Comparison of Performance Test Results to CFD and Structural Models of Non-Contacting Finger Seals

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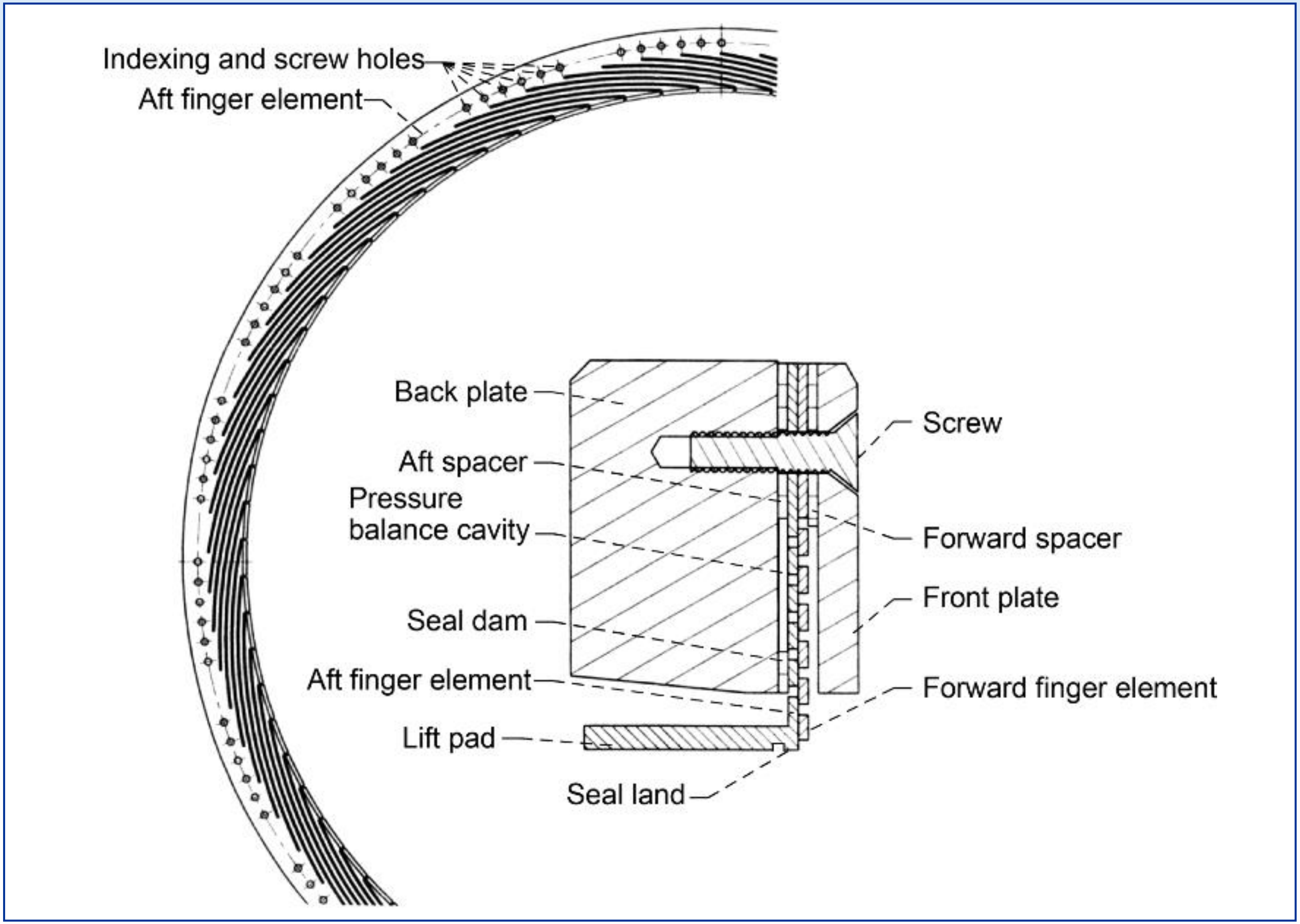
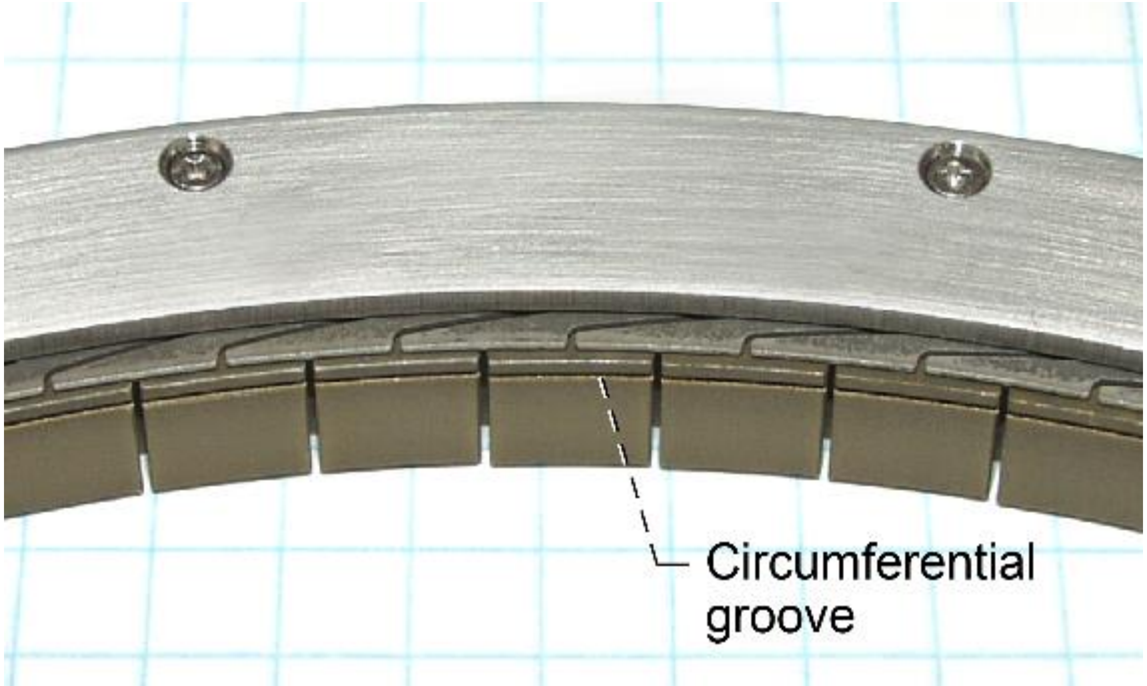
2018 STLE Annual Meeting and Exhibition
Minneapolis, Minnesota
May 20-24, 2018

Baseline Non-Contacting Finger Seal (NCFS)



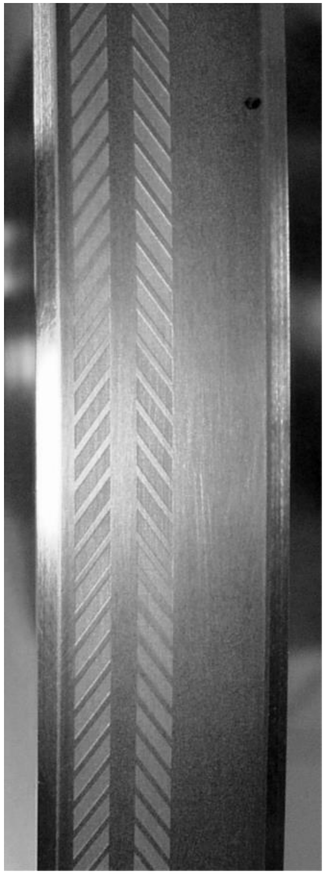
Non-Contacting Finger Seal—Pretest



- Haynes®–188
- Temperatures up to 1089 K
- Radial clearance to rotor = 24 µm (0.0009 in.)
- Lift pads ride over herringbone grooves

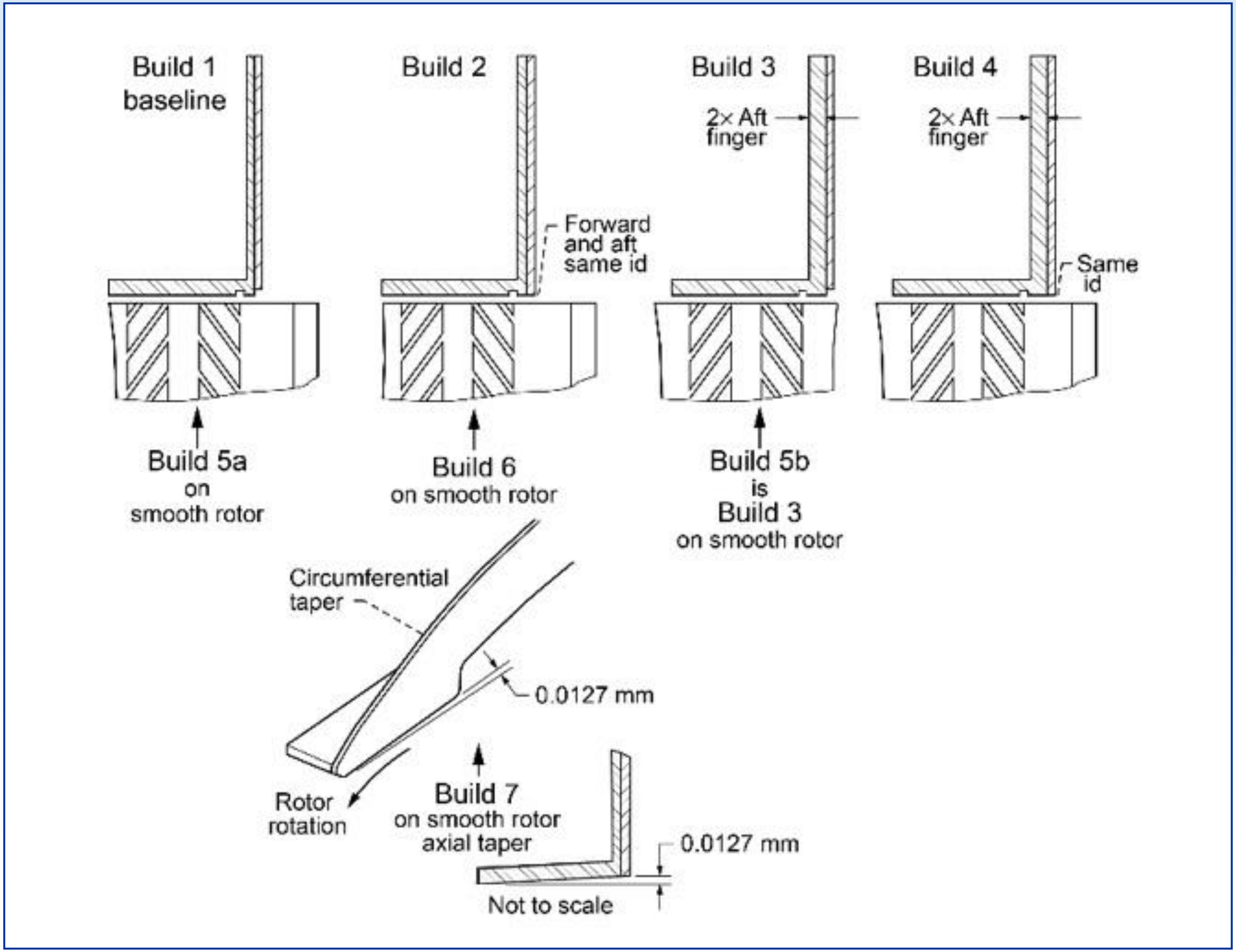
Herringbone Grooves on Seal Test Rotor—Pretest

Rotation



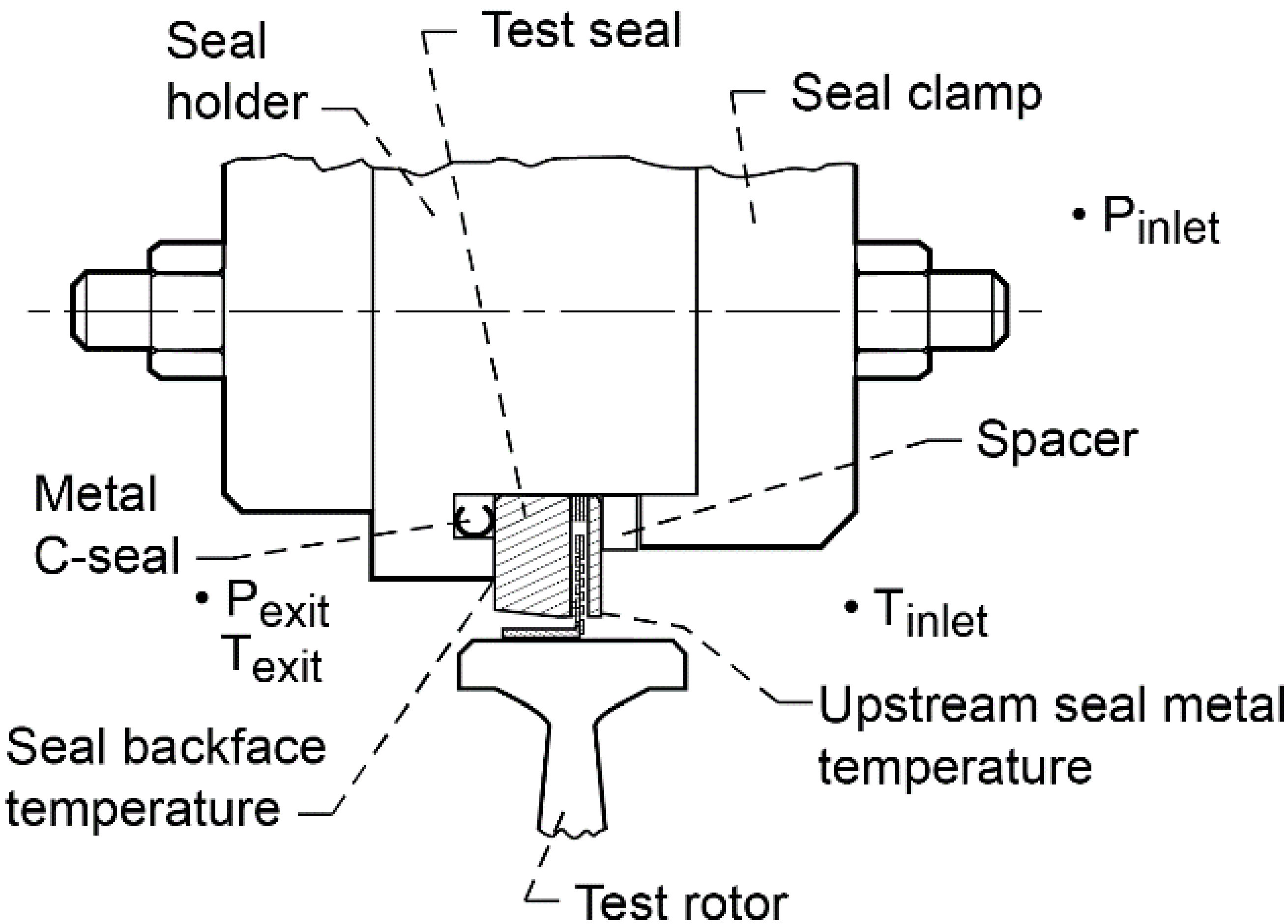
- Rotor od: 216 mm (8.5 in.)
- Grainex Mar-M–247 rotor
- Chrome carbide coating (HVOF)
- Surface finish: 0.2 μm (8 μin.)
- 536 grooves (268 around circumference)
- Groove depth: 20 μm (0.0008 in.)
- Groove ends:
  - Begin at middle of circumferential groove on lift pads
  - Extend past low-pressure edge of lift pads

Builds 1 to 7



Build 1
baseline
Build 2
Forward
and aft
same id
Build 3
2× Aft
finger
Build 4
2× Aft
finger
Same
id
Build 5a
on
smooth rotor
Build 6
on smooth rotor
Build 5b
is
Build 3
on smooth rotor
Circumferential
taper
0.0127 mm
Rotor
rotation
Build 7
on smooth rotor
axial taper
0.0127 mm
Not to scale

Test Seal Configuration and Location of Research Measurements



Flow Factor

$$\phi = \frac{\dot{m}\sqrt{T_{avg}}}{P_u \times D_{seal}}, \ \frac{\text{kg-}\sqrt{\text{K}}}{\text{MPa-m-s}}$$

$\dot{m}$ = air leakage flow rate, kg/s.

T_{avg} = average seal air inlet temperature, K.

P_u = air pressure upstream of seal, MPa.

D_{seal} = outside diameter of the test rotor, m.

Prior NASA Work Found…

Preliminary tests of the baseline NCFS at 300 K and 5000 rpm demonstrated noncontacting operation at 14 to 241 kPa and no measurable wear after 93 min of testing.

In static testing:

- Build 4 had the lowest flow factor and the least hysteresis.
- All builds experienced bind-up when the pressure differential became too high.
- Build 4 bind-up pressure at room temperature was 344 kPa.

References:
- *Proctor, Margaret P.; and Delgado, Irebert R.: Preliminary Test Results of a Non-Contacting Finger Seal on a Herringbone-Grooved Rotor. NASA/TM—2008-215475 (AIAA 2008–4506), 2008. http://ntrs.nasa.gov*
- *Proctor, Margaret P.: Non-Contacting Finger Seals Static Performance Test Results at Ambient and High Temperatures. AIAA 2016–4921, 2016.*

Dynamic Performance Tests

Builds 2, 7, 3, and 4 were tested in that order.

Room-temperature (300 K) lift-off test and performance tests were conducted for each of these seals.

Additional performance tests were conducted for NCFS Build 4 at

- 69 kPa and 558 to 600 K
- 69 kPa 700 K
- 69 kPa 922 K

Then at

- 172 kPa and 294 K

Modeling Non-Contacting Finger Seals

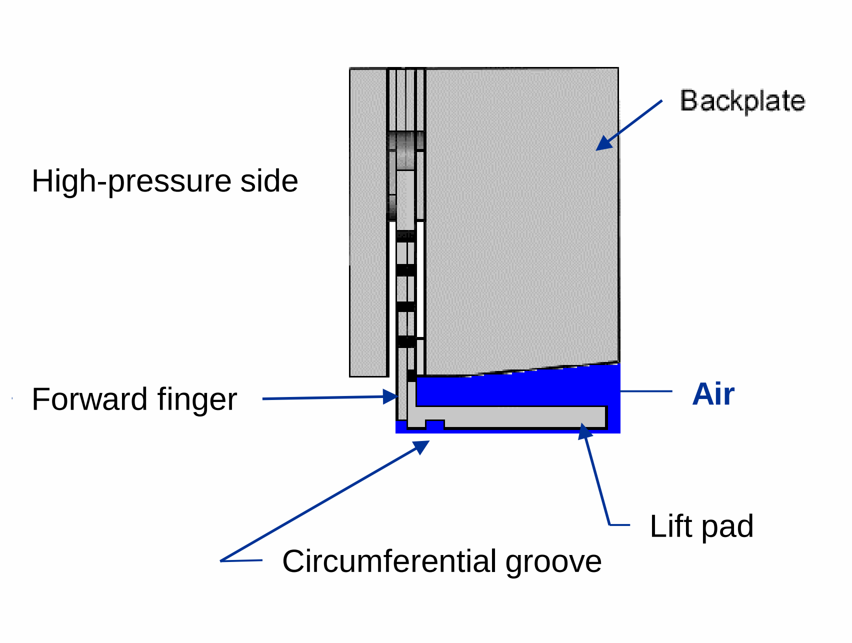
Purpose:

- Understand bind-up and predict leakage rate and pressure capability of NCFS.
- Develop tools to guide design modifications.

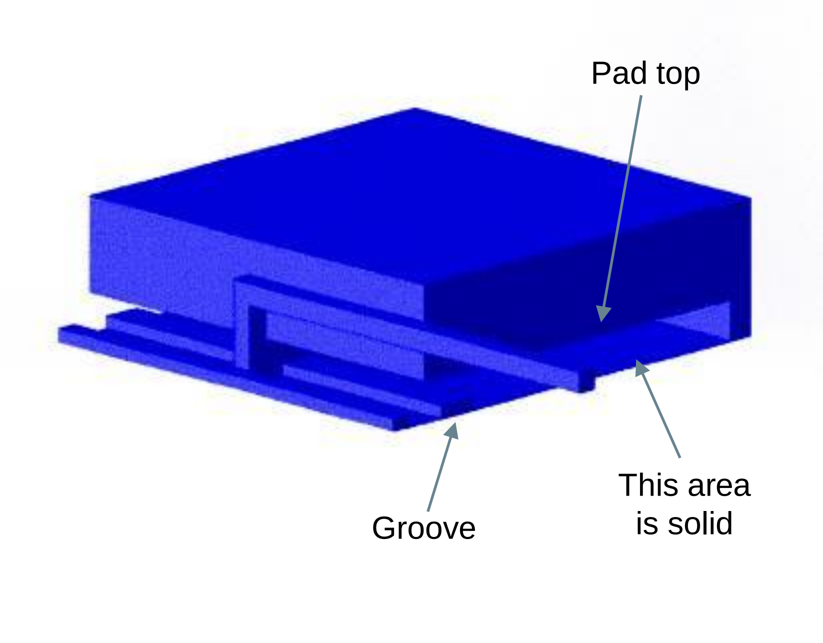
Approach:

- Developed CFD model of seal with as-built geometry, but with smooth, stationary rotor.
- Used experimentally measured seal inlet and exit pressure and temperature conditions from static tests as inputs to the CFD model.
- Used CFD model to compute the seal flow rate and flow factor and the pressures in the seal.
- Applied pressures from the CFD model to the structural model to determine deformation and stresses.
- Used ANSYS FLUENT and ANSYS Mechanical.
- Selected NCFS Build 4 as the verification case.

Simplified CFD Model



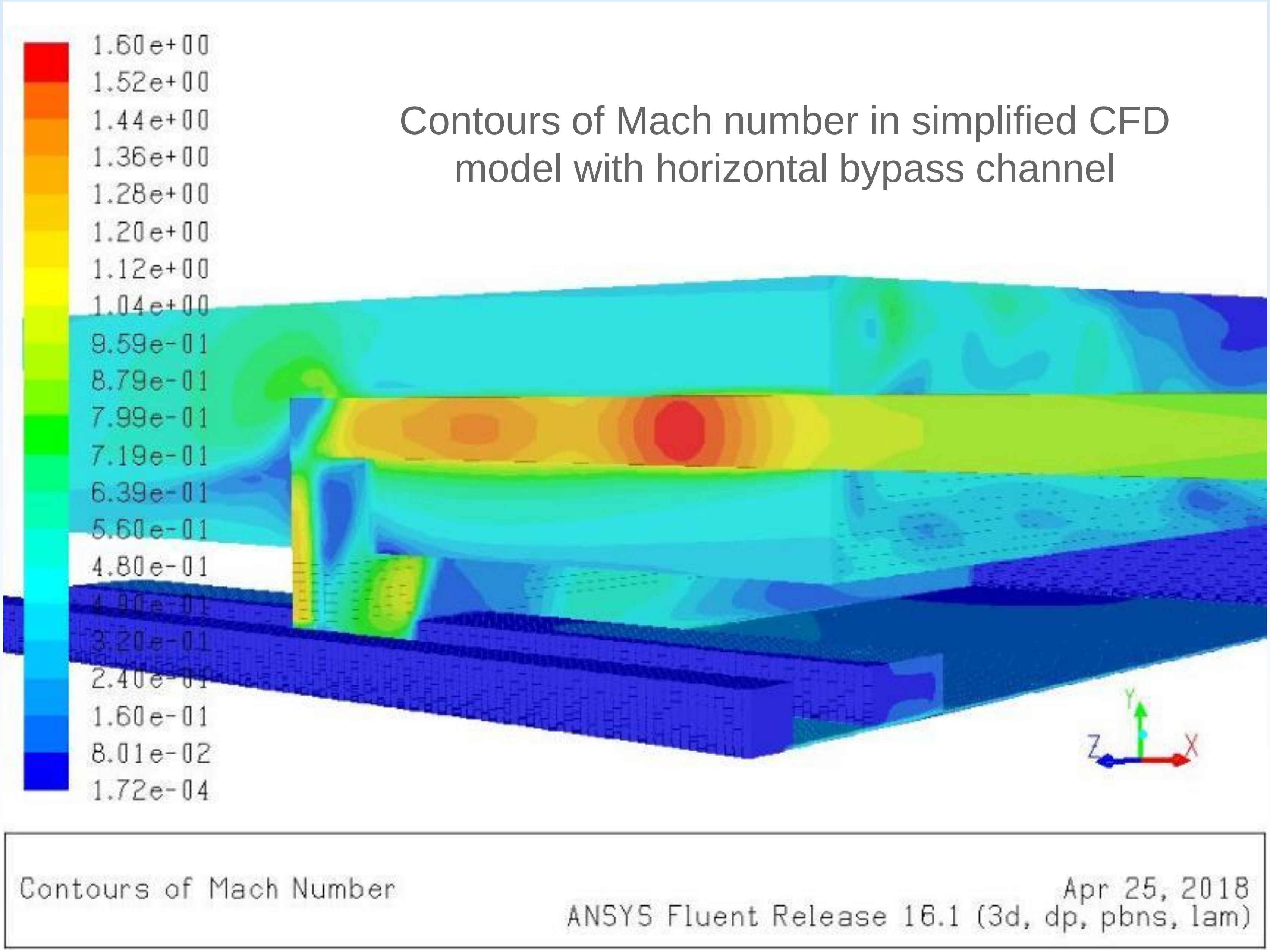
Noncontacting finger seal solid model



Simplified CFD model of air

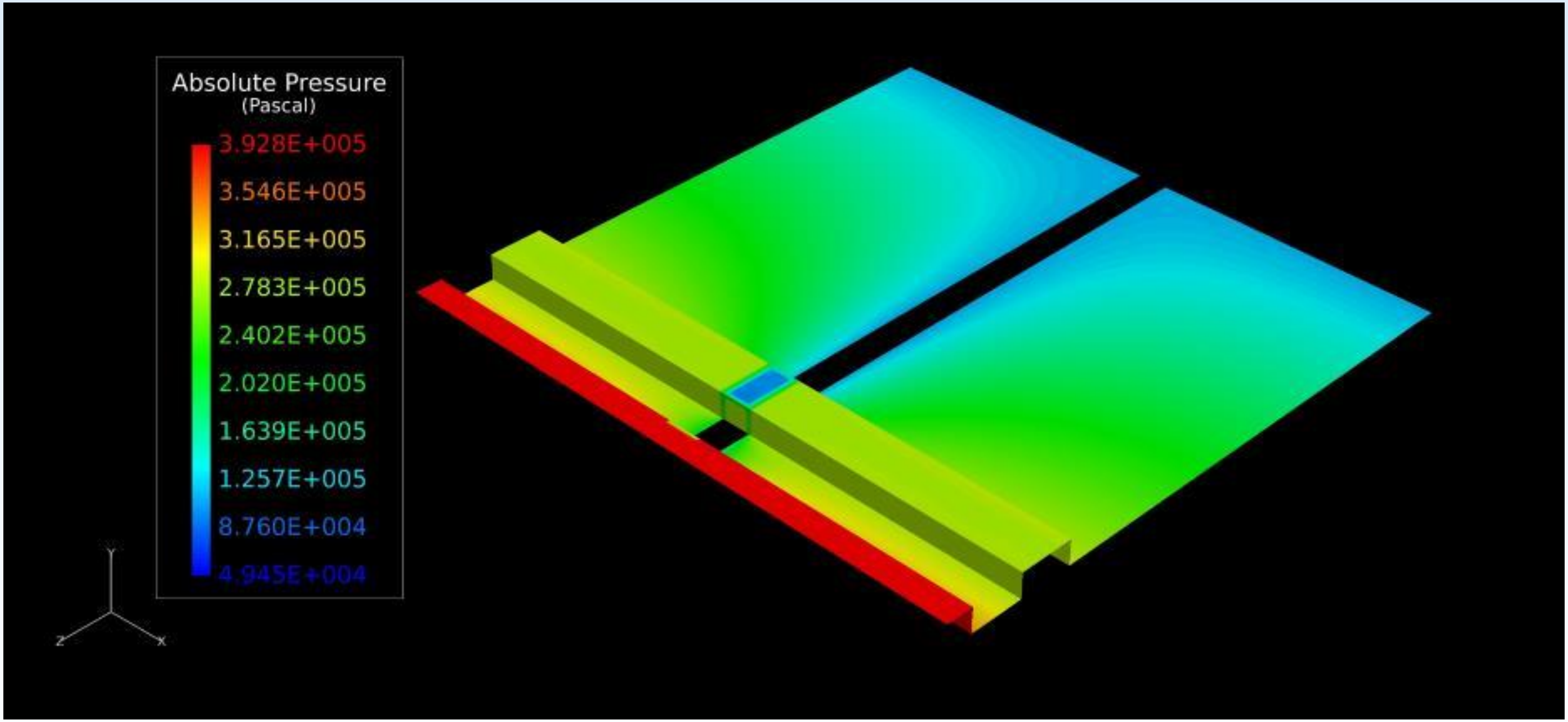
- Air above and below 2 half-aft pads and 1 forward finger is modeled.
- Curvature is removed since clearance is much less than seal radius.
- Channel formed by gap between aft fingers and the seal dam is straight and either horizontal or vertical (2 models built).

Typical Results From CFD Model



Contours of Mach number in simplified CFD model with horizontal bypass channel

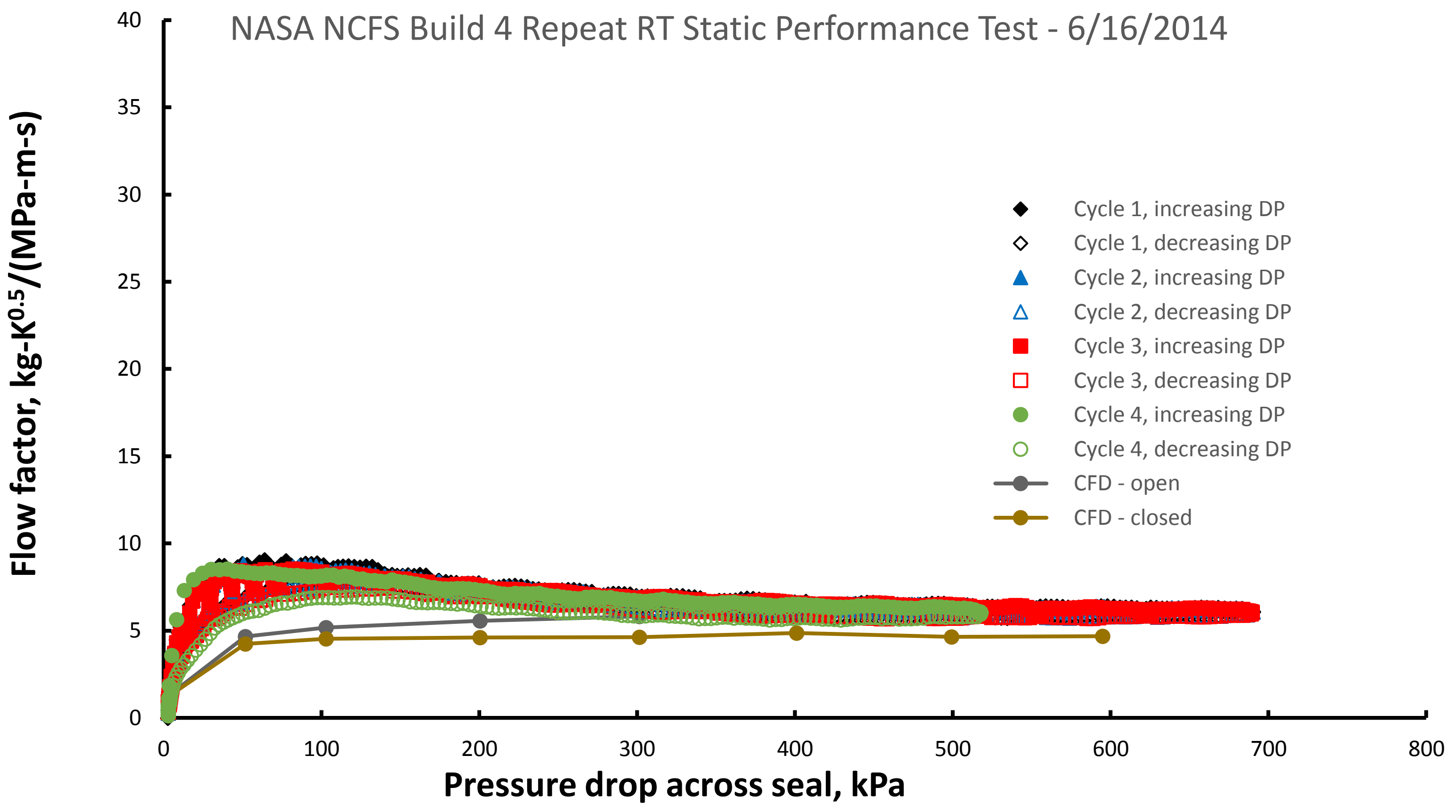
Typical Results From CFD Model



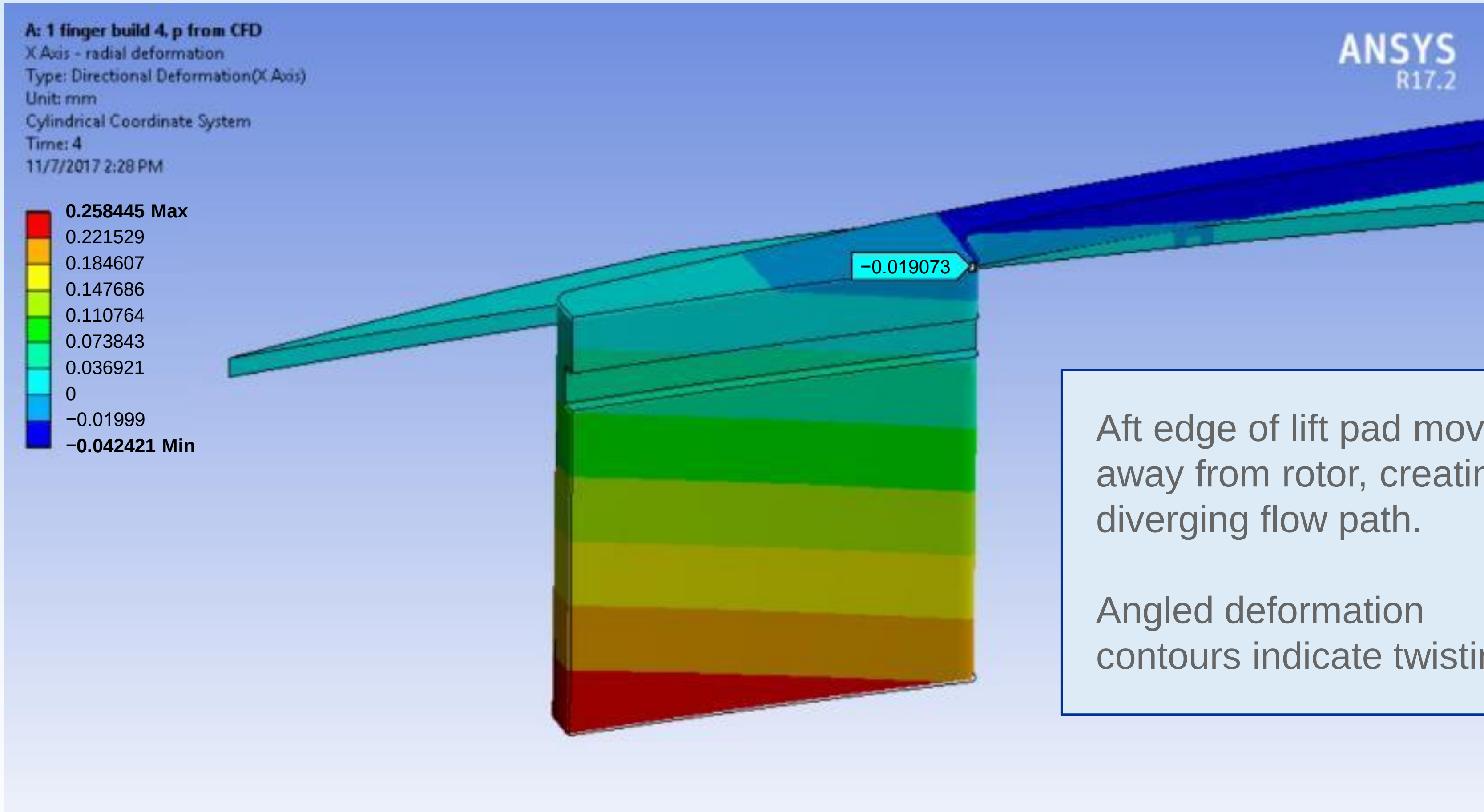
Contours of absolute pressure on the NCFS Build 1 seal id at pressure differential of 278 kPa

Comparison of CFD Predicted Flow Factor and Experimental Data

CFD model has same trend, but slightly underpredicts test data.



Single-Finger Structural Model

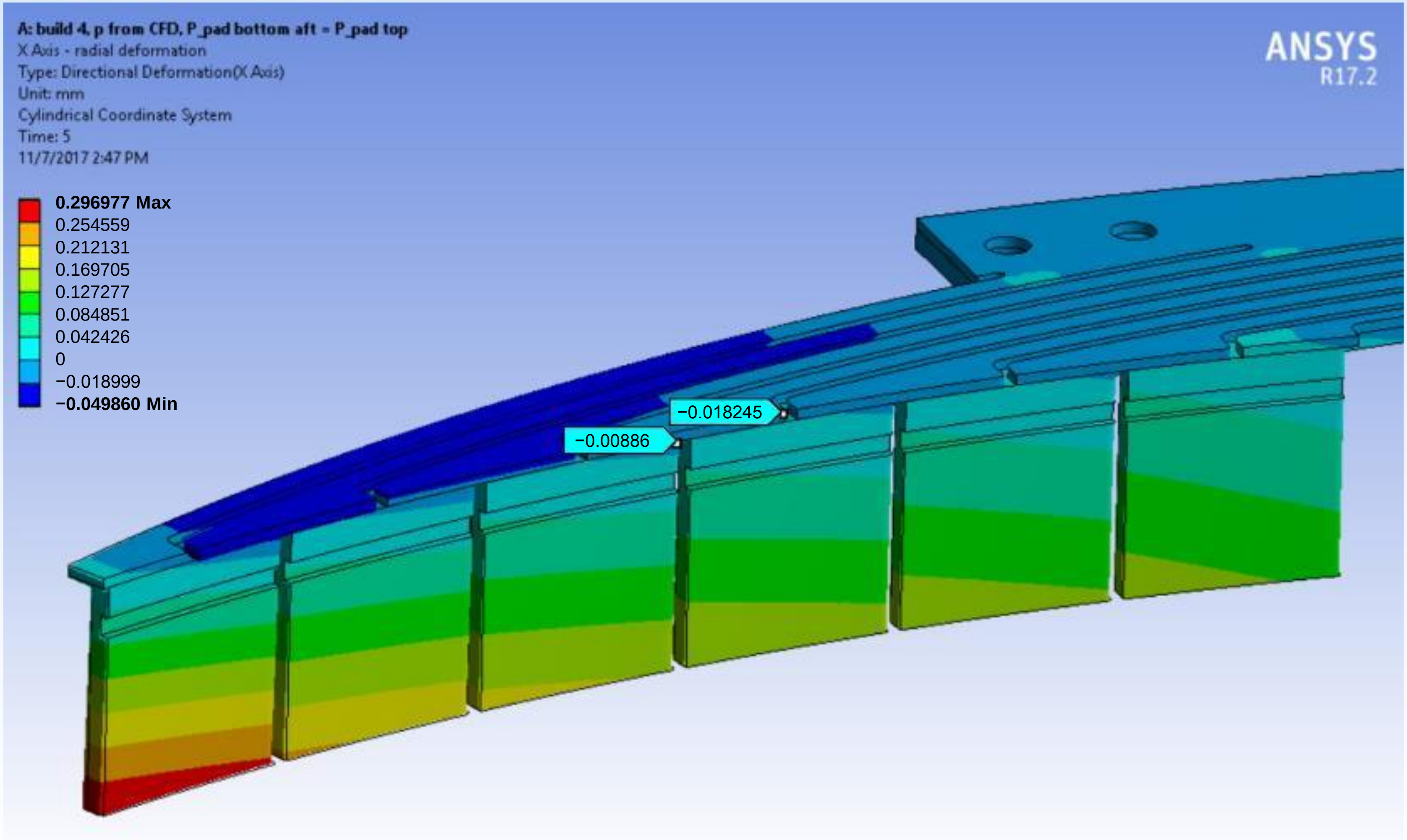


Aft edge of lift pad moves away from rotor, creating a diverging flow path.

Angled deformation contours indicate twisting.

Radial deflections for single-finger model of NCFS Build 4, load case 4 (301.3-kPa pressure differential)

Six-Finger Structural Model



Radial deflections of NCFS Build 4 predicted with six-finger model at load case 5 (400.5 kPa). Positive deflections are radially outward. Deflections reported for third full-forward and aft fingers from the left.

Radial Deflections and Stress From Single-Finger Model

Deflections greater than the as-built radial clearance of the aft finger of 0.02 mm are in bold face type, indicating contact with the rotor.

Radial Deflection and Stress vs. Pressure				
Model: 2017-07-10_build4_1finger				
Load case	ΔP (kPa)	Aft deflection (mm)	Max. equivalent stress (kPa)	Max. principal stress (kPa)
1	51.7	1.58E−03	36,568	34,439
2	102.8	−4.23E−03	68,803	70,906
3	200.5	−1.15E−02	140,212	148,734
4	301.3	−1.91E−02	217,054	230,244
5	400.5	**−2.59E−02**	292,296	310,057
6	499.3	**−3.34E−02**	364,629	386,782
7	594.9	**−4.05E−02**	445,450	459,529

Using linear interpolation, contact with the rotor—or bind-up—would first occur at 314 kPa.

Predicted and Measured Bind-up

Single-finger model predicts bind-up at 314 kPa

- Is 9 percent lower than measured bind-up of 344 kPa

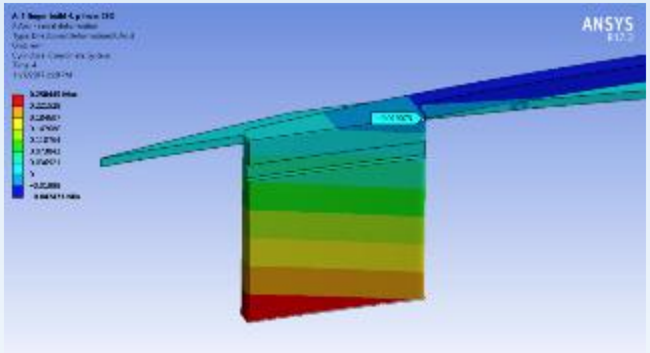
Six-finger model predicts bind-up at 414 kPa

- Is 20 percent higher than measured
- Has both forward and aft fingers to support pressure load and has more frictional surfaces, so more pressure differential is needed to move the fingers

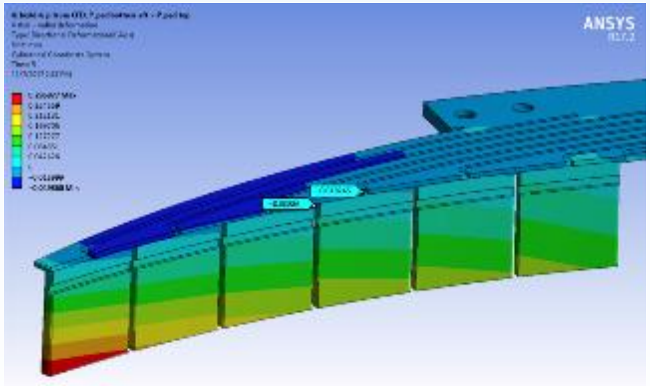
Recall that CFD model is for a fixed clearance. Once fingers start to move, the clearance changes and subsequently so do the internal pressures in the seal.

Predicted Deformation vs. Wear Pattern

Simplified modeling approach yields deformations similar to wear patterns after performance tests of NCFS Build 4 at 300 K and 172 kPa.



Single-finger model deformations



Six-finger model deformations

Summary of Findings

1. The simplified CFD models underpredict the flow factors, but have the same trend as the experimental data.

2. The difference between predicted and measured flow factors results from the model having a fixed clearance and in reality, the clearance changes due to deformation of the seal when pressure is applied.

3. Iterating between the fluid and structural models would improve the predictions. However, much can be accomplished with the design tools developed to date.

4. Structural modeling shows the downstream edge of the lift pad moves radially outward with a twist such that the heel of the finger foot at the upstream edge actually moves radially inward.

5. Wear patterns on the inner surface of the seal are similar to predicted radial deflection of the lift pad and validate the modeling.

Conclusions

1. Deflection of the lift pad at 172 kPa changes the geometry of this specific non-contacting finger seal such that the features intended to create hydrodynamic lift cannot work. Specifically, the lift pad does not remain parallel to the rotor surface and deforms to a diverging flow path.

2. For applications with high-pressure differentials, designs that use hydrostatic forces to control seal clearance will likely be more effective for compliant, low-leakage seal designs.

3. Further work on compliant, noncontacting, low-leakage seal designs is recommended for future gas turbine engine applications.