# Development of a Fan for Future Space Suit Applications

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## Abstract

NASA's next generation space suit system will place new demands on the fan used to circulate breathing gas through the ventilation loop of the portable life support system. Long duration missions with frequent extravehicular activities (EVAs), the requirement for significant increases in reliability and durability, and a mission profile that imposes strict limits on weight, volume and power create the basis for a set of requirements that demand more performance than is available from existing fan designs.

This paper describes the development of a new fan to meet these needs. A centrifugal fan was designed with a normal operating speed of approximately 39,400 rpm to meet the ventilation flow requirements while also meeting the aggressive minimal packaging, weight and power requirements. The prototype fan also operates at 56,000 rpm to satisfy a second operating condition associated with a single fan providing ventilation flow to two spacesuits connected in series. This fan incorporates a novel nonmetallic "can" to keep the oxygen flow separate from the motor electronics, thus eliminating ignition potential. The nonmetallic can enables a small package size and low power consumption. To keep cost and schedule within project bounds a commercial motor controller was used. The fan design has been detailed and implemented using materials and approaches selected to address anticipated mission needs. Test data is presented to show how this fan performs relative to anticipated ventilation requirements for the EVA portable life support system. Additionally, data is presented to show tolerance to anticipated environmental factors such as acoustics, shock, and vibration. Recommendations for forward work to progress the technology readiness level and prepare the fan for the next EVA space suit system are also discussed.

## Introduction

NASA is designing an EVA space suit portable life support system (PLSS) that utilizes separate assemblies for the fan and water pump and does not require an electrically powered rotary moisture separator. This approach allows the separate fan and water pump to be individually optimized for the PLSS ventilation and thermal loops. Figure 1 shows the PLSS schematic [1]. The requirements derived from NASA's PLSS architecture studies dictate a fan design that is different from the fan used in the extravehicular mobility unit (EMU), NASA's current space suit design. The top level requirements are provided in Table 1 and show the need for an extremely low power, lightweight and small fan assembly [2]. Coupled with these sizing requirements are performance requirements incorporating three operating points. The first operating point is based on the nominal flow and pressure rise required to manage carbon dioxide and humidity levels within the space suit helmet and to drive gas flow through the ventilation loop. As this operating point is the only one with a known power requirement, it is the aerodynamic design point for this fan and is termed the “Design Point.” The second operating point has been termed the “Buddy Point” and is associated with a failure condition of one PLSS so that a single fan drives flow through two space suits connected in series via an umbilical. The final point, called the “Maximum Flow Point” is based on an alternate space suit design that requires a higher flow rate in the ventilation loop than the baseline PLSS design.

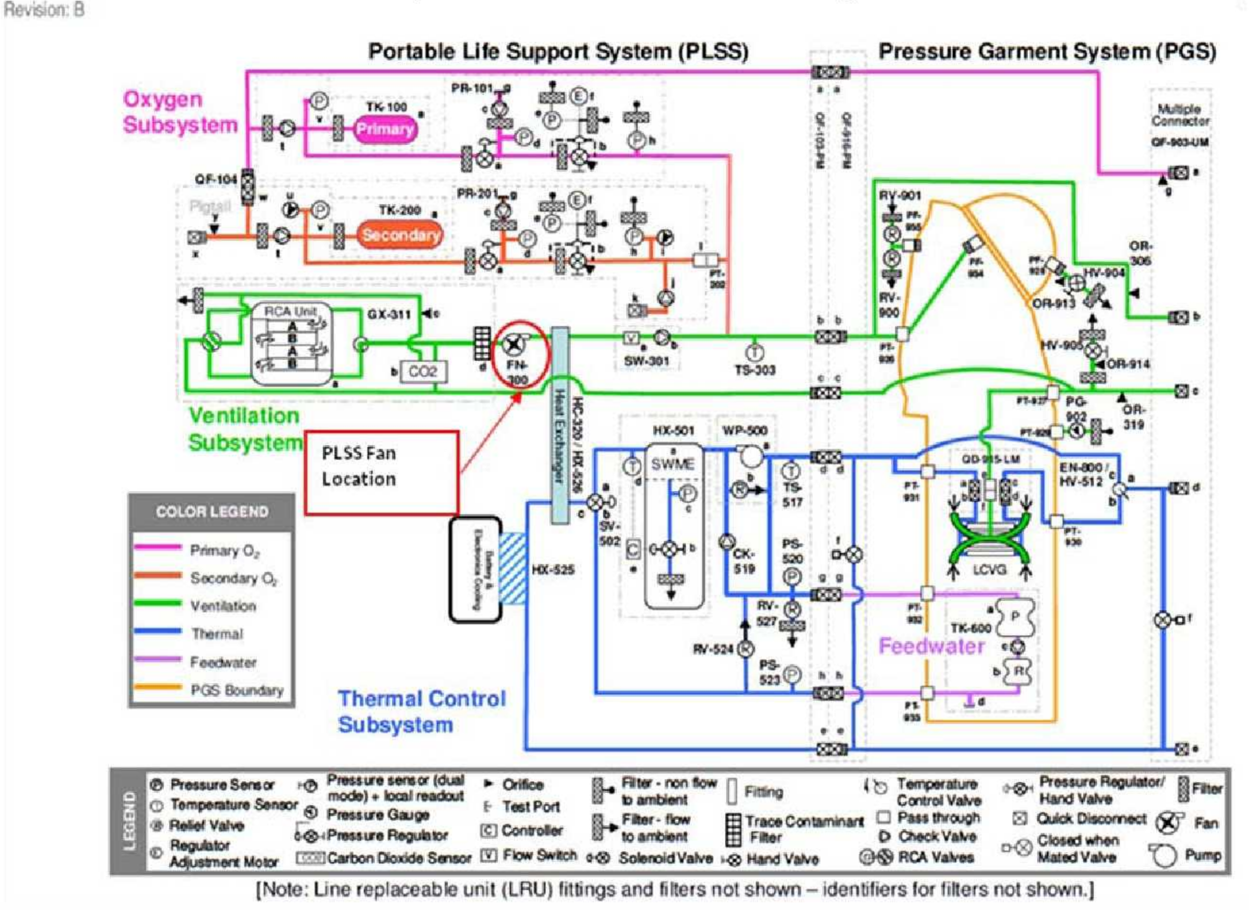


**Figure 1: PLSS Schematic with Fan Identified [1]**

**Table 1: Critical Fan Assembly Requirements**

| Parameter | Design Point | Buddy Point | Max Flow Point |
|---|---|---|---|
| Fan Assembly Overall Power (W) | 14 | - | - |
| Motor Input Power (W) | 6 | - | - |
| Mass (kg/lb$_m$) | 0.91 / 2.0 | same | same |
| Envelope (m$^3$/in$^3$) | 4.9x10$^{-4}$/30 | same | same |
| Flow & Pressure Rise (m$^3$/sec & Pa) or (cfm & inches $H_2O$) | 2.22*10$^{-3}$ / 672<br>4.7 cfm / 2.7 in $H_2O$ | 4.44*10$^{-3}$ / 1681<br>9.4 cfm/ 6.75 in $H_2O$ | 2.8*10$^{-3}$ / 1021<br>5.9 cfm / 4.1 in $H_2O$ |
| Inlet Conditions (Pa / psi) | 29649 / 4.3 | same | same |

A centrifugal fan design was deemed most appropriate for this application. A centrifugal fan by definition has the flow exiting the impeller in a radial plane. To facilitate PLSS packaging, it was desirable to turn the ventilation flow 90 degrees using the fan, therefore a configuration with flow entering axially and exiting in the radial plane was designed. The resulting conceptual design (Figure 2) meets the specified performance requirements.

**Figure 2: The PLSS Fan Conceptual Design**

## Requirements, Goals, and Design Considerations

The NASA specification for this project contained three categories: requirements, goals and design considerations, described as follows and summarized in Tables 2 through 4:

- **Requirements**—NASA provided functional requirements (Table 2) for the fan and further mandated that all the requirements be demonstrated by functional operation and measurement. Exceptions were provided for the working gas requirement (R4, Table 2) for test purposes and for the useful life requirement (R5, Table 2).
- **Goals**—Goals are design needs that shall be addressed but are not required to be implemented exactly as specified (Table 3).
- **Design Considerations**—Design considerations are needs that should be considered but are not necessarily incorporated into the fan assembly (Table 4).

**Table 2: Fan Assembly Goals**

| Requirement # | Description | Requirement |
|---|---|---|
| **R1** | Minimum Delta Pressure at $2.22\times10^{-3}$ $m^3$/sec (4.7 cfm) | 672 Pa<br>(2.7 in $H_2O$) |
| **R2** | Overall Power Consumption | 14.0 W |
| **R3** | Gas Inlet Pressure and Temperature | 29,649 Pa (4.3 psia)<br>20 °C (68 °F) |
| **R4** | Fan Working Gas | Design for 100% oxygen; test with nitrogen |
| **R5** | Useful Life | 2,500 hours min<br>(2.5 x EVA Life) |
| **R6** | Fan/ Motor External Operating Environment Pressure | 101,356 Pa (14.7 psia) |
| **R6a** | Fan/ Motor External Operating Environment Pressure | less than $10^{-4}$ Torr |
| **R7** | Associated Electronics External Operating Environment | 101,356 Pa (14.7 psia) |
| **R8** | Supply Voltage | 28 Vdc |
| **R9** | Assembly Mass | 0.91 kg (2.0 $lb_m$) |

**Table 3: Fan Assembly Goals**

| Goal # | Description | Goal |
|---|---|---|
| G1 | Fan/Motor Subassembly Power Consumption | 6.0 W Maximum |
| G2 | Associated Electronics Power Consumption | 8.0 W Maximum |
| G3 | Fan Assembly Maximum Volume | $4.9\times10^{-4}$ $m^3$<br>(30 $in^3$) |
| G4 | Minimum Delta Pressure at $2.8 \times 10^{-3}$ $m^3$ /s (5.9 cfm) | 1021 Pa<br>(4.1 in $H_2O$) |
| G5 | Minimum Delta Pressure at $4.44 \times 10^{-3}$ $m^3$/s (9.4 cfm) | 1681 Pa<br>(6.75 in $H_2O$) |

**Table 4: Fan Assembly Design Considerations**

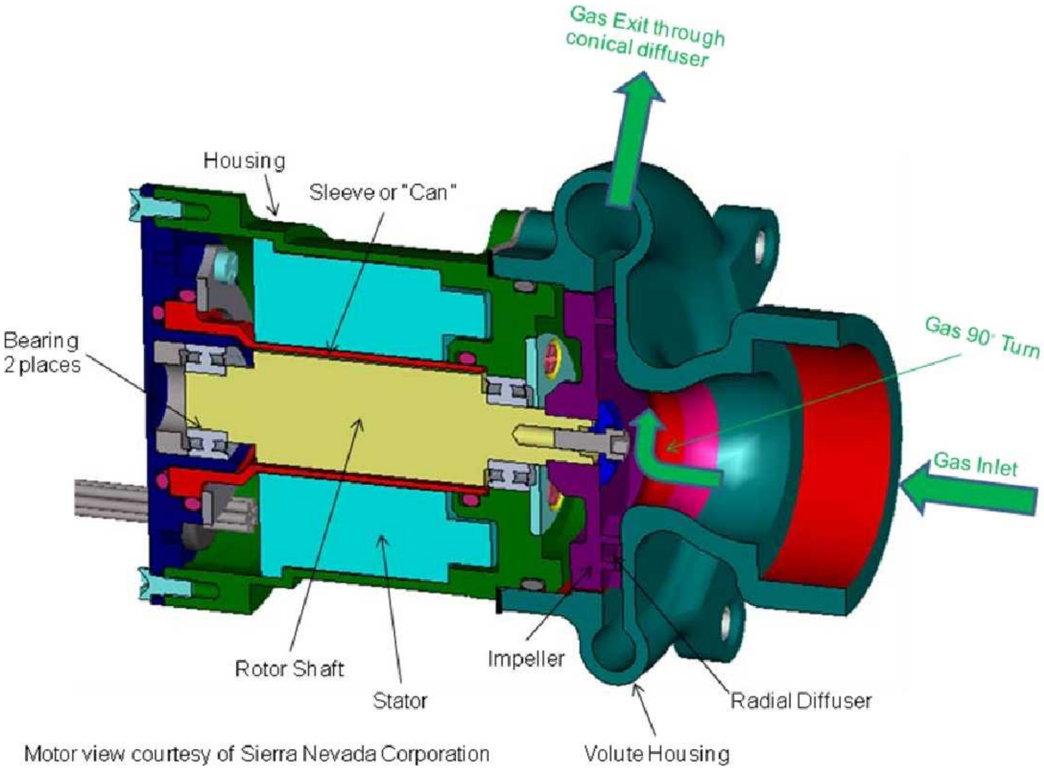
| Design Consideration # | Description |
|---|---|
| DC1 | The effects of cooling the motor by internal gas flow or a separate water loop on fan performance should be evaluated |
| DC2 | Fan performance sensitivity to inlet and outlet flow path geometry should be considered in conjunction with the current PLSS package concepts. |
| DC3 | The fan must pass thru a minimal amount of particulates from the ventilation loop. |
| DC4 | Different materials are to be traded for the structure of the fan/motor subassembly to minimize mass while meeting structural and oxygen compatibility requirements. |
| DC5 | Lessons Learned from previous fan assembly designs for space suits and vehicles should be taken into consideration, including failure modes and effects. |
| DC6 | Fan performance should not be affected by impact loads associated with falling on the Lunar surface, assumed to be 40-g loading to the component in any direction. |
| DC7 | Noise levels due to fan operation should be in accordance with the requirements specified in CxP 70024. |

Requirements for power (R2, Table 2), mass (R9, Table 2), and volume (G3, Table 3) govern the overall fan package design and were met by the conceptual design produced in this effort. The Design Point is captured in requirement R1 and defines the expected nominal EVA operating condition. This requirement assumes that carbon dioxide and humidity levels in a hemispherical helmet can be kept below threshold levels with a gas flow rate less than what is required currently for EMU helmet washout. Goal G4 adds a flow rate and pressure rise comparable to the EMU for consideration in the event that the gas flow rate and therefore the Design Point must be changed to meet requirements for carbon dioxide and humidity control. Goal G5 is the Buddy Point, a contingency operating mode where one fan flow through two PLSS ventilation loops.

The conceptual design for the fan assembly met all requirements specified; however the design did not include an integrated motor controller. A commercial motor controller was used for this effort to enable the majority of the available budget to be used on the fan design and testing. Hamilton Sundstrand has design numerous space qualified motor controllers and no unusual issues are foreseen with future design of an integrated motor controller for this fan.

## Fan Design

For this fan design, guidelines showed that the proper blade loading could be best met with a radial inlet to the impeller. Figure 3 shows the cross-section of the fan assembly. Gas flow enters the fan axially and is turned in the radial direction by the impeller where it then procedes to enter a radial diffuser. The diffuser's primary function is to turn dyanamic pressure into static pressure and thereby increase the performance of the fan. This diffuser also reduces acoustic source noise. Since the fan is centrifugal, it has a volute. The flow coming off the impeller consists of pressure waves as each impeller blade has differing pressures on its upstream side versus its downstream side. Additionally, each blade has a trailing edge with a certain thickness, which induces wakes in the downstream flow. These pressure waves and wakes impinge on the volute throat, producing acoustic noise. The diffuser puts distance between the impeller trailing edge and the volute throat which allows the pressure waves and flow wakes to dissipate and thus reduce the source noise generated at the volute throat.



Motor view courtesy of Sierra Nevada Corporation

Figure 3: Fan Assembly Cross Section and Oxygen Flowpath

The oxygen ultimately exits the fan through a conical diffuser. Like all diffusers, this takes high speed flow exiting the volute and slows it down in a controlled manner to turn dynamic pressure into static pressure. Conical diffusers typically have an included angle of near 14° for optimum pressure recovery. With the given diffuser inlet area and a ¾" duct diameter, a 14° cone would extend beyond what is allowable to meet the assembly envelope requirement. Therefore, the cone was extended as far as possible while still meeting the envelope requirement, and then truncated. With this configuration, a small reduction in aerodynamic performance was accepted in order to achieve a small fan envelope. Further optimization is possible when the fan is integrated with the rest of the ventilation loop.

**Figure 4: Fan Impeller**

The impeller itself has a relatively simple two dimensional design. The impeller is shown in Figure 4. The impeller spins counter-clockwise as oriented in this figure. The blades have a significant backsweep. Blade backsweep provides more stable flow through the impeller over a range of flows. This is a desirable aspect of the impeller design since the Buddy Point is aerodynamically removed from the Design Point and it is desirable for this design to cover a range of operating conditions.

**Motor Design**

The initial motor design was driven by two sources. First, the requirements specified a 28 Vdc power source (R8, Table 2), motor power consumption less than 6 W at the Design Point (G1, Table 3) and an assembly maximum mass of 2 $lb_m$ and maximum volume of 30 $in^3$ (R9, Table 2 and G3, Table 3, respectively). The second input source for the motor design was the initial fan aerodynamic assessment consisting of initial impeller and housing type and size. This assessment indicated operating parameters of approximately 40,000 rpm and 0.085 in-oz torque for the Design Point and approximately 58,000 rpm and 0.269 in-oz torque for the Buddy Point. This starting point quickly lead to a motor design that features a four pole, permanent magnet, brushless direct current (DC) motor, utilizing Hall Effect sensors for motor commutation.

The small fan envelope size drove the need for high rotational speeds. A challenge in the motor design was to operate at these high speeds (in the range of 35,000 – 70,000 rpm) without sacrificing motor efficiency. In addition, the motor has to operate in 100% oxygen, so the stator electronics had to be isolated from ignitable sources. This problem was overcome by "canning" the motor stator. A "canned" motor has the stator electronics physically isolated by a barrier (the "can") from the combustible oxygen in the flow stream. Canned motors are not new and the EMU uses a canned motor for these same reasons. To date canned motors have used a low ignition potential stainless steel alloy, typically Inconel. The downside of a metallic canned motor is that the motor experiences losses in efficiency due to the presence of metal in the magnetic field between the motor stator and the rotor magnets. Existing canned motors have compensated for this by allowing the motor to consume more power to overcome these losses. However, the baseline PLSS has a very limited power budget. This fan could not utilize a traditional canned motor approach and meet its requirements. To avoid these canning losses, a non-metallic can design was explored that would still provide the hermetic seal to isolate the stator electronics but avoid the losses caused by metallic cans. Several candidate materials were considered for the can and ultimately zirconia was selected because it machines easily, is durable, and could provide a good surface finish for sealing.

A rolling element bearing is located at either end of the motor to simplify the balance and assure smooth operation. The Hall Effect Device (HED) boards are located at the end of the motor and, for convenience; the electrical harness is routed out the back of the motor. Both aluminum and stainless steel were evaluated for the housing and 300 series stainless steel was chosen for dimensional control, corrosion resistance, and because the weight impact was small due to the small overall package size. The fully assembled motor weighs only 0.72 $lb_m$.

### Motor Controller

To save cost and schedule and to allow the bulk of the development effort to focus on the fan design, a modified commercial motor controller was housed in a dedicated box with a manual speed control and digital tachometer on the front (Figure 5). This motor controller is capable of driving much larger motors which made the losses in the motor controller for this application higher than what would be expected in a flight design, but still within the 14.0 W requirement. Future fan assembly development efforts will involve an integrated motor controller to optimize the overall design and further minimize power needs.

Motor Controller - Front Motor Controller - Rear

**Figure 5: External Motor Controller Using a Commercial Design**

## Test Set-up and Results

The fan was mounted in a ¾" PVC circuit with a flow meter and a ball valve to vary system resistance. The setup is shown in Figure 6 and the fan test article is shown in Figure 7. The circuit was connected to a facility vacuum source. The circuit pressure was continually maintained at 4.3 psia during testing.

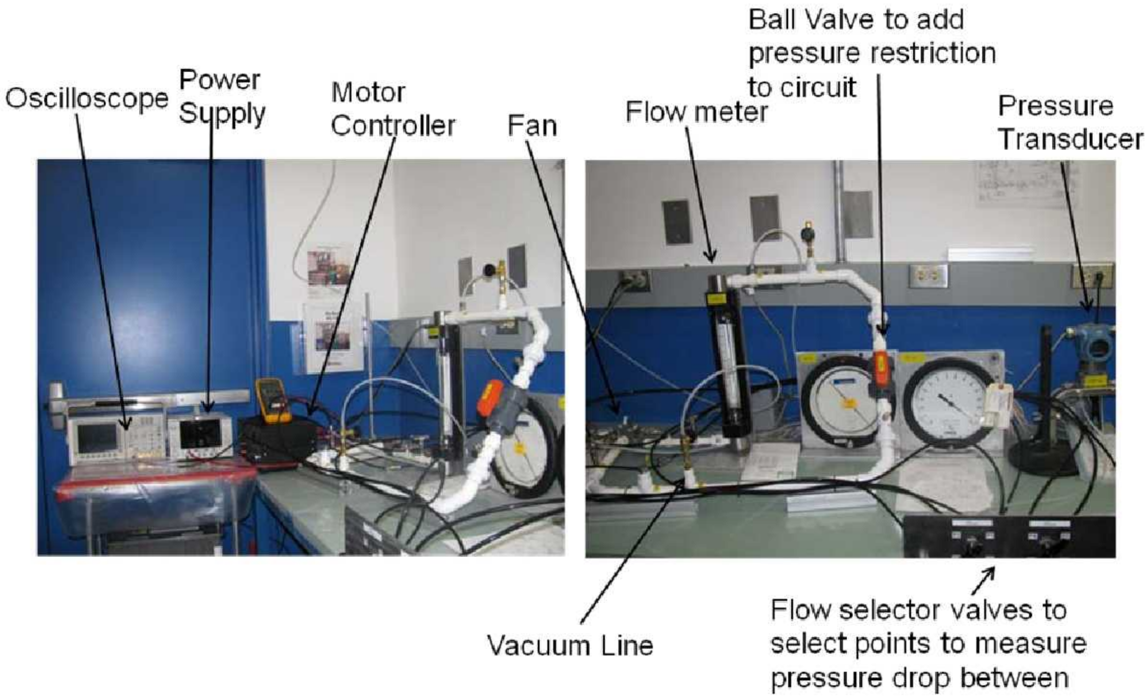


Figure 6: Fan Assembly Test Setup

The first points tested were the Design, Maximum Flow and Buddy points. Table 5 shows the results of these tests, along with the performance requirement or goal. The requirements are applied against operation in oxygen ($O_2$), but the test was performed using air as the process fluid. Therefore, the pressure rise ($\Delta P$) requirement was adjusted so that the fan would operate at the same head rise in air as required in $O_2$. Similarly, since the motor input power was measured using air as

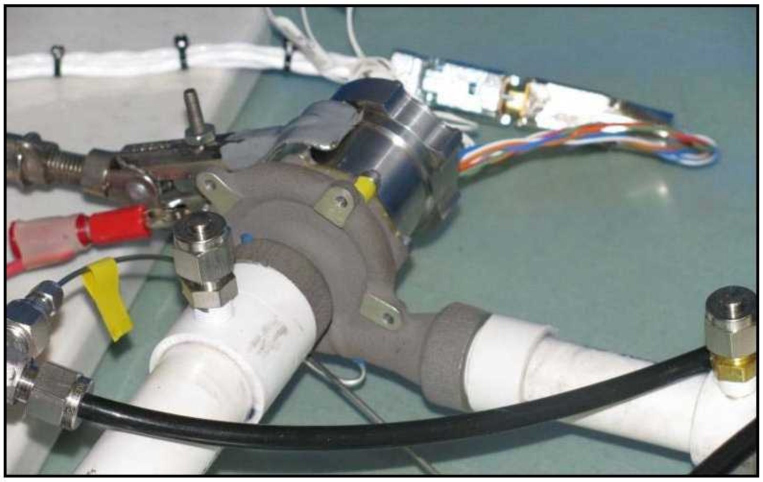


Figure 7: Fan Test Article

the process fluid, power was adjusted to account for operation in $O_2$. This adjustment is provided in Table 5.

**Table 5: Fan Performance at Specified Fan Operating Points**

| | | Design Point | Maximum Flow | Buddy Point |
|---|---|---|---|---|
| **Requirement or Goal** | Flow (cfm) | 4.7 | 5.9 | 9.4 |
| | $O_2$ $\Delta P$ (in. $H_2O$) | 2.70 | 4.10 | 6.75 |
| | *Air $\Delta P$ (in. $H_2O$)* | *2.44* | *3.71* | *6.12* |
| | Motor Input Power, $O_2$ (W) | **6.0** | -- | -- |
| **Test Result (air)** | Speed (rpm) | 39,404 | 51,350 | 72,736 |
| | Motor Input Power (W) | 4.30 | 8.08 | 20.08 |
| | Motor Efficiency | 51.6% | 57.9% | 62.1% |
| | Aero Efficiency | 61.8% | 56.3% | 54.8% |
| **Estimate** | Motor Input Power, $O_2$ (W) | **4.75** | 8.91 | 22.15 |

Figure 8 presents a fan performance map that includes the controller input power. The imposed requirement (R2, Table 2) for maximum overall fan assembly power consumption is 14 W. Figure 8 shows that for the Design Point, the total power consumption is just over 10 W which meets this requirement.

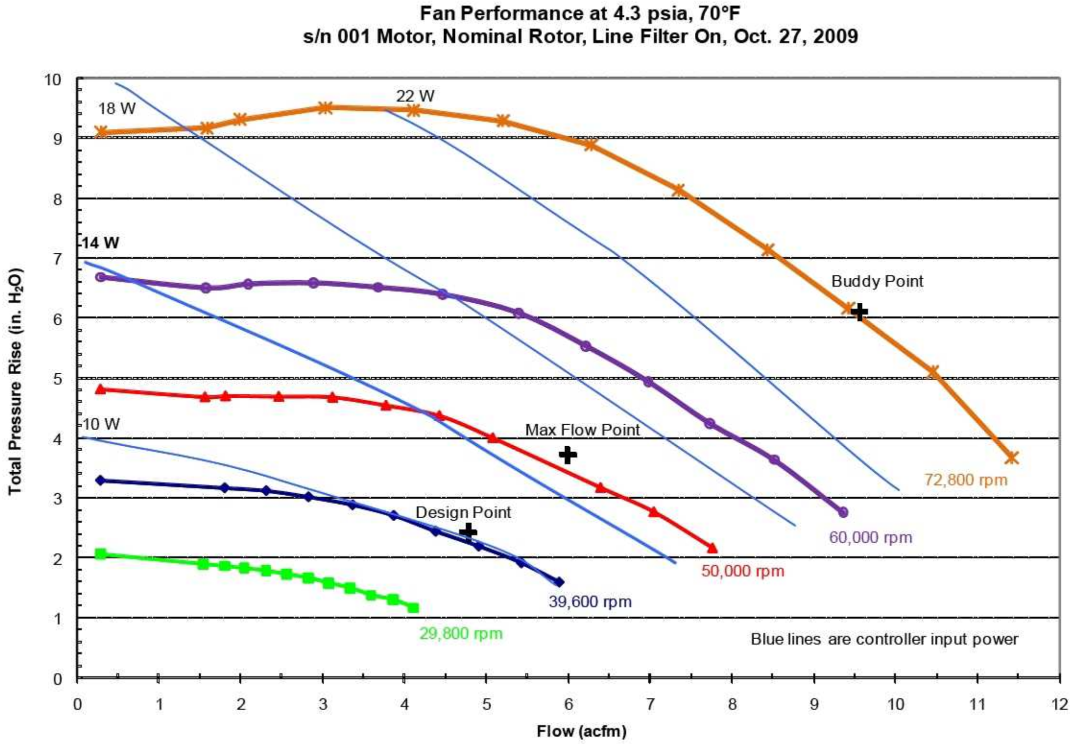


**Figure 8: Motor Controller Input Power**

Table 5 shows that the fan design meets the maximum motor input power goal of 6 W (G1, Table 3), and the impeller assembly motor input power in $O_2$ is 4.75 W. The rotational speed of near 40,000 rpm is higher than the anticipated design speed of 35,000 rpm. With limited $\Delta P$ instrumentation along the air flow path internal to the fan, it is not possible to determine exactly what is causing the need for this speed increase at the Design Point. However, design speed is an internal parameter (transparent to the requirements and goals of the program) and the program goal of 6 W motor input power is met. Additionally, the program goals of operating at the Maximum Flow and Buddy points are also achieved.

It is important to note that the aerodynamic efficiencies and motor input power cited in this section are based on power measurements using a Yokogawa power meter with a 6.5 kHz line filter switched on. This is associated with use of a commercial motor controller being used at the upper limit of its speed control range and exhibiting more signal noise than would occur with custom space qualified motor controller that is designed to match the motor.

## Thermal, Acoustic and Vibration Testing

### *Thermal Testing*

Thermal performance is important since the fan is subjected to a vacuum environment inside the PLSS. For testing, the fan assembly was covered with polyurethane foam insulation to mimic the thermal environment of space (Figure 9). With this test configuration, the only significant heat path out of the motor is through the fan test article and into the gas flow stream, just as it would be in space.

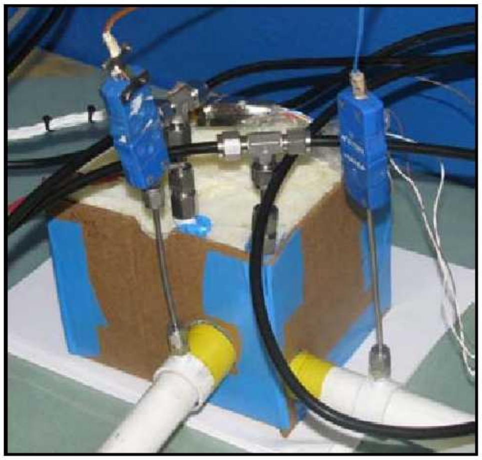


**Figure 9: Fan Thermal Test Article**

The fan was tested with the flow stream at 4.3 psia until steady state temperatures were obtained. The motor has built-in temperature sensors at the HEDs and in the motor's stator windings. Table 6 shows the results of this testing running at the Design Point and at the Buddy Point. These thermal test results show a generous temperature margin at the two most temperature sensitive locations in the motor, even at the Buddy Point.

**Table 6: Thermal Steady State Test Results**

| Location | Limit | Design Point | Buddy Point |
|---|---|---|---|
| Motor Input Power (W) | -- | 4.88 | 19.24 |
| Motor Stator (°F) | 275 | 126 | 160 |
| Motor HED (°F) | 185 | 124 | 156 |
| Ambient (°F) | -- | 69 | 69 |

*Acoustic Testing*

The fan was tested for acoustic emissions. Acoustic test results (Figure 10) show that this fan is designed very efficiently from an acoustics perspective. It does not exhibit broadband noise as a result of turbulence or stall, but future work will need to be done to control tonal noise at the rotational and blade-pass frequencies either at the fan or in the duct design to meet the Tonal and Narrow-Band Limit in CxP70024, Constellation Human Systems Requirements, HS3080 [3]. Table 7 lists a summary of the tonal noise outages for the Design and Maximum Flow Points. Additional noise control methods may be needed to meet the continuous noise requirement (HS3076 [3]) above the 500 Hz octave band, but more test and analysis is needed to confirm this. Acoustic noise results are summarized in Figure 10. The chart on the left shows an example of tonal noise exceeding the threshold in two places, and the chart on the right shows that the Design Point and Maximum Flow point broadband noise will probably exceed the continuous noise limit above 500 Hz.

**Table 7: Tonal Noise**

| Operating Point | Inlet Tonal Noise Limit | | Outlet Tonal Noise Limit | |
|---|---|---|---|---|
| | Rotational Frequency | Blade Pass Frequency | Rotational Frequency | Blade Pass Frequency |
| Design Point | **Concern** | **Concern** | **Concern** | **Meet** |
| Max. Flow Point | **Concern** | **Meet** | **Concern** | **Meet** |

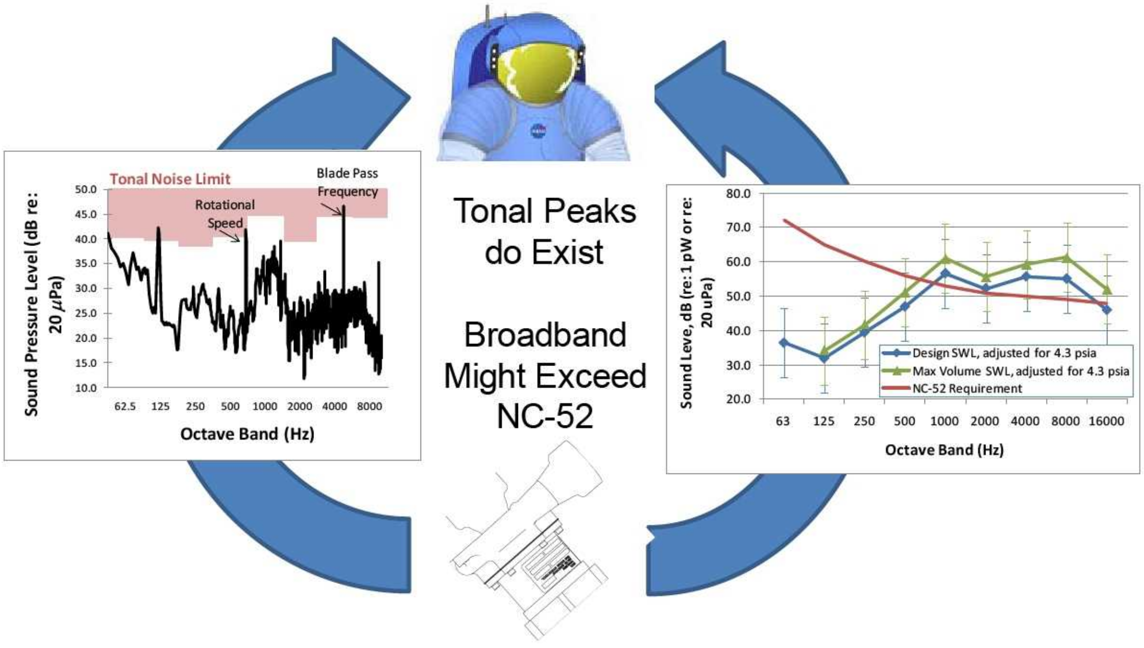


**Figure 10: Acoustic Test Results**

*Vibration Testing*

The motor for this fan utilizes a nonmetallic can machined from zirconia, which is a ceramic material. Because there is no prior experience with this type of motor can, a risk was identified relative to the structural capability of this approach. Would the can crack under vibration or shock loads? To address this question the motor was subjected to the random vibration loads required for the nominal Orion Crew Module random vibration for the Air Revitalization Subsystem (ARS) at the pallet level [4]. This was selected because currently the PLSS does not have a random vibration requirement defined. Figure 11 shows how the selected vibration test level compares to existing vibration requirements for the European ATV (Automated Transfer Vehicle) and the Japanese HTV (HII Transfer Vehicle) along with other vehicles and systems. Additionally, this test induced all the vibration directly into the motor. The leading packaging concept for the PLSS soft-mounts components in foam which would result in considerable damping and a much less severe condition than what was tested. In addition to vibration testing, the motor was tested to the shock loads specified in Table 8. The 40 g shock level represents the maximum load calculated for the space suit system impacting a stationary object at a velocity of 4.3 m/s [5].

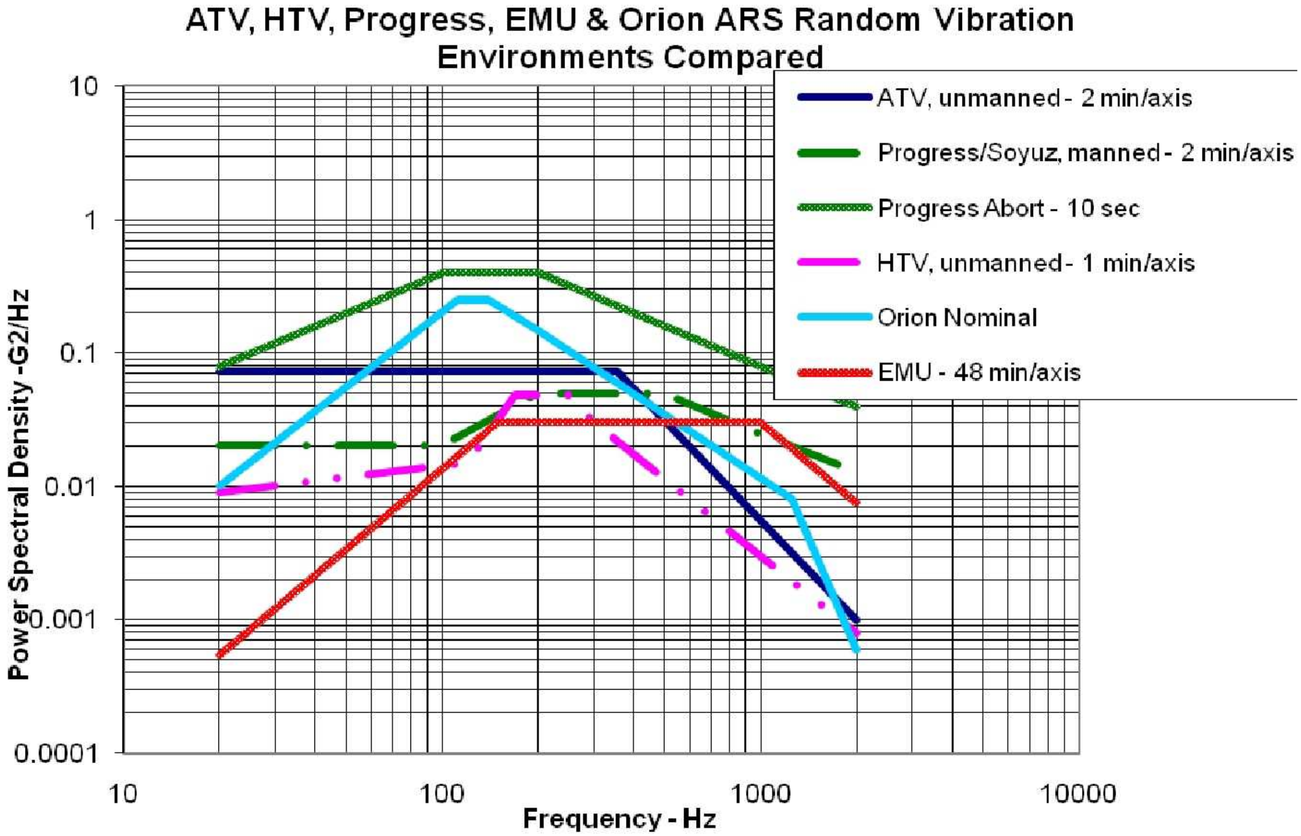


**Figure 11: Test Condition (Blue) as Compared to Known Vibration Environments**

**Table 8: Shock Input Profile**

| Pulse Type | Input Level | Duration |
|---|---|---|
| **Terminal Sawtooth** | 40 g +/- 15% | 11 milliseconds |

In order to evaluate the structural integrity of the motor's ceramic can, multiple test configurations were conducted at the three axial positions with varying loads. All testing was performed in the Hamilton Sundstrand Space, Land and Sea vibration laboratory. The motor was hard-mounted to a rigid vibration fixture, and three-axis accelerometers were placed on the vibration fixture, as well as on the motor itself in order to measure the response to the vibration levels that were experienced.

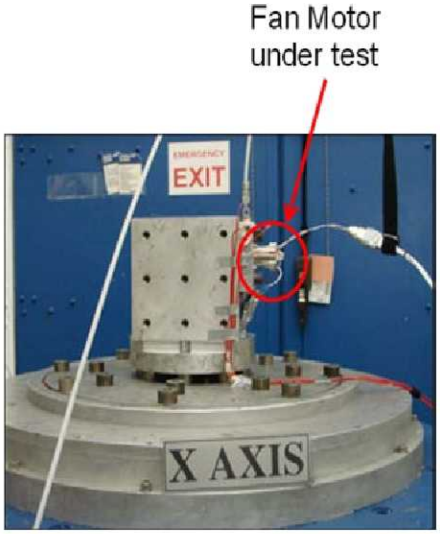


**Figure 12: Vibration and Shock Test Set-Up**

For the duration of testing, the motor was hard mounted to the vibration table and spinning at approximately 30,000 rpm. The Orion random vibration loads were applied to the motor on the x, y and z axes, both at half load levels (-6 dB) and at full load levels (0 dB). The X-axis test configuration is shown in Figure 12. The shock loads of 40 g at a nominal duration of 11 ms were tested on the positive and negative x, y and z-axes. Prior to and following each test, a leak check was performed on the motor to check the integrity of the can. No leakage was observed during any of the testing.

Once testing was completed, the motor was completely disassembled and visually inspected. The ceramic can was removed from the motor and thoroughly examined. The ceramic liner was in very good condition as seen in Figure 13. There is no reason to question its structural integrity.

**Figure 13: Zirconia Motor Can After Disassembly**

## Conclusions

This effort to design, manufacture, and test a PLSS fan assembly revealed the following conclusions:

- A compact fan can be designed to meet NASA's PLSS fan performance requirements.
- NASA's Design Point can be met within the 14.0 W power limitation.
- A single fan can meet both the Design Point and Buddy Point requirements.
- A simple two dimensional blade centrifugal fan design is a promising approach and can be implemented with low technical risk.
- The fan is ready to support further performance and life cycle testing at the NASA Johnson Space Center

The fan assemblies designed and built for this technology development effort have met all performance requirements and goals. Design of a space-qualified motor controller remains as forward work; however, this is not considered technology development. Opportunities exist to optimize the fan design as more complete PLSS ventilation requirements are established and interfacing components are designed. This conceptual fan design has mitigated much of the technical risk for fan development for the PLSS architecture.

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