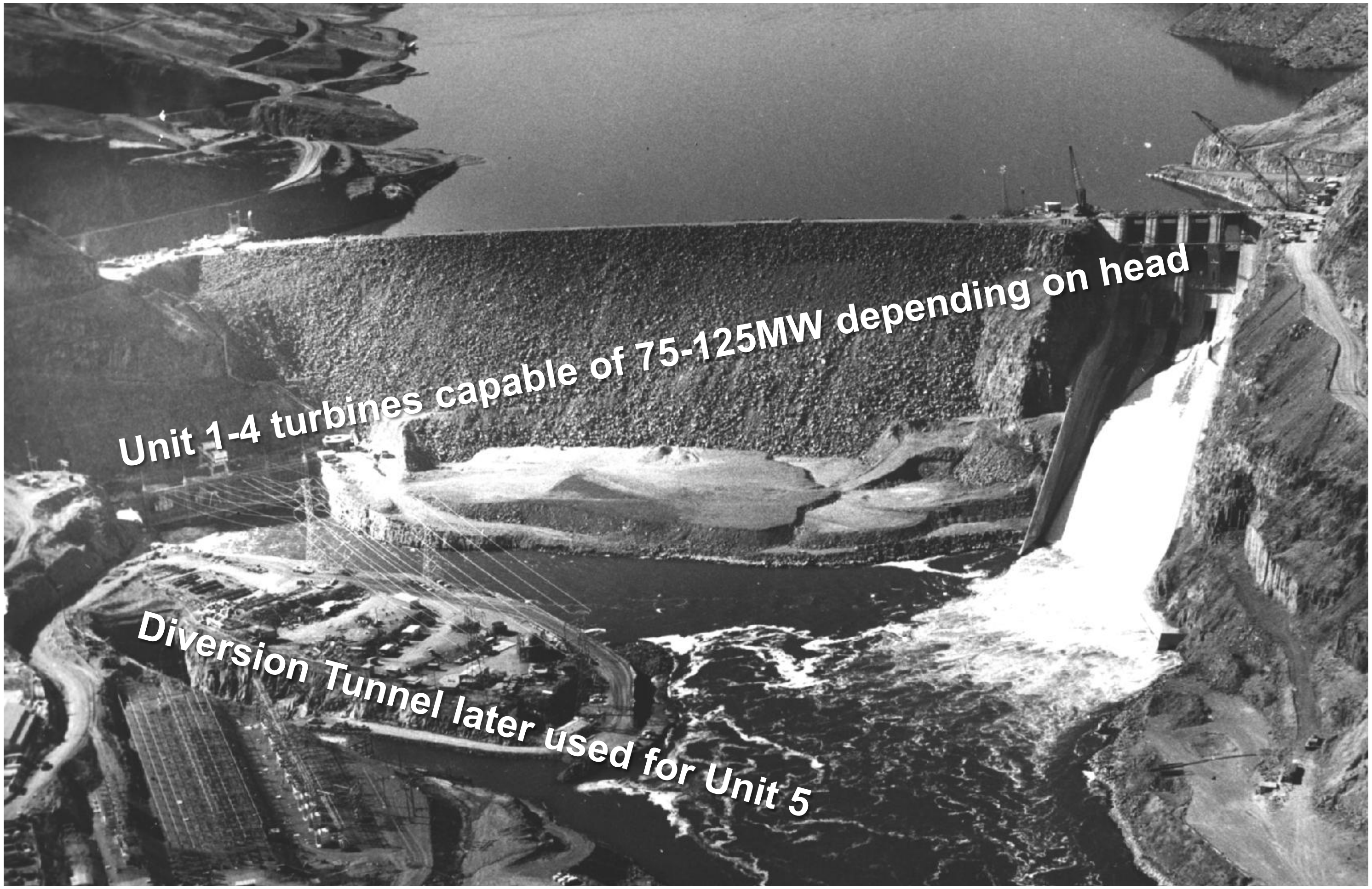
Extending the Operating Range of Brownlee Unit 5

Brownlee Plant History

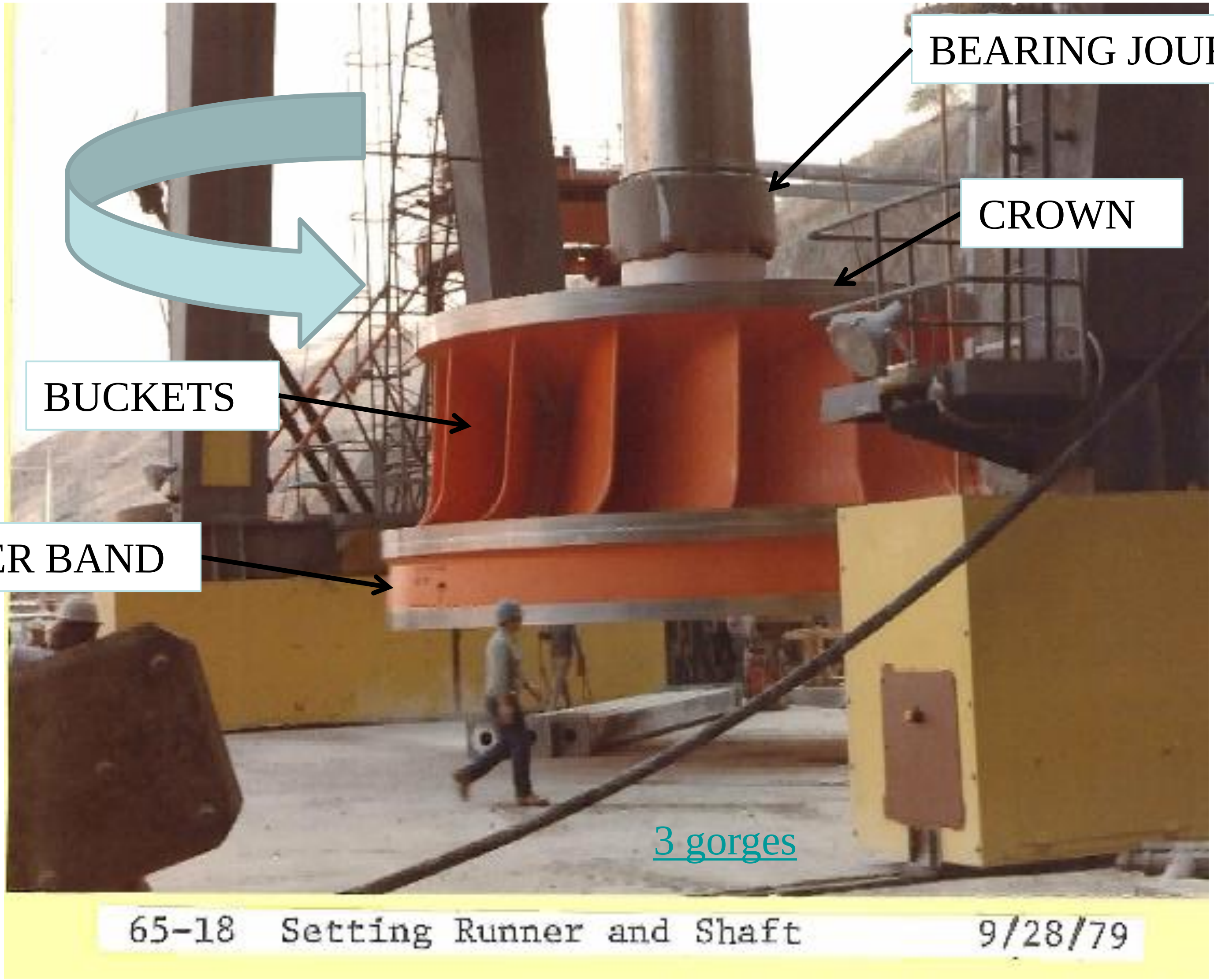
- Original Plant built in 1958 with four 100MW rated units



Brownlee Plant History

- New 250MW Hitachi unit 5 added to plant in 1980

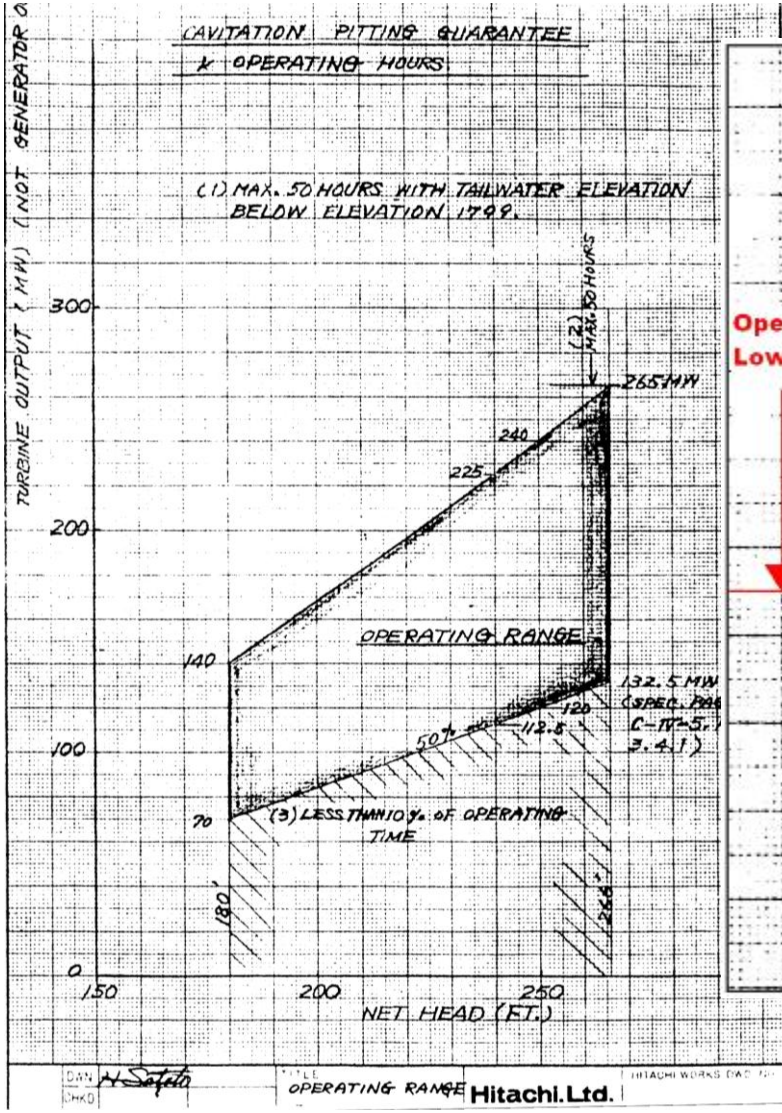
Unit 5 Francis Turbine (Runner)

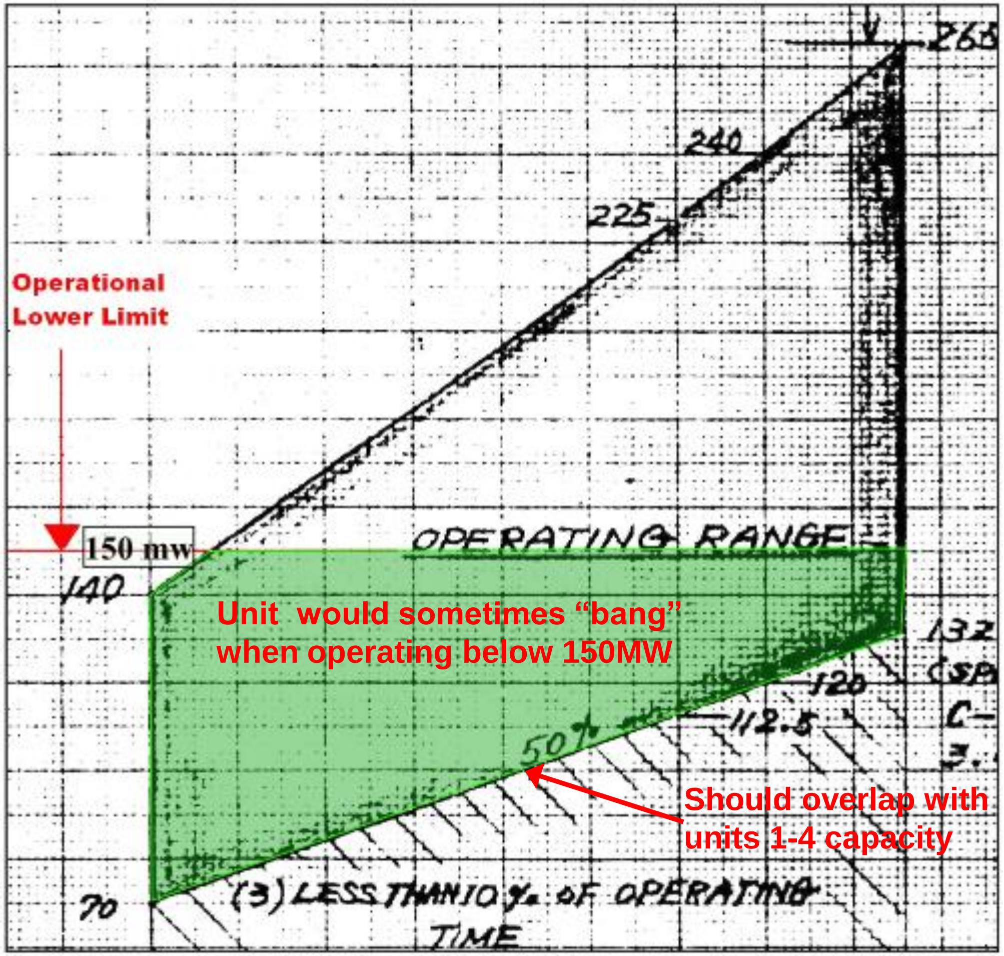


Unit 5 Rough Zone History (1) …

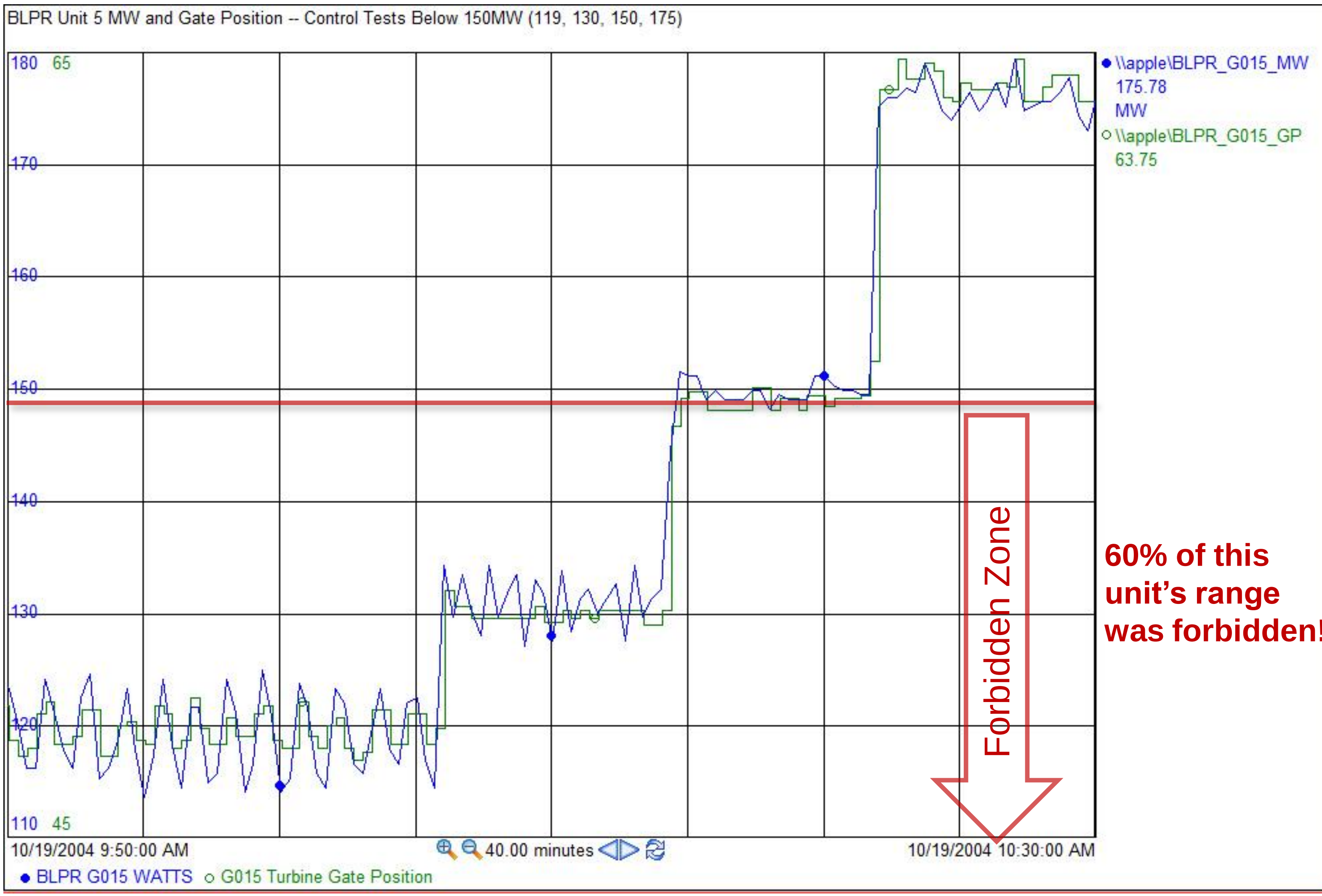
- A severe rough zone was identified during commissioning in **1980**
  - avoid that zone (below 50% gate), why operate off peak efficiency?
- Higher rough zone limits noticed during **1997** flood control draft
  - probably an issue with the vent valve operated by gate position
- MW oscillations noticed during AGC testing in **2004**
  - tested AVR and PSS to rule out control or electrical causes
  - focused attention on hydraulics (turbine?)
  - AGC implemented with forbidden zone below 150MW
- Generation dispatch requested a study to expand unit 5's operating zone to help with regulating margin and unit swapping in **2006**
  - of course once they got used to having it on AGC control….
  - need became urgent as we tried to integrate more wind generation

Brownlee Unit 5 Guaranteed Operating Range





Brownlee Unit 5 MW Oscillations below 150MW

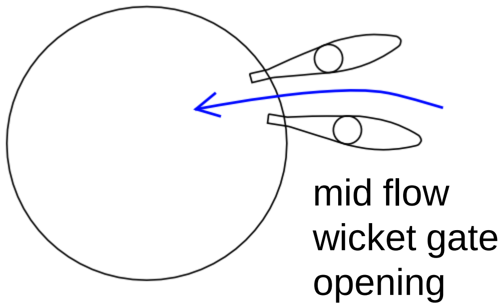


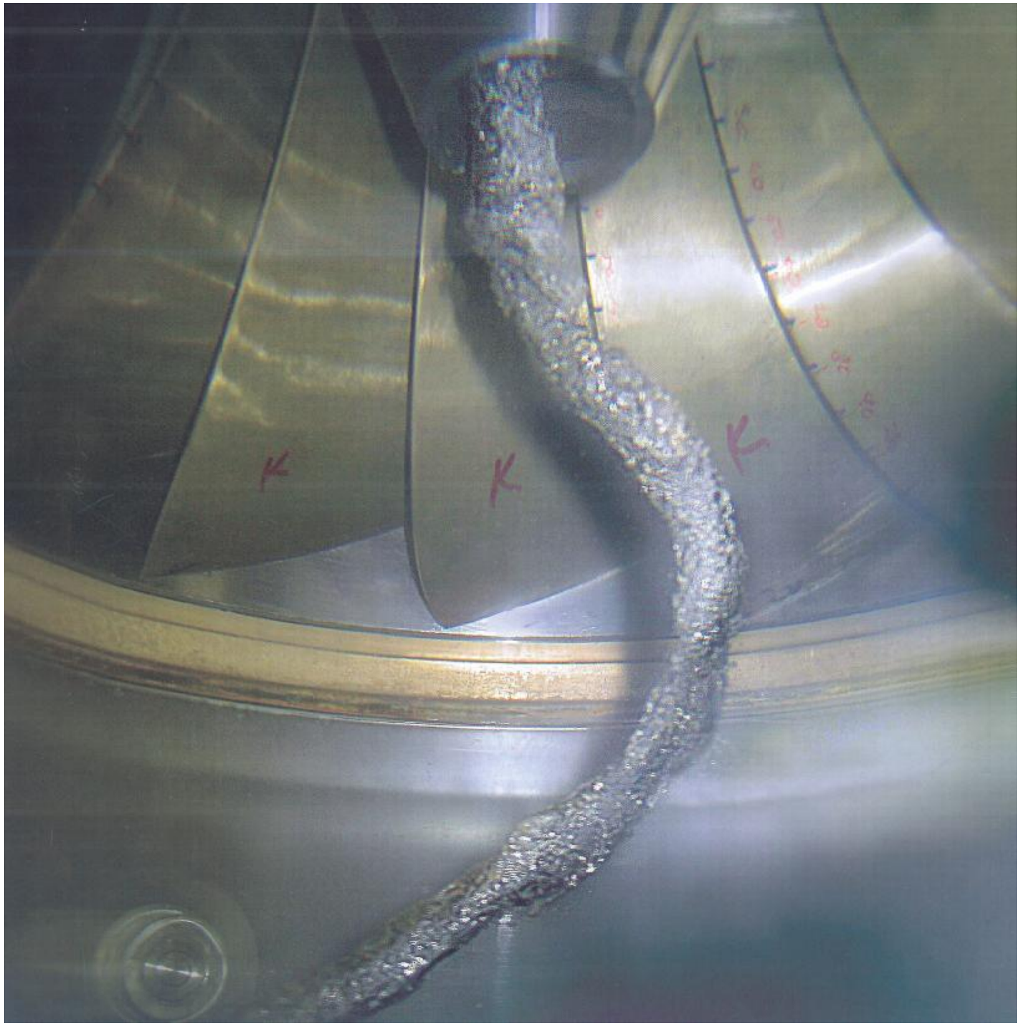
…**Unit 5 Rough Zone History** (2)

- In **2008** a consultant was hired for the rough zone study
  - **Rheingan's vortexing** in mid-gate regions
  - risk of vortex collapse and "bang" only happens in upper vortex zone 2
  - **blade cavitation** in lower-gate regions
  - rough zones vs. head water and gate position seemed well-behaved
  - discovered unused piping system for injecting compressed air into turbine
- Improved vent valve control could help in **vortexing** region
  - originally implemented with cam-driven switches in governor cabinet
  - use PLC to operate valves with both head-water and gate position (or MW)
  - use a **second** vent valve (normally used to vent depression air)
- Compressed air injection could help in the **cavitation** region
  - use the "**compressed air subsystem**" piping just discovered
  - used depression air tanks to inject pressurized air in front of the turbine blade
  - air-flow requirements estimated at **5000cfm**, 1000 hp, **750kW** electrical service

Draft Tube Vortex (Rheingans)

- Swirl occurs below 50% wicket gate opening;
- Vortex rope spins at 20-30% of running speed;
- Needs lots of venting air to avoid collapse;
- Vortex collapse can cause large vibrations at Browlee 5 plant



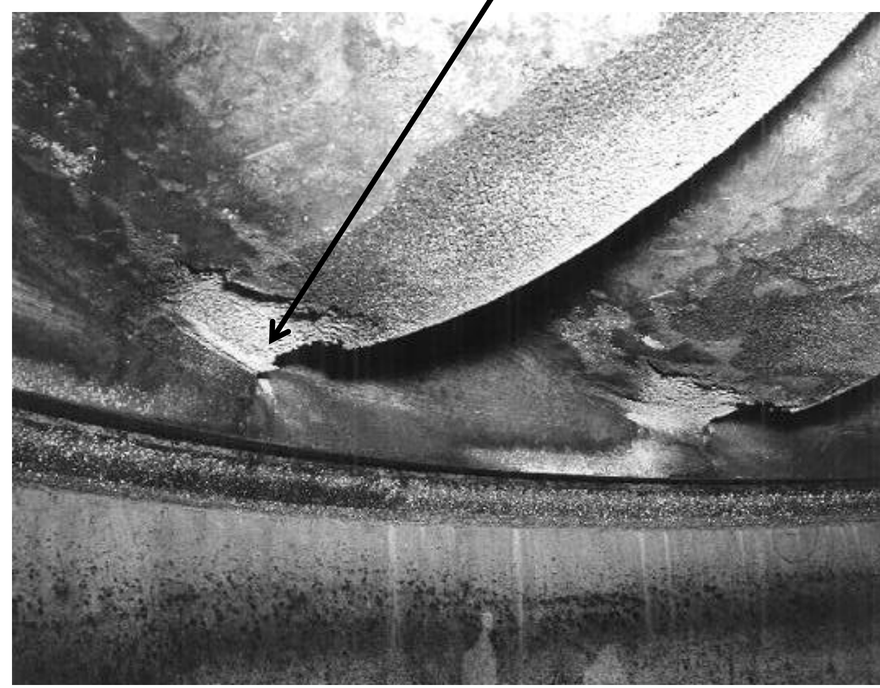


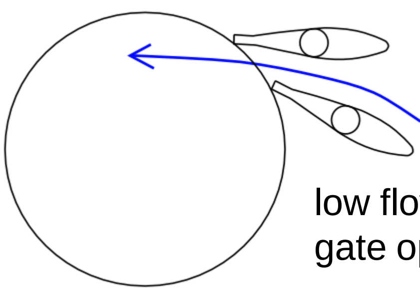
Vortex Animation

Cavitation Damage

INLET EDGE CAVITATION DAMAGE

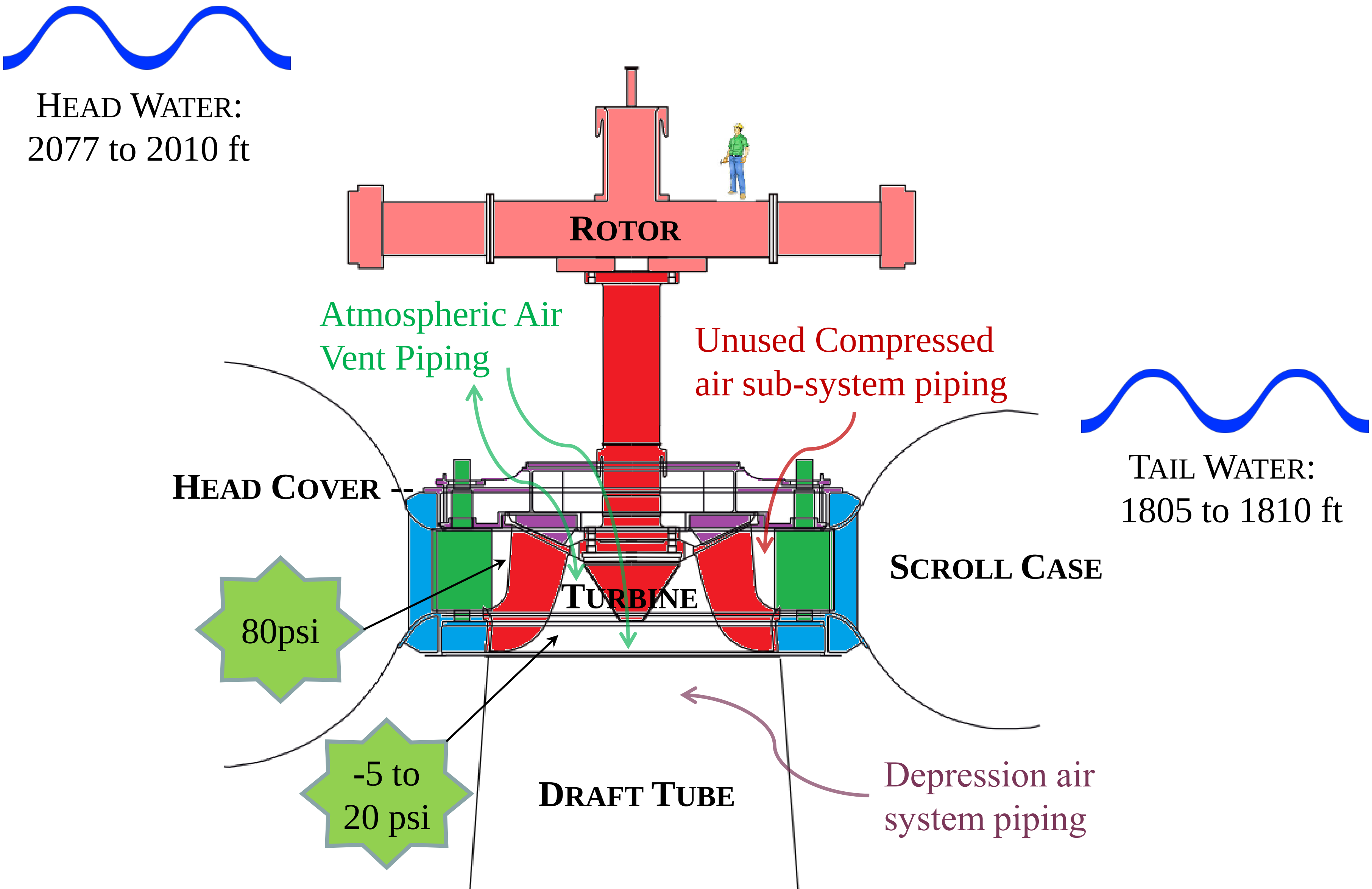
EXIT EDGE CAVITATION DAMAGE





low flow wicket gate opening

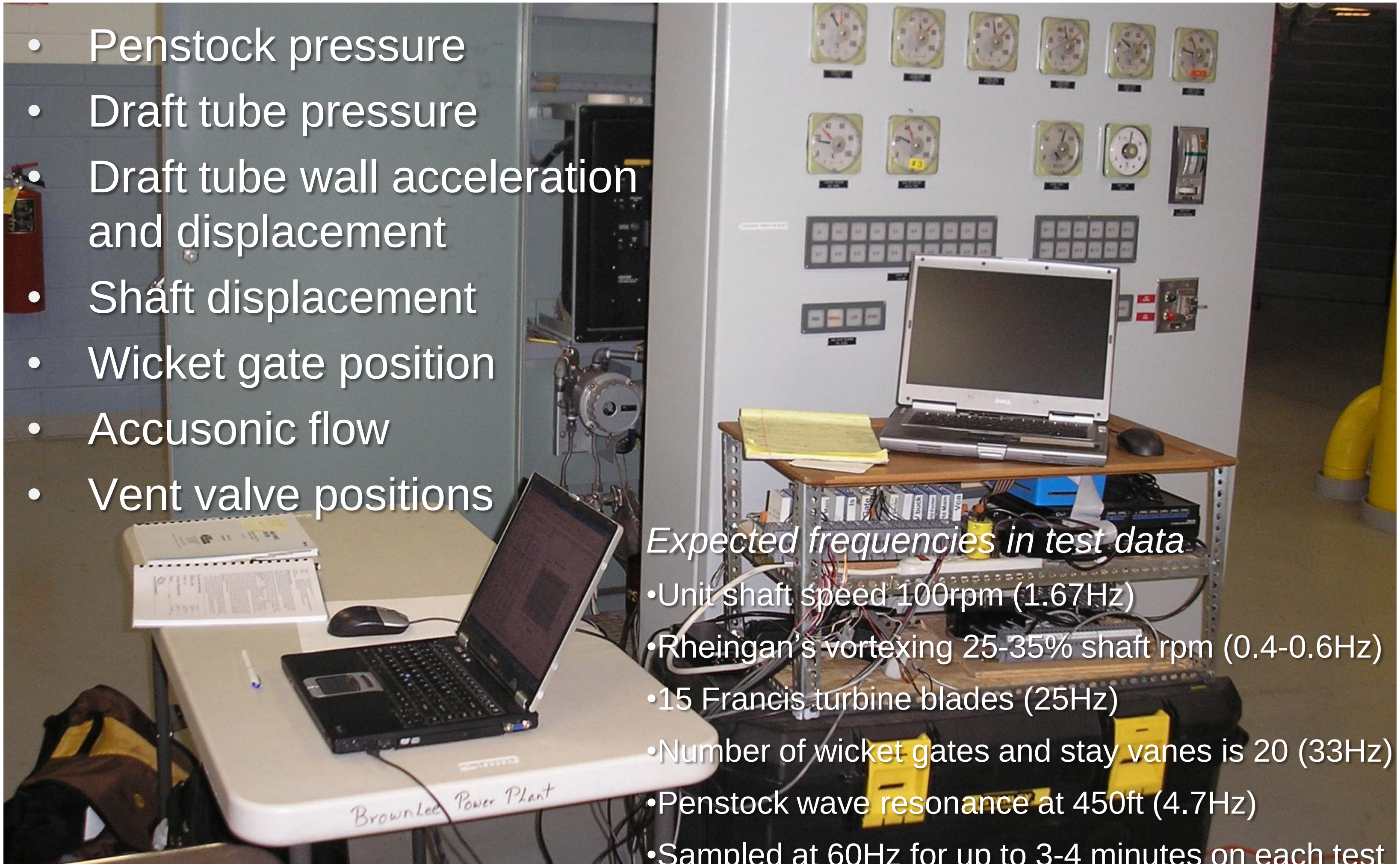
Brownlee Unit 5 Turbine Air



Temporary Air Injection for 2008 Testing

used air stored in depression air tanks for short duration smoothing air injection tests

2008 Rough Zone Study
Test Equipment Set-up



- Penstock pressure
- Draft tube pressure
- Draft tube wall acceleration and displacement
- Shaft displacement
- Wicket gate position
- Accusonic flow
- Vent valve positions

Expected frequencies in test data

•Unit shaft speed 100rpm (1.67Hz)

•Rheingan's vortexing 25-35% shaft rpm (0.4-0.6Hz)

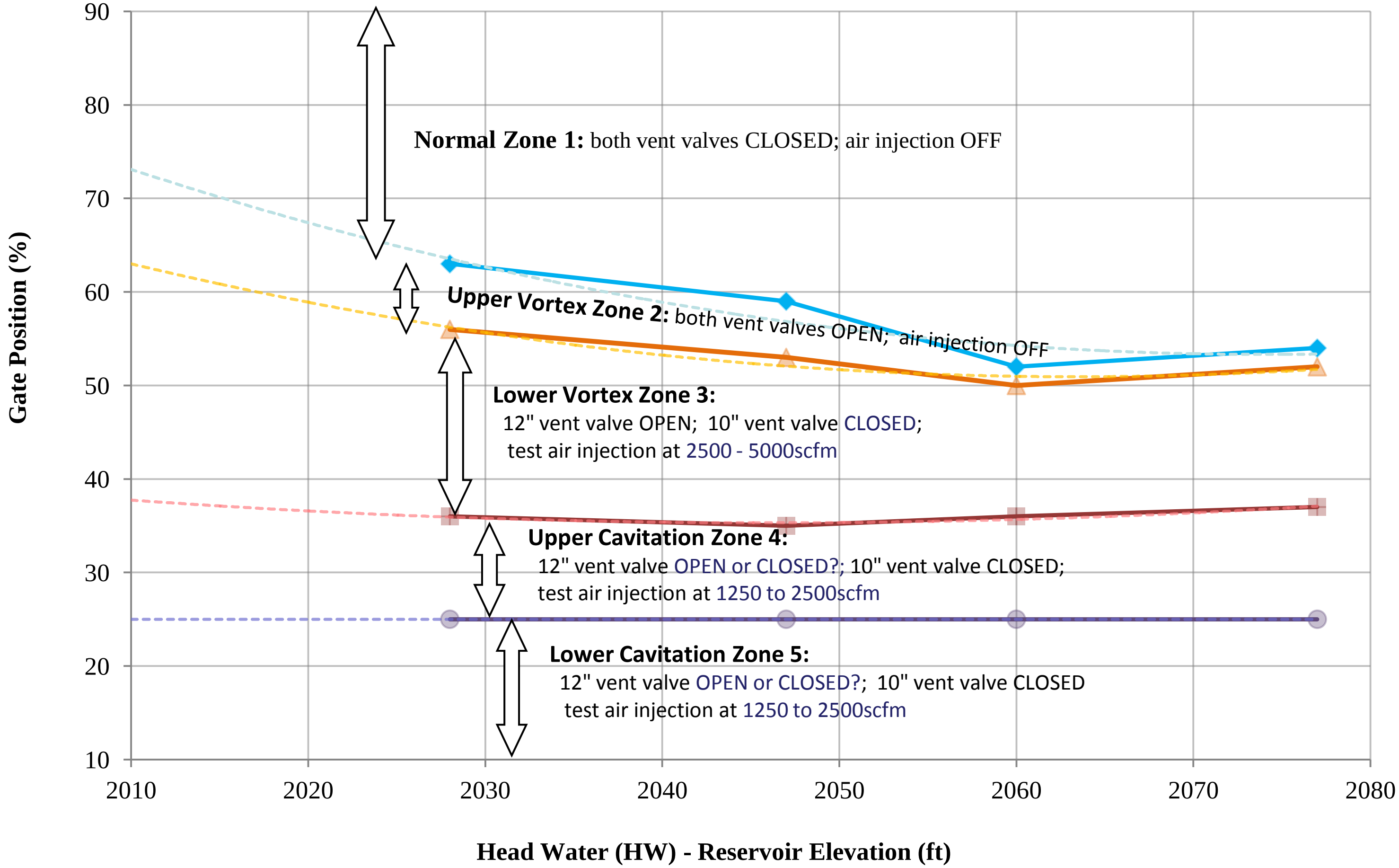
•15 Francis turbine blades (25Hz)

•Number of wicket gates and stay vanes is 20 (33Hz)

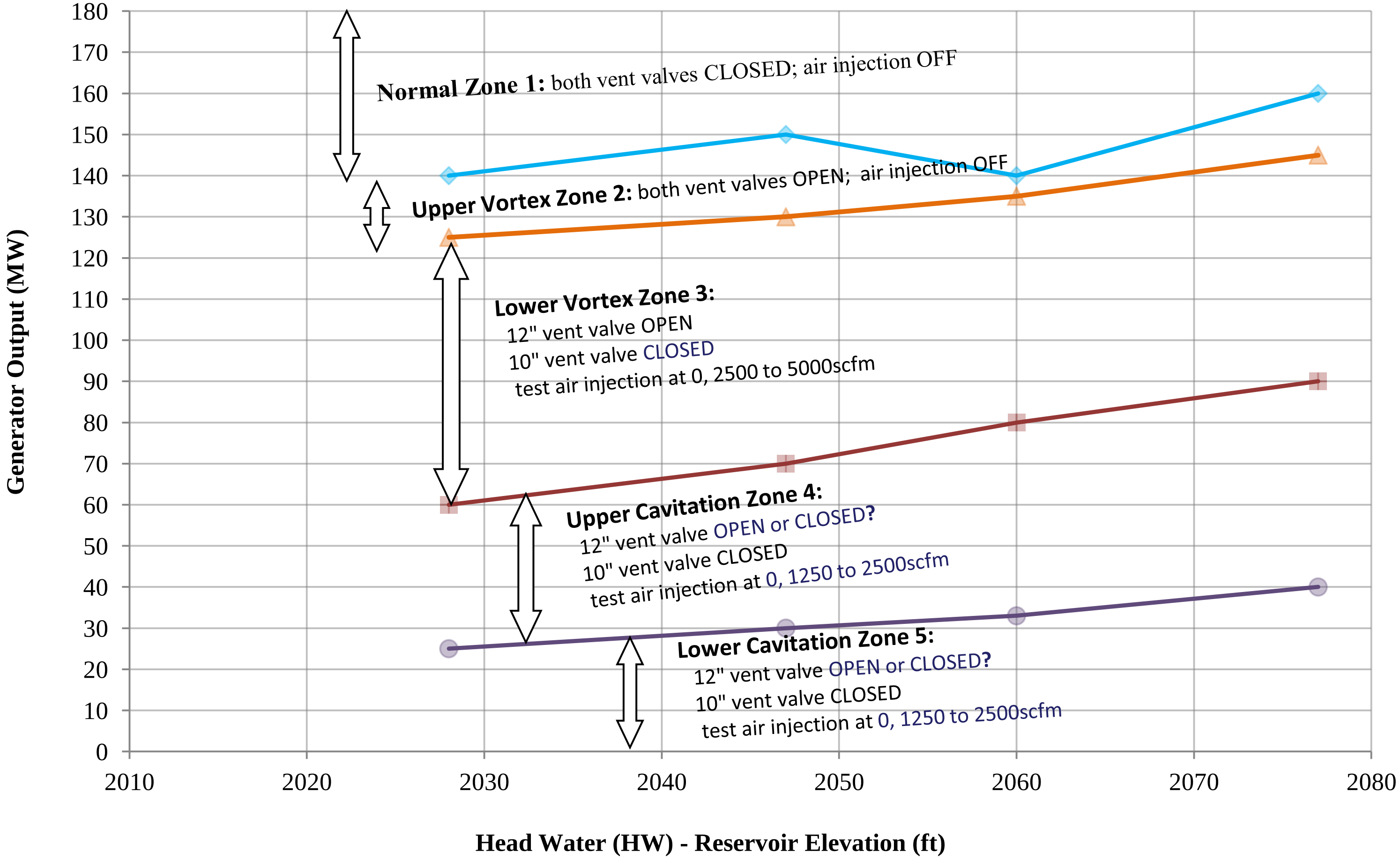
•Penstock wave resonance at 450ft (4.7Hz)

•Sampled at 60Hz for up to 3-4 minutes on each test

2008 Operating Zone Map - Gate Position (non-linear)



2008 Operating Zone Map - MW (more linear)



…Unit 5 Rough Zone History (3)

- In **2010** we decided to install the air compressor system
  - least expensive alternative for gaining regulating margin on our system
  - compressor system losses and lost unit efficiency still less than depressing unit
  - needed the down regulation with increasing wind generation on our system
- In **2011** we installed a vibration monitoring system, and started…
  - history of damaged air piping on this unit if operated in rough zone
  - generations of plant operators learning not to operate the unit below 150MW
  - severe "banging" and some head-cover movement if vortex collapses in zone 2
  - Sayano-Shushenskaya hydro plant accident in Russia
- …a test program to determine control requirements in the rough zones
  - map out unit 5's operating zones with smoothing air mitigation
  - extend operating zones as far as possible
  - determine vibration alarm levels to protect machine

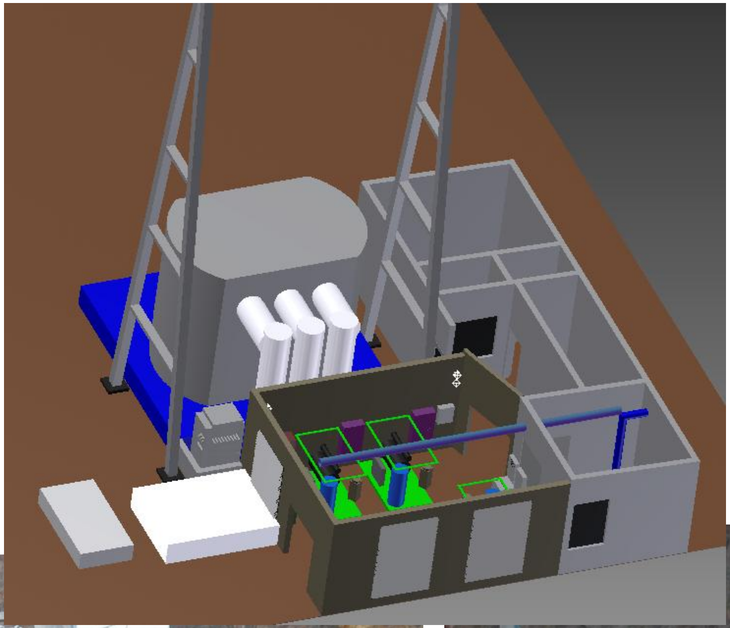
IDAHO POWER
An IDACORP Company

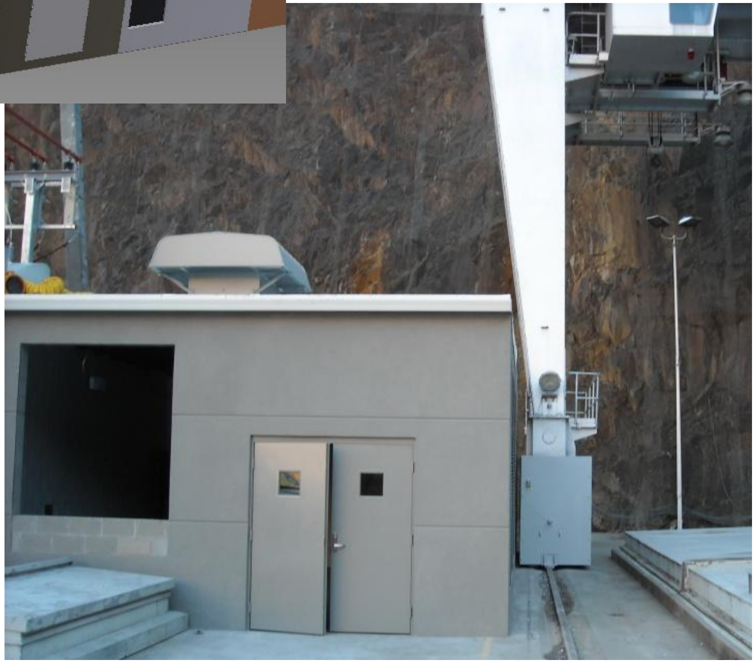
Compressor Building before…

Challenges:

- Physical Location
- Supply Power
- Control Integration

Compressor Building after…





Inside Compressor Building

System specifications:

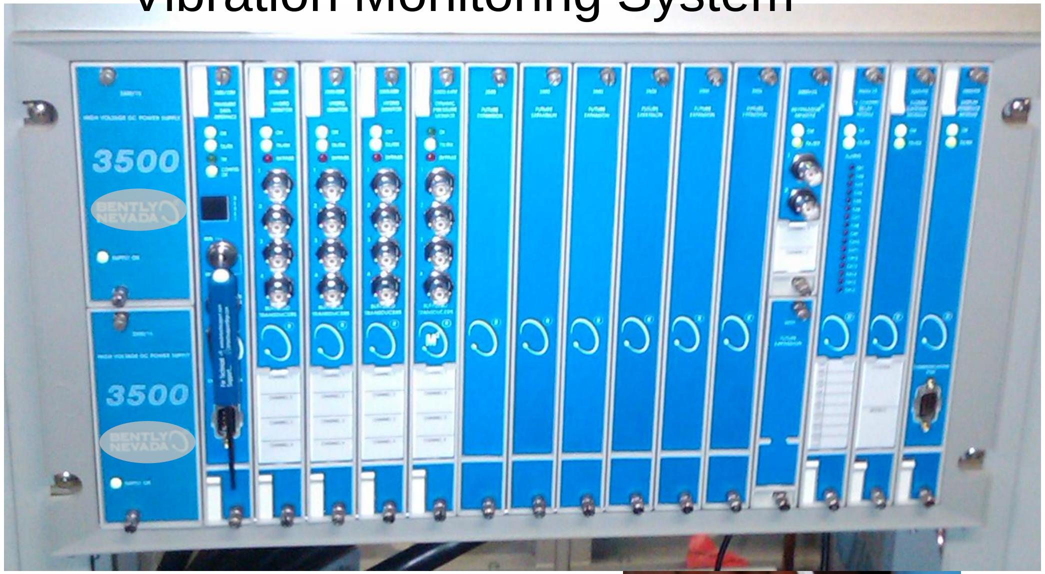
- Four 300-hp rotary screw compressors (1 VFD)
- 1,250 scfm of air delivery each
- 50-100 psi delivery pressure (variable)
- Sequencer/controller interfaced with plant PLC

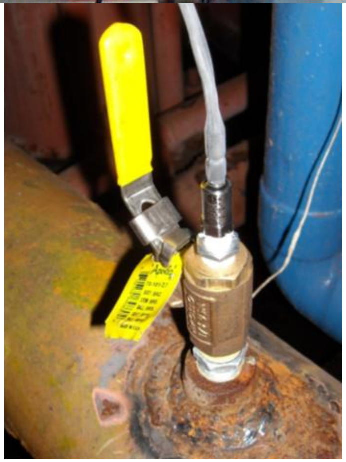
Power Taps into Iso-Phase Bus

- used two spare local service transformers
- current-limiting fuses needed for fault duty
- very tight fit, but sufficient cooling air flow

2011 Operating Zone Mapping Test Equipment Set-up

Vibration Monitoring System





Fast sampled data:

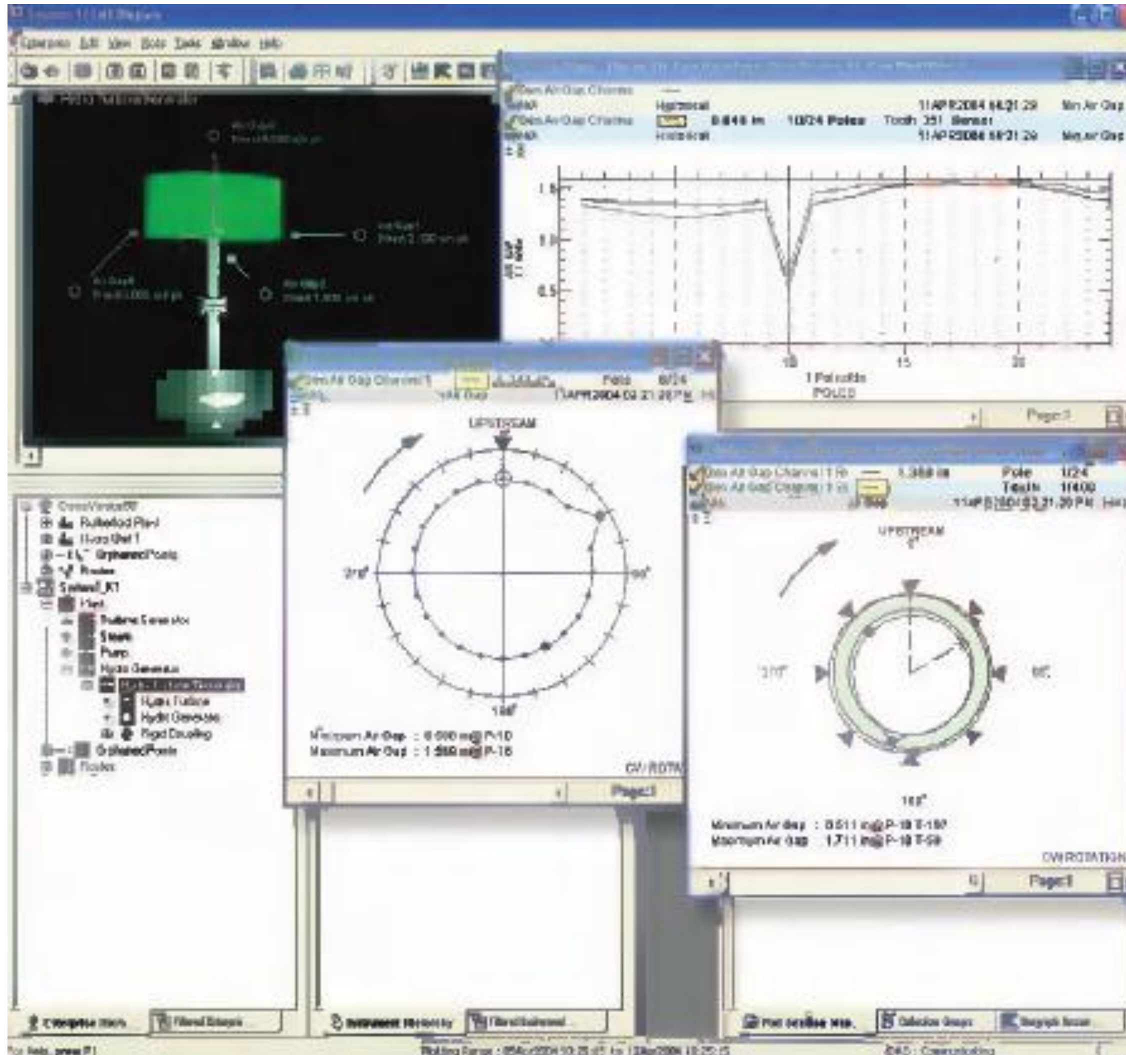
- Penstock pressure
- Draft tube pressure
- Draft tube acceleration
- Head-cover acceleration
- UGB vibration
- TGB vibration
- Thrust on shaft

Slower sampled data:

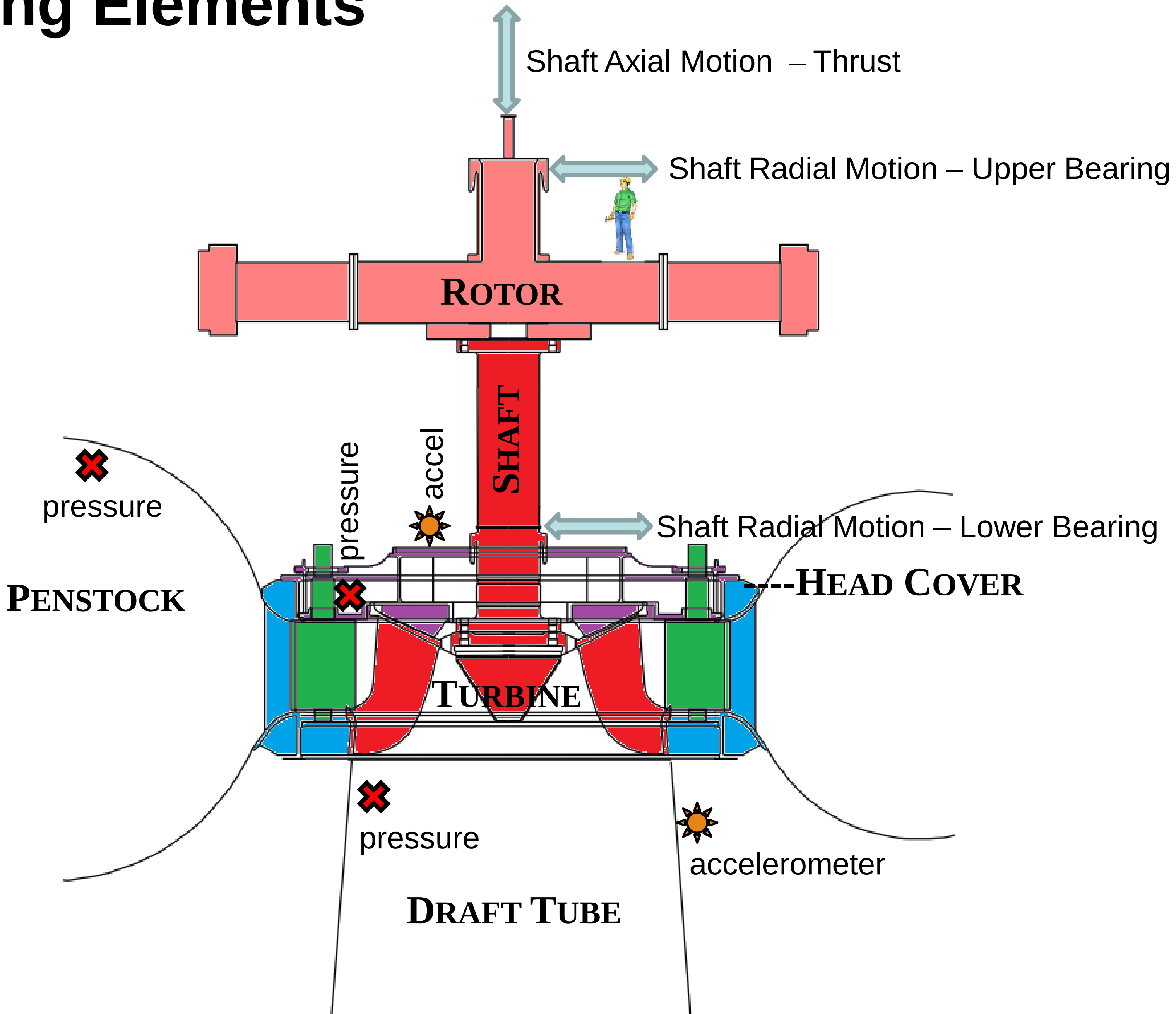
- MW output
- Wicket gate position
- Accusonic flow
- Air valve positions
- Air flow and pressures

Data Collection & Analysis Software

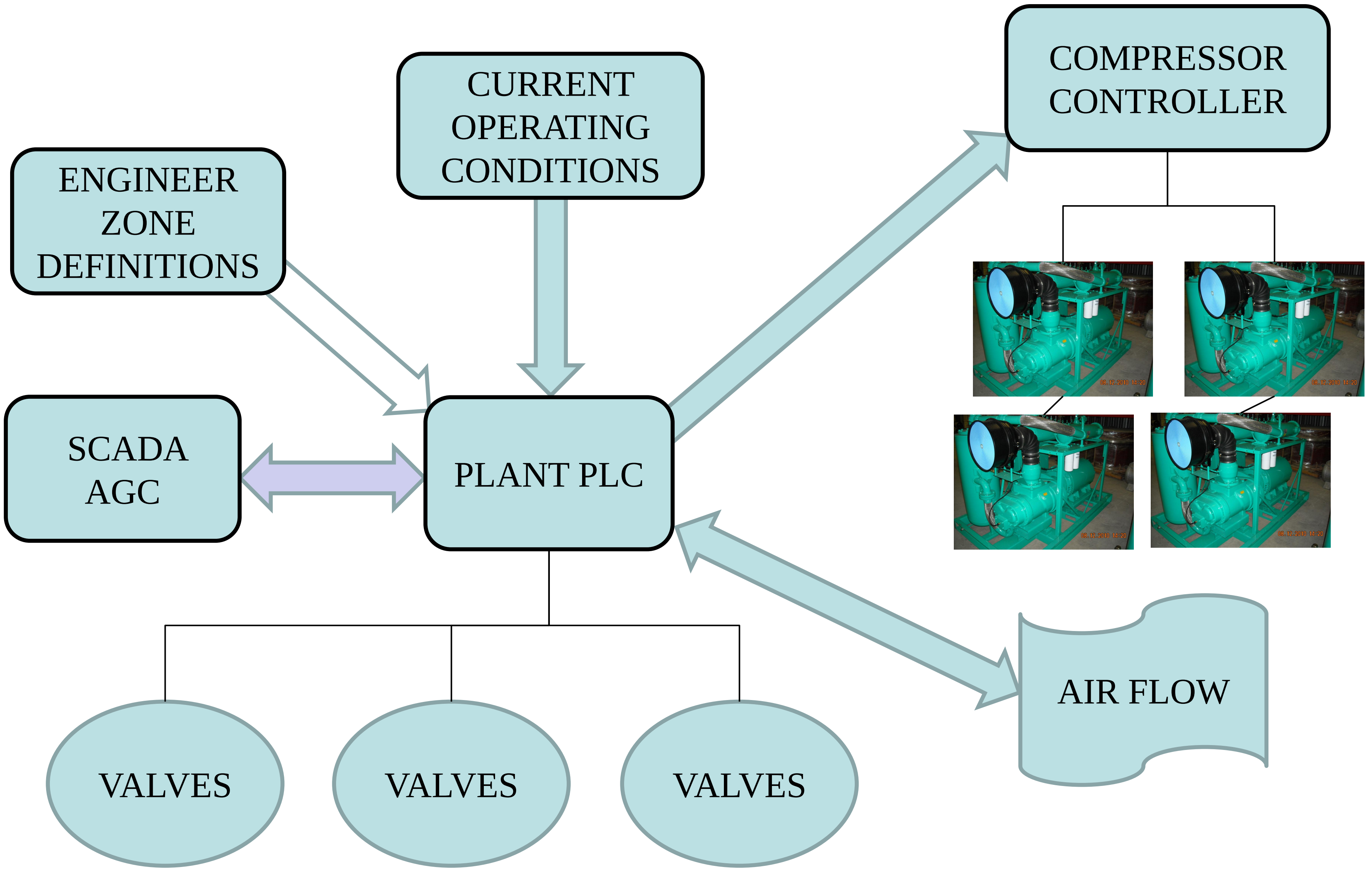
- Permanent data collection system
- Additional machinery diagnostic capabilities



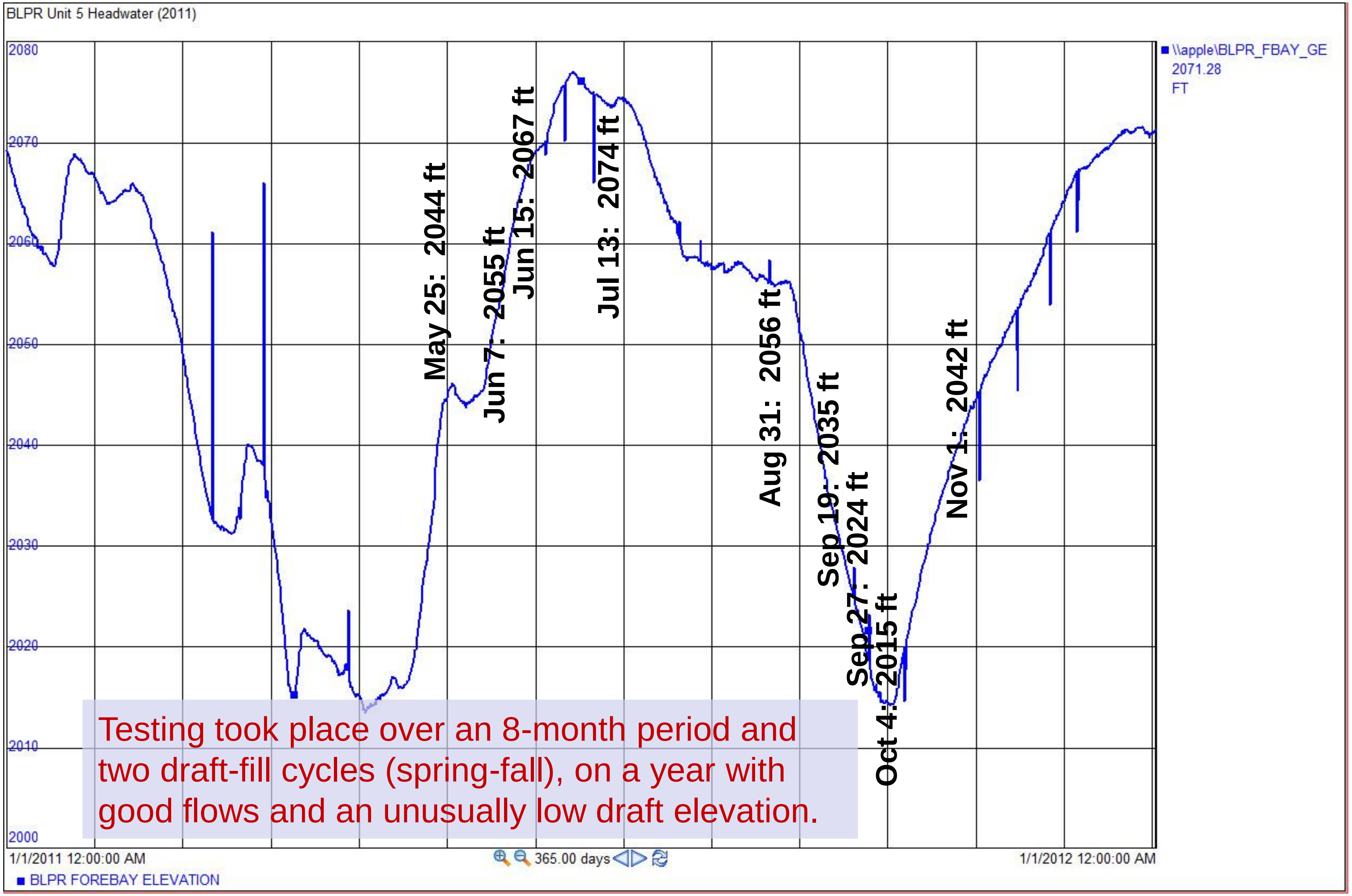
2011 Sensor Locations- Rotating Elements



Control System Overview

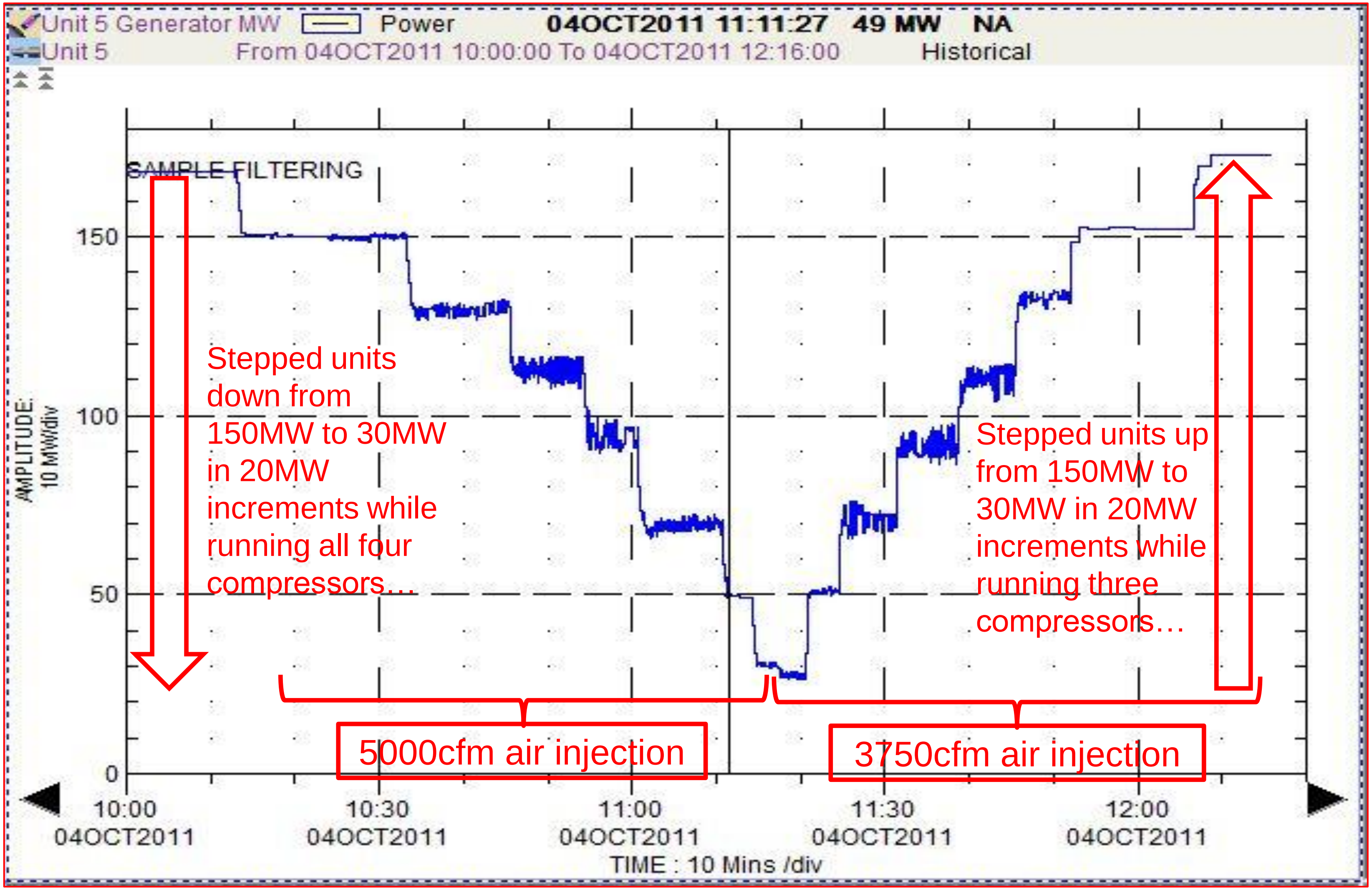


Brownlee Headwater 2011 Test Opportunities

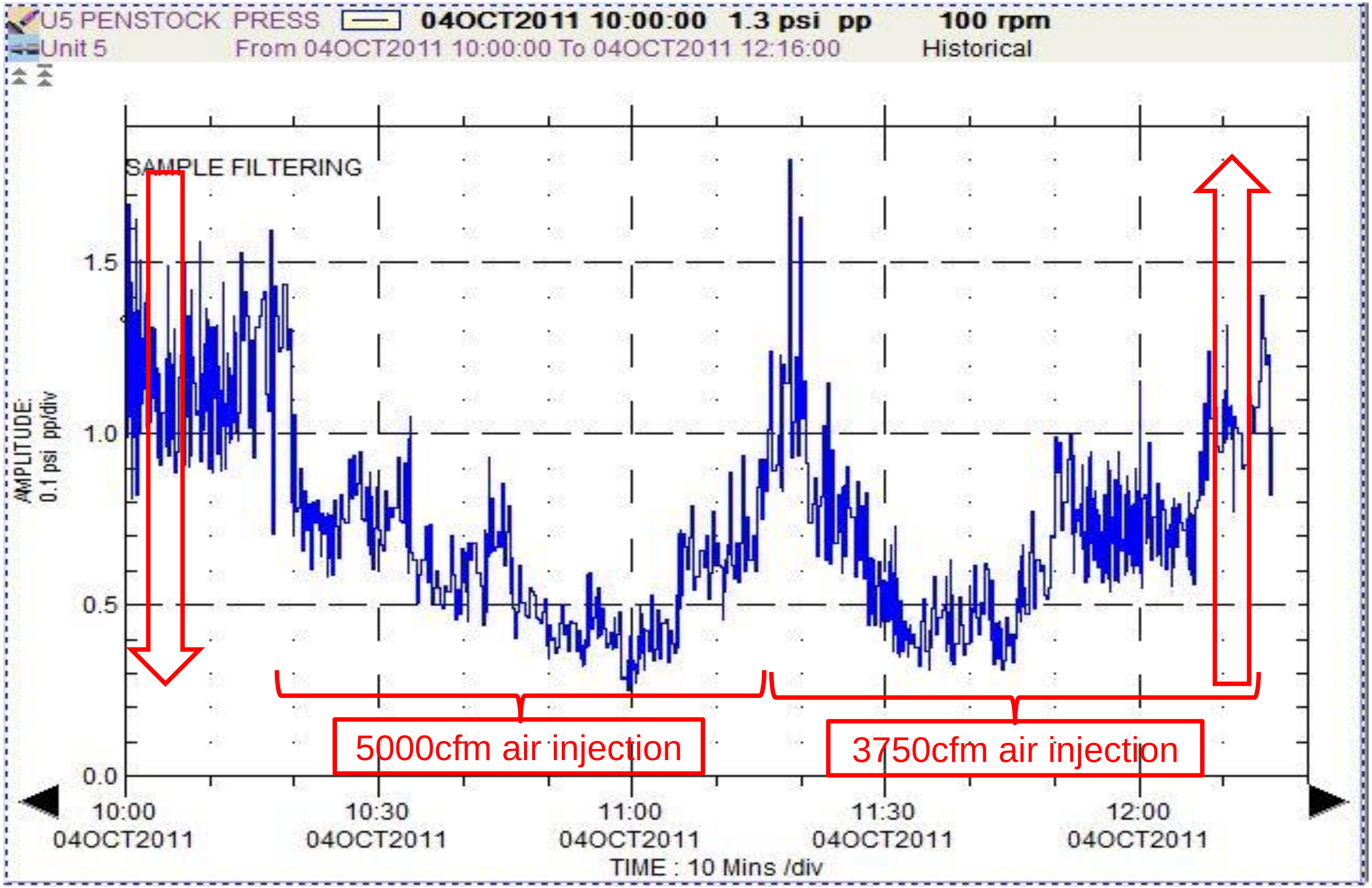


Testing took place over an 8-month period and two draft-fill cycles (spring-fall), on a year with good flows and an unusually low draft elevation.

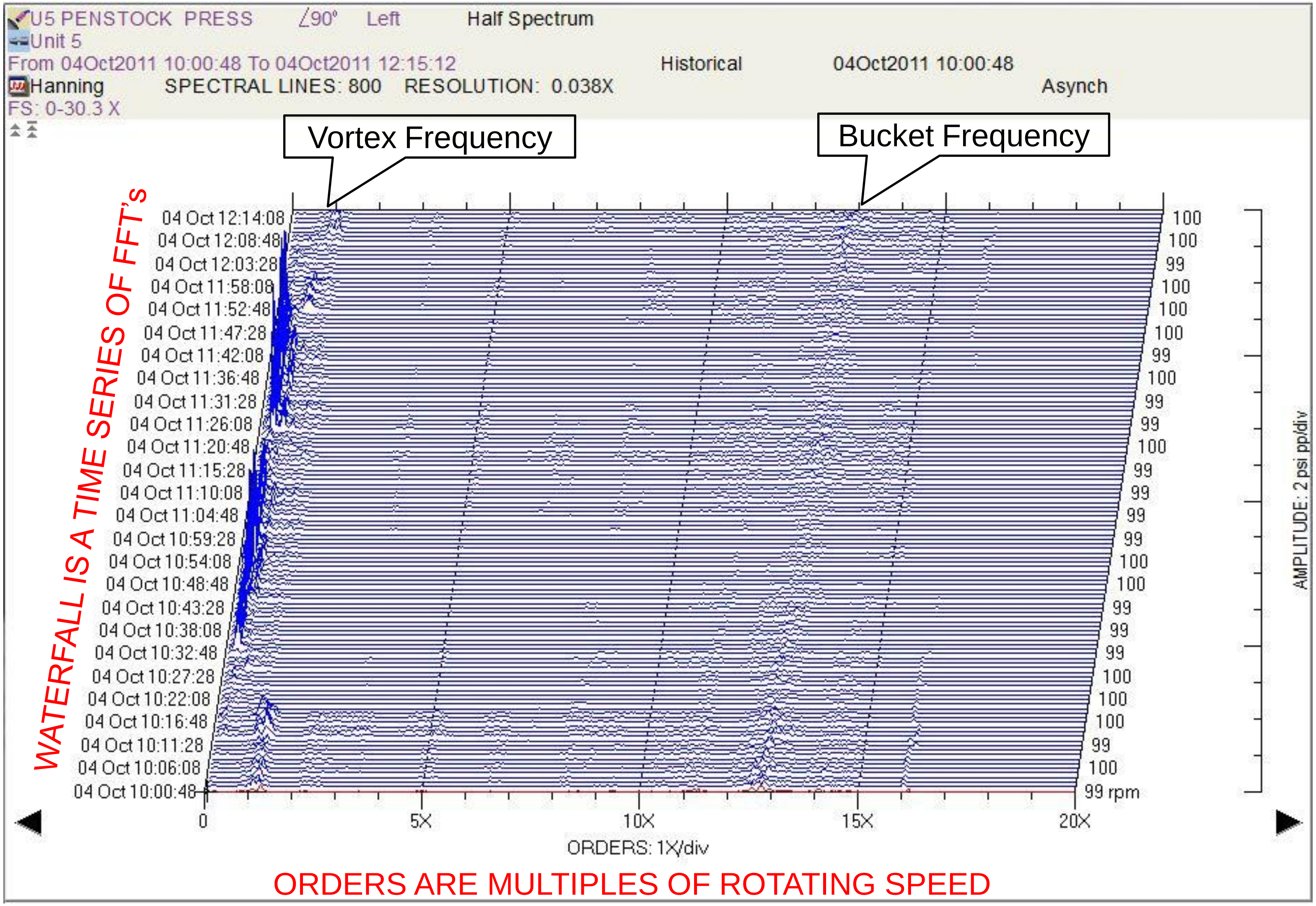
MW variation at 2015ft



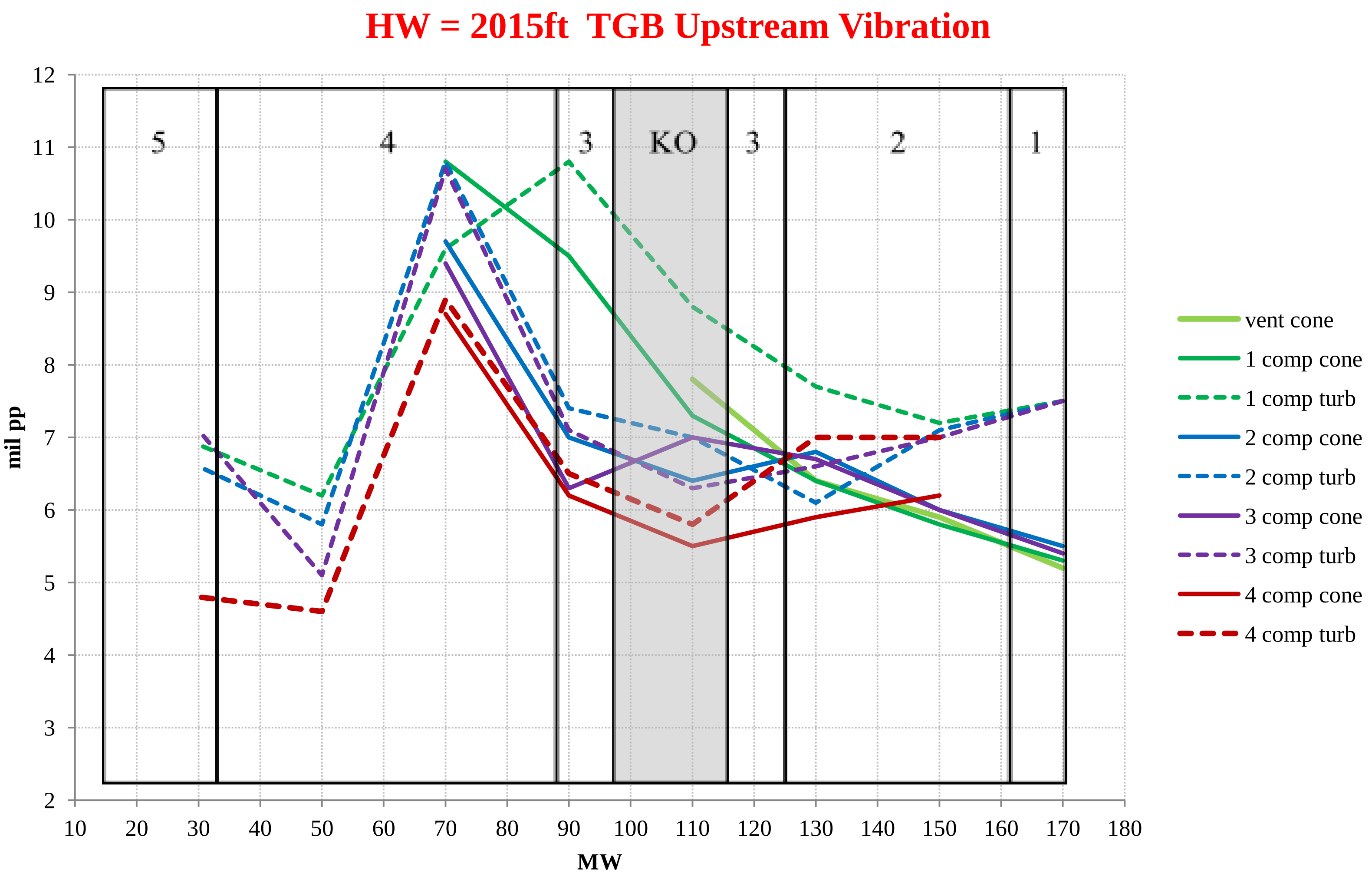
Penstock Press at 2015ft



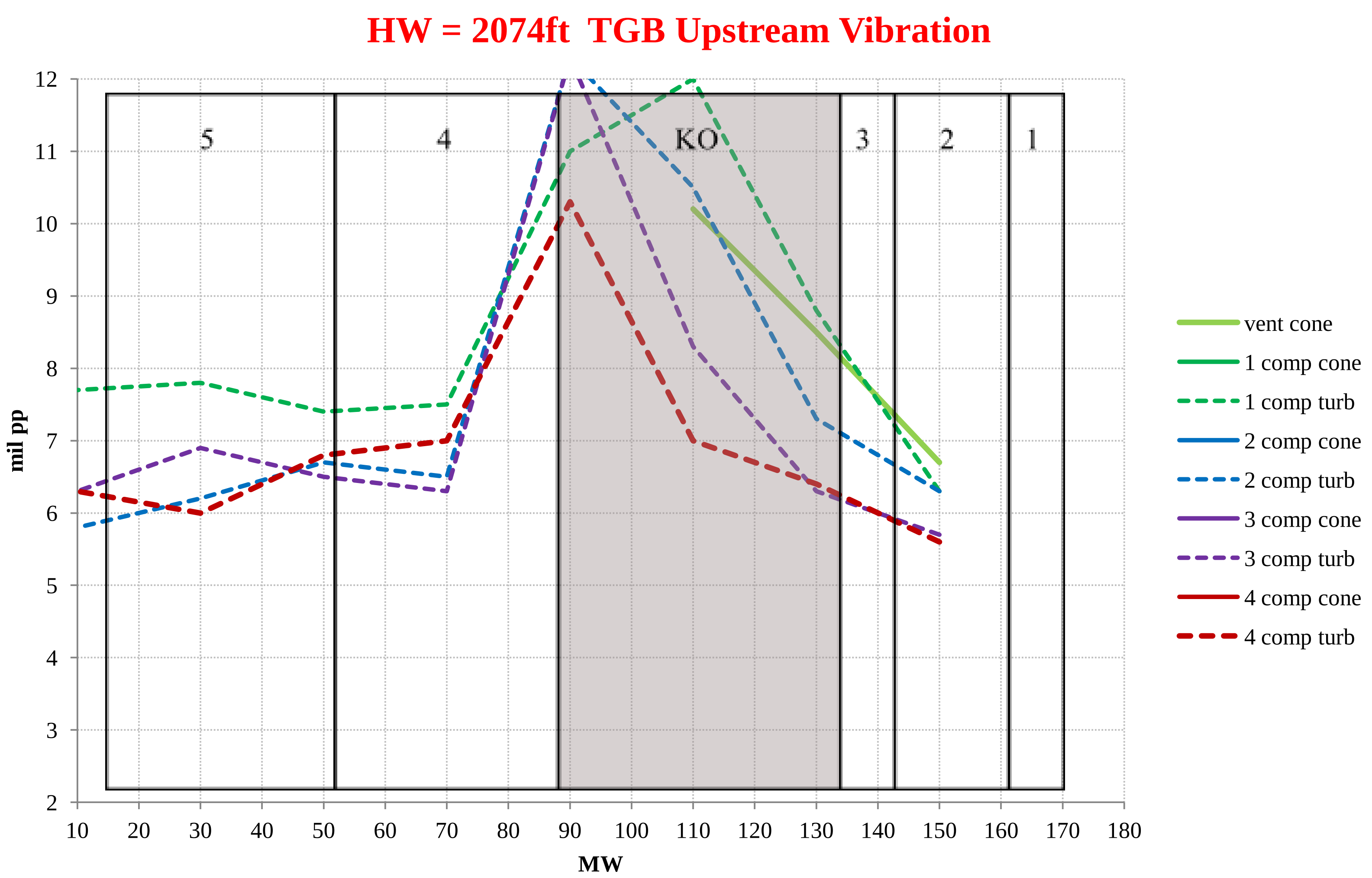
Penstock Press FFTs at 2015ft



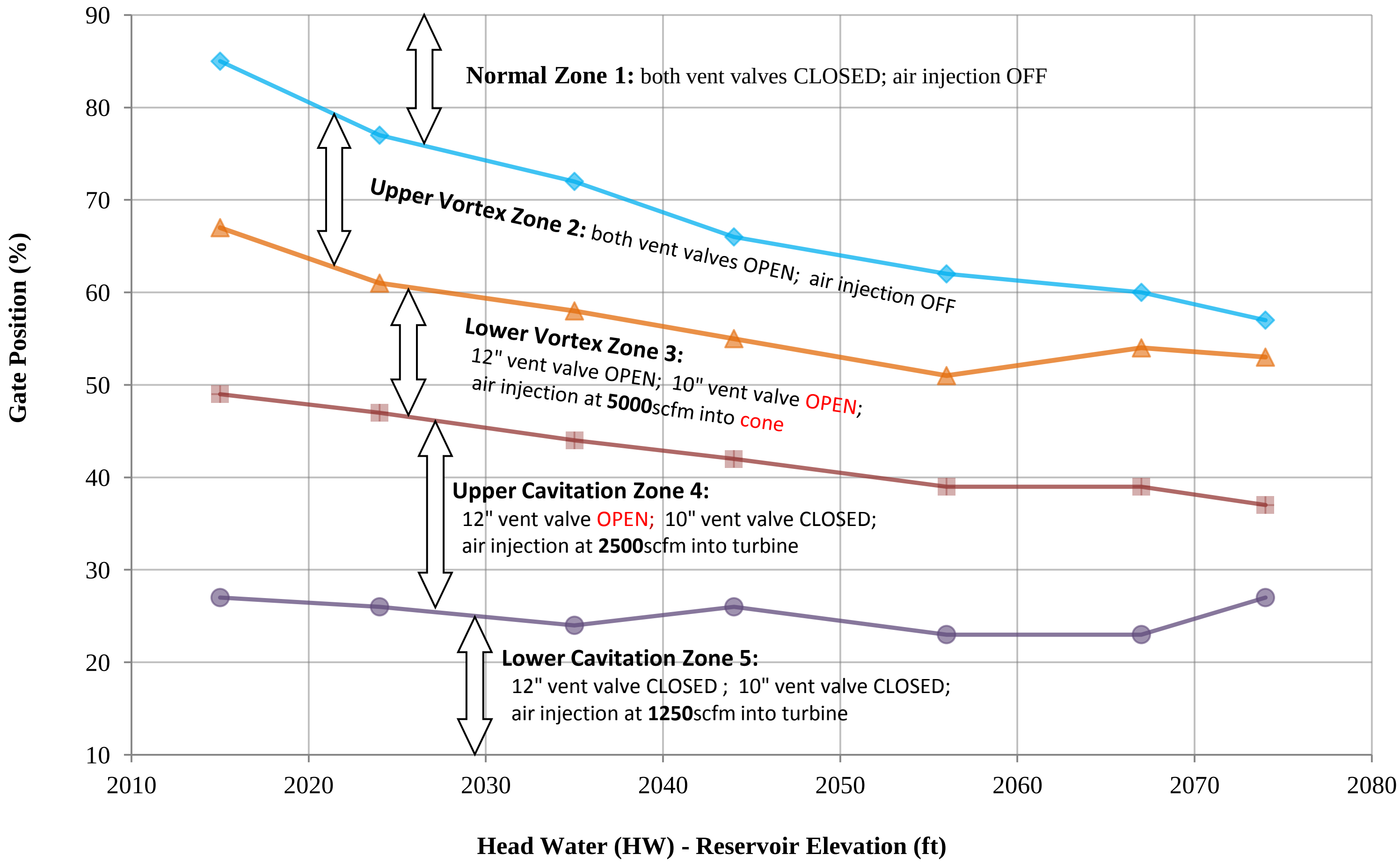
Turbine Guide Bearing Max Vibration



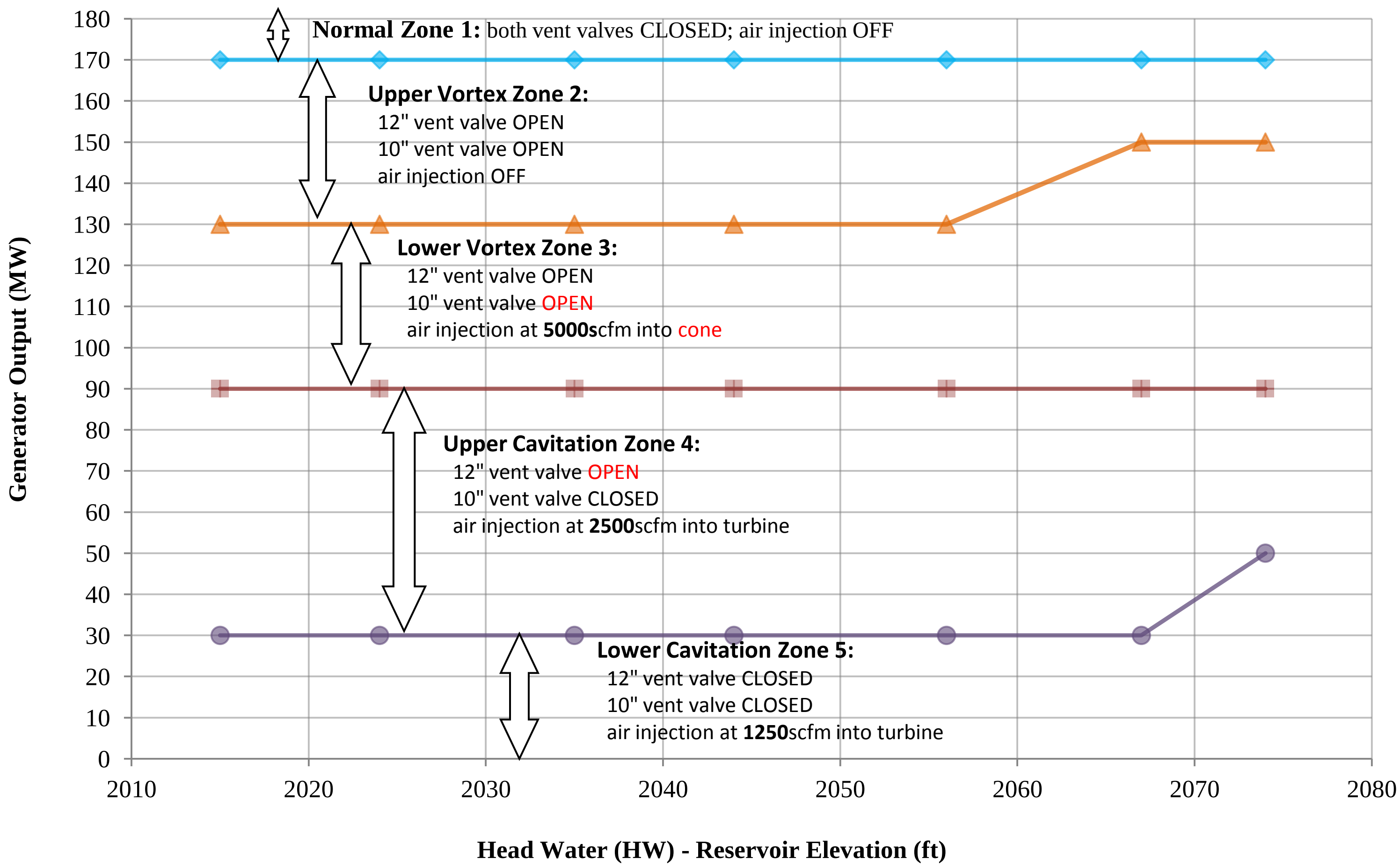
Turbine Guide Bearing Max Vibration



2011 Operating Zone Map –
Gate Position (open valves earlier at low head)



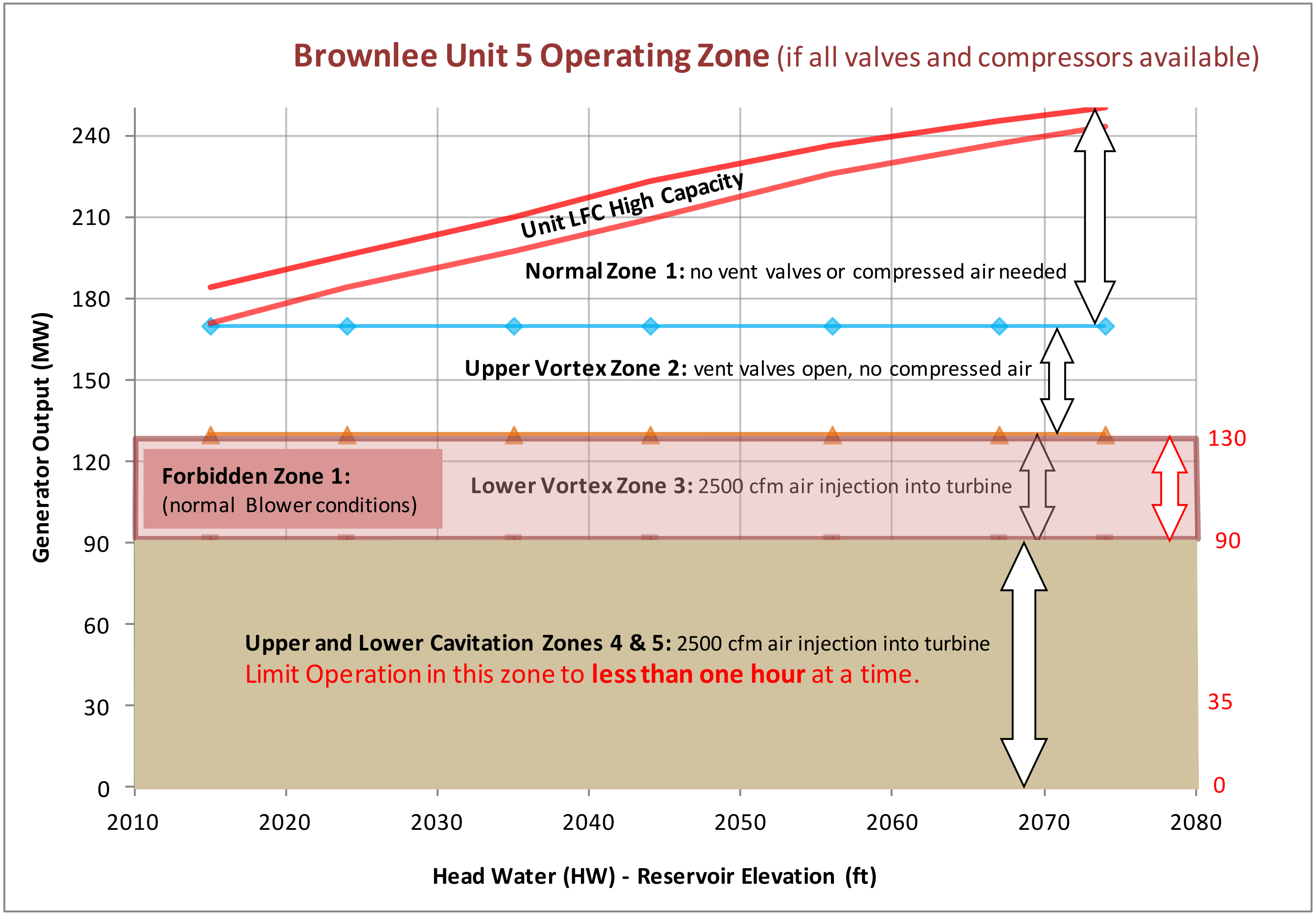
2011 Operating Zone Map – MW (surprisingly linear – easier PLC program)



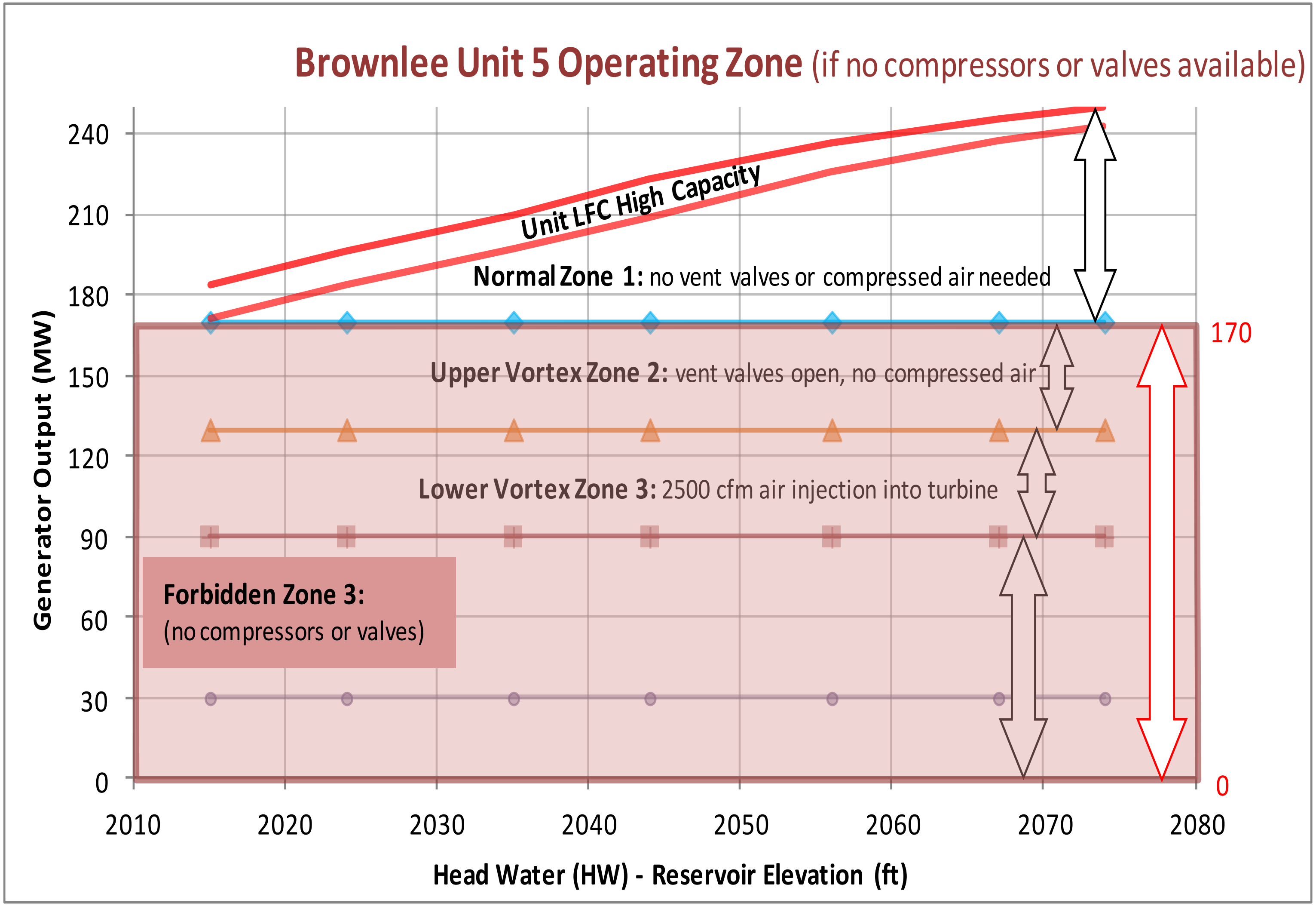
…**Unit 5 Rough Zone History** (4)

- Implemented compressor and vent valve controls in **2012**
  - forbidden zone limits depend on valve and compressor control conditions
  - PLC telemeters limits to AGC, which honors the forbidden zone
  - PLC moves unit out of rough zone and turns off AGC if high vibration detected
  - continuous vibration monitoring, event logging, and protection
- Using the system during normal operations on **2013**
  - with a “dynamic” forbidden zone limits from plant PLC to AGC

2013 Operating Zone Map – MW (for dispatch and operations)



2013 Operating Zone Map – MW (for dispatch and operations)



Lessons Learned (1) …

- Francis Turbine vortex rough zones are worse in some turbines
  - history of “bangs” in Brownlee unit 5 plant, but no issues with units 1-4
  - say Sayano-Shushenskaya?
- Detecting a vortex collapse can be tricky
  - random timing on a non-periodic signal
  - thrust forces cause mostly axial shaft and head-cover movement
  - know your zone boundaries
- Operating in the vortex rough zone presents risk but is possible
  - maximize air flow with venting and compressed air controls
  - or design controls to pass through zone quickly
- Operating in the cavitation rough zone is easier to do and less risky
  - need enough compressed air and controls to get it when and where it is needed
  - reduce risk with vibration monitoring
  - need to evaluate long-term effects on turbine blades or buckets

…**Lessons Learned** (2)

- Big compressors can be expensive as a retro-fit
  - large air volume requirements, tight fit in old plant
  - do a more detailed design and budget up-front
- Testing needed to define rough zone boundaries can take years
  - need to catch a range of reservoir levels and flows
  - dependent on dispatch and crew availability
  - can’t schedule testing ahead of time for duration of project
- Need long term monitoring, maintenance, and engineering support
  - control performance monitoring and tuning
  - somebody needs to look at all that vibration data
  - challenge to keep resources focused

Questions?

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