Justification

**Trends in High Performance Turbomachinery**
- Higher speeds & more compact units
- Extreme operating temperatures and pressures
- More efficient & reliable

**Issues of Importance**
- Reduce secondary flows (parasitic leakage)
- Reduce specific fuel consumption
- Increase power delivery
- Eliminate potential for rotordynamic instability

Source: GE Energy
Labyrint and pocket damper seals

Labyrinth Seals (LS)  Pocket Damper Seals (PDS)

- PDS leaks more than LS.
- PDS provides ++ more effective damping and reduces rotor vibration amplitudes more effectively than a LS.

Vance, J. M., and Li, J., 1996
• PDSeal over predicts leakage (4-10%) compared to test results.

• PDSeal predicts direct damping coefficients in agreement with test data.

• Direct stiffness & damping coefficients and leakage are weak functions of rotor speed. Cross-stiffnesses are typically small.

Li, J., San Andrés, L., Vance, J., Ransom, D., and Aguilar, R.
**Progress in 2012-2013**

**XLPDS© GUI created to interface with PDSEAL©**

GUI linked to XLTRC² suite to predict performance of pocket damper seals (sharp blades)

(a) Leakage  
(b) Stiffness and damping coefficients

vs. pressure difference, rotor speed and excitation frequency.

On December 2013, Weilian Shan, MS research assistant, withdrew from graduate program due to health issues. (16 months support lost)
Differences PDS & FPDS

Commercial PDS and FPDS have **thick walls**

Original PDS had **sharp blades**

Pocket damper seal (PDS)  
Fully partitioned pocket damper seal (FPDS)

Known issue:

Predicted effective damping for FPDS is grossly in error when compared to GE test results.

PDS\textcopyright{} needs to be improved for better prediction for FPDS with thick walls.
• Update bulk-flow flow model for PDS and FPDS. Model will include real gas properties including supercritical CO2 and steam.

• Perform more code calibrations: compare predictions to test data for leakage and force coefficients.

• Begin extensions of the model to include two-component mixtures (liquid and gas).
<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support for graduate student (20 h/week) x $2,200 x 12 months</td>
<td>$23,400</td>
</tr>
<tr>
<td>Fringe benefits (2.4%) and medical insurance ($118/month)</td>
<td>$2,050</td>
</tr>
<tr>
<td>Tuition &amp; fees three semesters ($363/credit hour x 24)</td>
<td>$8,712</td>
</tr>
<tr>
<td>Others (Mathcad® and portable data storage)</td>
<td>$220</td>
</tr>
<tr>
<td><strong>Total Cost:</strong></td>
<td><strong>$37,382</strong></td>
</tr>
</tbody>
</table>

Year III: Complete computational model for prediction of FPDS leakage, drag power, and force coefficients for gas and steam turbines
Questions (?)
Background

Labyrinth seals (LS) in a straight-through compressor

Neumman leakage model

\[ \dot{m}_i = \frac{(C_k C_f H)_i}{R_g T} \sqrt{P_{i-1}^2 - P_i^2} \]

Main flow equation

\[
\frac{1}{R_g T} \left[ \frac{\partial(PA)_i}{\partial t} + \frac{\partial(PAU)_i}{R_a \partial \Theta} \right] + \zeta_r (\dot{m}_{i+1} - \dot{m}_i) = 0
\]

Circumferential momentum equation

\[
\frac{1}{R_g T} \left[ \frac{\partial(PAU)_i}{\partial t} + \frac{\partial(PAU^2)_i}{R_a \partial \Theta} \right] + \zeta_r (\dot{m}_{i+1} U_i - \dot{m}_i U_{i-1}) = -\frac{A_i}{R_a} \frac{\partial P_i}{\partial \Theta} + \Delta \tau_{xi}
\]

Wall shear stress difference (Moody’s friction factor)

Li, J., San Andrés, L., and Vance, J., 1999
Model PDS as a grooved seal

Continuity equation

\[
\frac{L}{\xi_r} \frac{\partial (dP_i)}{\partial t} + \frac{\partial (HPV_i)}{\partial z} + \frac{\partial (dPU_i)}{R_r \partial \theta} = 0
\]

Circumferential momentum equation

\[-\frac{1}{R_r} \tau_{\theta,i} - \frac{\partial (dLP_i)}{R_r \partial \theta} = \frac{1}{ZR_g T} \left[ \frac{1}{\xi_r} \frac{\partial (dLPU_i)}{\partial t} + \frac{\partial (dLPU^2_i)}{R_r \partial \theta} + \frac{\partial (HLPUV_i)}{\partial z} \right] \]

Axial momentum equation

\[-\left[ \frac{1}{R_r} \tau_{z,i} + \frac{\partial (HLP_i)}{\partial z} \right] = \frac{1}{ZR_g T} \left[ \frac{1}{\xi_r} \frac{\partial (dLPV_i)}{\partial t} + \frac{\partial (HLPV^2_i)}{\partial z} + \frac{\partial (dLPUV_i)}{R_r \partial \theta} \right] \]

Replaces empirical leakage equation

Considers blade thickness

Kim, C. H., Childs, D. W., 1987
### GE tests – seals geometry


<table>
<thead>
<tr>
<th></th>
<th>14 bladed LS</th>
<th>8 bladed, 8 pocket FPDS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blades properties</strong></td>
<td>All active</td>
<td>Active / Inactive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(without notch / with notch)</td>
</tr>
<tr>
<td><strong>Cavity depth</strong></td>
<td>4 mm</td>
<td>3.175 mm</td>
</tr>
<tr>
<td><strong>Cavity axial length</strong></td>
<td>5 mm</td>
<td>14 mm / 6.35 mm</td>
</tr>
<tr>
<td><strong>Blade thickness (tip)</strong></td>
<td>~ 0</td>
<td>6.35 mm / 3.175 mm</td>
</tr>
<tr>
<td><strong>Radial clearance</strong></td>
<td>0.3 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td><strong>Seal overall length</strong></td>
<td>65 mm</td>
<td>103 mm</td>
</tr>
<tr>
<td><strong>Rotor diameter</strong></td>
<td>170 mm</td>
<td>170 mm</td>
</tr>
</tbody>
</table>
### GE tests: operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pressure</td>
<td>6.9 bar (Absolute pressure)</td>
</tr>
<tr>
<td>Back pressure (Atmosphere)</td>
<td>1 bar (Absolute pressure)</td>
</tr>
<tr>
<td>Excitation frequency</td>
<td>0 - 250 Hz</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>286 K (13° C)</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>7 krpm 15 krpm 7 krpm 15 krpm</td>
</tr>
<tr>
<td>Rotor surface velocity</td>
<td>62 m/s 133 m/s 62 m/s 133 m/s</td>
</tr>
<tr>
<td>Inlet preswirl velocity</td>
<td>0 0 60 m/s 60 m/s</td>
</tr>
<tr>
<td>Preswirl ratio</td>
<td>0 0 0.96 0.45</td>
</tr>
</tbody>
</table>

**Inlet preswirl ratio** = \( \frac{\text{inlet circumferential flow speed}}{\text{rotor surface velocity}} \)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td>28.97</td>
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<tr>
<td>Gas compressibility factor</td>
<td>1</td>
</tr>
<tr>
<td>Specific heat ratio</td>
<td>1.4</td>
</tr>
<tr>
<td>Viscosity</td>
<td>18 µPa·s at 13° C</td>
</tr>
</tbody>
</table>