Non-Contacting Finger Seals Static Performance Test Results at Ambient and High Temperatures

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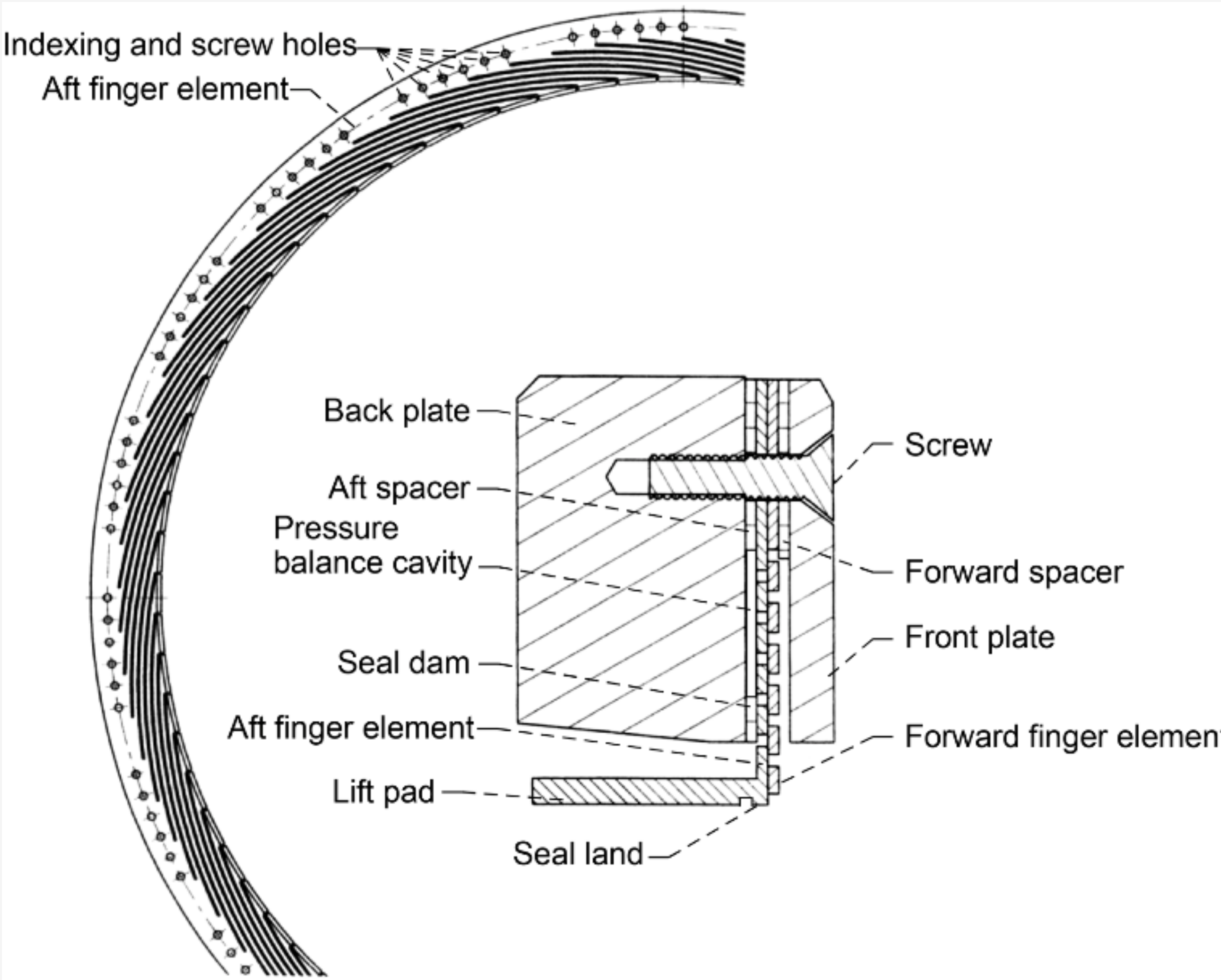
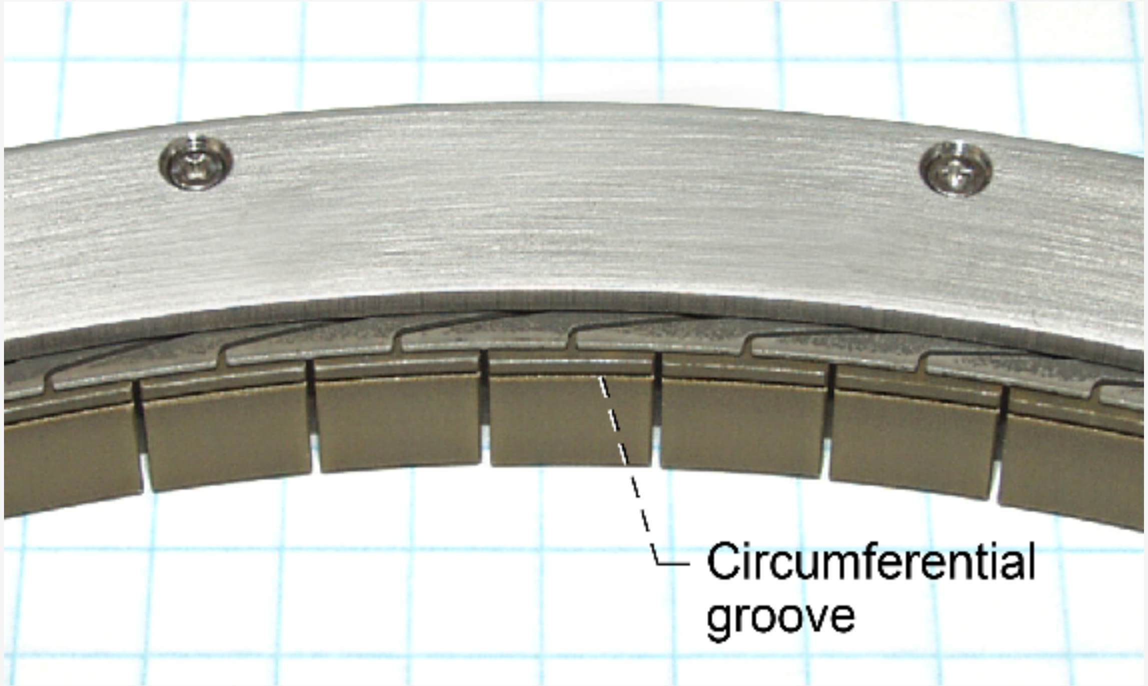
Baseline Non-Contacting Finger Seal (NCFS)



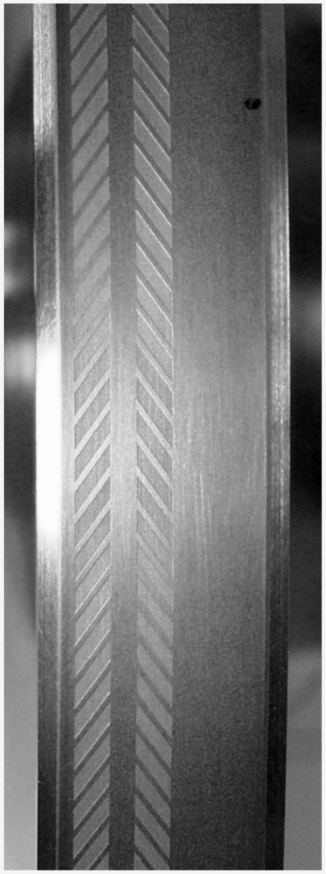
Non-Contacting Finger Seal—Pre-Test



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

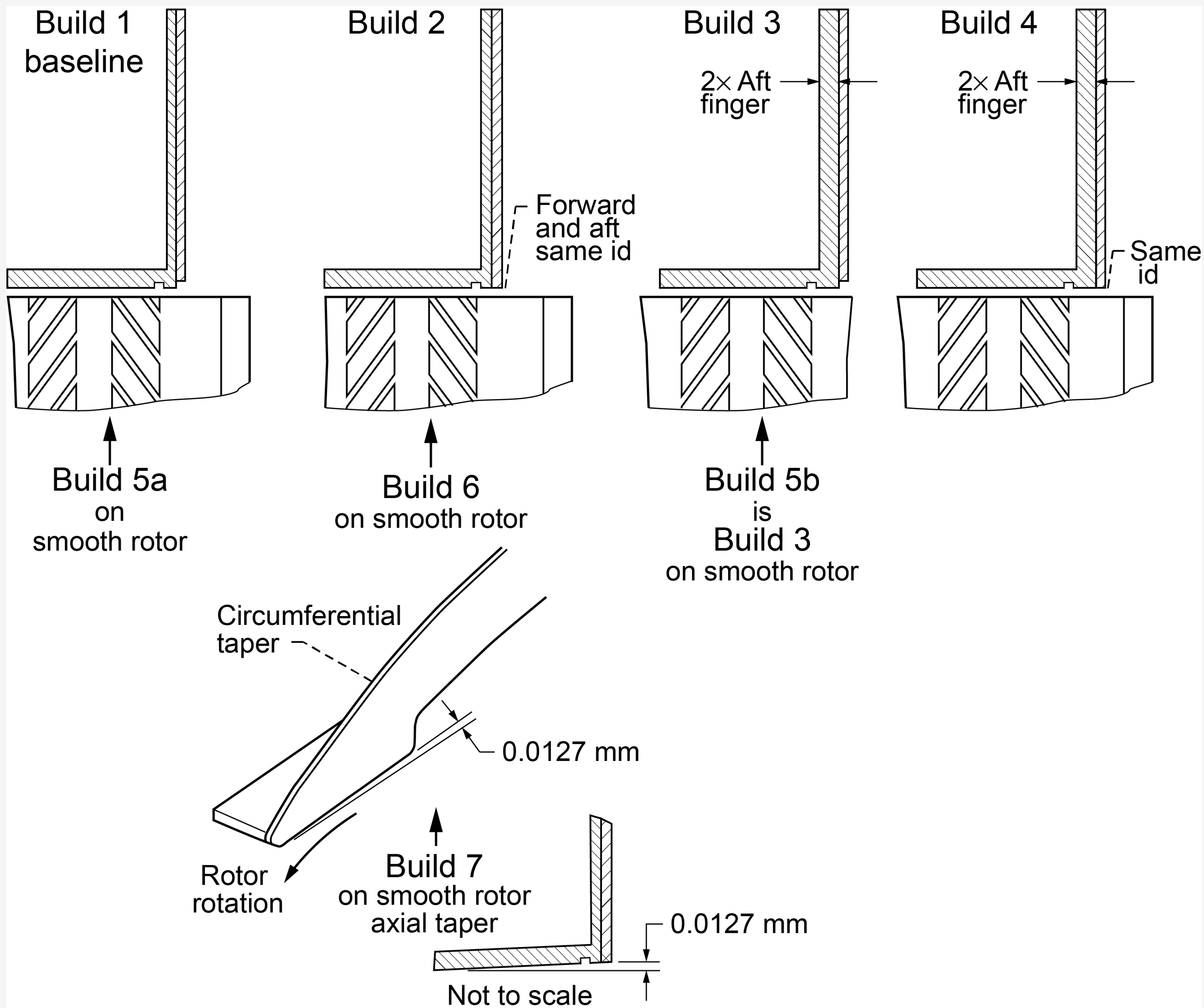
Herringbone Grooves on Seal Test Rotor—Pre-Test

Rotation ↓



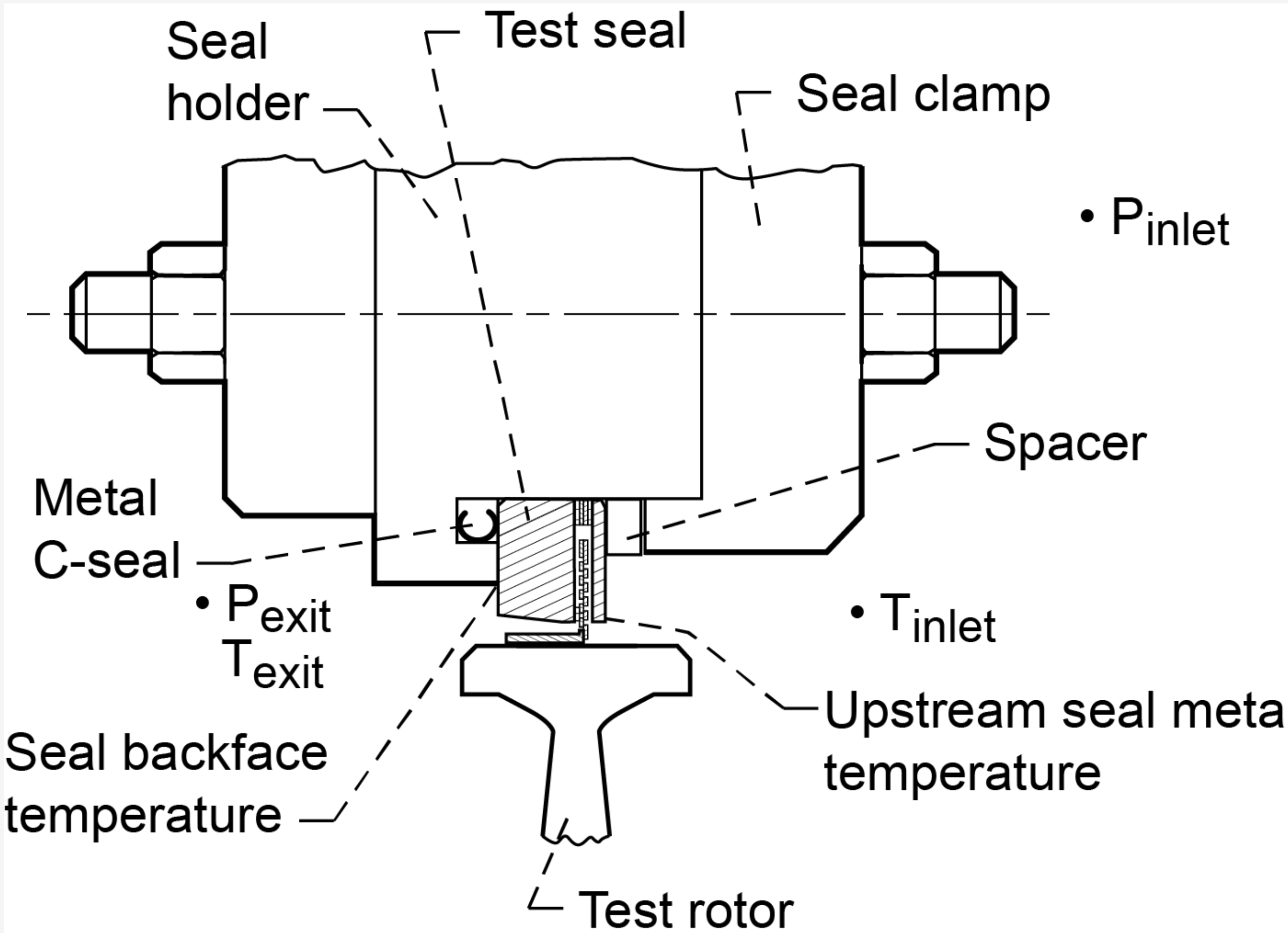
- Rotor O.D.: 216 mm (8.5 in.)
- Grainex Mar-M–247 rotor
- Chrome carbide coating (HVOF)
- Surface finish: 0.2 μm (8 μin.)
- 536 grooves (268 around circumference)
- Groove depth: 20 μm (0.0008 in.)
- Groove ends:
  - Begin at middle of circumferential groove on lift pads
  - Extend past low pressure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

High-Temperature, High-Speed Turbine Seal Rig

Test Seal Configuration and Location of Research Measurements



Flow Factor

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

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

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

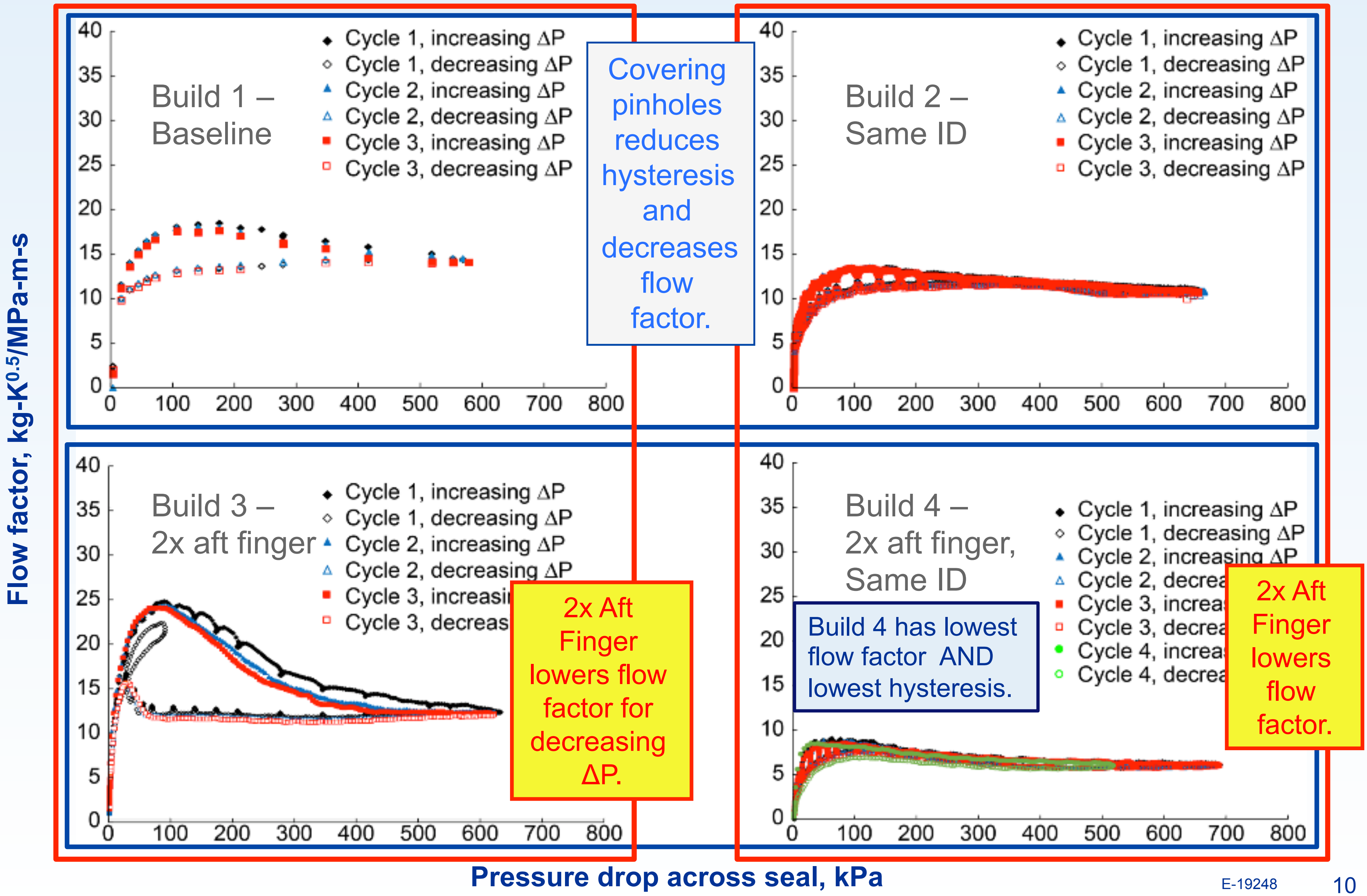
P_u = air pressure upstream of seal, MPa.

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

Test Procedure

- Initial room temperature static test
- Bind-Up test
- Repeat room temperature static test
- Static test with bigger clearance
- Static performance test at 533, 700, and 922 K

Static Leakage Performance of Non-Contacting Finger Seals at ~300 K

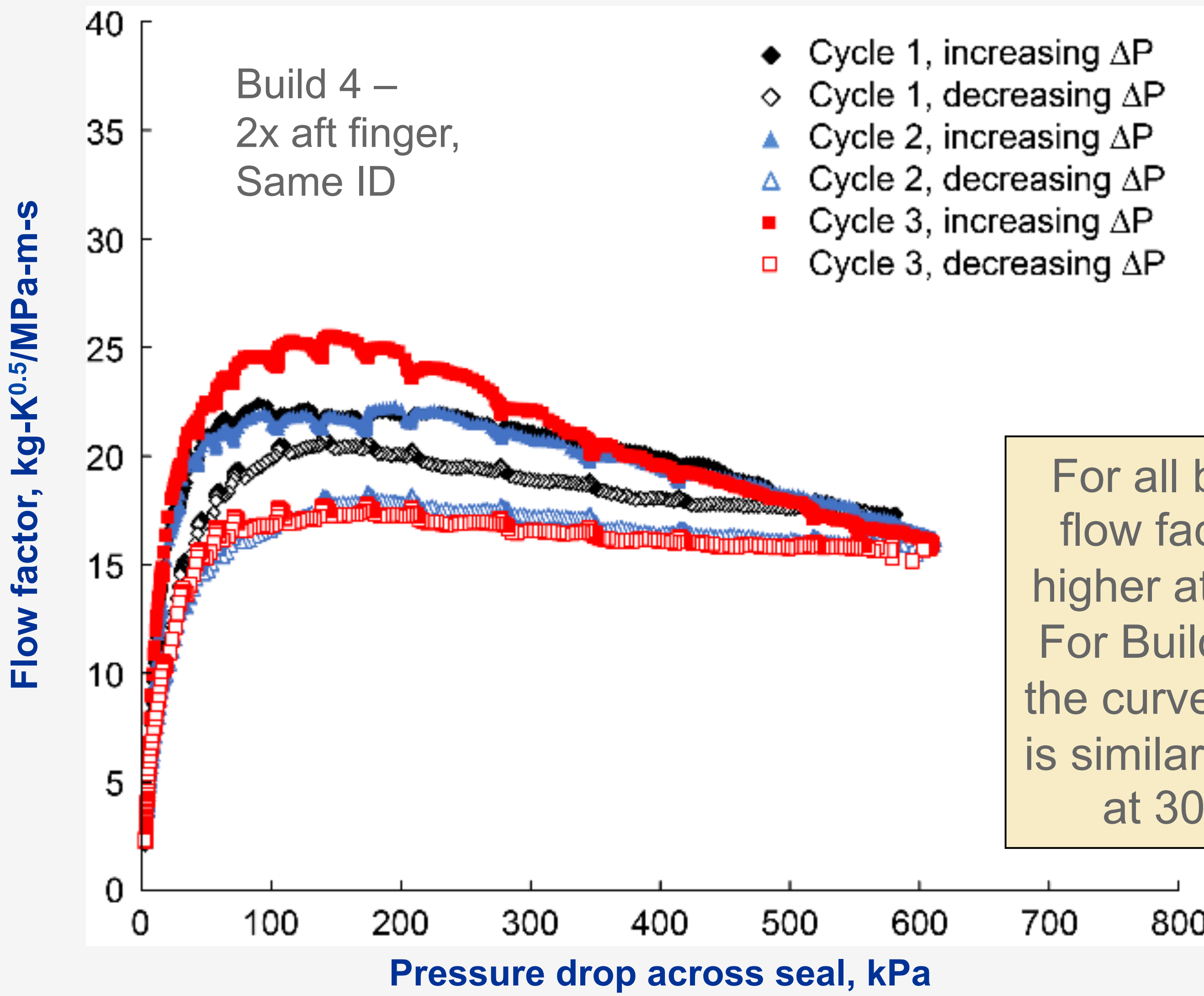


Factors Contributing to Effect of 2X Aft Finger

2X Aft Finger:

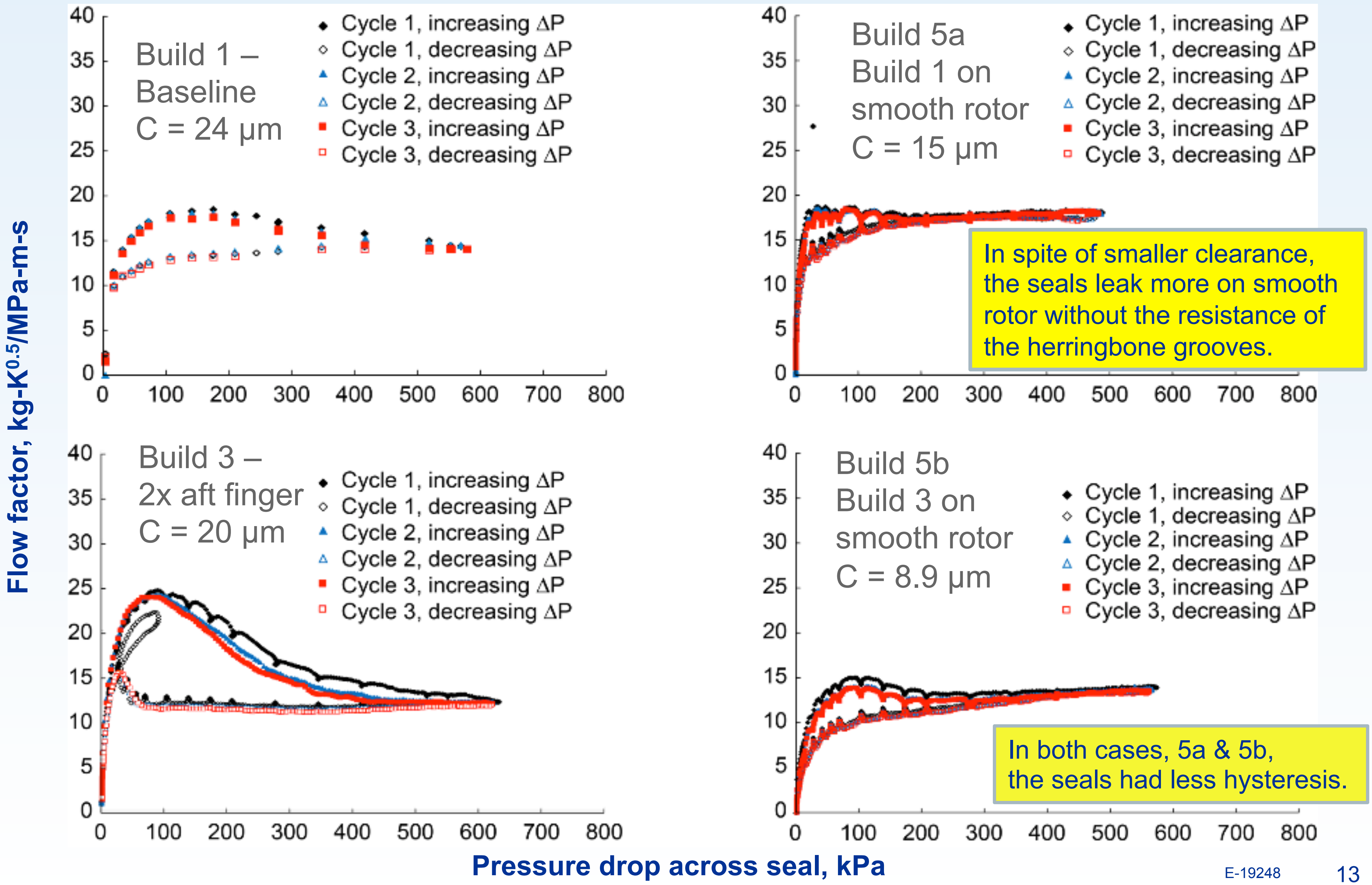
- Radial clearance is 6.35 μm smaller
- Seal land is 1.36 times longer
- Radial stiffness is 2 times greater
- Axial stiffness is 8 times greater

Static Leakage Performance of Build 4
Average Inlet Air Temperature = 862 to 911 K

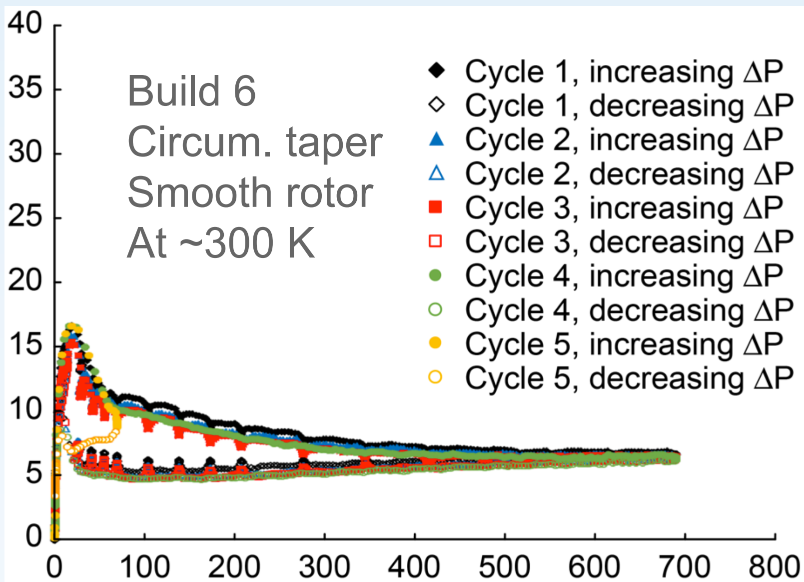


For all builds, flow factor is higher at 922 K. For Builds 1-4, the curve shape is similar to data at 300 K.

Comparison of Static Leakage Performance of NCFS on Herringbone-Grooved Rotor to Smooth Rotor at ~300 K

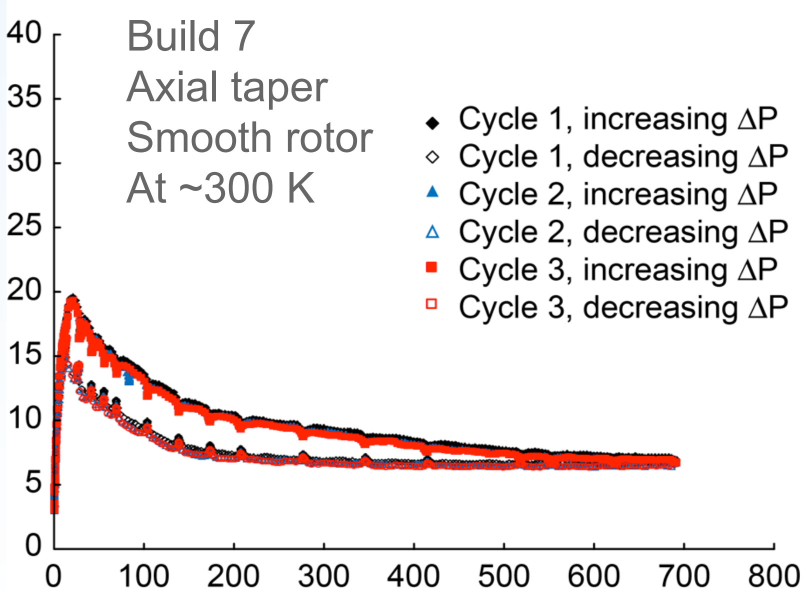


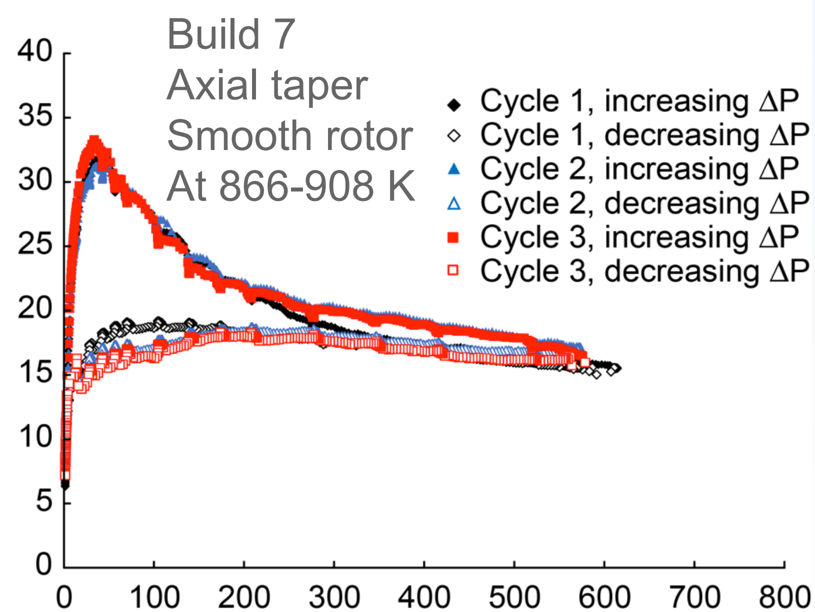
Static Leakage Performance of NCFS With Tapered Lift Pads and No Circumferential Groove



For Builds 6 & 7:

- Above 300 kPa, flow factor is similar to Build 4.
- At lower pressures, there is more hysteresis than Build 4 and a different curve shape.
- The peak at ~20 kPa suggests the lift pad initially moves away from rotor.
- Entire lift pad is the seal land.
- Tapers create a different pressure distribution under the lift pad.
- At 900 K, the peak in flow factor doesn't occur when decreasing pressure.





Flow factor, kg-$K^{0.5}$/MPa-m-s

Pressure drop across seal, kPa

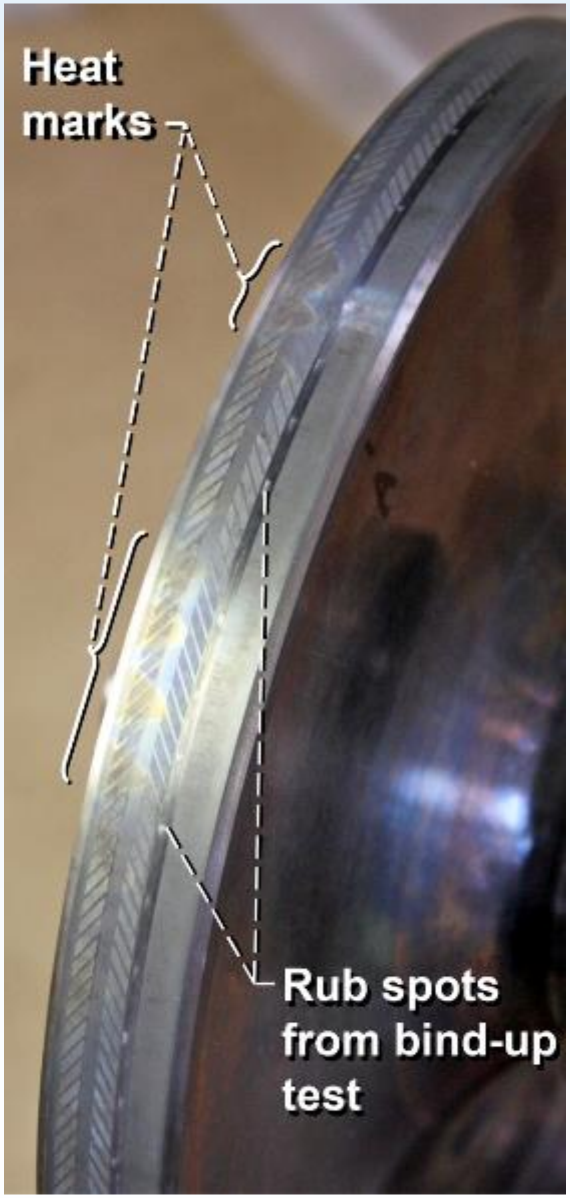
Bind-Up Test Results

Table 6 Bind-up test results: Pressure differential across the seal, kPa

Build no.	Less free wheeling	Free wheeling stopped	Tight	Comment
1	83	124	248 (faint squeak)	2 N-m at 248 kPa
2	55	83	165-248	At 248 kPa light squeak
3	96.5	317	386	
4	96.5	303	344	At 517 kPa very hard to turn
4 at 672 K	317	358	414	
5a	68.9	262	372	
5b	83	138	345	At 150 kPa, 6.8 N-m
6	83	248	414	At 414 kPa, 4 N-m
7	96.5	276	317 (faint squeak)	

- Maximum ΔP Capability at 300 K ranged from ~100 to 300 kPa.
- Builds 3 & 4 with 2X Aft Finger had the greatest ΔP Capability.
- At 672 K, Build 4 radial clearance increased due to different coefficients of thermal expansion and has more ΔP Capability.

Inspection of Build 1
After 922 K Static Performance Test



- Heat marks indicate that flow fans out from point sources.

- Bind-up is due to contact of seal land at the heel of aft finger.

Conclusions

1. ΔP and some rotation is needed to seat the seal for repeatable flow measurements.

2. ΔP across the seal deflects the fingers to contact and bind the rotor.
   - Contact occurs at the heel of the aft finger.
   - Wear pattern suggests the aft finger may deflect axially and twist slightly and/or that the forward finger contacts the rotor as well.
   - The ΔP at which bind-up occurs increases with increased radial clearance.

3. Completely covering the gaps between aft fingers with forward fingers of the same ID significantly reduces leakage.

4. Longer seal lands as in the tapered lift pads can cause more leakage with increasing pressure due to lift of the fingers. The taper provides a path for more high pressure to access the lift pad ID and there is more area for the high pressure to act compared to lift pads with a circumferential groove.

Conclusions Continued

5. The maximum ΔP capability of the NCFS tested at static conditions was …

   between ~100 to 300 kPa at 0 rpm.

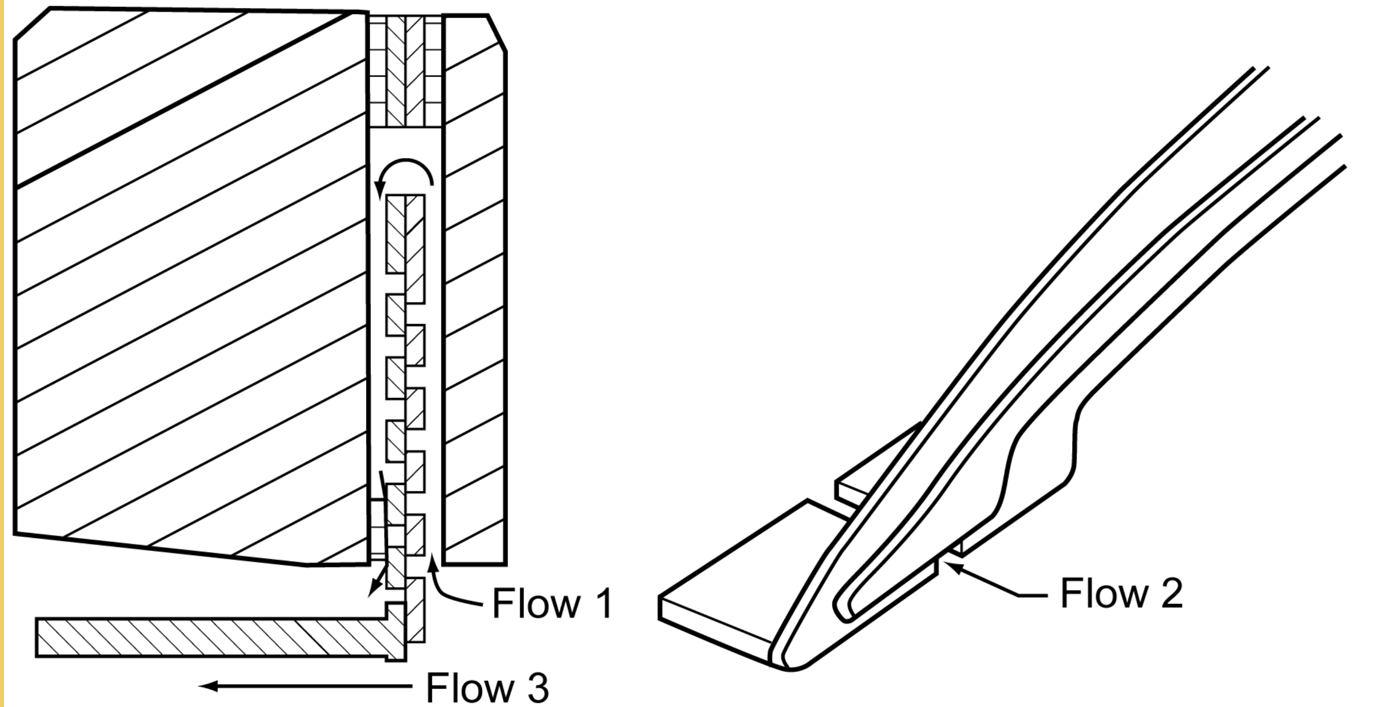
   Due to centrifugal growth of the rotor, the maximum ΔP capability should be adjusted downward as speed is increased.

6. Build 4 (2X Aft Finger and same ID Forward Finger)
   - had the lowest flow factor of ~7 kg-$K^{0.5}$/(MPa-m-s)
   - and the least hysteresis.

7. Performance testing below the maximum ΔP capability is needed to determine if hydrodynamic lifting forces will prevent contact as the shaft grows with rotational speed.

Backup slides

Leakage Flow Model

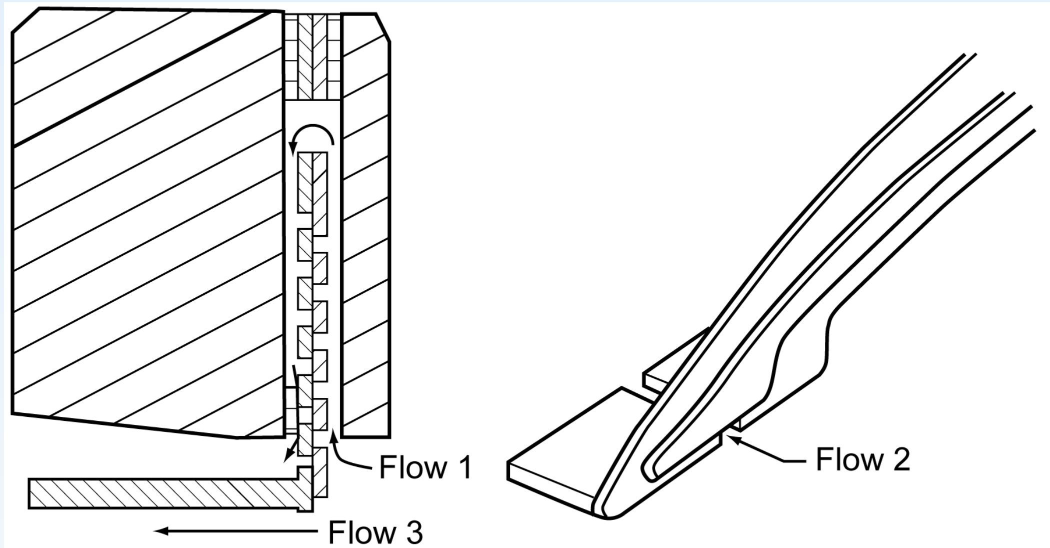


Assumptions

- Isentropic flow
- Seal leakage area is sum of areas of each flow path
- Geometry is fixed
- Lift pads remain concentric to rotor
- Finger elements held tightly to each other and seal dam so there is no leakage between contacting areas
- Pressure in balance cavity equals seal inlet pressure

Flow Areas

Max to Min Ranking	
Build No.	**Flow area, mm^2**
3	50.0
5b	44.0
1	42.4
4	37.6
5a	36.4
2	30.0
6	14.9
7	14.9



Build no.	Description	Flow areas (mm^2)			
		At seal dam	Pin holes	Under lift pads	Total
1	Baseline	13.8	13.0	15.6	42.4
2	Baseline with same ID	13.8	0.6	15.6	30.0
3	Baseline with two times aft finger	25.5	13.0	11.5	50.0
4	Two times aft finger and same ID	25.5	0.6	11.5	37.6
5a	Build 1 on smooth rotor	13.8	12.8	9.8	36.4
5b	Build 3 on smooth rotor	25.5	12.8	5.7	44.0
6	0.0127 mm circum. taper	13.0	0.3	1.6	14.9
7	0.0127 mm axial taper	13.0	0.3	1.6	14.9

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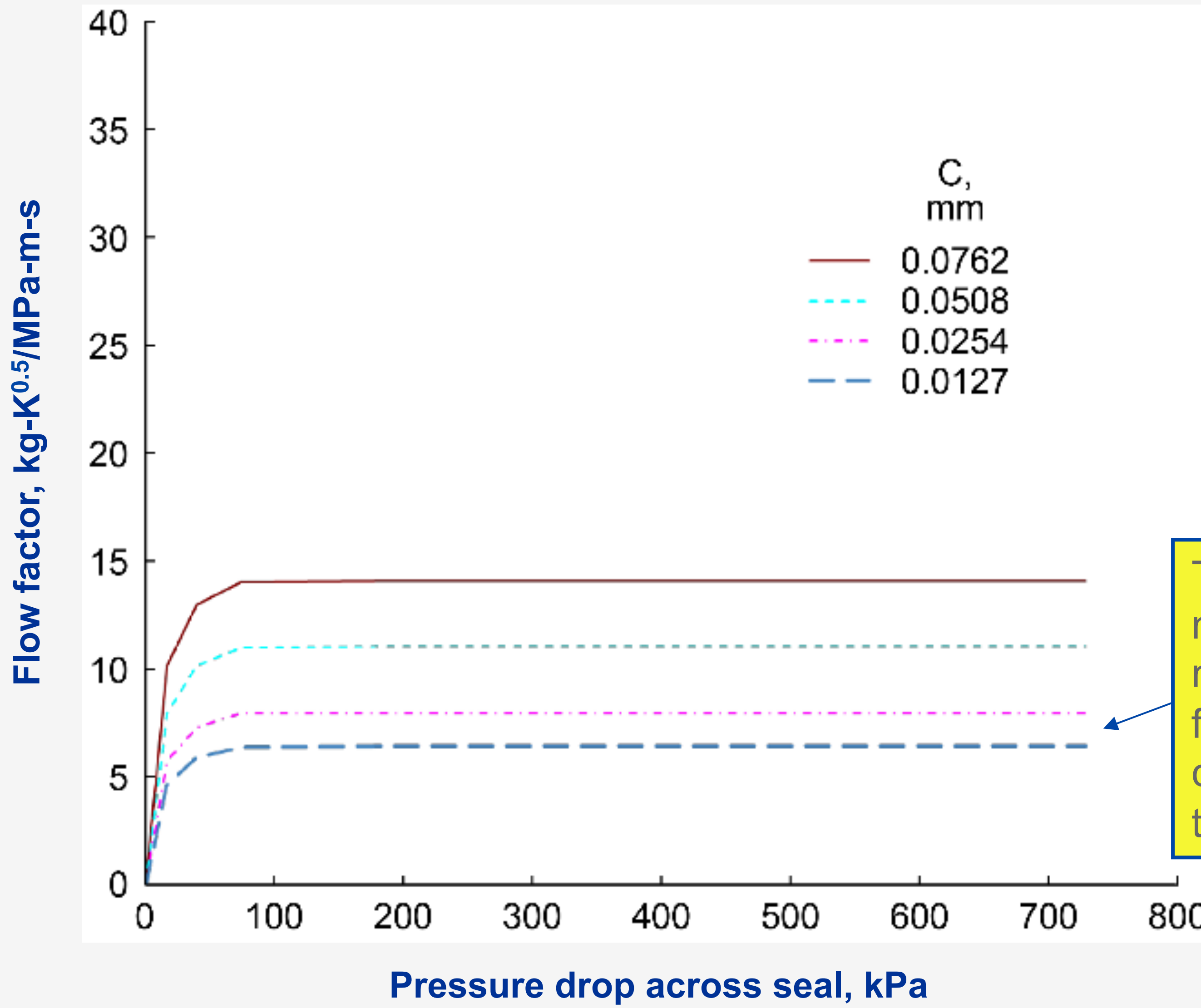
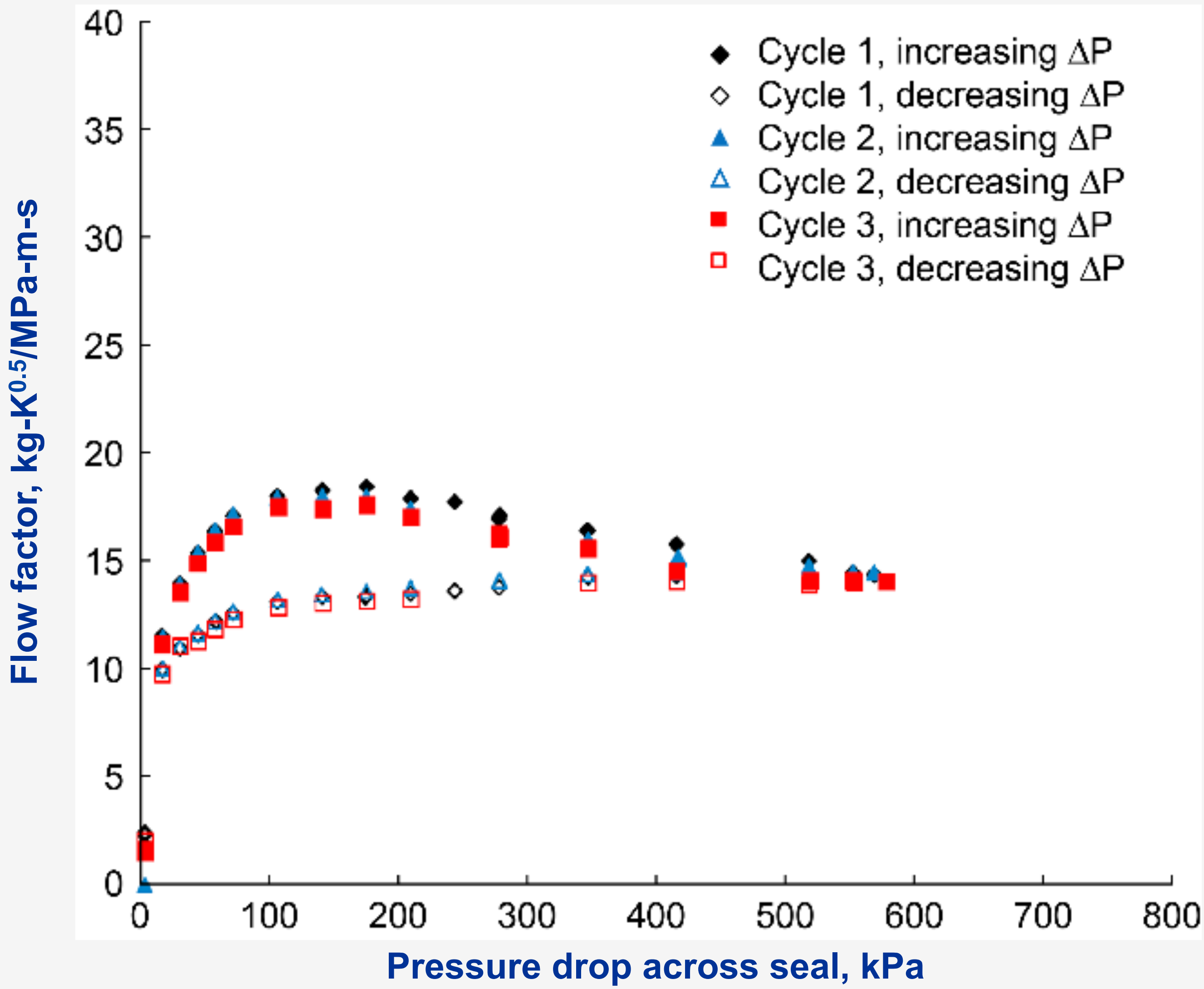
Predicted Flow Factor for Build 4

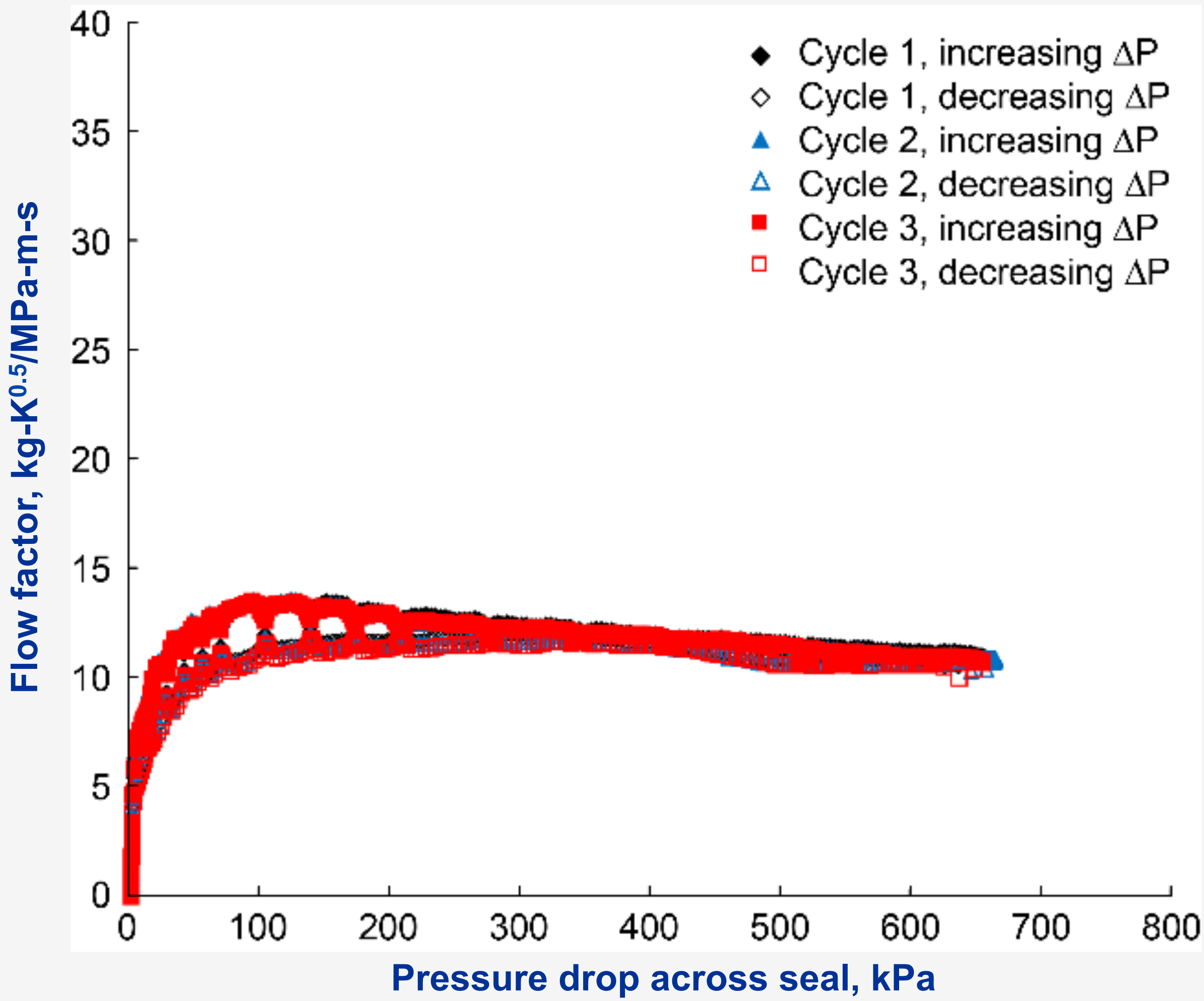


Test data at 300 K most closely matches predictions for radial clearance of 0.0127 to 0.0254 mm.

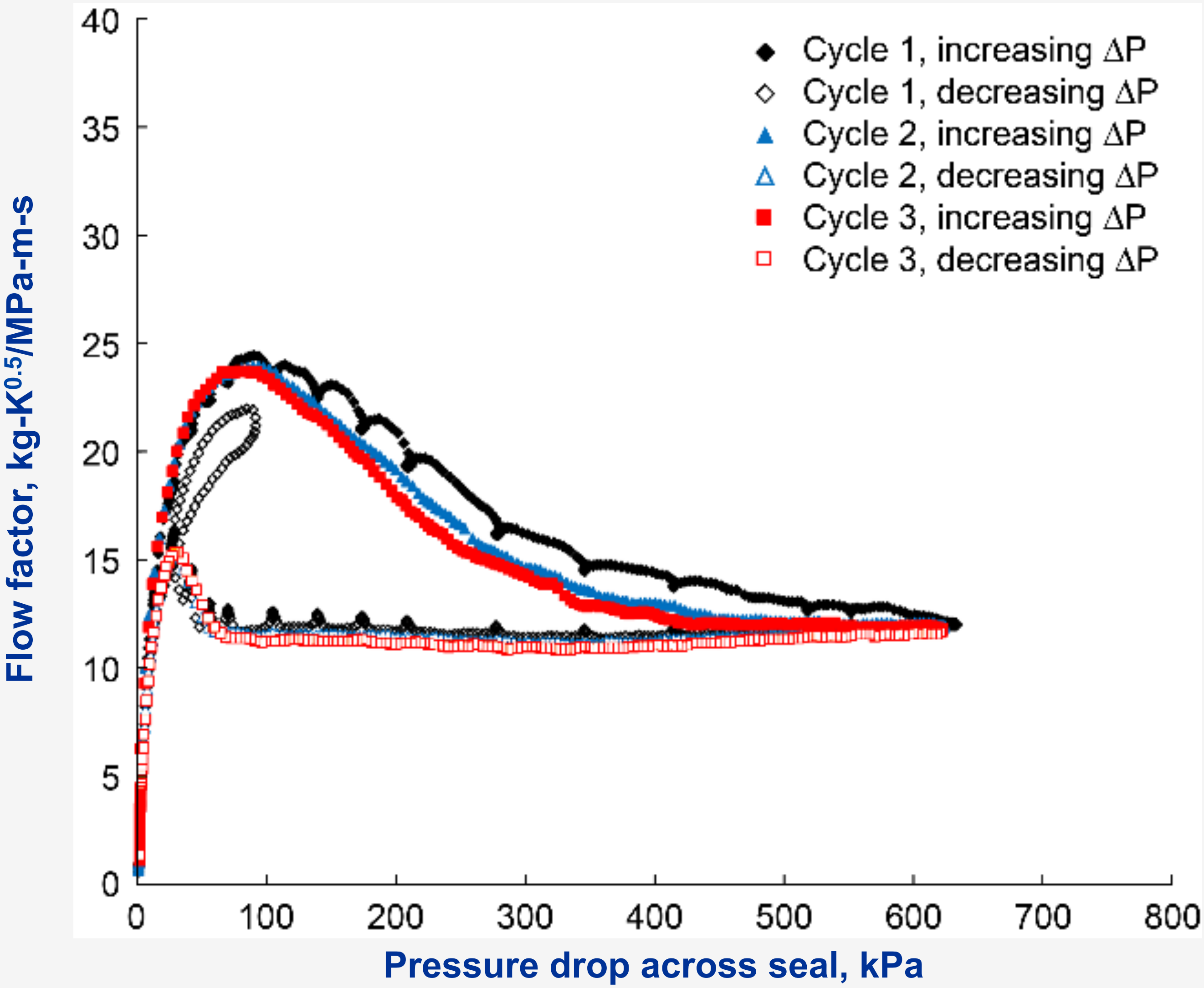
Static Leakage Performance of Baseline Non-Contacting Finger Seal, Build 1, 276 to 294 K



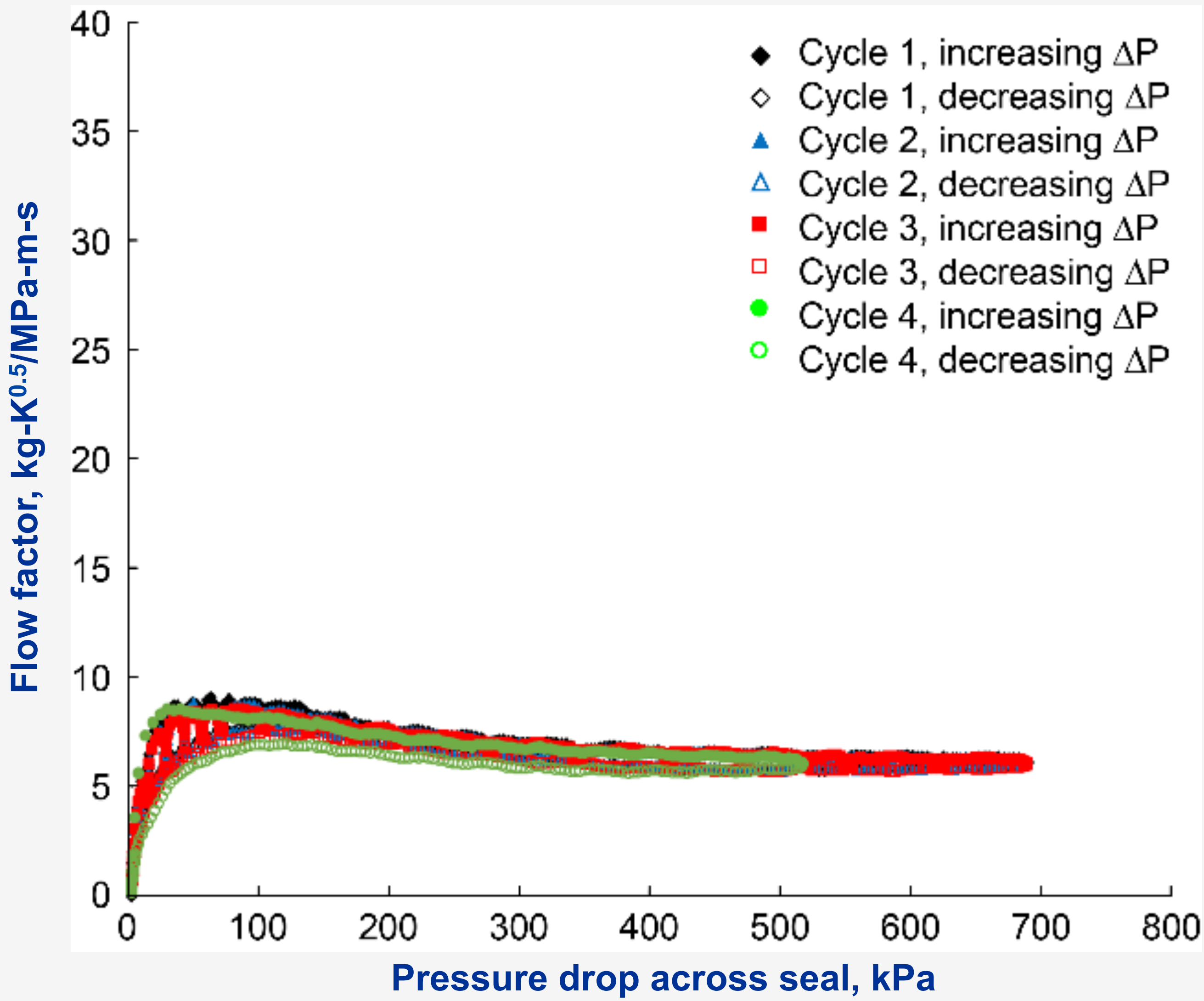
Static Leakage Performance of Build 2
Average Inlet Air Temperature = 297 to 299 K



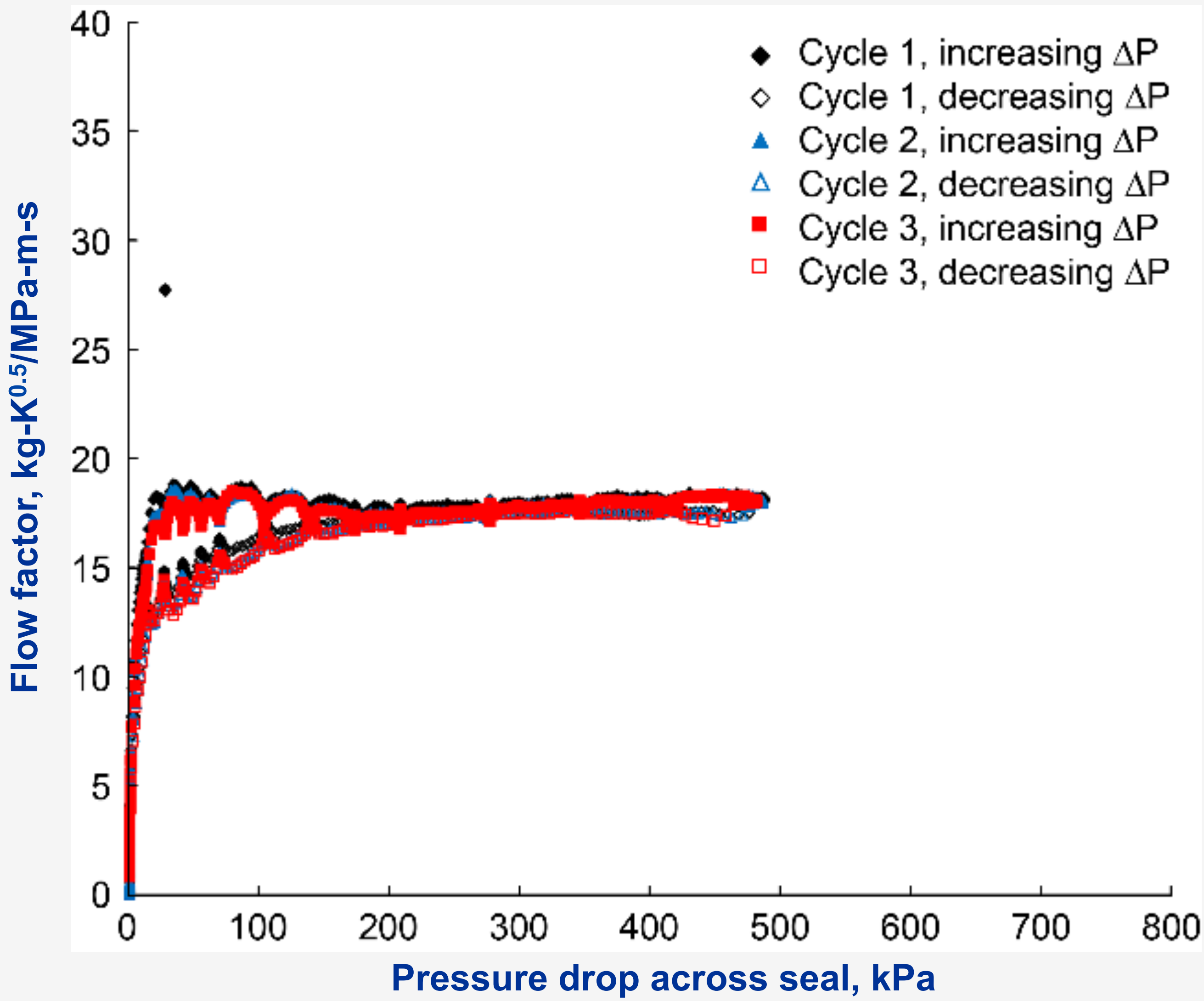
Static Leakage Performance of Build 3
Average Inlet Air Temperature = 301 to 303 K



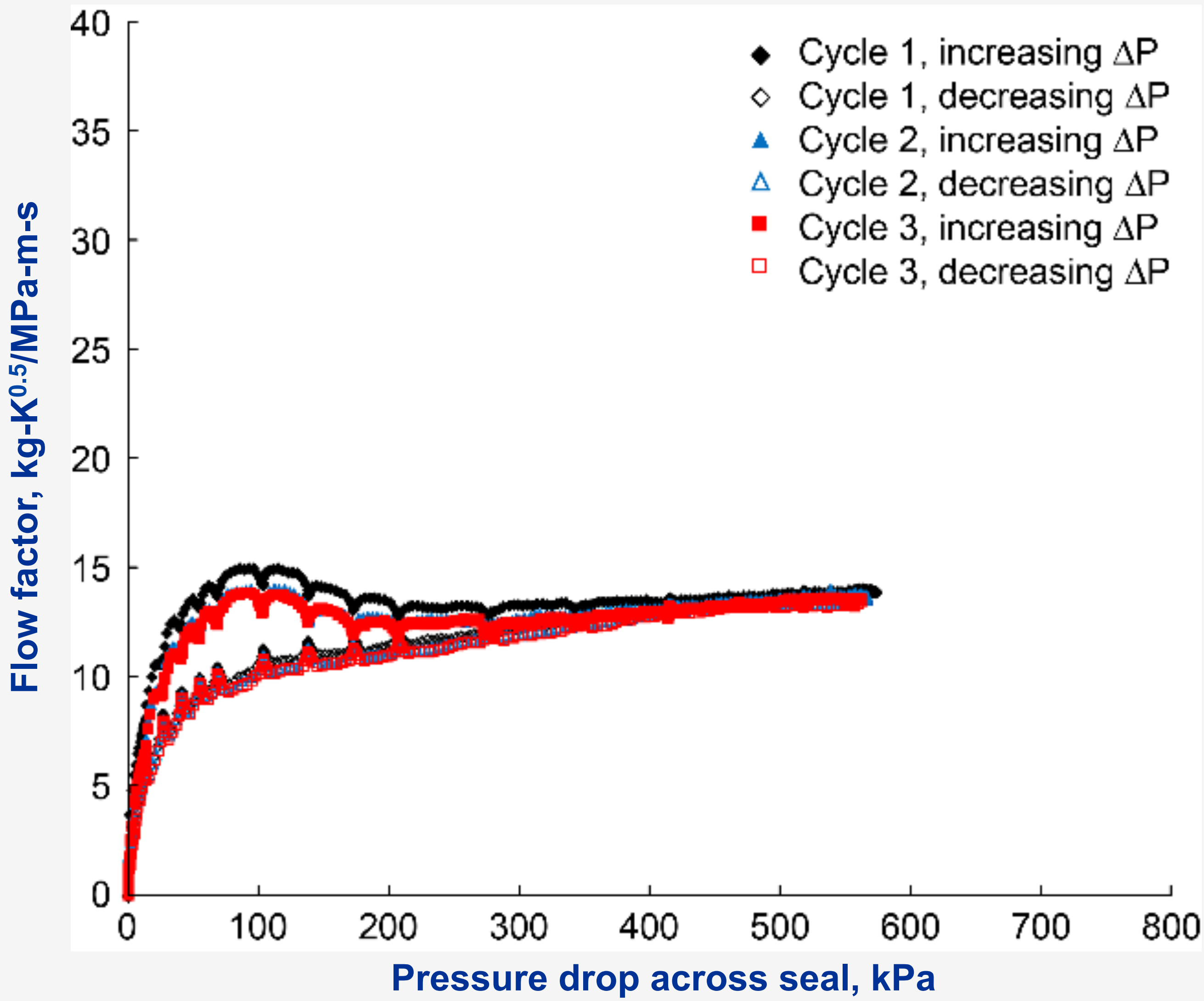
Static Leakage Performance of Build 4
Average Inlet Air Temperature = 303 to 304 K



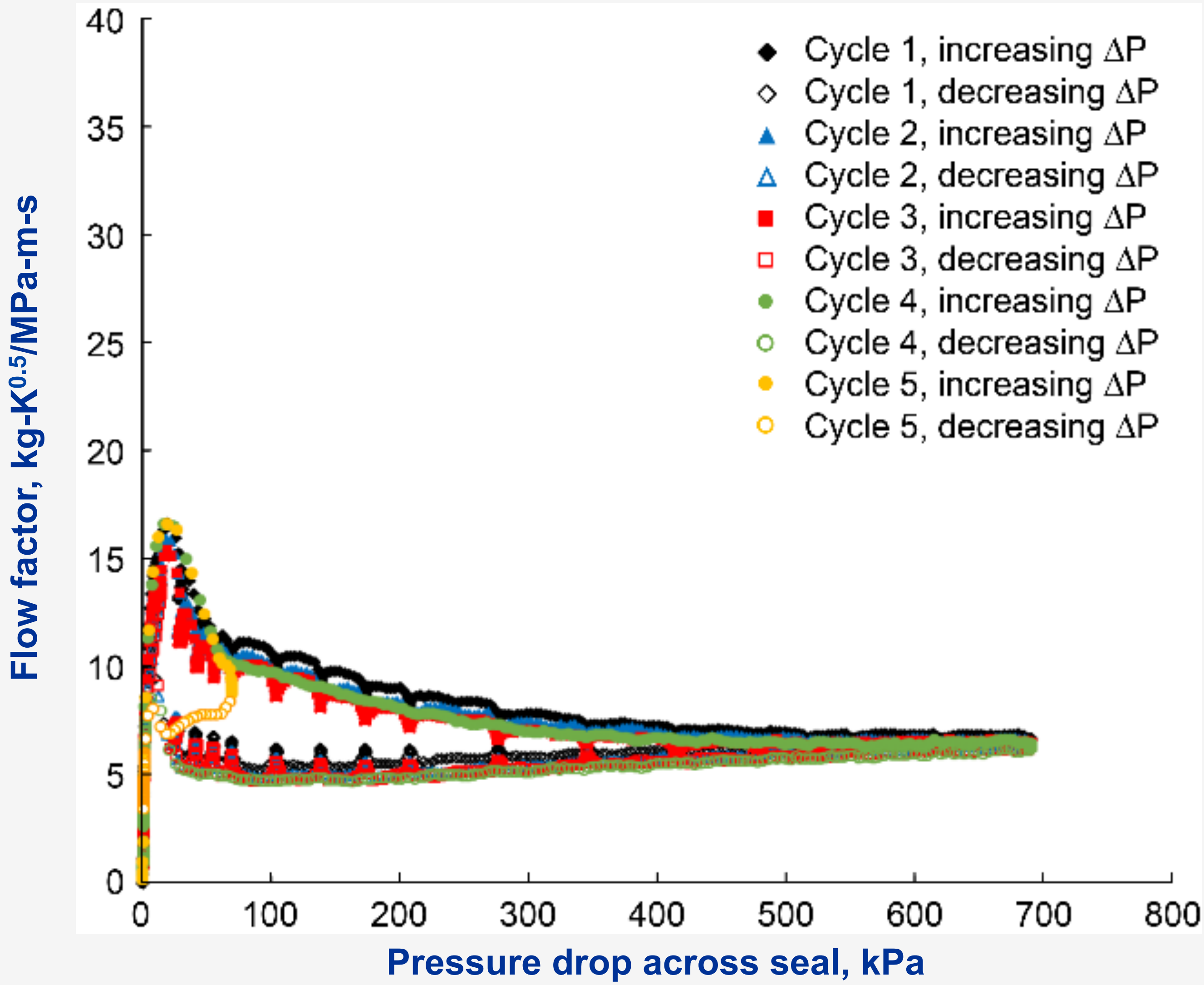
Static Leakage Performance of Build 5a
Average Inlet Air Temperature = 280 to 292 K



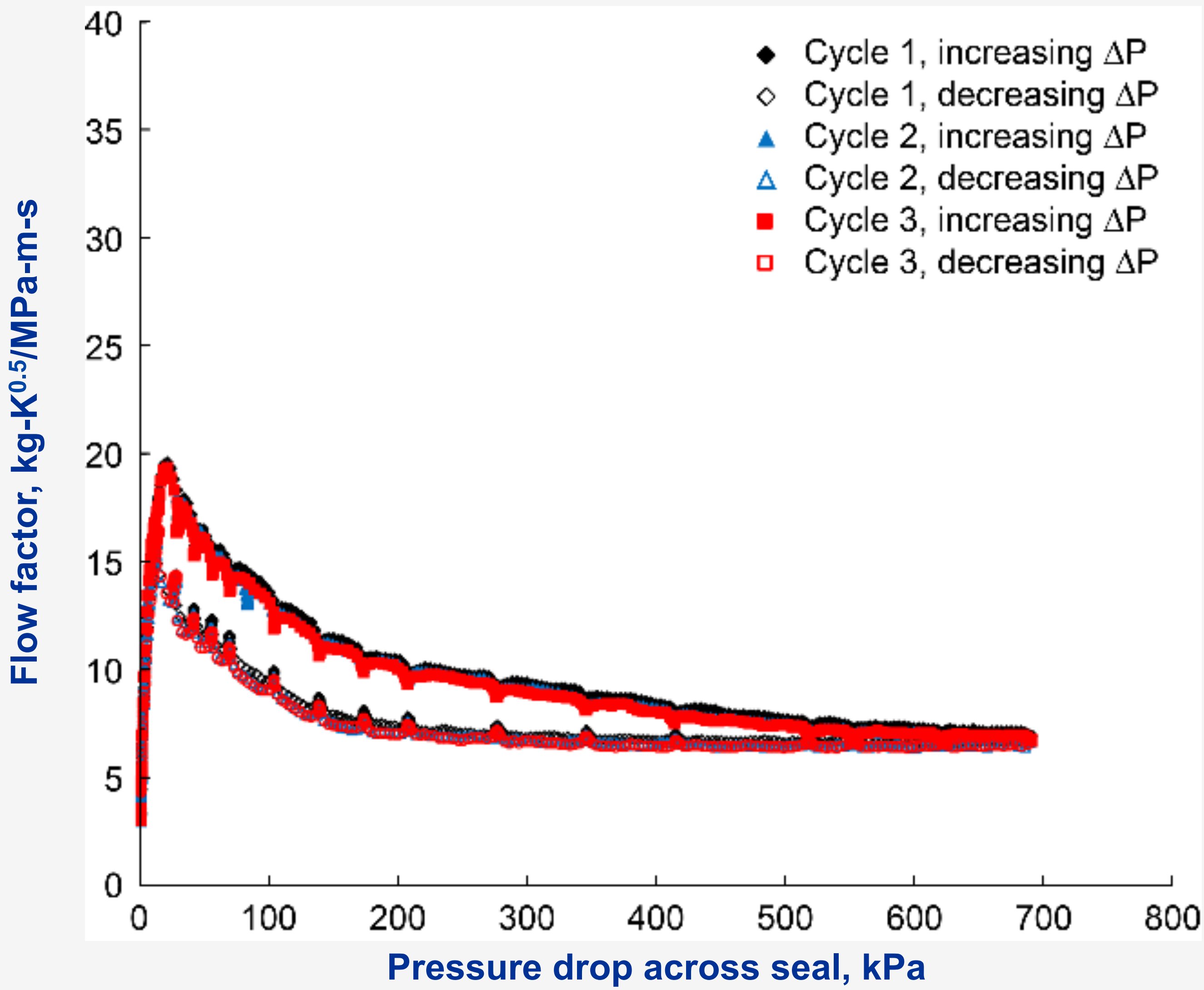
Static Leakage Performance of Build 5b Average Inlet Air Temperature = 282 to 289 K



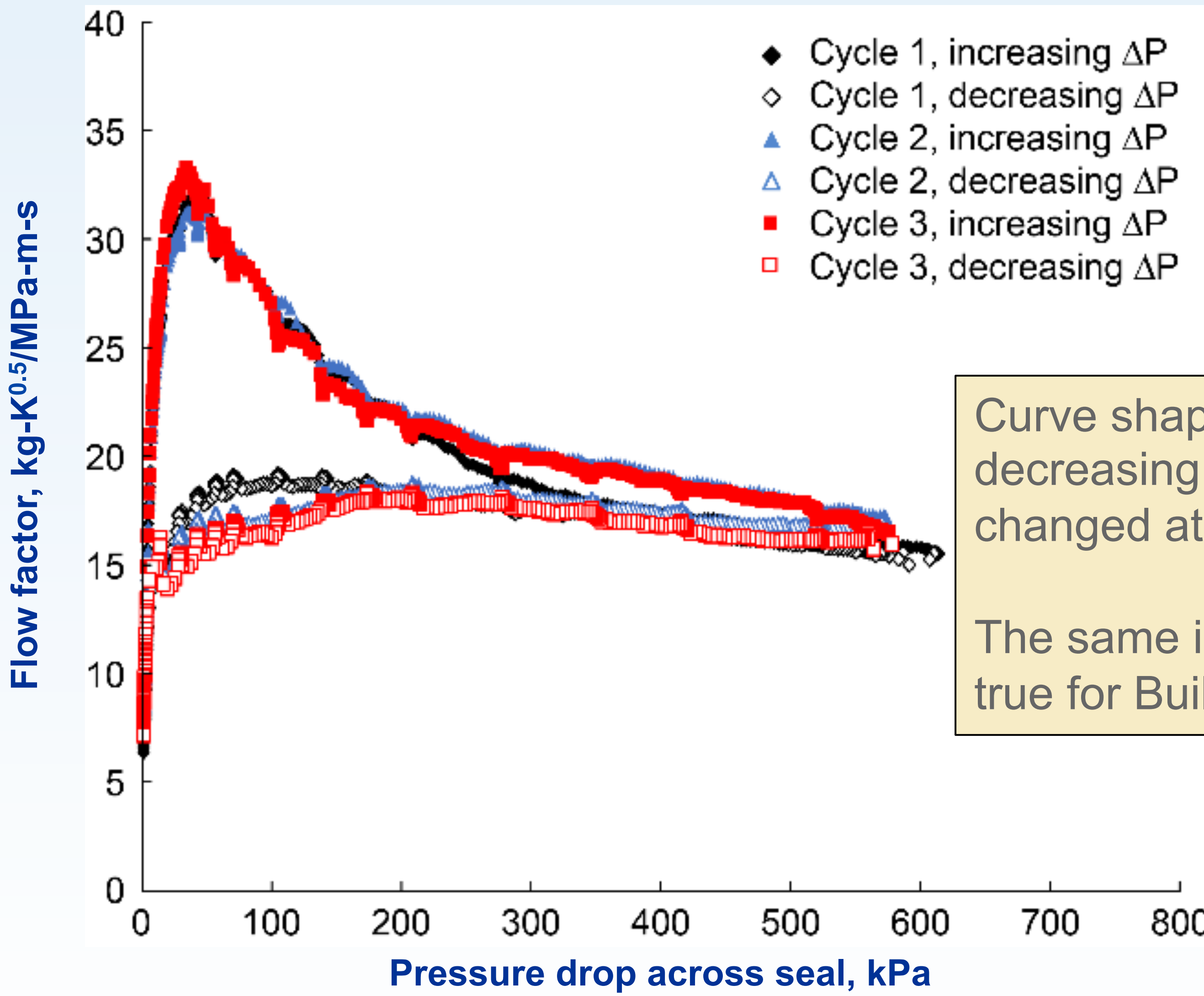
Static Leakage Performance of Build 6
Average Inlet Air Temperature = 283 to 294 K



Static Leakage Performance of Build 7
Average Inlet Air Temperature = 275 to 298 K



Static Leakage Performance of Build 7
Average Inlet Air Temperature = 866 to 908 K



Curve shape for decreasing ΔP is changed at 900 K.

The same is also true for Build 6.

Leakage Flow Model

$$\dot{m} = \frac{P_u}{\sqrt{RT_u}} \cdot A\sqrt{\gamma}M\left(1+\left(\frac{\gamma-1}{2}\right)M^2\right)^{1/2\,\frac{\gamma}{\gamma-1}}$$

where

$$M = \left[\left(\left(\frac{P_u}{P}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)\frac{2}{\gamma-1}\right]^{\frac{1}{2}}$$

For air (γ = 1.4), when $P/P_u \leq 0.5283$ the flow is choked

$$\dot{m} = \frac{P_u}{\sqrt{RT_u}} \cdot A \cdot (0.6847)$$