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FINAL PROJECT REPORT

GREATER ENERGY EFFICIENCY IN SERVER COOLING USING BIOMIMETIC FANS

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Greater Energy Efficiency in Server Cooling is the final report for the Greater Energy Efficiency In Server Cooling project (grant number PIR-10-020) conducted by PAX Scientific, Inc. The information from this project contributes to the Energy Research and Develoopment Division's Industral, Agricultural, and Water End-Use Energy Efficiency Program.

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ABSTRACT

Rack servers used in data centers produce excess heat as a byproduct, and require internal cooling fans to cool Central Processing Units and other components. These fans use significant energy to operate; this power is parasitic since it is not used for any actual computing task. PAX Scientific, Inc. has developed the PAX Streamlining Principle, a technology based on principles of fluid movement found in biological systems. The PAX Streamlining Principle, when applied to fan blade geometries, creates fans that are more energy efficient and quieter (noise is wasted energy) than fans designed by conventional means.

This project demonstrated PAX Scientific's energy efficient, biomimetic fans working in a server chassis to adequately cool its components while dropping fan power use at least 15 percent compared with conventional fan technology. The PAX fans surpassed this original goal and reduced power 35-45 percent for matched cooling in the Cisco Nexus 7000 Series server switch.

This final report includes the entire project specifications, information on developing fan design tools and computational fluid dynamics simulation models, data from experimental testing, and the final results, as tested by Cisco comparing the performance of the PAX fan to the current best-in-class.

Keywords: fan, server, IT cooling, parametric design

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EXECUTIVE SUMMARY

Computer servers, and their associated cooling and auxiliary infrastructure use roughly 1.7 to 2.2 percent of the total electricity demand in the United States, according to a 2010 report. Large server farms are intensive users of electricity and they are sited based on electricity cost and availability. Rack servers used in data centers produce a lot of heat, and require internal cooling fans to cool Central Processing Units (CPUs) and other components, in addition to general room air conditioning. These 40mm-150mm fans mounted within the server chassis use significant energy to operate – as much as 25 percent of the total power to the server. This power is parasitic in that it does not go towards any actual computing task and is responsible for higher operating costs.

PAX Scientific, Inc. (PAX) is a San Rafael, California-based research, development, and licensing company (C-Corporation) that specializes in finding innovative, streamlined solutions for fluid-related industrial problems using biomimicry. Biomimicry is an emerging field of engineering design that seeks to emulate the energy-efficient systems that have evolved in the natural world and apply nature's "best designs" to man-made systems. PAX has developed and patented the PAX Streamlining Principle, a technology based on principles and geometries of fluid movement found in biological systems. The PAX Streamlining Principle, when applied to fan blade geometries, creates fans that are more energy efficient and quieter (noise is wasted energy) than fans designed by conventional means.

PAX Scientific partnered with Cisco Systems Inc and Jabil for their knowledge, support, and test facilities. This project demonstrated PAX Scientific's energy efficient, biomimetic fans working in a server chassis to adequately cool its components using at least 35-45 percent less energy when compared with conventional fans. The 12 fans targeted initially used about 700W of power at full duty cycle, and the PAX fans use less than 400W. This power savings only represents one 9-slot chassis. A typical data farm would have hundreds or thousands of these chassis. Switching to PAX fans in the server will have significantly reduce wasted energy, which will lower operational cost and greenhouse gas emissions. The PAX fans are the same cost to manufacture and fit into the existing architecture.

This report details the method and results PAX followed to optimize their fan design to this application.

CHAPTER 1:
Project Overview

1.1 PAX Technology

PAX Scientific, Inc. (PAX) is a San Rafael, California-based research, development, and licensing company (C-Corporation) that specializes in finding innovative, streamlined solutions for fluid-related industrial problems using biomimicry. Biomimicry is an emerging field of engineering design that tries to emulate the energy-efficient systems that have evolved in the natural world and apply nature's "best designs" to man-made systems. After recognizing as a young boy that spiraling flows could be found in all forms of nature, naturalist and PAX CEO Jay Harman used that observation years later to identify a common set of geometries that nature applies ubiquitously to reduce friction and drag in flow structures, plants, and animals. By applying these forces of nature to innovations in technology, Harman patented these geometries as they apply to many different product areas in a wide range of industries including fans, blowers, mixers, thermal products, surface profiles, propellers, pumps, and turbines.

PAX geometries bring a variety of benefits to products, including:

- Friction and drag reduction in fluid handling
- Reduction in fluid noise/cavitations
- Improved energy efficiency in rotating blade and propulsion mechanisms
- Improved structural integrity in surface profiles
- Reduced environmental impact

To date, a major focus of PAX Scientific's design efforts is generating efficient fan designs. PAX employs biomimicry at several levels of the fan design to reduce turbulence over the blade profile, which leads to a reduction in power usage and noise. The benefits achieved using PAX technology differs by project - usually efficiency improvements vary from 15-65 percent while also achieving a significant noise reduction. A sampling of case studies is available on PAX's website [www.paxscientific.com].

For production, PAX currently partners with companies who either use fans in their products or who provide, sell, and/or manufacture fan-related components (motors, heat exchangers, etc) to original equipment manufacturers. PAX focuses its efforts on the aerodynamics of the actual fan blade and housing design, and uses outside companies for manufacturing and motor design.

1.2 Application

Computer servers, and their associated cooling and auxiliary infrastructure account between 1.7-2.2 percent of the total electricity demand in the United States, according to a 2010 report[1].

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[1] Jonathan Koomey. 2011. *Growth in Data center electricity use 2005 to 2010.* Oakland, CA: Analytics Press. August 1. <http://www.analyticspress.com/datacenters.html>

Large server farms are intense users of electricity and are located based on electricity cost and availability. Extensive permitting is necessary to secure a potential data center location, and at least one in California has been turned down due to the power draw exceeding the proposed location's power production.

Servers, in addition to being located in air-conditioned rooms, primarily cool themselves with several small fans mounted in the chassis of the device. These pull air across the circuit boards and other vital components. These fans are typically 40-150mm in size and use up to 200 watts of power per fan. The number of fans per system varies directly with the computing power – 12 to 24 fans per server chassis are not uncommon. A typical data center would have a network of hundreds or thousands of chassis.

1.3 Project Goal

Because of the necessity for reduced power consumption in server fans, this is a great application for PAX's patented technology. Prior to this grant, PAX had obtained some samples of server-type fans and found that the PAX fans reduced power use. To date, however, PAX had not tested their fans in an actual server nor had they been able to demonstrate the power savings they achieved for a major server manufacturer.

This project goal was a 15 percent reduction in the energy consumption of server fans by substituting the current best-in-class commercially available fans for PAX fans designed using PAX's biomimetically-inspired streamlining process. In this demonstration, PAX retrofitted a commercially-available server with multiple fans that they designed and prototyped. The energy consumption of this modified server was monitored over a range of typical operating conditions to quantify the energy savings of the PAX fans. To achieve this, PAX:

1. Worked with a server manufacturer to select a server platform & design a test procedure
2. Iterated on the in-house PAX design tools (analytic and computational fluid dynamics) to prepare them for server-specific fan designs
3. Designed a fan optimized for the selected server and completed baseline tests
4. Fabricated pre-production samples
5. Installed PAX fans in a server and monitor power usage under typical operating conditions to compare with current best-in-class server fans

PAX selected Cisco Systems, Inc, and Jabil Circuit, located in San Jose, California as partners. Cisco is a worldwide leader in IT hardware and software and Jabil is a supply chain management and manufacturing partner who currently provides many components, including fans, to Cisco. Both partners felt that a 15 percent reduction in fan power would demonstrate a significant energy savings over the current best fans in the server chassis.

CHAPTER 2:
Project Specifications

2.1 Server Selection

The first server fan targeted was a mid-range 120x120x38mm fan. This type of fan is typical of server chassis, is very power intensive, and is of particular interest to Cisco. Cisco currently uses this fan in its line of Nexus 7000 server switches: a 9-slot chassis and an 18-slot chassis. The 18-slot version uses 24 of the 120x120x38mm fans and the 9-slot version, referred to as "Boxster," uses 12 of these fans. Both Cisco servers sell approximately 1,000 - 2,000 units/month, which would lead to 500,000 - 800,000 of these 120mm fans sold per year for the 5-7 year lifetime of each server platform. Each fan uses about 1.1Amps (at 48Volts) which can account for as much as 25 percent of the total power use to the server. All of the power going to these fans is lost in cooling the server, rather than actively adding to its computing capability. Cisco is eager to find a new fan solution that will reduce the power used by the fans and also decrease the noise.

The Boxster is a 9-slot server chassis of approximate dimensions 18″x24″x24″ (Figure 1-3). The total power usage in the Boxster chassis is 6KW at maximum. It is cooled by 12 - 120x38mm fans and six 80x38mm fans (which PAX will not be altering initially). One side of the chassis is perforated with hexagonal holes of about 2mm across where the air enters. The air is pulled across the server nodes (perpendicular to the rack) by the fans which are flush with the outlet wall of the chassis (also with perforated hexagonal holes).

Figure 1: Boxster air inlet view

Figure 2: Boxster air outlet view

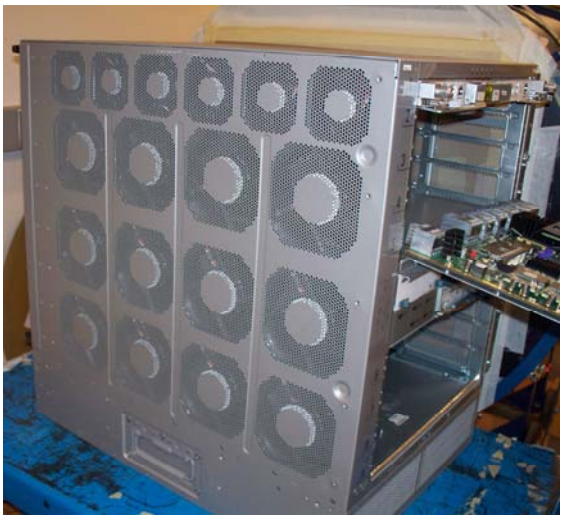
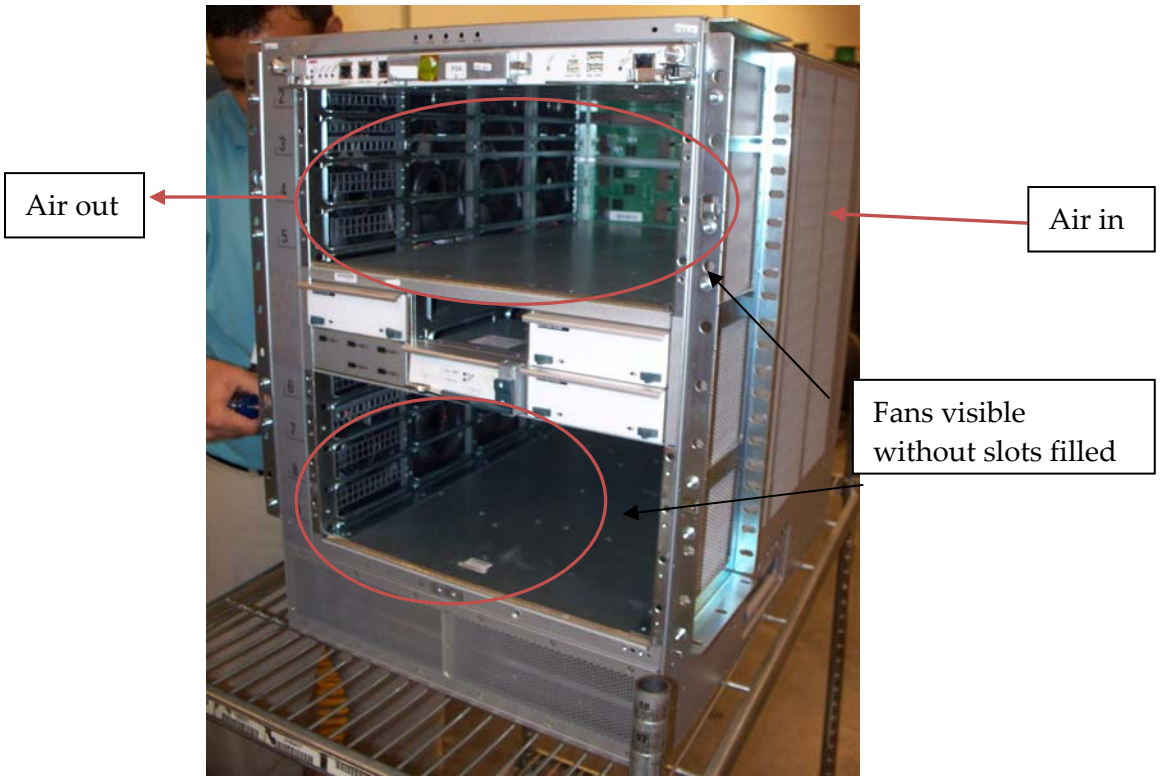


Figure 3: Boxster front view with fans visible



The fans are installed into a tray which slides into the side of the chassis for assembly. The fan tray has 12-120x38mm fans and 6-80x38mm fans. This server typically ships with a combination of Delta fans (model numbers AFC1248DE and FFB0848GHE) or Nidec fans (model numbers

T12E50BS2M7-07and V80E50BS2A7-07) (Figures 4 and 5). To isolate the 120x38mm fan performance, the 80x38mm fans will not be powered during in-unit testing.

Figure 4: Upstream view of Nidec fans in tray

Figure 5: Downstream view of Delta fans in tray

2.2 Competitor Fan

The primary fan for comparison will be the Nidec Model T12E50BS2M7-07 (Figures 6 and 7). The outer casing is 120mm x 120mm x 38mm. The fan has an imbedded 50V motor, and the speed is controlled using pulse-width-modulation software. Secondarily, the 120mm x 120mm x 38mm Delta Model AFC1248DE was also compared. These fans currently ship in the majority of Boxster units and were identified by Cisco as being "best-in class." The baseline data for the fans is shown in Figures 8 and 9.

Figures 6 & 7: Upstream and Downstream View of Competitor Fan

Figure 8: Airflow & Speed Baseline Data

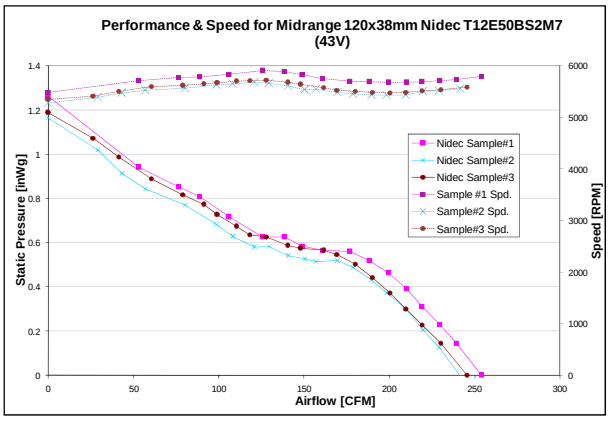
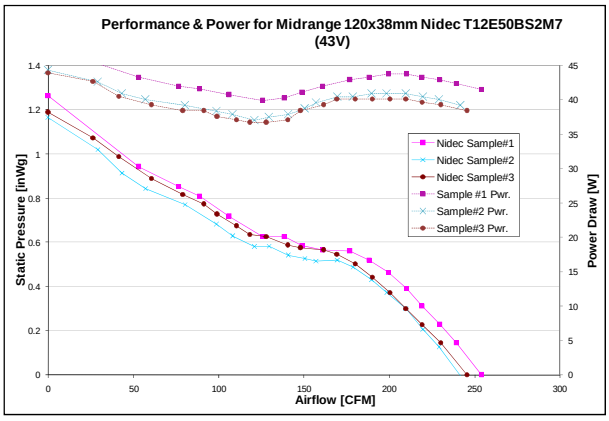


Figure 9: Airflow & Power Baseline Data

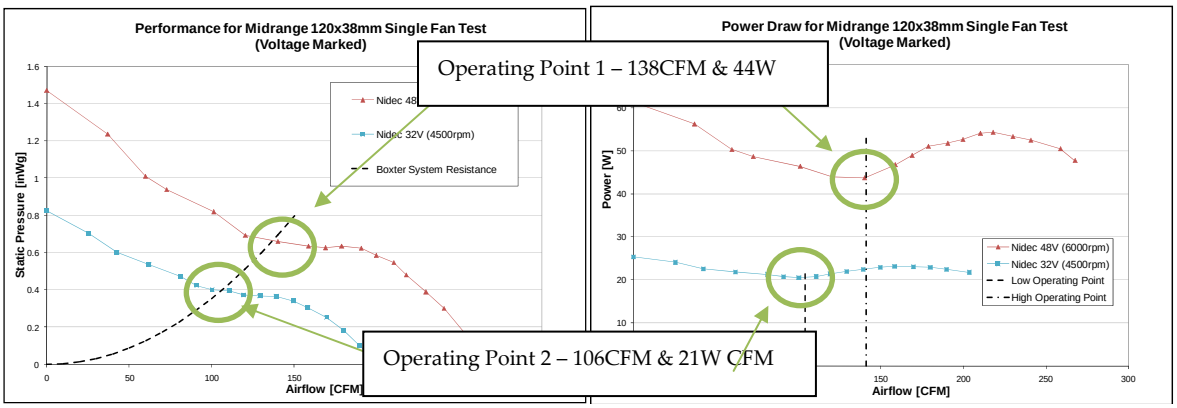


2.3 Test Procedure with Correlation

To demonstrate the PAX fan power reduction in a repeatible, real-world environment, a test procedure was developed with collaboration between Cisco and PAX. The details of the test procedure can be found in Appendix A and Appendix B of this report and are in accordance with AMCA 210 and international standards. The initial fan-alone airflow and noise tests were completed at the PAX Scientific Fan Laboratory in San Rafael, California. The tests with the fans installed in the server were completed at the Cisco Test Laboratories in San Jose, California. Throughout this project, PAX and its partners found a very high level of correlation between the two facilities.

The single fan data for the midrange 120x38mm fan which Cisco is currently using in the Boxster chassis is shown in Figures 10 and 11). Cisco also provided PAX with an operating point which represents the system resistance imposed on the fan by the fully loaded chassis. Using the performance curves and the system resistance data, PAX can approximate how the fan will perform when installed in the Boxster chassis. The curves show the midrange Nidec fan performance in a single fan test at two different speeds.

Figures 10 & 11: Baseline Airflow & Power Data - PAX Lab



Following the tests at the PAX facility, twelve Nidec fans were brought to the Cisco test facility for testing (Figure 12).

Figure 12: Baseline Airflow & Power Data – Cisco Lab

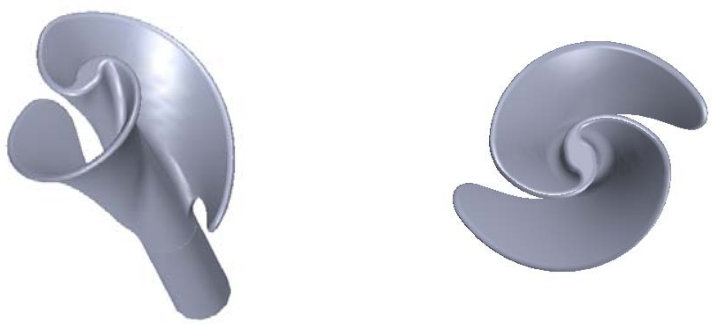
Nidec Fans in Boxster Chassis (12 Fans)							
12 Fans					Per Single Fan		
Duty Cycle	Airflow	Speed	Power	Leq	Airflow	Power	Leq
[%]	[CFM]	[RPM]	[W]	[dB]	[CFM]	[W]	[dB]
20	752	2824	94.6	71.0	63	7.9	60.2
30	869	3225	125.0	73.9	72	10.4	63.1
40	997	3645	162.1	76.8	83	13.5	66.0
50	1110	4009	210.6	79.1	93	17.5	68.3
60	1252	4438	268.3	81.5	104	22.4	70.7
70	1379	4849	350.6	84.1	115	29.2	73.3
80	1438	5232	425.2	85.7	120	35.4	74.9
90	1573	5690	512.3	88.0	131	42.7	77.2
100	1690	6003	632.9	89.5	141	52.7	78.7

These, shown in red, correspond closely to the speeds shown in the graphs of the PAX data. Using the operating point predictions for airflow from the PAX tests, the approximated values can be compared to the actual values tested in the chassis at Cisco. PAX approximated the output at 138CFM and 106CFM, at the 100 percent and 60 percent duty cycle operating points, respectively. Looking in the above chart, the actual airflow values per fan were 141CFM and 104CFM, respectively. These match closely. The power predictions also correlate, with the PAX test slightly under predicting.

CHAPTER 3:
Iteration of Tools

Prior to beginning this grant, PAX engineers had achieved a high level of expertise using computational fluid dynamics (CFD) and in-house design tools for biomimetic design. These prior efforts were focused on other industrial applications, such as the fluid mixers (Figure 13). To achieve this, the parametric design of an impeller is created in computer-aided design (CAD) software where the geometry of an impeller depends on a set of parameters. Then an optimization algorithm combined with computational fluid design (CFD) modeling is used to find the value for each parameter which maximizes the performance of the impeller. This methodology has proven to be effective and valuable for the impeller design and could be applied in theory to any other application involving a parametric design optimization (PDO) problem, such as cooling fans. As part of this grant, PAX took its prior knowledge and tools and tailored them to this server fan application

Figure 13: PAX Water Mixer



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3.1 CFD Parameters

PAX engineers use CFD simulations both as a performance predictor and, more importantly, as a flow visualization tool. By studying the pressure contours and velocity contours along the blade surfaces and in the downstream vortex, PAX can reduce areas of unwanted turbulence and improve performance. However, before PAX could use the CFD simulations for fan design, PAX investigated various geometric, grid, and physical modeling assumptions to establish a method with good experimental correlation.

PAX's first task was to find the proper geometric control volume for defining the CFD model. It was decided that modeling the actual flowmeter tunnel in the PAX Laboratory would give the best correlation. In particular, the 1000 CFM flowmeter tunnel (Figure 14) is used for the development of the energy efficient IT Fan. This flowmeter has two basic sections. The first section is where one mounts the fan and its shroud/housing flush to the front plexiglas surface that opens into a rectangular chamber that has pressure taps for measuring the rise of pressure from ambient. The opposite or exit surface (parallel to the surface the fan is flush with) has

multiple nozzle exits that can either be open or closed. The next section allows the air to either exit to ambient if the rear plexiglas surface is removed or exit to a large flexible hose that is connected to a blower that can be operated in tandem with a pivoting baffle over the flexible hose exit to control flow rate through the flowmeter tunnel. In additon the flow meter has details, e.g., screens for flow straightening, etc., that are ignored. In fact, the actual rear section with flexible hose with pivoting baffle and blower will be ignored altogether. Figure 15 shows this simplified flowmeter tunnel geometry with IT Fan attached to the right and three inch exit nozzle on the left with typical air particle paths.

Figure 14: 1000cfm Flowmeter Tunnel

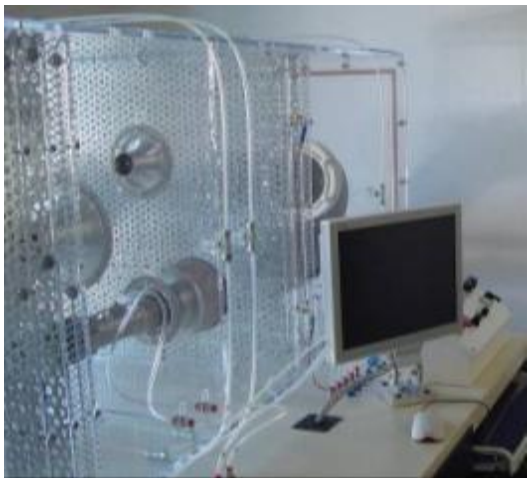
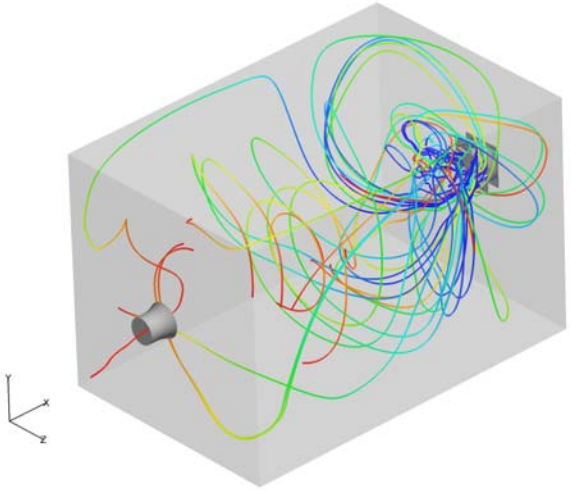


Figure 15: Simplified Flowmeter Tunnel Geometry



To finalize the computational control volume geometry, the means the flow rate and pressure drop (operating point) will be regulated multiple times to define a fan curve must be addressed. The classic approach is to create two artificial regions - one upstream of the fan and one downstream of the exit nozzle - and specify constraints on them. The flow boundary

conditions are applied to these two surfaces by defining a inlet mass flux (inflow) on the upstream surface and a pressure at the downstream surface, or by defining the inlet surface with a pressure to drive the flow. Either one of these is artifical but typically done. The 'novel' approach is to model a large portion of the air surrounding the flowmeter and drive the flow only by the fan and its rotation. With this approach, different operating points can be achieved by changing the exit nozzle diameter and geometric shape. In this manner, no inlet or outlet boundary conditions are specified. In the following subsections, these two different geometry approaches will be described. The details of this comparison are found in Appendix C. PAX found that the "novel" room control volume was preferred since its result showed a pressure near ambient just upstream of the fan and in the nozzle exit region. This model was used for the remainder of the project.

For the second task, PAX carried out a mesh sensitivity study. The goal in crafting a proper specification of isotropic mesh sizes (and viscous layer sizes) is to explore how mesh size variation effects the primary fan performance measure for a given simulation (pressure drop, flow rate and torque of the fan). In this way, a serious attempt to make the predicted results independent of the grid is executed.

Figure 16 shows the summarized results of this grid study (For an extensive look at the grid study, please see Appendix D). In particular the difference between the most refined grid and the coarsest grid (Case 1 and Case 8) for mass flux is 7 percent, for pressure drop 10 percent and for torque 5 percent. The mesh size of Case 1 or ~60+ million elements is the upper limit of PAX's computer cluster capability. The benefits of a grid at this fine level compared to ~30+ million elements are slight but under some circumstances useful. The case can be made for using Case 2 and Case 3 mesh specifications as the nominal settings and Case 1 is nearly the same result, thus one backs up to the next coarsest mesh for production simulations.

Figure 16: Mesh/Grid Study Table for AcuSolve MRF

Mesh/Grid	room, chamber, upstream, wake, nozzle, exit, fan air, stator air and fan – Size mm	Number Elements or Cells	Mass Flux – kg/s	Pressure Drop - Pa	Torque - Nm
Case 1	100,10,10,6,3,5,2,2,.7	64,123,368	0.03871	19.94	0.1076
Case 2	150,15,15,9,4.5,7.5,2,2,.7	26,749,016	0.03907	20.24	0.1069
Case 3	200,20,20,12,6,10,2,2,.7	20,296,289	0.03927	20.65	0.1063
Case 4	250,25,25,15,7.5,12.5,2,2,.7	17,358,330	0.03906	20.62	0.1058
Case 5	300,30,30,18,9,15,2,2,.7	15,424,620	0.03937	21.02	0.1057
Case 6	500,50,50,30,15,25,2,2,.7	13,898,567	0.04058	22.08	0.1031
Case 7	500,50,50,30,15,25,2,2,2	7,377,665	0.04097	22.10	0.1028
Case 8	500,50,50,30,15,25,3,3,3	4,698,202	0.04136	21.92	0.1025

All simulations were carried out using PAX's High Performance Cluster (HPC). The cluster has a head node and 16 compute nodes for a total of 192 cores which include Infiniband interconnect to improve inter-processor communication and decrease memory latency. Two different commercial CFD packages were used: AcuSolve from Altair Engineering and STAR_CCM+ from CD_ADAPCO. Using both codes helped ensure reliability and consistency

since both codes fundamentally use the same governing laws of nature. Simulations were completed using both steady and unsteady physical modeling to help remove error in the computed results due to not resolving temporal features of the flow properly. A discussion of this can be found in Appendix E.

Figures 17 and 18 present IT fan curve results for CFD simulations and an experimental test and Figures 19 and 20 present those of a commercial cooling fan. The single point curves labeled mrfbig2again and bigmesh2 are single multiple reference frame (MRF) and detached eddy simulation (DES) simulations using mesh grid Case 1 specificiations. The IT fan has a complex stator geometry as part of its housing/shroud design while the commercial cooling fan has a more basic shroud design. Comparing CFD and experimental curves indicate that the CFD results for the commercial cooling fan are good while those of the IT fan are fair. In general both sets of fan curves show that steady MRF simualtions are not as accurate, and if one has the time for the unsteady simulation one should do it. The fact that AcuSolve and STAR_CCM+ both produced similar unsteady results is assuring with respect that it helps to confirm that the simulations with basically the same 'ingredients' result in the same thing. STAR_CCM+ seems to be more efficient with respect to time to compute. To date, it does not appear that the CFD simulations are fully capturing the effect of the downstream stator on the IT fan. PAX will continue to investigate it further. For example, the smaller size of the stator relative to the fan blade chord might suggest that a even smaller time step might help or using different turbulence models.

Figure 17: IT Fan Pressure/Airflow Simulation Results

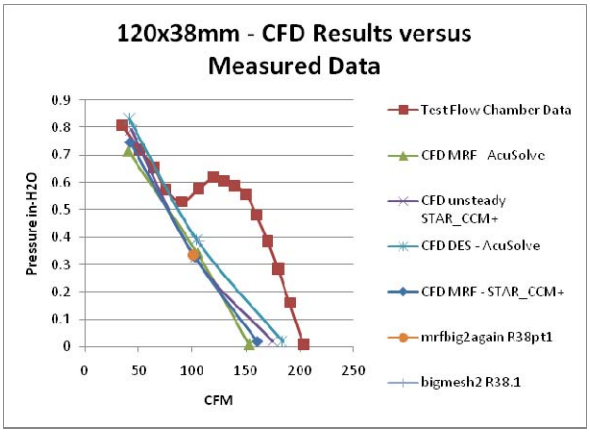


Figure 18: IT Fan Torque/Airflow Simulation Results

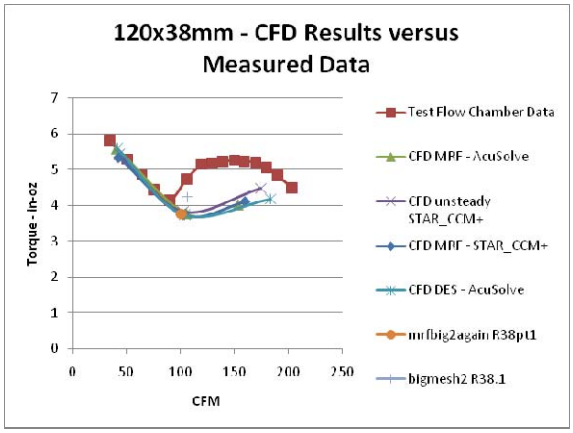


Figure 19: Cooling Fan Pressure/Airflow Simulation Results

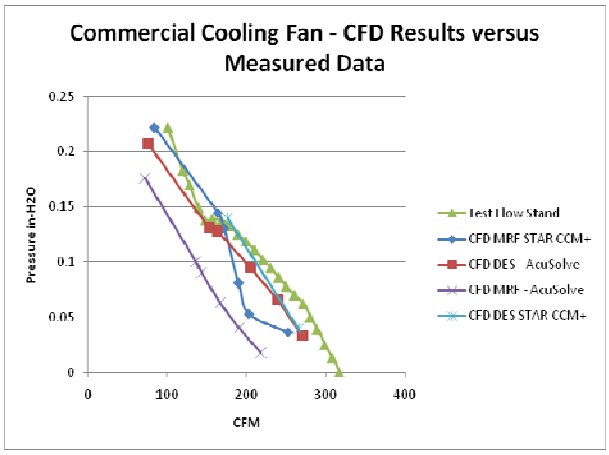
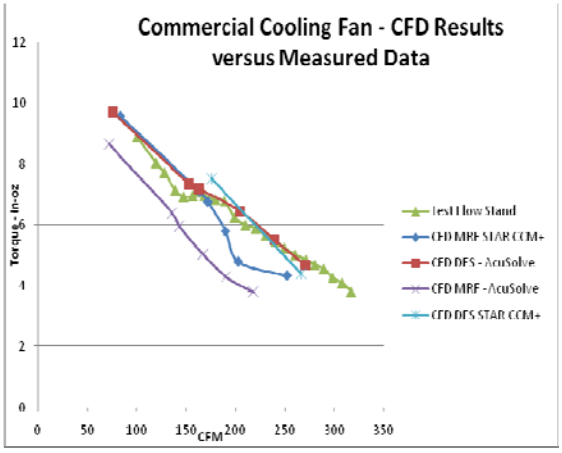


Figure 20: Cooling Fan Torque/Airflow Simulation Results



For the remainder of this project experimental results will be used to accurately characterize the overall performance of each fan design. However the CFD simulations were still very useful for the fan design. In particular, its 'added' value was to provide fine grain flow characteristics using scientific flow visualization software for a given baseline fan operating point and another improved fan design variant nominated by PAX's Fan Parameter Optimizer (see next section) as a means to understand WHY certain fan geometric parameter changes improve or reduce fan performance. Visualization of the three dimensional fan flow regime (pressure, velocity and turbulence) is a real benefit.

3.2 Fan Parameter Optimizer

The first challenge in applying the PAX optimization process to cooling fans was to develop an efficient optimization objective function specific to a cooling fan. The mathematical formulation of the optimization problem is

$$\hat{X}(OC) = \underset{X}{\operatorname{argmin}}\, f(X, OC)$$

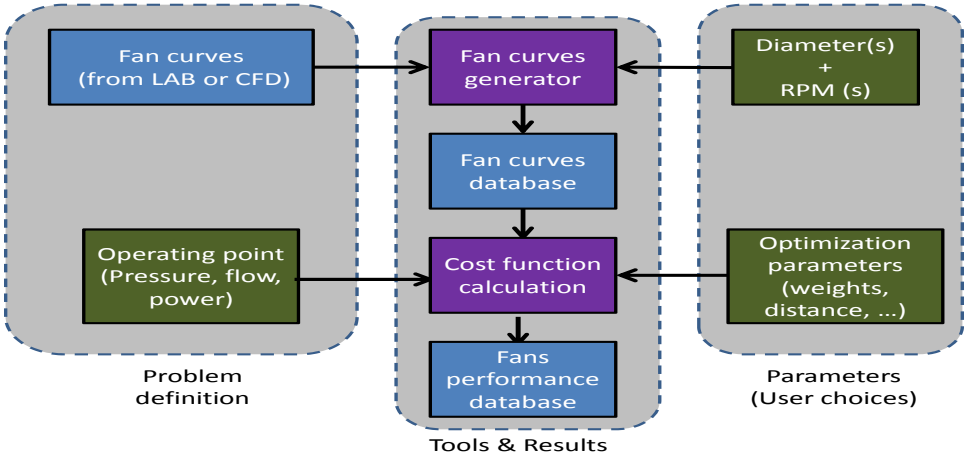
where f is the cost function, X is the set of geometrical parameters, OC is the set of operating conditions (such as flow, pressure, power, etc.) and $\hat{X}$ is the optimum set of parameters that minimize the cost function.

The main difference between that mathematical formulation of the fan optimization problem and the one used previously for the impeller application resides in the presence of the operating conditions taken into account explicitly in the cost function.

The fan performance is usually characterized by fan curves consisting of the pressure and power as a function of the air flow rate supplied by the fan. A certain fan will generally perform better under a specific range of operating conditions. Therefore, the selection of an optimal fan depends directly on the operating conditions.

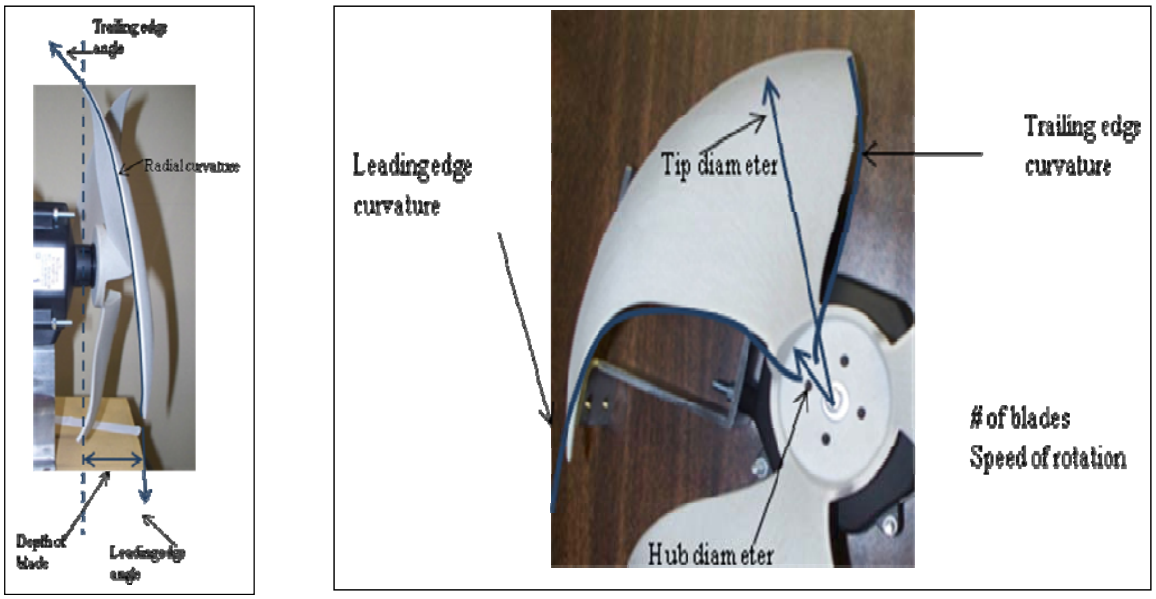
In that context, it was necessary to formulate an objective function that incorporates the operating conditions, such as airflow rate, pressure and/or power, and uses the fan curves as the input information. The methodology implemented in the PAX PDO toolbox is depicted in Figure 21.

Figure 21: Implementation of an Objective Function Applied to Cooling Fans



The second challenge was to select and quantify the parameters used for the fan design tool. Thoughtful discussion went into the selection criteria. Although the framework of the optimizer will work for a large number of parameters, it made sense to pick a reasonable number to start with, so that the software could work faster and visualization of results was easier. PAX eventually decided on 25 initial parameters for this version of the optimizer, but plans are to increase this number during the design process. Some of the parameters chosen are shown in Figures 22 and 23.

Figure 22 & 23: Fan Side and Top View with Parameters Labeled



The third step was to develop the working process for the software. This process had to generate fan curves at various diameters and motor speeds, using the existing database and

scaling laws. This creates a master database of fan curves that can be used to properly compute an objective function.

The next step is to select an operating point along the fan curve (pressure and flow) for which the optimization will be performed. Then, each fan curve is analyzed using the following cost function equation,

$$f(X, OC) = \begin{cases} Power, & if \;\; OC \in FC(X) \\ \infty, otherwise \end{cases},$$

where FC(X) represents the fan curve for a specific set of parameter X.

Basically, if a fan curve lies in the operating region then the cost function reduces to the power consumption at the operating conditions, otherwise the cost function is assumed to be infinite. This approach allows PAX to identify the fans that could operate in the specified operating region, and the resulting cost function can be used to effectively quantify the performance of a fan using a single number, which was required by the PAX parametric design & optimization methodology developed this far.

Using this parameterized fan model, methodology, and process just discussed, PAX developed a functioning Fan Parameter Optimizer. In its current form, using MATLAB coding and visualization software, it was used in developing the high efficiency PAX server fan in combination with CFD and prototype testing.

Development work on this optimizer and the CFD simulation models will never be "completed." As PAX actively uses the software, parameters and additional mathematical relationships will be added, along with improvements to the graphical user interface. Additionally, with each fan curve added to the database, the Optimizer is getting "smarter" and increasing its range of parameter knowledge. Similarly, PAX engineers learn more about the fan's simulations as they are performed and continue to improve their prediction capability.

CHAPTER 4:
Fan Design

4.1 Process

To use the PAX fan parameter optimizer described in the previous section, PAX began its design work by creating a large database of fan samples. These fan samples should be diverse in their parameter combinations to provide insight over the largest range. One of the methods used to create a random sampling of parameter combinations was the Orthogonal Method (Figure 25). Design of experiments techniques in general help engineers to determine simultaneously the individual and interactive effects of many design parameters that can affect the engineering performance results desired. Since design of experiments helps provide insight into the interaction between design parameters, this methodology can help achieve a robust design. For this effort, orthogonal pairs method is used in selecting the combination of values and levels.

Once these designs are created in computer aided design (CAD) software, the fan performance curves must be generated so that the optimizer can evaluate a cost function correlating the parameters to how well the fan performs. Each of the fan designs was generated in CAD, and a rapid prototype was generated using the outside vendor Harvest Technologies. The fan was then tested in-house using PAX's flowmeter and torque cell dynamometer in accordance with AMCA 210 Standards and Appendix A of this report.

Figure 25: Samples of Initial Fans Made Using Orthagonal Method Parameterization

Once the parameter combinations were established, the CAD files generated and prototyped, and all the testing completed, the PAX parameter optimizer helped PAX analyze their results. With each design iteration, PAX studied the parameter values of the most promising designs, and narrowed its focus to a subset of geometric factors that led to further improvements in design (see Appendix F for optimizer details and data from several fan iterations).

4.2 Final Design

Using this iterative process, PAX developed a parameter set and fan design they felt confident would meet the client's goal of 15 percent power reduction in the Boxster chassis. Figures 26 and 27 show data generated using prototype materials and run using PAX's dynamometer. Compared with the Nidec fan, the PAX design predicts a much higher output at the operating point (circled in black on the graphs), while using less power. When run slower just to match the cooling capability of the competitor Nidec fan, this initial estimate predicts that the PAX V1 fan design will produce about a 35 percent drop in power usage compared to the best-in-class Nidec fan currently shipping in the unit.

Figure 26: Airflow/Pressure Data for Final PAX V1

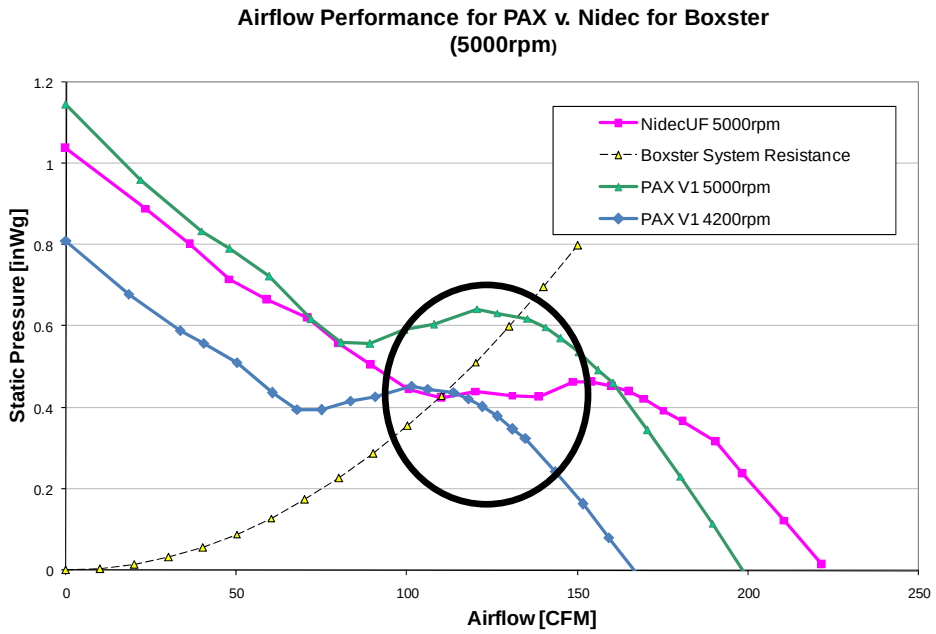
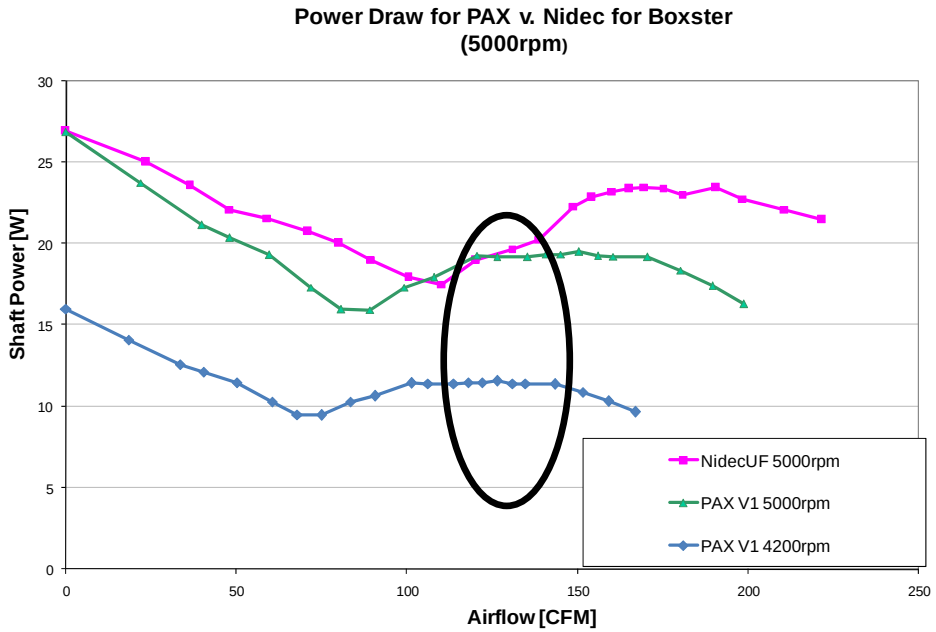


Figure 27: Airflow/Power Data for Final PAX V1



4.3 Pre-Production Prototypes

The next task of this project involved creating a more hearty, manufacturing-ready version of the PAX prototype on a Nidec motor for testing in the Boxster chassis at Cisco. To complete the Power Consumption Monitoring Tests for this grant, PAX had to fabricate samples which could interface with the Boxster chassis. The samples being tested by Cisco required all of the same outer and mounting dimensions as the conventional fans. More importantly, they had to interface with the server's existing internal controller and adjust in speed in an analogous manner to the conventional fans. It was determined that the best way to accomplish this was to use the motor from a conventional fan currently being used in the server – the Nidec model number T12E50BS2M7-07 – and assemble it within the finalized PAX fan and housing design.

Figure 28: PAX Fan Blade in CAD & Prototype

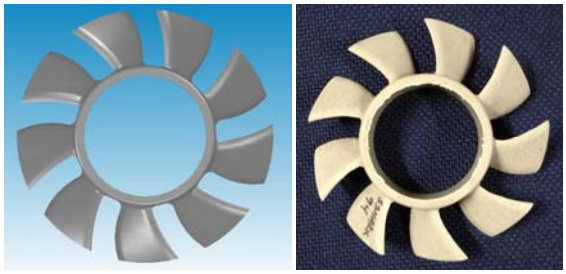
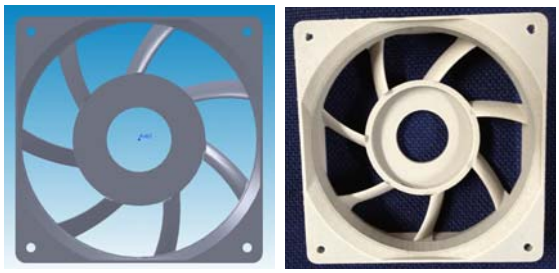


Figure 29: PAX Fan Frame in CAD & Prototype



A sample set of the Nidec motors was obtained, isolated from their initial fans and frames and verified for acceptable performance. Then the motors were assembled into rapid prototypes of the PAX fan and frame design created from the optimized parameters (Figures 28 - 31). Because of the high rotational speeds these samples would be tested at, it was necessary to have the functional samples balanced. The assembled samples were sent to an outside vendor who measured the imbalance of each sample while powering the fan, and then added small epoxy masses in the inner hub to reduce the imbalance. Performance of the samples was verified at the PAX lab and corresponded well to the initial dynamometer results discussed in Section 4.2 .

Figures 30 & 31: Upstream & Downstream Views of PAX V1 Pre-Production Samples

CHAPTER 5:
Comparative Power Consumption Monitoring

All of the following test results were generated at the Cisco Test Facility in San Jose, California by Cisco engineers with the assistance of PAX engineers. The procedure followed was in accordance with AMCA 210 and followed the procedure dictated in Appendix B. The tests measured the performance from a 12-sample installation of three different 120x38mm fans:

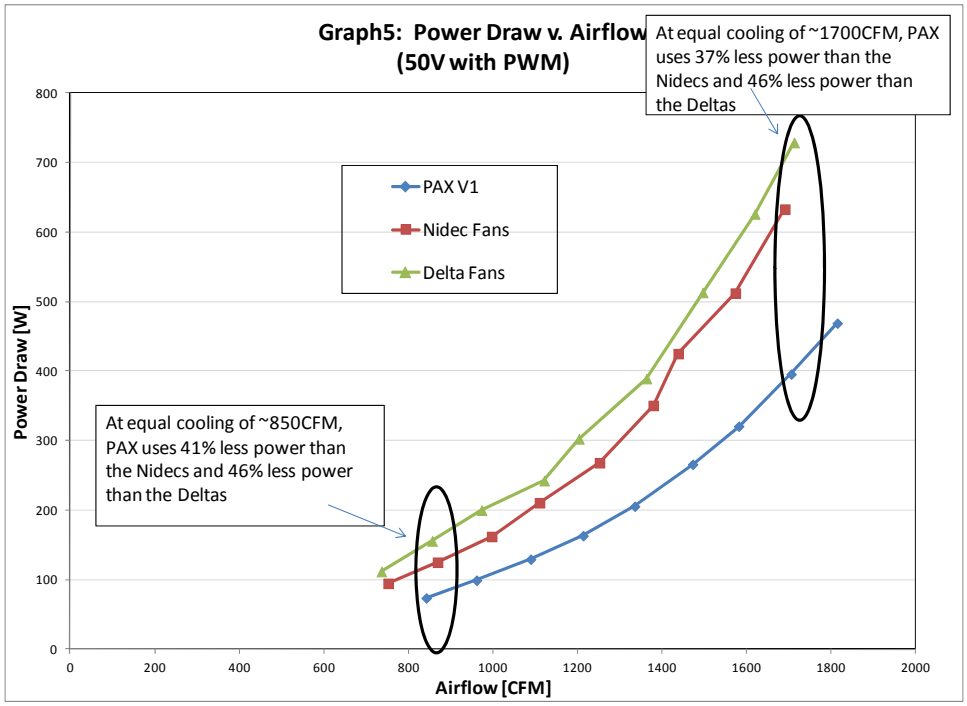
1. The PAX V1 Pre-Production Samples
2. The Delta Electronics Model #AFC1248DE (currently ships in unit)

The Nidec Model #T12E50BS2M7-07 (currently ships in unit)

5.1 Boxster Chassis

Figure 32 shows the 12-fan airflow output (proportional to cooling) measured from the Boxster chassis across the x-axis, and the power draw necessary to create that amount of airflow along the y-axis for each fan set. The PAX fans are shown in blue, the Nidec fans are in red, and the Delta fans are in green. The lower end of the curves represent the lowest duty cycle tested – 20 percent. The upper right-hand side of the curve represents the high duty cycle – 100 percent. During normal service, the chassis software adjusts the duty cycle to meet the cooling needs, which depending on the computing demand. To examine equal cooling, one can draw a vertical line through the graph showing equal airflow output, and then look to the left axis to see how much power is used by each fan set. Throughout the entire duty cycle, the PAX fans use significantly less power than both the Nidec and Delta fans for equal cooling.

Figure 32: Airflow/Power Comparison for PAX & Competitors Installed in Server



At a low duty cycle, with about 850CFM of cooling, the PAX prototypes use 41 percent less power than the Nidec fans and 46 percent less power than the Delta fans. At the high duty cycle with about 1700CFM of cooling, the PAX prototypes use 37 percent less power than the Nidec fans and 46 percent less power than the Delta fans.

Figure 33: Airflow/Sound Comparison for PAX & Competitors Installed in Server

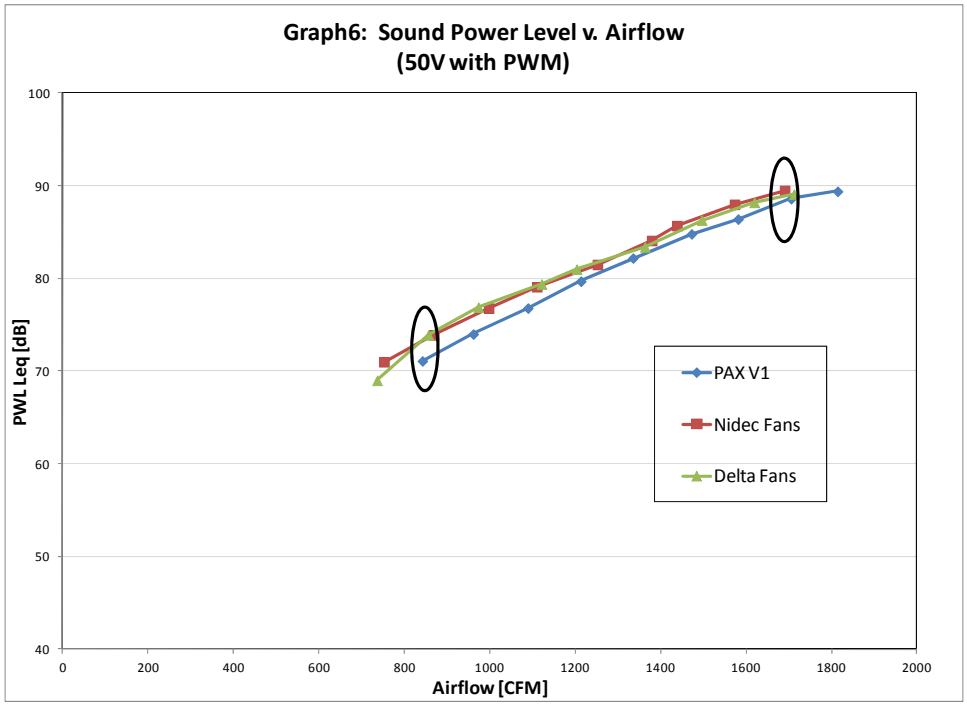


Figure 33 shows the same airflow output but graphs it against the total sound power level generated by each fan set in the Boxster chassis. The same low and high duty cycle comparison examples are highlighted, and this graph can be analyzed in a similar manner, by drawing a vertical line for equal cooling and comparing each fan type's sound power level. At the lower duty cycle point, the PAX prototypes are 2.8dB quieter than both the Nidec and Delta fans for equal cooling. At the higher duty cycle point, the PAX prototypes are about 1dB quieter than the Nidec and Delta fans for equal cooling. Although this is only a small drop in noise, the PAX prototypes are never louder than the competitor fans throughout the duty cycle, while greatly reducing the power consumption.

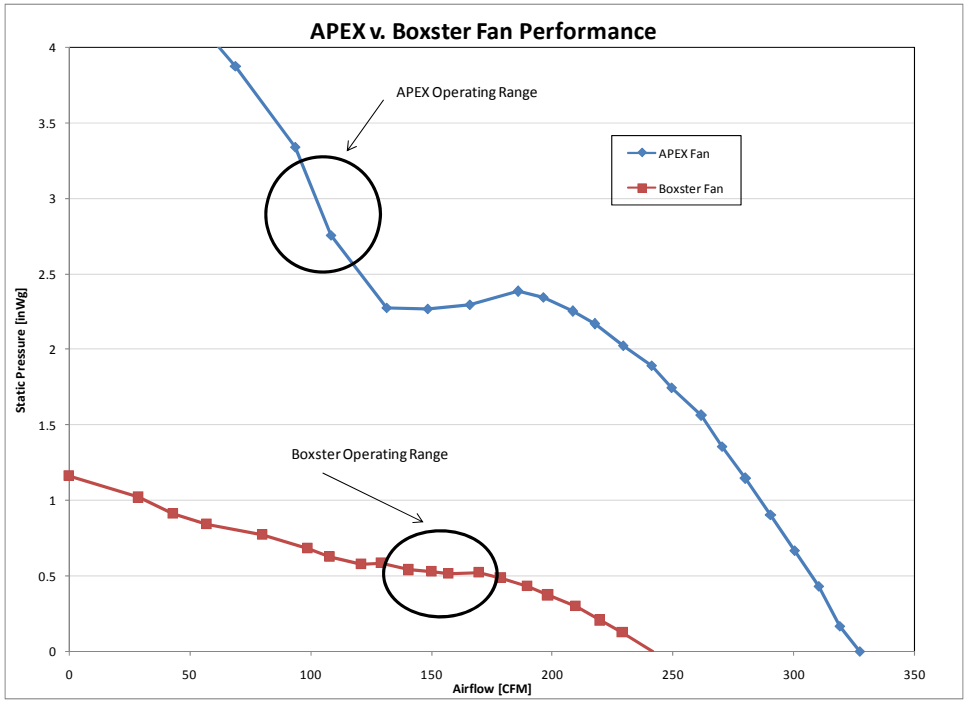
5.2 Additional Work – APEX Chassis

The PAX fan design for the Boxster chassis was very successful and far exceeded the power drop goal established at the beginning of the project and grant. Because of this achievement, PAX's partner was interested in choosing an additional system to target for a new PAX fan design.

The second chassis chosen was called the APEX chassis, and it was a brand new platform that the PAX partner plans to release in the next one-two years. The new chassis will use twenty-one 120x120x38mm fans. This was the same size fan PAX designed for the Boxster chassis, but because the architecture of this chassis is very different and much more tightly-packed, it required a much different fan design. Figure 34 compares the Boxster operating point, and the

new APEX operating point. Because it is a new product, the system was not available for in-system testing as of the date of this report.

Figure 34: Airflow/Pressure Comparison for Boxster & APEX Chassis



The fan design for this system was to reach maximum output in the operating range while keeping the maximum power draw below 120W and there was an additional goal to achieve a significant noise reduction. The design process used for this additional work followed the procedure PAX dictated in Chapter 4 of this report. This work further validated the procedure and tested the CFD and Optimizer for robustness on a different server fan application.

After several iterations using CFD and the PAX fan parameters optimizer, the PAX V2 fan, without housing and motor, showed a marked performance increase compared with the conventional EBM fan (Figure 35). At that speed, the PAX fan produces 15 percent more airflow while using 12 percent less power at the operating point (Figures 36 and 37). The final speed of the PAX fan can be adjusted to maximize airflow while matching power, or match airflow while minimizing the power. At the current time, PAX's Partner is considering either option going forward. Additionally, the PAX V2 fan design was 5dB quieter than the EBM competitor fan.

Figure 35: PAX V2 Design

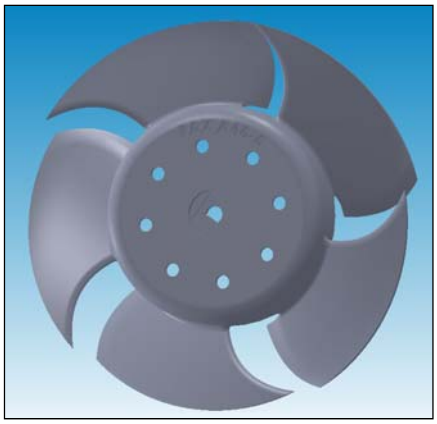


Figure 36: Airflow/Pressure Comparison for PAX in APEX

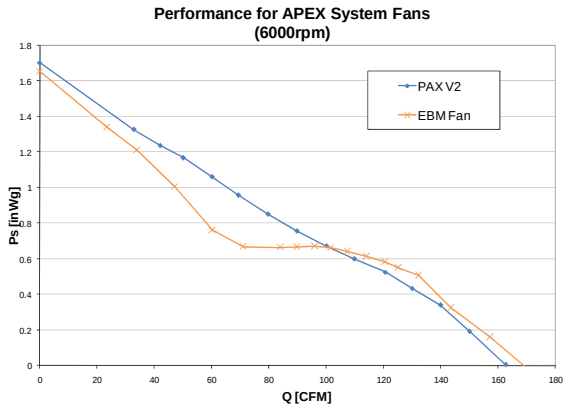
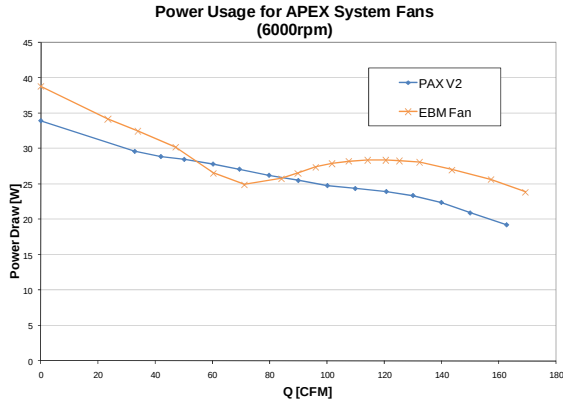


Figure 37: Airflow/Power Comparison for PAX in APEX



From these results, PAX is confident that this new fan design will also demonstrate a significant energy savings of 20-25 percent when the full power consumption monitoring tests are completed by the partner when the APEX chassis becomes available. This exceeds the project goal to demonstrate a 15 percent reduction in power for matched cooling and is considered another success by the PAX partner.

CHAPTER 6: Conclusion

PAX and Cisco are excited about these results. PAX surpassed the 15 percent goal of reducing power draw for matched output in a server and designed a fan that produced a 35-45 percent power drop in the selected server chassis compared to the current best fans, as specified and tested by Cisco and Jabil. PAX had an additional noise reduction benefit as well, which was very important to their partner. This result was also demonstrated on a second chassis. The 12 fans targeted initially used about 700W of power at full duty cycle, and the PAX fans use less than 400W. This power savings only represents one 9-slot chassis. A typical data farm would have hundreds or thousands of these chassis. Switching to PAX fans in the server will have a significant reduction in wasted energy that will reduce operational cost and greenhouse gas emissions. And the PAX fans are the same cost to manufacture and fit into the existing architecture.

Based on the results of this project and grant, PAX and Cisco plan to implement their Technology Transfer Plan and Product Readiness Plan. Additionally, PAX and Cisco must identify the right manufacturer and direct supplier to Cisco. PAX also hopes to expand its server-targeted fan designs to include more sizes and operating ranges.

GLOSSARY

Term	Definition
AMCA	Air Movement & Controls Association
Anechoic chamber	Room designed to completely absorb sound wave reflections
CAD	Computer Aided Design
CFD	Computation fluid dynamics – software used to simulate airflow using CAD geometries
CPR	Critical Project Review
CPU	Central Processing Unit (inside server)
DC	Direct Current
DES	Detached Eddy Simulation
DOE	Design of Experiments
Dynamometer	Used to drive (spin) the fan at a constant speed for testing without a motor and measures fan torque in combination with a torque cell
Downstream	Region just past the fan in the direction of airflow
Flowmeter	A windtunnel configured with calibrated nozzles and pressure gages for measuring a fan's airflow across a range of backpressures
HVAC	Heating Ventilation and Air Conditioning
Impeller/rotor	The rotating part of the fan, pump, etc designed to move fluids by rotation
IT	Information Technology
MRF	Multiple Reference Frame
Operating point	Pressure, airflow, and fan speed conditions where the fan's performance curve crosses the system's resistance curve
PAC	Project Advisory Committee
PDO	Parametric Design Optimization
PIER	Public Interest Energy Research
PWM	Pulse width modulation – a modulation technique often used for controlling speed of a fan
RD&D	Research, Development and Demonstration
Server chassis	A metal structure that is used to house or physically assemble servers in various different form factors
SLS	Selective laser sintering

Stator	The stationary part of the fan, pump, etc that can be designed to improve efficiency by converting the rotational energy of the fluid
Upstream	Region just prior to the fan in the direction of airflow

APPENDIX A:
Test Procedure – PAX Scientific Facilities

Airflow Test Apparatus & Procedure

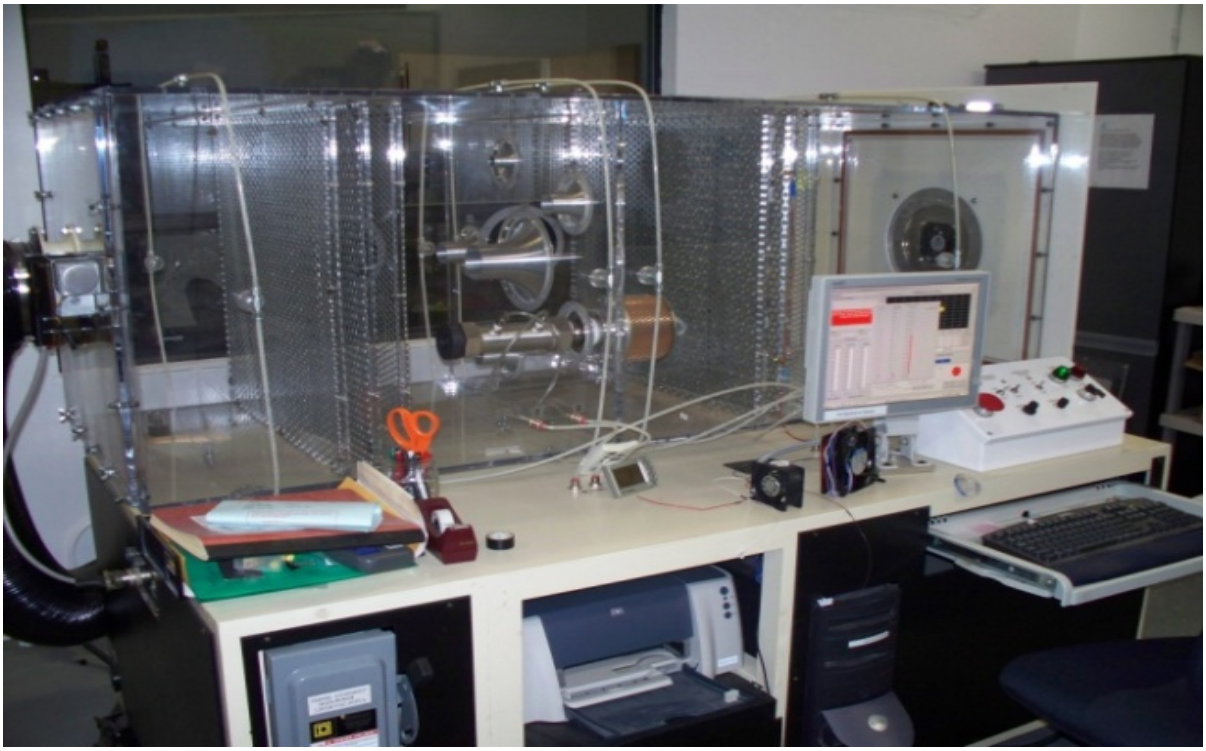


Figure A1: PAX FM1000 Flowmeter

PAX Scientific (PAX) will run all fan-alone tests using its Torrington FM1000 flowmeter in accordance with AMCA 210 standards. The flowmeter (pictured above in Figure A1) can measure from 2-1000CFM and 0-5"Wg. The backpressure in the test chamber is controlled using an auxiliary blower (located inside test stand), and a set of calibrated nozzles are opened according to the range of airflow measured. An optical speed sensor is used to measure fan speed. Fans with a range of 0-33Vdc are tested with a power supply internal to the flowmeter – a Sorensen DCS33-33E. Higher voltage fans are tested with an auxiliary dc power supply: an Agilent E3634A. Data is logged using Torrington's flowmeter software. For the dynamometer tests, a custom-built 0.1Nm torque cell dynamometer will power the fan and measure shaft torque.

For the initial dynamometer fan-alone tests, each prototype fan will be press fit onto a hub attached to a frame (with or without stators). The frame will be mounted onto the test fan end of the flowmeter. Tape will be added to maintain an airtight seal. The test fan will attach to the dynamometer drive chuck using a flexible coupling. This is pictured below in Figure A2. The fan will be powered to a constant speed throughout the test. For each fan test run, the fan will

start at free-air (0”Wg in the test chamber) and data will be taken at regular intervals as the pressure is increased in the test chamber until the fan’s maximum (shut-off pressure). The pressure in the test chamber is controlled manually using the auxiliary blower and a damper. Rotational speed, change in pressure across the nozzle(s), chamber pressure, shaft torque, and air density parameters will be monitored and logged throughout. Final data will be corrected for standard temperature and pressure. Each sample and prototype physically created by PAX will be tested in this manner. From the results of these airflow tests, researchers can calculate and compare the static efficiencies of different PAX fan designs to the fans Cisco is currently using. Once given the system resistance curve of the server, PAX can predict from this data how the fan will perform in the in-unit tests at Cisco.

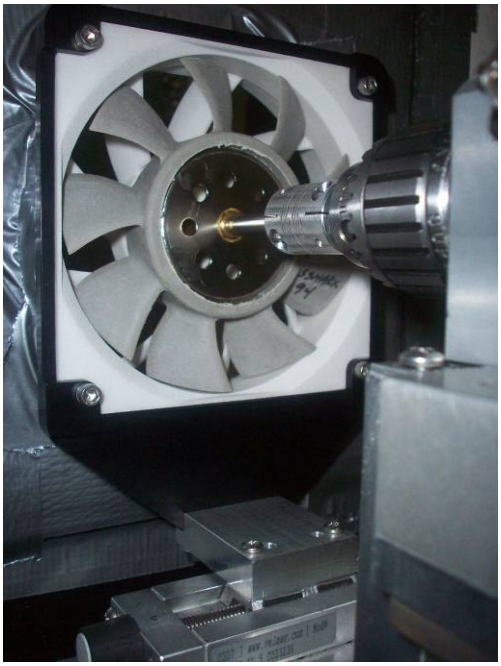


Figure A2: Prototype Fan & Stator Frame Attached to Dynamometer

For the final motor fan-alone tests, the tests will be run in much the same manner. Instead of using the dynamometer, the prototype fan will be fit onto a motor. The motor leads will be attached to the DC power supply and set at a constant voltage throughout the test. Five minutes of motor warm-up will be given before the first data point is taken. The test will proceed as above from free-air delivery to shut-off with voltage and power to the fan being monitored as well.

Sound Test Apparatus & Procedure

Figure A3: Microphone in PAX Anechoic Chamber

Figure A4: Mylar Plenum in PAX Anechoic Chamber

On promising fan designs, PAX will run sound tests in PAX's semi-anechoic chamber. These can only be run once the fan prototype has been fit to a motor. The chamber has a noise floor of 25dB A-weighted. The test will be run using a mylar plenum as specified in ANSI S12.11. The plenum allows for backpressure to be generated in the box (using the slider), but the mylar is acoustically transparent. Pressure is measured in the plenum using a Cole-Parmer transducer. Sound pressure level will be measured at a single location upstream of the fan, A-weighted, and analyzed using narrow bands. Data will be logged using Labview software.

For these tests, the fan will be powered using the commercial frame/motor and a DC power supply at constant voltage. The fan will be powered up at free-air, and then the pressure

increased using the slider until shut-off condition. Sound, pressure, and speed data will be taken at each test point and frequency band data calculated. Once given the system resistance curve of the server, PAX can predict from this data how the fan will perform in the in-unit tests at Cisco.

APPENDIX B:
Test Procedure - Cisco Facilities

Airflow Test Apparatus & Procedure

The in-unit airflow tests will be completed at Cisco's San Jose, CA facility using their 3000-5000CFM chamber. The chamber was manufactured by Airflow Measurement Systems and uses a Dwyer pressure transducer. It is a nozzle chamber that is 36" in diameter, 10' in length, and uses a 10hp auxiliary blower. To get the best measurement range, the nozzle wall will use two 6" nozzles open between the test chamber and auxiliary chamber.

For measuring airflow through the entire chassis, the entire inlet side of the chassis will be attached over the flowmeter opening, using a circle-to-rectangle adapter. The chassis will be taped all around to ensure no air leakage between the flowmeter and chassis. All fans present in the system but not involved in the test will be taped over. This restricts all the air that flows through the flowmeter and into the chassis to go past the specific fans that are being tested. A supervisor node will be added to the top two slots, and test blades fit into the rest of the slots to simulate the pressure drop of an actual server (Figure B1).

Figure B1: Cisco Flowmeter with Boxster Chassis Mounted

During the airflow tests, the competitor fans will be powered using the internal power supply and supervisor. Cisco will use a laptop to connect into the supervisor and control the fan speeds. The supervisor uses pulse-width modulation (PWM) to control the fans speed. For all the tests, the fans not being tested will be powered off. Then by entering the hex equivalent,

Cisco test engineers will set the duty cycle for the twelve 120x38mm fans. The duty cycle will be varied from 20-100 percent with a data point taken every 10 percent. For each data point, the duty cycle will be set, the auxiliary blower increased until the pressure reaches 0inWg in the test chamber, the fan speed checked using a Monarch tachometer, and the data logged manually. The data logged will include the duty cycle with hex equivalent, the fan speed, and the change in pressure across the nozzle (later used to calculate the airflow). Standard atmospheric conditions in the test room will be assumed.

The airflow tests for the PAX samples will be run in a similar manner, but powered externally. Because the PAX fans will not be wired for use with the supervisor, an external Agilent power supply will be used in combination with a Tektronix arbitrary function generator for the PWM. The same duty cycles will be specified, and the amount of power usage logged as well as the other variables. Power usage for the competitor fans will be logged separately as not to include the supervisor power.

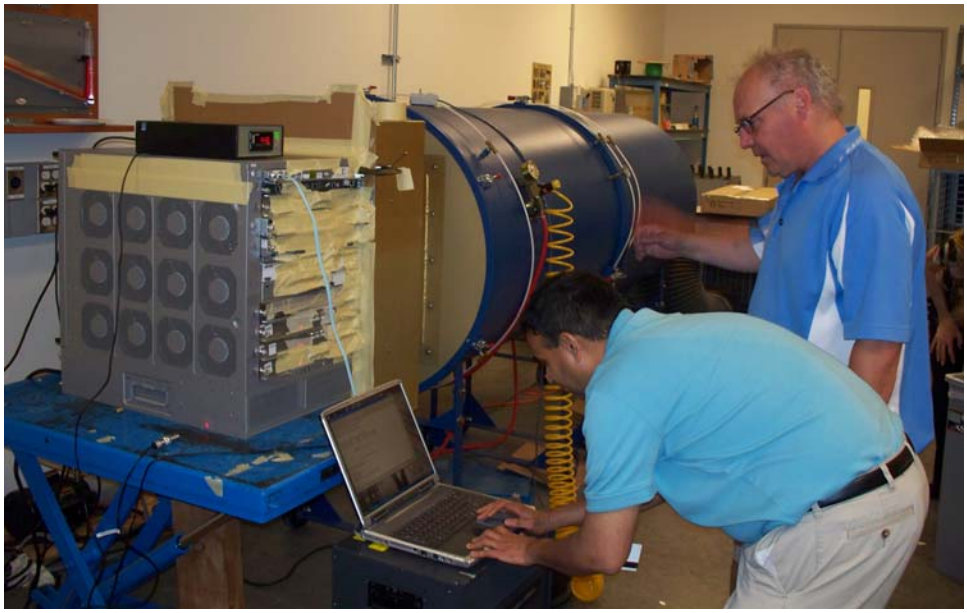


Figure B2: Cisco engineers completing airflow tests

Sound Test Apparatus & Procedure

All in-unit sound tests will be run using Cisco's 14,250 cubic feet Acoustic Hemi-Anechoic Chamber, an ISO 3745 Precision Grade Facility (Figure B3 below). The chamber features double-wall construction, very low noise background (17dBA), 10" thick flush concrete isolation slab floating on springs, controllable temperatures, and approximately 1700 acoustic wedges for noise isolation. For our sound measurements, ten ½" microphones will be arranged at various heights in a hemisphere around the center of the Boxster server, in accordance with ISO 7779. The measurements will be analyzed using Nelson Acoustic's Trident software, and the microphones will be calibrated to 94dB.

The fans will be oriented in the chassis and powered similarly to the airflow tests (competitor fans using the internal power supply and PAX using an external one). Data will be taken at each of the same duty cycle percentages. To silence the noise produced by the internal power supply during the test, its own 80mm fan will be stopped using a prop. The overall sound power values will be analyzed as well as the narrow band data.

Figure B3: Boxster in Cisco Sound Chamber

APPENDIX C:
CFD Control Volume Comparison

Figures C1-C8 below compare velocity magnitude ($V_{mag} = \sqrt{V_x^2 + V_y^2 + V_z^2}$) in m/s and pressure in Pa for steady Multiple Reference Frame (MRF) and unsteady (DES) simulations for both the 'classic' inlet and outlet type control volume and the 'innovative' room type control volume. Comparing velocity distribution for steady simulations (Figures C1 and C5) with velocity distribution for unsteady simulations (Figures C3 and C7), one sees finer flow features in the unsteady simulations. Comparing pressure distribution for steady simulations (Figures C2 and C6) with pressure distribution for unsteady simulations (Figures C4 and C8), one sees that unsteady simulations show a more pronounced change of pressure along the fan rotation axis. Both results support the conclusion that unsteady simulations are important. Also, Figures C2 and C4 for pressure using the 'classic' control volume, one sees the effect of driving the flow via boundary conditions does not result in ambient pressure near the fan air ingestion and nozzle exit regions simulataneously. However, Figures C6 and C8 for pressure using the 'innovative' room control volume does result in ambient pressure near the fan air ingestion and nozzle exit regions. It is for this reason, the 'innovative' room model is preferred.

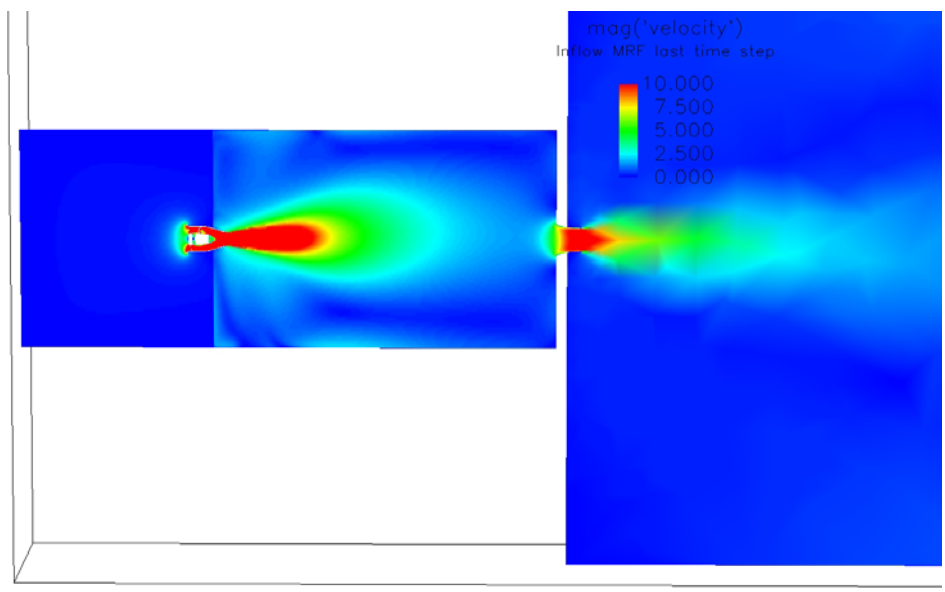


Figure C1: Velocity Distribution in 'Classic' Control Volume (at y = 0) – Steady MRF

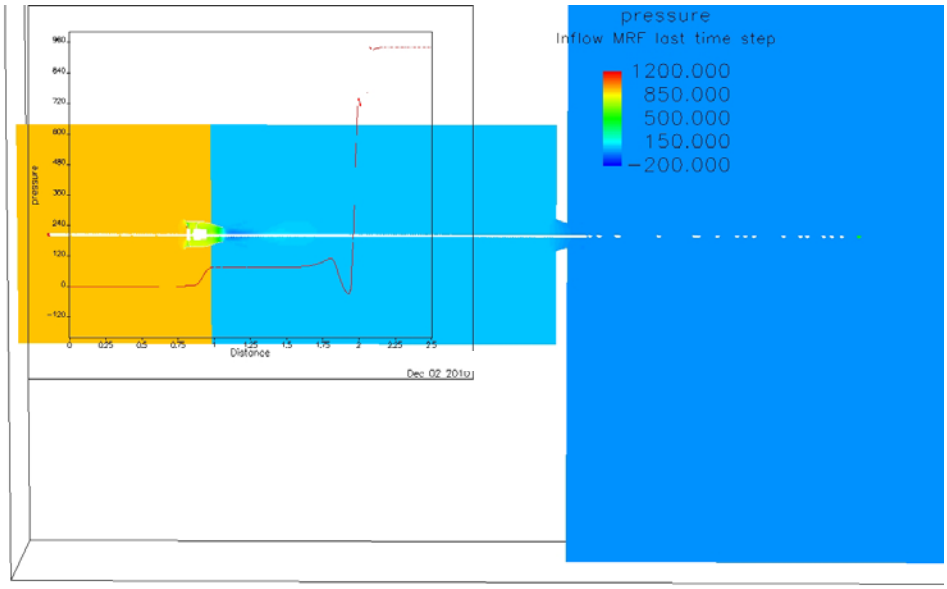


Figure C2: Pressure Distribution in 'Classic' Control Volume (at y = 0) – Steady MRF

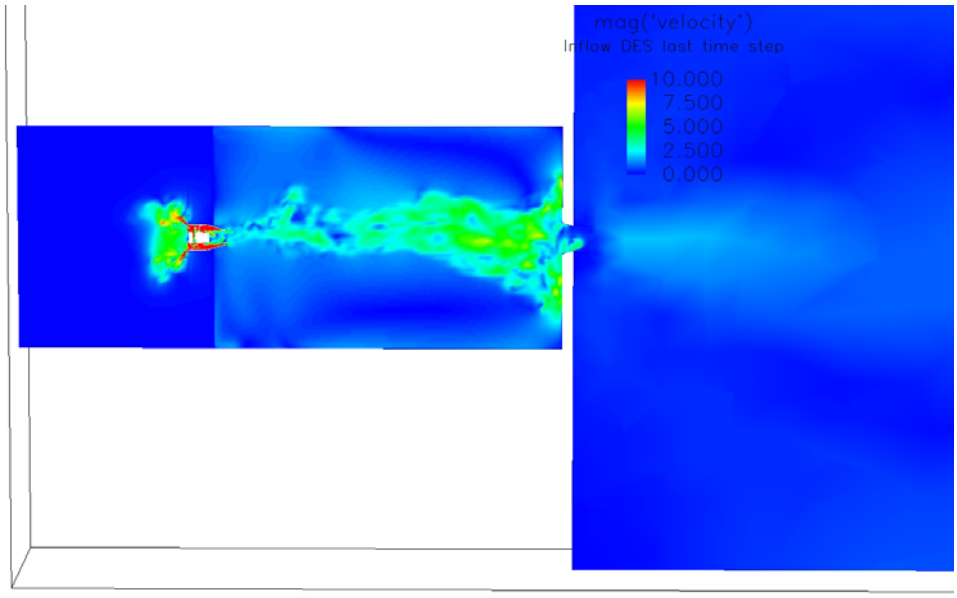


Figure C3: Velocity Distribution in 'Classic' Control Volume (at y = 0) – Unsteady DES

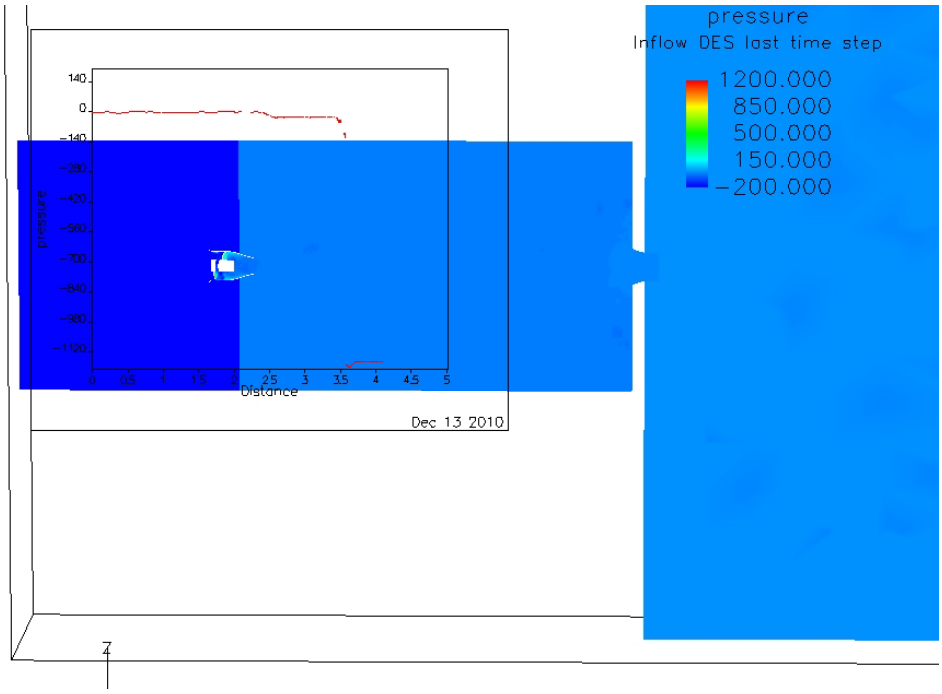


Figure C4: Pressure Distribution in 'Classic' Control Volume (at y = 0) – Unsteady DES

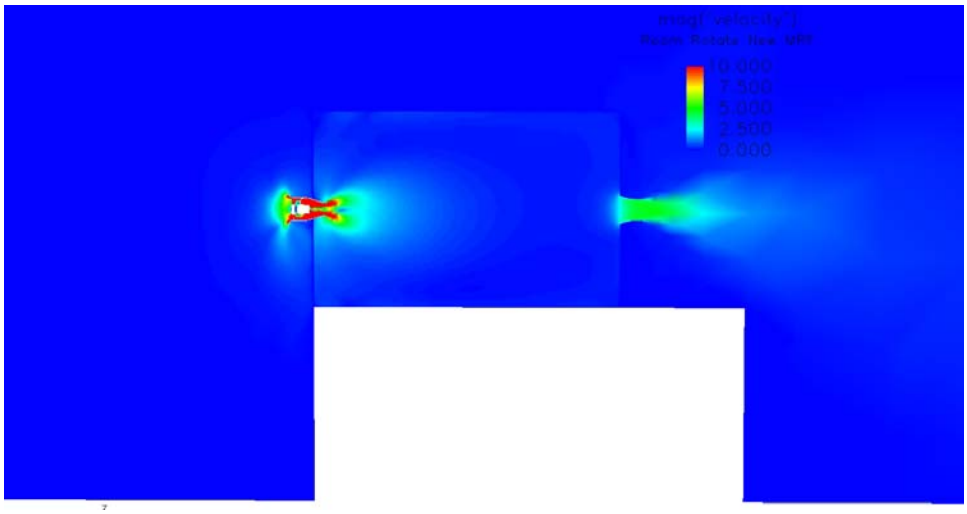


Figure C5: Velocity Distribution in Overall Room Control Volume (at y=0) – Steady MRF

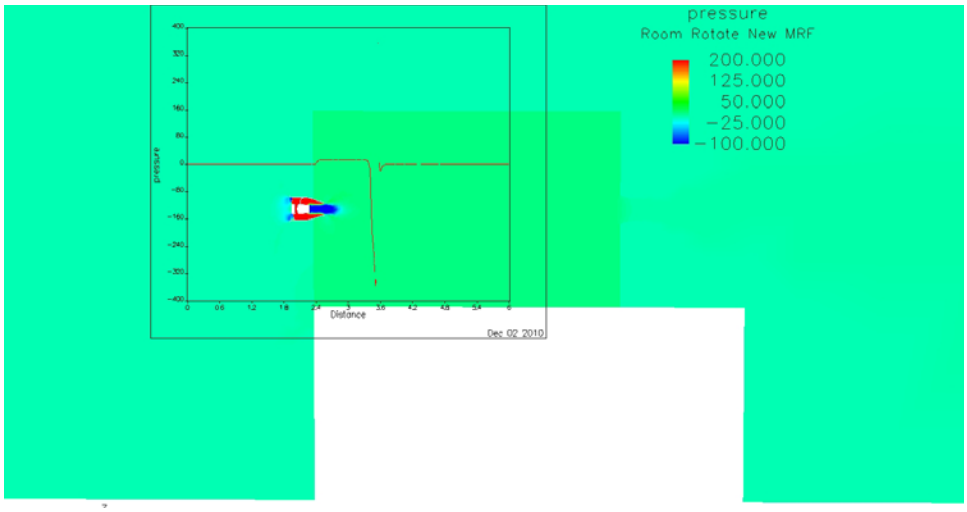


Figure C6: Pressure Distribution in Overall Room Control Volume (at y=0) – Steady MRF

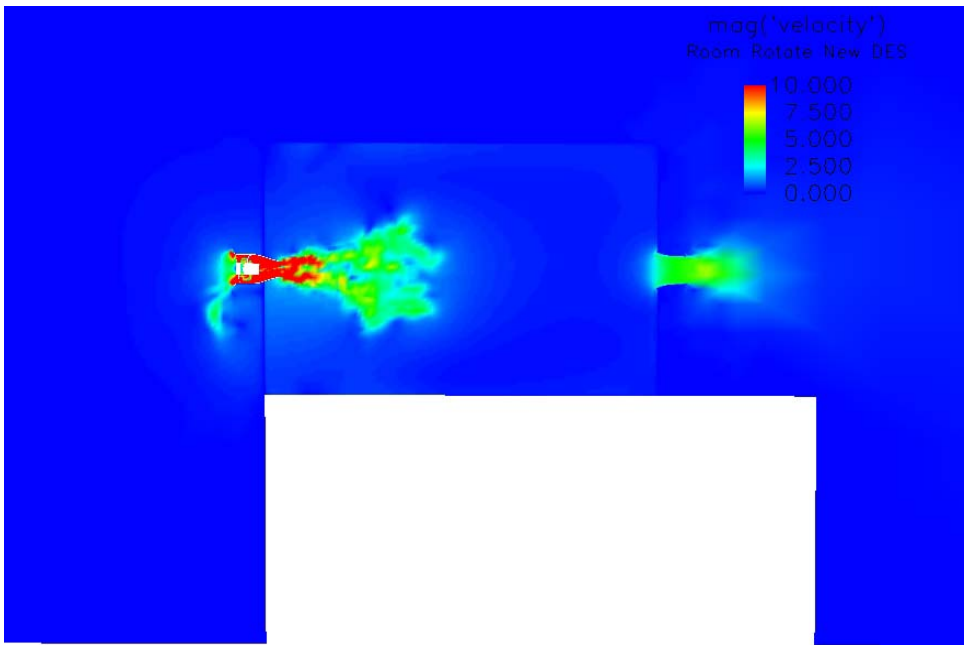


Figure C7: Velocity Distribution in Overall Room Control Volume (at y=0) – Unsteady DES

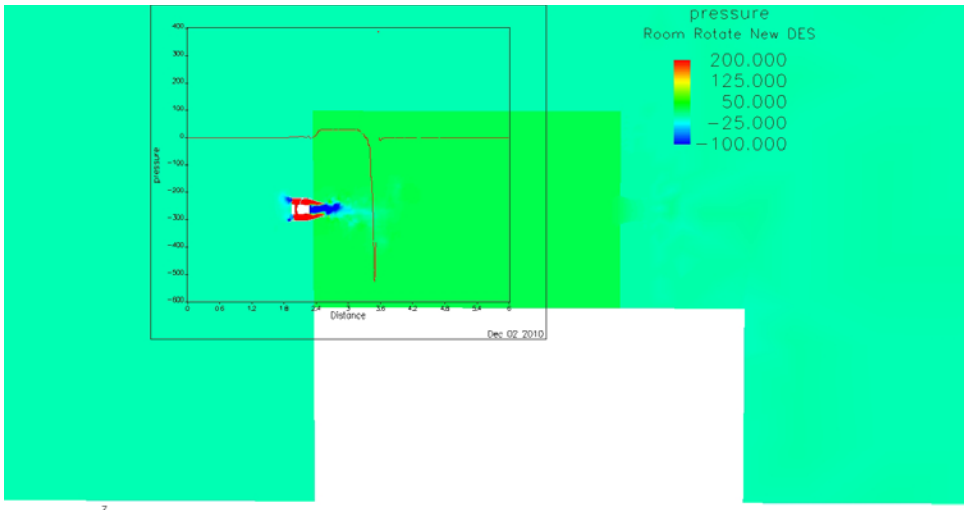


Figure C8: Pressure Distribution in Overall Room Control Volume (at y=0) – Unsteady DES

APPENDIX D:
CFD Grid Study

A CFD mesh or grid is the discrete form of the fan geometric control volume. Both are the real geometry of the same physical model. The difference is the mesh or grid is comprised of small volume regions which are tetrahedra (AcuSolve CFD) or general polyhedra (STAR_CCM+) depending on which commercial CFD software is exercised. The size and thus the quantity of these small regions need to be defined such that they capture the length scales of the flow itself. In particular, the fundamental physics partial differential equations of Navier Stokes and turbulence has pressure, velocity and turbulence quantities as the unknown variables for each fluid cell nodes or cell center. Therefore where the air quantities have larger gradients, etc., the size of the cells need to be smaller to accurately compute the flow field.

Each one of the earlier mentioned regions (upstream, stator/housing, fan, wake, chamber, nozzle and room or exit) can have cell size defined isotropically to spatially place more or less elements in different parts of the overall control volume as required to capture the flow field properly. In addition, commercial CFD mesh generation software has viscous boundary layer grid generation capabilities to provide anisotropic meshes normal to physical wall surfaces where the length scale normal to the surface is very small compared to the length scales tangent to the surface. This capability captures viscous turbulent boundary layers and small eddy/vortical flow features around the fan and stator/housing near field and walls. The range of size in the overall control volume for fan CFD are hundreds of millimeters in the far field, millimeters in the near field of the fan/stator/housing/wake and tenths of a millimeter in the viscous layer of walls. Figures D1-D3 are images of the mesh for a room, classic control volumes, and clip plane of the mesh near a fan and housing, revealing the viscous grid near a wall.

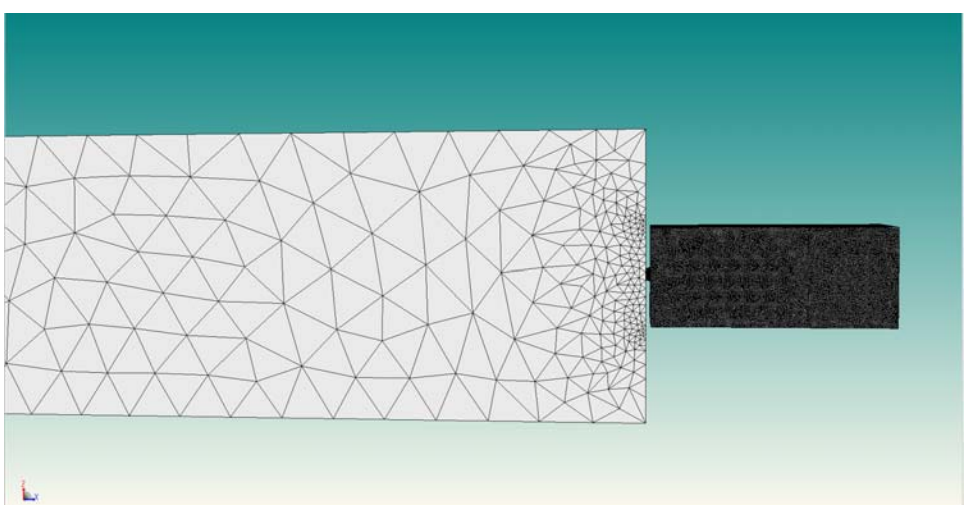


Figure D1: Inflow and Outlet Mesh Model

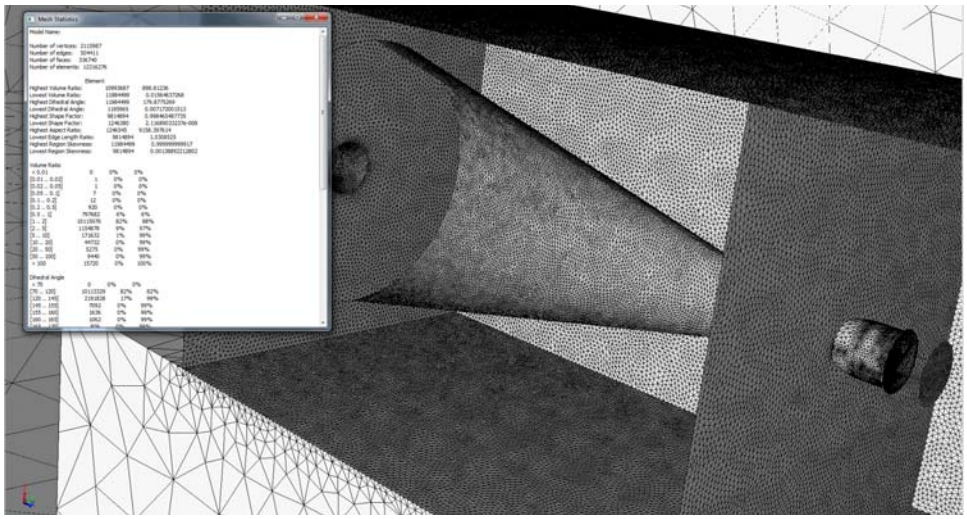


Figure D2: Room Mesh Model

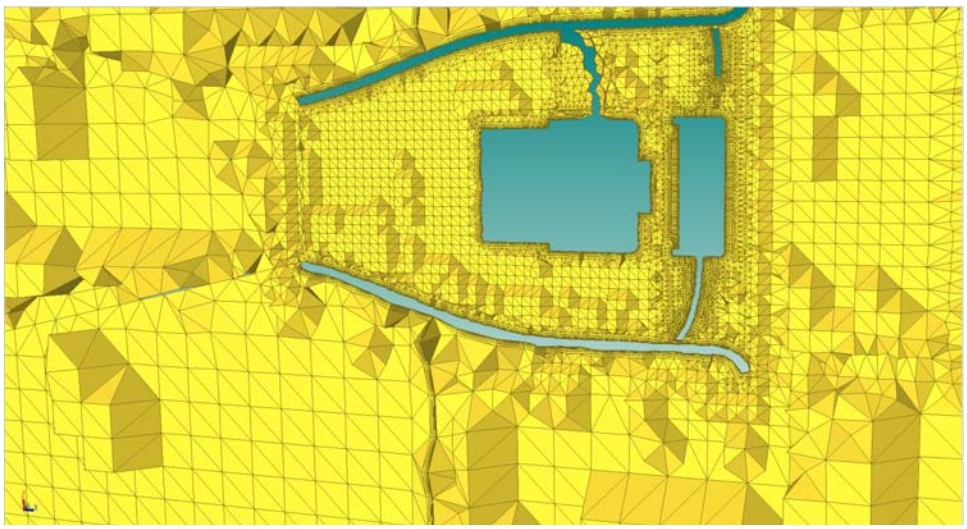


Figure D3: Fan Level Mesh Model

APPENDIX E:
CFD Steady and Unsteady Simulations Effects

The dominant flow characteristics of fan flow are due to the fan's rotational motion. If this rotation is at a constant RPM (which is the case for the IT fan), there are two basic ways to model this fan effect: steady or unsteady flow. This is true for AcuSolve or STAR_CCM+ CFD software; both commercial packages provide these two options. However, in reality no flow is truly steady. The flow properties of pressure, velocity and turbulence are not constant at any particular x,y,z position in space. But the steady approach in some cases is a satisfactory approximation, and takes a lot less computer resources and elapsed time to compute.

This steady approach is called "Multiple Reference Frame" or MRF where a particular region of air (fluid) surronding the rotating device (fan) is defined, distinct from the rest of the control volume. Care is taken to define this particular region as a cylinder, where its outer boundary has the same r and z shapes (cylindrical radius and length) for all theta angles. In this way the equations of motion, or equations of first principles (Navier Stokes and the turbulence model), can have centrifugal, coriolis and angular acceleration terms that are a function of the angular velocity and RPM of the rotational center on the x, y and z axis. The rest of the control volume has its reference to ground, with no motion (stationary). Thus, MRF means that different zones of a problem can have different rotations about different rotation centers. This type of simulation is steady, and individual blade shedding vortical flow effects are neglected. Furthermore, the nodes of the fluid cells at the surface interfaces between the rotating air around the fan and stationary regions are the same, i.e., there is no mesh motion.

On the contrary, an unsteady fan CFD simulation has the same geometric definition, but in this case the fan air region/mesh actually rotates. As a result for unsteady runs, the nodes at the interface between the rotating and stationary regions need to be doubly defined, i.e., different node number pair at each mesh vertex on the surface interface, to allow mesh sliding. A steady calculation requires many less time steps for AcuSolve or iterations for STAR_CCM+ compared to unsteady calculations. In fact, the unsteady fan CFD requires the steady calculation be run first to provide proper initial conditions for all flow quantities at time equal to 0. The small time step for unsteady simulation is typically computed using the fan RPM and the actual amount of time for the number of radians of rotation for a single blade divided by some number, typically 10. This means in a given time step the simulation advances a fan blade ~1/10 of its nominal chord in radians. For the IT Fan the time step of 1.4e-5 seconds was used (additionally, 1.4e-4 seconds was used to show that the difference in results does require 1.4e-5 seconds). This results in needing in the range of 3000-3500 time steps of simulation to achieve 4 revs of the fan rotation. Another note, for AcuSolve CFD MRF steady simulations, Spalart-Allmaras turbulence RANS (Reynolds Average Navier Stokes) model is recommended and for unsteady a detached eddy simulation (DES) turbulence model is recommended. For STAR_CCM+, their turbulence swirl model was used for both steady and unsteady.

APPENDIX F:
Fan Design Iteration Detail & Data

A database was created from the parameter variables and performance data and entered into the first stage of the optimizer toolbox . Figure F1 shows the PAX Optimizer user interface after the test results are read into the database and evaluated for the desired operating point.

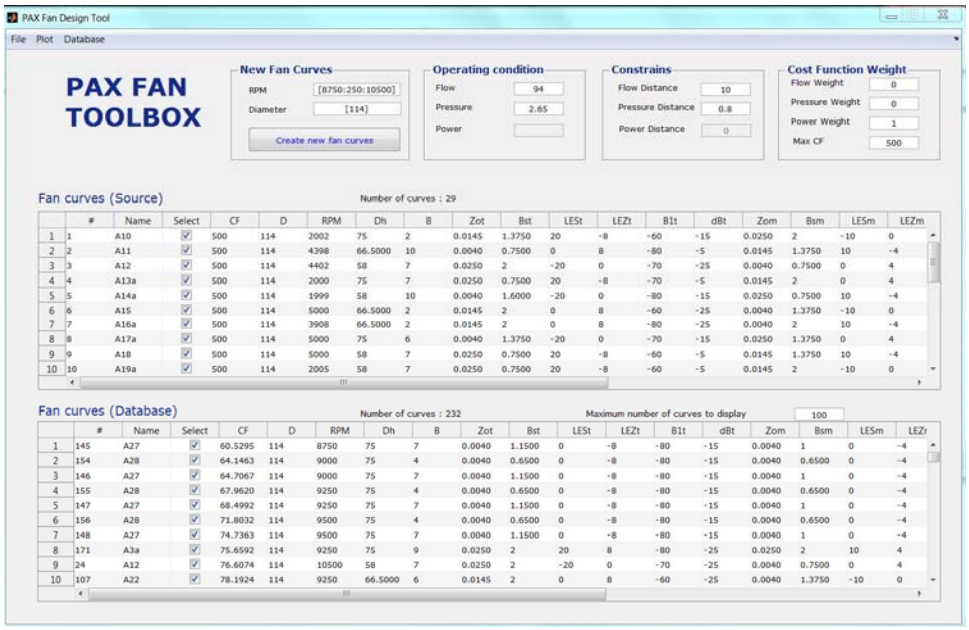
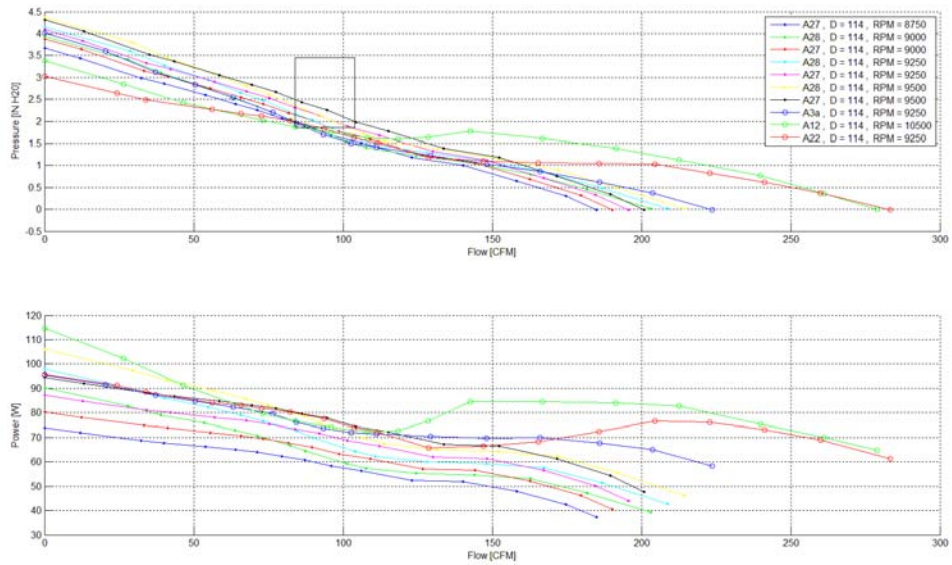


Figure F1: PAX Optimizer User Interface with Initial Iteration Results

Specifically, the operating condition were entered in the upper portion, i.e., RPM range, Diameter range, Flow and Pressure at a specific operating point and with a bounding box range of these parameters deemed acceptable. The CF or cost function is power, i.e., achieve the operating point with minimum power. The middle of the user interface form shows where the experimentally measured fan performance curves are read in and the bottom portion shows the result of the optimizer scaling these results to different diameters and rpms and computing the CF or cost function for each. The lower the value to the CF the better. Figures F2 and F3 show the predicted fan curve plots for the most 'fit' choices. The box in the upper portion of the figure is the entered range in operating point entered.



Figures F2 & F3: Airflow/Pressure & Airflow Power Fan Curves for Initial Iteration (Prediction)

Once the parts were physically created and tested, PAX compared the predicted data above with the experimental results shown in Figure F4.

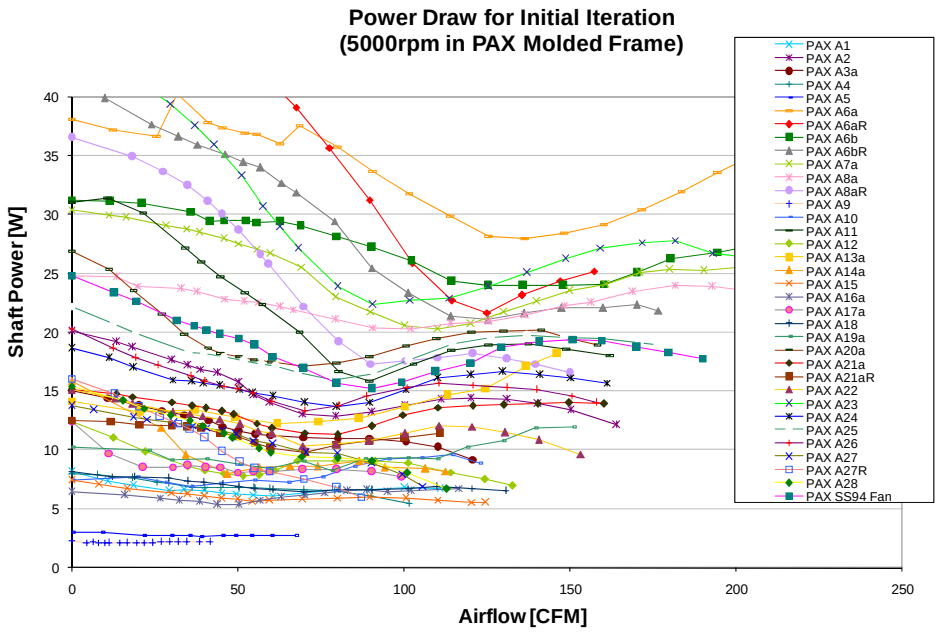


Figure F4: Airflow/Power Fan Curves for Initial Iteration (Experimental)

As one can see in the graphs above, copious amounts of data were generated, and it's not immediately obvious what fan design is best for the application. Using its optimizer analysis tool, PAX was able to upload this database and analyze it more fully. In the output range PAX is targettting, the designs A3a, A22, A27, and A28 appear to have the most promise. PAX's next design iteration built on these designs and further examined the parameter ranges in our attempt to improve on the design.

From analyzing the first iteration data, PAX had many insights into possible design improvements for efficiency. Several design changes were made to the four most promising designs mentioned above. They were prototyped in the same manner and tested.
In addition, since PAX's client is also interested in a sound drop, in addition to the power drop, PAX isolated the parameters most responsible for noise mitigation and will perform specific sound testing to all the most promising designs. PAX generated a small sample of fan designs geared towards this goal using a reduced orthogonal method. And so PAX continued with this iterative process until the desired performance was achieved.

APPENDIX G:
Extended Data for Power Consumption Monitoring

Airflow

The following graphs show the airflow data versus duty cycle for the three sets of fans tested.

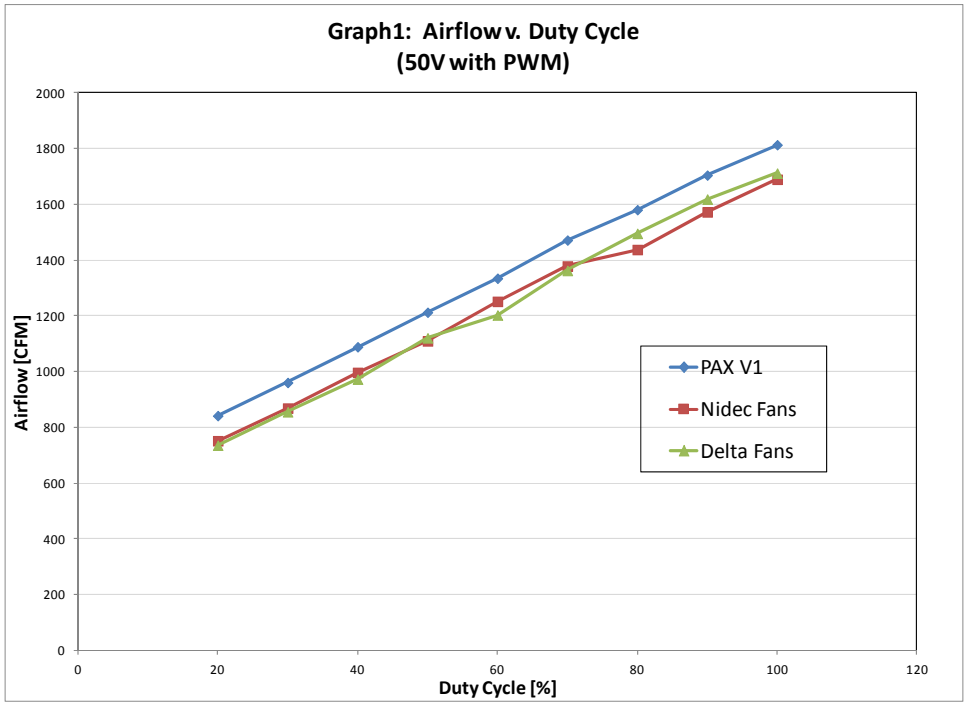


Figure G1: Airflow/Duty Cycle for 12 Fans Inside Boxster Chassis

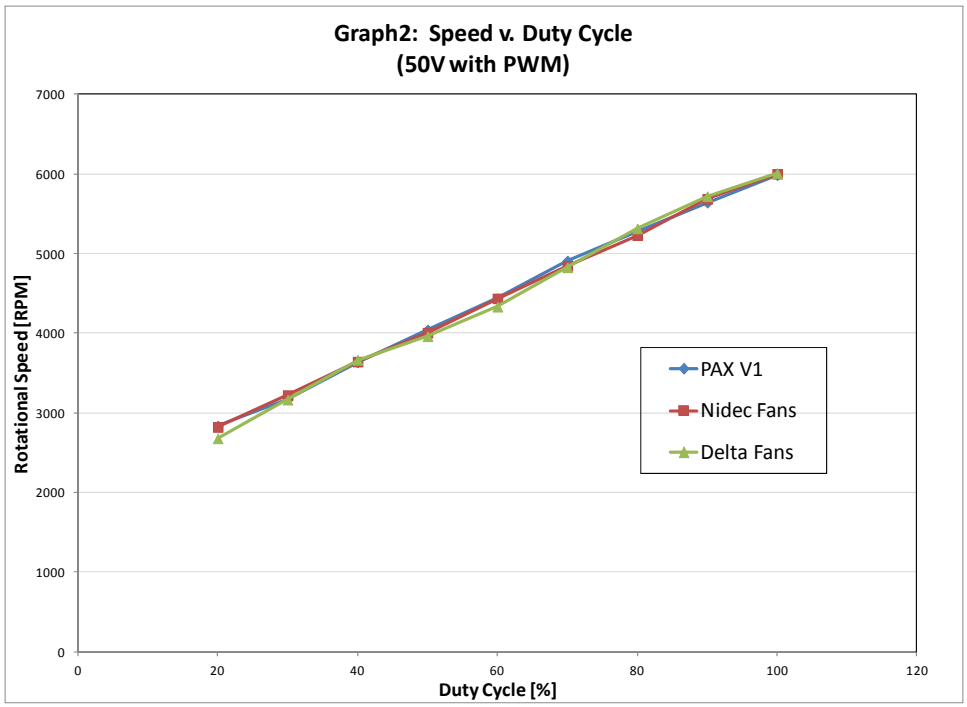


Figure G2: Rotational Speed/Duty Cycle for 12 Fans Inside Boxster Chassis

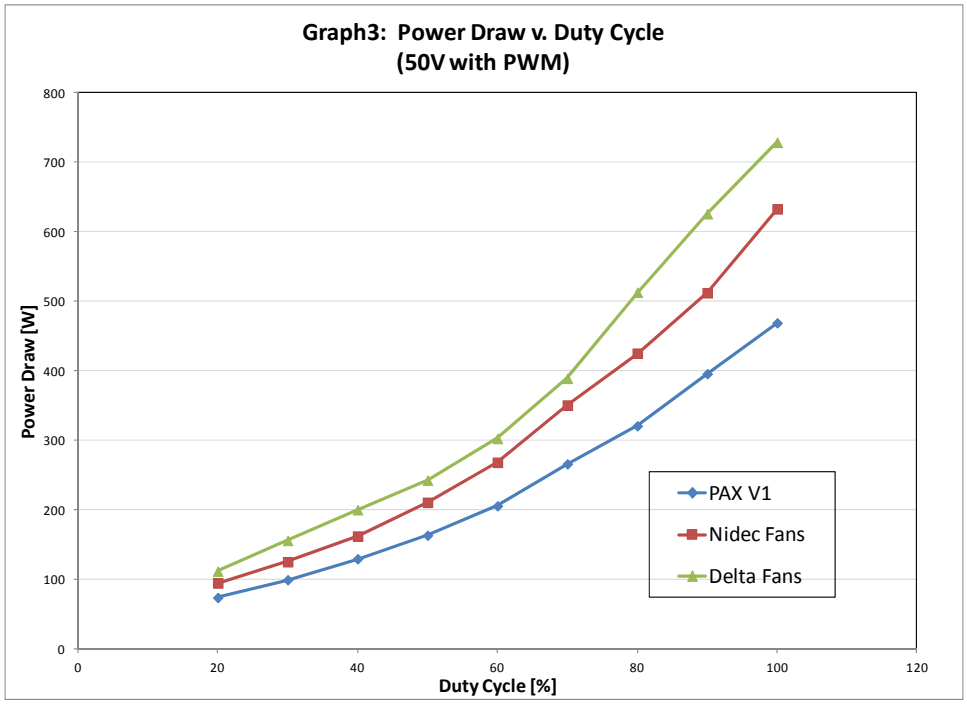


Figure G3: Power/Duty Cycle for 12 Fans Inside Boxster Chassis

Sound

The following graph shows the sound data versus duty cycle for the three sets of fans tested.

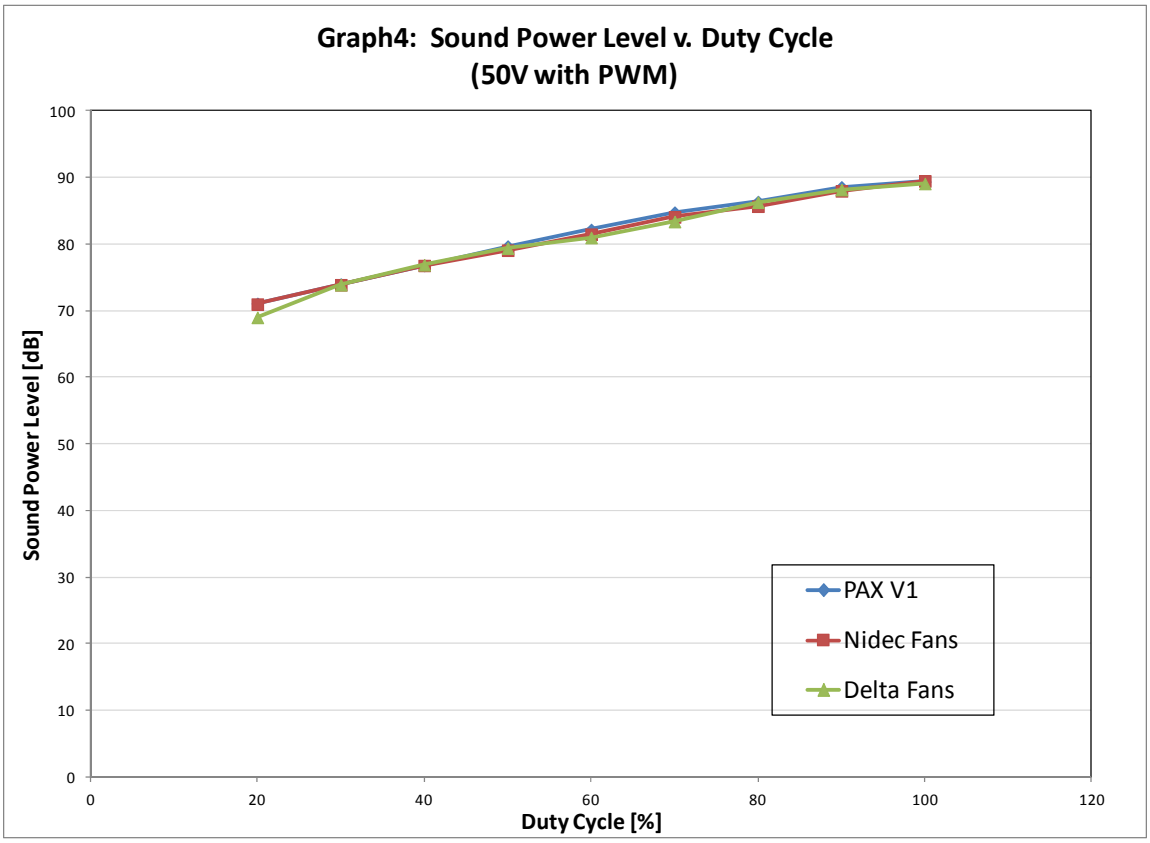


Figure G4: Sound Power Level/Duty Cycle for 12 Fans Inside Boxster Chassis

Summary

The following charts show all the data generated during the tests for the three sets of fans tested.

Chart 1: PAX Fans in Boxster Chassis (12 Fans)							
12 Fans					Per Single Fan		
Duty Cycle	Airflow	Speed	Power	Leq	Airflow	Power	Leq
[%]	[CFM]	[RPM]	[W]	[dB]	[CFM]	[W]	[dB]
20	842	2842	73.6	71.1	70	6.1	60.3
30	961	3171	99.1	74.0	80	8.3	63.2
40	1089	3635	129.4	76.8	91	10.8	66.0
50	1213	4048	163.3	79.7	101	13.6	68.9
60	1335	4440	205.5	82.2	111	17.1	71.4
70	1472	4914	266.0	84.8	123	22.2	74.0
80	1581	5286	320.7	86.4	132	26.7	75.6
90	1705	5641	395.7	88.6	142	33.0	77.8
100	1814	5986	469.0	89.4	151	39.1	78.6

Figure G5: Summary Chart for 12 PAX Fans Inside Boxster Chassis

Chart 2: Nidec Fans in Boxster Chassis (12 Fans)							
12 Fans					Per Single Fan		
Duty Cycle	Airflow	Speed	Power	Leq	Airflow	Power	Leq
[%]	[CFM]	[RPM]	[W]	[dB]	[CFM]	[W]	[dB]
20	752	2824	94.6	71.0	63	7.9	60.2
30	869	3225	125.0	73.9	72	10.4	63.1
40	997	3645	162.1	76.8	83	13.5	66.0
50	1110	4009	210.6	79.1	93	17.5	68.3
60	1252	4438	268.3	81.5	104	22.4	70.7
70	1379	4849	350.6	84.1	115	29.2	73.3
80	1438	5232	425.2	85.7	120	35.4	74.9
90	1573	5690	512.3	88.0	131	42.7	77.2
100	1690	6003	632.9	89.5	141	52.7	78.7

Figure G6: Summary Chart for 12 Nidec Fans Inside Boxster Chassis

Chart3: Delta Fans in Boxster Chassis (12 Fans)							
12 Fans					Per Single Fan		
Duty Cycle	Airflow	Speed	Power	Leq	Airflow	Power	Leq
[%]	[CFM]	[RPM]	[W]	[dB]	[CFM]	[W]	[dB]
20	736	2680	111.6	69.0	61	9.3	58.2
30	856	3166	155.7	73.9	71	13.0	63.1
40	973	3667	199.9	76.9	81	16.7	66.1
50	1121	3962	242.3	79.4	93	20.2	68.6
60	1203	4334	302.6	81.0	100	25.2	70.2
70	1363	4829	389.2	83.4	114	32.4	72.6
80	1496	5316	513.1	86.3	125	42.8	75.5
90	1619	5721	626.2	88.2	135	52.2	77.4
100	1712	6012	728.9	89.1	143	60.7	78.3

Figure G7: Summary Chart for 12 Delta Fans Inside Boxster Chassis