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Brush Seal Performance Evaluation

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Abstract

The development of brush seals for large ground running gas turbines has resulted in new more robust designs. These new designs have larger bristle wires than seals used in aerospace applications, increased fence heights and a much taller section. A series of static leakage tests were performed on 4 brush seals fitted with interchangeable front and back plates. The seals had wire sizes ranging from .0028" up to .0056", fence heights were variable from .010" up to .2" and the front plate gap was also variable. The effects of bristle wire density and also bristle to rotor clearance are also examined.

Nomenclature

Df	Front plate bore (inches)
Dr	Rotor diameter (inches)
Fh	Fence height (inches)
g	Acceleration due to gravity (ft/s^2)
P1	Absolute pressure upstream of seal (psia)
Pu	Pressure just upstream of seal (psi)
Pd	Pressure just downstream of seal (psi)
PR	Pressure ratio
R	Specific gas constant (ft lbf/lb R)
q	Mass flow rate (lbs/s)
T1	Gas temperature upstream of seal (^{o}F)
w	Length or circumference of seal (inches)
γ	Ratio of specific heats
μ	Flow function

Introduction

Cross have been making brush seals for the aerospace industry for more than 20 years, supplying many engine manufacturers and research establishments. In the past 4 years there has also been a great deal of interest from the power generation industry. Many manufacturers are now fitting brush seals into their ground running gas turbines[1,2] and investigating possible steam turbine applications. The application of brush seals into these large ground running machines, has meant that new seals designs have been developed of a more robust nature to cope with this operating environment. These new designs have larger bristle wire sizes, increased fence heights and variations on bristle density and free length.

Cross has on ongoing, self funded, test and development program utilising two dynamic rigs, one of which is capable of testing a 5" diameter seal at speeds of up to 45000 rpm, at temperatures of up to 800 ^{o}F and pressure drops of up to 80 psi. As well as the dynamic rigs, Cross also have many static rigs for leakage testing round, segment and straight brush seals.

This paper discusses some results from one of the static test rigs. The effects that the following seal parameters can have on the leakage through and the pressure capacity of a brush seal are investigated:-

a) Bristle wire diameter.
b) Bristle density
c) Fence height
d) Free bristle length
e) Bristle to rotor clearance

Test Apparatus

The static test rig used in all the tests detailed in this paper is shown schematically below in Figure 1. The leakage flow rate was measured with vortex shedding flow meters and the pressures with silicon diaphragm pressure transducers. All data was recorded via a data acquisition and control unit connected to a PC.

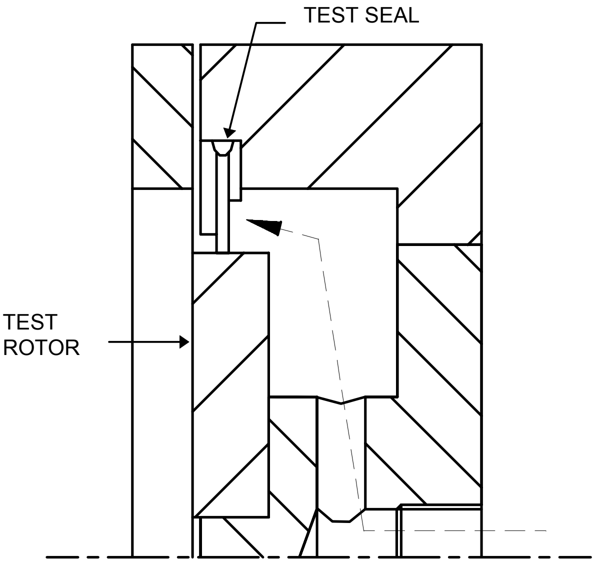

Figure 1. Schematic of Static Test Rig

Some tests were also performed with the clamp ring replaced by an end plate fitted with a flow control valve. This facilitated performing some tests with constant up stream pressure with varying down stream pressure. All other tests were performed with ambient down stream conditions.

In total 4 different bush seals were tested, each seal was made to accept the interchangeable front and back plates as shown in Figure 2. These plates enable the fence height and the free length of the bristles to be varied. The main differences between the test seals are shown in Table 1.

Seals B, C and D were all dimensionally identical except for the details in Table 1. Seal A was similar but had a free bristle length of 49% of the others.

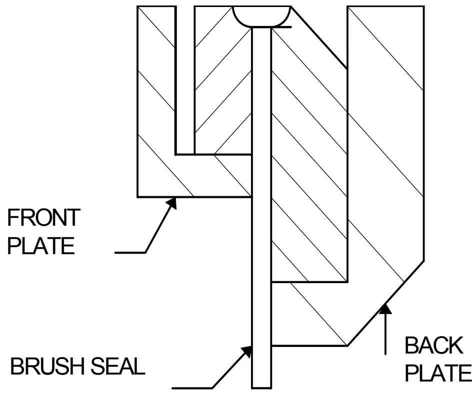

Figure 2. Test Seals with Interchangeable Front and Back Plates

Seal	Wire Size inches	Bristle Density wires per inch
A	.0028	*A*
B	.004	*.73A*
C	.004	*1.47A*
D	.0056	*.53A*

Table 1. Key Seal Dimensions.

Seal A is typical of a seal for an aerospace application and seal D is typical of that used by the power generation industry.

Test Procedure

The test procedure was very simple in the majority of cases. For most of the tests the respective seal was fitted with the required front and back plates and then assembled into the rig with the required test shaft. Pressure was then applied in 5 psi increments up to a maximum of 80 psi or less if the characteristic curve of the seal indicted that its pressure limit was less than 80 psi. These curves were plotted as the tests progressed to ensure that the seals did not suffer any damage due to over pressurisation.

The tests performed with constant up stream pressure and varying down stream pressure were conducted in a similar manner. The pressure drop across the seal was incremented by adjusting the flow control valve after the seal.

Discussion of Results

Results from the tests are presented in this section. All the data is plotted as effective clearance versus pressure drop.
The effective clearance is defined as follows:-

$$\text{clearance\_eff} = \frac{q\sqrt{(T1+460)}}{P1.w.\mu}$$

μ the flow function is defined as follows:-

$$\mu = \sqrt{g.\gamma / R}.\sqrt{((2/(\gamma-1)).PR^{-(\gamma+1)/\gamma}.(PR^{(\gamma-1)/\gamma}-1))}$$

For choked flow (where PR>1.89) the flow function is held at the value for a Mach number of 1 at the seal.

All the graphs except Figure 3. below are plotted as clearance_eff versus pressure drop. The reasons for doing this are very clear if we study Figures 3 and 4. These two graphs show the same data but one is plotted against pressure ratio and the other against pressure drop. It is very clear that the data needs to be plotted against pressure drop and not pressure ratio.

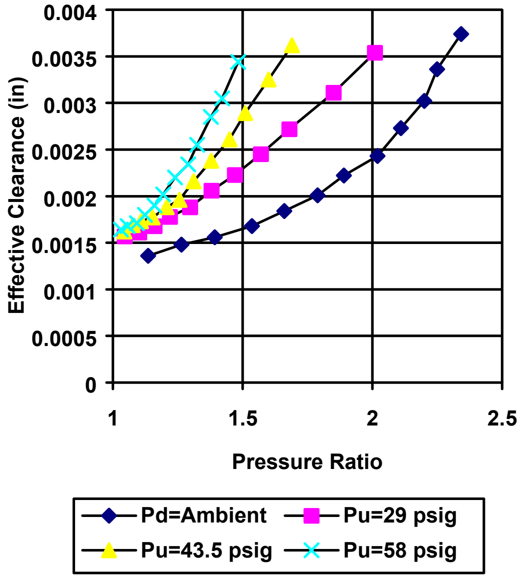

Figure 3. Graph of Effective Clearance for Seal B against Pressure Ratio

For the purpose of this test seal B was fitted with a back plate to give a .123" fence height, giving the seal a fairly low pressure capacity.

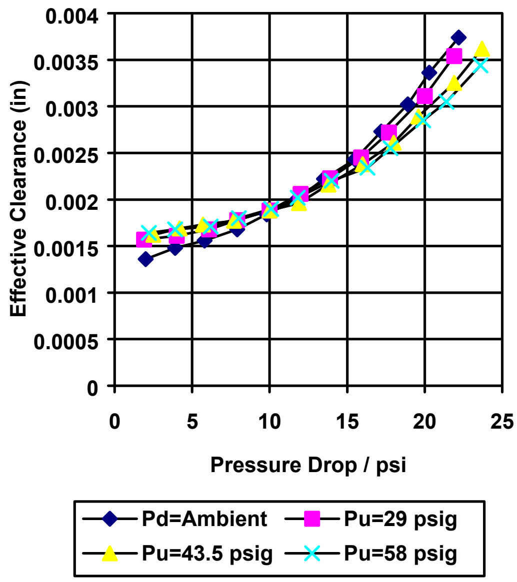

Figure 4. Graph of Effective Clearance for Seal B against Pressure Drop.

From a sealing point of view a brush seal should be considered as a flexible membrane single stage labyrinth seal. The characteristics of the seal are governed by the flexing of the sealing membrane or bristles and this is related to the pressure drop across the membrane and not the pressure ratio.
Extreme caution must be exercised when plotting any brush seal leakage parameter against pressure ratio. Every brush seal has a pressure drop capacity limit, on the seal B above this would be about 15 psi. This could represent a pressure ratio of 2 with ambient downstream conditions or only 1.15 with 100 psia downstream, clearly two very different numbers.

The characteristic curve of the brush seal is clearly a function of the pressure drop across the seal, the pressure ratio is needed to calculate the effective clearance but should only be used for such calculations. All further graphs in this paper will be plotted against pressure drop and we would ask everyone else in the brush seal industry to do the same.

Typical Characteristic Curve

A typical characteristic curve for a brush seal is shown in Figure 5. This graph has been broken down into three segments to indicate the three different functional characteristics of the seal. Section 1 is usually from a pressure drop of 0 up to about 15 psi and is typically curved as shown. It is not clear why this first section is curved as any effects due to compressibility are taken into account by the effective clearance calculation. Section 1 is usually of little interest to most brush seal designers as most applications have a pressure drop substantially greater than 15 psi.

Section 2 is the area where most correctly designed seals function. The curve in this section is usually very nearly a straight line with a slight positive incline. This section is usually from a pressure drop of about 15 psi up to a pressure drop determined by the dimensional characteristics of the seal, this may range from as low as 20 psi or up to in excess of 300 psi. In this section the seal is performing well with stable sealing performance and a low risk of seal damage.

Section 3 is the area to be avoided when designing a brush seal, in this section the gradient of the curve is rapidly increasing as the sealing efficiency of the seal deteriorates. The deterioration of the sealing performance is caused by the bristles bending and opening up a gap between the bristle bore and rotor, and also because the bristle tips are bent the discharge coefficient of the bristle / rotor interface also increases. This bending has been presented in a paper by Modi[3]. At Cross we call the start of section 3 the pressure limit of the seal.

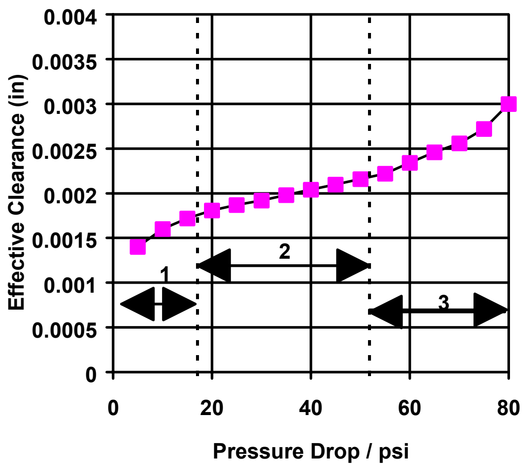

Figure 5. Typical Characteristic Curve

Effect of Wire Size and Fence Height

The graphs shown in Figures 6 to 9 very clearly show the effect that the bristle wire diameter and the fence height has on the characteristic curve of the brush seal.

As you would expect the larger the wires the higher the effective clearance is, up to the pressure limit of the seal. The fence height has a very strong influence on the sealing performance, this is illustrated best in Figure 10, where the effective clearance is plotted against fence height with constant pressure lines for seal B. It can be seen that, as long as you stay away from the pressure limit of the seal, increasing the fence height from .060" to .150" only increases the leakage by 25% (at 5 psi). Clearly the leakage through a brush seal is not directly proportional to the fence height, as at first might be expected, but is a much more complex expression governed by all the bristle pack dimensional parameters.

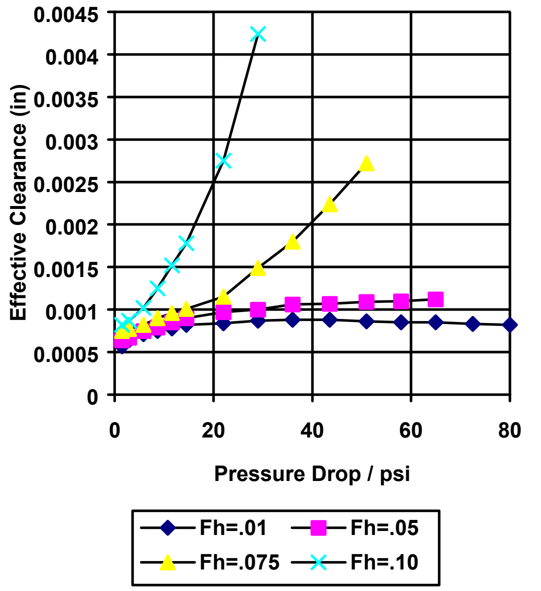

Figure 6. Graph of Effective Clearance for Seal A against Pressure Drop.

Effect of Bristle Wire Density

The effect of the bristle wire density can be seen by studying Figures 7. and 8. together. Seals B and C are identical in all respects except seal C has twice the number of bristle wires as seal B. This has the effect of reducing the base line leakage by about 33% and increasing the pressure capacity of the seal for any given fence height.

It would appear that the pressure capacity for a given fence height is more than doubled if we double the seal density. This indicates that the pressure drop through the sealing pack is not linear as is sometimes assumed. As we increase the density, or number of wires through the bristle pack, the stiffening effects caused by friction between adjacent bristles increases thus raising the pressure capacity further.

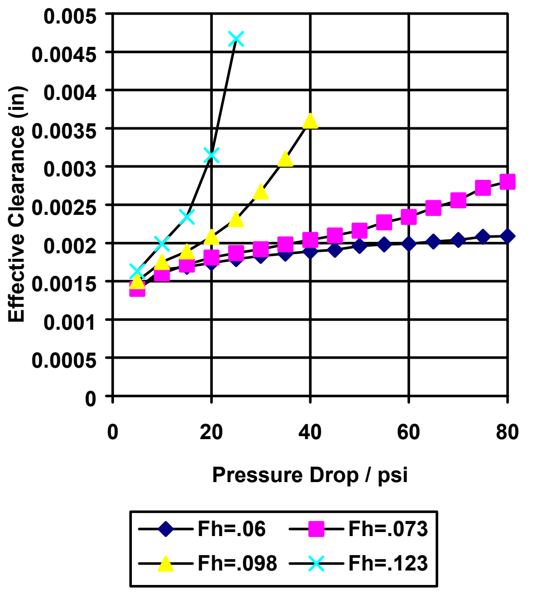

Figure 7. Graph of Effective Clearance for Seal B against Pressure Drop.

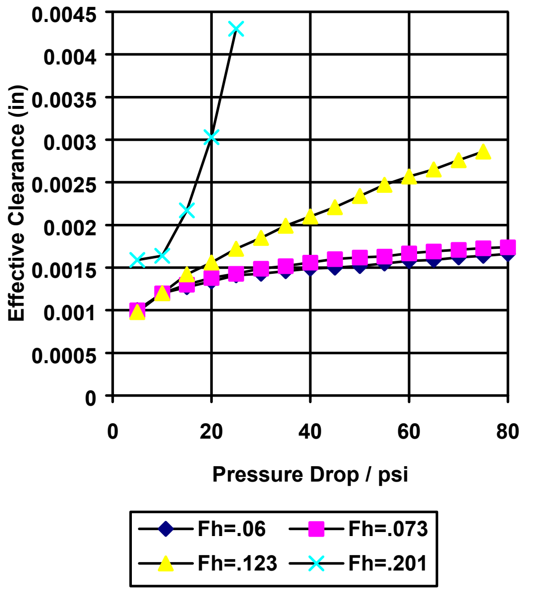

Figure 8. Graph of Effective Clearance for Seal C against Pressure Drop.

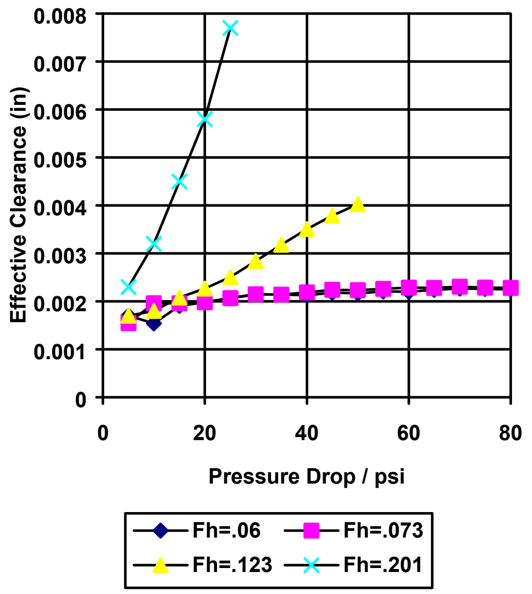

Figure 9. Graph of Effective Clearance for Seal D against Pressure Drop.

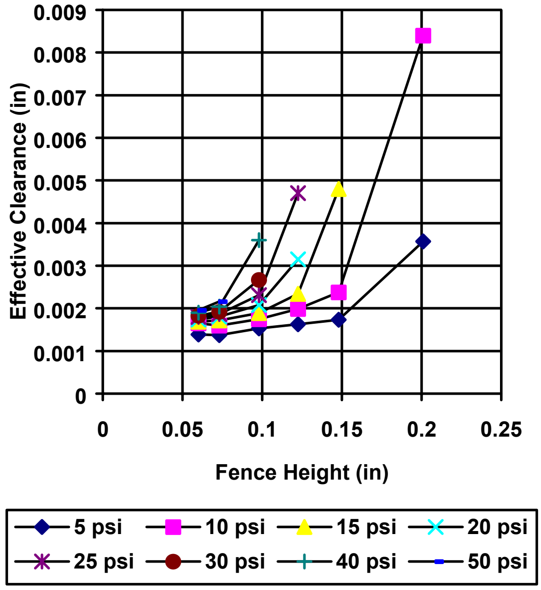

Figure 10. Graph of Effective Clearance for Seal B against Fence Height.

Effect of Free Bristle Length

The effect of the free bristle length on the performance of seal B is shown in Figure 11. It is clear that decreasing the front plate bore and thus shortening the free bristle length has the effect of reducing the leakage. It should also be noted that, as we shorten the bristle, section 3 of the characteristic curve becomes less well defined. This effect was presented by Modi[3].

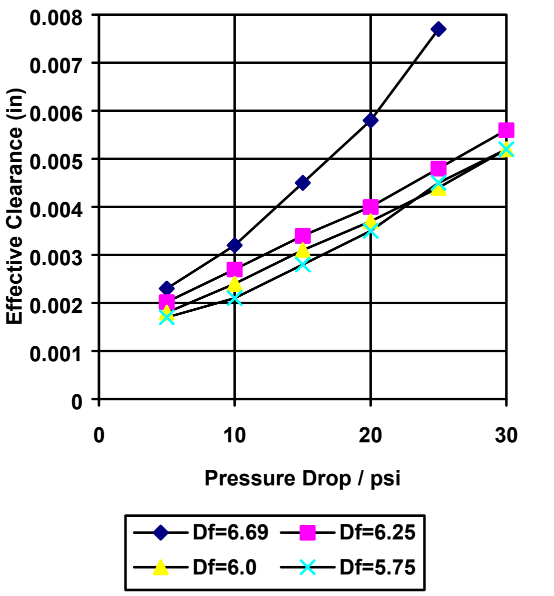

Figure 11. Graph of Effective Clearance for Seal D against Pressure Drop (Fh=.201)

A word of caution, from the above it would appear to be a good idea to keep the bristles as short as possible to reduce leakage levels, however as we shorten the bristle we increase its stiffness and this in-turn increases the heat generated by the seal. For each seal application there is usually an optimum bristle stiffness governed by the operating condition. It is not usually possible or advisable to optimise the leakage by reducing the bristle free length.

Effect of Rotor to Bristle Clearance

The effect of changing the clearance between the rotor and the bristles is shown in Fig 12. The seal used for this test had a mean bristle bore of 5.093". When tested with a 5.100" rotor the effective clearance is in the range .0015" - .0017" for a pressure drop of 15 to 40 psi. When the rotor is replaced with a 5.090" one, giving a radial gap of .0015" between the bristles and rotor we find that the effective clearance has increased to .0023" - .0025". That can indicate one of two things:-

1) The discharge coefficient of the seal rotor interface is about .53
2) The bristles "blow down" and close the gap by .0007"

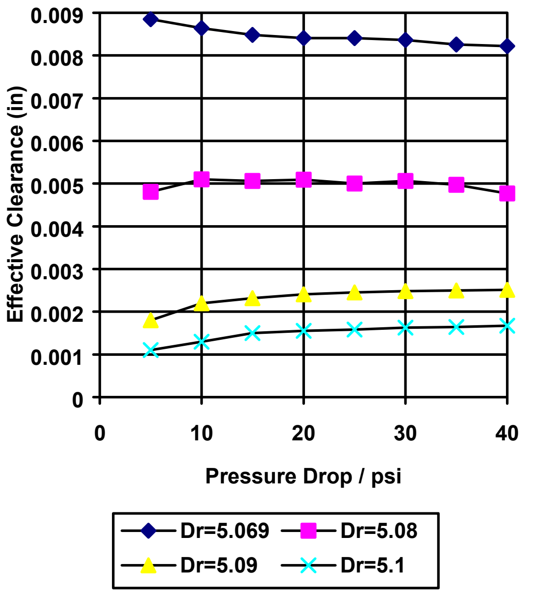

Figure 12. Graph of Effective Clearance for Seal B against Pressure Drop for Varying Rotor Sizes (Seal fitted with 6" front plate and 5.245" back plate)

Now looking at the curve for Dr=5.08, this gives a mean radial clearance of .0065" with an increase in the effective clearance to .005" again this either indicates that the bristles are blowing down about .003" or that the discharge coefficient of the gap is about .54.
Now for the case where Dr=5.069,this gives a .012" gap with an effective clearance of about .0085". This gives a discharge coefficient of .58 for the gap or the bristles are blowing down .005". From the shape of the graph it is clear that the bristles are blowing down to some extent as the effective clearance is falling as the pressure is increased. Attempts to optically measure the bristle blow-down have not been wholly conclusive so we feel that brush seals do blow- down but not to the extent that some might lead you to believe.

Derived Equations

With the knowledge built up over the past 12 years of brush seal testing by Cross, we have derived expressions for the pressure limit and the leakage through brush seals. These equations have been used to successfully design many brush seals for the aerospace and power generation industry.

Conclusions

Brush seal development continues at Cross. We now have 12 years of testing experience and more than 20 years of manufacturing experience. The functioning of the brush seal is becoming more understood and more people are starting to use them, especially in the power generation industry.

It is important to relate the pressure drop that any brush seal sees to the flow parameter and not the pressure ratio. The characteristic curve of any brush seal is much more closely related to the pressure drop than the pressure ratio.

The dimensional parameters that were varied on the seals tested had the following general effects:-

1. Wire size

    Larger wires exhibited higher pressure capacities but higher leakages.

2. Fence height

    The fence height when combined with the wire size has the greatest effect on the sealing performance of the seals. The pressure capacity is severely reduced as the fence height is increased.

3. Wire density

    Doubling the wire density had the effect of reducing the leakage by some 30% whilst also more than doubling the pressure capacity.

4. Free bristle length

    The pressure capacity of any given seal can be increased and the leakage reduced by making the free bristle length shorter. This however can lead to other problems.

5. Bristle to rotor clearance

    The sealing characteristics of a seal assembled with a clearance exhibit some closure or blow down of the bristle pack. This results in a discharge coefficient in the range of .5 - .6.

Acknowledgements

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