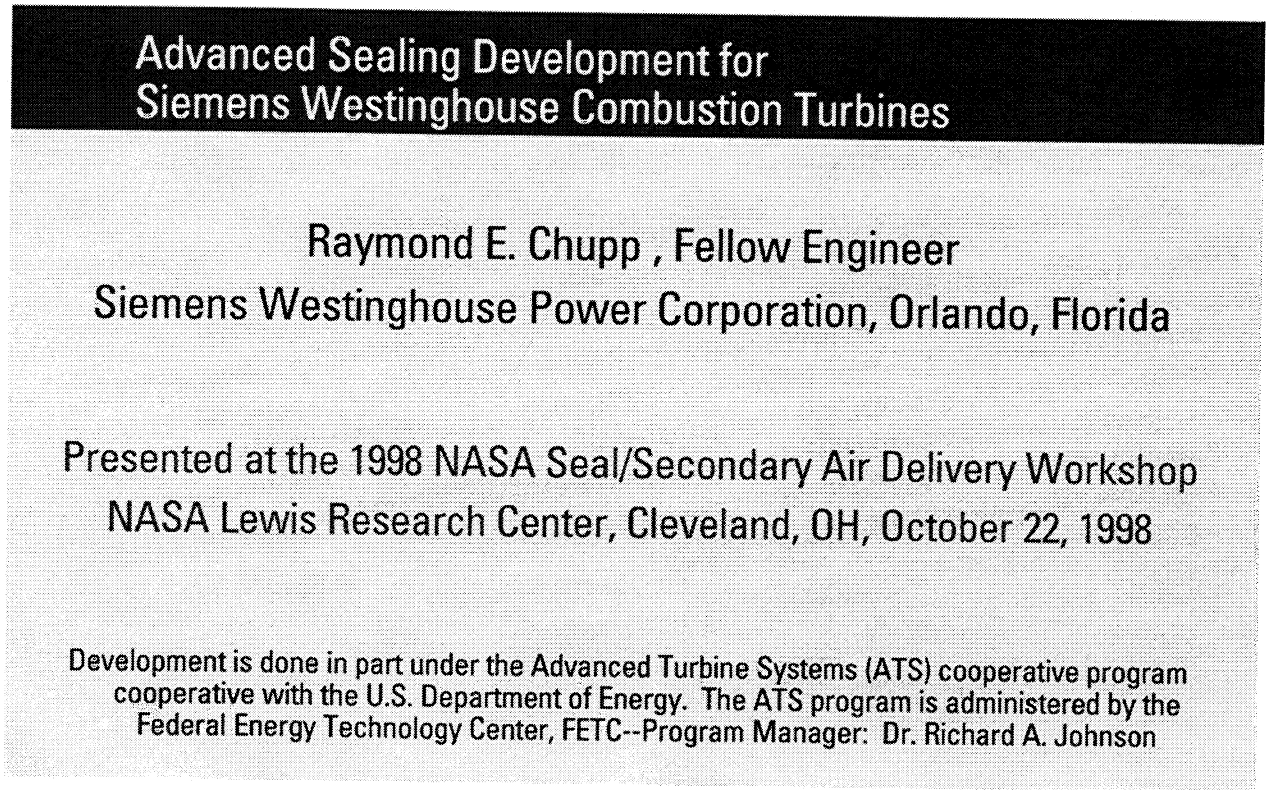
ADVANCED SEAL DEVELOPMENT FOR SIEMENS WESTINGHOUSE COMBUSTION TURBINES

Raymond E. Chupp
Siemens Westinghouse Power Corporation
Orlando, FL 32826-2399



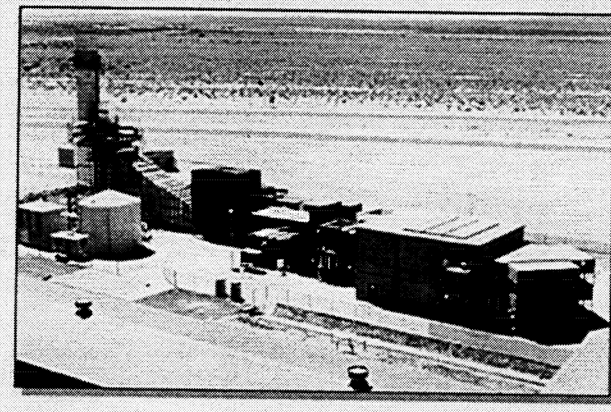
Siemens Westinghouse Power Corporation was formed from Siemens AG of Germany and Westinghouse Power Corporation in August of this year (1998).

ABSTRACT

Several efforts are in progress at Siemens Westinghouse to develop advanced sealing for large utility industrial gas turbine engines (combustion turbines). Much of this effort focuses on transitioning aero gas turbine technology to combustion turbines. Brush seals, film riding face and circumferential seals, and other dynamic and static sealing devices are replacing labyrinth and other seals. For combustion gas turbines, advanced sealing can significantly reduce leakage flows because of the enormous size of the components and the relatively constant operating conditions. Challenges include: extremely long operating lives; infrequent but large position excursions; difficulty in coating or treating larger components; plus maintenance, installation, and durability requirements. The development includes rig testing and engine validation of prototype designs. This effort is part of the Advance Turbine Systems (ATS) engine development being done under a cooperative agreement between Siemens Westinghouse and the US Department of Energy, Office of Fossil Energy.

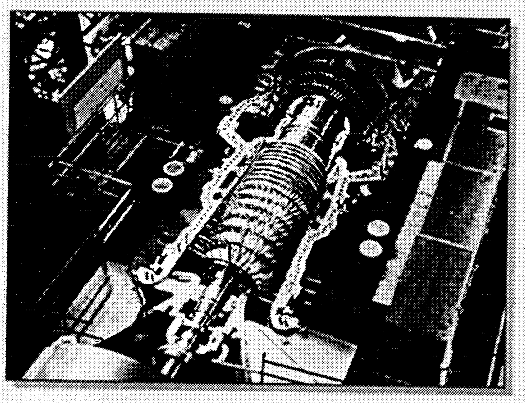
What is ATS? -- The Next Generation of Gas Turbine Technology

- Key to America's competitiveness in the global electrical market
- A university, utility, industry, government partnership. Supported by universities and vendors throughout US
- Lowest cost producer of electricity (10+% reduced electricity cost ==> >60% net plant eff.)
- Environmentally superior (< 10 ppm NOx emissions)
- Fuel-flexible design--natural gas + future use of coal or biomass fuels
- Reliability-availability-maintainability (RAM) maintained
- Commericialization near Y2K

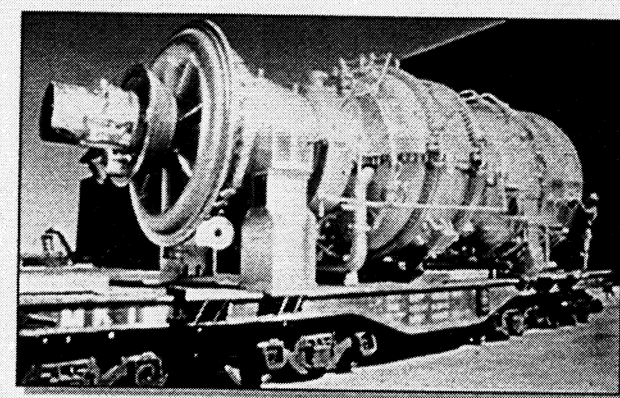


The Department of Energy's (DoE's) ATS program is a major driving force in the U.S. to improve industrial power plants. Over the last few years, large combustion turbines have evolved via. integrating advanced technology into their design. Overall plant efficiencies have increased from under 40% to over 60% in the ATS plant being developed. ATS objectives address efficiency, emissions, cost of electricity, fuels, RAM, and commercialization by near Y2K. The ATS program is a catalyst for the power generation industry to develop the next generation of gas turbine technology.

Large Combustion Turbines

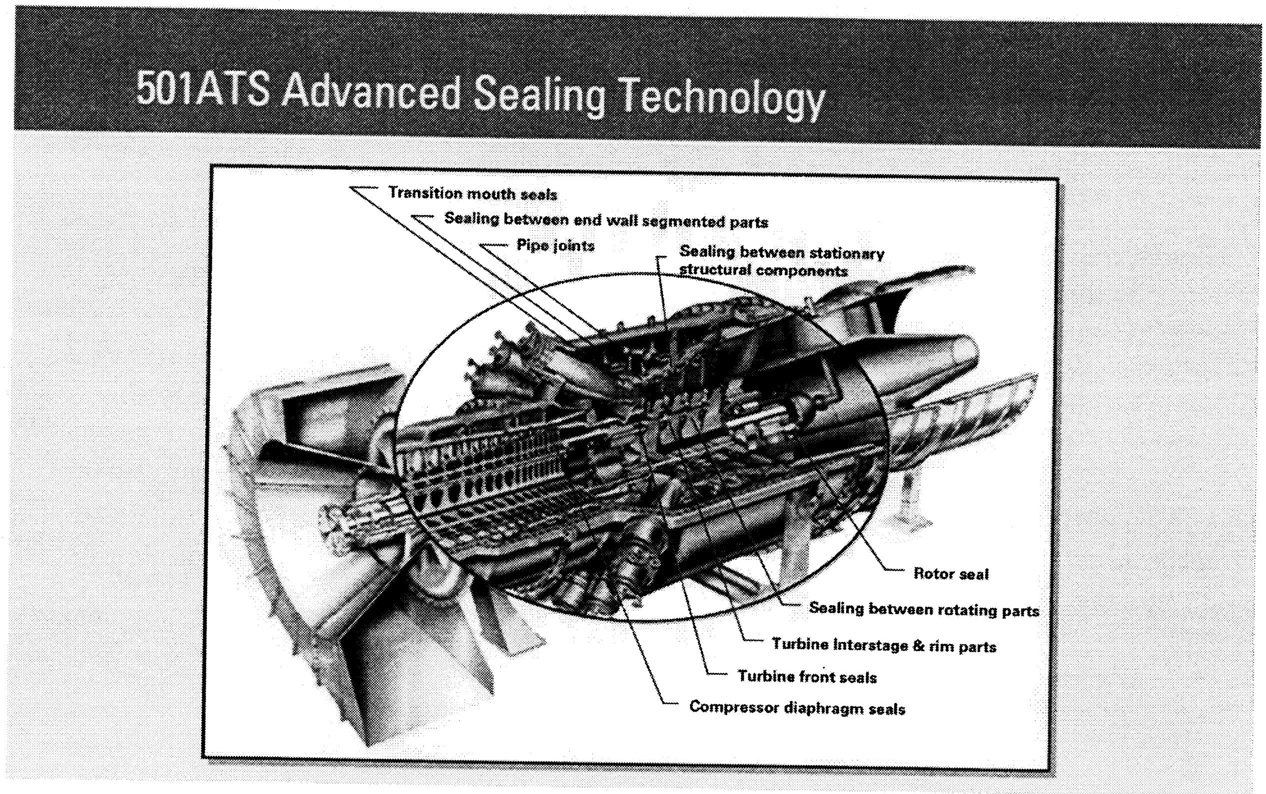


During assembly



Prepared for shipment

The man in the background on the right gives an indication of the size of the large gas turbines used in the utility industry. The turbines have a split casing as shown on the left. This offers convenience in assembly and in the field repairs. However, when the rotor is removed the lower half of seals are at risk of someone walking on them. So the seals need to be designed to withstand this event.



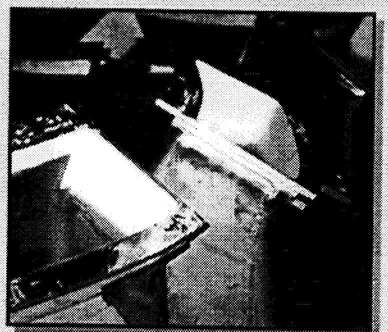
The various types of advanced sealing applications addressed in the 501ATS are shown by the callouts on this chart; static types are denoted at the top and dynamic ones on the bottom. In the 501ATS, the closed-loop rotor cooling air is brought in from the rear and exits from the front of the turbine into the compressor exit cavity. Today, the main areas of this presentation are transition mouth seals, brush seals, and the rotor rear seal.

Potential Benefits for Improved Sealing

- Improved plant cycle efficiency (decreased plant heat rate) and increased power output--for a 1% decrease in leakage:
  - 25+ BTU/hr/Kwh heat rate reduction
  - 1+% increase in power output
- Lower NOx emissions (via. improved static sealing in front of 1st turbine blade row)
- Maintained/improved component mechanical integrity (e.g., disk cavities)

The benefits of the improved sealing in improved performance and lower emissions are significant in comparison to the cost of the new hardware.

Transition Mouth Sealing

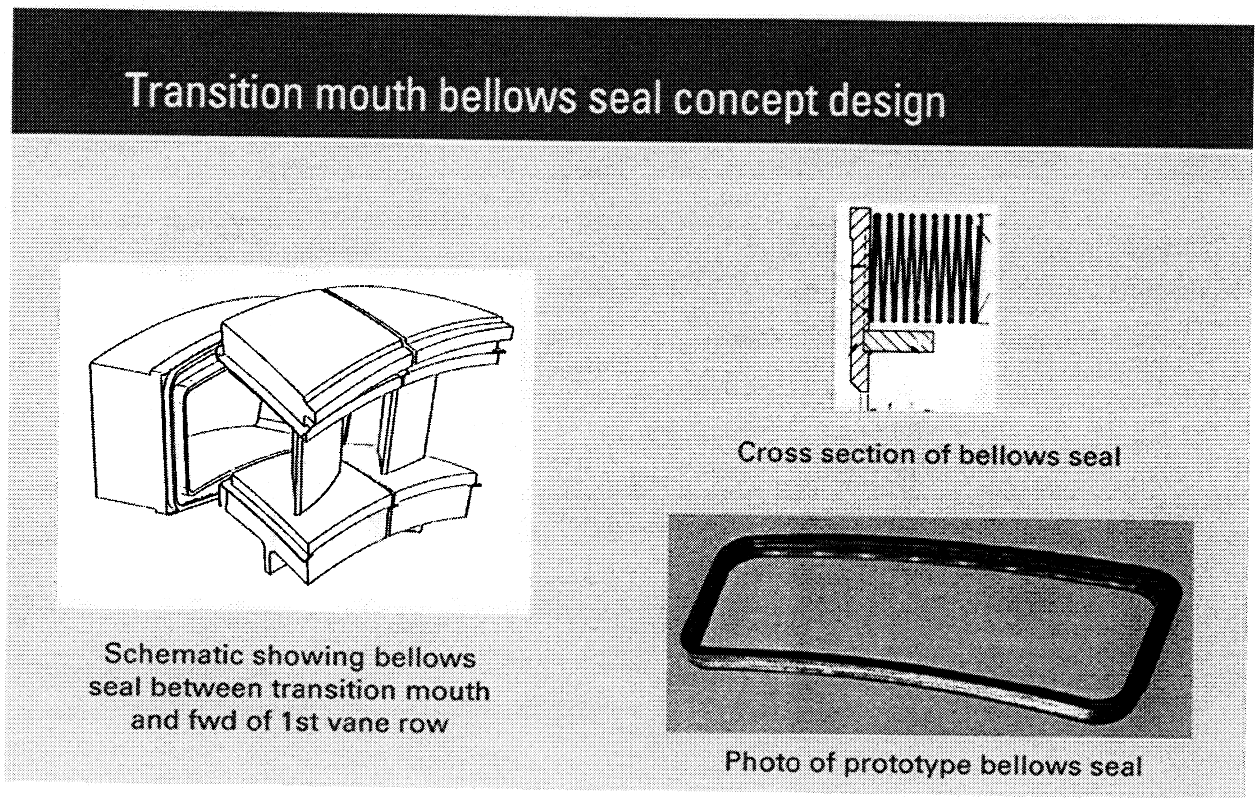


Transition mouths with side labyrinth seals

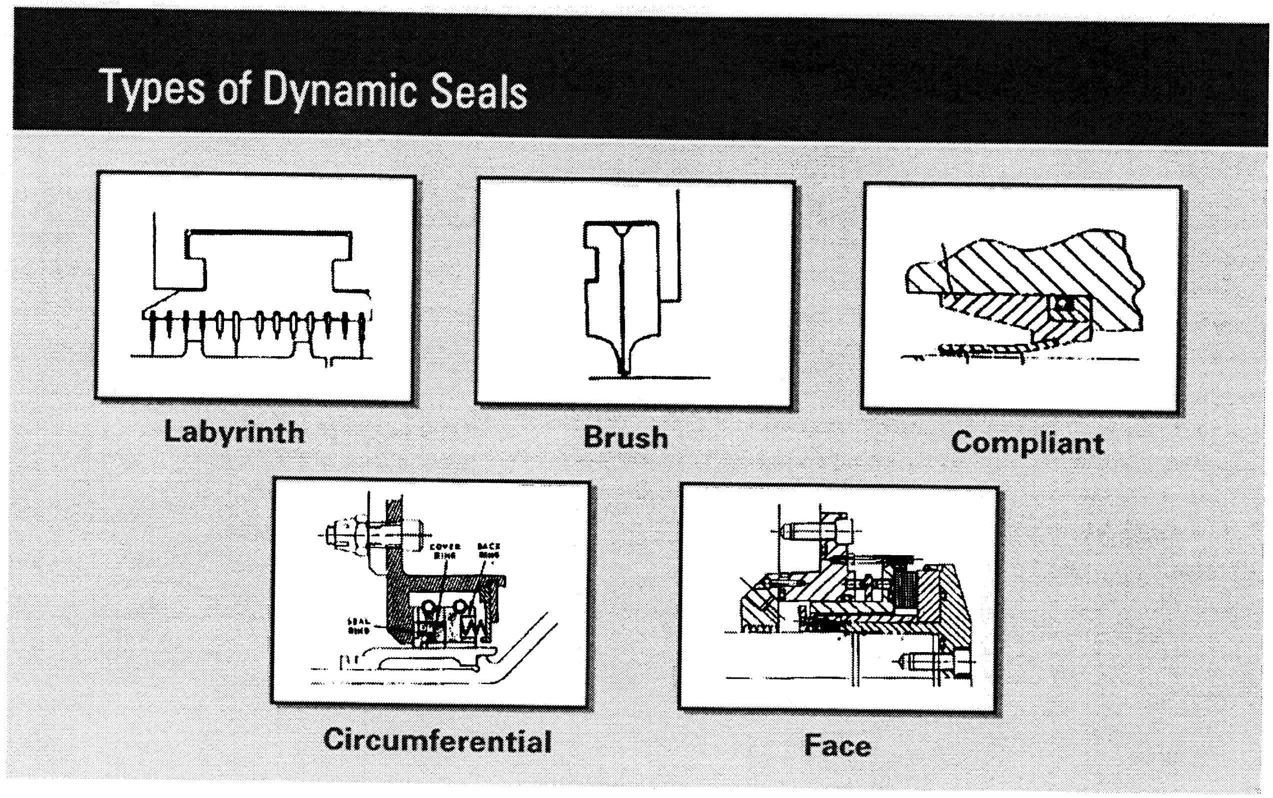
Top / bottom seal between transition mouth and 1st row vane endwalls

- Advanced transition mouth sealing must:
  - reduce leakage to sustain emission levels, while providing hardware cooling
  - Be robust to survive hostile thermal/vibration environment; and field installation and handling (including periodic transition removal for hardware inspections)

The ATS program includes a systematic approach to improving sealing for static locations. An example is sealing around the exit mouth of combustor transition liners. Leakage at this location is beneficial for cooling adjacent parts, but significantly increases emissions. The two photographs show how sealing is affected in current hardware. The seals are made of heavy metal because of the hostile environment at this location. Also, these parts are robust to allow rugged handling.

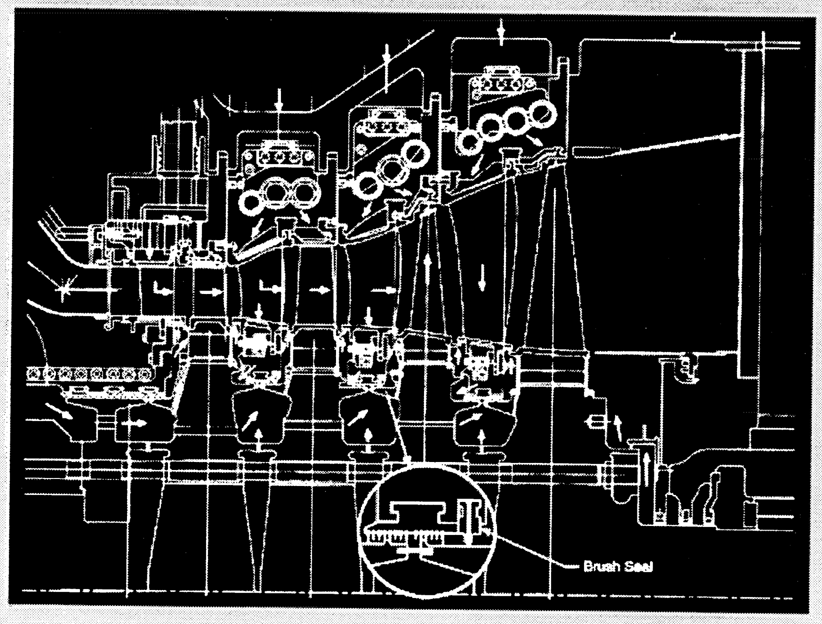


For the 501ATS, one improved sealing approach being considered is to put a seal around the mouth behind the transition, in front of the vane. The seal shown is a prototype bellows seal built by EG&G for SWPC. It is to be rig tested.



This simple chart shows the various types of dynamic seals. Prime ones include: labyrinth seals; brush seals to replace key labyrinth seals; and a face seal at the rear of the turbine rotor. The latter is needed to meet tight sealing requirements of the closed-loop rotor cooling air system.

501G Turbine Cooling/Leakage Flows



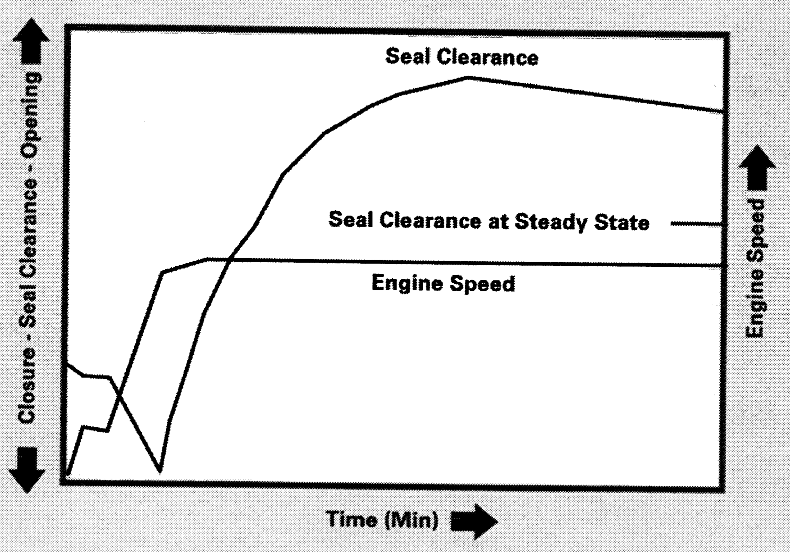
This chart shows a cross section of the Siemens Westinghouse 501G engine. The circle enlargement shows where one of the brush seals is installed. This engine is to be run in the future and the data acquired will be used to demonstrate validity of the brush seal design.

Applying Brush Seals to Industrial Engines

- Requirements:
  - Segmented
  - Durable for handling, etc.
  - Initially installed in series with labyrinth seals
- Challenges:
  - Large radial closures during start up or shut down
  - Long operating life
  - Need to run against uncoated rotor surfaces

The requirements and challenges of installing brush seals include: large closures during startup and shutdown, long operating lives while maintaining low leakage, running against uncoated rotor surfaces, and good handling, durability, etc.

Typical Start-Up Cycle for Brush Seal Locations



- **Closure mechanisms**
- **Pressure, temperature also changing**
- **Whirl closures not shown**

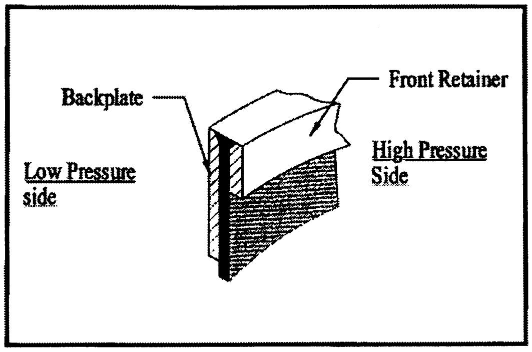
This chart shows a representative startup closure cycle, starting from cold build, then closing initially as the engine speed increases and then leveling off at 3600 rpm for 60 cycle machines and 3000 for 50 cycle ones. The closure decreases to several thousandths and then increases and eventually reaches a steady state level. The challenge with the brush seals for this cycle is at the steady state level is where the seal should run line to line, but eventually will wear line to line at the most closed point. The difference between the minimum closure and steady state minus bristle blow down will be the steady state clearance beneath the bristles.

Brush Seal Development

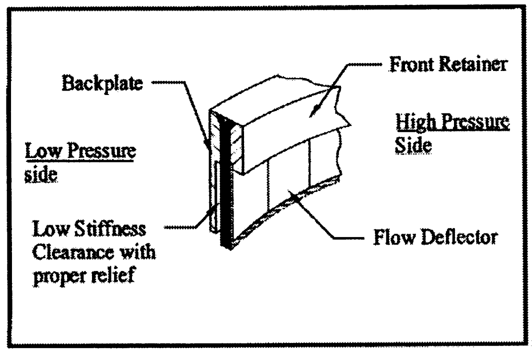
- Approach
  - Determine potential seal locations, benefits, etc.
  - Conduct focused development for selected engine locations
  - Validate in service engines
- EG&G chosen to support focused development efforts
- For each development location:
  - Define operating conditions, requirements
  - Design brush seals to meet requirements
  - Conduct tribology and aero rig testing of candidate seal designs
  - Design full-scale brush seals for validation testing

The approach taken in the ATS program for brush seal development is shown in this chart. EG&G aided in the development. For each seal location, the operating conditions and requirements were defined. This was complicated by not knowing how the engine would be run. For example, the larger new engines are intended for base load operation rather than for peak loads. The brush seal wound not have to experience too many closure cycles. It turns out that the first application may be for peaking with many starts. Or during electrical brown outs, power producers will run their units however they can to produce the most power because of the income possible. They are willing to pay the consequences later. Thus, you need to have margin in the design. Then you design brush seals to meet each engine location requirements rather than design one seal to meet all applications. You may be able to have more universal designs for labyrinth seal, but not with the complex brush seal designs. The development includes tribology testing and aero rig testing of the candidate seal designs, and then full-scale seal design and testing.

Brush Seal Designs



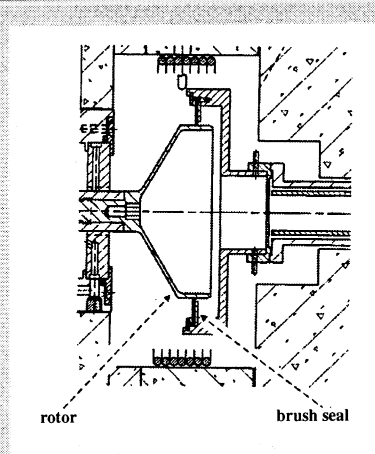
Standard Seal Design



EG&G Advanced Seal Design

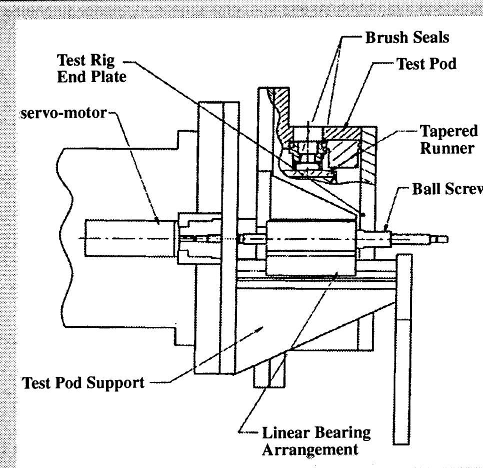
Two basic type brush seal configurations have been considered. One has a standard, generic design similar to brush seals produced by several manufacturers. The other has advanced features developed by EG&G. These features address seal hysteresis and bristle wear. Initial subscale seal testing evaluated the two brush seal configurations for the turbine interstage location. This testing demonstrated feasibility and the advantages of the advanced design. Consequently, only brush seals with advanced features were investigated for the other selected engine locations, i.e., compressor diaphragm, turbine front, and turbine rim.

Brush Seal Testing Approach



Tribology Rig

- Miniature, high speed brush seal rig to conduct accelerated testing
- Temperature, speed, materials, surface condition, contact pressure modeled
- Matrix of bristle alloys and rotor materials/surface conditions tested
- Torque/temperature histories and hardware inspections used to rank bristle/rotor matl's



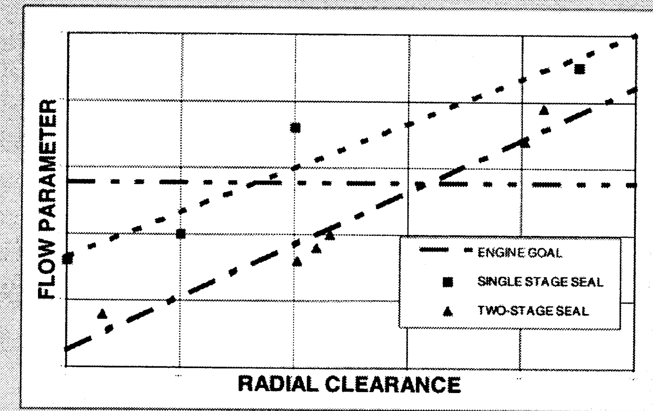
Aerospace Rig

- High speed/temperature rig (1/4 to 1/6 scale)
- Candidate seals tested from design/tribology
- Closure cycle simulated with speed and pressure drop varied
- Steady-state leakage/bristle wear measured
- Borescope viewing of bristle movement
- Static stiffness and leakage also determined

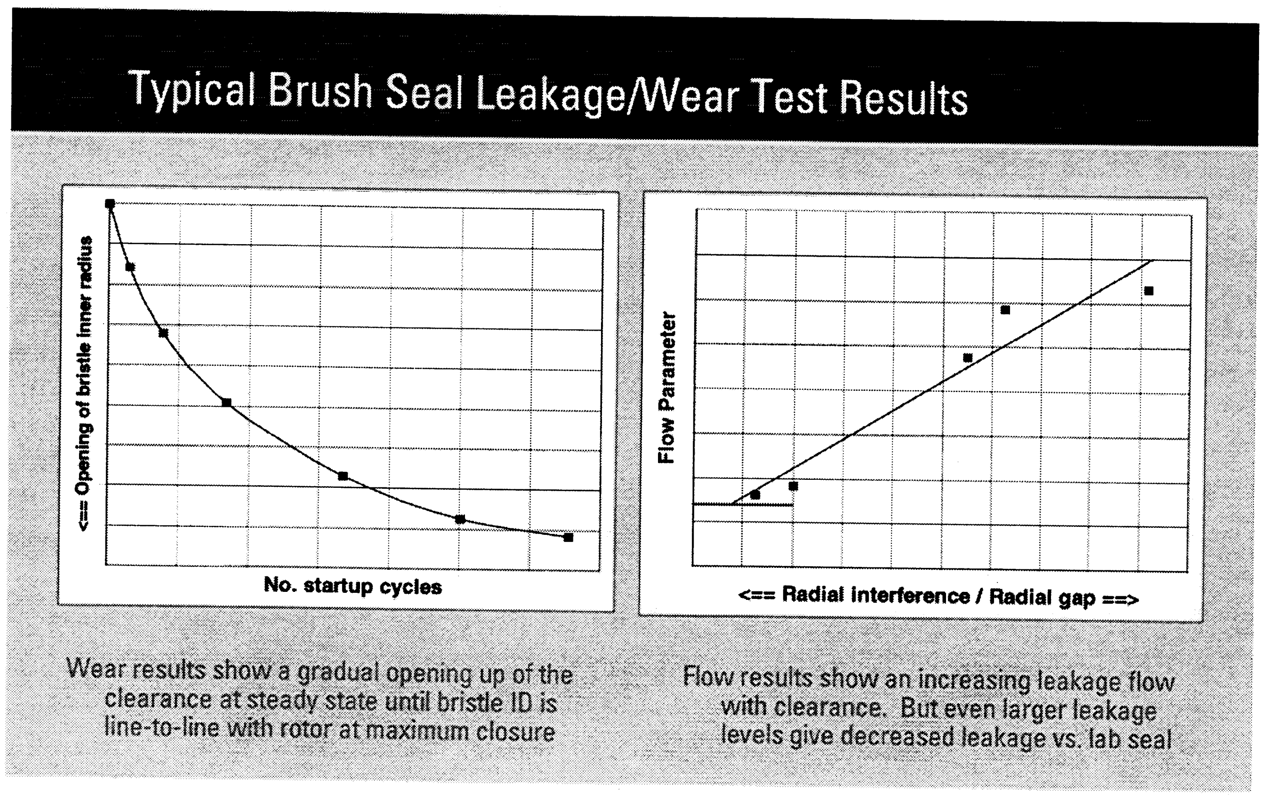
This chart shows the two types of rig tests run at EG&G. The first is a tribology rig to test bristle materials running against uncoated surfaces having different surface roughnesses to determine wear characteristics. Torque characteristics and temperature rises were measured to indicate the wear. Candidate brush seals were evaluated for wear and performance characteristics in EG&G's Aerospace Test Rig. The seals were subscale size with engine pressure drop and rotor speed variations and temperature levels modeled. The rig has been updated to simulate seal closure by providing controlled axial seal movement along a tapered rotor surface.

Turbine Front Brush Seal Rig Results

- Feasibility of a two-stage brush seal demonstrated for the large pressure drop, turbine front location
- Flow characteristics of 1 and 2 stage brush seals determined
- Dynamic character of pressure drop split between two seals determined
- Required clearance to pass desired leakage flow versus overall pressure drop determined



This chart shows results for the turbine front brush seal. It was desired to put a two-stage seal in this location because of the high pressure drop. In the testing, both single- and two-stage seals were evaluated. For the two-stage seal, it was desired to measure the dynamic character of the pressure drop between the seals since the seals are not fixed orifices. The horizontal line indicates the desired leakage flow rate to provide purging of a downstream disk cavity. The results indicate the required clearance beneath the brush seals for one- and two-stage seals.

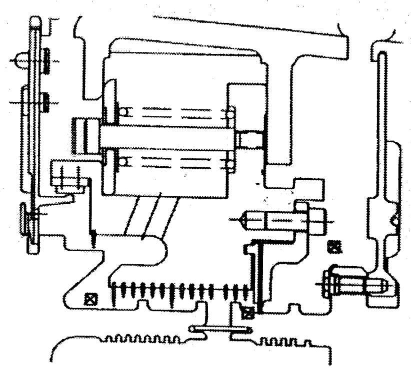


This chart shows the basic concept of how seals wear. For example during the startup cycle, a maximum amount of interference compared to steady state would be the height in the left-hand plot. This plot could also represent the number of steady state hours with a fixed interference. The result is an expected exponential wear decay curve. On the right side is the flow parameter versus radial interference/clearance. For interferences, the leakage flow parameter is nearly constant. For clearances the line is nearly linear with gap. The gap shown is for zero pressure drop across the seal. For pressure drop conditions, the bristles will blow down toward the rotor, so the slope of the line reflects an area change with pressure drop.

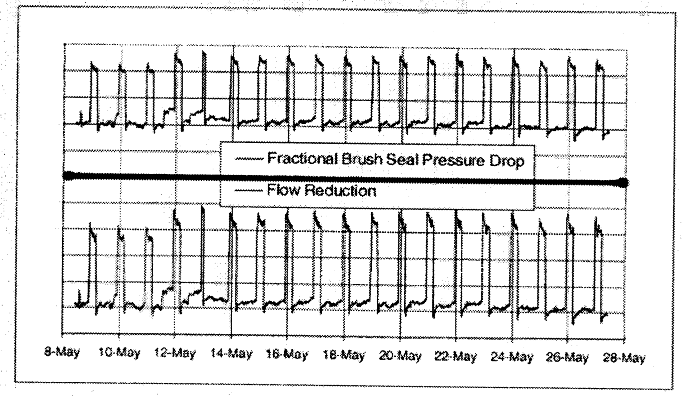
Validation of Brush Seals in Combustion Turbines

- Brush seals installed in 501D5, 501F, 501G (in turbine interstages)
- Brush seals at several locations in the 501ATS being designed

Typical Engine Data for 501D5 Turbine Interstage Brush Seal



Pressure tap locations



Brush seal performance showing effect of varying load

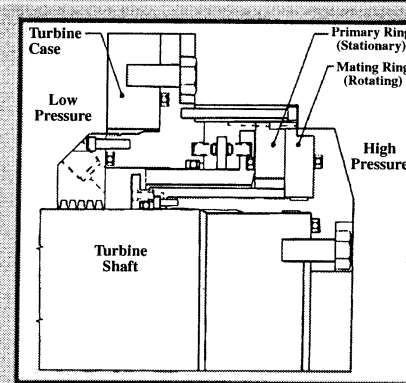
This chart shows field data acquired recently for a brush seal installation. The instrumentation included pressure taps upstream of the labyrinth seal, between the labyrinth and brush seal, and downstream of the brush seal. The y axis for the upper curve is the fraction of the total pressure drop across the brush seal. These data are for over several days without an intervening shut down. At night the load to the unit is reduced causing the steps in the plot. These steps are caused by changes in the air temperature from part to full load, which in turn causes a different clearance beneath the brush seal. The fractional pressure drop data are used to calculate the flow reduction due to the brush seals as shown in the lower plot. This calculation is possible from the known flow characteristics of the labyrinth seal. Thus, the labyrinth seal provides a measurement device. The actual flow reduction can be calculated from an assumed clearance. Results from these calculations showed a significant leakage flow reduction due to adding the brush seal.

501ATS Rotor Rear Seal Development

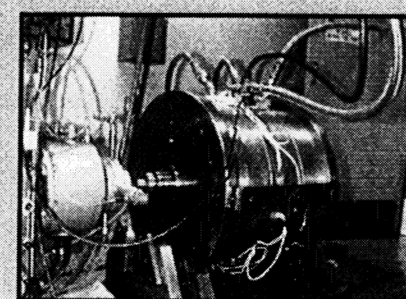
Requirements
- Low leakage
- Large axial movement
- High pressure drop
- Robust, long life with part time low speed operation
- Handle particles in leakage air
- Smaller dia., not necessarily segmented

Selection
- Vendor - John Crane Inc.
- Seal - Non-contracting, dry running gas lubricated end face seal - hydrodynamic type
- Design - based on current Crane Type 28 seals with modifications to meet requirements

Evaluation
- Long life with part time low speed operation
- Large axial movement
- Proper installation/durability capability
- Handle air contamination



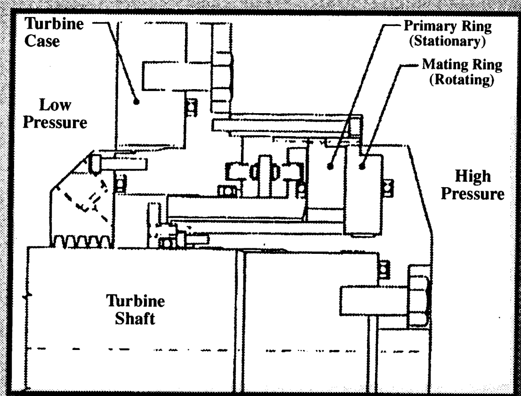
Rotor rear seal schematic

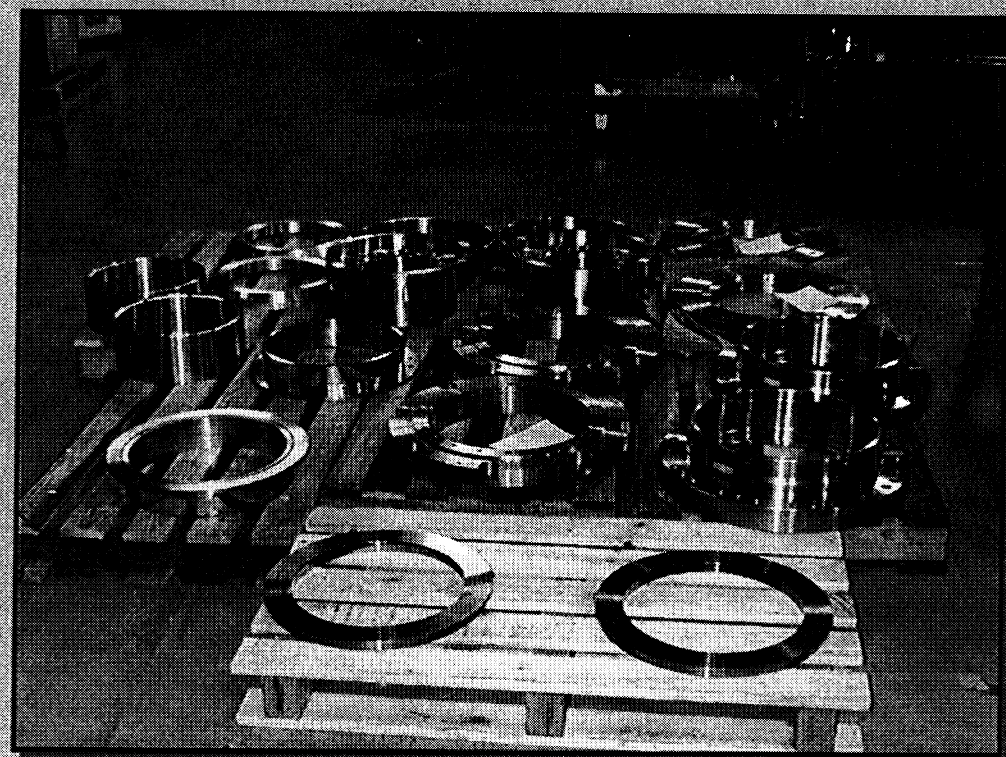


John Crane test rig to simulate engine conditions

A separate development effort focused on providing very low leakage of cooled compressor discharge air as it enters the 501ATS rotor at the rear. John Crane Inc.'s spiral groove face seal technology was adapted to this location with larger diameter and axial movement than in previous applications. Rig testing has been done to verify the seal's design and low leakage over a range of engine operating conditions. This chart shows a cross section of one of Crane's seals. There are several issues to address: the air to be sealed needs to be free of particles above a certain size, the axial movements are large, the swash level is high, the expected operation hours is high, and there will be times when the engine is not running that the rotor will be rotated at slow speed on a turning gear with no pressure drop across the seal. The latter was evaluated by including a special test at low speed.

Rotor Rear Seal Design and Hardware Prior to Assembly



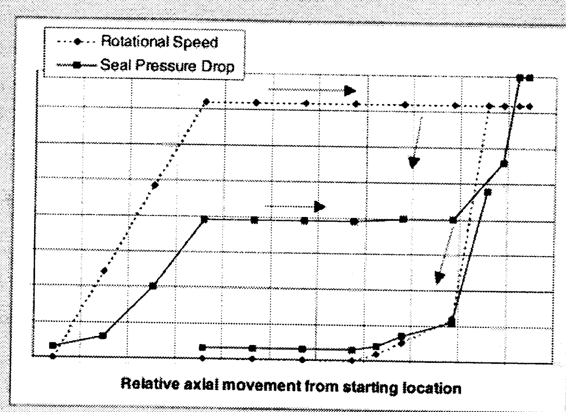


This chart shows a photo of unassembled hardware for two rotor rear seals. Two seals were required for the test set up.

Rotor Rear Seal Rig Testing

Tests Performed:

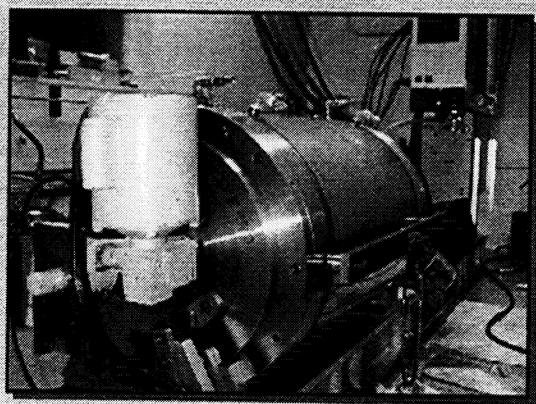
- Performance testing
  - With simulated operation cycle
  - Large axial travel evaluations
  - Angular misalignment
  - Leakage & wear assessed
- Over-speed spin testing
- Extended turning gear operation



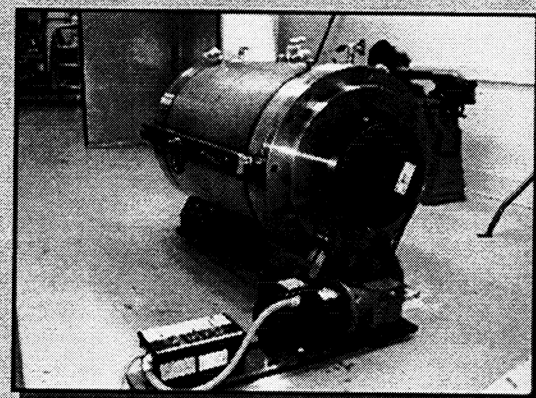
Simulated operation cycle

This chart lists the various tests performed and the engine start-up/shut down simulation cycle used to evaluate seal performance and leakage.

Rotor Rear Seal Rig Test Pods



Test pod used in performance testing with axial stepping motor mounted



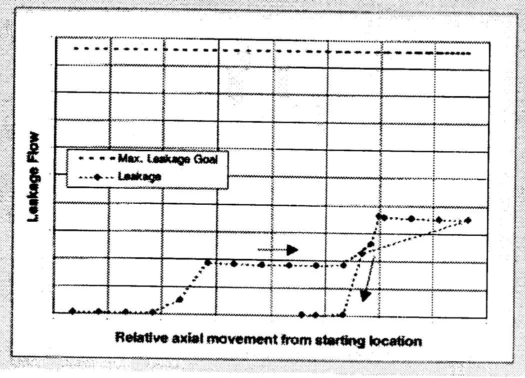
Turning gear test arrangement

The left-hand side of this chart shows the test pod used for the performance testing. The motor in the foreground was a new addition to Crane's test rig to provide axial movement during operation. The right-hand side shows the test arrangement for the low speed testing.

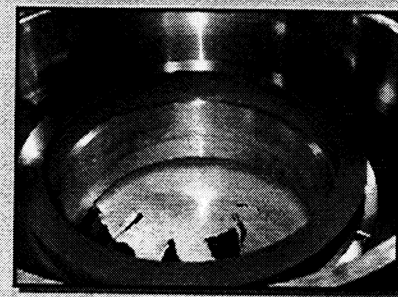
Rear Seal Testing Results

Testing showed:

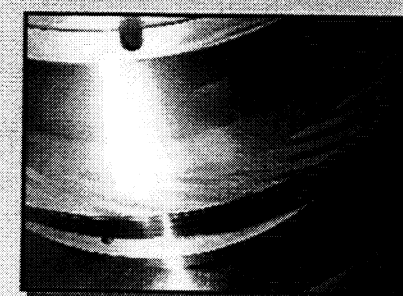
- Leakage was well below goal
- Seal can readily handle large angular swash and axial travel
- Caused no observable wear to seal faces



Primary Ring



Mating Ring



Test results for the rotor rear seal showed that the leakage was well below the goal. This goal is significantly below what a labyrinth or brush seal could provide. Thus, spiral-groove face seals are indeed very low leakage devices. Post-test inspection of the seal faces showed that there was no observable wear, not even minor scratches. After the very successful testing, the two seals are awaiting installation into a 501ATS engine.

Summary

- Improved sealing in large combustion turbines has significant payoff in increased efficiency, reduced emissions, maintaining RAM
- Static seals are improved by adapting/advancing proven concepts
- Dynamic sealing improvement has focused on developing brush seals for turbine interstages, rims, and front; and compressor diaphragms
- Focused brush seal development is complete for the turbine interstages and compressor diaphragms;
- Full-scale turbine interstage brush seals are being validated / commissioned in several CT's.
- Non-contact, dry-gas, spiral-groove face seal has been designed, fabricated, and rig tested for the 501ATS rotor rear

In summary, advanced seal has a significant payoff—much more that the added costs to implement the new seal hardware. Further, very few units need to be sold, before the R&D costs can be recovered.