NASA Wind Tunnel “Bad Days”

AvTech, Dayton, Ohio
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Dr. Ron Colantonio, Portfolio Manager (PM)
NASA Glenn Research Center

Aerosciences Evaluation and Test Capabilities (AETC) Portfolio

Portfolio Objectives

- **Strategically** manage a critical portion of aerosciences ground test capabilities in support of Agency testing requirements
- Ensure the **availability and ease of access** of a **minimum critical suite of aeroscience ground test assets** that are necessary to meet the long-term needs of the Agency

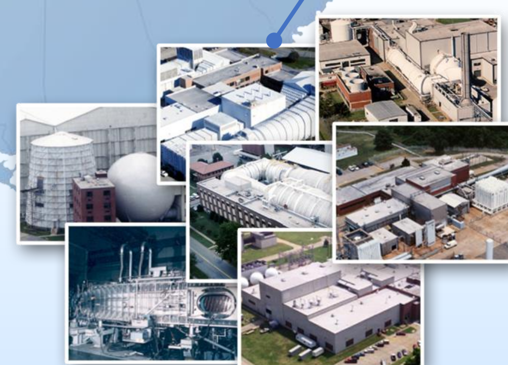
NASA Glenn Research Center (GRC)
Cleveland, OH

NASA Ames Research Center (ARC)
Moffett Field, CA

Portfolio Scope

- Aerosciences ground test facilities deemed critical to Agency (i.e. the Portfolio)
- Operations, maintenance, new capability, test technology and CFD-experimental integration advancements investments

NASA Langley Research Center (LaRC)
Hampton, VA



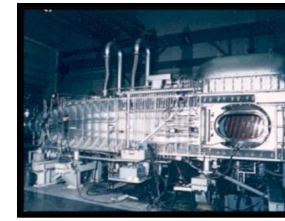
AETC Portfolio Assets

LaRC 14'x22' Subsonic Tunnel
Subsonic, Alternate Uses

LaRC National Transonic Facility
High Reynolds Number Flow

ARC Unitary Plan Wind Tunnels
11'x11' Transonic Wind Tunnel
9'x7' Supersonic Wind Tunnel

LaRC Unitary Plan Wind Tunnel
Supersonic Speed Range



LaRC Aerothermodynamics Laboratory
Exploration Workhorse

Subsonic → **Transonic** → **Supersonic** → **Hypersonic**

GRC 9'x15' Low Speed Wind Tunnel
Low-speed Propulsion Acoustic
GRC 8'x6' Supersonic Wind Tunnel
Transonic-Propulsion

LaRC Transonic Dynamics Tunnel
Aeroelasticity & Flutter

GRC 10'x10' Supersonic Wind Tunnel
Large-scale Supersonics & Propulsion

LaRC 8' High Temperature Tunnel
Large-scale Hypersonics & Propulsion

Specialty Tunnels:

GRC Icing Research Tunnel
Aircraft Icing Condition Simulation

GRC Propulsion Systems Laboratory
Engine (and Icing) Simulation at Altitude

LaRC 20' Vertical Spin Tunnel
Spin Characteristics & Dynamic Stability

AETC Investment Areas

Invest in workforce and assets (facilities, related systems and support tools) necessary to meet technical needs within NASA. The investments are broken down into five categories:

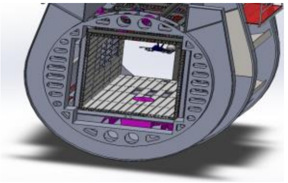
Operations: Directed to key facilities to support labor and procurement needs so that the facilities continue to be available to NASA researchers and projects.

Workforce for LaRC 14' x 22' Wind Tunnel to Conduct Testing

Maintenance: Directed for the sustainment of key facilities to ensure current and future operations while minimizing risk to customer testing.

Support for the LaRC Compressor Station Heat Exchanger Repair Keeps Facilities Running

Capability Advancement: Directed to create new capabilities needed by NASA in specific facilities (e.g. data systems, tunnel and model controls, new test environments, and facility systems).

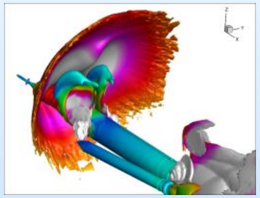


Support Investments such as the "Optical Test Section of Tomorrow" at the Ames Unitary Plan Wind Tunnel

Test Technology: Directed to improve measurement capabilities (pressure, force, flow, and temperature), test techniques and processes, and develop technologies critical to meeting NASA research needs and applicable to a multitude of facilities.

Support Investments such as Force and Moment Test Techniques

CFD and Test Integration: Directed to evaluate accuracy and efficiency of CFD compared to wind tunnel testing for past, present, and future problems of interest.



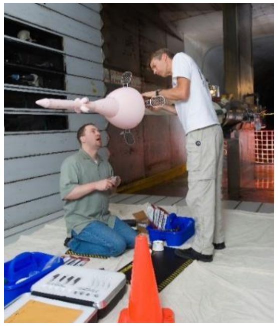
Evaluate CFD performance as compared to testing

Condition of Facilities

- The majority of our world class facilities were constructed over fifty years ago. NASA AETC needs to maintain and improve our ability to enable Agency mission by addressing those facilities that support core competencies and agency goals, while pursuing divestment opportunities among redundant and unneeded facilities and infrastructure systems.

- Many NASA Wind Tunnel “Bad Day” experiences were not predicted or tied to any preventative maintenance list. AETC is working to manage this risk. Our aging infrastructure has raised the probability that these “Bad Days” could increase.

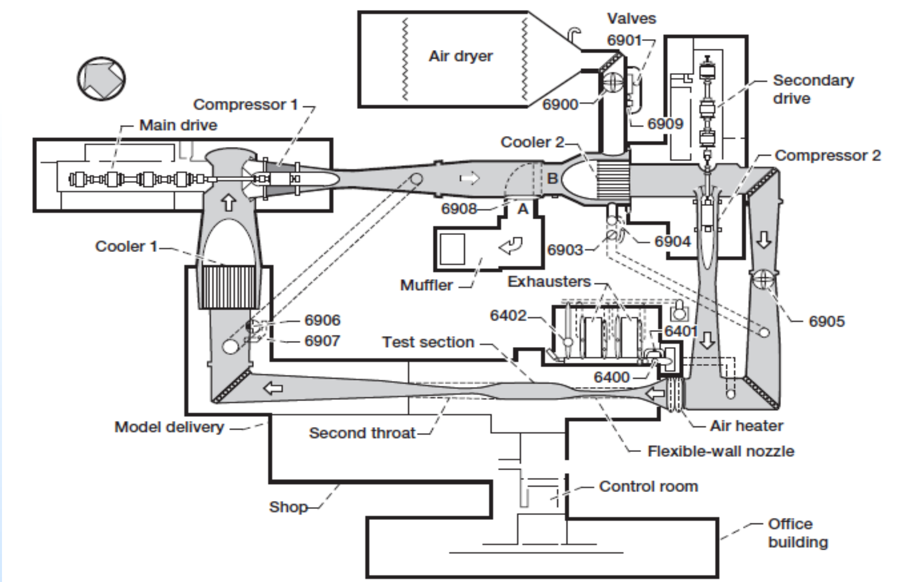
- NASA AETC balances maintenance investments with new capabilities and test technologies needed to best minimize facility downtime yet prepare facility to meet new mission requirements.

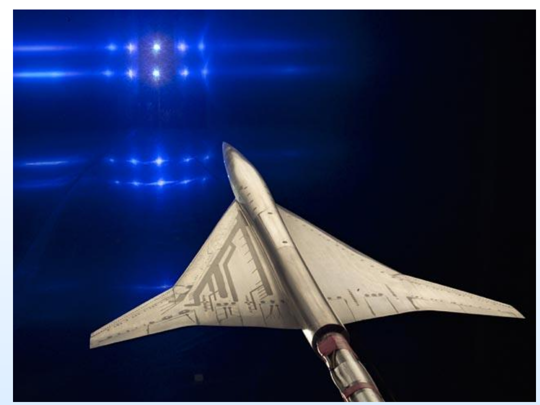



GRC 10’x10’ Supersonic Wind Tunnel (SWT)

The Abe Silverstein Supersonic Wind Tunnel (10x10) was designed to test supersonic propulsion components such as inlets, nozzles, and engines. The facility is also ideally suited for launch vehicle tests and other fuel burning applications. It can operate as either a closed loop system (aerodynamic cycle) or open-loop system (propulsion cycle) and can reach test section speeds ranging from Mach 2.0 to 3.5.

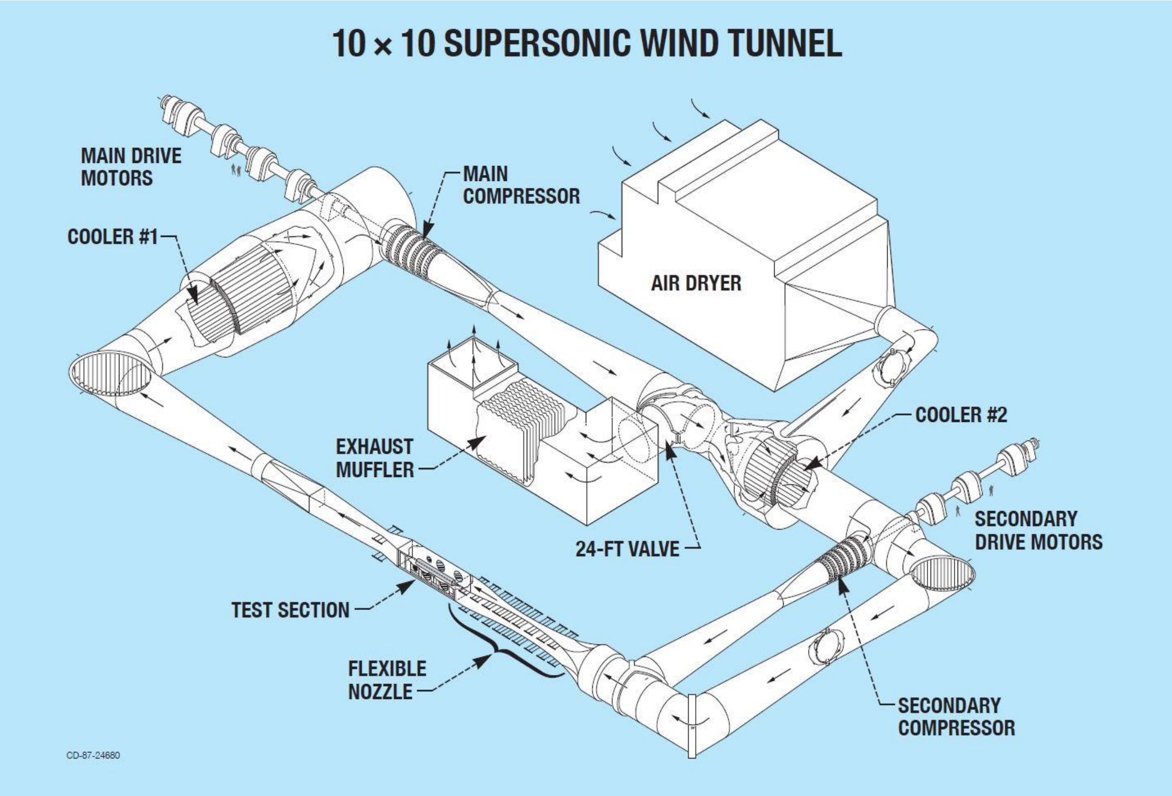
Mach Number:	**0 to 0.36 and 2.0 - 3.5**
Test Section:	**10-ft high by 10-ft wide by 40-ft long**
Reynolds No./ft: (supersonic operation)	**• 0.1 - 3.4 x 10^6 (Aerodynamic Mode) • 2.2 - 2.7 x 10^6 (Propulsion Mode)**
Dynamic Pressure:	**• 20-720 psf (Aerodynamic Mode) • 500-600 psf (Propulsion Mode)**
Altitude: (supersonic operation)	**• 50,000 to 154,000 ft (Aerodynamic Mode) • 57,000 to 77,000 ft (Propulsion Mode)**
Temperature:	**• 540-750°R (Aerodynamic Mode) • 520-1140°R (Propulsion Mode)**





NASA "Bad Day" No.1 – Freezing Damage of 10'x10' SWT Heat Exchangers

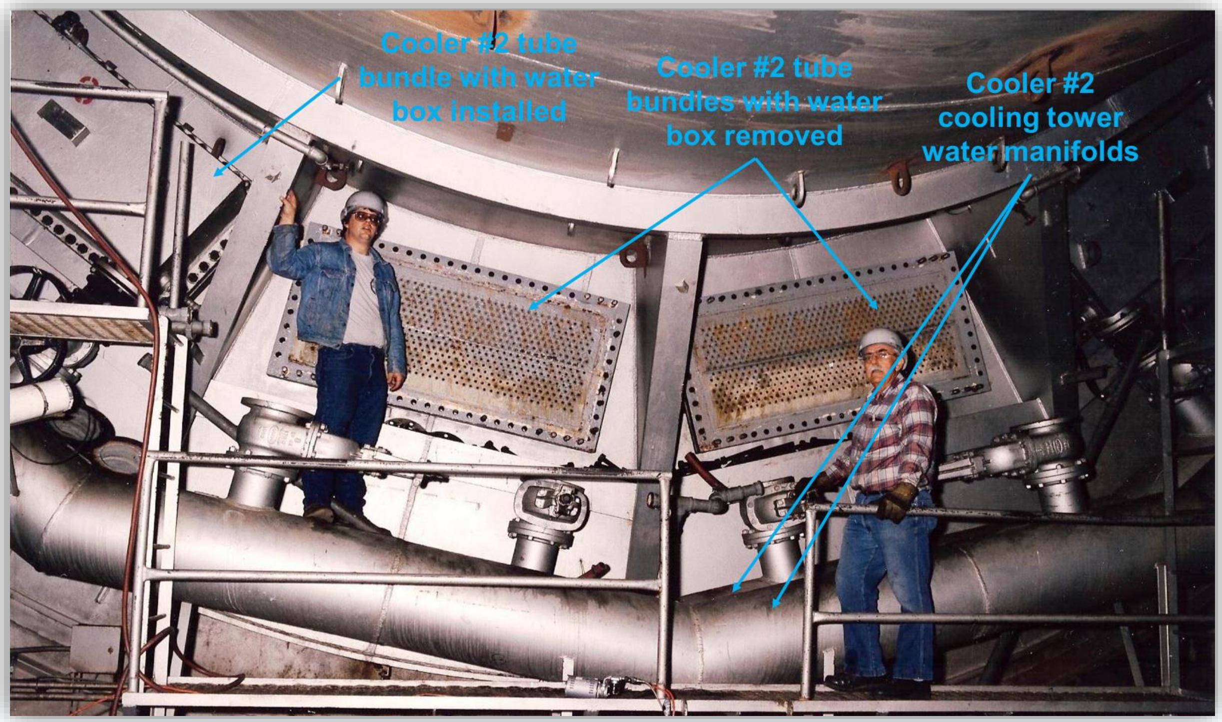
- On January 2, 2018 a **leak occurred in the cooling tower water (CTW) supply pipe** located in the 10'x10' SWT complex.
- The **water supply was shut off quickly** to minimize discharge into a local storm drain, and to prevent undermining of the nearby foundation and retaining wall.
- Because there is **no temperature control inside the tunnel**, normally, water is continuously cycled through the wind tunnel coolers from the CTW supply to protect tubes from freezing during cold weather.
- Once the CTW supply water was shutoff, the **facility staff began to drain the water from the coolers as quickly as possible**, however multiple isolation valves were leaking and slowed the process.
- Before everything could be drained **water froze in tubes of Cooler 2 and the Exhauster (Ross) Cooler causing damage.** Cooler 1 was not damaged.



10 x 10 SWT with Heat Exchanger and Water Leak Locations

NASA Cooling Water Towers that Supplies Water to 10 x 10 SWT Heat Exchangers

Major Heat Exchanger Tube Damage



Heat Exchangers Tube Modules Damaged and Removed for Repair

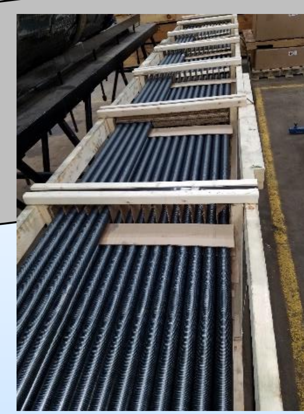
Timely and Costly Repairs

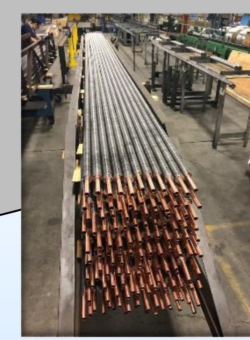
Heat Exchanger Module Prep

January 2018: Freezing Damage
May 2019: Tunnel Back to Operations

Heat Exchanger Module Installation

Heat Exchanger
Module Checks





Finned Cooling Tube
Assembly

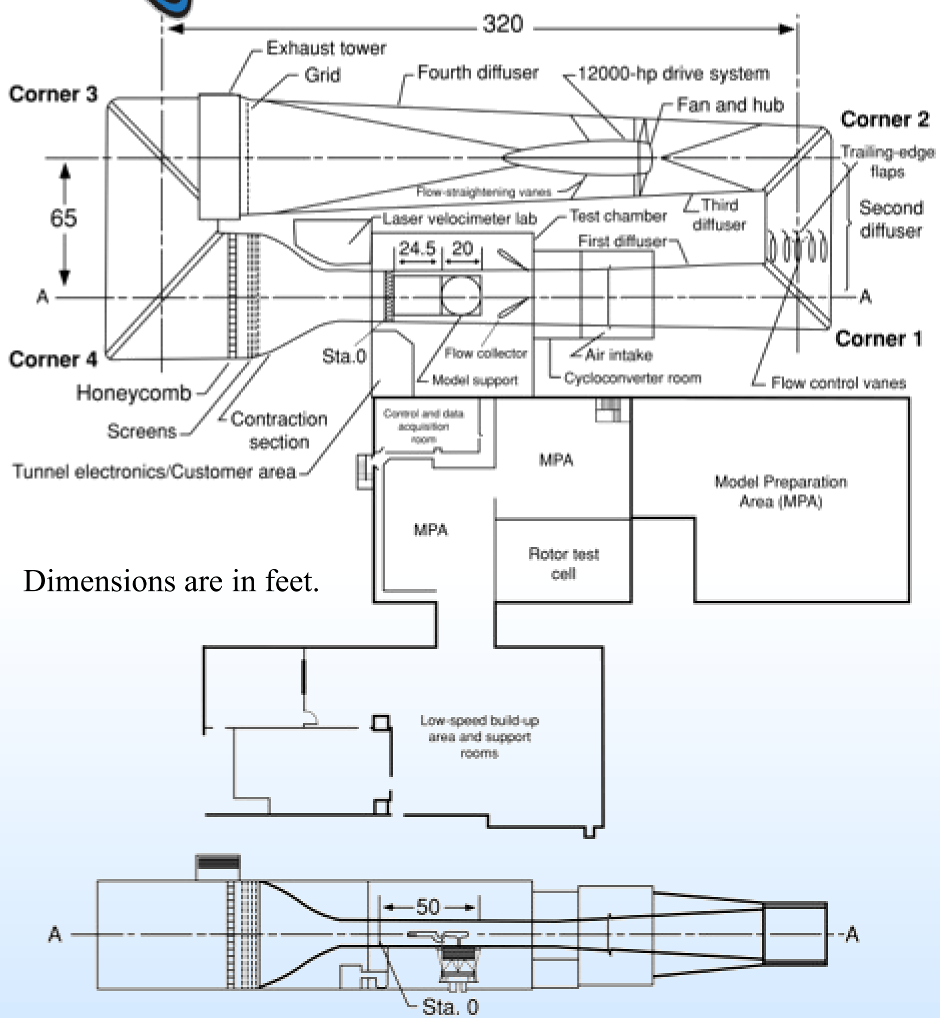
Lessons Learned

- Develop appropriate plans, instrumentation and facility controls to ensure similar freeze mishap events do not occur.
  - Active measures currently being taken at the 10'x10' SWT
  - Other tunnels across the AETC portfolio cognizant of incident and taking measures

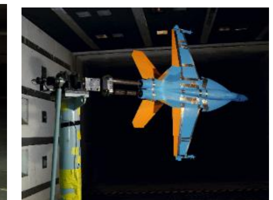
- The tube bundles repairs represented a technical risk as they haven't been removed since the construction of the 10 x 10 in the 1950s. A like-for-like repair was presumed but the lack of design details, drawings and other documentation for the original hardware prevented this approach. As such effort underestimated the complexity, scale and scope of the work.

- Effort should not be viewed as a simple repair that has the potential to have less care and engineering rigor, insufficient oversight and inadequate engagement of the required disciplines (technical, procurement, management).

LaRC 14’x22’ Subsonic Tunnel



Dimensions are in feet.

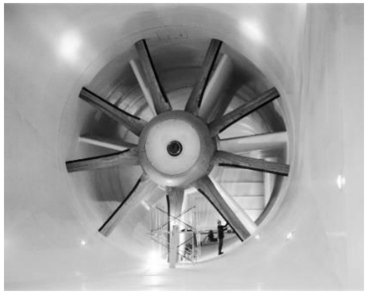


Characteristics:

- Closed circuit, single return, atmospheric
- Closed and open test section configurations
- Speed, foot per second………348 (closed), 283 (open)
- Reynolds number, per feet…..0 to 2.2 x10^6
- Test gas……………………...Air
- Test section size, feet………..14.5 x 21.75
- Test Section Length, feet……50
- Drive power, horsepower……12000 continuous
- Model build-up in large Model Preparation Areas
- Model support on different Model Carts

NASA “Bad Day” No.2 – 14’x22’ Main Drive Repair

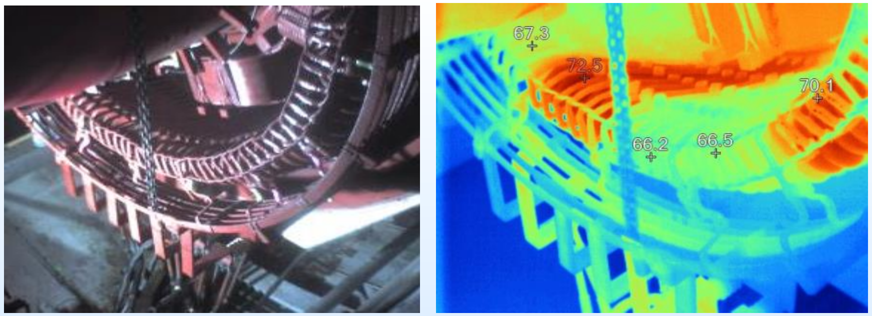
- In 2002 a new 9MW, 15Hz, 300 rpm motor with cycloconverter drive installed.
- In mid-FY14, normal periodic maintenance testing on the **drive motor indicated erratic resistance readings** in the stator windings.
- **Predictive maintenance discovered increase in motor stator winding resistive imbalance.** Additional testing was inconclusive.
- In early FY15, with a research test in the tunnel, there were again indications of problems in the drive system. Drive system **protective trips stopped operations** because of a 30% lower current in one motor phase compared to the other two phases.
- Several different motor service companies and experts were consulted, including the manufacturer of the motor. No failure points could be **found except inconsistent resistance of the motor stator windings.**
- It was concluded that the motor had an **internal short developing** in the stator windings, and it would be best to stop operation prior to a catastrophic short in the motor, which would result in extensive damage to the winding and stator core steel.
- Over 1 year taken to remove, repair and re-install drive motor, replace drive motor controls electronics, and replaced/repaired electrical drive system components.



Fan Assembly

Nacelle

Top Hatch



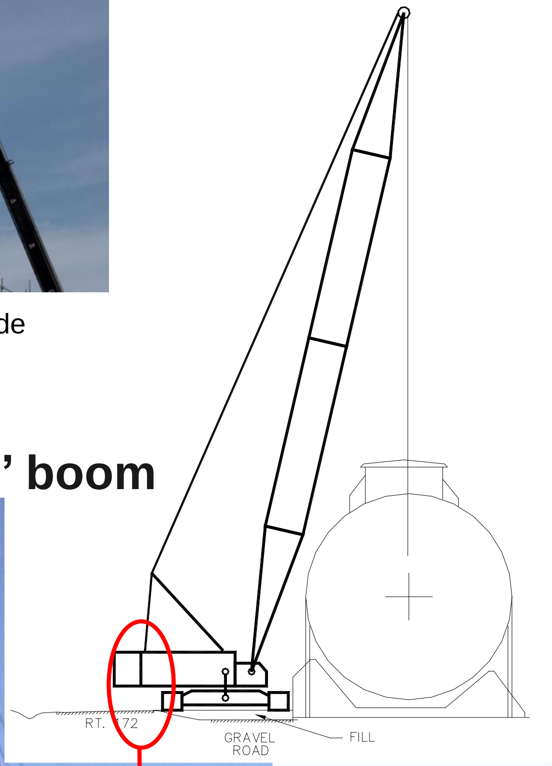
Visual and IR Images of End Winding

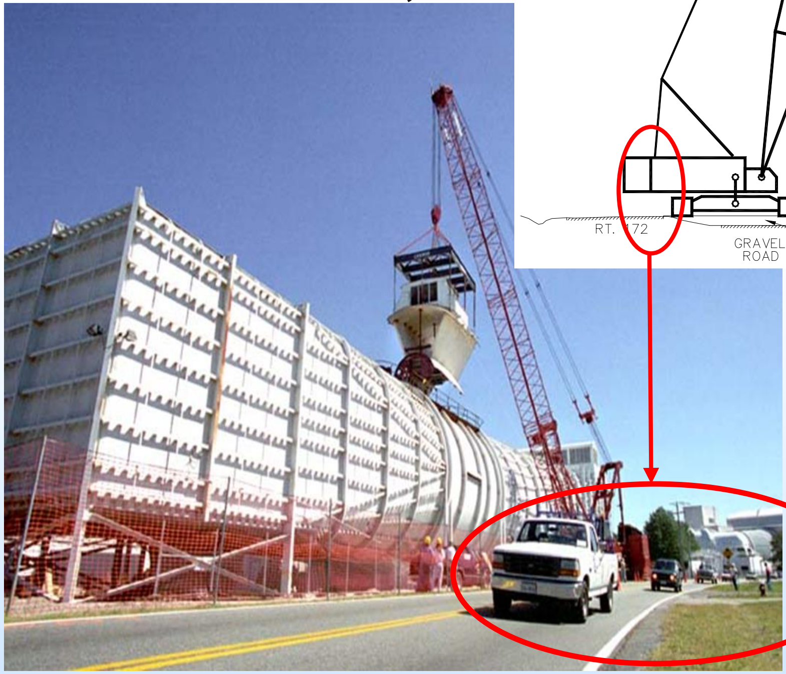
Critical Lift for Main Drive Removal

Removal of fan blade

Removal of main drive

Manitowoc 2250
300T crawler crane, 150’ boom





Required Lane Closure

Removal of part of the nacelle and tunnel structure

Removal of drive motor

Lessons Learned

- Periodic maintenance testing and predictive maintenance assessments prevented much more major damage to occur on drive motor.
- More advanced Condition Based Maintenance (CBM) tools need to be further evaluated across drive systems in the NASA portfolio and should include vibration, lube oil and electrical system monitoring.
- Considering the length of time to refurbish drive motors other ancillary and supporting systems should be evaluated and corrected if necessary in parallel to minimize future downtime.

NASA Team Investigating Drive Motor Damage

Harmonic Filter Reactor Replacement

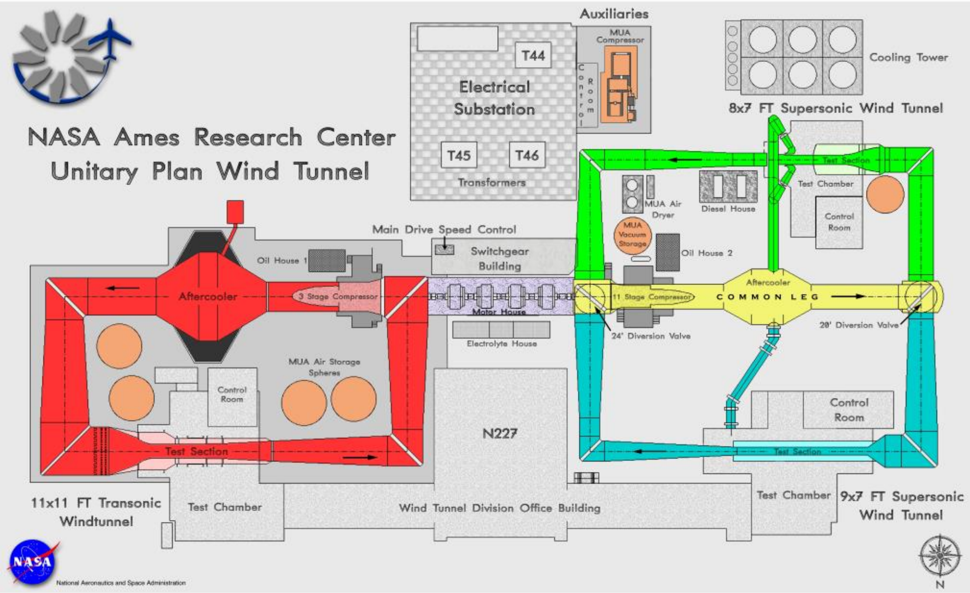
Rotted Wireways Replacements

UPS Replacement

ARC Unitary Plan Wind Tunnels

9x7 Foot Supersonic Wind Tunnel (SWT)
The 9 X 7 SWT is a closed-return, variable-density tunnel with an asymmetric, sliding-block nozzle. It is one of two separate test sections powered by a common drive system. Interchangeability of models among the Unitary test sections allows testing across a wide range of conditions. Airflow is generated by an 11-stage, axial-flow compressor powered by four variable-speed, wound-rotor, induction motors.

Speed:	**Mach 1.55 to 2.55**
Reynolds Number:	**0.90 - 5.6 x 10^6 per foot**
Pressure:	**4.4 to 27.0 lbs. per square inch**
Temperature:	**110 ± 20°F**
Test Gas:	**Ambient atmosphere**
Test Section Size:	**7 feet high by 9 feet wide**
Length:	**14 feet**
Area:	**63 square feet**

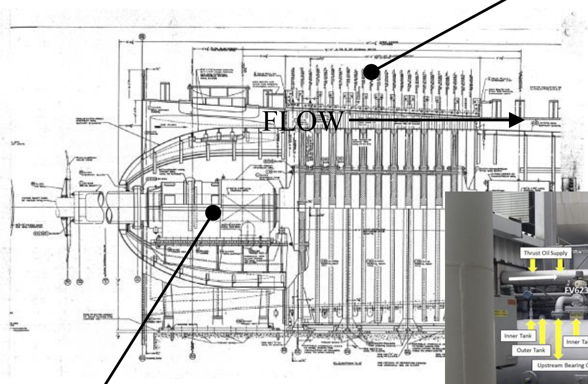


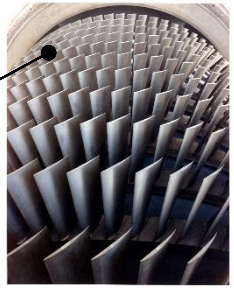
11x11 Foot Transonic Wind Tunnel (TWT)
The facility is used extensively for airframe testing and aerodynamic studies and has played a vital role in every manned spaceflight program, including NASA's new Orion space capsule, on which astronauts will fly to the International Space Station, the Moon and beyond. The 11 X 11 Foot TWT is a closed-return, variable-density tunnel with a fixed-geometry, ventilated test section --- with evenly distributed slots on all four walls --- and a dual-jack flexible nozzle.

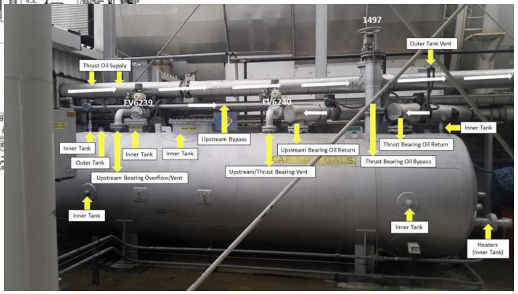
Speed:	**Mach 0.20 to 1.45**
Reynolds Number:	**0.30 - 9.6 x 10^6 per foot**
Pressure:	**3.0 to 32.0 lbs. per square inch**
Temperature:	**100 ± 20°F**
Test Gas:	**Ambient atmosphere**
Test Section Size:	**11 feet high by 11 feet wide**
Length:	**22 feet**
Area:	**121 square feet**

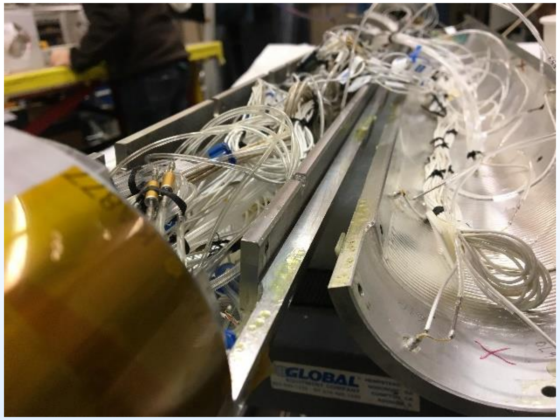
NASA “Bad Day” No.3 – Oil Spill In Wind Tunnel

- On November 6th 2017 the 9 x 7 Unitary Plan Wind Tunnel was operating when test engineers discovered **an oil leak**.
- The leak was perceived initially as humidity in the test section and then identified as oil once streaks on the test section windows appeared.
- **Over 500 gallons of bearing oil was released** in the wind tunnel in less than a minute.
- The aftercooler, was coated with oil, as were the compressor, tunnel walls and test model.
- A **compressor stop was initiated** in the 9 x 7 Wind Tunnel due to low flow of the upstream bearing circulation pump. The low flow condition at the pump was a result of the dropping oil reservoir level.
- Inadvertent opening of reservoir fill port while tunnel was sub-atmospheric resulted in **over-pressurization of the bearing labyrinth seals** and caused the release of over 500 gallons of oil into the 9 x 7 upstream nacelle and circuit.







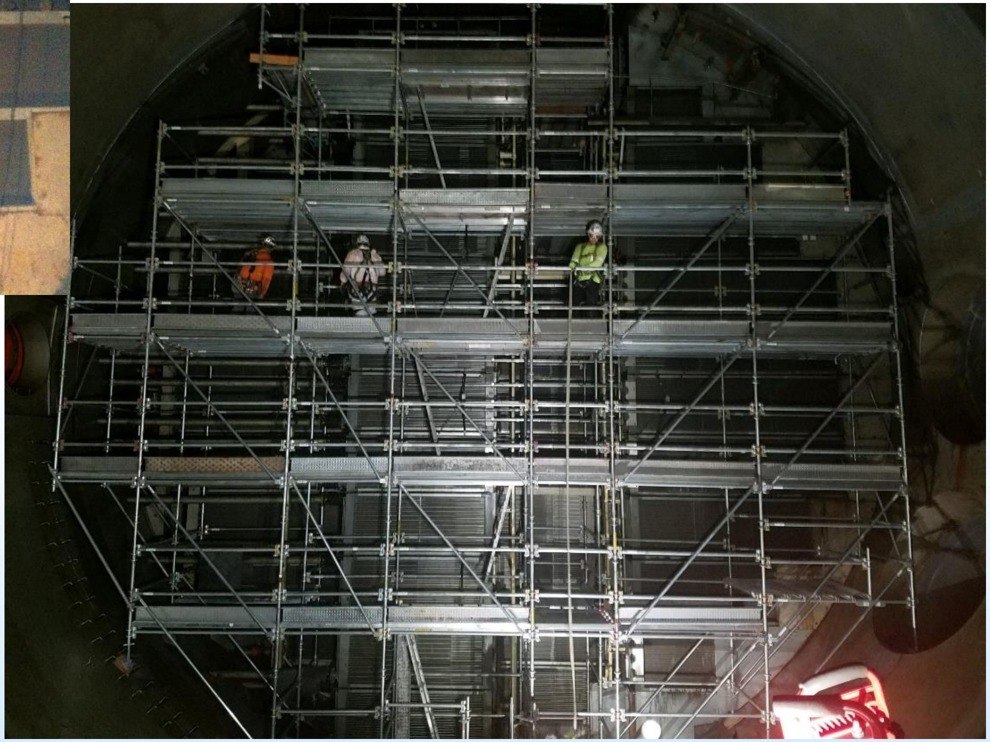


Model Oil Cleanup
Model Panels removed

ARC UPWT 9’x7’ SWT Oil Spill Cleanup

Initial cleaning upstream of aftercooler

Scaffolding downstream of aftercooler



Lessons Learned

- Periodically revisit tunnel work instructions such as oil replenishment in tank reservoir – is it up to date and current.

- Periodically train operators on tunnel operating procedures and response to all known alarms.

- Conduct a comprehensive gap analysis of the existing operator training program elements vs. desired training program elements. Consider the following:
  - Casualty training
  - Maintenance activities
  - Practical factors
  - Qualification boards
  - Assigning mentors
  - Pre-task planning
  - Communication skills
  - Safety

Strategy to Minimize the Next Bad Day

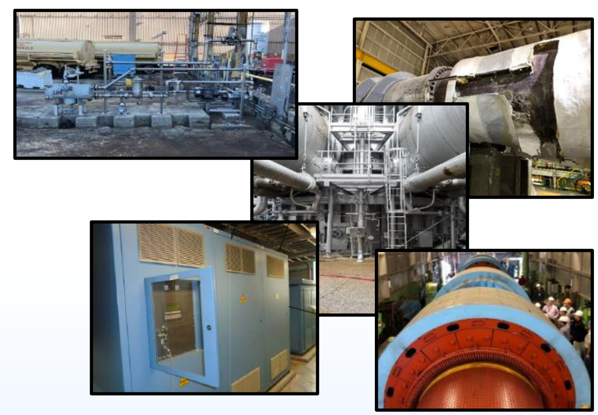
- Bad days will continue to occur but there are strategies to minimize such events.

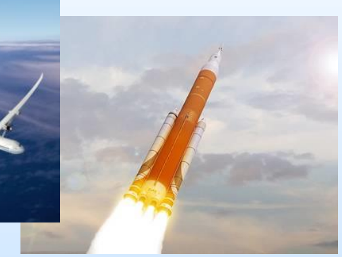
- NASA maintains deferred maintenance lists for its large tunnel portfolio each designated with a “risk-to-test” attribute.
  - Risks are assessed for cost, schedule consequence and probability of occurrence
  - Each tunnel’s lower level risks are rolled up to overall tunnel risk (i.e. risk score is defined)

- NASA forecasts test demand for each facility and defines facilities that are most critical in meeting future NASA objectives and initiatives.

- NASA defines and funds maintenance projects against critical tunnels to acceptable risk scores.

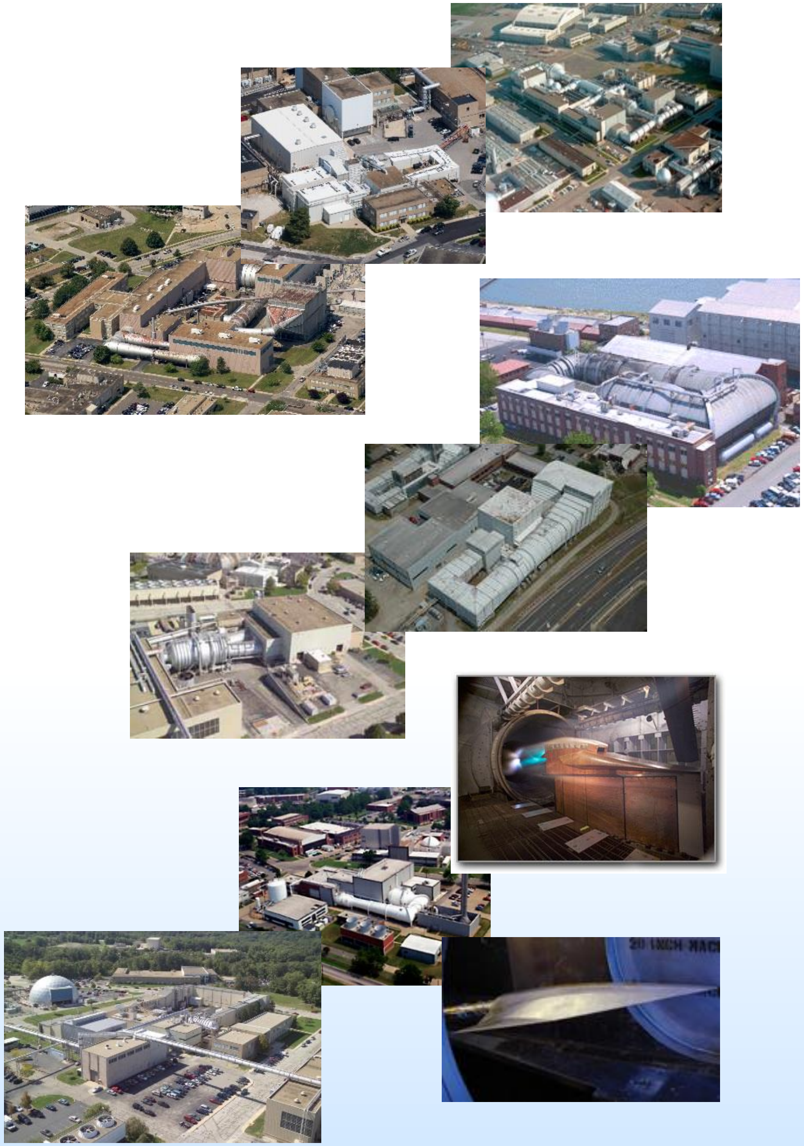
Likelihood						
	5	10	16	20	23	25
	4	7	13	18	22	24
	3	4	9	15	19	21
	2	2	6	11	14	17
	1	1	3	5	8	12
		1	2	3	4	5
	Consequence					





Summary

- Bad Days at NASA wind tunnels will occur just due to aging infrastructure.
- Lessons learned from NASA and DoD Bad Days need to be communicated across other wind tunnel managers and operators for proactive mitigation.
- NASA is taking measures to reduce the levels of Bad Days and its impact to test customers in the future such as factoring risk-to-test at the tunnel level and system level for effective investment decisions.



NASA