ADJUSTABLE-BLADE TURBINE RUNNER TECHNOLOGY: WATER FILLED HUBS NWHA TECHNICAL FORUM

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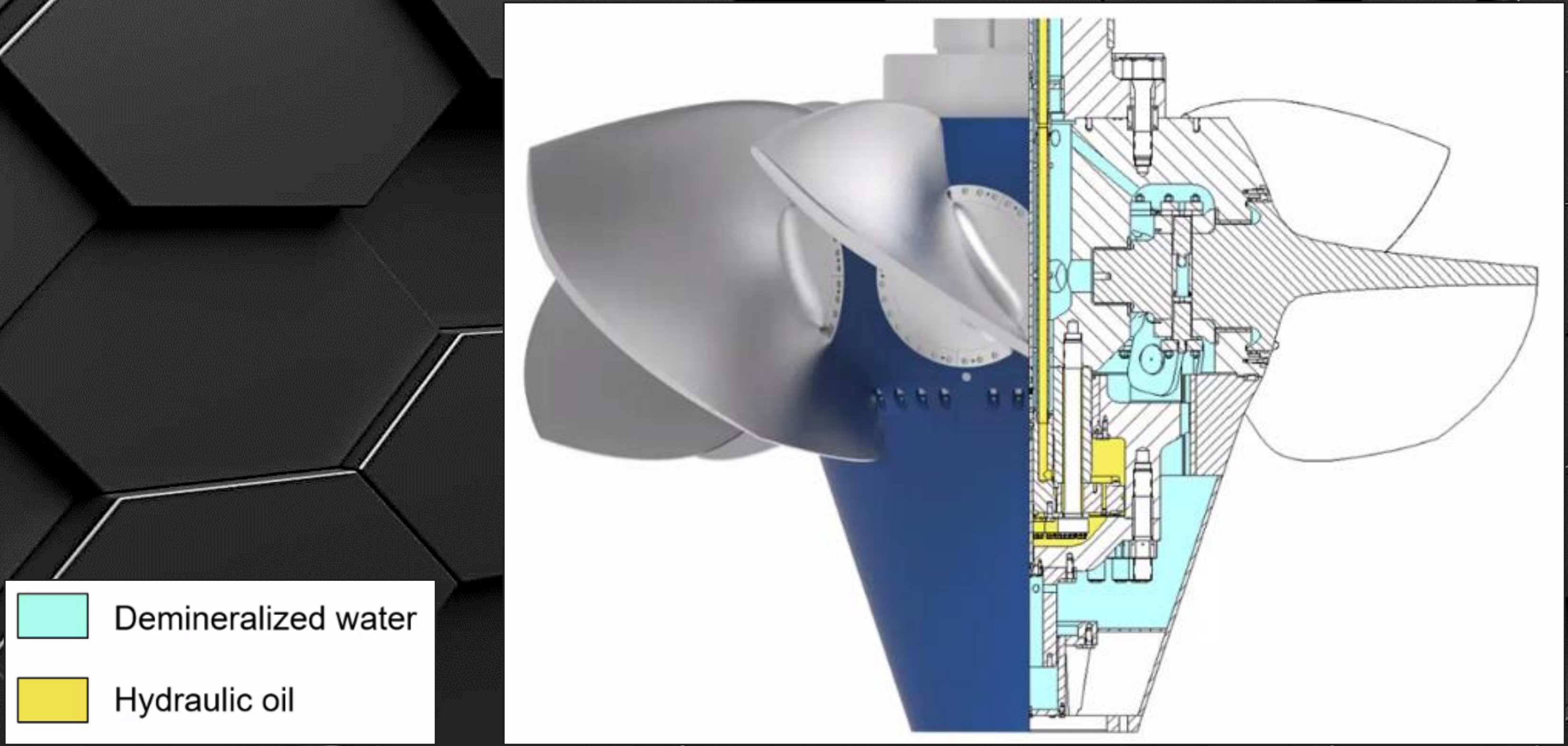
01 May 2025



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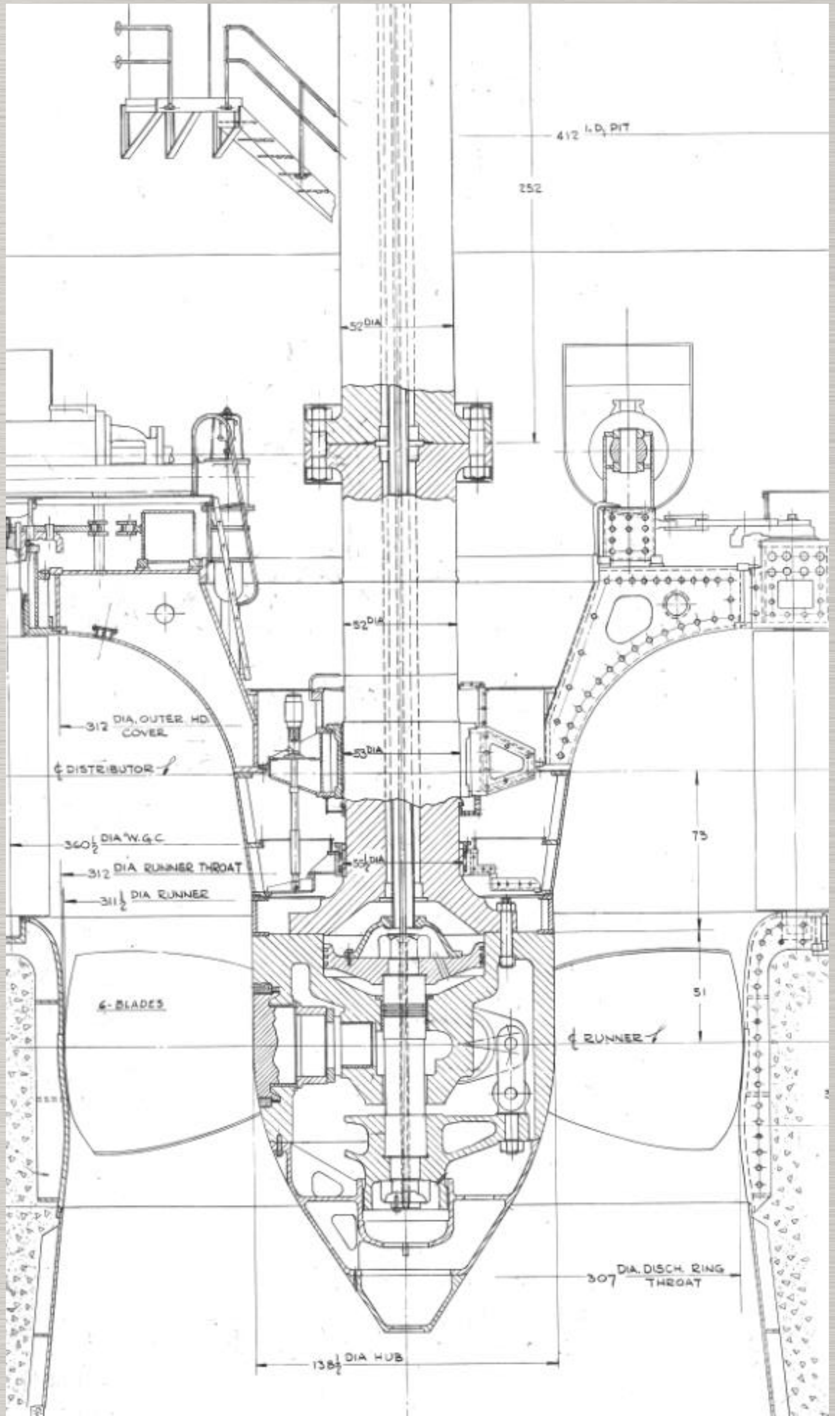
Agenda

1. History of Kaplan Hubs
2. Corrosion-Induced Fatigue Testing
3. Self-Lubricated Bushing (SLB) Testing
4. Conclusions



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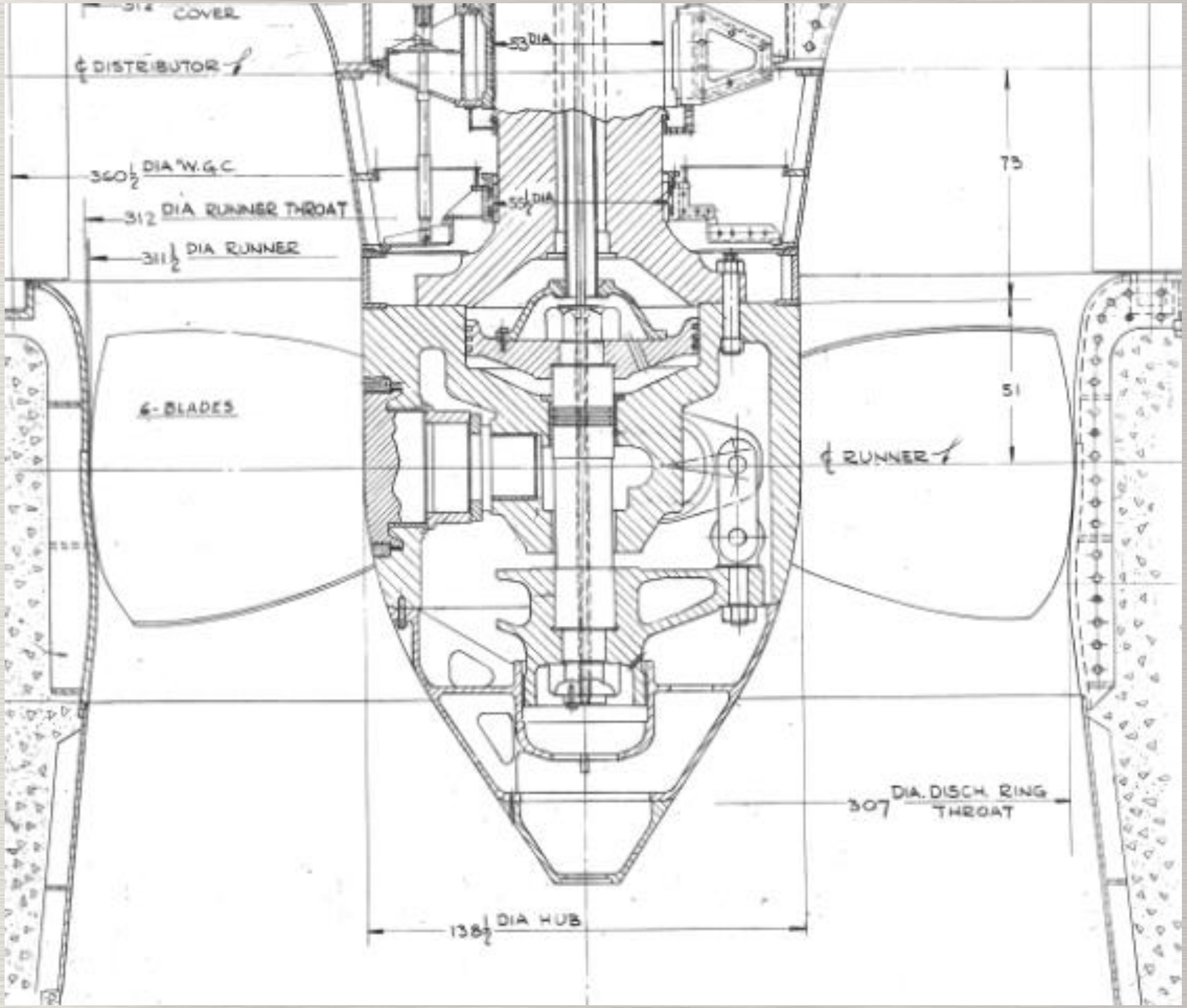
HISTORY OF KAPLAN HUBS

OIL-FILLED KAPLAN HUB HISTORY

- Lubrication of internal components
- Static oil pressure to keep water out
- Some history of failures
  - Servomotor piston caps
  - Link pins
  - Bushings rotating in housing



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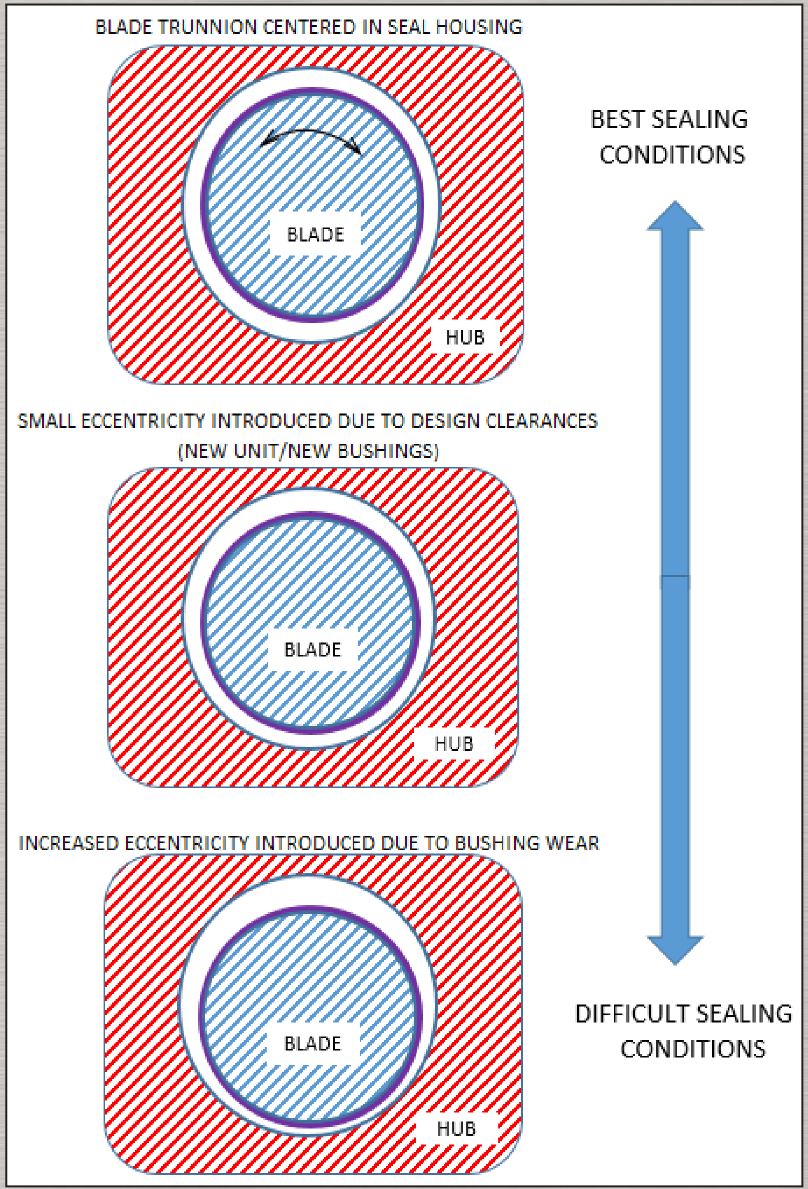
WHY OIL-FREE

- Dramatically reduce risk of oil entering water passageway
- Reduce impacts associated with fixing oil leaks
- No capital replacement costs for oil
- Reduced O&M in dealing with oil accountability
- Reduce risk of lawsuits associated with oil
- Could reduce permitting requirements
- Improve public image/high visibility
- Oil-free hubs may end up with smaller hubs due to lower coefficients of friction, higher bearing pressures, and corrosive resistant materials



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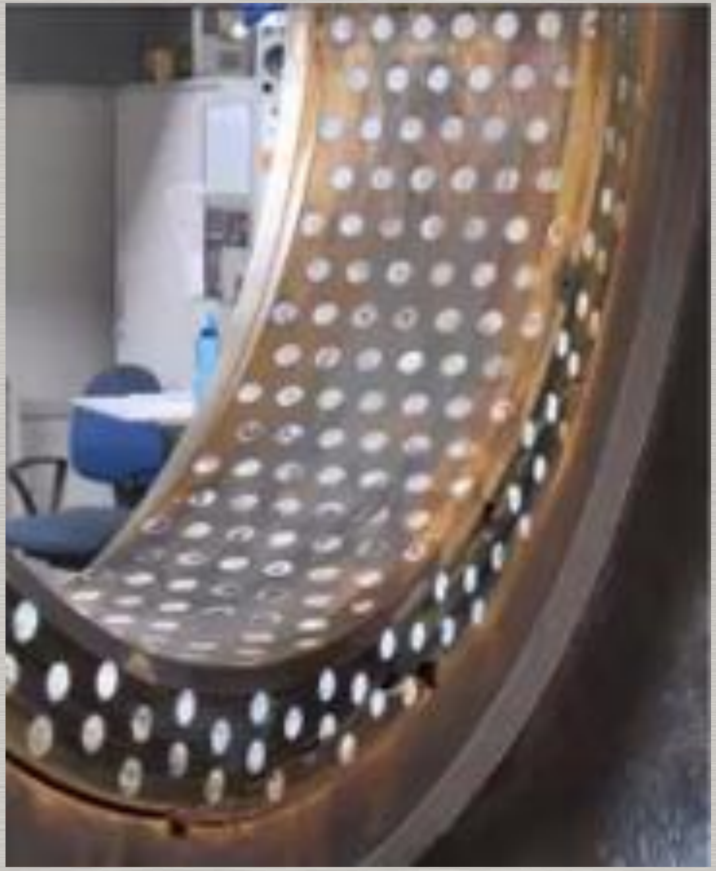
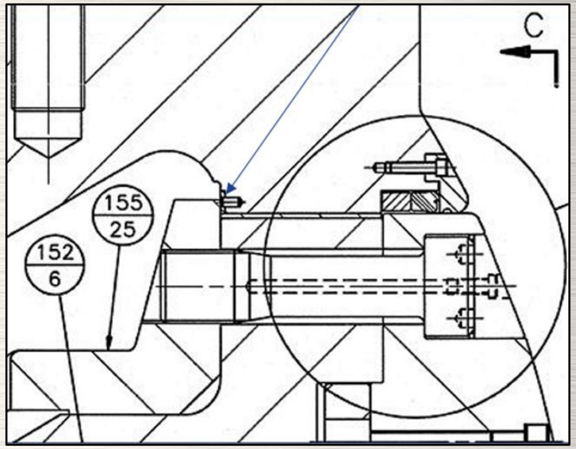
KNOWN PAST ISSSUES

HDC conducted interviews with all vendors and some end users of oil-free.

Case studies indicate failures were largely due to two major sources:

1. Poor bushing material/design
2. Poor design practices





CONCERNS FOR WATER-FILLED HUBS

Other water-filled hub concerns:

1. Corrosion induced fatigue
2. Blade trunnion bushing wear and friction

USACE and PNNL have led efforts to conduct testing to reduce technical risks.

CORROSION-INDUCED FATIGUE TESTING

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CORROSION INDUCED FATIGUE

The removal of oil exposes highly stressed, critical Kaplan components to a corrosive environment.

Testing was completed that accelerated the impacts due to stainless steels exposed to water.

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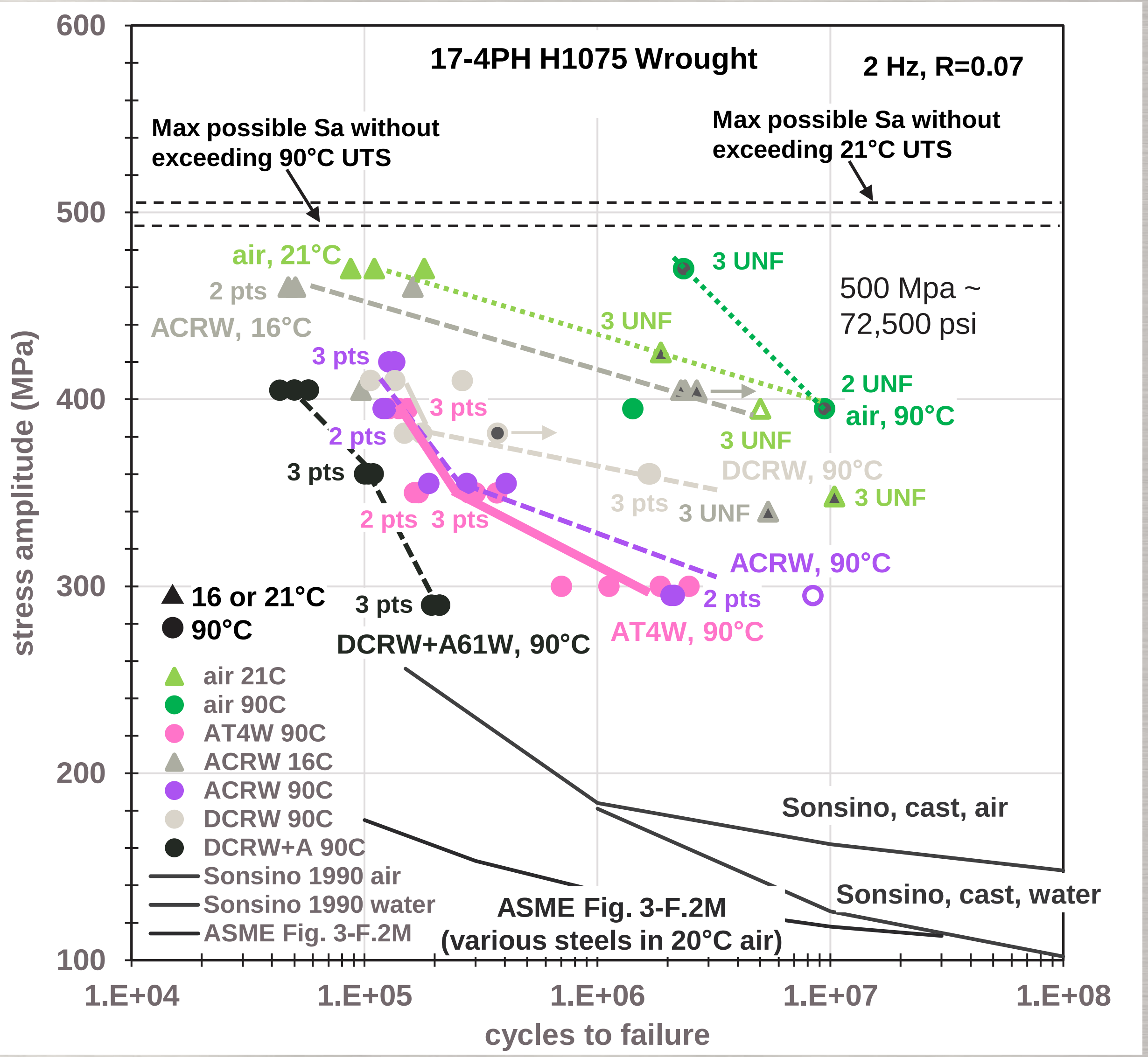
RESULTS

- When compared to data in air, there is life reduction for 17-4 in water at a similar stress amplitude.
- When compared to cool temperatures, there is life reduction for 17-4 at hot water temperatures (there is a corrosion acceleration)
- Rust inhibitor reduced life in the laboratory.



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CONCLUSIONS FROM FATIGUE TESTING

- Fatigue testing and selection of 17-4 PH (wrought or forged) allows for more design flexibility for designs for Improved Fish Passage (good news)

- Testing identified little difference between Columbia River Water and ASTM Type 4 water. This indicates a blade seal failure does not require an immediate forced outage and can be done during a scheduled outage (good news)

- The addition of a rust inhibitor did not increase life. In fact, there is risk that it may have an adverse effect. Additionally, there was indication from one self-lubricating bushing manufacturer that rust inhibitors could negatively affect bushings. Rust inhibitor will not be included in any oil-free designs. This will reduce the O&M efforts associated with maintaining inhibitor quality and potential reporting requirements and reduce scope of bushing testing (good news)

- 17-4 PH has a higher material cost, about four times greater than carbon steel per pound (bad news)

SELF-LUBRICATED BUSHING (SLB) TESTING
PNNL BUSHING TEST STAND

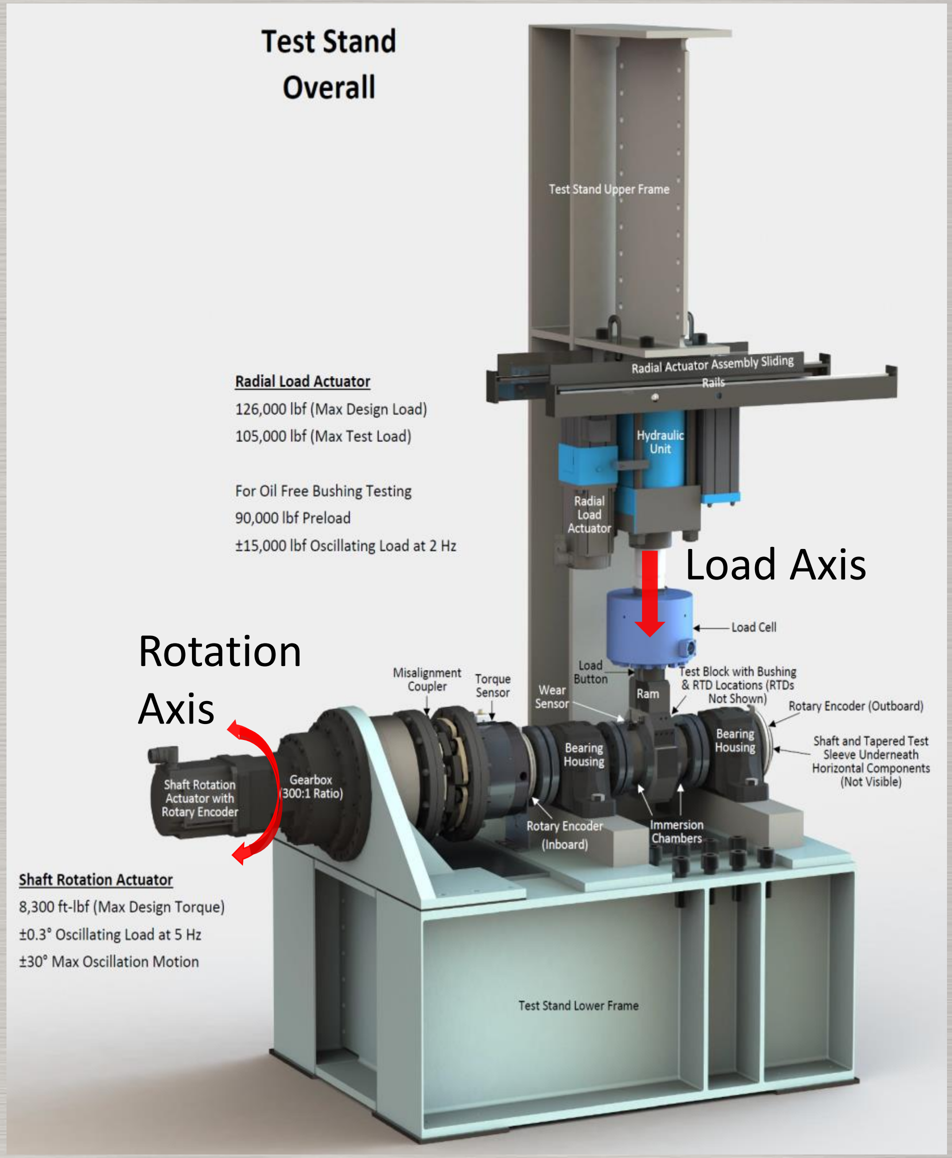
PNNL BUSHING TESTING

Bushing Test Stand designed and built by PNNL for USACE to assess Kaplan trunnion self-lubricating bushing (SLB) replacement of bronze at John Day Dam.

- Accelerated testing simulates 50 years life in 1 month
- Two phases of testing: Set & Creep, Friction & Wear
- Key parameters: Coefficient of Friction (COF) & Wear
- Comparative testing enables the relative performance (i.e. better/worse) to be directly applicable, although some absolute values determined from testing may not scale directly to the field.

Key Test Stand features applicable for this testing:

- Oscillating radial loads to 126,000 lbs.
  - **Bronze** 60,000 lb. base load with ± 15,000 at 2 Hz
  - **SLBs** 90,000 lb. base load with ± 15,000 at 2 Hz
- Oscillating rotations with minimal backlash, torque up to 8,300 ft-lbs. available
  - 5 million Minor oscillations of ± 0.3° at 4-5 Hz



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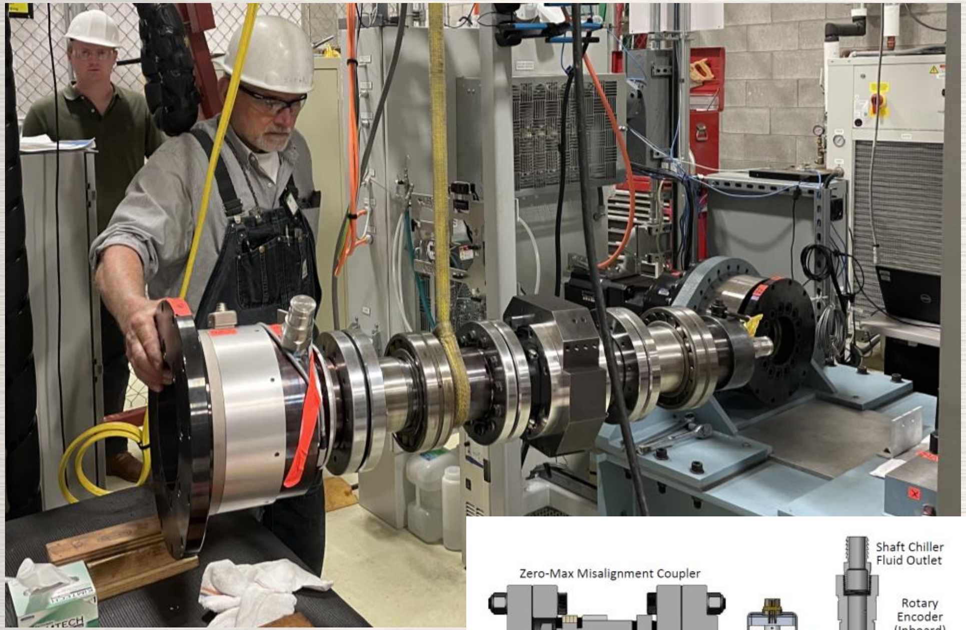
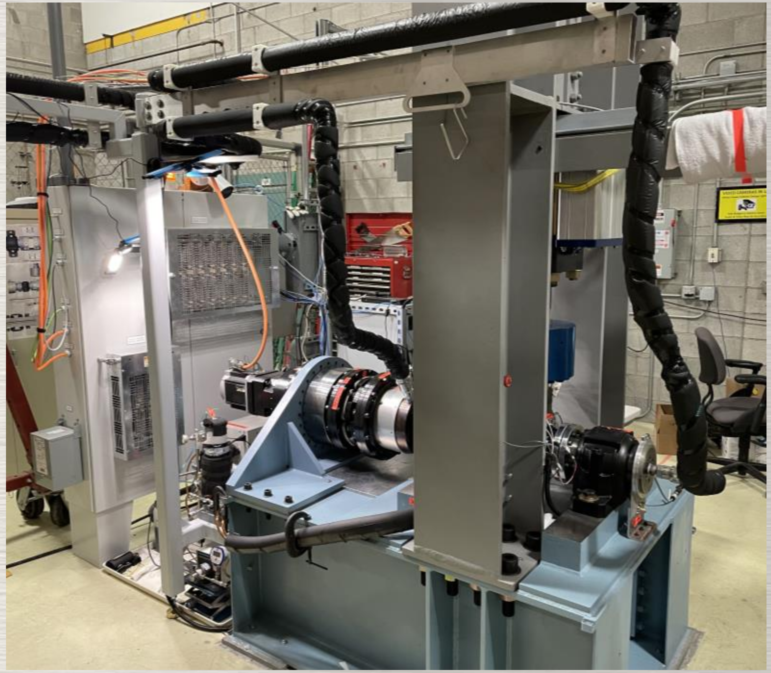
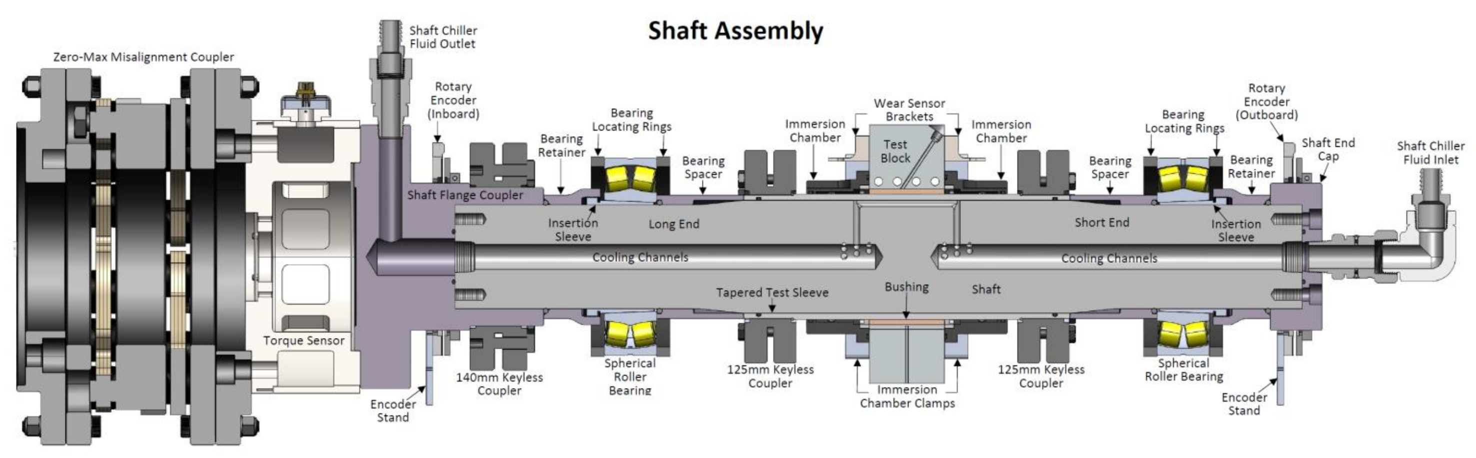
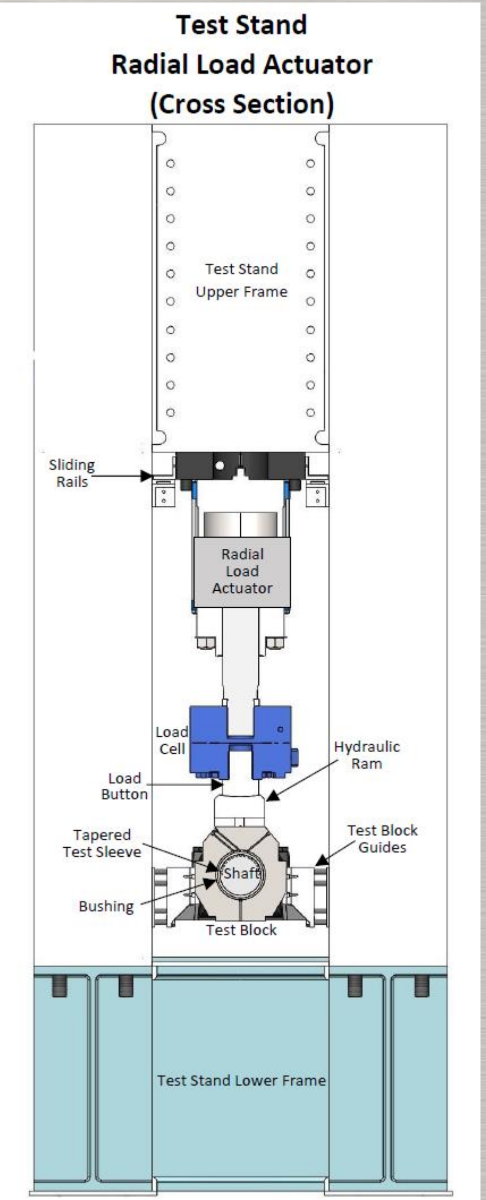
TEST STAND – OVERALL VIEWS









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SPECIAL TESTING FEATURES

DESIGN CRITERIA TO SIMULATE JOHN DAY DAM OPERATIONAL DATA AND ENVIRONMENTAL CONDITIONS

Scaled down bushing to 5-inch diameter (actual size 24 & 32-inch diameter)

The following are improvements over similar bushing testing done in 1990s

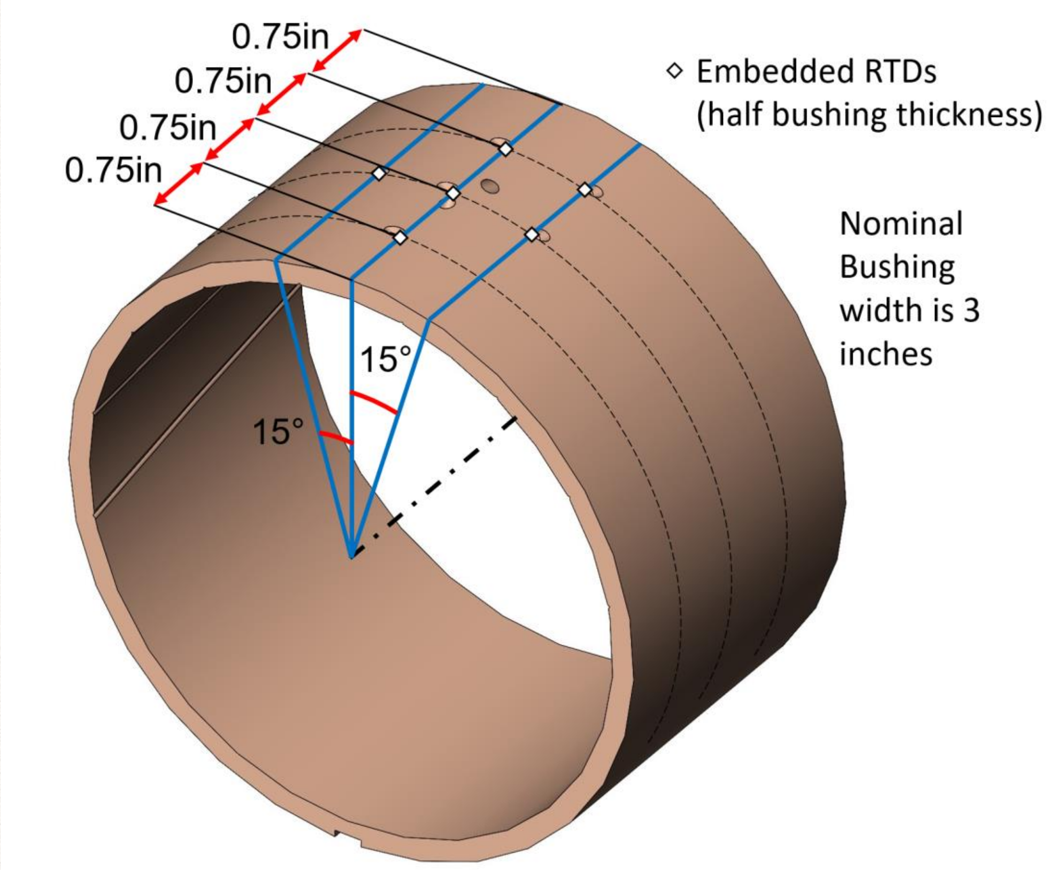
- Maintained bushing <u>and</u> bushing medium temperature at 10 - 15°C utilizing specialized cooling features
- Bushing submerged in bushing fluid medium
- Instrumentation – numerous, accurate, high resolution
- Continuous complex operational routine with remote monitoring and alerts
  - Periodic Matrix testing added (starting Test 4A) to assess scaling to prototype (actual)
- Calculation of “Equivalent Cycles” compared to “Cycles” or “Time”

TEMPERATURE MEASUREMENTS

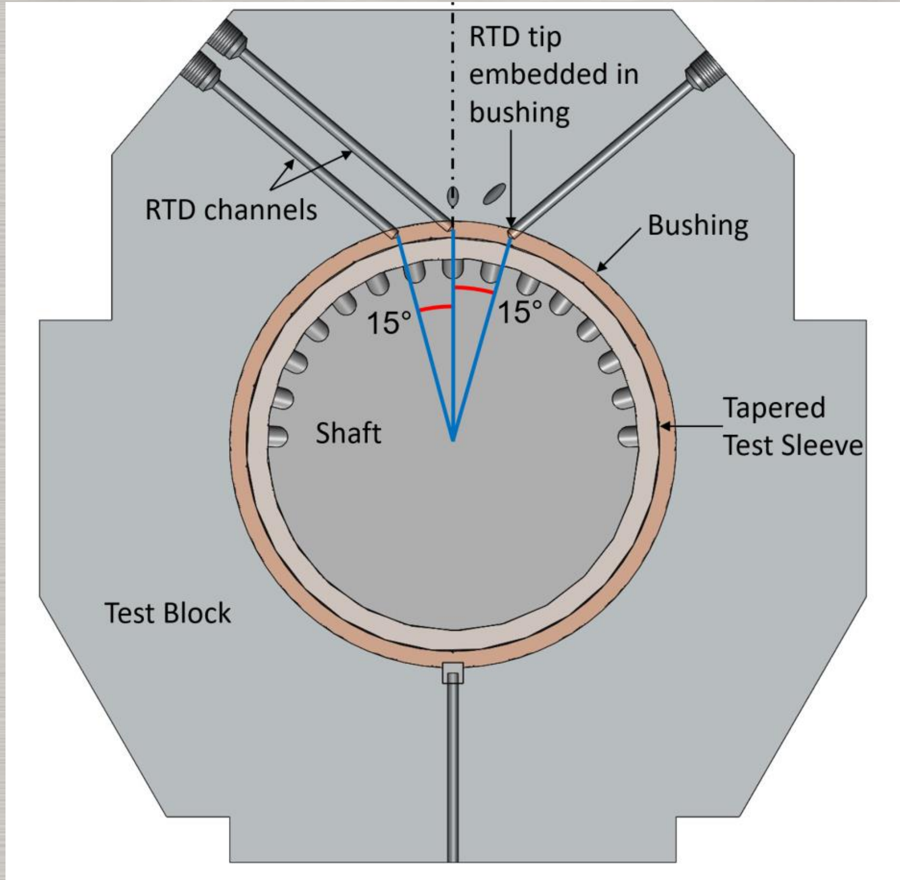
Numerous Temperature Measurements:

- Bushing (center of bushing thickness) – 3 on radial load centerline, 3 off centerline by 15°
- Bushing/Sleeve Interface – 2 on radial load centerline
- Bushing Medium – 2 at inlet and outlet lines to immersion chambers

RTD Locations in Bushing



RTD Holes Through Test Block



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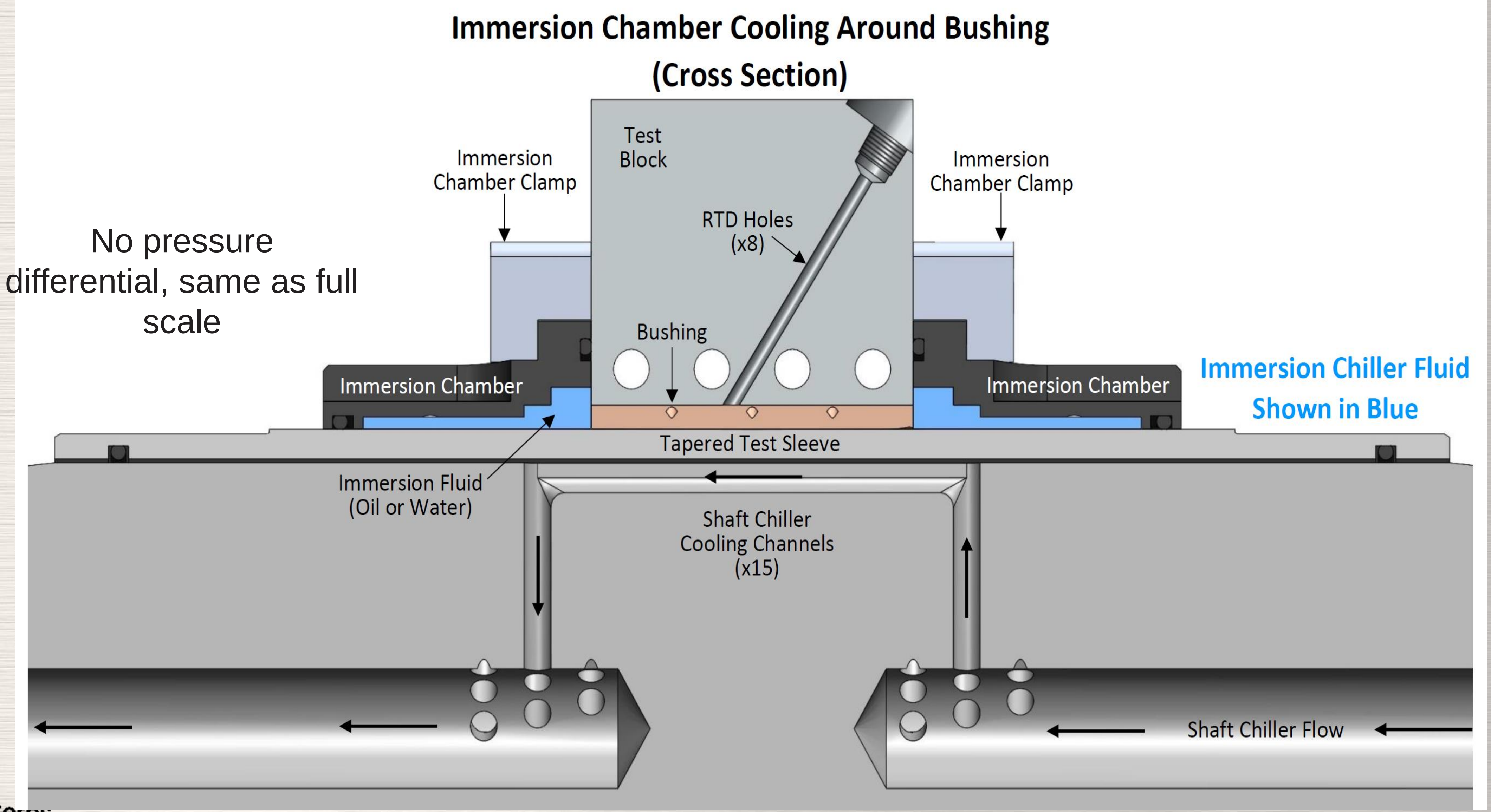
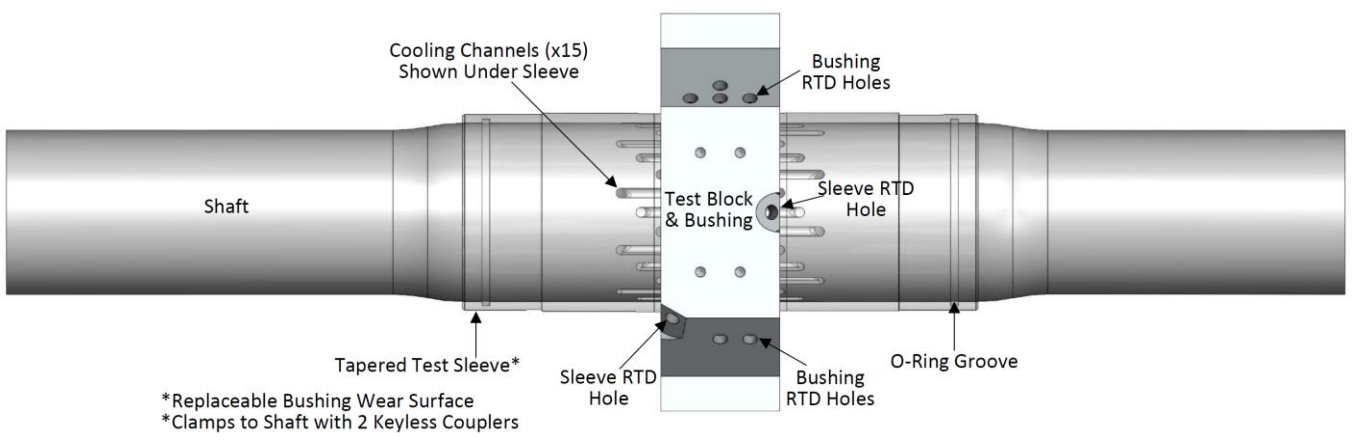
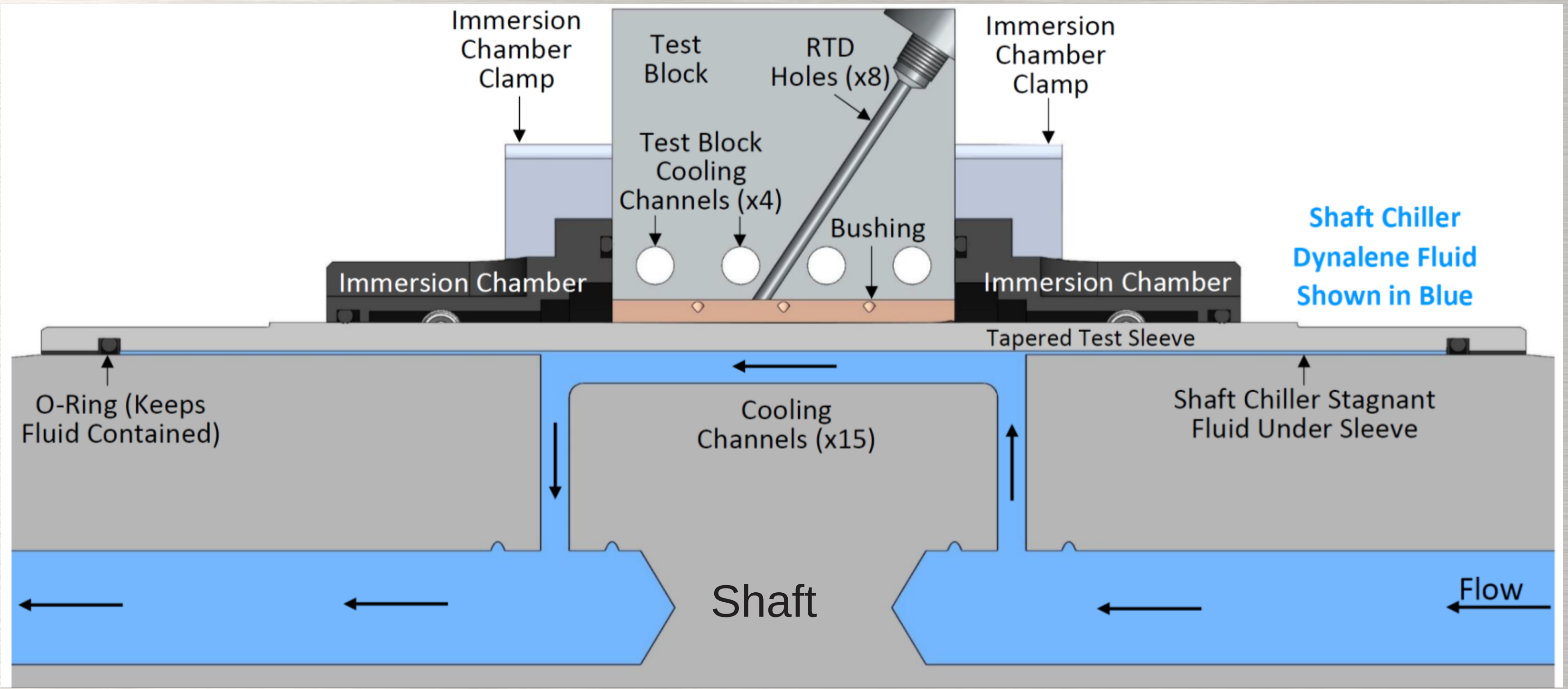
TEST STAND – BUSHING MEDIUM FLUID

No pressure differential, same as full scale



TEST STAND – SHAFT AND TEST BLOCK COOLING





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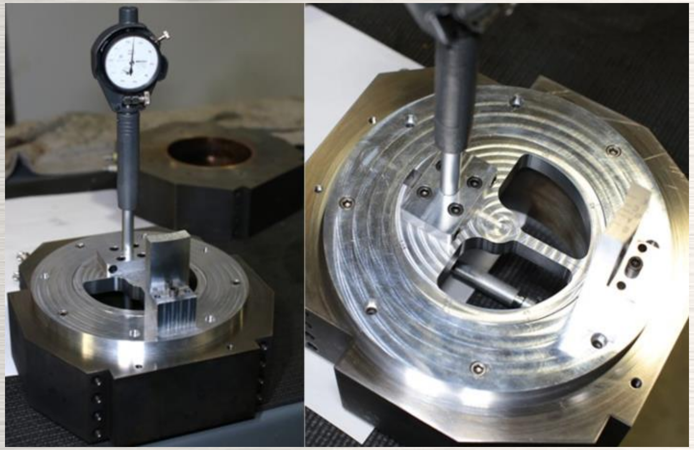
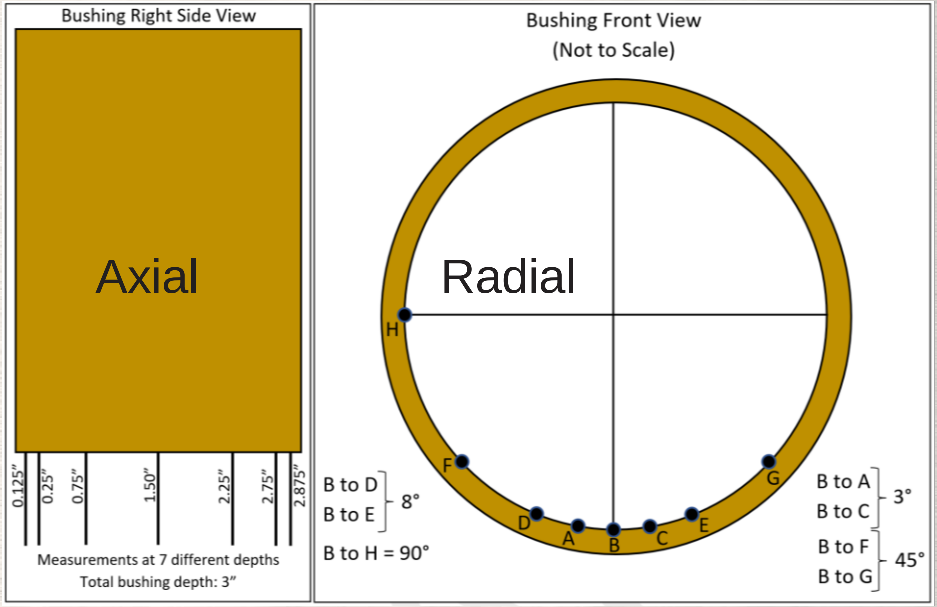
WEAR - MEASUREMENTS



PHYSICAL WEAR

Before and After Testing

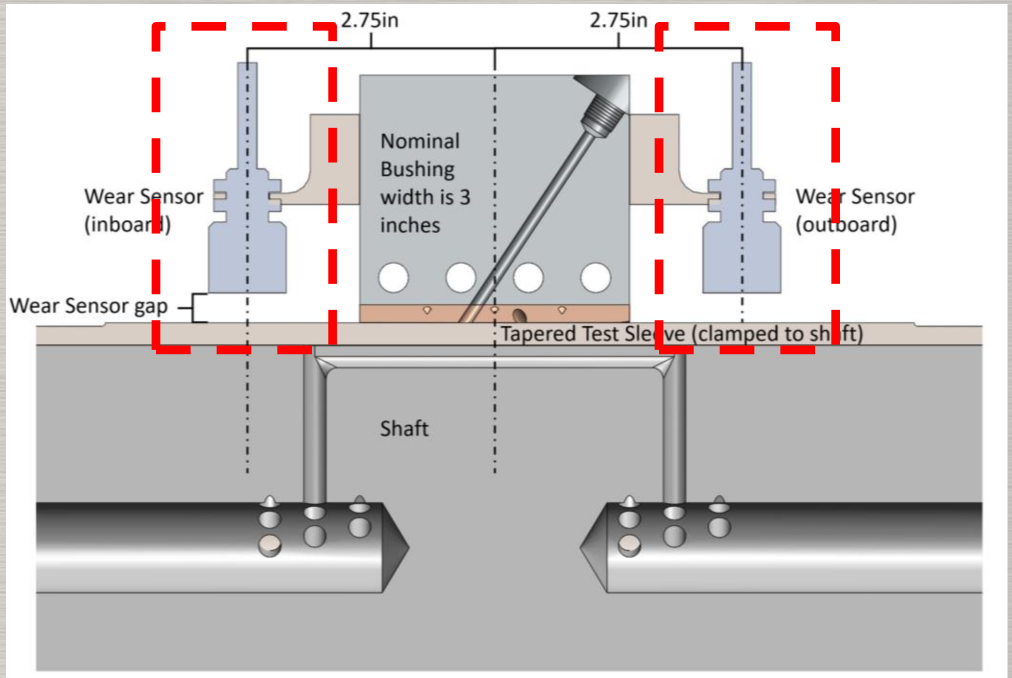
- Repeatable locations
- 8 radial positions
- 7 axial depths
- Up to 56 total measurements



TRENDING WEAR

During Testing

- 2 ultrasonic wear sensors
- Measure shaft movement as bushing wears
- Single line wear under load centerline only
- Shows wear rate changes over time



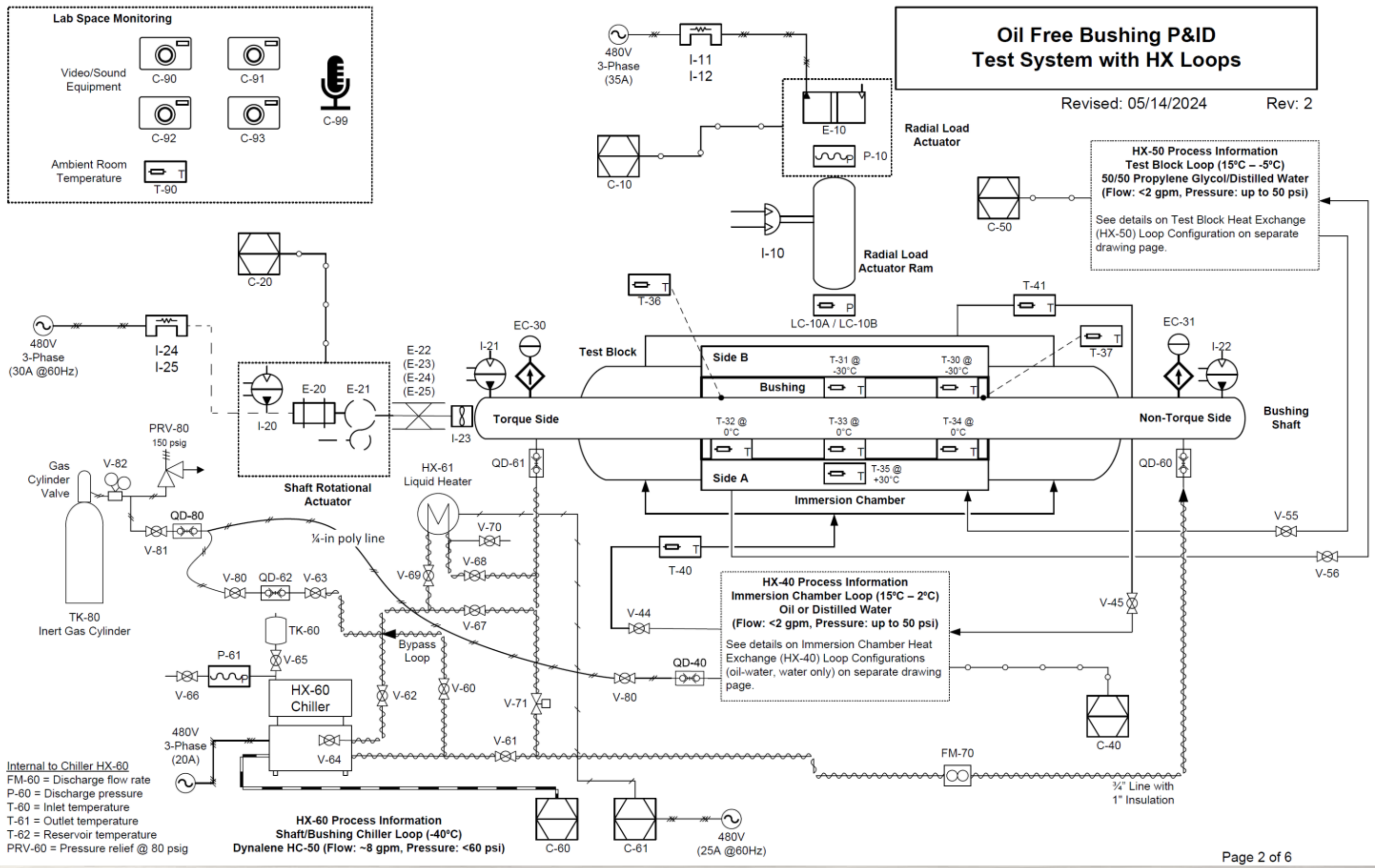
TEST STAND – EQUIPMENT & INSTRUMENTS

Key Instruments

- Temperature (RTDs)
  - *Bushing, Bushing Medium, Ambient*
- Force - Radial (Load Cell)
- Torque (Torque Sensor)
- Shaft Rotation (Rotary Encoders)
  - *One on each side of bushing*
- Wear (Distance Sensor)
  - *One on each side of bushing*

Key Equipment

- Force – Radial Actuator
- Rotation - Shaft Actuator
- Chillers
  - *Shaft, Bushing Medium, Test Block*
- Data Acquisition & Control System
- Remote Monitoring & Control



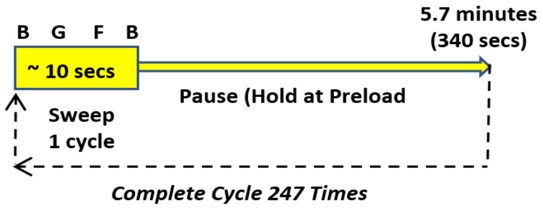
PNNL BUSHINGS TESTED – COMPLETED (7/2024)

- Testing performed comparison of baseline bronze to three different SLBs (Orkot, deva.tex, KAron V)
- Repeatability testing performed on bronze and one SLB (Orkot)

Test #	Bushing	Fluid	Purpose	Minor Cycles	Major - N	Major - S	Runtime (Hours)	% Long Term	Wear ±8° (in)	Wear/Major (in*E-6)	Load (lbs.)
Shakedown	Bronze	Oil	System Test	2,153,120	4485	299	269.6	42.7%	Unknown	Unknown	60,000
1	Bronze	Oil	Long Term Wear	5,132,267	10694	719	642.8	101.8%	0.00485	0.45	60,000
2	Orkot TXMM	Water	Long Term Wear	5,269,723	10979	732	660.0	104.6%	0.00069	0.06	90,000
3	KAron V	Water	Long Term Wear	5,117,030	10665	711	641.1	101.6%	0.00479	0.45	90,000
4A	Bronze	Oil	Scale Load	1,220,506	2602	169	156.4	24.8%	0.00152	0.58	60,000
4B	Bronze	Oil	Scale Viscosity	1,239,210	2593	172	155.9	24.7%	Unknown	Unknown	60,000
4C	Br Square Groove	Oil	Scale Grooves	302,863	633	42	38.1	6.0%	0.00643	10.16	60,000
4D	Br Round Groove	Oil	Scale Grooves	1,310,437	2735	182	164.4	26.0%	0.01771	6.48	60,000
1A	Bronze	Oil	Bronze Repeat	1,282,659	2678	178	161.0	25.5%	0.00312	1.17	60,000
2A	Orkot TXMM	Water	Rerun with Matrix	3,996,205	8500	565	510.9	81.0%	0.00065	0.08	90,000
Shake 2024	Orkot TXMM	Water	Post-Move Test	1,583,506	3311	220	199.0	31.5%	0.00043	0.13	90,000
5	deva.tex	Water	Long Term Wear	5,049,120	10519	700	641.0	100.2%	0.00076	0.07	90,000
Total 13				33,657,000	70,400	4,689	4,240				

LOADING & MOVEMENT MAP

(Two Testing Phases per Bushing, Total Test Duration: Less than 30 days continuous 24/7)



Set & Creep Phase - Bushing Conditioning for Testing

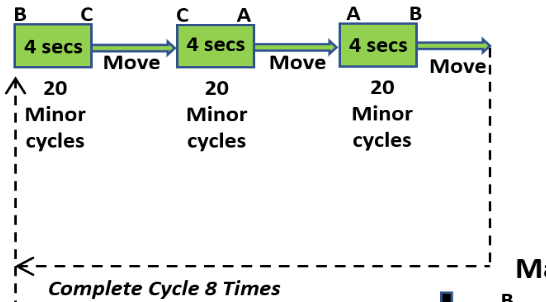
Oscillation Cycles (±5.0°) Completed = 247
Duration for This Test Phase: 24 hours

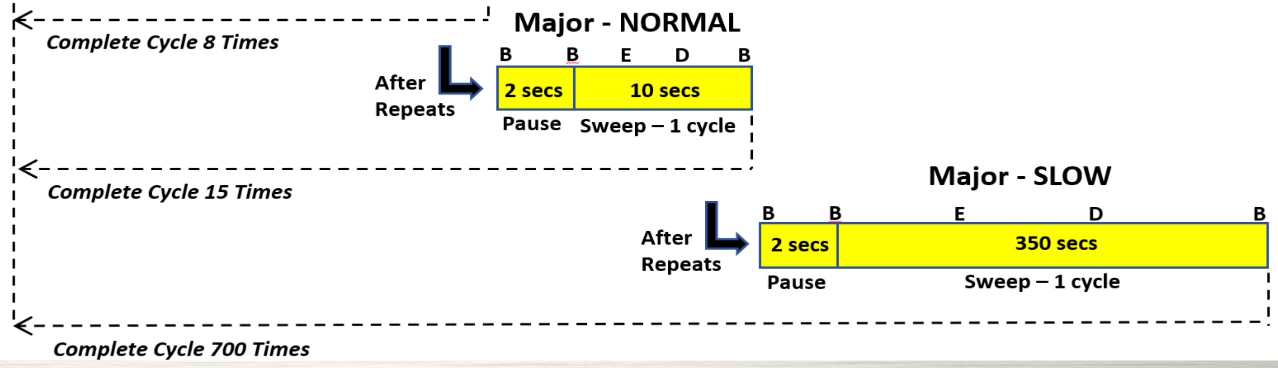
Friction & Wear Phase – Bushing Operational Testing

Minor Oscillation (±0.3°) Cycles Completed: 5,040,000
Major NORMAL Oscillation Cycles (±8.0°) Completed: 10,500
Major SLOW Oscillation Cycles (±8.0°) Completed: 700

Durations for This Test Phase:
Note: Durations shown in figures are for movements and set pauses only. These times do not include additional pause times for data queries for operational switching and movement ramping.

- 20 Minor cycles: 8 secs
- 60 Minor cycles: 24 secs
- Minor cycle (8) repeats + Major-Normal cycle: 3 minutes, 36 secs
- Major-Normal cycle (15) repeats + Major-SLOW cycle: 54 minutes, 16 secs
- Total Test with 700 Major-Slow cycles: 641 hours, 26.7 days





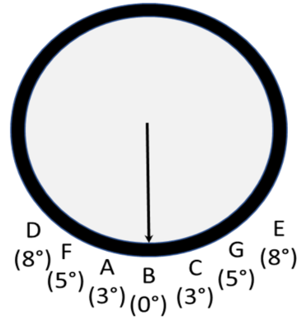
Legend

Loading:

Preload Only

Preload with Oscillating Load

±0.3° Oscillations Centered on Lettered Locations



Not to Scale

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COF FOR ALL BUSHING TESTS

Coefficient of Friction (COF)

CONCLUSION: Bronze and SLBs both meet 50-year life conditions.

<u>Test Results</u>

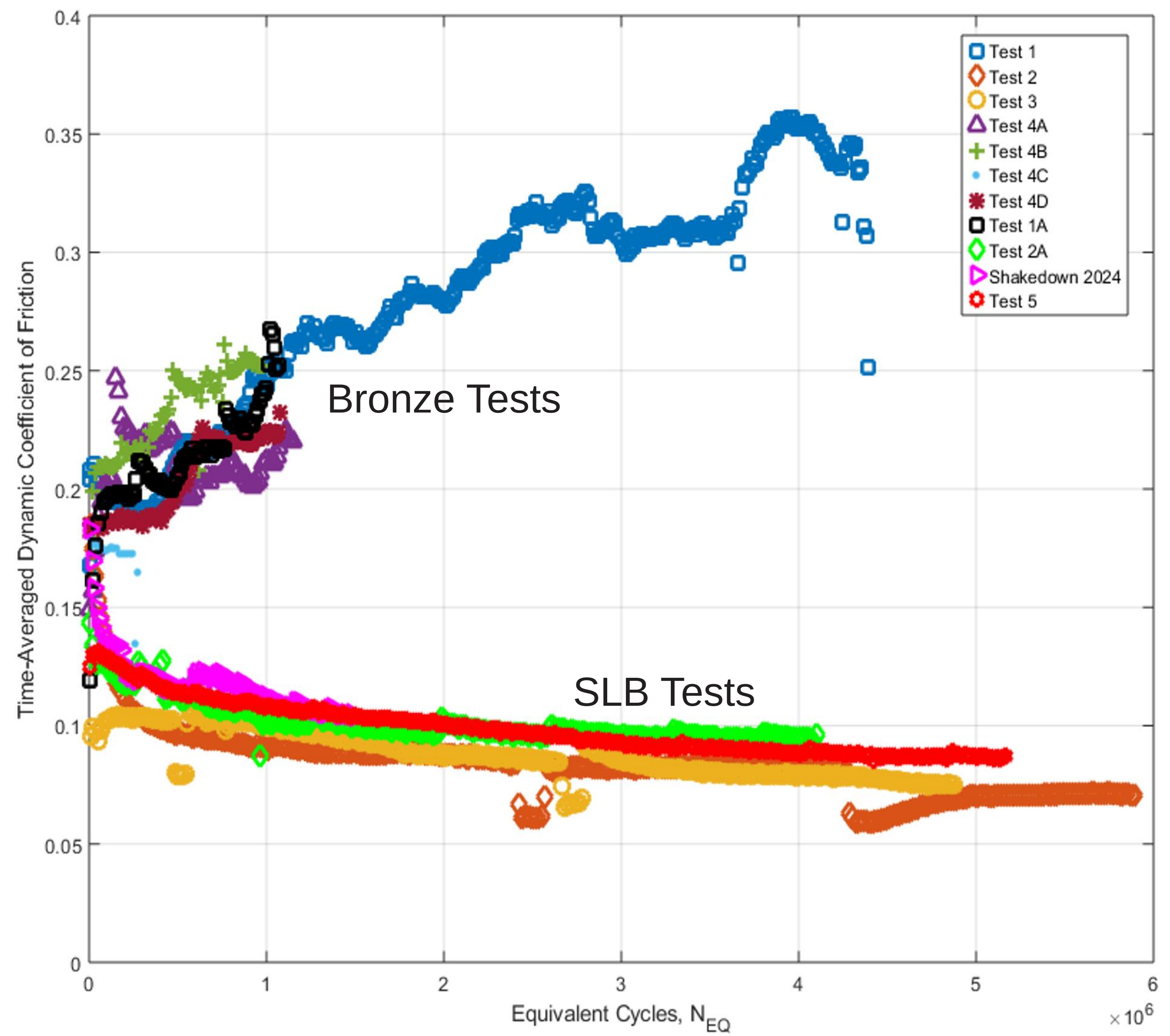
<u>Bronze bushings</u>

- Increasing COF with time

<u>Self-lubricated bushings (SLBs)</u>

- Decreasing COF with time

For SLBs, COF decreases at higher loads, therefore, smaller bushings can be utilized compared to bronze for the same application.



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TYPICAL WEAR TRENDS FOR BRONZE & SLB

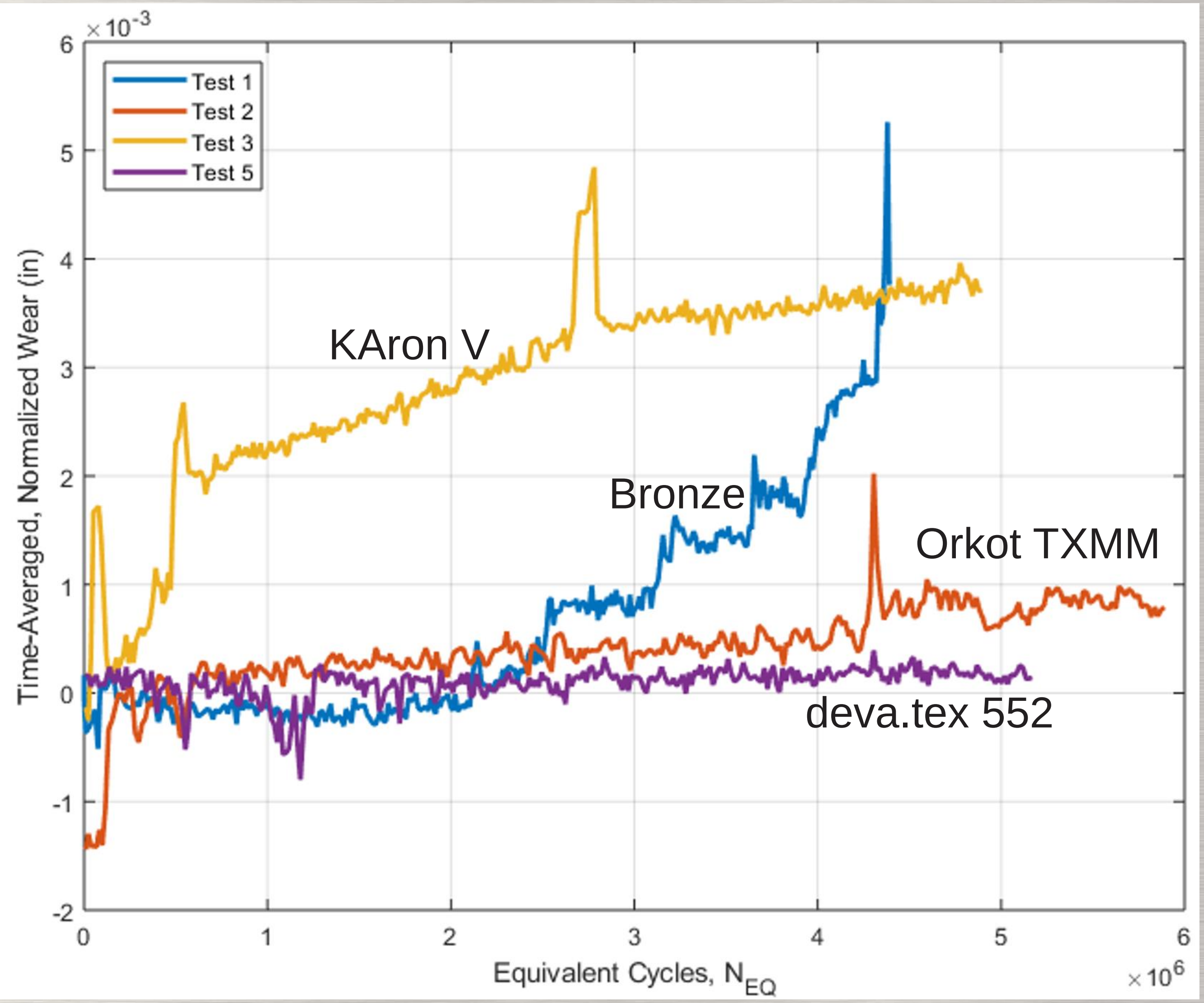
Wear

CONCLUSION: Bronze and SLBs both meet 50-year life conditions with maximum wear on the order of 0.005 inches.

Test Results

- Bronze bushing wear increases with time
- Self-lubricated bushings (SLBs) wear levels off with time

Note:
Immediately after testing, learned that KAron V manufacturer is no longer supporting bushings for this application.



TEST EVENT CHART (TYPICAL) – TEST 5

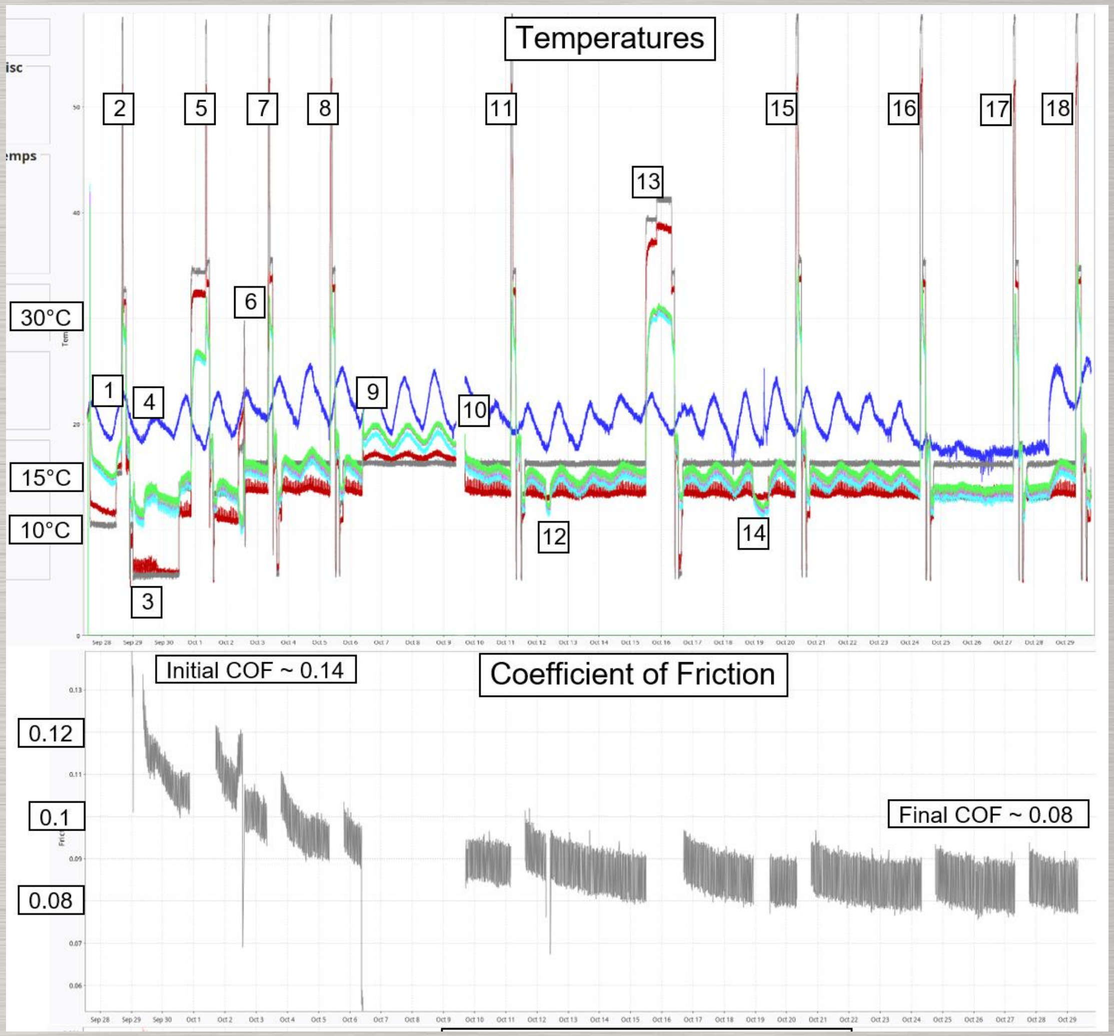
TESTING KEY FEATURES:

- Direct comparison of all data over time.

- Test events can be seen in data.
  - Gaps for Matrix testing
  - Temperature manipulation from Matrix testing

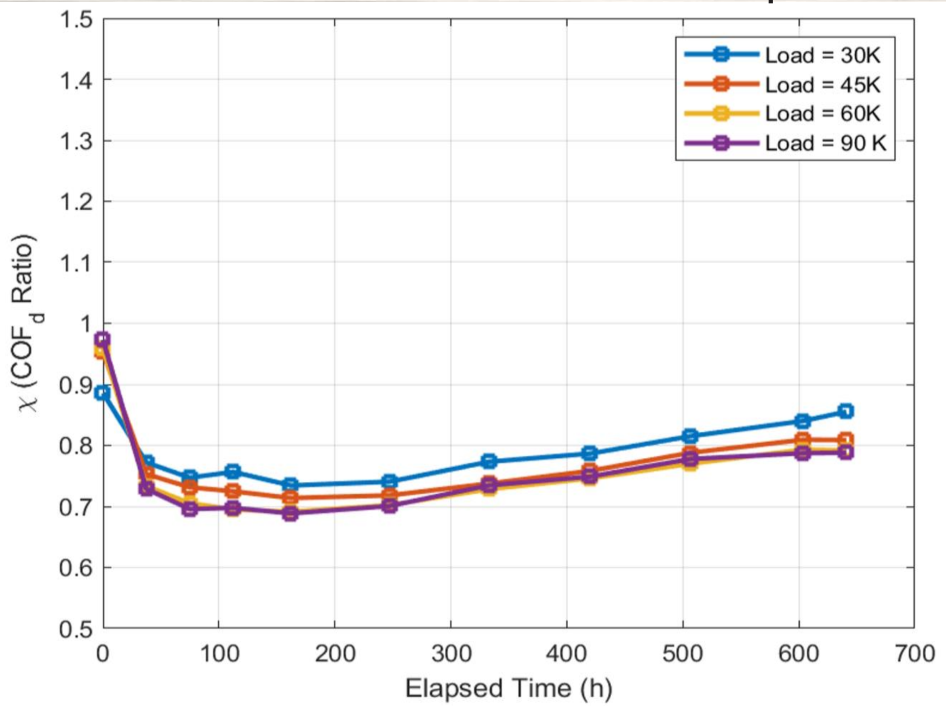
  Note: Test pauses or equipment excursions outside of normal parameters affects data.

- Increased temperatures decrease COF in SLBs
  - Actual temperatures will be in narrow operating range of 10 - 15°C so these effects will be minimized.



SCALING – MATRIX TESTING

- Compares various test parameters to prototype and determines factors with most influence
- Performed at test start, periodically during testing, and at end of test
- 3 factors were varied in a matrix for 30 or 60 total combinations of conditions
  - 5 angular velocities with increased sweep angle for stable dynamic torque
  - 3 varied loads for bronze and 4 varied loads for SLBs
  - 3 varied temperatures – 12.5°C, 18°C, 30°C



Test Condition	Normal Load (klb)	Related Operating Cycle Description	Angle of Continuous Sweep (deg)	Angular Velocity (deg/sec)	Target Avg. Tangential Velocity (cm/sec) ((in./sec))	No. of Repeat Cycles
A1/B1 C1/D1	30/45 60/90	Prototype minor	8	0.02	0.003 / -0.001	1
A2/B2 C2/D2	30/45 60/90	Prototype minor	8	0.06	0.0133 / -0.005	2
A3/B3 C3/D3	30/45 60/90	Prototype intermediate	8	1.39	0.154 / -0.061	5
A4/B4 C4/D4	30/45 60/90	Test scale major	8	3.2	0.355 / -0.14	5
A5/B5 C5/D5	30/45 60/90	Test scale minor	8	4.8	0.532 / -0.209	5

PNNL BUSHING TEST CAPABILITIES & REPORT

See Report for More Information

Report Title: *Self-Lubricating Bushing Testing for John Day Dam Kaplan Turbine Replacement*
Report Number: PNNL-37577

Test Stand Operations
- Run Testing Scenarios in Test Stand

Test Development
- Test Definition & Planning
- Scaling Assessment
- Test Plan

Test Preparations
- Test Design
- Procurements & Fabrications
- Test Setup
- Procedure Development
- Software Development

Test Analysis
- Data Analysis
- Data Reporting

PNNL Bushing Test Stand Team Members

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CONCLUSIONS

CONCLUSIONS FROM BUSHING TESTING

- The quality of data coming from PNNL far exceeds any testing to date (good news)

- The testing has been determined to be a valid test for comparison purposes on a cycle-per-cycle basis (good news). This is based on rigorous testing all variables associated with scalability of the bushing testing (speed, loading, viscosity).

- Analysis shows that test results will be more adverse or comparable to what is installed in the field. This is for both friction and wear and for all materials (good news) to varying degrees. This means absolute scaling to the field is not possible (less than ideal).

- There is adequate data to make feasibility level decisions on comparison between self-lubricating bushings and oiled-bronze for design purposes (good news)

OVERALL CONCLUSIONS

- Technical concerns with corrosion-induced fatigue were addressed; there appears to be about a 3 times improvement in fatigue life with 17-4 PH
- Technical concerns with self-lubricating bushings were addressed; friction and wear for self-lubricating bushings performed better than oiled-bronze
- Cost estimates for switching to water-filled hubs have uncertainty but came in at $1M - $2M per unit
- O&M efforts are anticipated to be equal to or less than oil-filled hubs

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QUESTIONS