Portable Life Support System 2.5 Fan Design and Development

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NASA is building a high-fidelity prototype of an advanced Portable Life Support System (PLSS) as part of the Advanced Exploration Systems Program. This new PLSS, designated as PLSS 2.5, will advance component technologies and systems knowledge to inform a future flight program. The oxygen ventilation loop of its predecessor, PLSS 2.0, was driven by a centrifugal fan developed using specifications from the Constellation Program. PLSS technology and system parameters have matured to the point where the existing fan will not perform adequately for the new prototype. In addition, areas of potential improvement were identified with the PLSS 2.0 fan that could be addressed in a new design. As a result, a new fan was designed and tested for the PLSS 2.5. The PLSS 2.5 fan is a derivative of the one used in PLSS 2.0, and it uses the same nonmetallic, canned motor, with a larger volute and impeller to meet the higher pressure drop requirements of the PLSS 2.5 ventilation loop. The larger impeller allows it to operate at rotational speeds that are matched to rolling element bearings, and which create reasonably low impeller tip speeds consistent with prior, oxygen-rated fans. Development of the fan also considered a shrouded impeller design that could allow larger clearances for greater oxygen safety, assembly tolerances and particle ingestion. This paper discusses the design, manufacturing and performance testing of the new fans.

Nomenclature

acfm	=	actual cubic feet per minute
cfm	=	cubic feet per minute
dB	=	decibel
H_2O	=	water
Hz	=	hertz
PLSS	=	Portable Life Support System
psia	=	pounds per square inch absolute
RCA	=	Rapid Cycle Amine
SPL	=	sound pressure level
W	=	watts

I. Introduction

Exploration beyond low Earth orbit will require an advanced extravehicular mobility unit to allow crew members to perform work and activities outside of their spacecraft, habitat or rover. NASA has been developing advanced extravehicular mobility unit systems and technologies in preparation for these future missions. The first system, Portable Life Support System (PLSS) 1.0,[1] was a breadboard that performed the functions of a PLSS, but without the tight packaging requirements or optimized components needed for a flight unit. A second PLSS was designed, built,

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and tested to advance key technologies, and progress the system and packaging toward a flight-like unit. This unit was designated as PLSS 2.0, and it completed crewed testing at atmospheric conditions in 2015.[2]

The ventilation loop fan for PLSS 2.0 used a nonmetallic canned motor with rolling element bearings and a radial flow centrifugal impeller and volute.[3] The fan was shown to consume less than 5 watts (W) into the motor at its nominal design point of 4.7 acfm, 2.7 inches of water head rise, and 4.3 psia operating pressure. The 2010 ICES paper titled “Development of a Fan for Future Space Suit Applications” details the design and performance of the fan.

The next system being constructed, PLSS 2.5, will use a more flight-like components in a package that is representative of a final volume. As a result, requirements for the fan have matured, and the previous fan is not expected to provide an adequate pressure head to the ventilation loop. The need for a new fan prompted NASA and Hamilton Sundstrand Space Systems International to develop a new centrifugal fan (Figure 1). Two fans were designed, built and tested. The first was a derivative of the fan used in PLSS 1.0 and PLSS 2.0, with a traditional, open impeller design. The second fan used a shrouded impeller design that was intended to maintain the needed efficiency while relaxing the need for tight clearances within the fan housing. This paper reports on the design and evaluation of the fans.

Figure 1. PLSS 2.5 fan and motor.

II. Requirements and Analysis

PLSS 2.5 is being designed for a ventilation flow rate of up to 6.0 acfm at a nominal pressure of 4.3 psia of oxygen. The system pressure rise is expected to be 5.8 inches of water. In contrast, the previous fan was designed for a nominal pressure rise of 2.7 inches of water at 4.7 acfm. As a result, the new fan had to supply over 2.5 times more fluid power at its optimal design point than the previous fan. Table 1 shows the critical design criteria for the new fan, and how it compares to its predecessor and to the particular design requirements of PLSS 2.5. There are two differences between what the fan was designed to and what the PLSS 2.5 requirements state. First, the pressure rise needed for PLSS 2.5 is 5.8 inches of water, but the team designed the fan to optimally produce 6.0 inches of water head rise. The PLSS 2.5 requirements were not finalized at the time, and the choice was made to protect against increases in system resistance as the PLSS design matured. Reducing the fan speed should give up little in efficiency if the system resistance is lower than 6.0 inches of water. The second difference between the design point and the requirements is the operating temperature. The new fan uses the same motor as the previous fan, so the nominal gas temperature was set at 68°F, which is consistent with what the motor was originally designed to.

Table 1. Fan Design Criteria

	PLSS 1.0 Fan	PLSS 2.5 Requirements	PLSS 2.5 Fan Design Point
Flow Rate	4.7 acfm	6.0 acfm	6.0 acfm
Pressure Rise	2.7 in H_2O	5.8 in H_2O	6.0 in H_2O
Operating Temperature	68°F	60°F	68°F
Operating Pressure	4.3 psia	4.3 psia	4.3 psia
Gas	oxygen	oxygen	oxygen
Motor Input Power	6.0 W	N/A	12.1 W

Power consumption in the new fan was estimated to be 12.1 W into the motor at its optimal design point. Table 2 shows the predictions of fan performance, envelope, and mass compared with the prior fan. The additional impeller torque puts the new fan onto a more efficient part of the motor curve, and the aero efficiency was predicted to to be higher as well. As a result, the fan was expected to gain 7% in overall efficiency.

Table 2. Fan Performance Predictions

Concept	PLSS 1.0 Fan	PLSS 2.5 Fan
Flow (cfm)	4.7	6.0
O_2 ΔP (in. H_2O)	2.70	6.0
Speed (rpm)	41,858	35,000
Impeller Torque (in-oz)	0.081	0.275
Motor Efficiency*	50.3%	59.0%
Aero Efficiency	55.7%	59.5%
Motor Input Power	5.51	12.1
Mass (lb_m)	0.91	1.08
Envelope (in^3)	29.7	27.3
Height (in)	2.60	2.60
Width (in)	3.46	3.00
Depth (in)	3.30	3.50

III. Design and Manufacturing

The fan was designed to reuse the high-efficiency motor from its predecesor, along with the rolling element bearings, oxygen-compatible bearing lubrication, and basic centrifugal approach that worked well for PLSS 1.0 and PLSS 2.0. Changes to the design include a larger impeller and volute, the addition of an adapter plate to mate the existing motor with the larger volute, and a change to flanged face seals for the inlet and outlet ports. Figure 2 shows a scaled comparison of the two fans. The diameter of the fan housing increased by 0.7 inches, or 30%, while the fan height was kept essentially the same.

The volute is machined from an aluminum casting, and its nominal impeller is machined aluminum. These same materials were used in the prior fan, and in a similar fan designed for the Orion Multipurpose Crew Vehicle. The Orion fan was designed to operate with 100% oxygen at 4.3 psia as well, although it is larger, with slightly higher impeller tip speeds than either PLSS fan. The Orion fan was evaluated for oxygen compatibility by NASA's White Sands Test Facility and found to be generally oxygen compatible, with some forward work necessary for oxygen certification. What work does remain is a more thorough evaluation and test to determine whether frictional heating of the impeller on the volute is credible. The low motor power and an anodized surface finish on the volute should both work to minimize or eliminate that ignition hazard, allowing the team to move forward with aluminum components at relatively low risk.

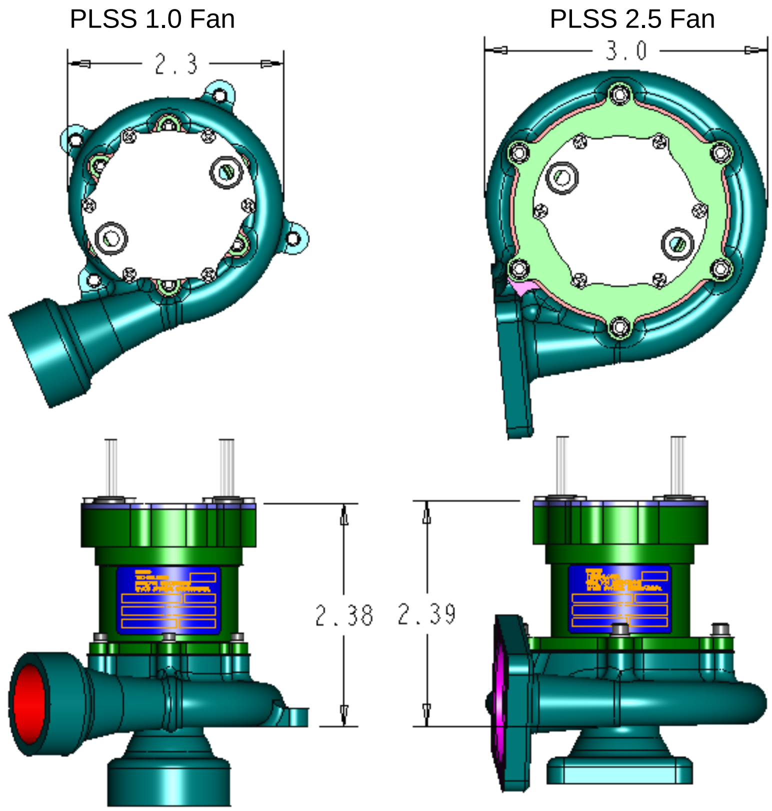

Figure 2. PLSS 2.5 fan and motor.

Redesigning the fan for PLSS 2.5 provided the opportunity to evaluate an alternative impeller design that offered promise for the PLSS. The nominal impeller is shown in Figure 3a. It relies on very tight tolerances between the edges of the blades and the housing to achieve high aero efficiencies. Smaller gaps create higher efficiencies, but in fans as small as these, the ratio of blade height to clearance gap is still relatively low. Decreasing the gap height further creates increased difficulties with installation, temperature changes, deflections during operation, and poor tolerance to particle ingestion. A solution to the these issues is to use a shrouded impeller, as shown in Figure 3b. The shroud eliminates the aero losses over the edges of the blades, but at the expense of increased drag between the impeller and the housing. A first comparison of the two impellers was done via a student experiment at the University of Connecticut in 2011. Results from that experiment were inconclusive due to the use of a plastic housing rather than a more dimensionally stable metal housing, but they indicated that the shrouded impeller created a slightly more efficient fan. These positive results, combined with the potential benefits stated above, motivated the team to create a second version of the new fan, which used the shrouded impeller.

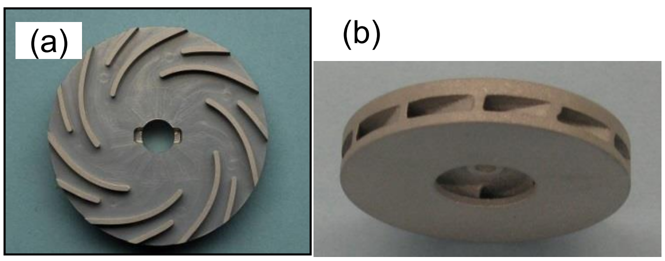

Figure 3. Open impeller (a) and shrouded impeller (b).

The rough casting of the fan volute and housing is identical for both versions of the fan, with the same interfaces to the ventilation flow and motor. The final machining of the housing is slightly different to accommodate the different impellers. The greatest difference is that the shrouded impeller fan has three times the clearance gap between the impeller and the housing for most of its radius. The shrouded impeller itself is made from an aluminum casting with final machining steps for the critical dimensions. Figure 3b shows the rough casting of the shrouded impeller.

IV. Baseline Motor Testing

The PLSS 2.0 fan motor had been used at NASA Johnson Space Center for hundreds of hours of operation before being used for this testing. Therefore, a no-load power test was run to help ascertain if there had been any performance degradation of the motor since it was originally assembled. Results are shown in **Error! Reference source not found.**. This plot readily reveals that the motor performance changed, given that in the original application, the motor input power under load was < 6 W, and that for PLSS 1.0 and PLSS 2.0 the operating speed range was 40,000-70,000 rpm.

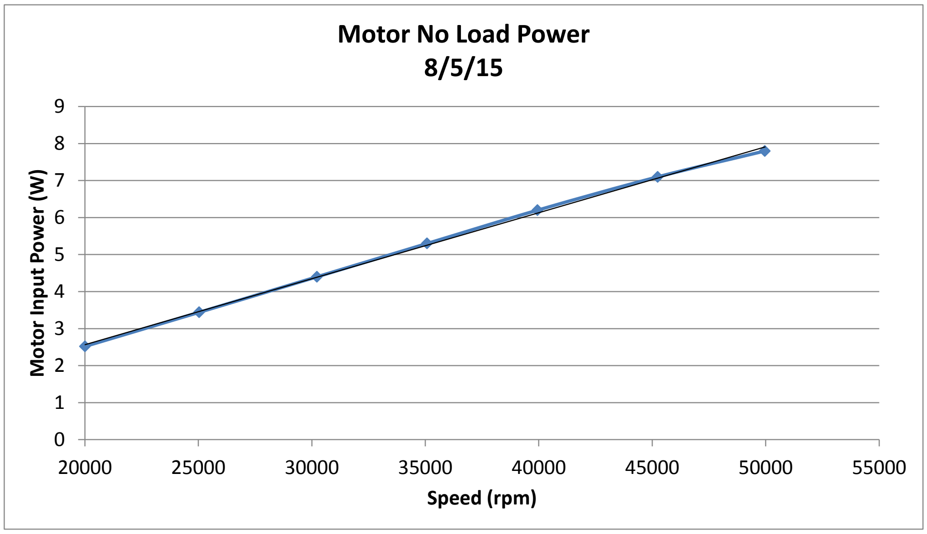

Figure 4. No-load power test of the fan motor showed increased power draw after several hundred hours of operation

A dynamometer was not available for precise measurements of the motor, so an analytical adjustment was applied to subsequent testing to determine the motor performance, from which aerodynamic fan performance was determined. This analysis is shown below.

To determine the difference in the fan motor between when the original testing was conducted in 2010 and now, performance between those two times were compared. Performance data at three no-load speeds were collected from the 2010 test and are shown below in Table 3.

Table 3—Motor Performance From 2010

	--------------------------------2010 Fan-----------------------------						No Load	ΔMtr Loss (W)
Speed (rpm)	Flow (cfm)	ΔP (in. H_2O)	Aero. Efficiency	Motor Input Power (W)	Shaft Power (W)	Motor Loss (W)	Motor Input Power (W)	
30000	2.0	2.0	52%	2.0	0.90	1.1	4.5	3.4
40000	4.0	2.7	56%	4.5	2.27	2.3	6.2	3.95
50000	6.3	3.3	55%	7.5	4.44	3.06	7.8	4.74
50000	1.0	4.8	30%	5.0	1.88	3.12	7.8	4.68

The "2010 Fan" columns show performance of the motor *under load* in 2010. The shaft power is calculated and shown in the table for these test points. The increase in motor losses is then given by taking the No-Load Motor Input Power and subtracting the motor loss calculated for the 2010 testing. These losses are plotted below in Figure 5. The curve fit of these losses versus speed are Equation 1.

$$1)\quad \Delta MotorLoss\ (W) = 1.0500E\text{-}09 \times N^2 - 1.8500E\text{-}05 \times N + 3.01$$

where N is speed in rpm.

This calculated increase in motor losses is added to the losses inferred in Section V to adjust the motor efficiency calculation used to reduce the PLSS 2.5 fan test data.

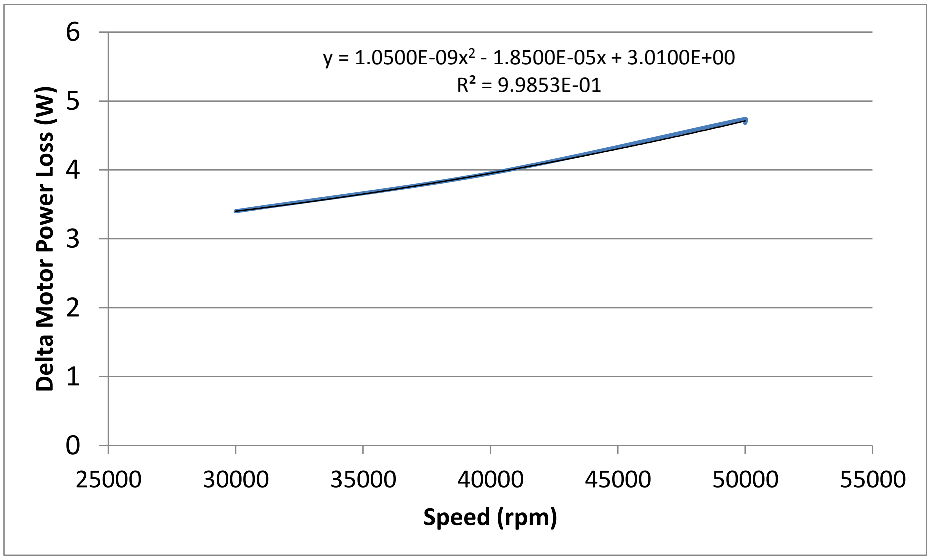

Figure 5—Motor Increased Losses

V. Fan Performance Testing

Both versions of the fan were assembled and tested using one of the motors from the prior PLSS 2.0 fan. They were tested at a range of speeds and head rise to create performance maps. Acoustic tests were also conducted on the open impeller fan. All testing was done using air as the operating fluid.

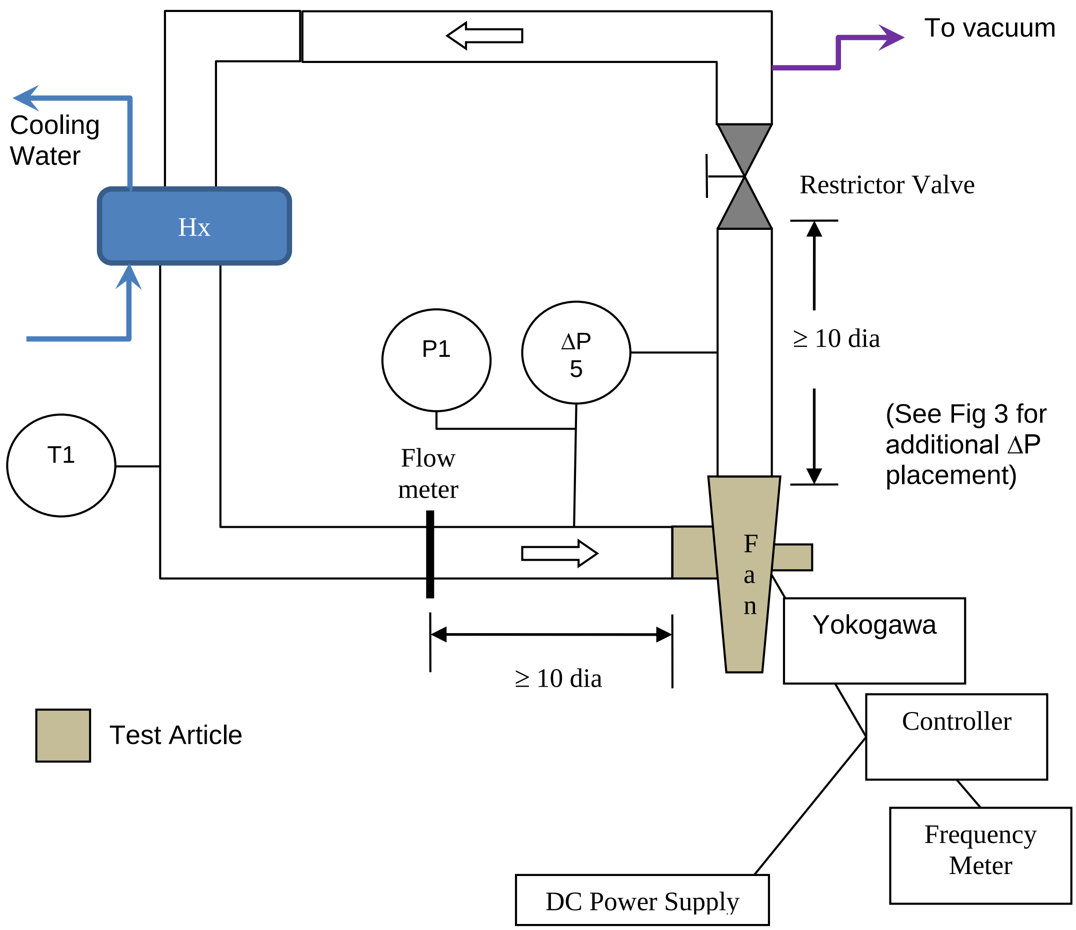

Figure 6. Fan test rig schematic

The fans were tested in a closed loop setup shown schematically in Figure 6. Measurements were taken of the temperature and pressure in the loop, pressure rise across the fan, motor temperature, fan speed, and motor power. The circuit was connected to a facility vacuum source to allow testing at 4.3 psia. Fan inlet temperature was maintained at 80 °F ±5 °F. Supply voltage was set to 28 Volts and the fan motor was left uninsulated, as characterization of the fan motor had been completed during the prior fan development effort[3].

The open impeller fan's design point and four additional PLSS 2.5 operating points were tested, as well as speed lines at speeds ranging from 25,000 to 50,000 rpm in 5,000 rpm increments. Table 4 shows the performance at the specific design and the additional PLSS 2.5 operating points. The top half of the table is the actual test data recorded near the defined points (recorded data is given in italics). From these data, motor and electrical efficiencies were calculated. The motor efficiency includes the increased losses calculated by equation 1. The bottom half of the table—"Corrected Performance"—takes these test data points and adjusts them for oxygen at the defined fan inlet pressures and temperatures. It is assumed that the "Test Data" points are sufficiently close to the defined operating points that the aerodynamic efficiencies are the same. Motor efficiencies were adjusted by removing the calculated increase in motor losses of equation 1. The resulting motor input powers are shown in the bottom row. The only motor input power requirement applies to PLSS Point 1, and it is 12 W. This compares to the 13.3 W calculated from the test data. Overall, this fan consumes only slightly more power than anticipated in the design. This difference may be attributed to a tip clearance that is 20% larger than the nominal design, although it still fell within the allowed machining tolerances.

Table 4—Operating Point Performance

		Design Point	PLSS Point 1	PLSS Point 2	PLSS Point 3	PLSS Point 4
Test Data	Process Fluid	-----Air-----				
	Suit Pressure (psia)	*4.3*	*4.3*	*8.40*	*4.3*	*23.61*
	Inlet Temp. (°F)	*76*	*76*	*80.7*	*76*	*80.7*
	Flow (cfm)	*6.59*	*6.36*	*6.47*	*4.99*	*4.79*
	ΔP (in. H_2O)	*6.0*	*5.8*	*11.5*	*5.3*	*27.3*
	Speed (rpm)	*36990*	*36360*	*35580*	*32400*	*30060*
	Motor Input Power (W)	*16.27*	*17.0*	*24.91*	*13.0*	*32.46*
	Motor Efficiency	45.6%	46.7%	53.4%	41.5%	56.8%
	Aero. Efficiency	57.0%	50.0%	36.1%	52.8%	N/A
Corrected Performance	Process Fluid	-----Oxygen-----				
	Suit Pressure (psia)	4.3	4.3	8.0	4.3	23.6
	Inlet Temp. (°F)	68	80	80	80	80
	Flow (cfm)	6.0	6.0	6.0	4.5	4.5
	ΔP (in. H_2O)	6.0	5.8	12.5	5.3	30
	Aero. Efficiency	57.0%	50.0%	36.1%	52.8%	N/A
	Motor Efficiency	61.2%	61.5%	63.2%	59.6%	63.5%
	Motor Input Power (W)	12.1	13.3	38.6	8.9	N/A

Figure shows the aerodynamic performance map for this fan, based on the rest of the speed line test data. This figure shows that the Design and two PLSS operating points are well positioned with the map.

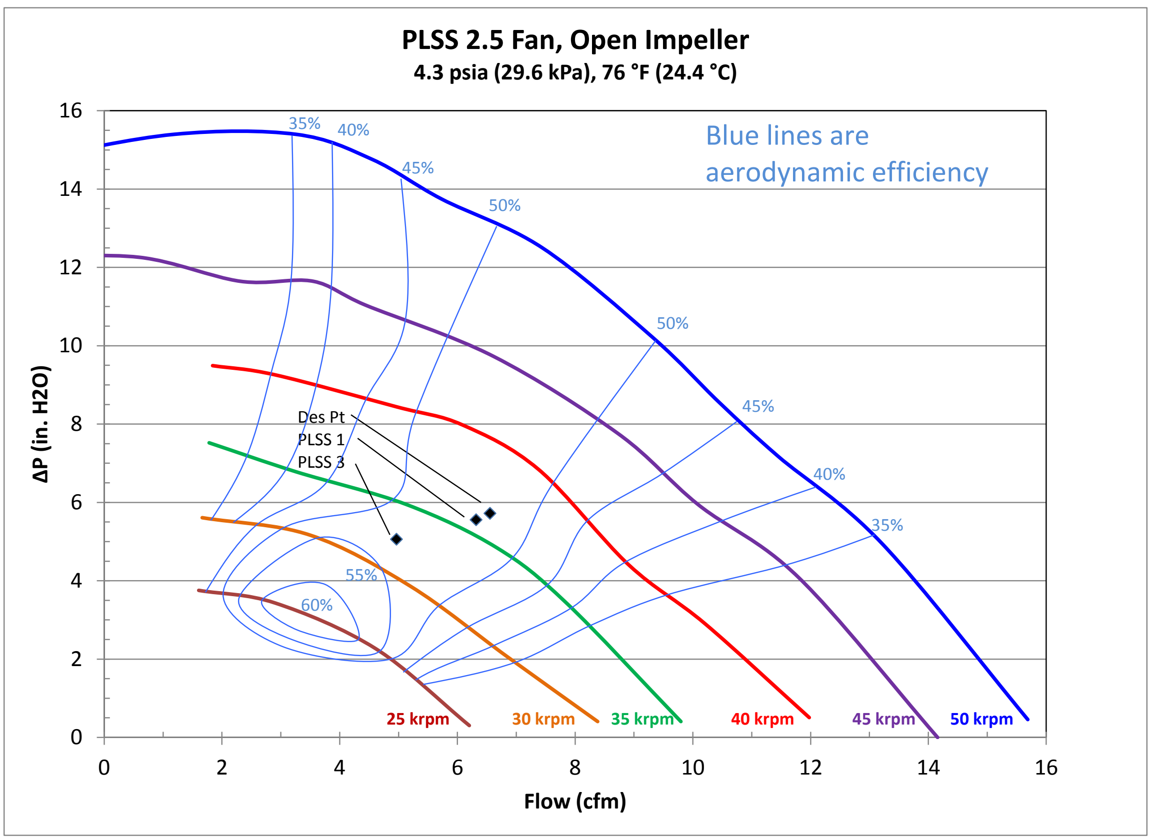

Figure 7—PLSS 2.5 Suit Fan Aerodynamic Performance Map

The fan assembled with the shrouded impeller was first tested at room ambient pressure in order to compare it with the open impeller fan performance. The intent was to provide a definitive assessment as to which impeller design is better. Assembly of the shrouded impeller fan resulted in clearances equal to the nominal design values. Figure shows the performance of each fan variant. The open impeller fan performed better than the shrouded impeller fan at ambient pressure, averaging 6% higher aero efficiency over a flow range of 2.5 ACFM to 8.5 ACFM. The open impeller fan achieved these results despite having larger than nominal clearances. These results were considered conclusive for these two fans, and further testing of the shrouded fan was not conducted.

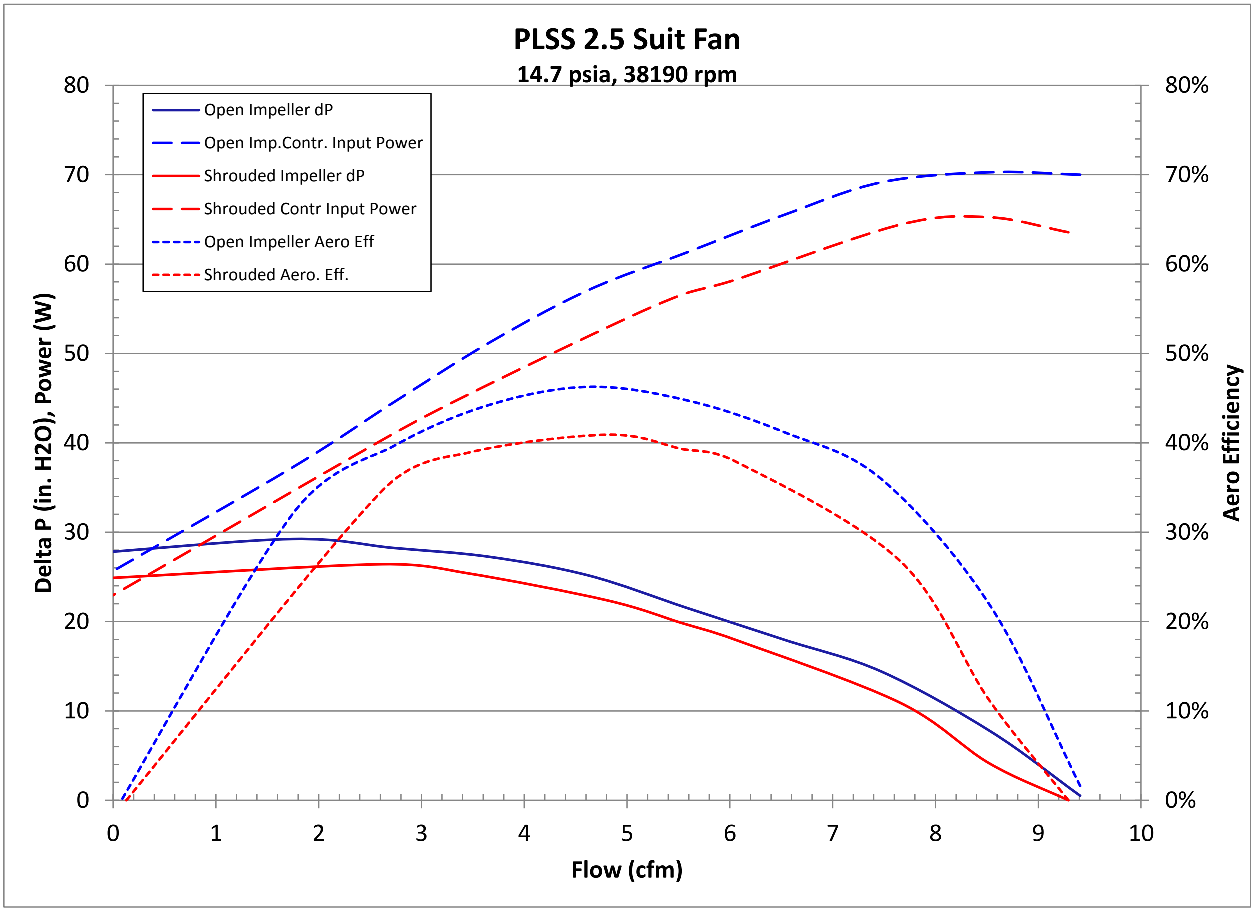

Figure 8—Open vs. Shrouded Impeller Performance at Room Ambient

Acoustic testing was performed on the open impeller fan in UTAS' acoustic test facility. All testing was done at room ambient pressure and temperature. An analytical approach was used to estimate the acoustic performance at sub-ambient pressures. The method, which is consistent with the PLSS 2.0 fan testing[3], takes a given operating point—PLSS 1 in this case—and records acoustic data at two conditions:

- "PLSS 1A": Run the fan at the operating point's full operating point speed (36,990 rpm) and flow rate (6 cfm). ΔP will be elevated proportional to the fan inlet pressures. In this case the ΔP will be 17.9" H_2O.
- "PLSS 1B": Run the fan on the same system resistance line as defined by the operating point; and reduce the speed, flow and ΔP until the impeller shaft power is the same as it is at the PLSS 1 operating point.

It is believed that these two points should bracket the acoustic performance that will occur at the operating point. Table 5 shows the fan's operating parameters used for taking acoustic measurements (points PLSS 1A and 1B). Sound pressure measurements were taken at three positions at both the inlet and exhaust ducts; and one position for case radiated noise.

Table 5—Acoustic Test Operating Points

	PLSS 1	PLSS 1A	PLSS 1B
Fan Inlet Pressure (psia)	4.3	14.7	14.7
Inlet Temp. (°F)	80	~72	~72
Flow (cfm)	6.0	6.0	4.0
ΔP (in. H_2O)	5.25	17.9	8.1
Speed (rpm)	36690	36690	24611
Motor Shaft Power (W)	8.8	--	8.8
Rotational Frequency (Hz)	611	611	410
Blade Passing Frequency (Hz)	7338	7338	4922

Error! Reference source not found. shows the outlet duct-borne acoustic readings. Data is presented as recorded in equivalent octave band frequencies. The duct-borne noise requirement of NC-55 is plotted on in the graph. The exhaust measurements are about 10 dB higher for 1A than 1B, which is expected given the increased fan power at that test point. The two sets of curves bracket the sound levels expected at 4.3 psia. Similar data were gathered for inlet duct noise and case-radiated noise. There is an NC-60 requirement for case radiated noise when the fan is operating in a 14.7 psi environment, and the fan met this level at both points. Table 6 shows the maximum acoustic excursions over the respective duct-borne and case radiated noise requirements and the octave center band frequencies in which they occur.

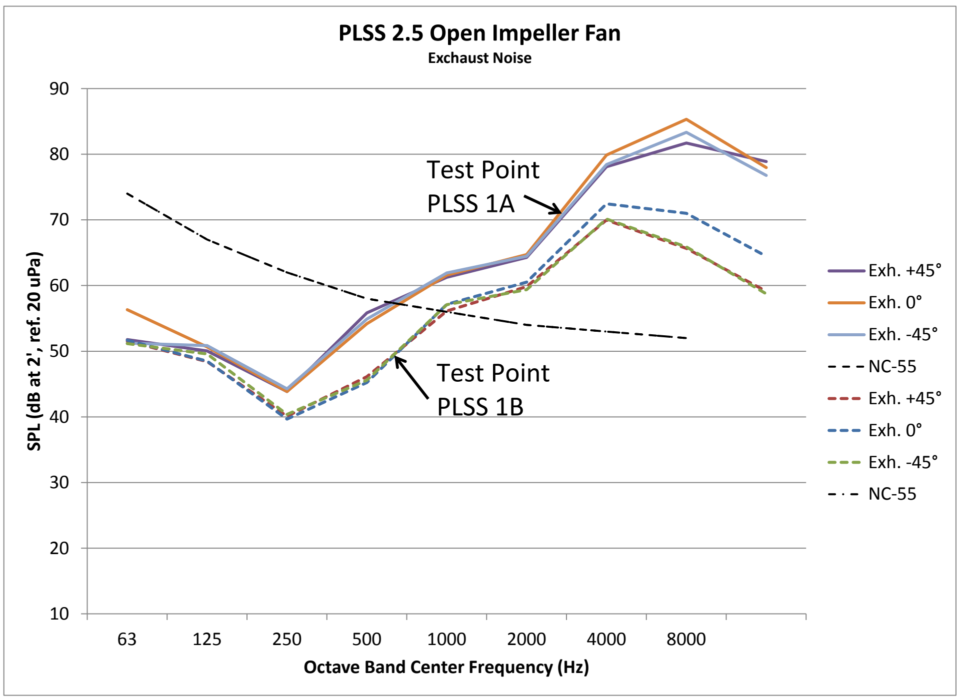

Figure 9: PLSS 1A & 1B exhaust duct octave center band SPL

Table 6—Maximum SPL Excursion over Requirement

Location		NASA 1A	NASA 1B
Inlet Duct	Max. Excursion (dB)	13.8	8.3
	Frequency (Hz)	4000	4000
Exhaust Duct	Max. Excursion (dB)	28.3	14.4
	Frequency (Hz)	8000	4000
Case Radiated	Max. Excursion (dB)	0	0
	Frequency (Hz)	--	--

VI. Conclusions

Two new centrifugal fans were designed, built and evaluated against the updated ventilation loop flow requirements of NASA's PLSS 2.5. The first fan was an upsized version of the one tested in PLSS 1.0 and PLSS 2.0, which used an open impeller design. The second fan used a shrouded impeller design, motivated by the potential for larger fan clearances and higher efficiency.

An initial check was conducted on the brushless DC motor fan that was re-used from the original PLSS 1.0 and PLSS 2.0 tests. The check revealed that the no-load power had gone up since it was first evaluated in 2010. An analysis was done to compensate for the increased motor power in the fan efficiency calculations. Performance testing of the fans showed that the open impeller design achieved an aerodynamic efficiency of 50% - 57% for the design condition and for the PLSS 2.5 nominal operating condition. Its overall power draw would be 13.3 Watts at the PLSS 2.5 condition, which is 11% higher than the target power of 12 Watts. Some or all of that difference can be attributed to the impeller clearance ending up at the high side of the allowed tolerance. Testing of the shrouded impeller fan showed that its aero efficiency was 6% lower than the open impeller fan's efficiency, which ruled it out for further PLSS 2.5 evaluations.

Acoustics tests showed that the fan outlet operates at up to 28.2 dB above the NC-55 level, and that the fan inlet noise peaks at 13.8 dB above the NC-55 level. However, there is a large trace contaminant control filter upstream of the PLSS 2.5 fan and the carbon dioxide and humidity removal system is immediately downstream of the fan. Both components can be expected to significantly attenuate the duct borne noise, such that fan design changes are not likely to be necessary based on acoustics. Case radiated noise met the NC-60 requirements of PLSS 2.5.

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