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Experimental Evaluation of the Effectiveness of Online Water-Washing in Gas Turbine Compressors

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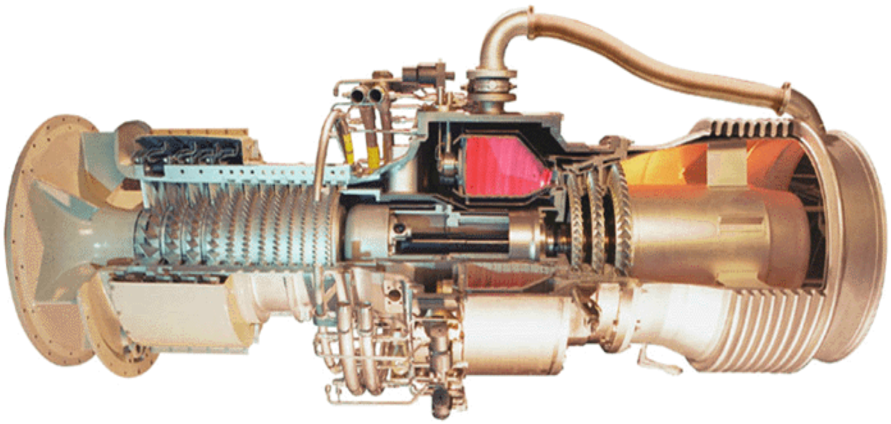
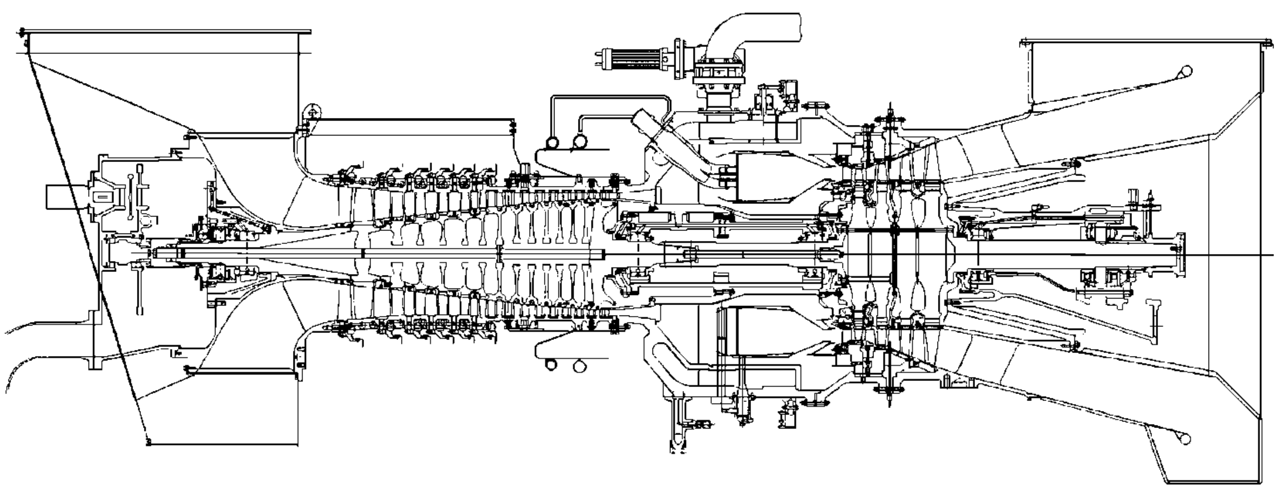
Gas Turbine Washing Background





Compressor Fouling Examples

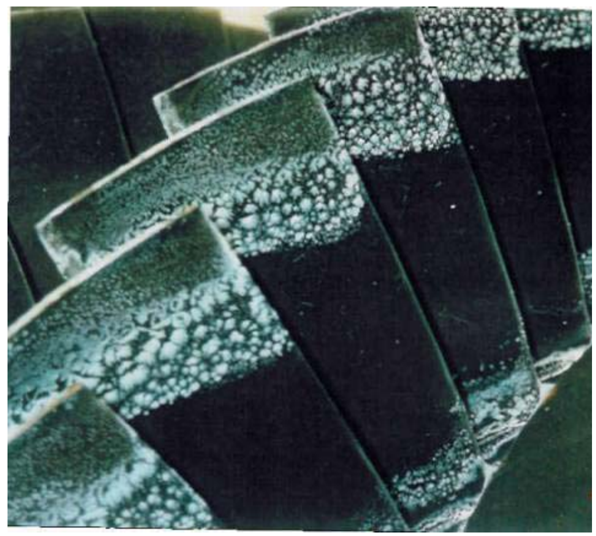
Left: Mixture of oil and salts
Lower left: Thin adherent oil film
Lower right: Internal oil leak

Oil and grease act as "glue" to trap and hold other fouling materials

Courtesy of Turbotect (USA), Inc.

Ingestion of Airborne Sea Salt

Salt leeching through
air intake filter
Courtesy: Altair Filter



Heavy sea salt deposits
on compressor blading

Compressor blade
pitting corrosion

Courtesy of Turbotect (USA), Inc.

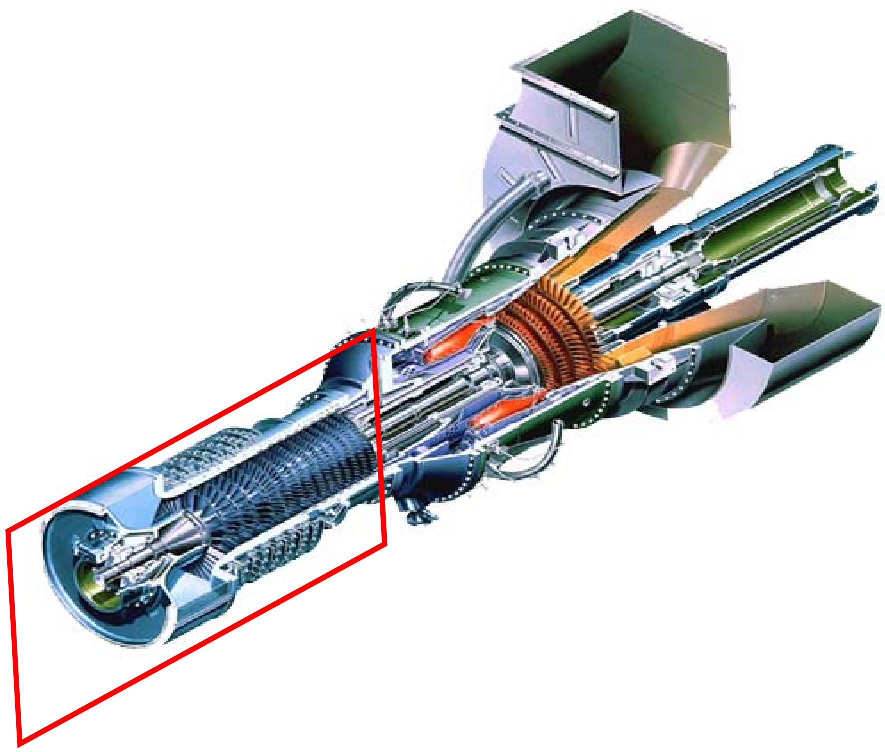
Typical Compressor Degradation Agents

Type	Cause	Effect
Sand	Filter Openings	Erosion
Dirt/Fines	Filter/Saturation	Fouling
Carbon/Oil	Exhaust Fumes	Fouling
Salt	Atmospheric Salt (Ocean)	Corrosion
Salt	Water Injection	Corrosion
Sulfur	Exhaust Fumes, Atmosphere	Corrosion
Calcium	Water Injection	Fouling

Water Washing

- Description
  - ❑ Method of cleaning GT between overhauls to renew performance lost due to fouling
- Purpose of Water Washing
  - ❑ Restore Engine Performance
    - ✓ Reduced Air Compressor Efficiency Results in Reduced Output Power and Increased Fuel Consumption
  - ❑ Maintain Engine TBO Life
    - ✓ Fouled Engine Requires Higher Firing Temperature for Given Load
  - ❑ Maintain Start Reliability
    - ✓ Compromised Compressor Increases Possibility of Hung Start Reduced Air Compressor Efficiency Raises Turbine's Self-Sustaining Speed so More Starting Power Needed

Water Washing: Extend of Cleaning



Gas turbine online/offline cleaning is only effective for the compressor.

Water Washing: General Observations

- The success of the water washing program is highly dependent on the cleaning frequency (both online and offline washing)
- Cleaning Frequency
  - Frequency and type of cleaning site specific
  - Every site different
  - Adjacent turbines may be different
  - Cleaning frequency must be based on site experience
  - Excessive contamination difficult and time consuming to remove
  - Cleaning should be frequent enough to prevent excessive contamination buildup

Online versus Offline Water Washing

Online Washing

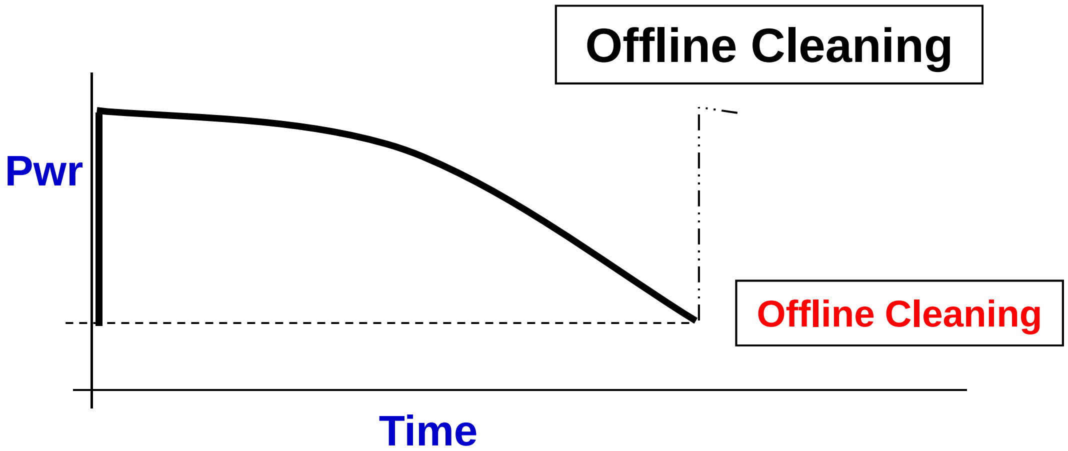
- Conducted while GT operating
- Cleaning only effective in IGVs and first few stages of compressor
- Uses DI water
- Online nozzles near IGVs
- Contaminants removed with washing carried downstream to other stages
- Best when used in conjunction with offline washing

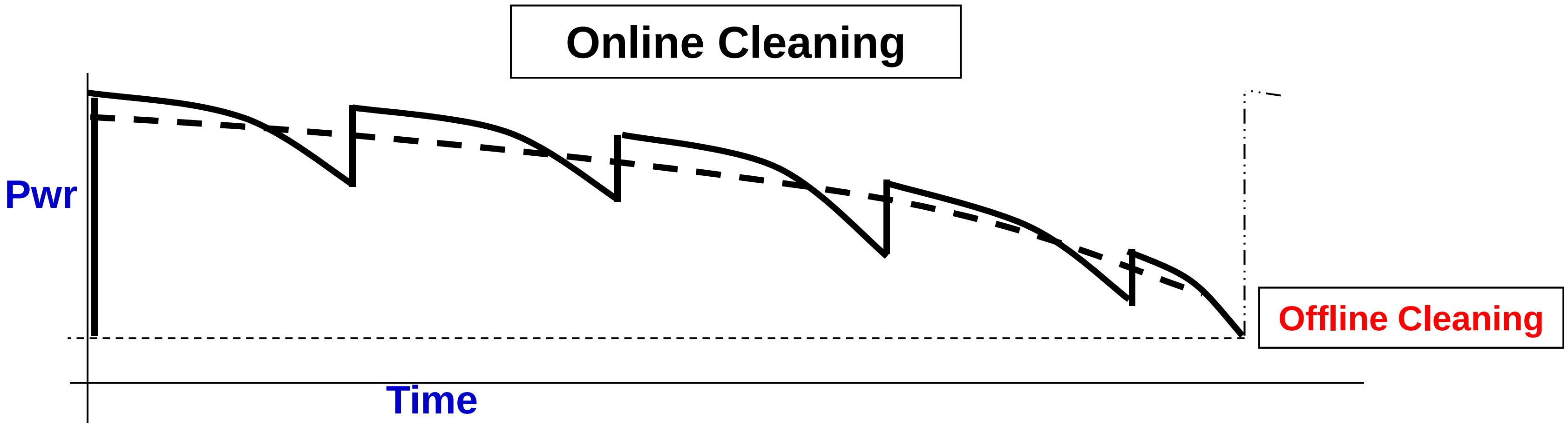
Offline (On-Crank) Washing

- Conducted while GT is shutdown
- Uses detergent and DI water
- Must vary crank speed, droplet size, IGV settings, and pressure off supply water to clean downstream stages
- Must wash downstream stages with water to fully remove detergent and contaminants after cleaning (multiple cycles)
- Check water resistance

Water Washing

Cleaning Frequency Considerations



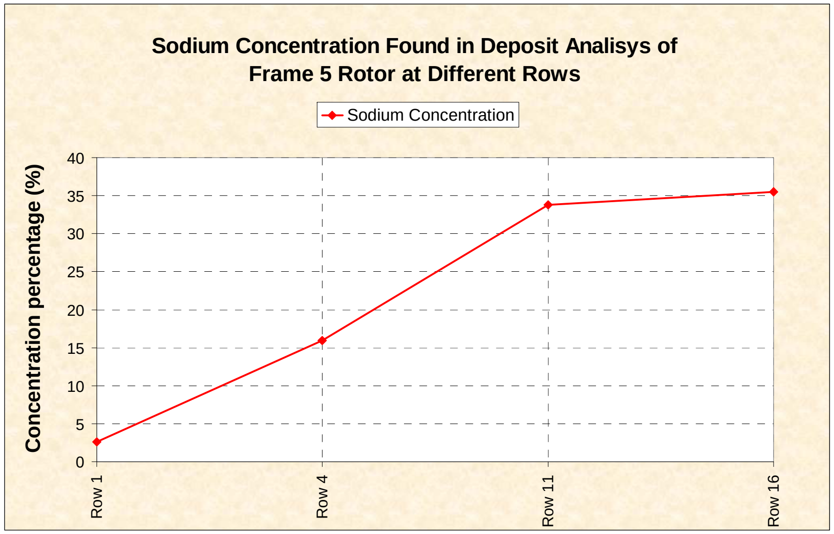


A comprehensive online **and** offline washing program will achieve the highest compressor performance.

Online Water Washing

Considerations:

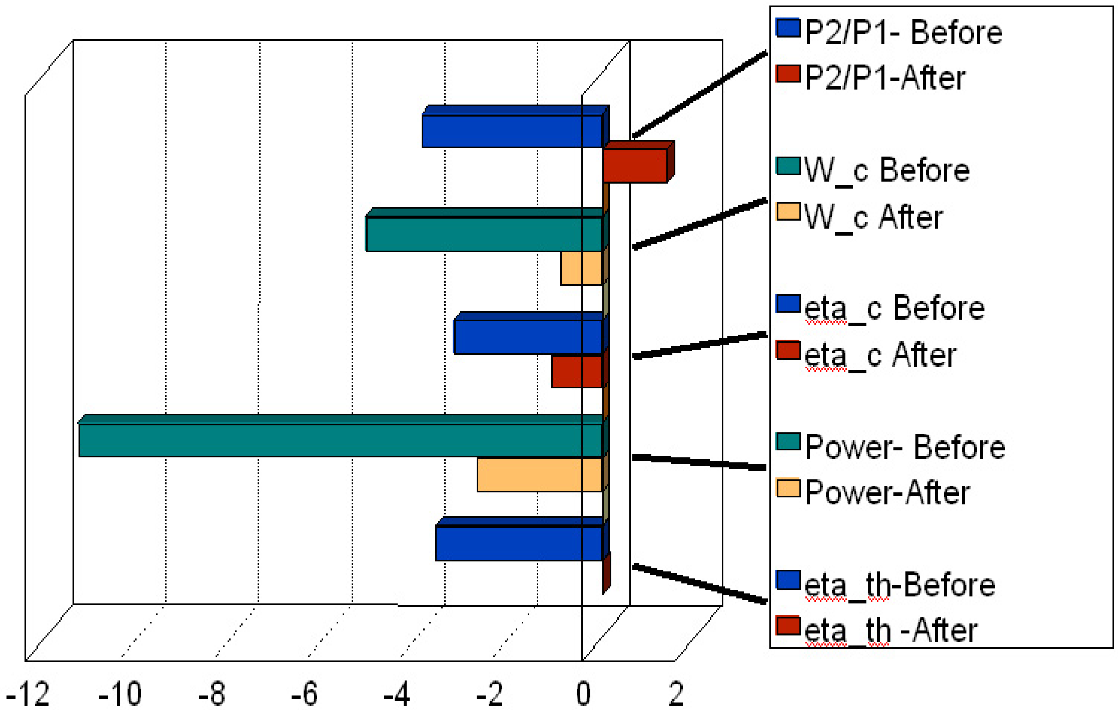
- Online cleaning is only effective over first few stages of air compressor (these stages collect most contamination).
- Online washing re-deposits contaminants into downstream stages.



(Brun, et al., 2012)

Offline Water Washing

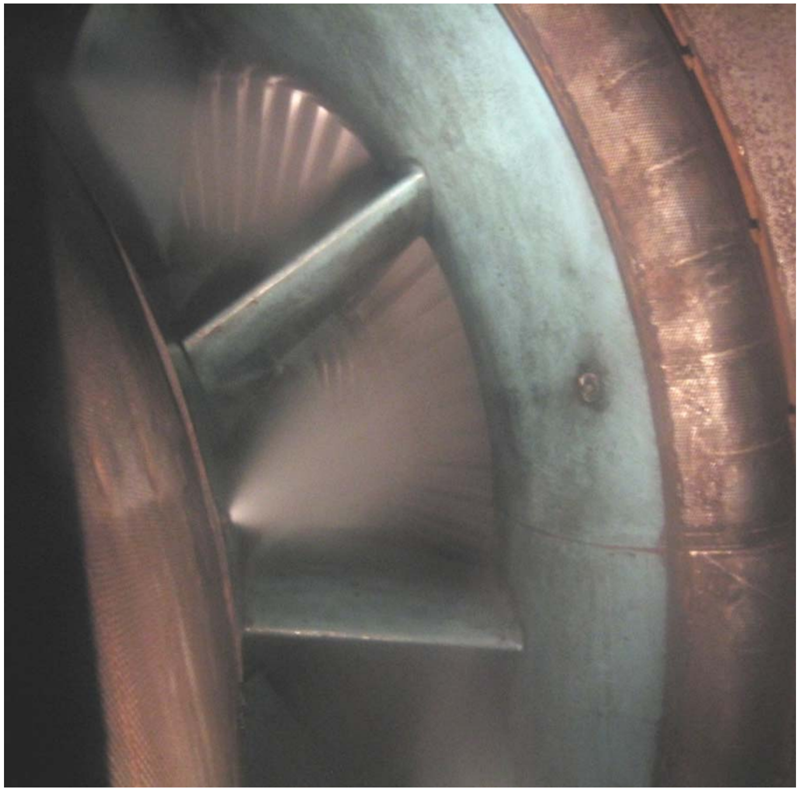
Considerations:



Water washing does not renew full compressor performance.

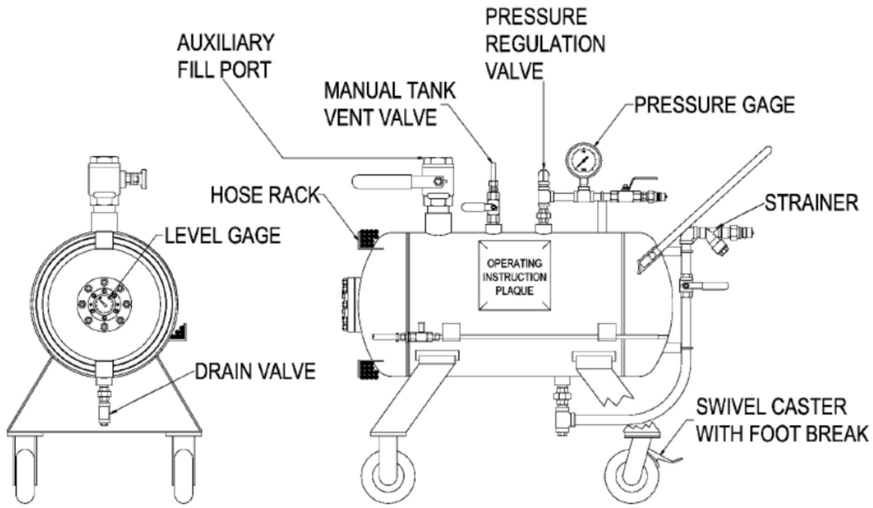
Axial Compressor Cleaning Systems

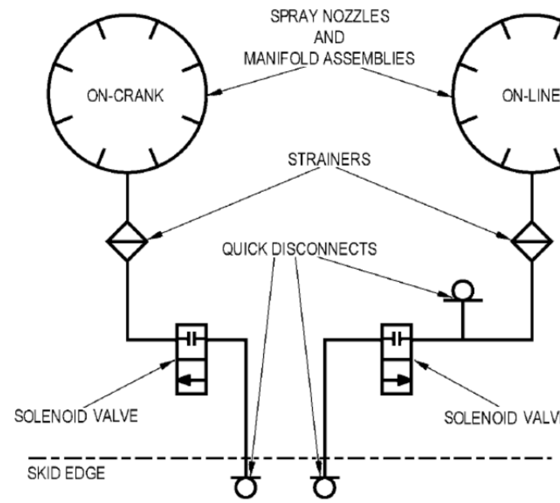
- On-line and off-line washing systems
- Separate distribution manifolds
- Pressure atomizing spray nozzles
- On-skid piping
- Filter
- Solenoid operated shutoff valves
- Operator interface panel



Courtesy of Turbotect (USA), Inc.

Axial Compressor Cleaning Systems





Courtesy of Turbotect (USA), Inc.

Project Objectives

A thorough experimental evaluation on the effectiveness of <u>online turbine</u> cleaning with various cleaning agents.

Fundamental questions:

- Does online cleaning work?
- Is there any difference between any of the online cleaning liquids?
- Will dirt be removed during online cleaning redeposit once the cleaning liquid has been evaporated?
- Do any liquids reduce the redeposit of dirt in the online washing process?
- Does online washing cause noticeable blade erosion?

Project Scope of Work

1. Sampling of fouled blades
2. Chemical analysis and characterization of fouling agent
3. Formulation and application of “generic” fouling agent (standard dirt) to blades
4. Trans-sonic wind-tunnel test blade test facility and washing fluid delivery system
5. Online washing testing and analysis method
6. Online wash test blade cleaning results
7. Fouling re-deposition tests (spray gun)
8. Fouling re-deposition tests (wind-tunnel)
9. Blade erosion tests (wind-tunnel)

Blade Dirt Analysis and Simulated Dirt Development

- An industrial gas turbine manufacturer provided seven sample blades severely fouled and five sample scrapings from a wide range of onshore and offshore locations.
- Fouling dirt was sampled from the compressor blades to characterize the composition and consistency of typical blade surface fouling.
- Detailed chemical analyses performed on “dirt” samples included x-ray diffraction (XRD), x-ray dispersion spectroscopy (EDS), and carbon hydrogen nitrogen sulfur analysis.

Fouled Blade Samples

Blade Sample 14

Front” Side of Blade Sample 13

Back” Side of Blade Sample 13

Blade Sample 9

“Front” Side of Blade Sample 10

Back” Side of Blade Sample 10

Blade Dirt Samples

- Deposits were primarily on the front (pressure) side of the blades.
- The streaking patterns, evident on all the blades, suggest that the material is deposited via radial flow from the root of the blade out.
- In most cases, the leading edge of the blade was cleaner than the rest of the blade. This suggests that areas with high velocity and incident angle are less susceptible to dirt deposit.
- Most deposits have a substantial amount of hydrocarbon mixed in with the "dirt."

Focus on testing of fouling removal from pressure side of blade

Blade Dirt Analysis

EDS Data for Major Elements Included in Simulated "Dirt"

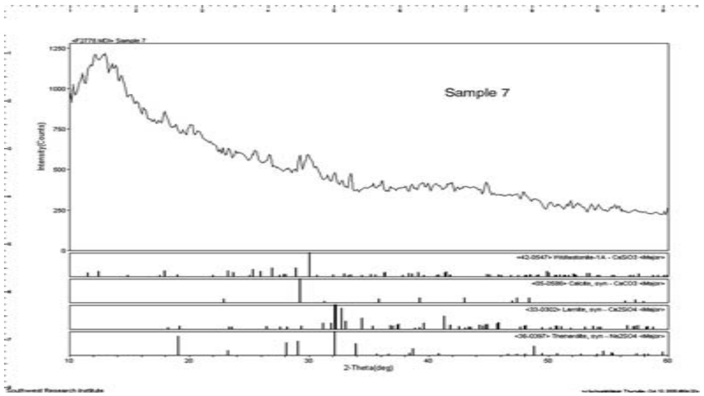
Sample	Na	Mg	Si	S	Cl	Ca
1	1.82	1.30	4.06	31.9	1.52	1.05
4	14.65	5.29	1.35	21.78	20.49	1.52
5	2.06	1.46	36.92	14.68	1.70	2.78
7	4.87	2.01	4.69	15.34	5.30	0.00
12	4.92	0.00	7.61	14.93	0.00	0.97
Average	5.66	2.01	10.93	19.73	5.80	1.26

CHNS Results

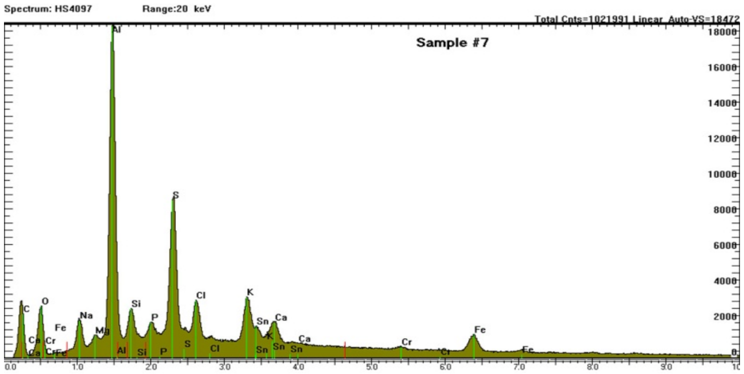
Sample ID	Conc. %C	Conc. %H	Conc. % N	Conc. %S
Sample 1	40.63	4.12	3.97	5.83
Sample 1 Duplicate	39.83	4.19	4.09	5.94

Percent of Elemental Components in "Dirt" Sample and Corresponding Compounds in Admixture

Avg. Elemental % of Sample	Compound Percent of Admixture
3.5% Cl	5.8% NaCl
1.2% Mg	5% MgSiO3
6.6% Si	5% MgSiO3 & 11.2% SiO2
0.76% Ca	1.9% CaCO3
5.9% S	26.1% Na2SO4
50% C	50% Carbon Lampblack



Example XRD Spectrum for Sample 7



Example EDS Results for Sample 7

Detailed chemical constituent analysis of dirt from fouled blades

Generic Foulant Mixture (Standard Dirt) and Application

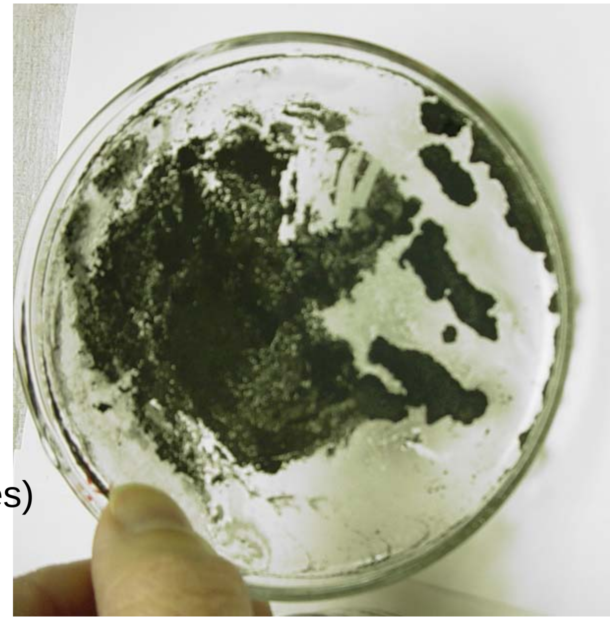
Turbine Blade Coating Formulation:

Dry Admixture Components, 100 gram batch (same as percent mass)

50.0 g Carbon Lampblack (amorphous carbon)
5.8 g NaCl (sodium chloride, salt)
26.1 g Na_2SO_4 (sodium sulfate)
1.9 g $CaCO_3$ (calcium carbonate)
11.2 g SiO_2 (silicon IV oxide)
5.0 g $MgSiO_3$ (enstatite, magnesium silicate)

Solvent and Binder Mixture Proportion

1 g PEG (poly [ethylene glycol], Average M_n = 3,400)
20 mL DCM (dichloromethane)

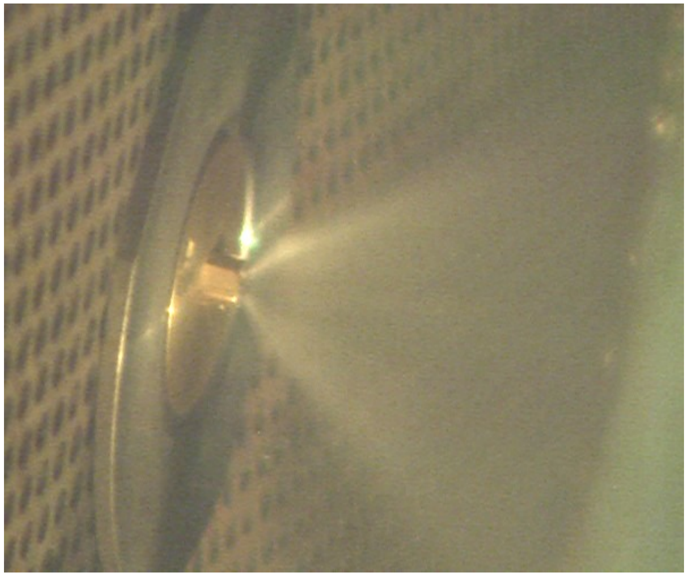


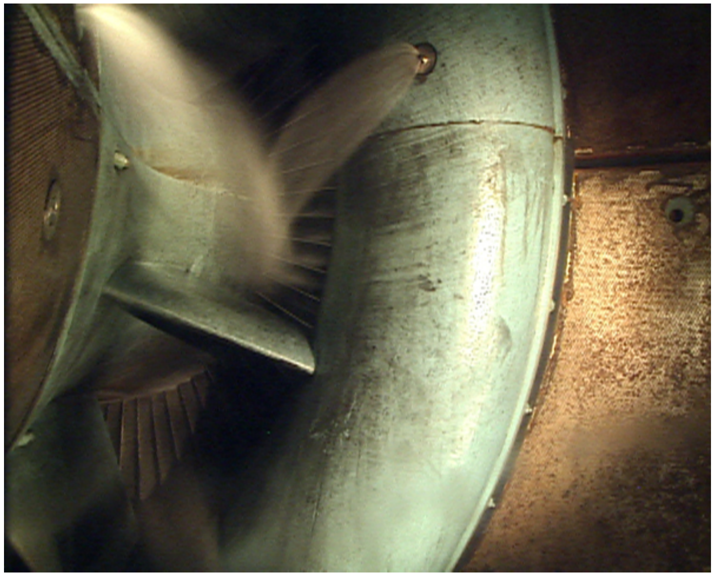
Blade cleaning and foulant coating:

1. Spray water cleaning (remove loose material
2. Acetone, simple green, isopropyl alcohol ultrasonic bath (20 minutes)
3. Wipe with acetone and wipe with de-fluxing cleaner
4. Spray paint coating to specified thickness using DCM as carrier
5. Condition blades for 10 minutes in wind-tunnel at full flow

Standardized fouling agent developed for consistent blade washing testing

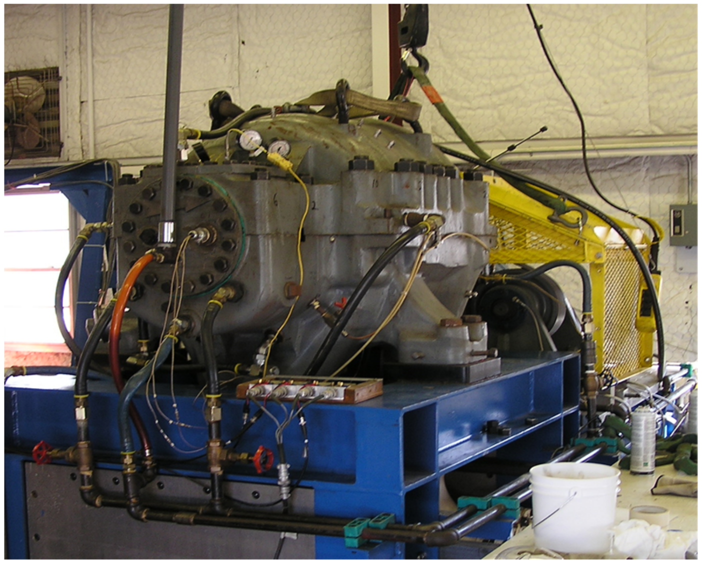
Online Single Blade Washing Tests in Wind Tunnel

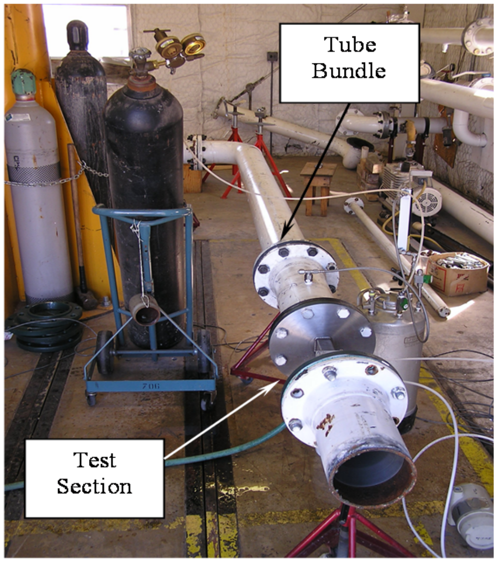




- **Does online cleaning work?**
- **Is there any difference between any of the online cleaning liquids?**

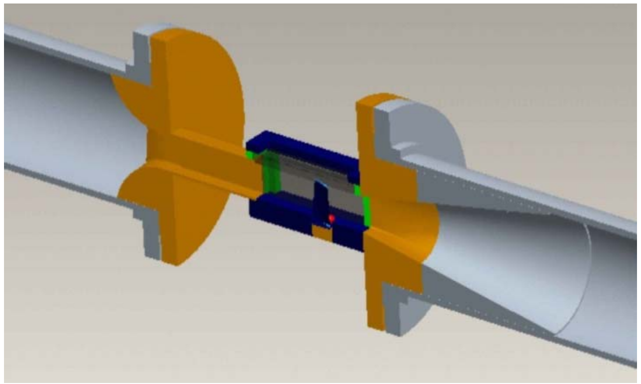
Trans-Sonic Wind-Tunnel for Single Blade Testing



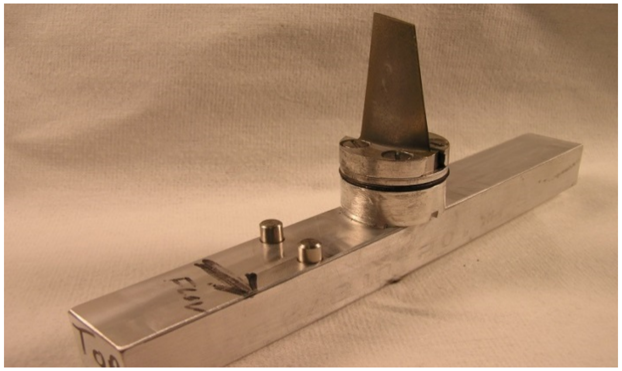


- Open loop variable speed centrifugal air compressor discharge
- Up to Mach=.95 (near atmospheric air)

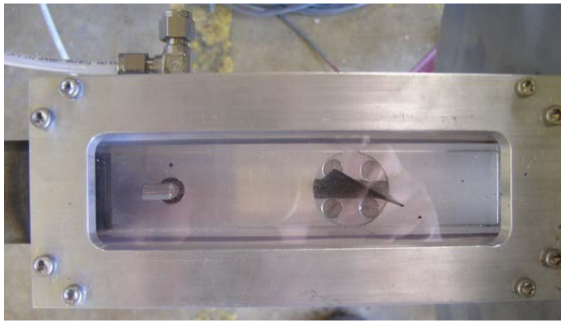
Test Section and Blade Mounting



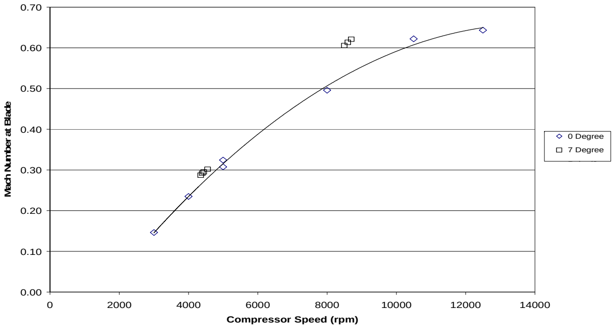
Single Blade Test Section Converging and Diverging Sections



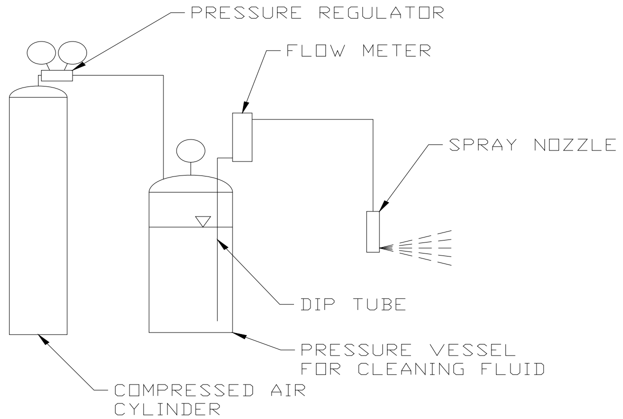
Blade Mounting Fixture with Blade Installed



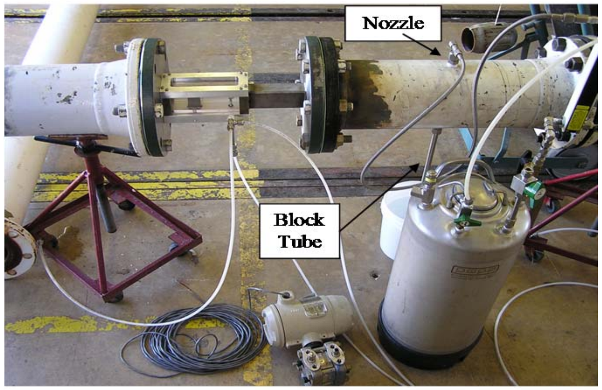
Top View of Blade Mounted in Test Section with Kiel Probe Upstream)



Fluid Delivery System



Schematic of Fluid Delivery System



Test Section with Cleaning Fluid Tank and Spray Nozzle Location

Flow Blockage Tube (Left) and Nozzle (Right)

Fluids Tested

1. Tap water
2. DI water
3. High Purity DI water
4. Laundry Detergent (Gain) and DI water
5. Commercial Compressor Cleaning Fluid

Water Ionization Levels

Fluid	Resistivity (MΩ-cm)
Tap Water	0.002-0.003
Deionized Water	10
High-purity Deionized Water	18

Test Sequence

Test Sequence	Compressor Speed (rpm)	Mach Number	Blade Angle (degree)
1	10,500	0.6	0
2	8,500	0.6	7
3	5,000	0.3	0
4	4,800	0.3	7

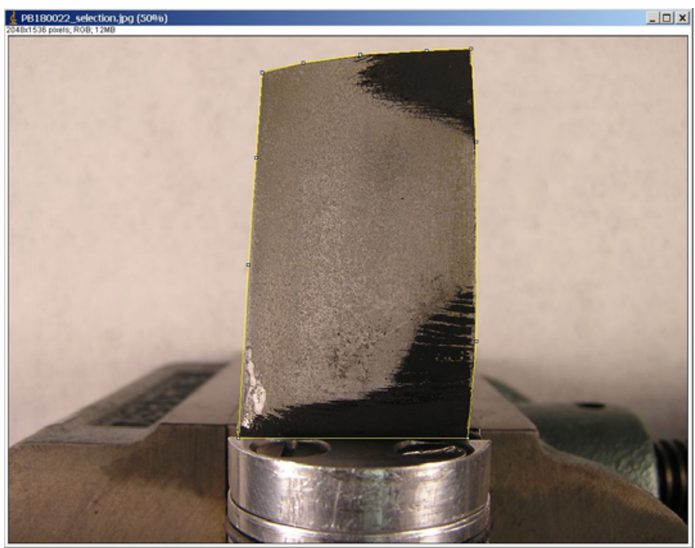
Used commercial online water wash nozzle at manufacturer recommended pressure and flow rate

Online Washing Test Procedure

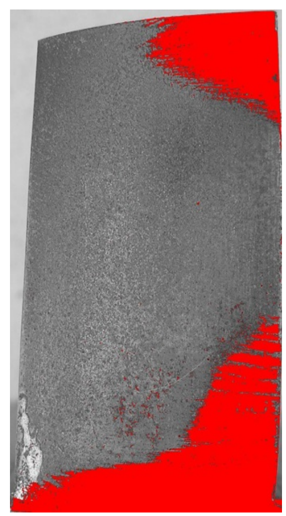
- Clean blade (previously described)
- Weigh Blade (±.001 g)
- Coat and condition blade with foulant
- Weigh Blade again
- Mount blade in wind-tunnel set desired flow angle and flow velocity
- Online wash blade at full flow
- Weigh blade again to determine foulant removal
- Optically process blade for cleaning efficiency
- Compare weight loss and optical results for validation

Analysis Methods

1. Blade weight differential (foulant removal)
2. Optical processing (ImageJ Software)



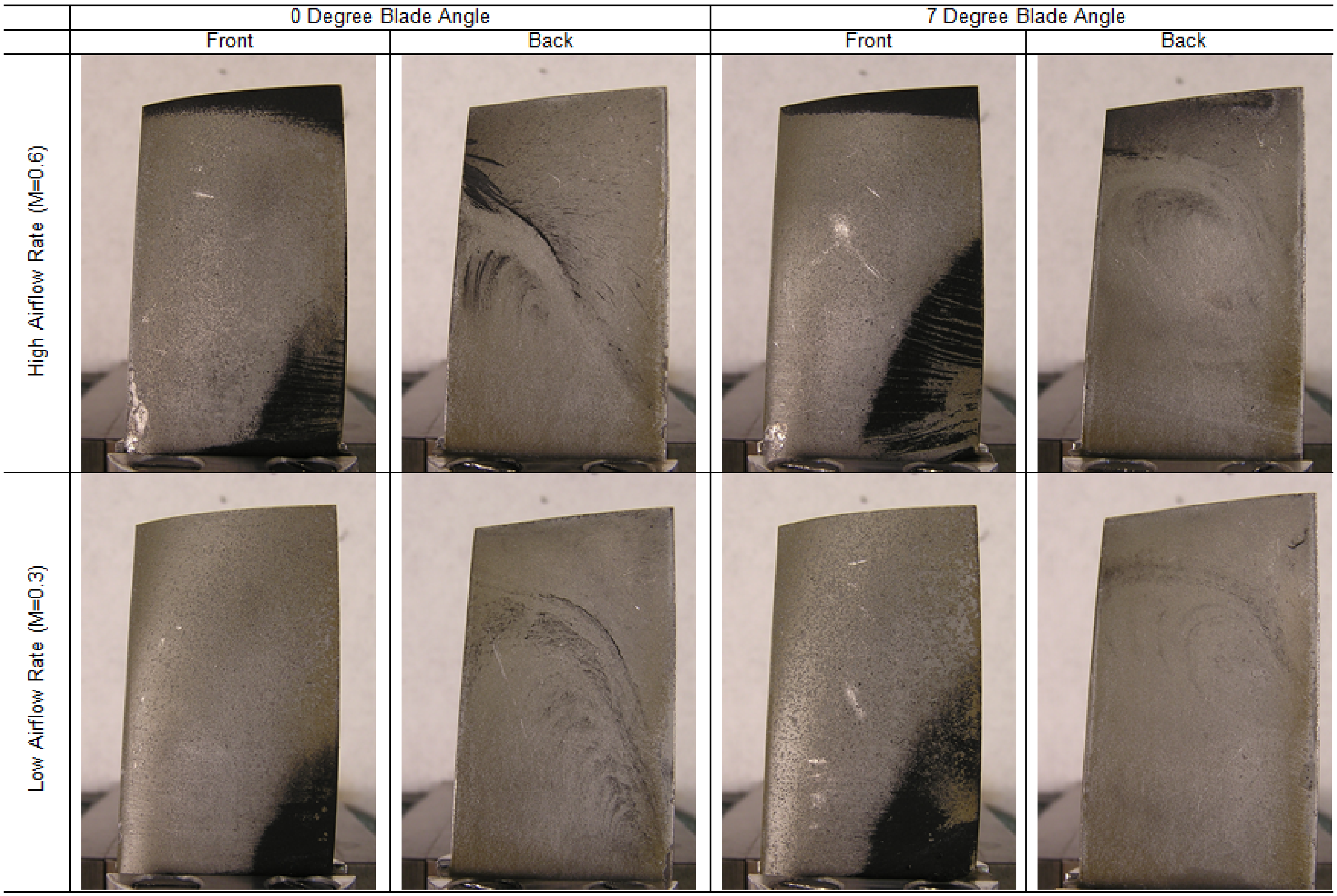
Blade Image Outlined for Processing



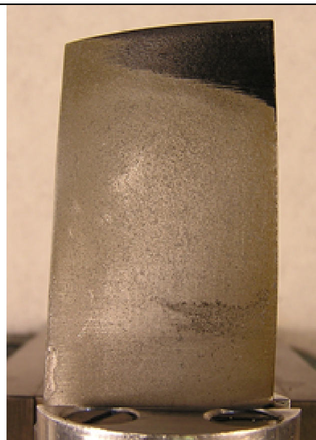
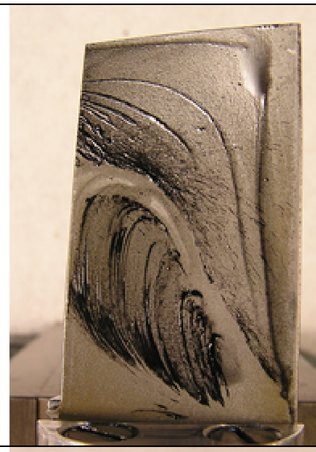
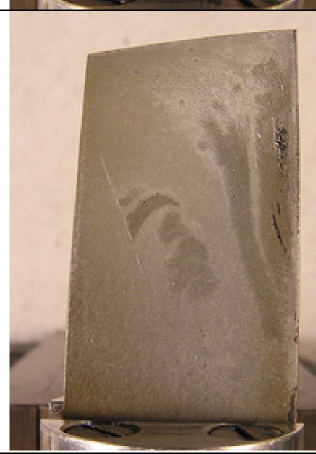
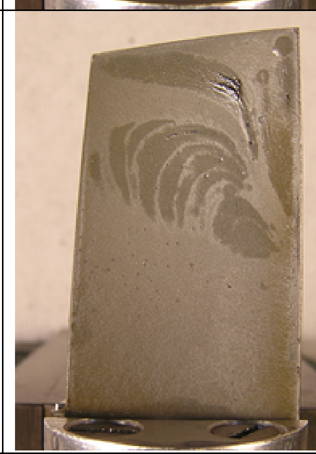
Area of Interest with Threshold Area Indicated

Image of “Particles” Found in Area of Interest (22.9% of Projected Blade Area for This Example)

Deionized Water Blade Cleaning Results



Commercial Detergent Blade Cleaning Results

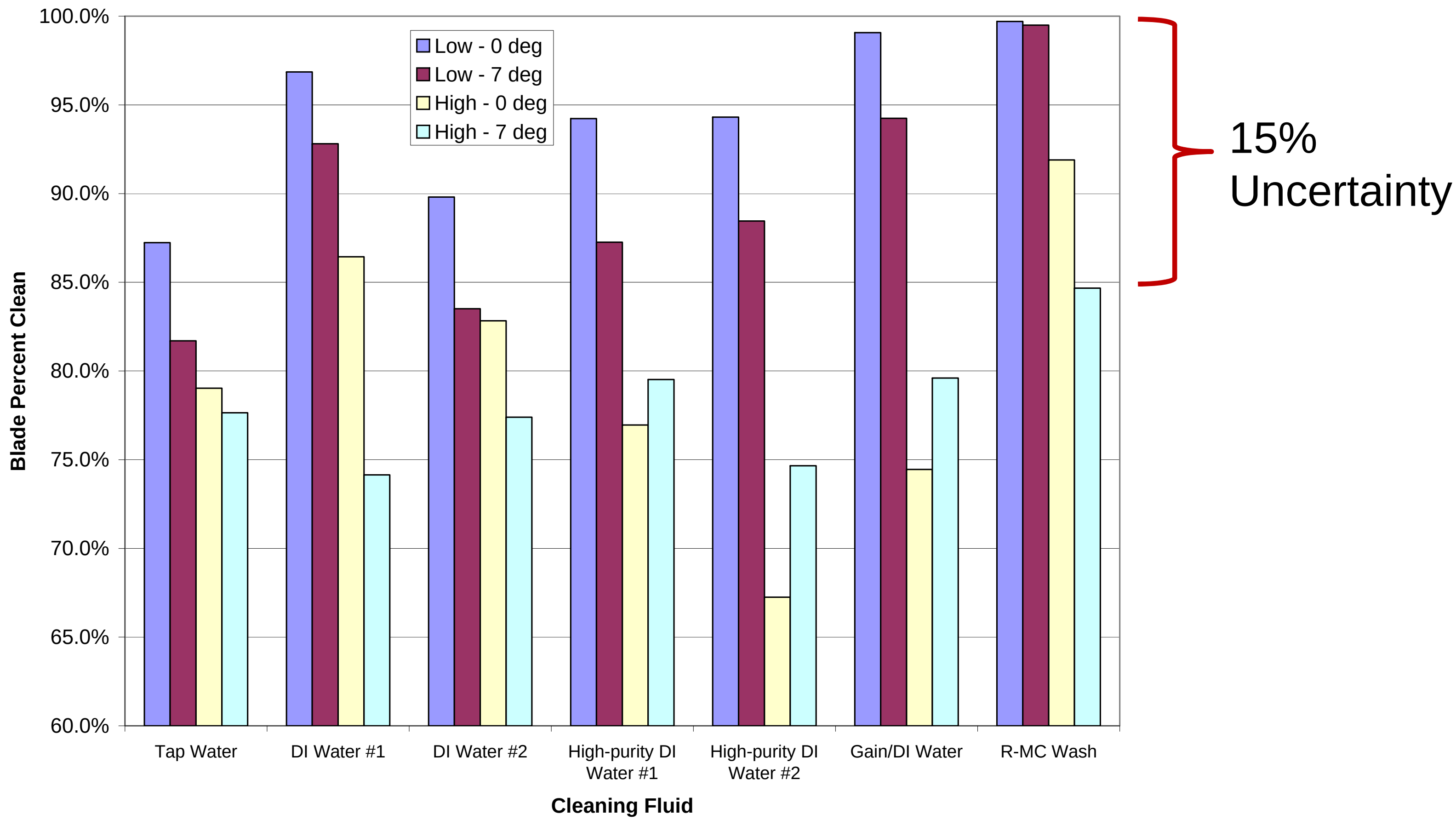
	0 Degree Blade Angle		7 Degree Blade Angle	
	Front	Back	Front	Back
High Airflow Rate (M=0.6)				
Low Airflow Rate (M=0.3)				

Blade Wash Tests: Percent Clean Summary

Fluid	Low Flow Air		High Flow Air	
	0 deg	7 deg	0 deg	7 deg
Tap Water	87.2%	81.7%	79.0%	77.6%
DI Water #1	96.9%	92.8%	86.4%	74.1%
DI Water #2	89.8%	83.5%	82.8%	77.4%
High-purity DI Water #1	94.2%	87.3%	77.0%	79.5%
High-purity DI Water #2	94.3%	88.4%	67.2%	74.7%
Gain/ DI Water	99.1%	94.2%	74.4%	79.6%
Commercial Detergent Wash	99.7%	99.5%	91.9%	84.7%
Average	94.5%	89.6%	79.8%	78.2%
Std Deviation	5%	7%	10%	5%

Measurement uncertainty – confirmed by repeatability – was about 15%

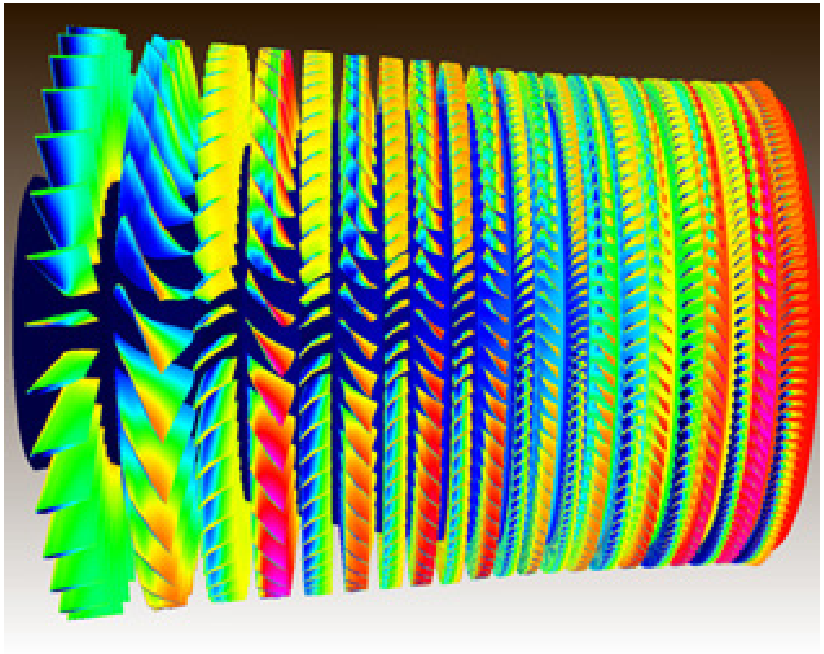
Graphical Summary of Blade Cleaning Results



Only small differences of blade cleaning effectiveness

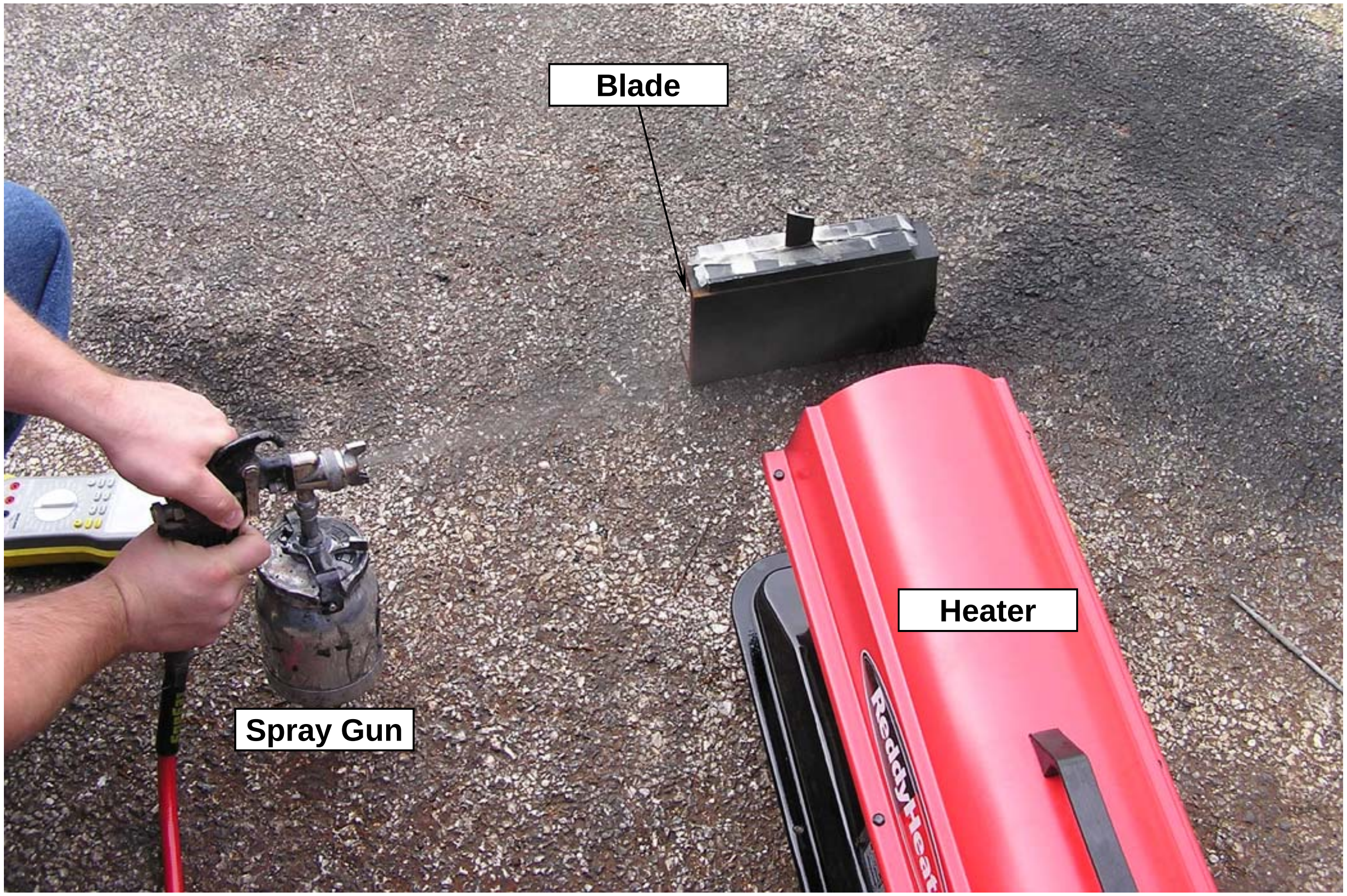
Dirt Redeposit Tests

- Spray Gun
- Wind-tunnel



- **Will dirt be removed during online cleaning redeposit once the cleaning liquid has been evaporated?**
- **Do any liquids reduce the redeposit of dirt in the online washing process?**

Dirt Redeposit Test (Spray Gun)



High Temperature Air Spray Tests

Redeposit Tests Results Spray Gun

Blade Sprayed with Dirt/Tap Water Mixture in Heated Air Stream

Blade Sprayed with Dirt/High-Purity Deionized Water Mixture in Heated Air Stream

Blade Sprayed with Dirt/Commercial Detergent Mixture in Heated Air Stream

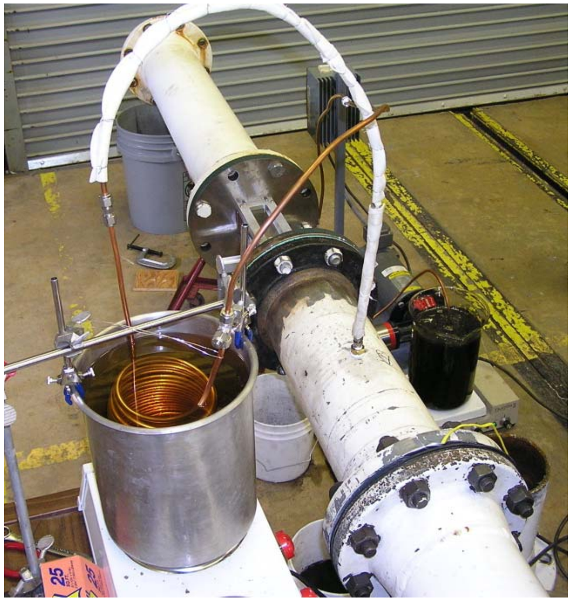
Blade Sprayed with Dirt/Gain/Deionized Water Mixture in Heated Air Stream

No Obvious Difference between Washing Fluids for Redeposits

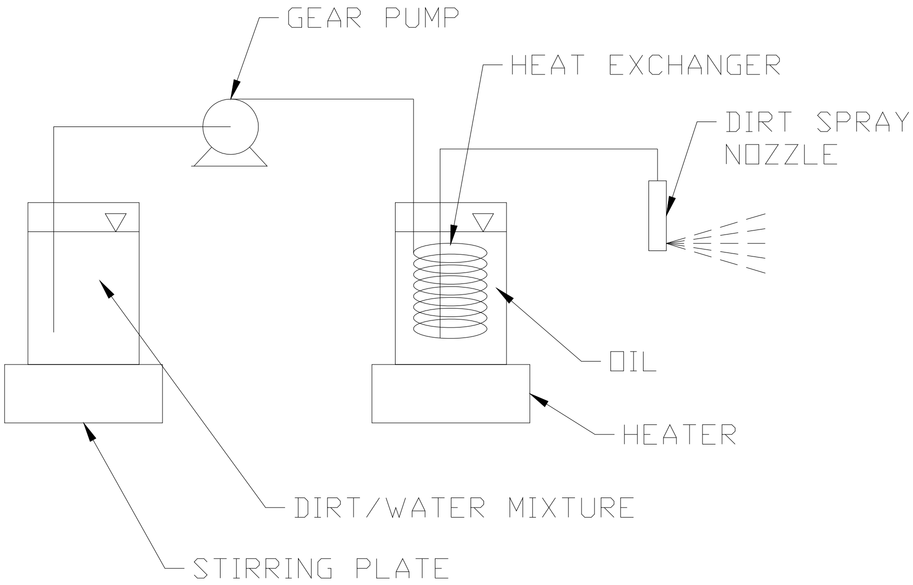
Flowing Deposit Tests (Wind-tunnel)

Test	Mach No. at Blade	Air Temperature (°F)
1	< 0.1	60-70
2	0.38	140 to 150

Flowing Deposit Test Conditions

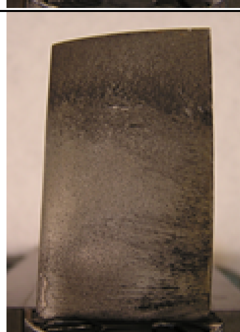
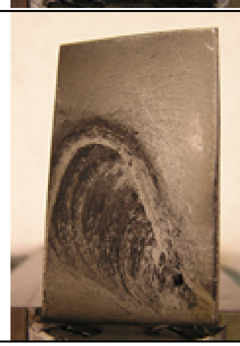


Heated Dirt/Water Injection Setup

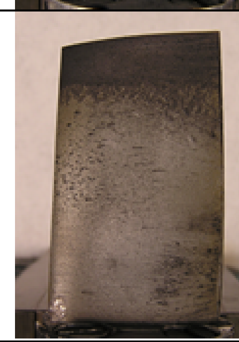
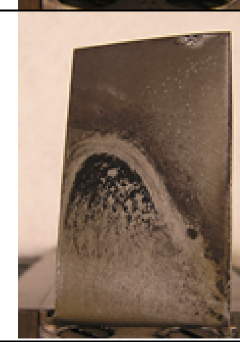


Schematic of Dirt Injection System

Redeposit Tests Wind-Tunnel

	Front	Back
M<0.1, Room Temperature		
M=0.38, T=140-150 °F		

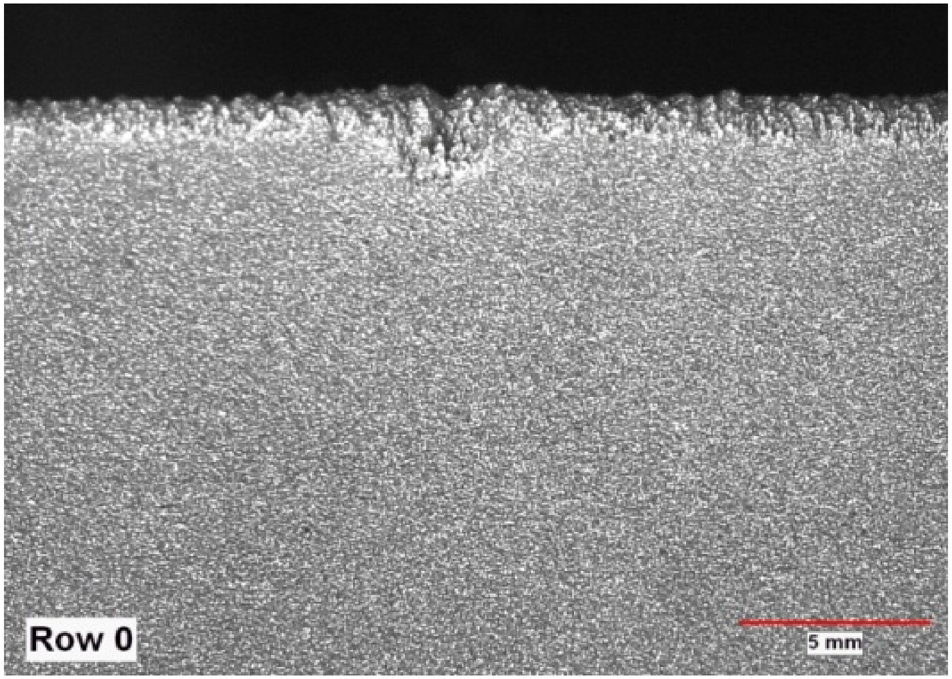
With Heated Dirt/DI Water Mixture

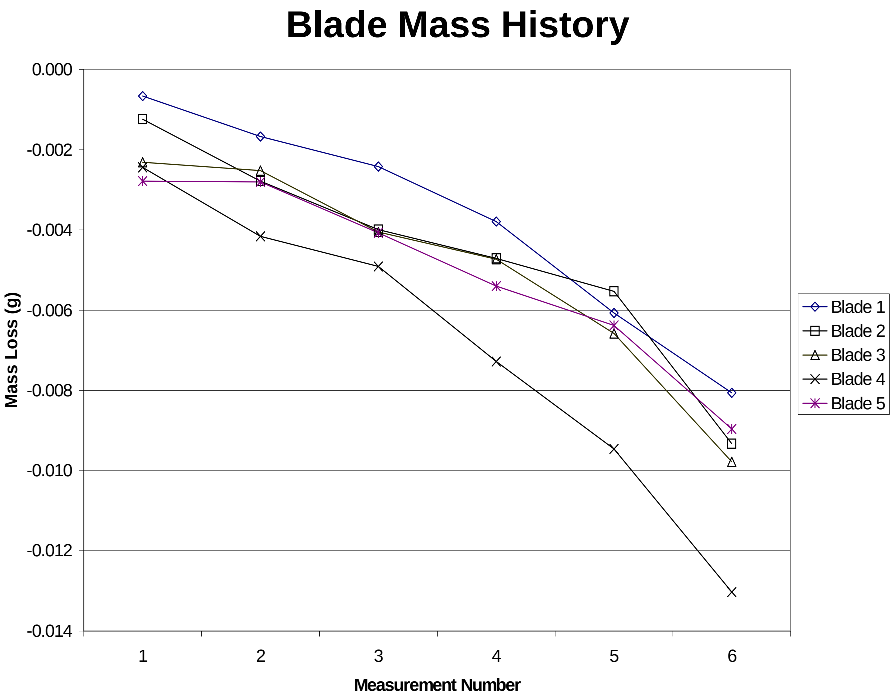
	Front	Back
M<0.1, Room Temperature		
M=0.38, T=140-150 °F		

With Heated Dirt/High-Purity DI Water Mixture

No Obvious Difference between Washing Fluids for Redeposits

Blade Erosion Tests





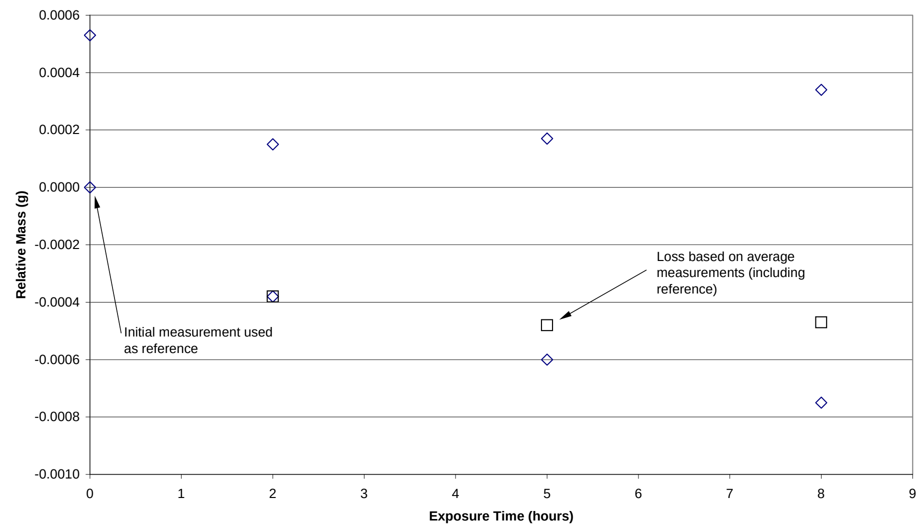
Will online washing cause noticeable blade erosion?

Wind-Tunnel Erosion Test

- 8 hour test run with two blades
- Mach 0.6
- Full water wash spray
- Measure weight of blades every hour

Blade Mass Measurements During Erosion Test

Time (hours)	Sample 1 (g)	Sample 2 (g)
0	25.00889	25.00942
2	25.00851	25.00904
5	25.00829	25.00906
8	25.00814	25.00923



Blade Mass Loss Results

Only 0.00047g weight loss over 8 hours of water washing. If washing is properly performed and only for 10 minutes per day, online water wash is a negligible cause for erosion.

Summary & Conclusions (1 of 3)

- Spraying cleaning fluid into a flowing air stream is a viable means of cleaning a compressor blade. Each of the fluids was able to clean the test blade at both low and high air velocities and at different blade incident angles. However, for all tested cleaning cases, there was always an area of the blade where some fouling deposits remained.
- The blade cleaning is primarily a mechanical (droplet impact) function and does not depend on the fluid used for cleaning. Test results show that most of the cleaning occurs shortly after the cleaning fluid is introduced into the flow stream. The type of fluid used did not have a significant impact on the cleaning effectiveness.

Summary & Conclusions (2 of 3)

- Dirt removed from the blades will redeposit in downstream stages as the cleaning fluid is evaporated. Redeposit occurred in flow recirculation zones during the cleaning tests, and heated flow tests demonstrated dirt deposit in the presence of a cleaning fluid. The type of fluid used for cleaning has no effect on the redeposit characteristics of the dirt.
- Blade erosion was not found to be a significant issue for the short durations that online water-washing is performed. However, uncontrolled water-washing (or overspray) for extended periods of time does result in measureable leading and trailing edge blade erosions.
- The results suggest that it may be beneficial to the cleaning process to slow the compressor speed or vary the cleaning fluids spray rate while the online wash is being performed.

Summary & Conclusions (3 of 3)

- Does online cleaning work? *Yes, wind tunnel blade test results indicated up to 95% removal of blade fouling is possible.*
- Is there any difference between any of the online cleaning liquids? No, there was no clear evidence that any of the liquids or detergent mixes improved the overall blade washing efficiency.
- Will dirt be removed during online cleaning redeposit once the cleaning liquid has been evaporated? Yes, redeposit tests showed that a significant fraction of the dirt will redeposit on downstream blades. The actual quantity of the redeposit depends strongly on the local flow field and the type of particles that are being carried in the freestream.
- Do any liquids reduce the redeposit of dirt in the online washing process? No, testing showed that redeposit occurred with all liquids tested, and there was no clear evidence that any mixtures or detergents reduced particle redeposit.

Thanks!
Any Questions?

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The 2nd Law of Thermodynamics Does Not Violate the 1st Law!