The History of the Low-Speed Wind Tunnel at San Diego State University

Alfonso Acosta[1], Kendall Miller[2], Bradley Zelenka[3] and Xiaofeng Liu[4]
San Diego State University, San Diego, CA 92182, USA

The San Diego State University Low Speed Wind Tunnel completed its first acceptance tests on December 13th, 1961, making the tunnel 60-years-old at the time of writing. The history behind its inception and construction in the late 1950's and early 1960's and years of continuous improvements to the tunnel and its data acquisition systems are loosely recorded through several documents. The present work serves as a compilation of these works such that details on the tunnel's history and capabilities are more effectively recorded.

I. Introduction

WIND tunnels are invaluable tools for aerodynamics research and instruction. The first wind tunnel in the world was built and tested in 1871 by Frank Wenham [1]. A later tunnel was built by the Wright Brothers to aid in the design of the Wright Flyer [1]. The first wind tunnel built for a University in the United States is arguably the "air tunnel," built at The Catholic University of America in Washington D.C. in 1901 by Albert Zahm [1, 2]. The University of Notre Dame also claims that Zahm had built what might have been the first hand-driven wind tunnel in America in 1882 so that he could study the lift and drag of various wing shapes [3].

Aviation has been a part of San Diego's history since the early 1900s. The city itself had earned the title "The Birthplace of Naval Aviation" in 1911 when Glenn Curtiss used Rockwell Field while developing the Curtiss A-1 Triad, the first ever seaplane [5]. This accomplishment, as well as many others, are what led to the region's prominence in aeronautical research and development.

Figure 1. A photo of the temporary Engineering Buildings in 1959 [4].

San Diego State University has been offering courses in the field of Engineering as early as 1922 [6]. However, the University's primary focus at the time had been on their school of education. It was not until 1942 when students were allowed to obtain a Bachelor of Science in Engineering [6].

San Diego State University's students of Engineering were already interested in the aviation industry. Even with a single-story building and limited resources, they constructed a wind tunnel in hopes of better understanding aerodynamics. The test section size was 12" (width) by 18" (height) with a maximum speed of about 60 miles per hour [7].

The Cold War fueled competition between the Soviet Union and the United States which led to increased investment of resources into the fields of Science, Technology, Engineering, and Mathematics [8]. One example of this increased investment was San Diego State University's establishment of its College of Engineering in 1964 [6]. The College of Engineering was established with four departments: civil, mechanical, electrical, and aerospace engineering [6]. The new college was bolstered by a new building that was completed in late 1961 [9].

Plans for this expansion of the school's curriculum had been underway for several years prior, having already hired Dr. William Shutts, who would eventually serve as the first chair of the Department of Aerospace Engineering from 1964 until 1968 [6, 10].

[1] Undergraduate student, Department of Aerospace Engineering, San Diego State University, Student Member AIAA
[2] Undergraduate student, Department of Aerospace Engineering, San Diego State University, Student Member AIAA
[3] Graduate student, Department of Aerospace Engineering, San Diego State University, Student Member AIAA
[4] Associate Professor, Department of Aerospace Engineering, San Diego State University, Associate Fellow AIAA. Email: Xiaofeng.Liu@sdsu.edu

II. The Proposal about the Construction of the Low-Speed Wind Tunnel

Dr. William Shutts had received his Ph.D. in Aeronautical Engineering from The University of Texas at Austin [10]. Having already been on the campus as an assistant professor since the 1950s, Shutts knew about the wind tunnel the students had built. However, the dimensions and the balance system were deemed far too inadequate for the tunnel to serve as an effective tool of instruction [8].

With these facts in mind, and with knowledge of the upcoming construction of an engineering building, Dr. Shutts wrote an eight-page proposal to the executive dean of San Diego State University [8]. In this proposal, Dr. Shutts outlined how aerodynamics and fluid mechanics is a key integral part of various branches of engineering. He quoted a statement from the Committee on Mechanics of Fluids of the American Society for Engineering Education, which read, "Some needs for an understanding of the behavior of fluids at rest and in motion pervades every branch of engineering…" Shutts argued the best way for students to be able to get the practical knowledge and experience in fluid mechanics was the construction of a wind tunnel at the school. "The wind tunnel is one of the most useful, versatile, and necessary pieces of laboratory equipment for demonstrating the basic principles of fluid flow" [8].

At the time, there was a concern that the original building plans and equipment specifications were not ideal for construction of a wind tunnel [8]. The original wind tunnel specifications Dr. Shutts proposed are listed in Table 1.

Table 1. Dr. Shutts's Proposed Wind Tunnel Specifications

Parameter	Value
Cross-sectional Area	10 sqft
Cross-sectional Dimensions	45 in by 32 in
Motor Power Output	150 hp

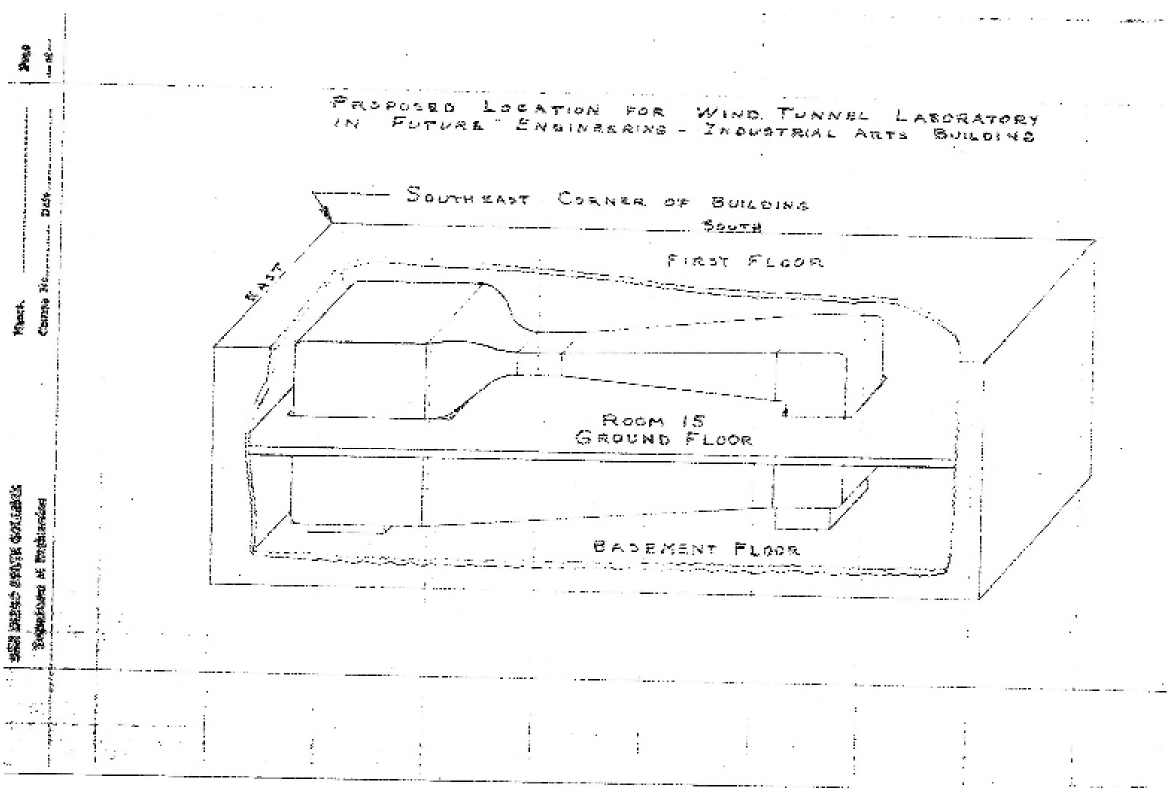

Figure 2. Dr. Shutts's preliminary drawing of the low-speed wind tunnel.

When the school was designing the brand-new building, the original plan was for the low-speed wind tunnel to have been placed in the location of the current supersonic wind tunnel lab [8]. This location had smaller dimensions

Figure 3. Portrait of Dr. Shutts, circa 1960 [11].

to work within, so the proposed wind tunnel from the school was to be a 6 square inch cross-sectional area. The power output was expected to be 75 horsepower [8]. This would have posed a problem not only for having a reliable undergraduate wind tunnel, but it also would have been a problem for the manufacturer. Dr. Shutts stated that the manufacturer would only manufacture wind tunnels that had a cross-sectional area of 10 square feet [8]. Thanks to the listed proposal and lobbying, Shutts's design for the wind tunnel was eventually accepted and plans to build it in its current location within the building were developed and put into action [12].

III. Construction of the Tunnel

The design of the Low-Speed Wind Tunnel was assigned to the Aerolab Development Company of Pasadena, California. It was a subsidiary of the Ryan Aeronautical Company (now owned by Northrop Grumman) [13]. Aerolab Development Company was founded to aid in the development of various tools and research in the aerospace industry [13]. Moreover, they aided in the design of wind tunnels for various colleges throughout the United States. Some of the schools for which this company provided wind tunnels were the California Institute of Technology, the University of Minnesota, and the University of California Los Angeles [8].

The bulk of the manufacturing took place in Pasadena then shipped and assembled on-site by the Trepte Construction company [14, 15]. While most of the parts had been newly manufactured for the wind tunnel, the fan that was used for the tunnel was adopted from a World War II aircraft propeller [6].

The force balance system was contracted to the Sandberg-Serrell corporation—a company that had been aiding in the design of various supersonic and transonic wind tunnels for the aviation industry [16]. The balance was a strain-gauge system that measured the lift, drag, and pitching moments within one percent limit-load accuracy. The balance system included an assembly to allow for altering the angle of attack of a test model during testing [16].

Measurements in the tunnel were made on an analog or mechanical basis at the time [16]. One example of this is the multi-tube water manometer. This piece of equipment included a series of tubes that are connected to various pressure taps on a model to measure the difference in local pressure compared to atmospheric pressure. A common use of this tool is to gather the pressure distribution across a 2D airfoil and is still in use for instructional purposes.

Figure 4. Construction of the engineering building in 1960 [17]. Note the basement floor to accommodate the low-speed wind tunnel being dug out in the left-foreground of the image.

The low-speed wind tunnel was embedded in the construction of the engineering building [18]. In parallel with the construction of the low-speed wind tunnel, a supersonic wind tunnel was built and housed in a room adjacent the low speed tunnel. Due to the high power coming out of both the proposed supersonic and low-speed wind tunnels, emphasis was placed on maintaining a low acoustic volume around the building while the wind tunnels were running. Design facets such as acousti-celotex, concrete block walls, gaskets for each of the doors, and the mounting the wind tunnel on an isolated slab were included in the design of the engineering building to keep noise to a minimum [18].

There were complications during construction. In 1959, a strike was organized by concrete truck drivers [15]. This led to a delay in obtaining materials for finishing the engineering building by one year, which subsequently delayed the final installation of the wind tunnel [15].

According to The Daily Aztec, San Diego State University's college newspaper, the tunnel's cost was estimated at $90,000 total for the low-speed wind tunnel hardware, construction, and various pieces of related equipment [15]. The Engineering building construction itself was estimated to cost about $3,300,000 [12].

IV. Commissioning of the Tunnels and the Building

On December 13th, 1961, Dr. Shutts reported that the low-speed wind tunnel had completed a successful 3-hour long test of the tunnel running at 225 mph to examine its temperature and noise impacts, serving now as the tunnel's de facto completion date [19]. It was found during these tests that the tunnel required a number of modifications, especially to reduce noise [19]. The Engineering building opened to the public in February 1962 [15]. The final specifications for the completed low-speed wind tunnel are shown in Table 2.

Table 2. Final Wind Tunnel Specifications as Constructed.

Parameter	Value
Test Section Dimensions	45 in x 32 in x 67 in
Type	Closed Return
Power	150 hp
Maximum Flow Speed	250 mph

Dr. Shutts' proposal had been realized [20], and the upcoming Aerospace Engineering students, only 11 members at the time, were excited to aid in learning about and improving upon the wind-tunnel over time. The tunnel became an integral part of the Aerospace Engineering curriculum, as any future student who would be going through the program would now spend at least one semester working in the tunnel from then on [6].

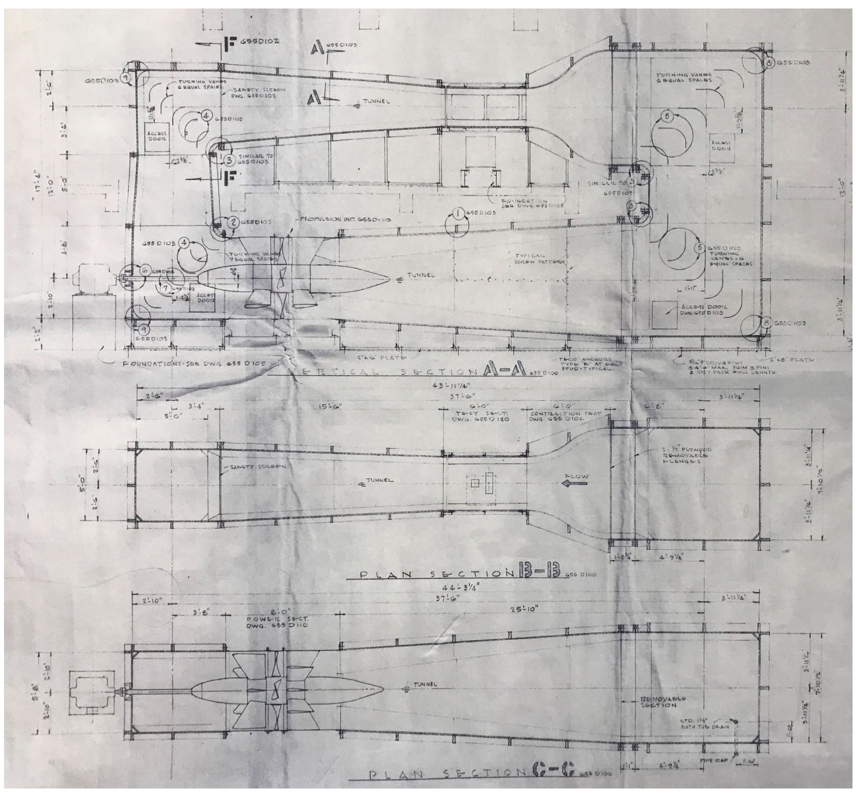

Figure 5. Scan of the final engineering drawings of the wind tunnel design on display adjacent the tunnel.

V. Research Carried Out at the Tunnel

The low-speed wind tunnel has been used in a variety of experiments related to aerodynamics research for various research projects of both academic and industry interest. What follows are several examples of such work from current faculty members.

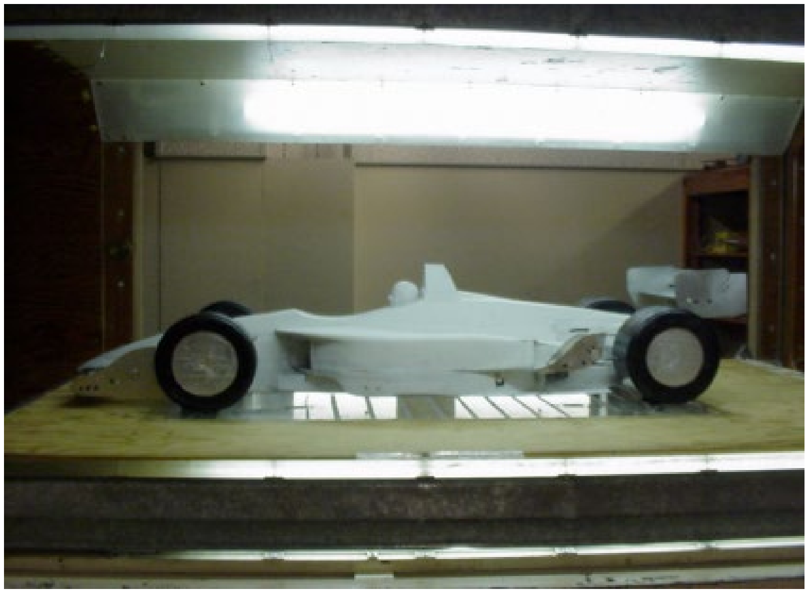

Figure 6. A model Indy car placed inside the wind tunnel [21].

Prof. Joseph Katz used the low-speed wind tunnel to test wing designs for unmanned aerial vehicles, air-foil testing, and for optimizing race-car designs [22]. Prof. Xiaofeng Liu and his graduate student, Bradley Zelenka are conducting NASA sponsored research with an investigation to eventually experimentally validate the predicted loading distributions present on a wing known as Preliminary Research AerodyNamic Design To Lower Drag (Prandtl-D) based on a stereoscopic Particle Image Velocimetry flow field survey [23]. Prof. Liu and his graduate student Vignesh Sudalaimuthu also investigated the effect of perforated holes of a hollow circular cylinder in reducing unsteady aerodynamic forces and moments in the low-speed wind tunnel [24]. Prof. Gustaff Jacobs and his students have recently investigated the use of synthetic jet actuators for lift control on a 3D-printed wind tunnel model for a NACA 65(2)-415 airfoil using the low-speed wind tunnel [25, 26].

Several companies have also performed research within the tunnel, including Northrop Grumman, Mazda, and many more [27]. More recently, the Netflix original production *White Rabbit Project* included a scene that a was filmed at the low-speed wind tunnel [28]. A model dragster was placed inside the test section to demonstrate how wind tunnels are used to refine the aerodynamics for vehicles [28].

The tunnel has even been used for research outside of the field of engineering. In 1975, the Zoology department at San Diego State University placed flying foxes inside the low-speed wind tunnel to measure metabolism, heartbeat, and water loss for the mammals while flying [29]. In 2014, graduate student Chad Espina utilized the wind tunnel with his drone to research how wind affects wildfires. [30].

VI. Continuous Improvement

Students and faculty together have been working on adjusting and improving the wind tunnel since its completion. Undergraduate students, Hermann Altmann and Dwight Woolhouse, spent the Summer of 1966 doing flow field surveys over the test section, resulting in the 1967 addition of flow conditioning screens within the tunnel settling chamber, reducing the test section turbulence factor from 2.0 to 1.27 [31]. Dr. Shutts also made upgrades to the low-speed wind tunnel over time. Soon after completion of the tunnel, the three-component balance system was upgraded to a six-component balance system, as had been planned since the tunnel's inception [16]. In addition to the original capabilities of measuring lift, drag, and pitching moments, aerodynamic force measurements could be taken for side force, roll, and yaw moment measurements as well [6].

Another milestone in upgrading the low-speed wind tunnel was in 1987, when the National Science Foundation awarded a grant to benefit both the low-speed and high-speed wind tunnels. Among the improvements funded by this grant was the addition of a MicroVax system: a computer that could digitally record measurements from the wind tunnel. Data acquisition was accomplished by the MicroVax computer, which could connect different pressure tubes to a Scanivalve rotary system. The MicroVax was in use for several years, until its replacement with a Microsoft Windows XP-based computer running LabVIEW 5.1 software for data acquisition in 2001 [6].

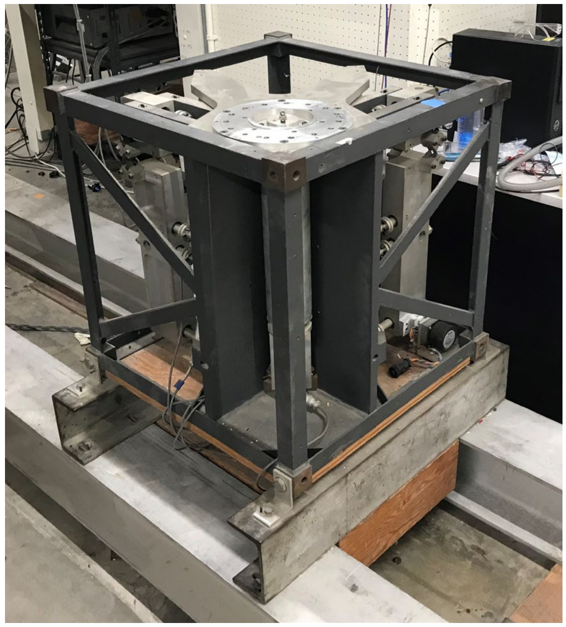

Figure 7. The force balance system currently installed in the wind tunnel.

In 2004, the World War II aircraft propeller used for the fan broke at the hub and damaged parts of the wind tunnel. Prof. Katz installed carbon blades as a replacement. As the new prop was fixed-pitch, a variable-frequency drive was installed to control the tunnel's motor, altering the power system from variable-pitch to variable-speed [6]. This change also lowered the maximum flow speed of the tunnel to 180 mph. The damaged propellers are kept in the wind tunnel lab storage.

In 2010, Greg Morris began serving as the part-time wind tunnel lab technician. He aided in installing a particle image velocity system to the tunnel to better visualize and measure the flow field over the test model during experiments in the wind tunnel [6].

VII. Modernization

Paul Ahlers has been the wind tunnel technician since 2017 [6]. Currently, the wind tunnel's maximum speed sits at approximately 165 mph with a turbulence factor around 1.29. Several additions and improvements in the wind tunnel lab have come about since then.

A hot wire anemometry system was donated by Solar Turbines in 2018 and is being used in laboratory experiments for both instruction and research-focused experiments. The Dantec Dynamics EduPIV system was also acquired in 2019 to provide undergraduate students with one of the first examples of particle image velocimetry lab instruction as a part of undergraduate curriculum in the country [32]. In Spring 2021 the 48-port rotary Scanivalve system for surface pressure measurement was updated to a 64-port Scanivalve ZOC33/64 unit, greatly enhancing the surface pressure measurement capabilities in the wind tunnel lab.

Also in Spring 2021, the force balance was recalibrated using a carefully developed 824-point static calibration design with a set of NIST-traceable calibrated weights at 50% load limit increments. The optimal math model was determined using the NASA *BALFIT* multivariate analysis tool, producing a 40-term balance calibration model. Measurement error standard deviations were observed to be far less than 1% of the balance's limit loads. A presentation by Bradley Zelenka and Aldair Herreion-Andrade about the wind tunnel aerodynamic force balance calibration, *Wind Tunnel Force Balance Calibration at the San Diego State University Low Speed Wind Tunnel*, won 2nd Place in the Master's Category at the AIAA Region VI student conference in April 2021 [33]. Table 3 shows the force balance's current load limits and error standard deviation recorded during the most recent calibration.

Additionally, the data acquisition system was modernized, producing several improvements. The Windows XP computer running LabVIEW 5.1 was upgraded to a Windows 10 machine running LabVIEW 17.0. The computer-interface board is an NI SCB-68A, and the analog-to-digital board is an NI 6351 PCIe card. The reading resolution was increased from 12-bit to 16-bit and the maximum single-channel sampling rate was increased from 100 kHz to 1.25 MHz. New data acquisition software was written, integrating digital recording of the test angle of attack, tunnel flow temperature, and freestream dynamic pressure [34]. Further, this modernization reintroduced capabilities which

Figure 8. The low speed wind tunnel test section with the newly updated data acquisition and control computer in the left foreground.

had not been functional for several years prior, including automatic control and regulation of free-stream dynamic pressure and test model angle of attack controls. These improvements have reduced the personnel requirements for testing in the tunnel to a single operator sitting at the control and data acquisition computer.

Table 3. Current Force Balance Load Limits and Error Standard Deviations as a Percentage of Limit Load.

Axis	Limit Load	Error Std. Dev.
Drag Force	40 lbf	0.31%
Side Force	80 lbf	0.35%
Lift Force	120 lbf	0.22%
Rolling Moment	800 lbf-in	0.60%
Pitching Moment	800 lbf-in	0.49%
Yawing Moment	800 lbf-in	0.25%

A project began during the Spring of 2021 to investigate the tunnel's cooling system to characterize the need for cooling the flow inside the tunnel and replace the system in the near future [35]. With this effort also come initiatives to replace the aging tunnel motor, variable frequency drive system, and the flow conditioning screens within the test section. The motor is original to the tunnel's construction, the variable frequency drive original to the prop replacement in 2004, and the screens have not been replaced since their initial installation in 1967.

The Department of Defense equipment fund (W911NF2110158) funded the Fall 2021 acquisition of a state-of-the-art particle image velocimetry system. This system includes 4 Photron FastCam SA-Z type 2100 high-speed cameras, a Photonics DM200 532 nm dual-head laser, and the LaVision DaVis 10 software suite for particle image velocimetry analysis. This system has been installed in the wind tunnel for the NASA Prandtl-D project [23]. A

LaVision aerosol generator is used to produce seeding particles with a mean particle diameter of approximately 1 micron. Working fluids include DEHS (Di-Ethyl-Hexyl-Sebacate, an insoluble, colorless, and odorless liquid suitable for producing steady aerosols, which evaporates completely, leaving no residue) and other light mineral and vegetable oils (such as olive oil). This cutting-edge system establishes the San Diego State University low speed wind tunnel lab as one of the premier labs in the world for particle image velocimetry research. Specifications of this recent equipment acquisition are shown in Table 4.

Table 4. Specifications for the Newly Acquired Particle Image Velocimetry System.

Specification	Capability
Camera Frame Rate	20 kHz at 1024 x 1024 pixels
Minimum Shutter Time	159 nanoseconds
Laser Type	Dual Head Nd:YAG
Wavelength	532 nm
Average Power Per Head	200 W at 10 kHz
Pulse Width	120 ns at 10 kHz
Pulse Energy Per Head	20 mJ at 10 kHz
Pulse Repetition Rate	1 kHz to 60 kHz
DaVis 10 PIV Analysis Suites	2D Planar, 3D Stereoscopic, and 3D Shake-the-Box for Tomographic

A celebration was held for the tunnel's 60th birthday on December 13th, 2021, to show off the tunnel and its capabilities where the tunnel blew out its 60th birthday candles. Several presentations were given on recent projects completed using the tunnel.

VIII. Conclusion

The low-speed wind tunnel remains a foundation not just to the Aerospace Engineering Department, but also the entirety of the College of Engineering at San Diego State University. It has been used to provide observations in aerodynamics for industry, celebrities, and academics. Thanks to the efforts of the founding faculty of the department, 5 different technicians, ongoing faculty, students, sponsors, and alumni at SDSU, the wind tunnel continues to fulfill the statement that Dr. Shutts had written in his proposal for the tunnel 62 years ago [8]:

> *"The wind tunnel is one of the most useful, versatile, and necessary pieces of laboratory equipment for demonstrating the basic principles of fluid flow."* – Dr. William Shutts.

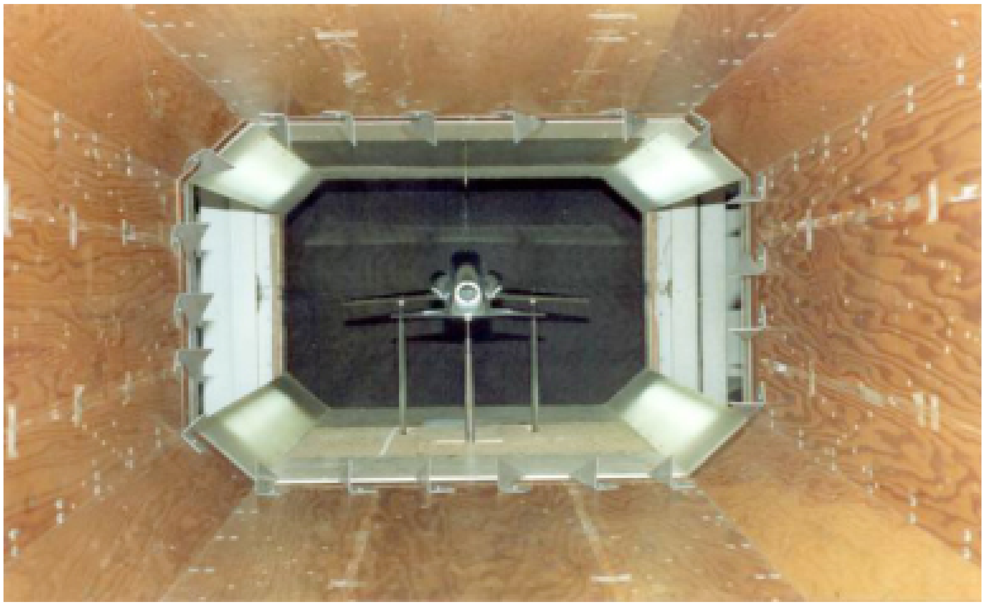

Figure 9. Inside the test chamber of the wind tunnel [20].

While it has provided invaluable information for various needs, it is important to also note that the aerospace industry and measurement techniques continues to change and grow. The SDSU Low-Speed Wind Tunnel itself, although sixty years old at the time of writing, has continued to adapt with the changes and stands as a state-of-the-art experimental facility for aerodynamics and fluids research alike.

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