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Quiet, Efficient Fans for Spaceflight: An Overview of NASA's Technology Development Plan

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Abstract

A Technology Development Plan to improve the aerodynamic and acoustic performance of spaceflight fans has been submitted to NASA's Exploration Technology Development Program. The plan describes a research program intended to make broader use of the technology developed at NASA Glenn to increase the efficiency and reduce the noise of aircraft engine fans. The goal is to develop a set of well-characterized government-owned fans nominally suited for spacecraft ventilation and cooling systems. NASA's Exploration Life Support community will identify design point conditions for the fans in this study. Computational Fluid Dynamics codes will be used in the design and analysis process. The fans will be built and used in a series of tests. Data from aerodynamic and acoustic performance tests will be used to validate performance predictions. These performance maps will also be entered into a database to help spaceflight fan system developers make informed design choices. Velocity measurements downstream of fan rotor blades and stator vanes will also be collected and used for code validation. Details of the fan design, analysis, and testing will be publicly reported. With access to fan geometry and test data, the small fan industry can independently evaluate design and analysis methods and work towards improvement.

1.0 Introduction

Noise has been a problem onboard the International Space Station (Ref. 1) and is expected to be a concern for future long duration human space exploration missions. Fans are known to be a dominant source of that noise. Many axial, mixed flow, and centrifugal fans are used in a variety of payload cooling and ventilation system applications. Fan noise can be attributed to the design of the fan itself (aerodynamic, mechanical, and electrical sources), to the way a fan is installed in a system, and to the fan's actual operating condition. Historically, spaceflight fan noise problems have been discovered late in a system design cycle when few changes can be feasibly applied. Most often, mufflers and enclosures have been used to control fan noise on the Space Station, though some especially noisy ventilation system fans have been redesigned and retrofit in-orbit.

NASA is now acting upon lessons learned and is adopting a more proactive approach to identify and address spaceflight fan noise problems. A Technology Development Plan for spaceflight fans has been created as part of NASA's Exploration Technology Development Program's Exploration Life Support Project. The goal of NASA's Exploration Technology Development Program (ETDP) is to develop technologies to enable NASA to conduct future human space exploration missions while reducing mission risk and cost. Funding for the Exploration Technology Development Program projects is provided based on needs prioritized by the Exploration Systems Architecture Study and the Lunar Architecture Team.

The spaceflight fan Technology Development Plan has been constructed to foster collaboration between the Exploration Life Support community and the research engineers in the NASA Glenn Acoustics Branch. The intent is to make broader use of the technology that has been developed at Glenn to increase the efficiency and reduce the noise of aircraft engine fans. The main goal is to develop a set of well-characterized government-owned fans nominally suited for spacecraft ventilation and cooling systems. Publicly reporting details of the design, analysis, and testing of these fans can effectively transfer NASA technology to the small fan industry at large. With access to fan geometry, analysis results, and high quality test data, industry can independently evaluate their tools and methods and work towards improvement. The baseline fans produced in this effort can also go on to be used to determine the benefit of new noise reduction concepts (such as improved motors or acoustic liners) in ground-based component and systems tests not described here.

2.0 Planned Efforts and Deliverables

Computational Fluid Dynamics (CFD) codes are routinely used to design and analyze aircraft engine fans. CFD is used to analyze preliminary fan designs, allowing an engineer to refine design code input parameters. These analysis codes are themselves in continual development, and high quality measurements are needed to assess the accuracy of predictions. In the aircraft engine industry, the need for high quality data has also been linked to the development of improved test techniques (Ref. 2).

CFD is not widely reported as a tool used by the small fan industry, and there are few reports of experiments conducted to collect the detailed measurements needed to validate CFD predictions of these small, low Reynolds number fans. We know of standardized test procedures suitable for some but not all of the small fans used in spaceflight applications. And while some of the known testing procedures are appropriate for quantifying the overall performance of a fan, the data from these tests are often not suitable for diagnosing the source of an aerodynamic or acoustic problem or shedding light on a numerical modeling issue. The long-term research effort described here aims to address these areas.

Reports describing the methods and tools used to design, analyze, and test the fans in this research program will made publicly available. The geometry of these fans and the test data will also be made publicly available. Once the tests described below have been completed, NASA's Exploration Life Support community can use the fans themselves in system tests or other technology development initiatives.

There are five phases of research for each baseline fan: identification, design, analysis, fabrication, and testing. Ideally, the team will strive to complete fan tests every 2 years in order to maintain interest and attention to this research. The flowchart in Figure 1 generally illustrates this work. Reports will be published to cover each phase of the research.

2.1 Identification Phase

Design point requirements must be determined for each fan by NASA's Exploration Life Support community: fan flow rate, pressure rise, pressure, temperature, and geometric size constraints (which may or may not include constraints on the hub diameter and length to accommodate a candidate motor). Ideally, fans considered to contribute the most noise would be studied first. The choice of fans studied will be influenced by what is known about past spaceflight fan installations, future mission needs, capabilities of the design and analysis tools, and limitations of our measurement techniques. Attempts will be made to identify existing fans that meet the design point requirements to serve as a reference fans so that comparisons can be made to assess the benefits of the new designs.

2.2 Design Phase

The aerodynamic design of each fan will be generated first. It is expected that a Computational Fluid Dynamics code would be used during the aerodynamic design process to identify and correct any problem areas. The fan will contain features that represent state-of-the-art aerodynamic and acoustic design, but will not include features that would be undesirable in a baseline fan. For example, while a baseline vaneaxial fan may include a contoured spinner on the rotor and use a blade to vane ratio selected to cut off tones at blade passing frequency, other features such as stator vane lean and sweep, serrated rotor blade trailing edges, or acoustic liners would not be included.

After the shapes of the rotor blades, stator vanes, and flow path have been determined, the mechanical and electrical design will be completed. Ideally, the mechanical and electrical design will not compromise the aerodynamic design of the fan. Balancing tolerances and methods will be identified. Since we want to collect detailed measurements of the flow velocities through these fans, special attention will be given to the mechanical design of the fan casing. Features will be added to accommodate the instrumentation needed, such as access ports located downstream of the blades and vanes for hot wire probes.

The motor selected should include a tachometer signal and speed control, so that the fan can maintain constant speed as it is throttled through its operating range during the aerodynamic and acoustic performance tests. The fan will not have to be certified for spaceflight, but should closely represent a spaceflight-worthy fan so that meaningful ground-based system tests can be conducted.

2.3 Analysis Phase

Once the aerodynamic design of the fan has been finalized, a more thorough analysis of its performance will be conducted. Steady-state solutions from a Reynolds-averaged Navier-Stokes solver will be generated. The design point of the fan will be studied most closely. Performance estimates at design point may be calculated for a few values of the rotor tip clearance gap, and the effects of differing turbulence models may be quantified. Off-design performance will also be predicted for several values of fan back pressure at design speed.

Predictions of fan pressure rise and flow rate will be generated and validated against the data collected in the aerodynamic performance tests. Ideally, predicted velocities in the wakes of the rotor blades and stator vanes would be compared against the velocity measurements collected in the validation tests described below.

2.4 Fabrication Phase

Ideally, several units of the fan will be produced. Even though the fans will be used in ground tests only, they should be constructed from the materials that would be used for the spaceflight fan. While stereolithography may enable the team to quickly produce a less expensive fan model, additional tests would need to be conducted to determine any differences in performance between a stereolithography model and its spaceflight-worthy counterpart.

2.5 Test Phase

Two types of tests shall be conducted: a) aerodynamic and acoustic performance tests and b) aerodynamic validation tests. These two types of tests are similar, but are not identical and cannot be conducted simultaneously. The objective of the performance tests is to experimentally measure the pressure rise and sound power emissions of the fan as a function of flow rate over the fan's entire operating range. The objective of the aerodynamic validation tests is to acquire velocity measurements in the wakes of the fan rotor blades and stator vanes. Data from both tests would be used to determine the accuracy of the CFD calculated values. The data from these tests, one of the key deliverables of this project, will be made publicly available.

2.5.1 Aerodynamic and Acoustic Performance Tests

Again, the purpose of these tests is to measure the pressure rise and sound power emissions of the fan as a function of flow rate when the fan is operated at constant design speed. Generating constant speed fan curves, rather than constant voltage fan curves, is meant to aid those responsible for the aerodynamic design and analysis of fans.

A complete map of both the aerodynamic and acoustic performance of the fans gives fan system designers the data they need to make informed design choices, information that is not often made available by today's small fan manufacturers. The performance maps generated by these tests will be incorporated into a database maintained by the NASA Johnson Space Flight Center's Acoustics Office that spaceflight system designers can used to help select a fan for their application.

Fans smaller than 0.15 m (6 in) in diameter that generate less than 746 Pa (3.0 inches of water) can use the apparatus and procedures described by ISO10302 as a guide to acquire the desired aerodynamic and acoustic performance data. A plenum compliant with ISO10302 has sides made of an acoustically transparent polyester film. Fans smaller than 0.15 m (6 in.) inches in diameter that generate over 746 Pa (3.0 in. of water) can use the modifications to ISO10302 procedures described by Bard and Nobile (Ref. 3) as a guide. All non-standard procedures followed in the course of this research would be documented.

NASA has two facilities capable of conducting these tests: the NASA Glenn Acoustical Testing Laboratory and the NASA Ames Anechoic Wind Tunnel. NASA Glenn has a half-size ISO10302 fan plenum, and NASA Ames has a full-size ISO10302 plenum. Both facilities have a hemispherical microphone array and data acquisition system needed to measure the sound pressure levels. The NASA Ames Anechoic Wind Tunnel had been used to generate the performance maps a number of fans now populating the web-based fan database maintained by NASA Johnson's Acoustic Office. The NASA Glenn Acoustical Testing Laboratory was used to measure the aerodynamic and acoustic performance of a spaceflight fan that was used in tests at NASA Glenn to take more detailed aerodynamic measurements using Particle Image Velocimetry and hot wire probes (Refs. 4 and 5).

2.5.2 Aerodynamic Validation Tests

Using a two-component hot wire probe, the axial and tangential velocities will be measured in the wake of the rotor blades and stator vanes. Measurements would be taken at design point conditions, and a few off-design point conditions. These data would be compared against the values predicted by the CFD codes.

The apparatus needed for this experiment would be similar, but not necessarily identical, to the apparatus used to collect the aerodynamic and acoustic performance maps. The fan would have to be throttled through its full operating range, but the plenum would not need to be acoustically transparent, as described in the ISO10302 standard. Rather, the fan would need to be mounted and throttled on a hard-walled plenum that in a way that provided easy access to the hot wire probe when it is installed downstream of the rotor and downstream of the stator. Velocity measurements would be compared against velocity predictions downstream of the rotor and stator.

3.0 Current Progress

A fan suitable for a spacecraft cabin ventilation application has been designed and analyzed by Tweedt using the tools and best practices commonly used for aircraft engine fan design (Ref. 6). Design point goals and the resulting predicted/model values are given in Table 1. Fan speed was minimized in an effort to reduce both fan and motor noise. The fan is shown in Figure 1a and in Figure 2. Contour plots of total pressure rise and velocity magnitude through the fan flow path indicate smooth flow from the inlet to the exit of the fan (Figure 3), but also show a large endwall loss region generated in the rotor blade tip gap. This relatively thick, higher-entropy region is thought to be associated with the low-Reynolds number flow through the fan (blade chord Reynolds numbers ~75,000). Mean flow predictions for two other values of the rotor blade tip clearance gap (0.006 and 0.012 in.) were also generated, with smaller than anticipated changes in calculated performance seen.

Predicted hydraulic efficiency and pressure rise as a function of corrected flow rate for design point conditions and a couple of points off design are given in Figure 4. Two different turbulence models were used in the analysis: a high Reynolds number model and a low Reynolds number model. The effect of the different turbulence models was slight, as indicated in Figure 4 and 6. Data from the aerodynamic performance tests are needed to validate these predictions. The values from the CFD solution have been plotted at a number of axial stations in the fan flow path, as indicated in Figure 5. Wake velocity profiles downstream of the rotor (Station 2a) and downstream of the stator (Station 3a) are given in Figure 6. Data from the aerodynamic validation tests are needed to confirm these predictions. The acoustic performance of the fan has not been predicted, and must be measured. Measured fan efficiency and overall sound power level are two quantities that may be suitable as Key Performance Parameters, metrics to gage research project progress.

TABLE 1.—SPACECRAFT CABIN FAN DESIGN POINT GOALS AND PREDICTED/MODEL VALUES

	Goals	Predicted/Model Value
Flow rate	0.709 m^3/s (150.3 cfm)	0.709 m^3/s (150.3 cfm)
Total pressure rise	906 Pa (3.64 in. of water)	925 Pa (3.716 in. of water)
Pressure	101 kPa (14.7 psia)	101 kPa (14.7 psia)
Temperature	21.1 °C (70 °F)	21.1 °C (70 °F)
Maximum diameter	0.102 m (4.0 in.)	0.089 m (3.5 in.) internal flowpath diameter
Maximum axial length	0.223 m (9.0 in.)	0.223 m (9.0 in.)
Rotor tip clearance gap	0.23 mm (0.009 in.)	0.23 mm (0.009 in.)
Rotor speed	Unconstrained	12,000 rpm
Number of blades	Unconstrained	9
Number of vanes	Unconstrained	11

4.0 Conclusion

NASA can play a unique role in improving the performance of small fans. A research program aimed at designing, building, testing a series of fans and making the geometry and test data publicly available has been described in a Technology Development Plan submitted to NASA’s Exploration Technology Development Program. A fan suitable for a spacecraft cabin ventilation system has been designed and analyzed using tools and best practices in commonly used in aircraft engine fan design. Test data is sought to validate predicted performance.

References

1. Goodman, J. R., "International Space Station Acoustics," nc03_125, 2003.
2. Strazisar, A., "The Role of Physical Experiments in Advancing the Design of Aircraft Gas Turbine Compressors," 2003.
3. Bard, S. E. and Nobile, M. A., "Acoustical implications of airflow impedance on both the inlet and outlet of an air-moving device," NC08-179, 2008.
4. VanZante, D. E., Koch, L. D., Wernet, M. and Podboy, G. G., "An Assessment of NASA Glenn's Aeroacoustic Experimental and Predictive Capabilities for Installed Cooling Fans: Part 1: Aerodynamic Performance," NASA TM-2006-214448, 2006.
5. Koch, L. D., VanZante, D. E., Wernet, M. and Podboy, G. G., "An Assessment of NASA Glenn's Aeroacoustic Experimental and Predictive Capabilities for Installed Cooling Fans; Part 2: Source Identification and Validation," NASA TM-2006-214450, 2006.
6. Tweedt, D. L., "Aerodynamic Design and Computational Analysis of a Spaceflight Vehicle Cabin Ventilation Fan," publication as a NASA Contractor Report pending.

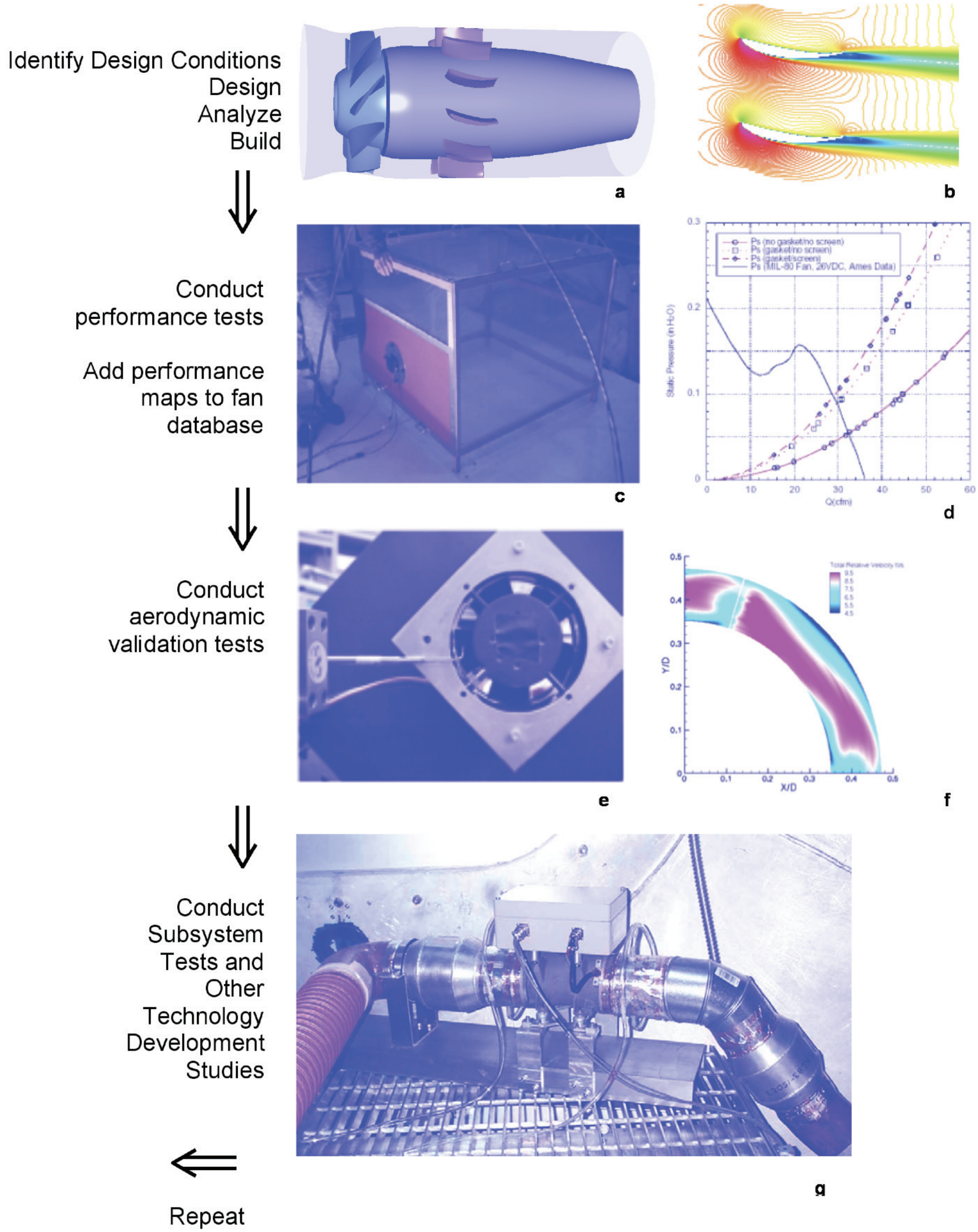

Figure 1.—Flow chart highlighting key efforts described in NASA's Technology Development Plan for spaceflight fans; a) cross-section of spacecraft cabin aerodynamic design, b) predicted stator velocity magnitude contours, c) fan plenum at NASA Ames Research Center, d) aerodynamic and acoustic performance maps as presented in NASA Johnson's Acoustic Office fan database, e) hot wire probe used to measure fan rotor wake velocity distribution, f) plot of total relative velocity measurements suitable for CFD code validation, g) system test of an Intermodule Ventilation Fan for the International Space Station.

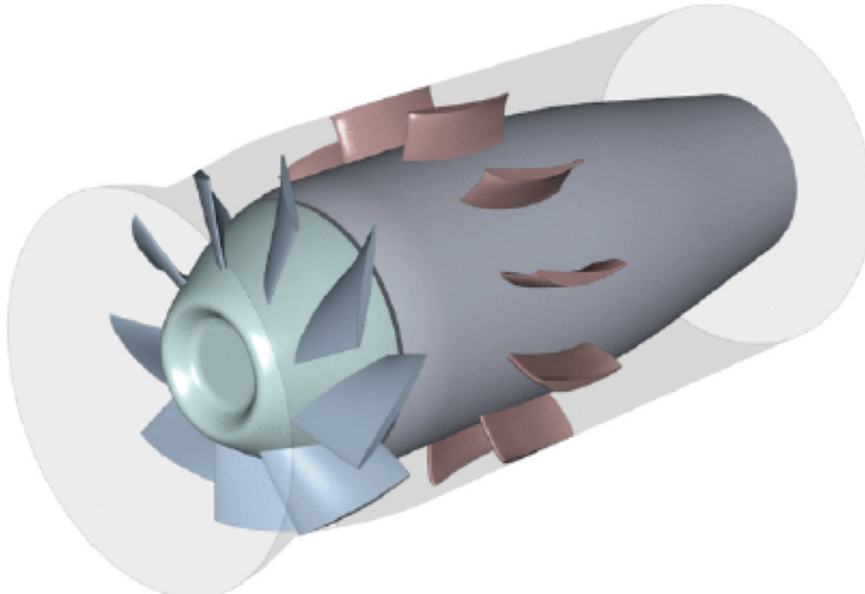

Figure 2.—Spacecraft cabin ventilation fan aerodynamic design.

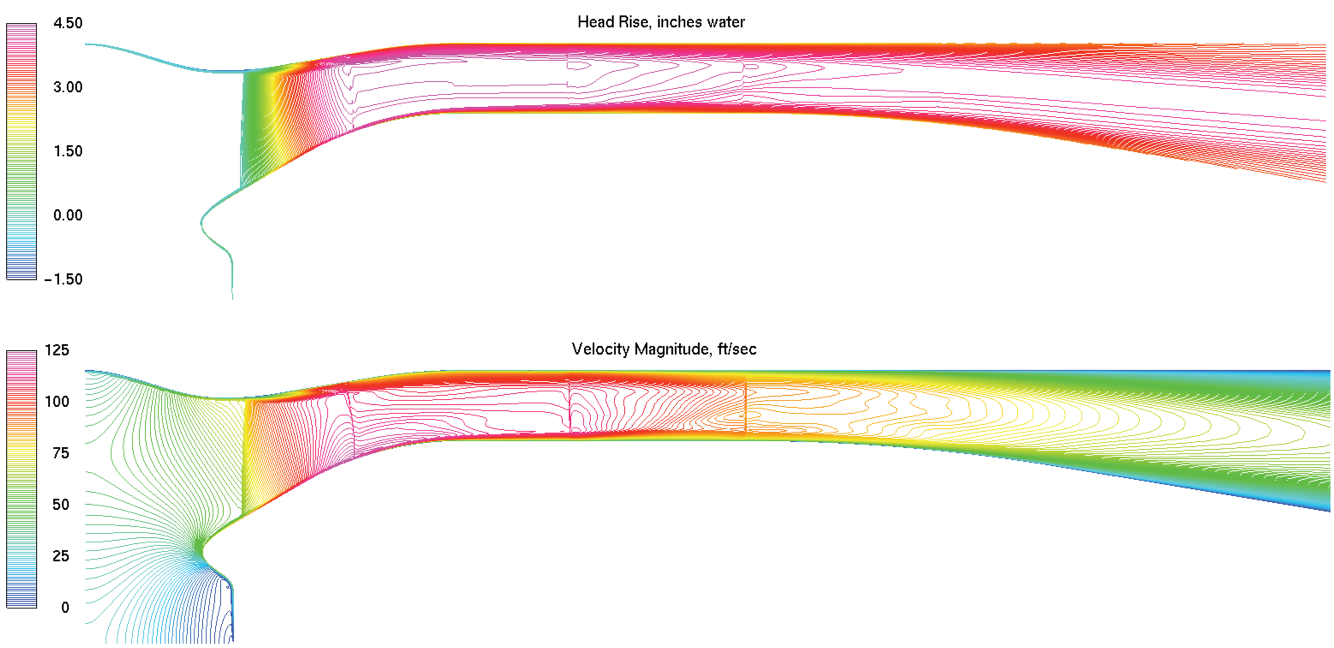

Figure 3.—Circumferentially averaged values of the predicted total pressure rise and velocity magnitude through the spacecraft cabin ventilation fan.

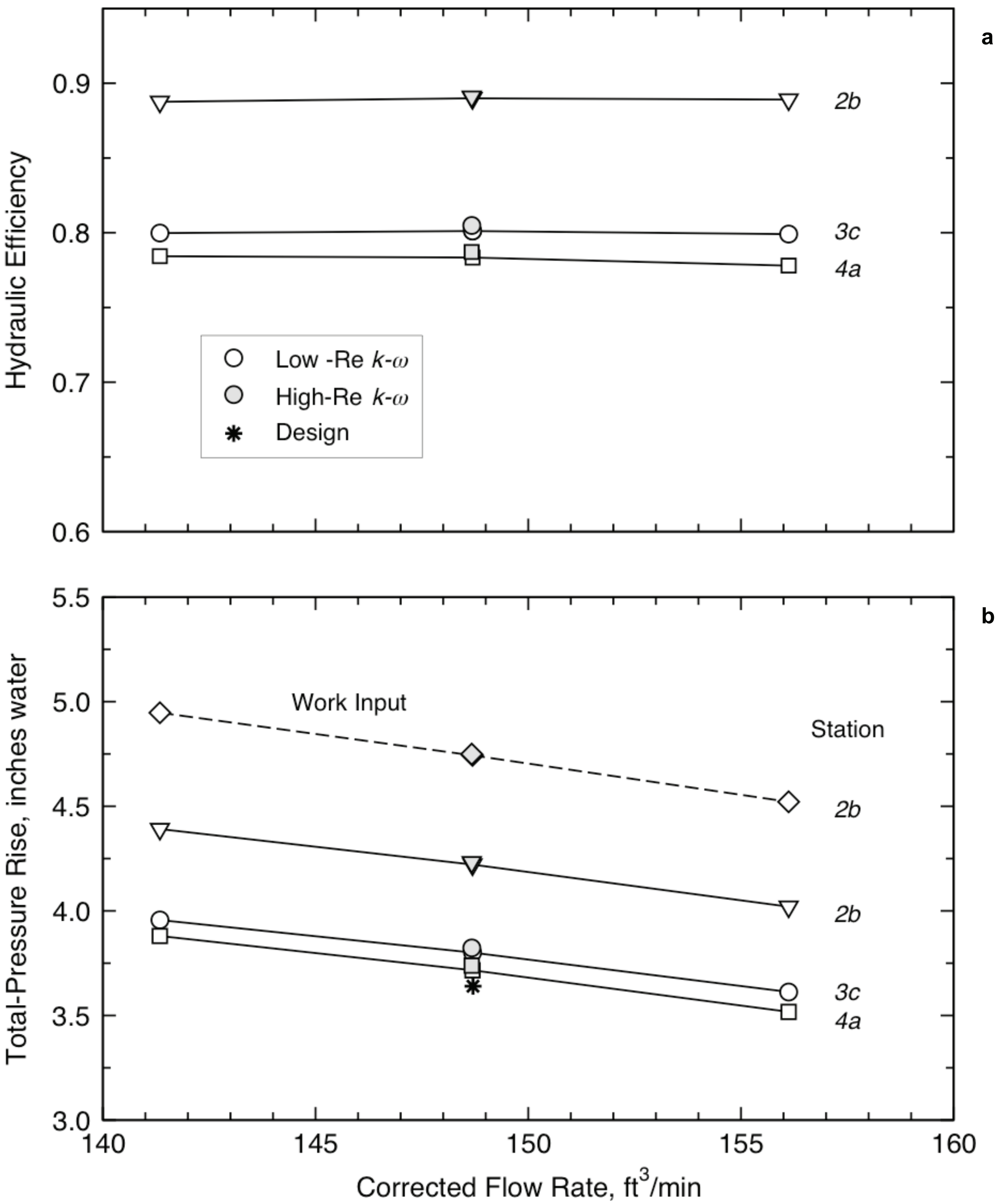

Figure 4.—Performance predictions for the spacecraft cabin ventilation fan at design speed, c) hydraulic efficiency as a function of fan flow rate, and b) total pressure rise as a function of fan flow rate.

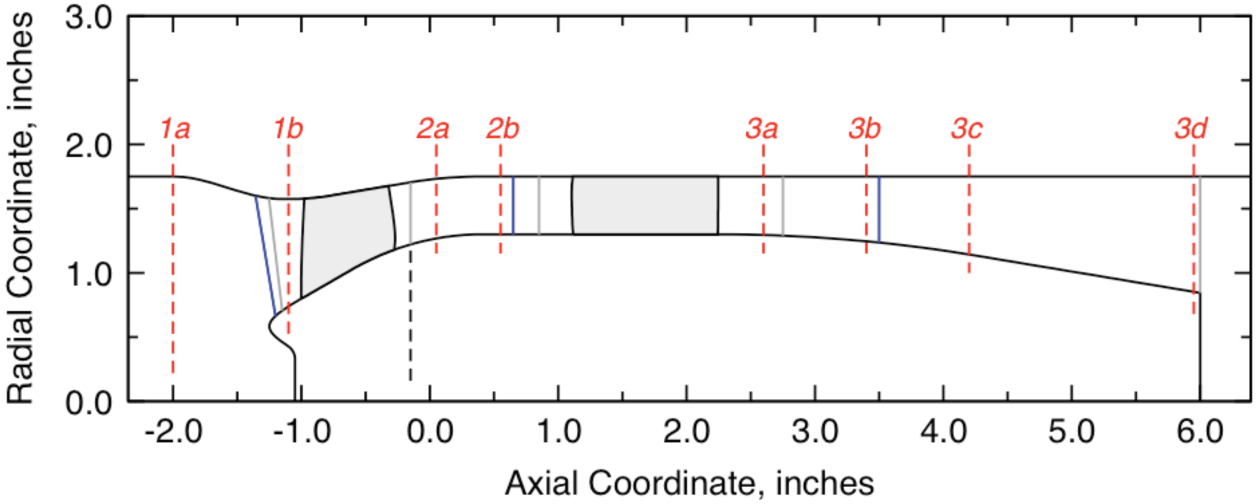

Figure 5.—Cross section of spacecraft cabin ventilation flow path marked to show axial stations where the CFD solutions have been plotted.

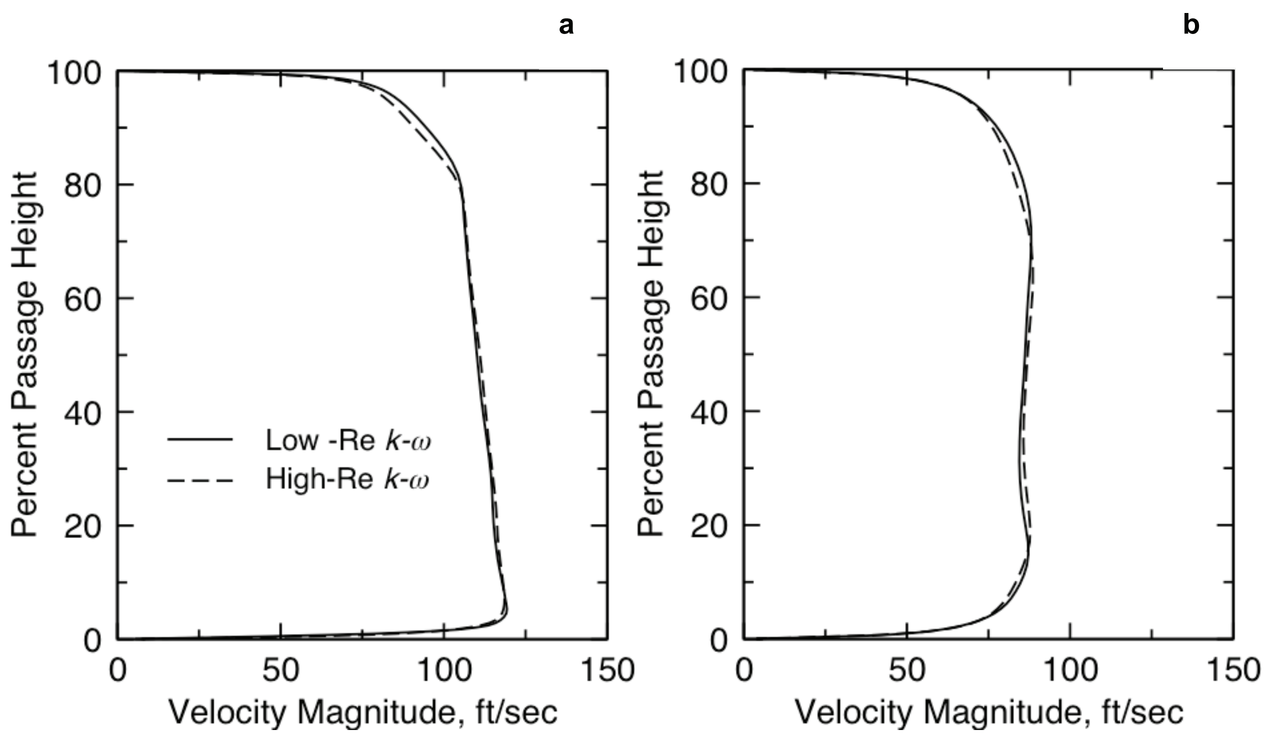

Figure 6.—Predicted velocity magnitudes plotted along the passage height at design point conditions a) downstream of rotor blade at Station 2a, and b) downstream of stator vane at Station 3a.

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14. ABSTRACT
A Technology Development Plan to improve the aerodynamic and acoustic performance of spaceflight fans has been submitted to NASA's Exploration Technology Development Program. The plan describes a research program intended to make broader use of the technology developed at NASA Glenn to increase the efficiency and reduce the noise of aircraft engine fans. The goal is to develop a set of well-characterized government-owned fans nominally suited for spacecraft ventilation and cooling systems. NASA's Exploration Life Support community will identify design point conditions for the fans in this study. Computational Fluid Dynamics codes will be used in the design and analysis process. The fans will be built and used in a series of tests. Data from aerodynamic and acoustic performance tests will be used to validate performance predictions. These performance maps will also be entered into a database to help spaceflight fan system developers make informed design choices. Velocity measurements downstream of fan rotor blades and stator vanes will also be collected and used for code validation. Details of the fan design, analysis, and testing will be publicly reported. With access to fan geometry and test data, the small fan industry can independently evaluate design and analysis methods and work towards improvement.

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