, selected for its ability to ingest gas bubbles without becoming gas bound or “air-locked”. There are a number of positive displacement pump types available, ranging from gear pumps and Gerotor pumps to screw and roots pumps, diaphragm pumps, reciprocating pumps and scroll pumps. Each type has numerous variations. We selected a gear pump as it offered the most compact and highest efficiency solution. Gear pumps are self priming and capable of ingesting non-condensable gas without becoming “air locked.” Honeywell also has considerable experience with gear pumps, having a number of designs that could be modified for this application with minimum effort and cost.

We eliminated Gerotor pumps as we deemed them more complex to fabricate and operate and provided no performance advantages. We deemed the extra complexity as making it more susceptible to failure from contamination which is possible in a biological system such as a space suit. We eliminated screw/roots type pumps as they are more suitable for larger applications than this and are complex and expensive to fabricate. Various types of diaphragm pumps were eliminated due to their high pressure pulses and concerns over diaphragm fatigue failures. Other types of pumps such as reciprocating pumps and scroll pumps were dismissed due to their complexity and cost for this application.

Detailed Design

The flight gear pump design uses an application specific pump head and motor design, operating at a nominal speed of 5600 rpm. The prototype pump uses the pump head and housings from a Honeywell Auxiliary Power Unit (APU) fuel pump connected to a motor based on Honeywell’s International Space Station Internal Thermal Control System Pump Package Assembly (PPA) with the stator rewound for this voltage. The modified PPA motor fits within the existing APU fuel pump motor housing. Figure 1 shows the APU Fuel Pump, Figure 2 shows the APU Fuel Pump Cross-section, Figure 3 shows the APU Fuel Pump Cartridge Section, and Figure 4 shows the APU Fuel Pump Cartridge Components.

The APU fuel pump was designed for different flow rates and pressure rise than the PLSS Waterpump. The gear lobes were lengthened and its nominal operating speed lowered to 3560 rpm in order to meet the specified pressure vs. flow requirements at the PLSS Waterpump design point.

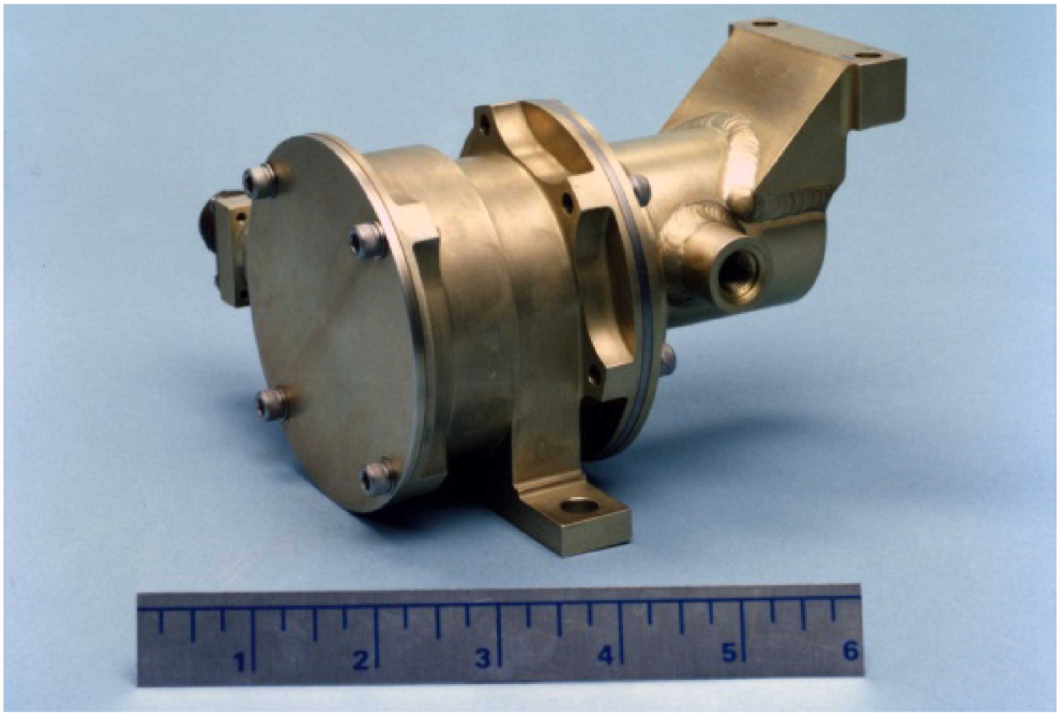

Figure 1, APU Fuel Pump

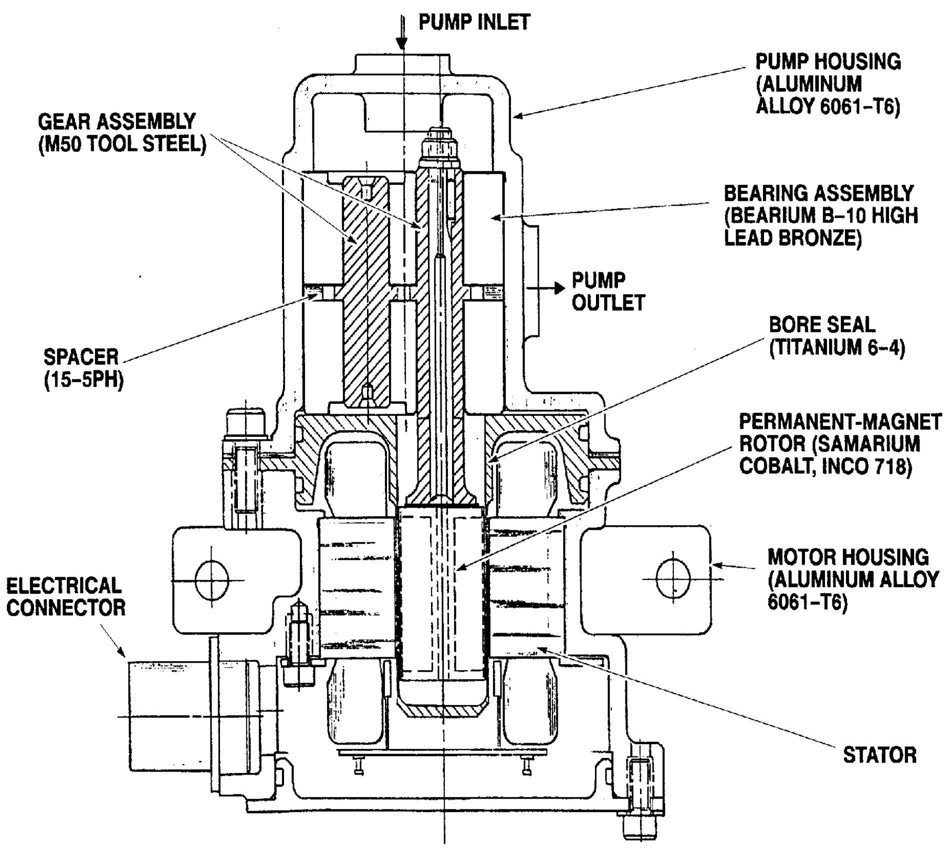

Figure 2. APU Fuel Pump Cross-section

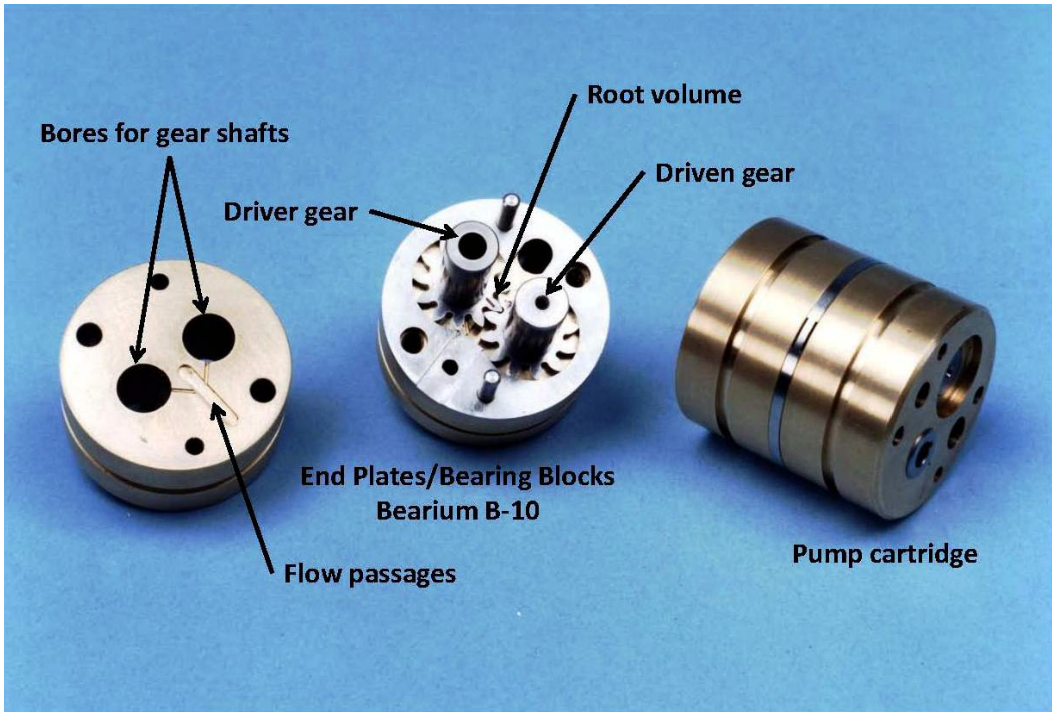

Figure 3, APU Fuel Pump Cartridge Section

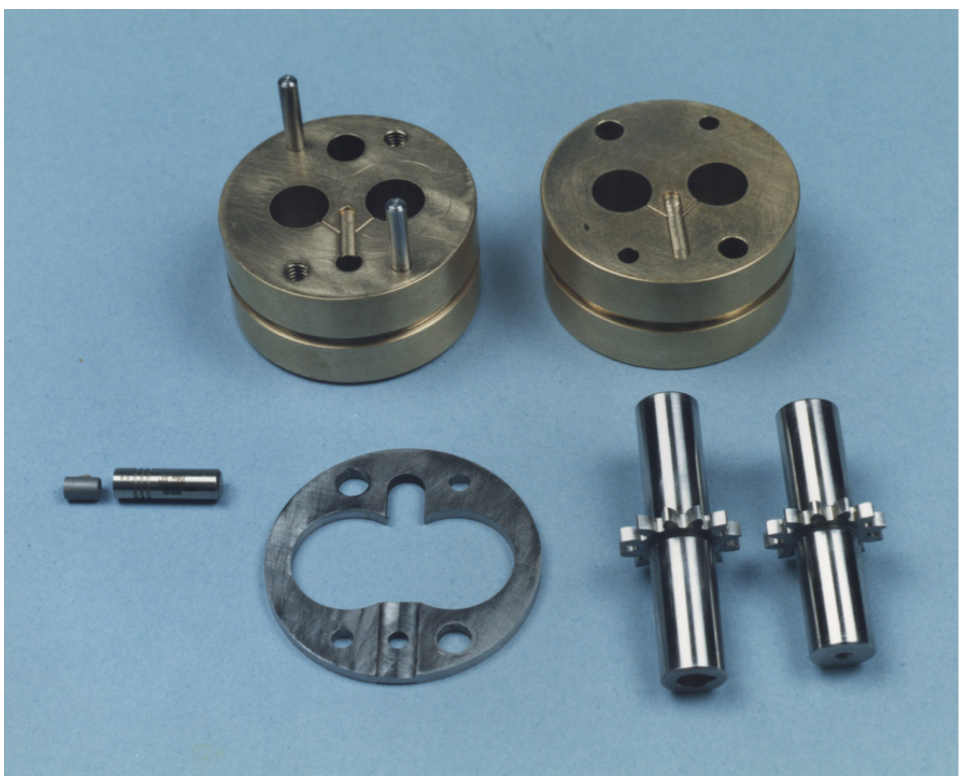
Figure 4. APU Fuel Pump Cartridge Components

The gear lobe profiles for both flight and prototype pumps are shaped specifically for a pump application, as opposed to gear profiles designed for power transmission. Many pumps use power transmission gear lobe profiles due to availability and manufacturing cost. These profiles minimize gear wear under high loads and are more efficient for power transmission, but less efficient for pumping. The difference between the two is the clearance or gap at the root of the gears when they are mated. Transmission gear profiles have a greater gap, resulting in a relatively large root volume. Incompressible liquid is trapped in the root volume, as shown in Figure 3. This trapped liquid is squeezed between the gears upon mating, increasing the fluid's pressure, and creating forces acting to separate the gears from each other. The energy that goes into increasing the trapped volume's pressure increases power consumption, reducing efficiency. The pump components also have to be larger to handle the side loads generated on the gears.

The peak and root of pump application gears are more closely matched, resulting in small root volumes and little trapped non-compressible liquid. The result is lower power consumption, higher efficiency and smaller, lighter pump components.

The pump cartridge end plates are fabricated from Bearium B-10, a bronze based bearing material and provide the journals for non-contacting hydrodynamic journal bearings for the gear shafts as shown in Figure 3. The gear's side surfaces also contact the B-10 bearing material in order to form better sealing to minimize internal leakage that would bypass the gear set.

Motor Design and Controller Selection

The motor operating voltage of 28 V DC was specified by NASA. We selected a two pole, brushless, permanent magnet motor utilizing a sensorless motor control scheme eliminating the need for Hall Effect rotor position sensors. Sensorless motor control schemes are standard for the current generation of Honeywell pumps for commercial aircraft, and so were deemed a mature and reliable technology. Sensorless motor control requires application specific control algorithms to achieve maximum motor efficiency and is therefore beyond the funding and schedule scope of this program. Low cost commercially available sensorless controllers, such as those used on model airplanes, were designed to operate at lower voltages, and so were deemed not applicable. Therefore, the prototype used conventional Hall Effect rotor position sensors and a generic Motion Control Systems motor controller, as shown in Figure 5. Using the Hall Effect sensor also gives the NASA the flexibility to use any other test rig controller during testing.

The motor stator is cooled by the working fluid. Motor stator heat generated is conducted from the stator windings through a stationary metallic fluid barrier to the fluid side of the barrier where the working fluid removes the heat convectively. Working fluid is diverted from the high pressure side of the pump cartridge to the motor area for cooling. It then exits the motor area via a center passage in the driver gear shaft to the low pressure side of the pump cartridge creating the flow necessary for convective heat transfer.

The motor rotor is cantilevered off of the driver gear shaft so no bearings dedicated only to the motor are used.

Figure 5, Motion Control Systems Motor Controller

<u>Pump/Motor Coupling</u>

The pump uses a direct shaft to the motor rotor, so no in-line magnetic coupling is used to maintain fluid sealing. A stationary fluid barrier encases the entire pump cartridge and rotor shaft, segregating the working fluid from the stator and Hall Effect sensors. The stationary fluid barrier terminates at the motor end of the assembly using an o- seal between the OD of the barrier and the ID of motor housing bore (bore seal). This provides semi-hermetic sealing of the working fluid. The magnetic coupling is from the stator to the rotor; as in a typical motor, only the magnetic flux passes through the thin metallic fluid barrier. Figure 6 shows the stationary fluid seal within the pump.

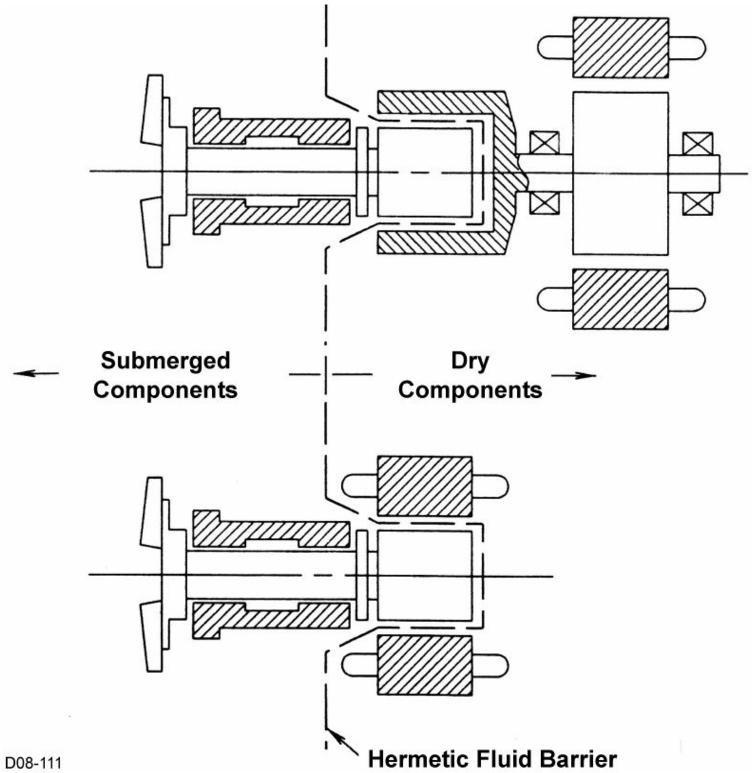

Figure 6. Pump/Motor Coupling.
Top figure is conventional magnetically coupled pump.
Bottom figure is Honeywell direct drive pump.

Predicted Performance/Characteristics

Table 1 summarizes key pump characteristics for the pre-flight prototype and the flight unit. The main differences between the pre-flight prototype and the flight unit are size, weight, power required, and the motor controller. The power consumption of the pump and motor are expected to be approximately 8 Watts at the design point. We anticipate a significant difference in total power consumption between the pre-flight prototype and the flight unit due to motor controller efficiency. For the pre-flight prototype, we assumed a commercial motor control with an efficiency of 50%, yielding a total power consumption of 16 Watts at the design point. The flight unit will use a sensorless motor controller specifically designed for this application, which should reduce the total power consumption to approximately 12 Watts at the design point.

Table 1. Key Pump Parameter Comparison

Parameter	Pre-flight Prototype	Flight
Design Point Flow, gpm	0.40	0.40
Design Point Delta P, psig	5	5
Design Point Power, W	8 (pump/motor) 16 (with controller)	8 (pump/motor) 12 (with controller)

Min. Inlet Press. Reqd., psia	2.6	2,6
Flow Range, gpm	0.1 to 0.8	0.1 to 0.8
Design Speed, rpm	3560	5600
Gear Diameter, inch.	0.72	0.46
Pump Head Max. Diameter, inch.	2.5	1.8
Pump Length, inch	5.9	2.15
Pump Weight, lb	3.1	0.82
Power Type, VDC	28	28
Coupling type	None; one piece rotor shaft	None; one piece rotor shaft
Rotor Position Feedback	Hall effect sensor	Sensorless
Bearings – Motor	None	None
Bearings – Pump	Integral hydrodynamic journal	Integral hydrodynamic journal
Gear Material	Stainless Steel	Stainless Steel
Shaft Material	Stainless Steel	Stainless Steel
Gear/Shaft Retention	NA – One piece integral	NA – One piece integral

Test Plan

The purpose of this testing is to demonstrate that the CUP meets the requirements of DO-37. From the requirements levied by NASA, we identified the following major testing requirements

1. 10 hours continuous operation

2. Surface temp 35 F to 100 F (also startup at that range of water inlet temperatures)

3. Flowrate and pressure rise

200 lbm/hr (1.5 l/min) at 5 psid (design point)
180 lbm/hr (1.35 l/min) at 10 psid (emergency)
Flowrate controllable from 20-120% of nominal (0.3-1.8 l/min) for all conditions

4. Inlet water pressure 3.3 – 10 psig

The independent variables for these tests will be water inlet temperature and flowrate. Inlet water pressure will be varied over its range during each test run. Water loop pressure drop will be set to 5 psid for most of the tests and 10 psid for a few of the tests. The dependent variables are power consumption (15 W +/- 10% at 5 psid) and surface temperature of the CUP. By demonstrating that power consumption and temperature remain within the allowable limits over the entire range of testing, we will have demonstrated that the CUP meets the requirements of the project.

Parameter values

T is inlet water temperature. Q is flowrate. Primary testing will occur with the water loop pressure drop set at 5 psid. Secondary testing will occur with the water loop pressure drop set at 10 psid. Inlet pressure will be varied from 3.3 to 10 psig during each test run. All testing will occur with the CUP in vacuum ($P<10^{-4}$ torr). Table 2 defines the values of each level of the main input parameters (temperature and flow rate). Table 3 lays out the test sequence with the loop pressure drop set at 5 psid.

Table 2. Parameter Level Definitions

Parameter Level	Temperature (^oF)	Flow rate (lbm/hr)
1	35	40
2	70	100
3	100	200
4	n/a	240

Table 3. Primary Test Sequence

Run Number	Parameter Values	Duration (hours)
1	T2 Q3	10
2	T3 Q2	2
3	T1 Q1	10
4	T1 Q4	10
5	T2 Q1	2
6	T1 Q2	2
7	T3 Q3	2
8	T2 Q4	10
9	T3 Q1	10
10	T2 Q2	2
11	T1 Q3	2
12	T3 Q4	10

Run 1 is the nominal operating environment for the pump. Runs 3 and 12 are the extreme operating environments. Run 9 is the expected highest temperature condition, due to the minimum fluid cooling of the pump. The other long duration runs are at the highest (most stressing) flow rates.

Table 4 lists the parameters for the 10 psid test runs.

Table 4. High Pressure Drop Test Sequence

Run Number	Parameter Values	Duration (hours)
13	T2 Q3	2
14	T3 Q4	2
15	T1 Q1	2

Data recorded will include power consumption of the pump and of the controller (measured as input voltage and current), pump inlet pressure, loop pressure drop, pump speed and water flow rate, pump surface temperature, and fluid inlet temperature.

Bubble/vapor testing

We expect vapor and gas bubbles to evolve within the water loop as we lower the pump inlet pressure. We will observe the evolution of these bubbles via the transparent sections in the piping. If the size and quantity of these bubbles do not, in our opinion, constitute a sufficient test of the pumps ability to operate despite ingesting bubbles, we will use the gas inlet port to introduce quantities of gas to the system, to create larger and more frequent bubbles. While not definitive, this testing should establish the basic ability of the pump to operate through gas ingestion, one of NASA's goals for the CUP.

Test Water Loop

Figure 7 is a schematic of the water test loop showing the piping layout and locations for the instrumentation. The vacuum boundary encloses those parts of the water test loop that are in vacuum; the remainder of the test loop is at ambient conditions. The pressure drop in the water loop will be controlled by the setting of the metering valve M1, while pump inlet pressure will be controlled by the settings on an eductor attached to the accumulator.

The loop will be set to the conditions specified for a particular run using the gear pump and the heating tape or cooling coils. Once the test conditions are set, the gear pump will be shut off long enough for the water in the loop to stop flowing. The gear pump will then be turned on, to demonstrate its ability to start under the full range of environments specified by NASA. The loop will be run to steady state at each pump inlet pressure, then the pump inlet pressure will changed to the next state point. We will cycle through the entire range of pump inlet pressures each run.

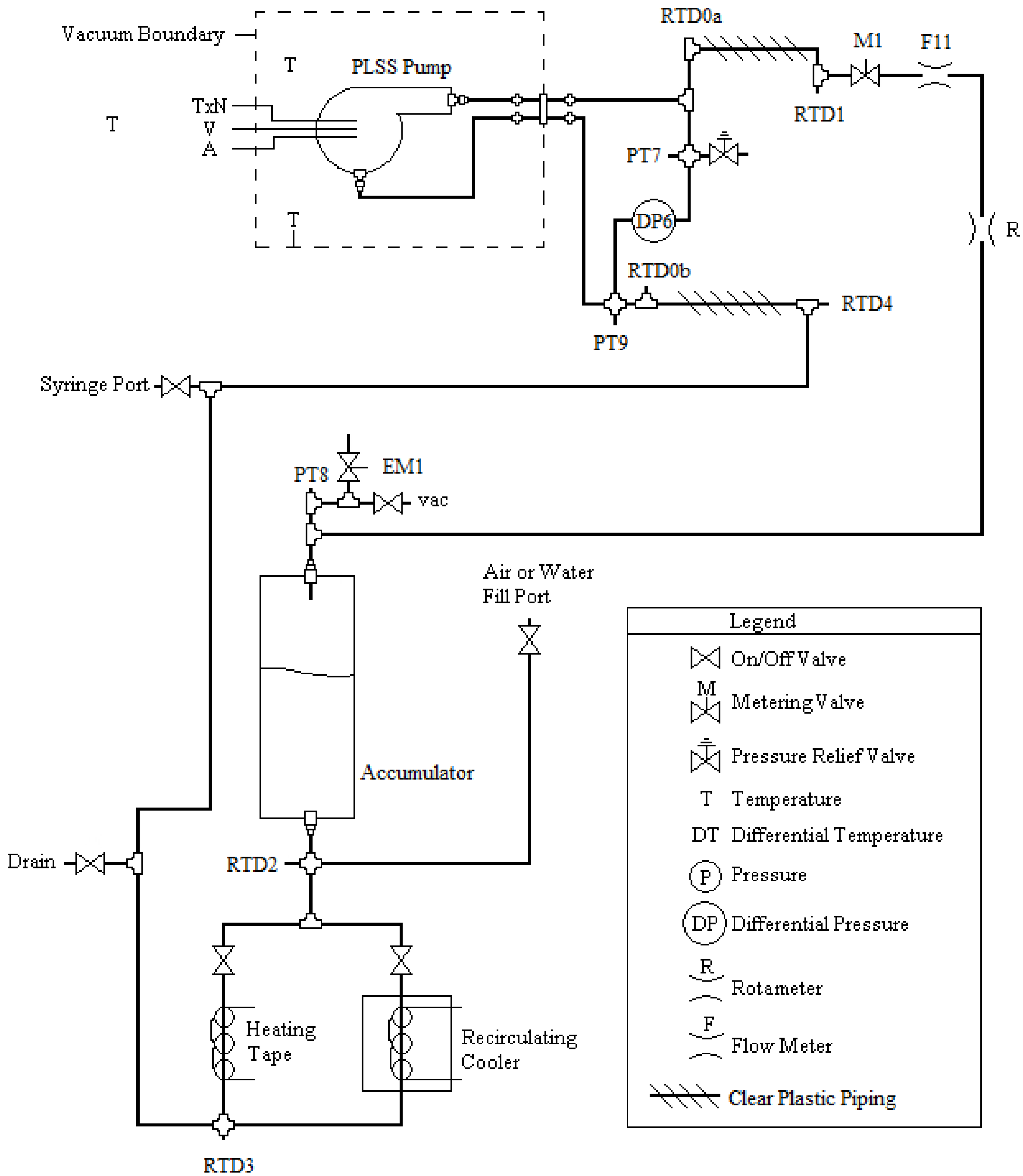

Figure 7. Water Loop Schematic for CUP Testing.

Expected Results

The output parameters will be the surface temperature and power consumption of the pump and motor. We plan to separately measure the power consumption of the pump controller. By showing that the output variables remain within the limits prescribed by the project over the entire input parameter range, we will have met the objective of the project. We expect that the power consumption of the pump and motor will not exceed 8 W and that the surface temperature will not exceed the inlet water temperature by more than 1 ^{o}F.

Summary

TEES and Honeywell have designed and are building a compact, efficient pump suitable for use in the Constellation Space Suit PLSS. We are prepared to test the pump over the range of operational conditions it will encounter in use in a vacuum environment.