DEVELOPMENT OF ADVANCED SEALS FOR INDUSTRIAL TURBINE APPLICATIONS

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A critical area being addressed to improve industrial turbine performance is reducing the parasitic leakage flows through the various static and dynamic seals. Implementation of advanced seals into General Electric (GE) industrial turbines has progressed well over the last few years with significant operating performance gains achieved. Advanced static seals have been placed in gas turbine hot gas-path junctions and steam turbine packing ring segment end gaps. Brush seals have significantly decreased labyrinth seal leakages in gas turbine compressors and turbine interstages, steam turbine interstage and end packings, industrial compressor shaft seals, and generator seals. Abradable seals are being developed for blade-tip locations in various turbine locations. This presentation summarizes the status of advanced seal development for industrial turbines at GE.

Corporate Research & Development

Development of Advanced Seals for Industrial Turbine Applications

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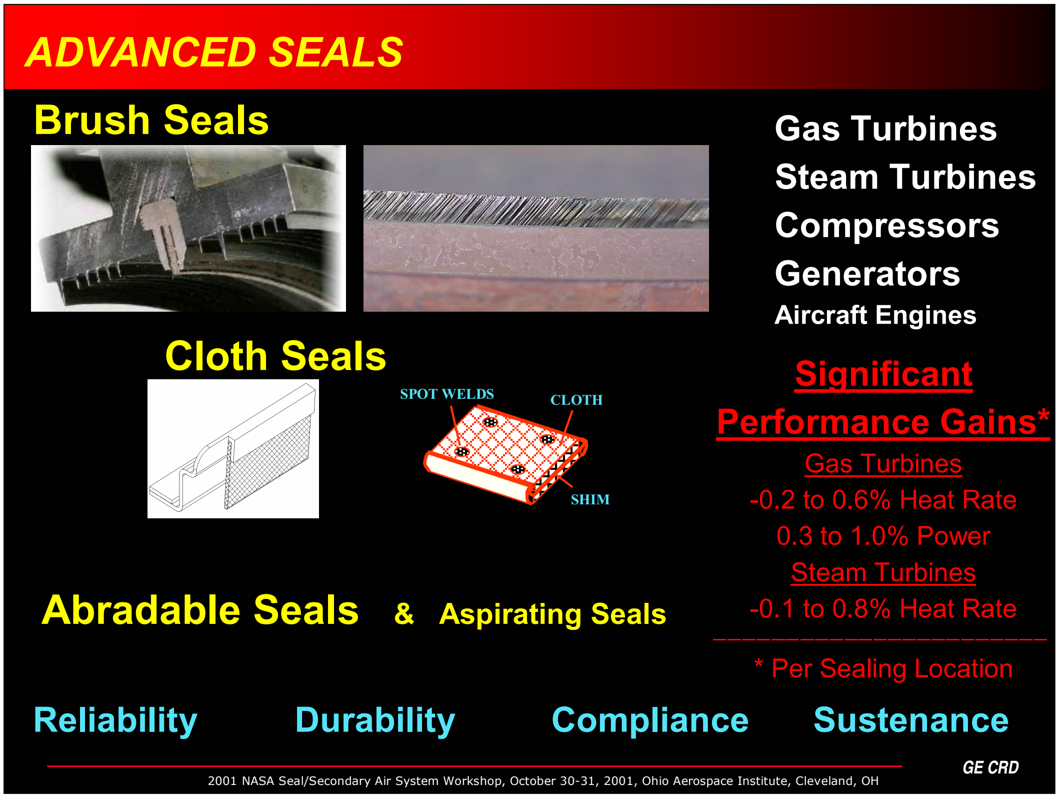
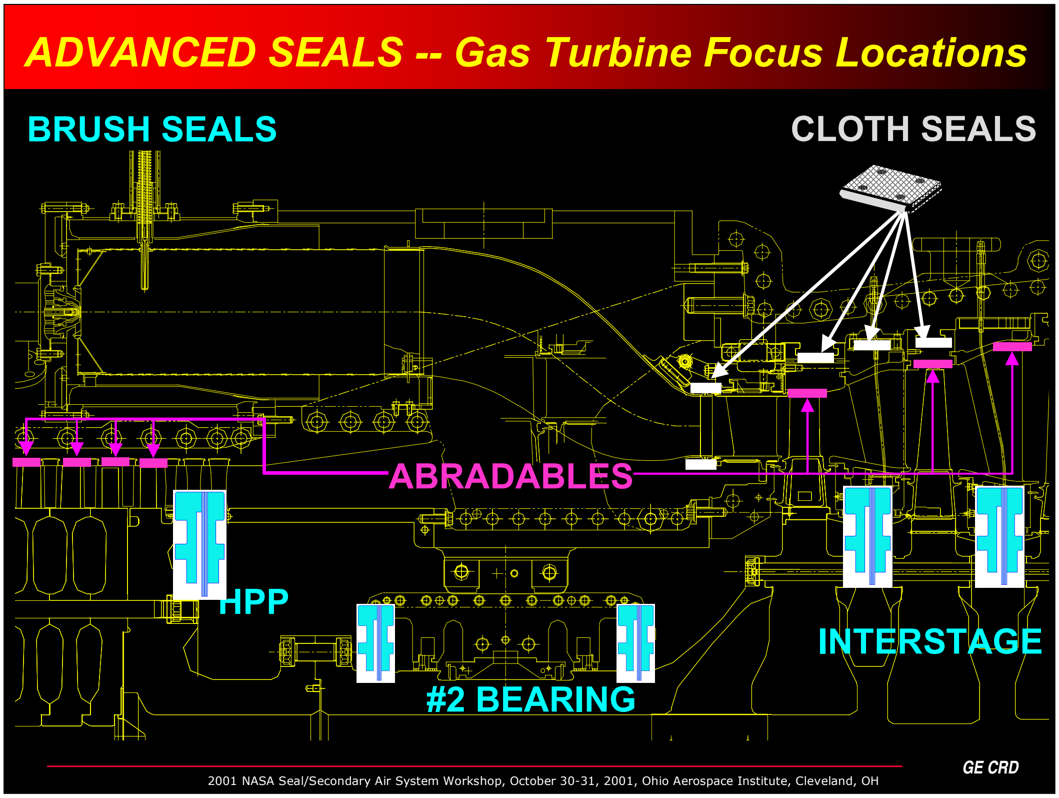
GE CRD

Improved sealing has been under development for several years for GE industrial turbine applications. The work summarized in this presentation is being carried out at GE's Corporate Research and Development center in cooperation with GE Power Systems customers. A team of over a dozen individuals at CRD focus on developing advanced seals for several turbine locations.

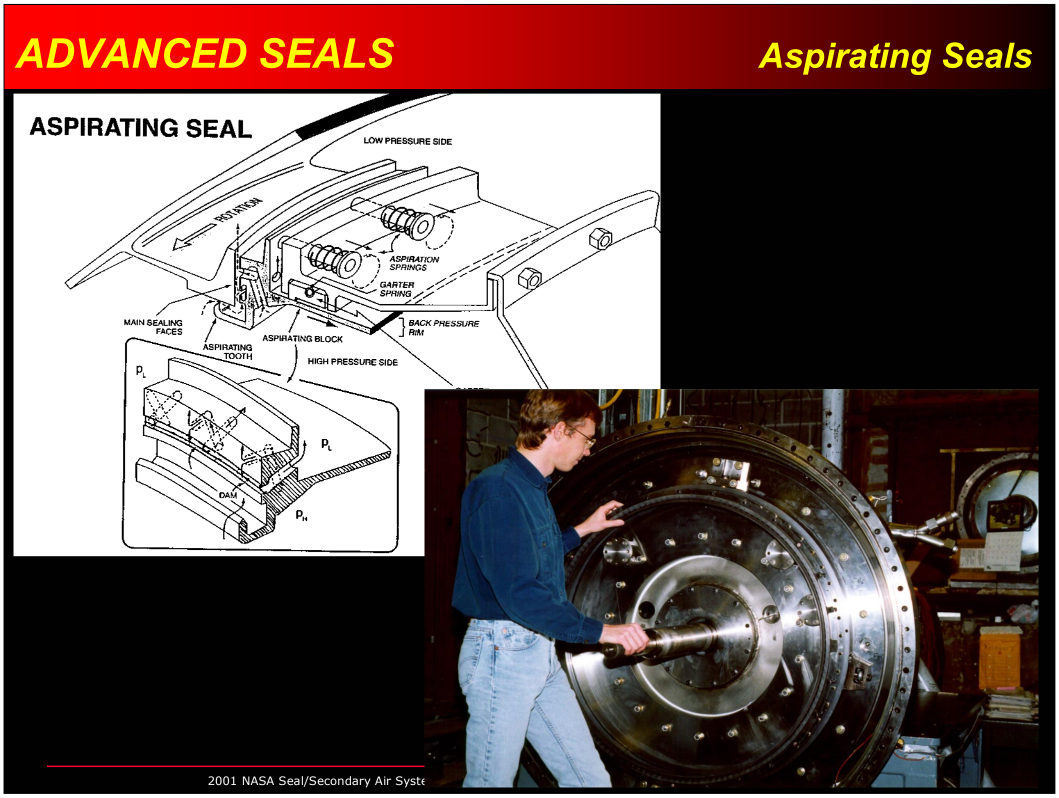
This presentation will include discussion of the development approach for seals, analysis methods, test facilities, and brief descriptions of development for the various seal types.



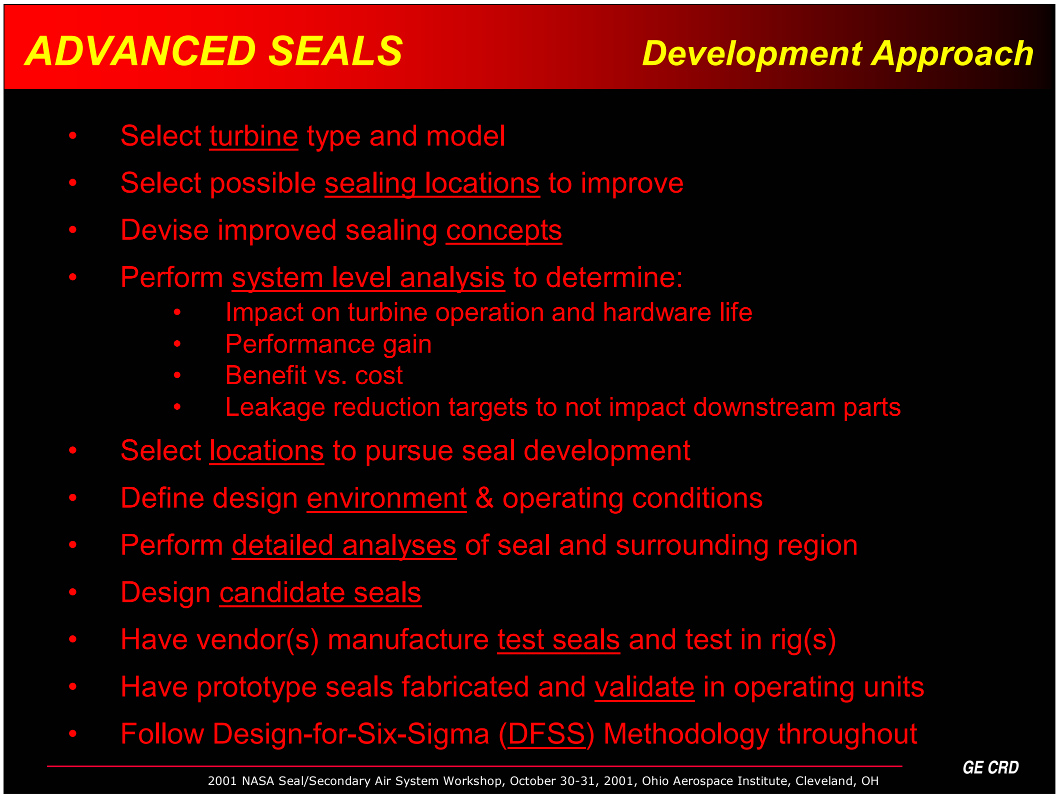
Improved sealing in industrial gas and steam turbines reduces parasitic leakages and thus gives better control of the the air system. This results in significant improved performance in both heat rate (efficiency) and power output. Applications for improved sealing include gas turbines, steam turbines, aero engines, industrial compressors, and generators. Several types of static and dynamic seals have been developed as shown in this chart.



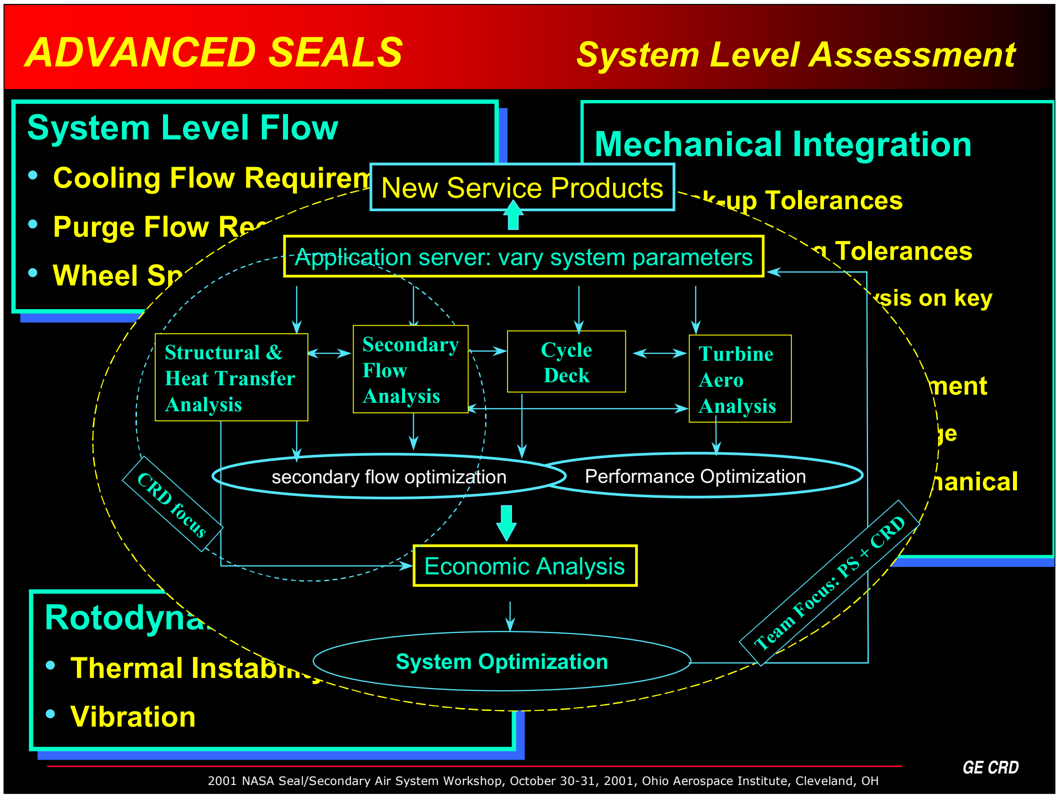
This chart shows representative sealing areas that have been addressed in industrial gas turbines. **Static cloth seals** have been implemented in gas turbine hot-gas path junctions and also steam turbine packing ring segment end gaps. **Brush seals** have been developed to significantly decrease labyrinth seal leakages in several locations. **Abradable seals** are being developed for several blade tip locations to reduce operating clearances.



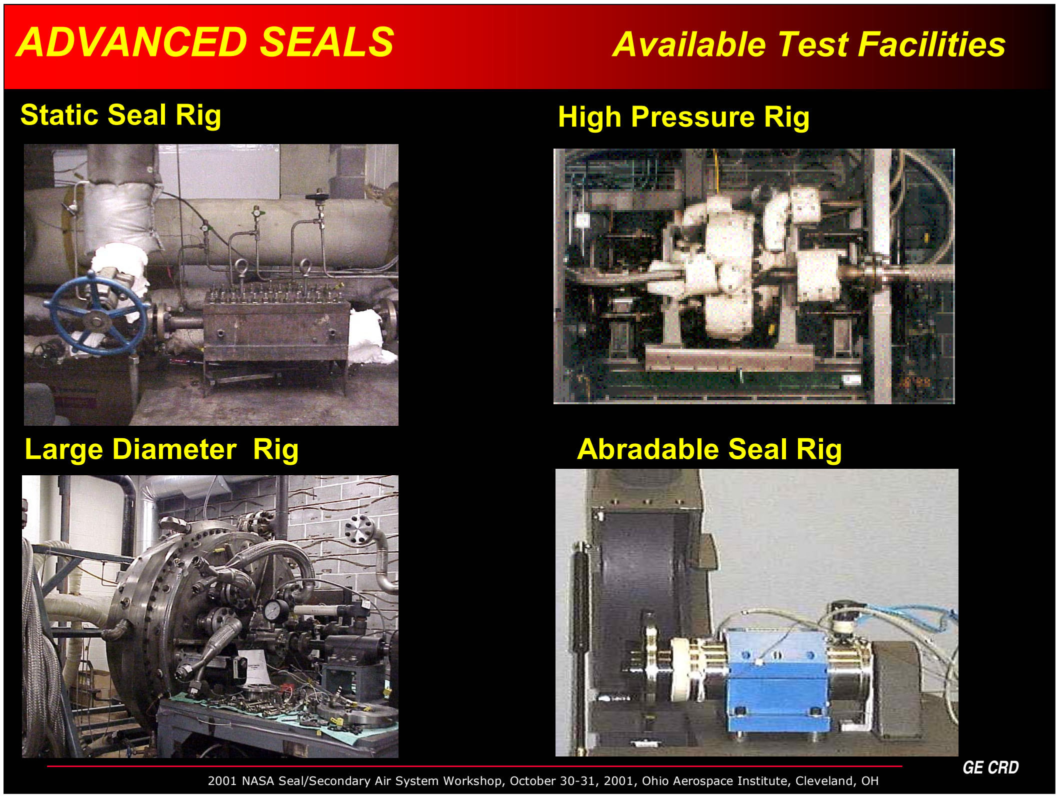
Aspirating seals have been developed in conjunction with GE Aircraft Engines and NASA as discussed in an earlier presentation today.



A systematic approach is followed in developing advanced seals based on the six-sigma methodology. A system level analysis is an important part of the effort to insure that all impacts of the improved sealing are considered and that the benefits are realistically assessed. The effort is carried through prototype engine testing to validate advanced seal designs.

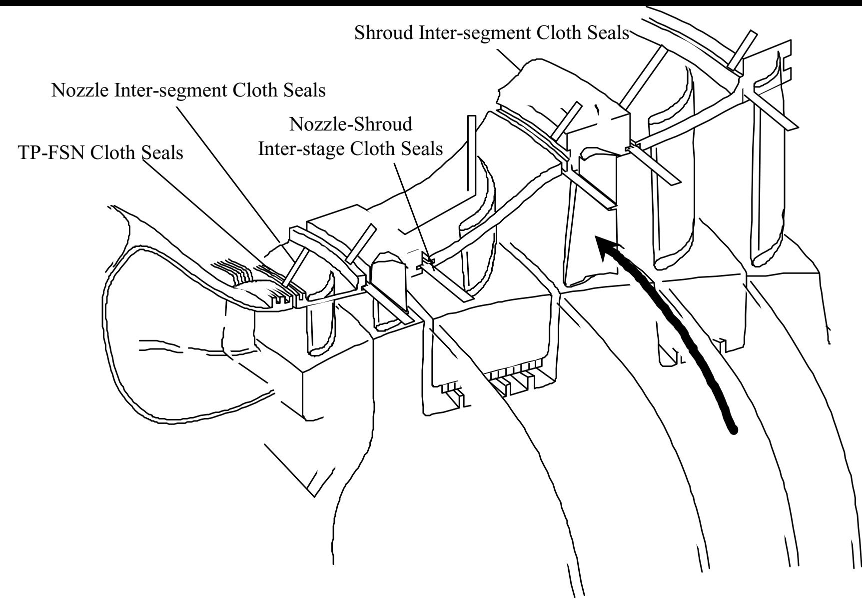


This chart gives an overview of the system level assessment for a gas turbine application. Often there is more leakage through the seals than necessary for component cooling and cavity purging of hot gas. These areas provide opportunities for improved sealing. But leakages can not be simply decreased to a minimum level possible by an advanced seal concept. The seals must be designed or the flow system modified to maintain required flow rates. Otherwise, decreased part lives or premature failures could occur.



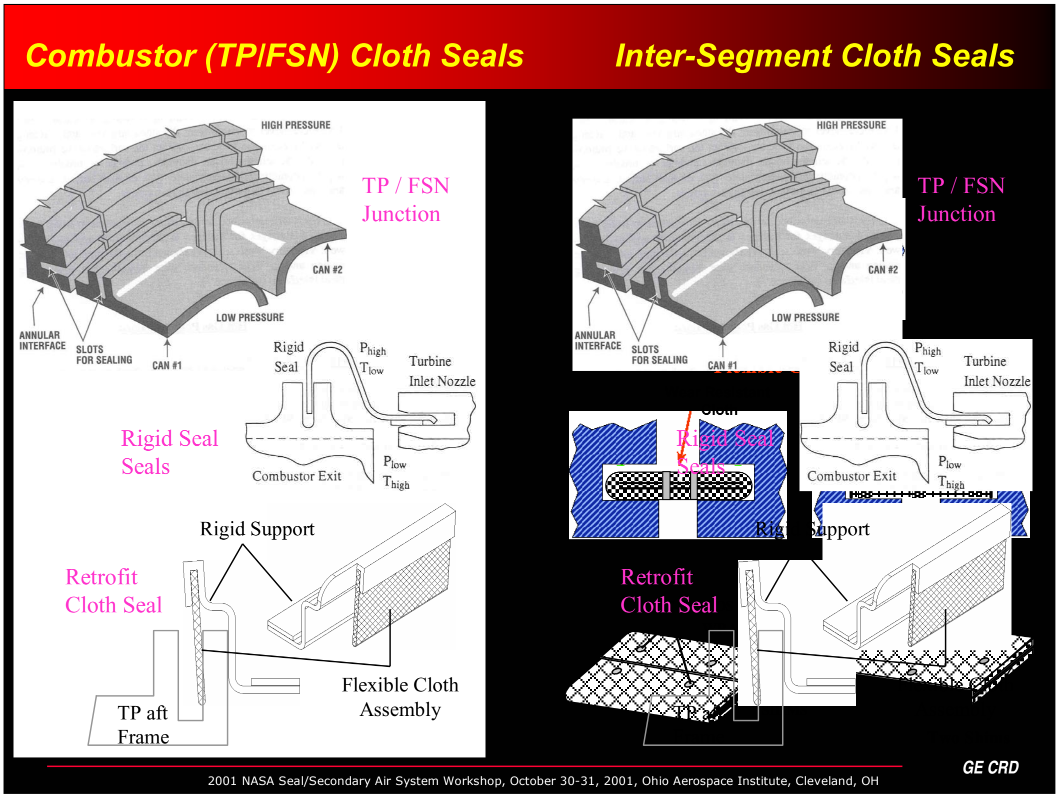
Several experimental rigs are used to quantify performance and characteristics of advanced seals. A **static rig** is employed for testing both static and dynamic seals. The rig is shaped like a shoebox. It is a high pressure, high temperature rig that gives comparative leakage performance data for various seals types, i.e., cloth, labyrinth, brush, honeycomb, C-, E-, etc. A **smaller rotary rig** is used for testing in air or steam of dynamic seals. This rig is used to test subscale seals at full turbine conditions. A **larger rotary rig** is used for testing full-scale dynamic seals at subscale conditions. This rig is the one that has been used to test aspirating face seals as well as brush seals. An **abradable rub rig** is a versatile rig for testing candidate abradable shroud materials rubbing against tipped and untipped blades. It can simulate turbine blade-tip rotation and incursion rates, and has heating capability to operate at turbine environment temperatures. Wear characteristics are determined from measured level of shroud and blade-tip wear.

CLOTH SEALS



Cloth Seal Applications in a Gas Turbine

Advanced static sealing applications in gas turbines include junctions between stationary components throughout the air system flow path. Typically, adjacent members have to sustain relative vibratory motion with minimal wear or loss of sealing. They must accommodate thermal growth mismatch and misalignment. Cloth seals have been applied in combustor transition pieces and turbine nozzles and shrouds.

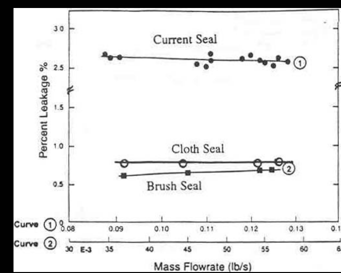


In gas turbine combustors (left side of this chart), cloth seals have been applied to seal the gaps between the can transition pieces (TP) and the first stage nozzles (FSN). Combustion dynamics and excessive thermal misalignments make combustor sealing very challenging. A typical application includes two TP's and FSN segments. Large axial offsets and relative skew/misalignments between neighboring TP's are common. The FSN segments experience relative misalignments causing seals to stick in the FSN slots. Jamming of the seal on the FSN side results in heavy wear. Cloth seals at this location have demonstrated reduced leakage and extended service lives.

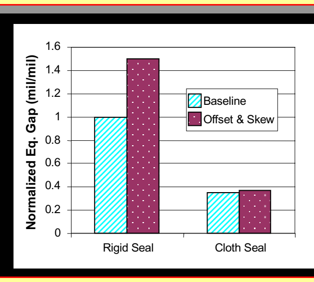
In gas turbine nozzle-shroud inter-segment seals (right side of this chart), cloth seals have been applied in many of the shroud and nozzle segments that require high temperature sealing. Typically, deep slots have been machined into mating parts and fairly stiff metal strips are used as seals. The relative motion between members can cause these seals to tip and toe, or jam against the slots. Lack of flexibility results in poor sealing and excessive wear. For smaller gap changes, conventional metal seals are adequate. Braided rope seals are used for demanding cases. For large gap changes, cloth seals have been replacing rigid metal seal strips. These seals have demonstrated improve turbine performance.

CLOTH SEALS

Status



• 35-60% leakage reduction for combustors



• 65-75% leakage reduction for Nozzles&Shrouds

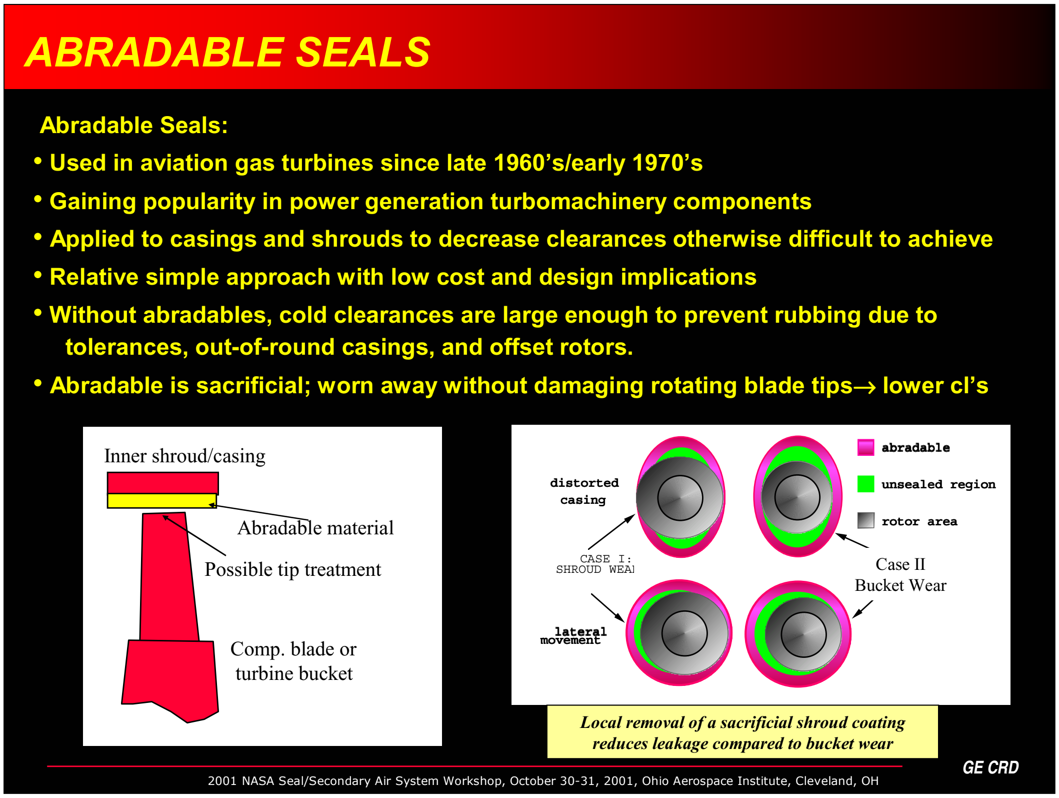
Business Impact

- HGP Cloth Seals commercialized for
  - E-Class: 3J, MS5N, MS5P, 6B, 7EA, 9E
  - F-Class: 7FA/FA+e, 9FA, 7FB
  - H-class
- Combustor Cloth Seals commercialized for
  - E-Class: 6B
  - F-Class: 6FA, 7FA/FA+e, 9FA

Benefits

- 2:1 Leakage Reduction
  - 35-60% leakage decrease in combustor; 65-75% decrease for nozzle-shroud-segments
  - 0.40% MW output increase in 9FA; 1.0% MW increase in 6B (S1S's only)
- 1-2 ppm NOx reduction for combustor applications
- 3:1 Improvement in life and inspection intervals
- 2:1 Reduction in combustor assembly time
- Improves hot-gas path temperature radial profile

This chart summarizes the current status of applying cloth seals to turbine inter-segments and between the combustors and the first stage nozzles. The performance gains and extended life of cloth seals are significant.



Abradable seals offer significant performance gains for turbines by decreasing the operating clearances of the compressor and turbine blade tips. Abradable seal materials are applied to the casings of gas or steam turbines. These seals are worn-in by the rotating blade during service with little wear of the blade tips. The seals can reduce operating clearances by allowing tighter cold-build clearances without fear of damaging blade tips by tip/shroud closures during turbine transients and at steady state. They also minimize the effect of casing out-of-roundness and rotor misalignment.

ABRADABLE SEALS

Materials

Generic Thermal Spray Abradables

Low Temperature (up to 400 ºC)

- Polymer
- Pure Aluminum
- Al-Si
- Al-Si + Polyester/Polyimide/Graphite/ hBN

Mid-Range (up to 750 ºC)

- Al-Bronze + Polyester
- Ni + Graphite
- NiCrAl + Bentonite Clay
- NiCrFeBnAl
- CoNiCrAIY + hBN + Polyester

High Temperature (750 to 1150 º C)

- Porous Super Alloys (require blade tipping)
- Ceramic (require Blade tipping)

Generic Fiber Metal Abradables

- Hastelloy (Tensile Strength 6.9 - 12 GPa)
- Haynes (Tensile Strength 10 - 13 GPa)
- FeCrAIY (Tensile Strength 9 - 19 GPa)

Typical Honeycomb* Seals

- Austenitic steel (e.g. type 321)
- Ni -Based Supper Alloys
- Mild steel
- Oxide Dispersion Strengthen alloys (e.g. MCrAIY, FeCrAly)
- Most other weldable ductile materials

* Typical Cell sizes: 0.80 - 4.75 mm
Typical Thickness: 0.025 - 0.130 mm

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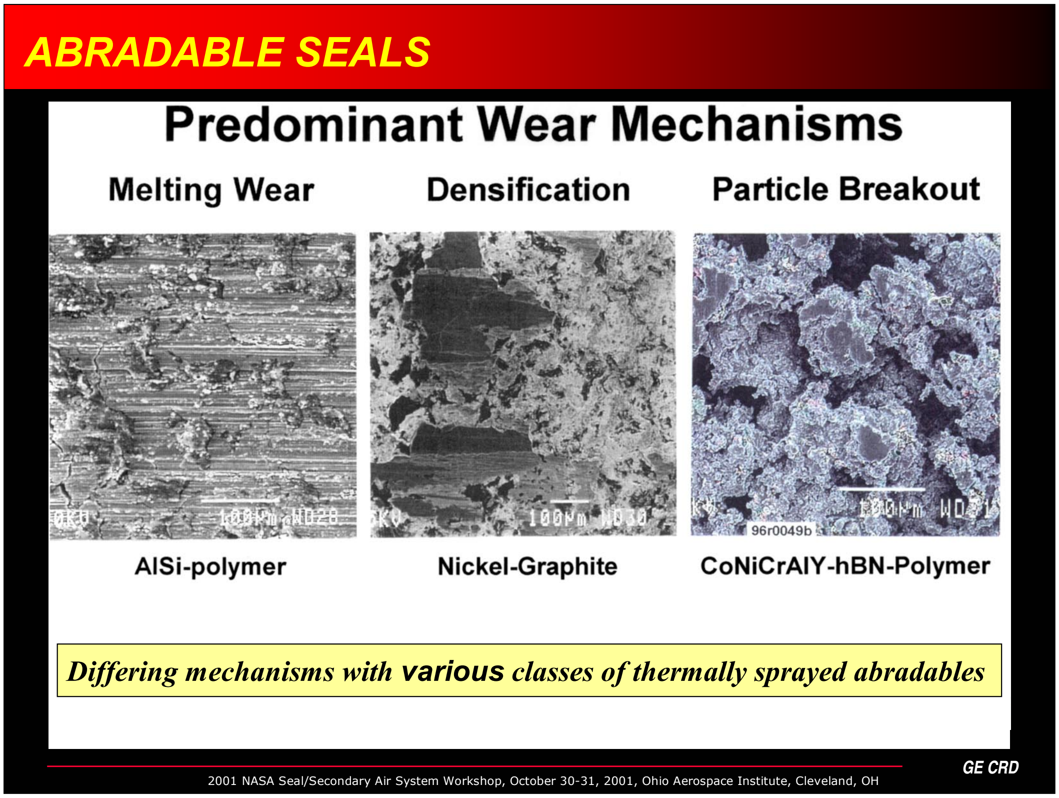
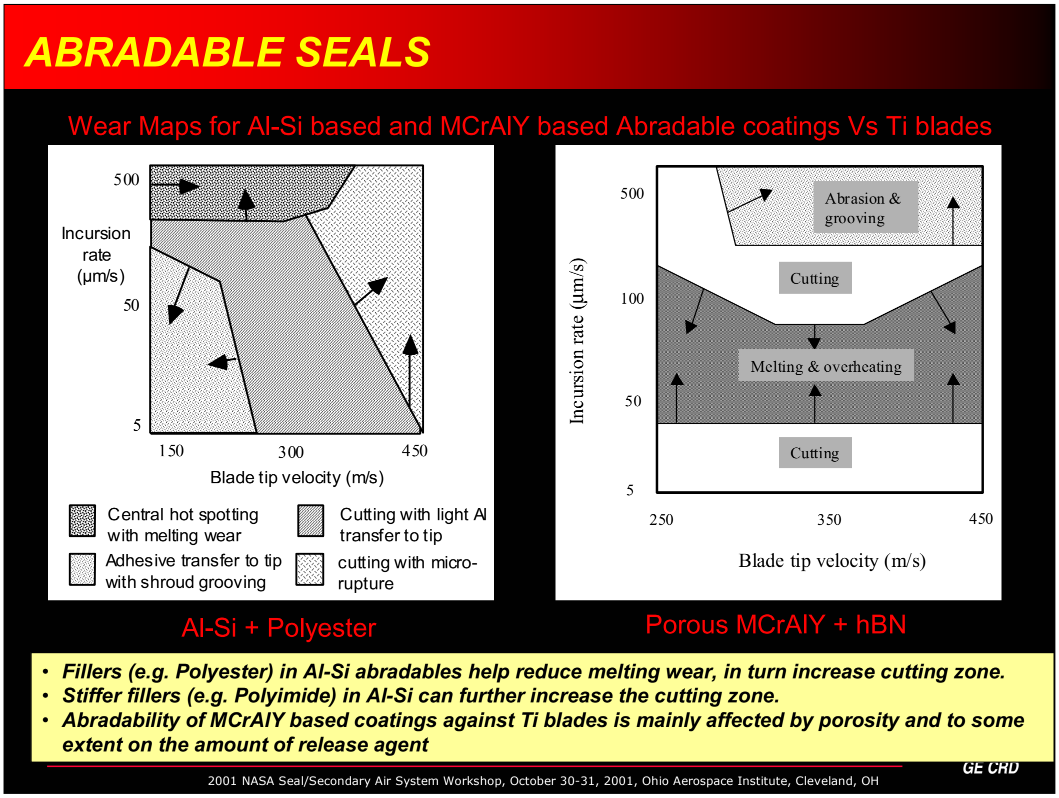
GE CRD

Abradable seal development is materials centered. These type materials can be classified into three categories according to their temperature capability. They can also be classified by how they are applied, i.e., (1) castings for polymer based abradables, (2) brazing or diffusion bonding for fibermetal (discussed in a presentation later today) and honeycomb structures, and (3) thermal spray coatings for a large range of powdered composite materials.

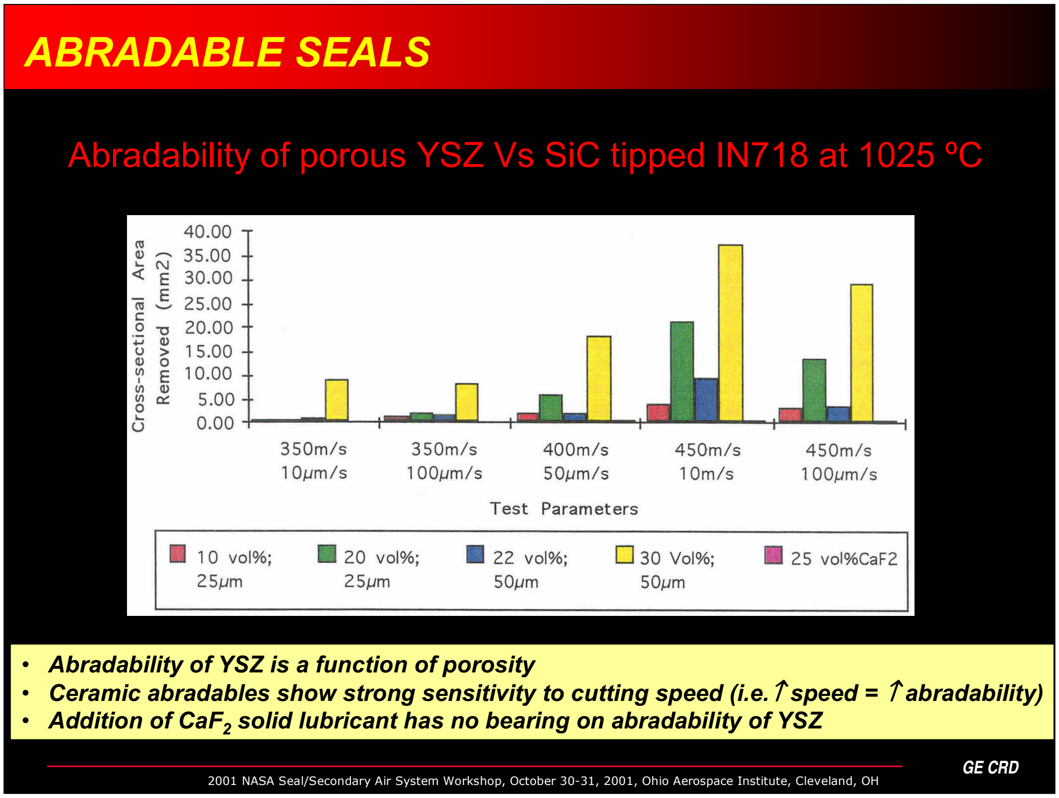


For thermally sprayed abradables, there are different wear mechanisms for different types of materials. The mechanism affects the depth of incursion without blade tip wear. For the third mechanism, a "lubricant" material, e.g., hBN, is often introduced into the coating to facilitate particle breakout.



This chart shows wear maps for low and mid-temperature abradable seals. For low temperature abradables (left side of chart), a second phase is often added. This phase usually consists of a polymeric material or release agent, i.e., solid lubricant. For Aluminum-Silicon based abradables, the second phase primarily promotes crack initiation. The type of second phase added determines the wear mechanism and abradability under various tribological conditions. The left-hand side of this chart shows a typical wear map for an Aluminum-Silicon-polyester coating for a 3 mm thick titanium blade at ambient temperature. The arrows indicate the movement of wear mechanism boundaries when a stiffer polymer than polyester is used as the second phase.

The right-hand side of this chart shows a wear map of a mid-temperature coating system abraded at 500 C (930 F) using titanium blades. This plot also shows the wear mechanism domains vs. blade-tip velocity and incursion rate. Again for this temperature range, additional phases are added to the base metal powder to make the material abradable. The arrows on the plot indicate the movement of the wear regime boundaries as the polyester level increases.

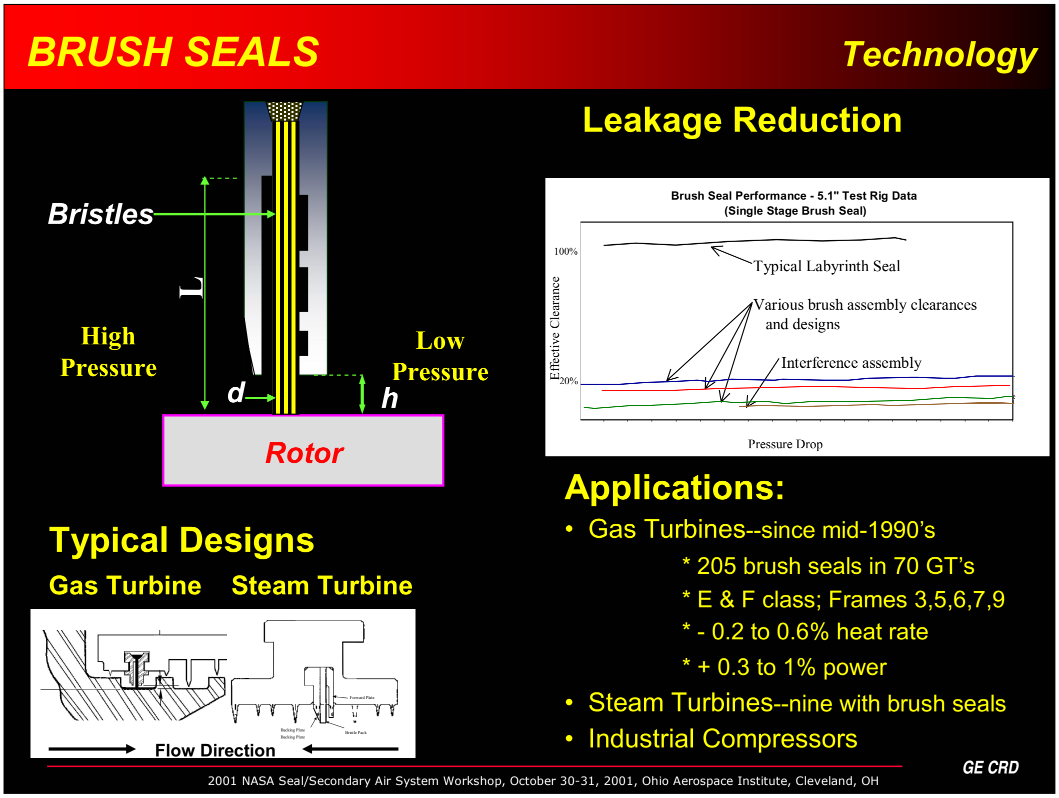


For temperatures above 760 C (1400 F), porous ceramics are generally used as the abradable material. The most widely used material is yttria-stabilized zirconia (YSZ). A fugitive polymeric phase is usually added to produce the desired level of porosity. To prevent blade tip wear, a cutting element is generally added on the blade tips, e.g., hard grits. Choosing the grits and processes to apply them has been investigated extensively and numerous patents issued. Most common grits are cBN, silicon carbide, aluminum oxide, and zirconium oxide. cBN is the best abrasive material against YSZ. But it has a relatively low oxidation temperature (850 C, 1560 F) so it only functions for a short time at elevated temperatures.

The ceramic coating microstructure and porosity are also important for abradability. The more porous the coating is, the higher its abradability but the lower its erosion resistance.

Thermally sprayed YSZ coatings display different tribological behavior compared to metallic abradables. Wear of ceramics is strongly influenced by blade-tip velocity with abradability improving with increasing velocity. Also, they tend to show poorer abradability at very low incursions rates (typical of power generation turbines), thus requiring blade tips.

The design considerations on this chart make the abradable system unique. The abradable seal must be design to fit the particular application. Thus, even though there are many off-the-shelf abradable seal materials, these materials usually have to be modified or redesigned to fit the particular design constraints.



Brush seals can significantly reduce leakage flows in rotating machinery vs. labyrinth seals. They have been under development by GE, other OEM's, seal vendors, Air Force, and NASA. GE's application of brush seals in their power generation turbines is summarized on this chart. Technology development continues to leverage aircraft engine applications. Typical applications put a brush seals in series with labyrinth seal teeth in current seal locations. This reduces the risk when applying a newer technology while providing a means of measuring brush seal performance and any long term deterioration.

BRUSH SEALS

Business Impact

HPP Brush Seals

Performance Improvement	
(Output/Heat Rate)	
HPP	
32G	+0.7%/-0.5%
32J	+0.7%/-0.5%
51P	+0.6%/-0.45%
61B	+1.0%/-0.5%
71E,EA	+1.0%/-0.5%
91E	+1.0%/-0.5%

#2 Bearing Brush

Performance Improvement	
(Output/Heat Rate)	
BRG2*	
71E	+0.3%/-0.2%
91E	+0.3%/-0.2%
HPP and BRG2**	
52C	+0.7%/-0.5%
52D	+0.9%/-0.6%
71B	+1.0%/-0.5%
91B	+1.0%/-0.5%

Brush Seals for Steam Turbine

Efficiency Benefit Compared to New Labyrinth Seals	
Large Steam Turbines (HP Section)	
End Packings	0.1-0.2% unit heat rate
Interstage Packing	0.5-1.2% HP section efficiency
	0.1-0.2% unit heat rate
Industrial Steam Turbines	
End Packings	0.4 - 0.8% efficiency
Interstage Packing	0.2 - 0.4% efficiency

Interstage Brush Seals

Performance Improvement	
(Output/Heat Rate)	
ISTG	
51N	+1.0%/-0.5%
51P	+1.0%/-0.5%
61B	+1.0%/-0.5%
71E,EA	+1.0%/-0.5%
91E	+1.0%/-0.5%

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GE CRD

These performance benefits of applying brush seals to GE turbines were taken from a recent company brochure. These gains are significant and the resulting financial benefits for turbine customers far exceed the cost of implementing brush seals into their machines.

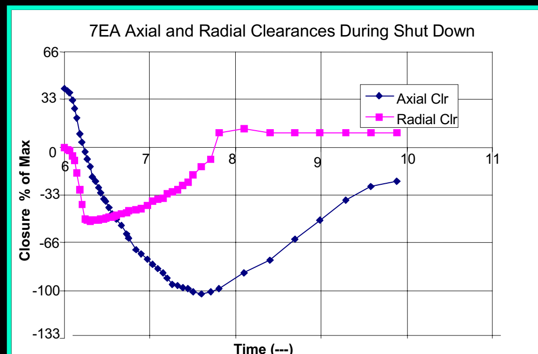
BRUSH SEALS Design Considerations 1 of 2

CTQ's & Constraints
- Performance & Life
- Cooling Flow Req.
- Retrofitability
- Space
- Other

Operating Conditions
- Pressure Differential
- Speed
- Temperature
- Radial Closures

Technology
- Advanced Design Features (High speed, High pressure & Temp)

Synergy
- Previous Experience
- Experience in other similar applications



GE CRD

This first of two charts listing brush seal design considerations shows the top level CTQ's and issues to consider. A system level analysis has previously been performed to define many of these considerations.

ADVANCED SEALS Design Considerations 2 of 2

Material

- Good Wear Couple
- Wear Resistance
- Creep Properties
- Oxidation Resistance
- Availability
- Cost

Preliminary Seal Design

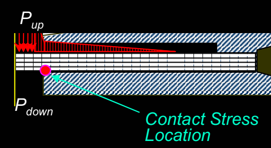
- Seal Fence Height
- Bristle Diameter
- Seal Density
- Cant Angle
- Seal Radial Free Height

Seal Stress & Deflection

- Back Plate Stress
- Bending Stress
- Contact Stress
- Axial Deflection

Pressure Distribution

- Linear
- Non-Linear

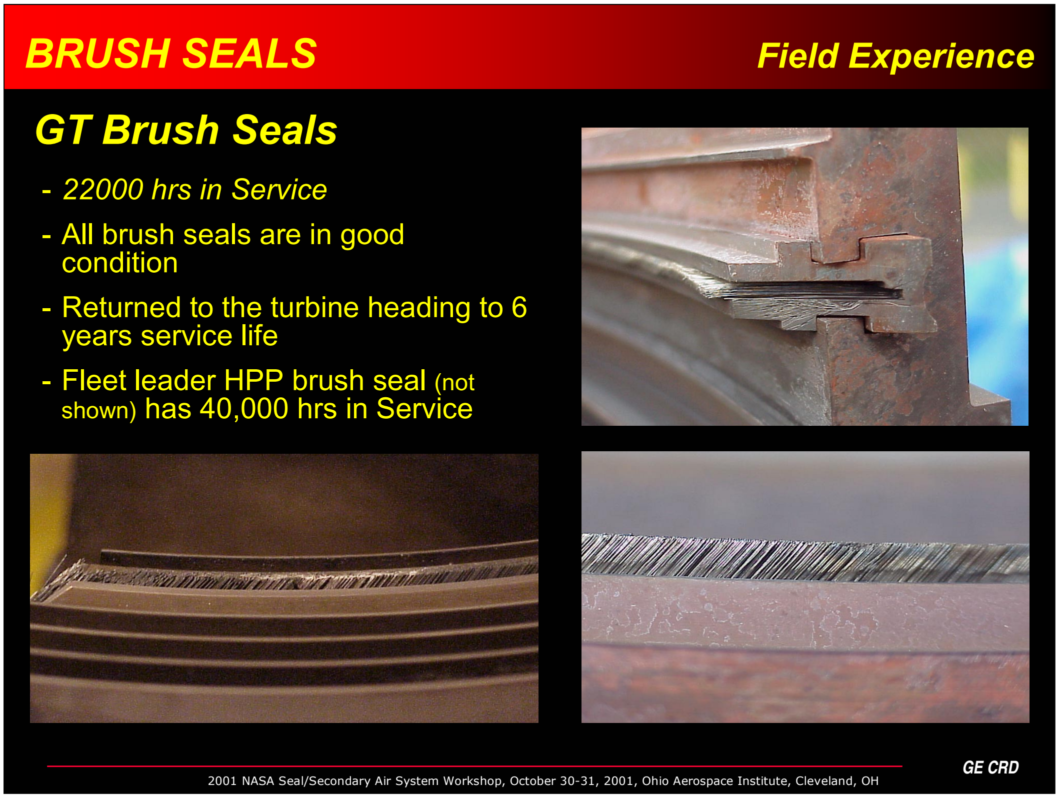


- Seal Stiffness/Tip Pressure
  - Design (free state)
  - Operating (under pressure)
- Seal Stability
  - Flow Induced
  - Rotor Induced
  - Transient & Steady State
- Bristle Deflection
- Heat Generation
- Tip Temperature
- Wear
- Bristle Natural Frequency
- HCF & LCF Analysis

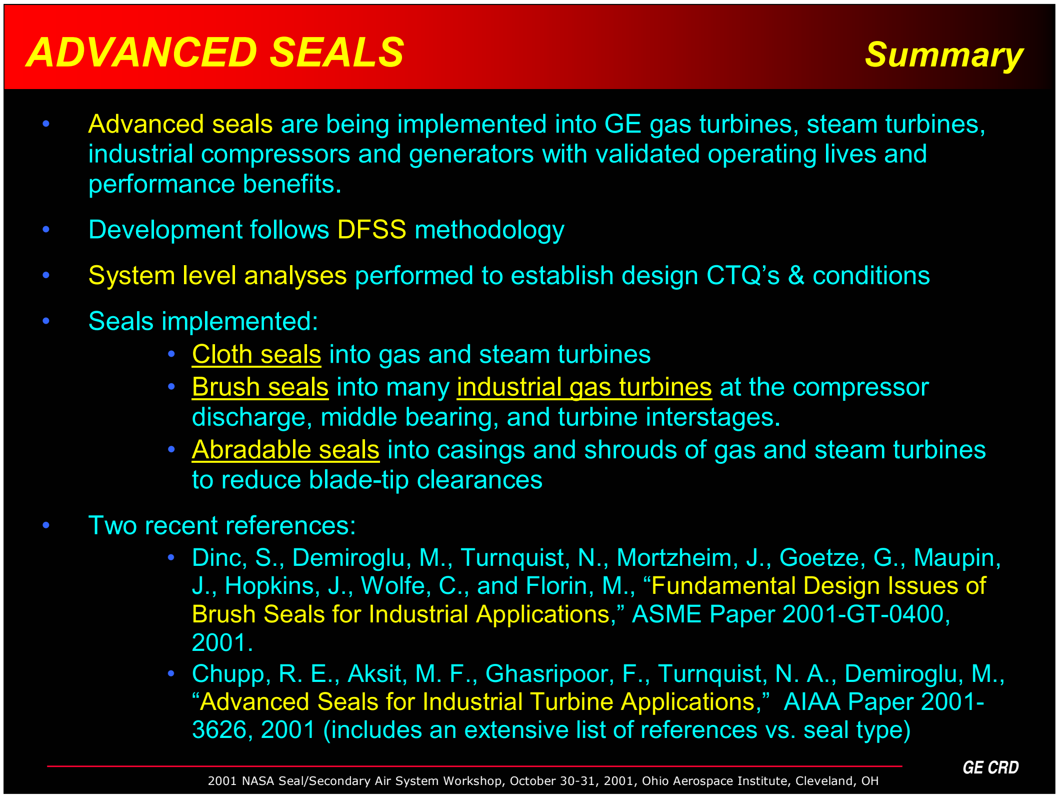
- Seal Leakage
- Blow Down / Hysteresis

GE CRD

This second chart gives a detailed list of the next level down design considerations. These are thoroughly addressed following company design practices. Detailed analyses and experimentally derived transfer functions are used in this process. Following this approach insures the brush seals are designed properly so that it meets the system requirements, the desired leakage reduction, and the desired operating life.



This chart gives a brief summary of field experience in applying brush seals to GE industrial gas turbines. The long life seal experience realized validates the seal design technology and practices in place.



In summary, advanced seals are well underway of being incorporated into GE industrial turbines. These include cloth seals, brush seals, and abradable seals. In the next part of this presentation, brush seals as applied to steam turbine will be discussed. More details of the application of advanced seals is given in two recent publications.