Rotor Retrofits Improve Pump Station Vibration

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Background - 1

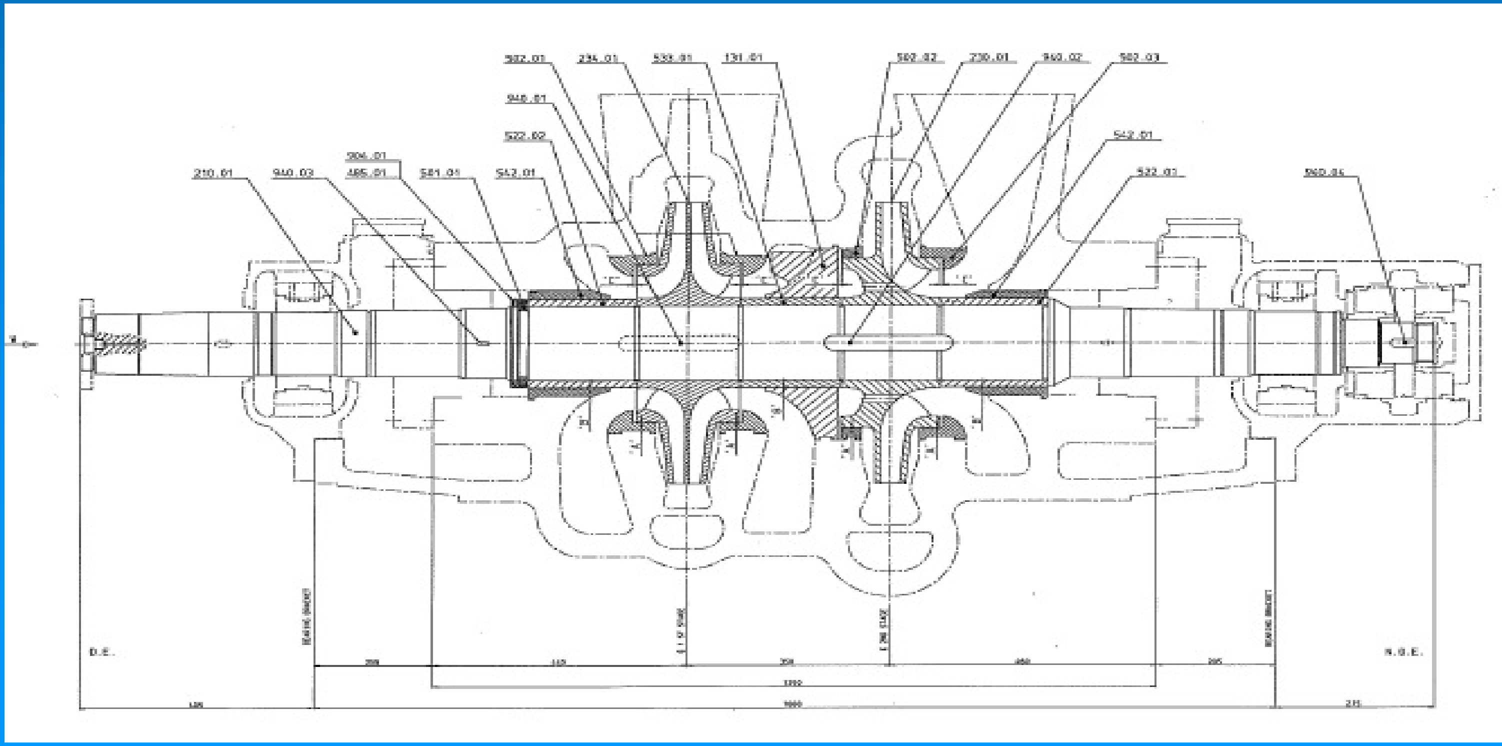
- Two nearly identical crude oil pump stations on a world-scale pipeline encountered significant vibration on initial startup

- Each station equipped with five each, 5 MW centrifugal Main Oil Line (MOL) pumps driven by variable speed, gas fuelled, spark ignited reciprocating engines

- Station throughput is achievable with four-pump operation with one spare

Background - 2

- MOL Pumps in parallel configuration
- Nominal driver speed is 700 RPM with speed increaser gear resulting in pump speed to approximately 3400 RPM
- MOL Pumps are identical, two-stage, horizontally split, double volute designs with double flow stage impellers



History - 1

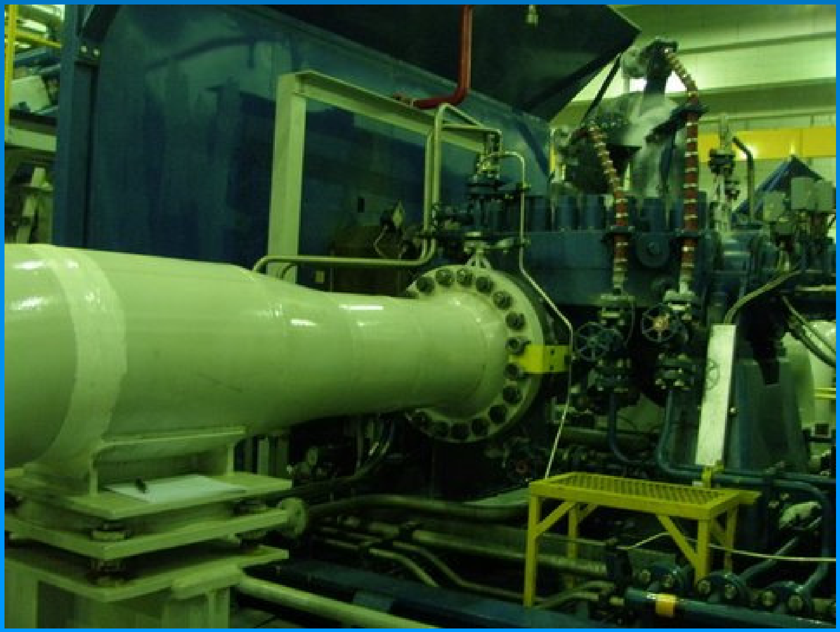
- At startup heavy vibrations appeared on Small Bore Connection (SBC) piping attachments: instrument, drain and vent connections to the pumps and throughout station
- Vibrations also evident on elbows and piping supports as a high-frequency “buzz” continuously and throughout operating speed range
- <u>Surprisingly, pump case vibrations, as well as shaft movement measured by proximity devices, were within recognized industry standards and OEM specifications</u>
- With concurrence of station designer and pump OEM, pipeline ramp-up continued to rated capacity

History - 2

- Within months the annoying vibrations developed into a major system integrity problem due to failures at SBC welds
- Inspections confirmed high-cycle fatigue as cause
- New and <u>repeat</u> failures occurred

History - 3

- Mechanical braces fitted on all SBC to limit vibrations
- Appropriate inspection and weld repair programs established to insure business continuity
- Diagnostics undertaken to determine cause of damage



Machinery / System Analysis

- Analysis confirmed the following to be acceptable and NOT be causative:
  - Pump rotor balance
  - Machinery alignment
  - Bearing stability
  - Rotor stability
  - Machinery and piping support
  - Engine and gear operation
  - Machinery train torsional resonance
  - Piping acoustic resonance

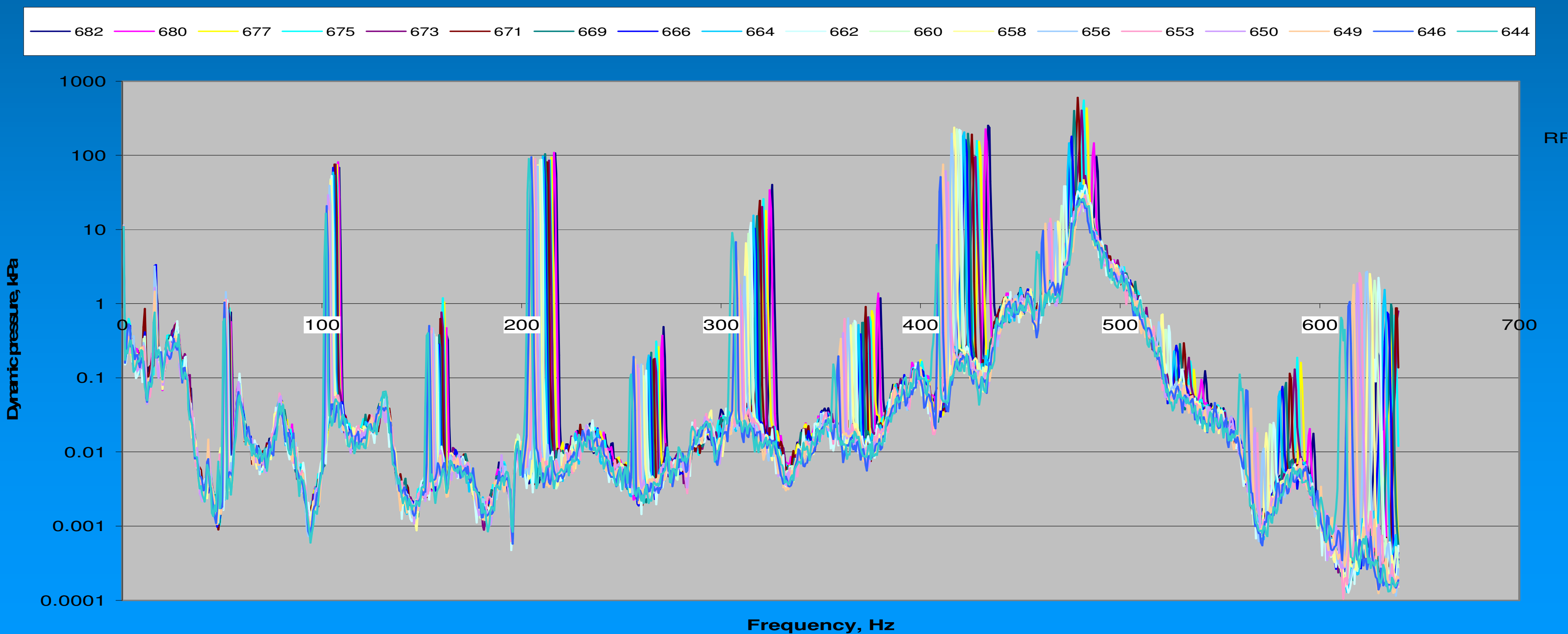
Damage Continues

- Header subsidence discovered in buried headers outside pumphouse
- SBC weld failures continue, now numbering >100 causing huge integrity and availability issues

Pulsation Study - 1

Suction pulsation spectrum

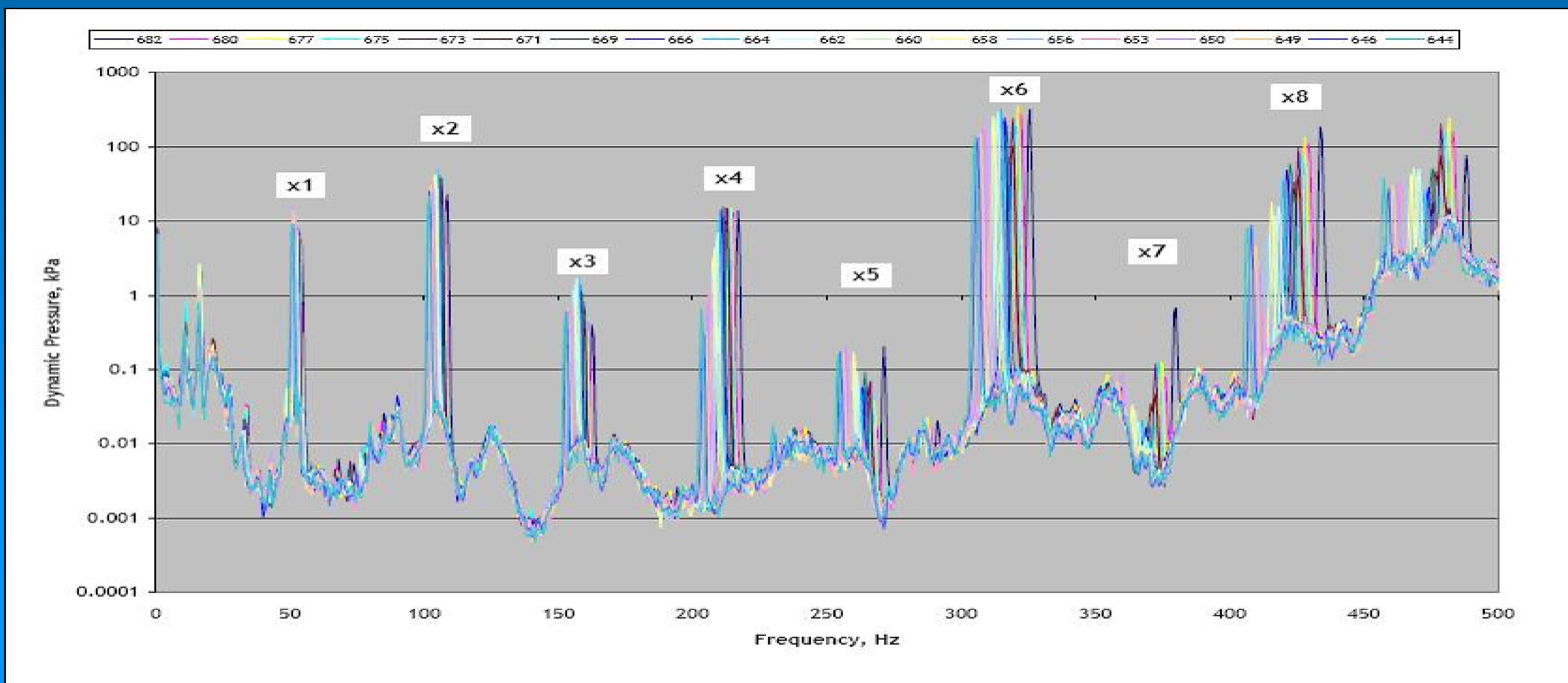
- High intensity pulsations discovered within pumped fluid column



Pulsation Study - 2

Discharge pulsation spectrum

- Discrete frequency spikes found “locked” to rotor speed



Measured Pressure pulsation spectra as a function of gas engine speed, discharge.

Problem Definition

- Dynamic pressure pulsations at damaging levels exist throughout the pumping systems that result in cyclic stress driven fatigue (high cycle fatigue) to SBC welds.
- Consequential damage occurs to instrumentation and support systems including buried headers outside pumping stations.

Root Cause Analysis

- Root Cause Investigation:
  - System integrity compromised
  - Weld failures
  - High-cyclic stress fatigue
  - Excessive vibration
  - Excessive pulsation energy
  - Rotor / impeller design suspect

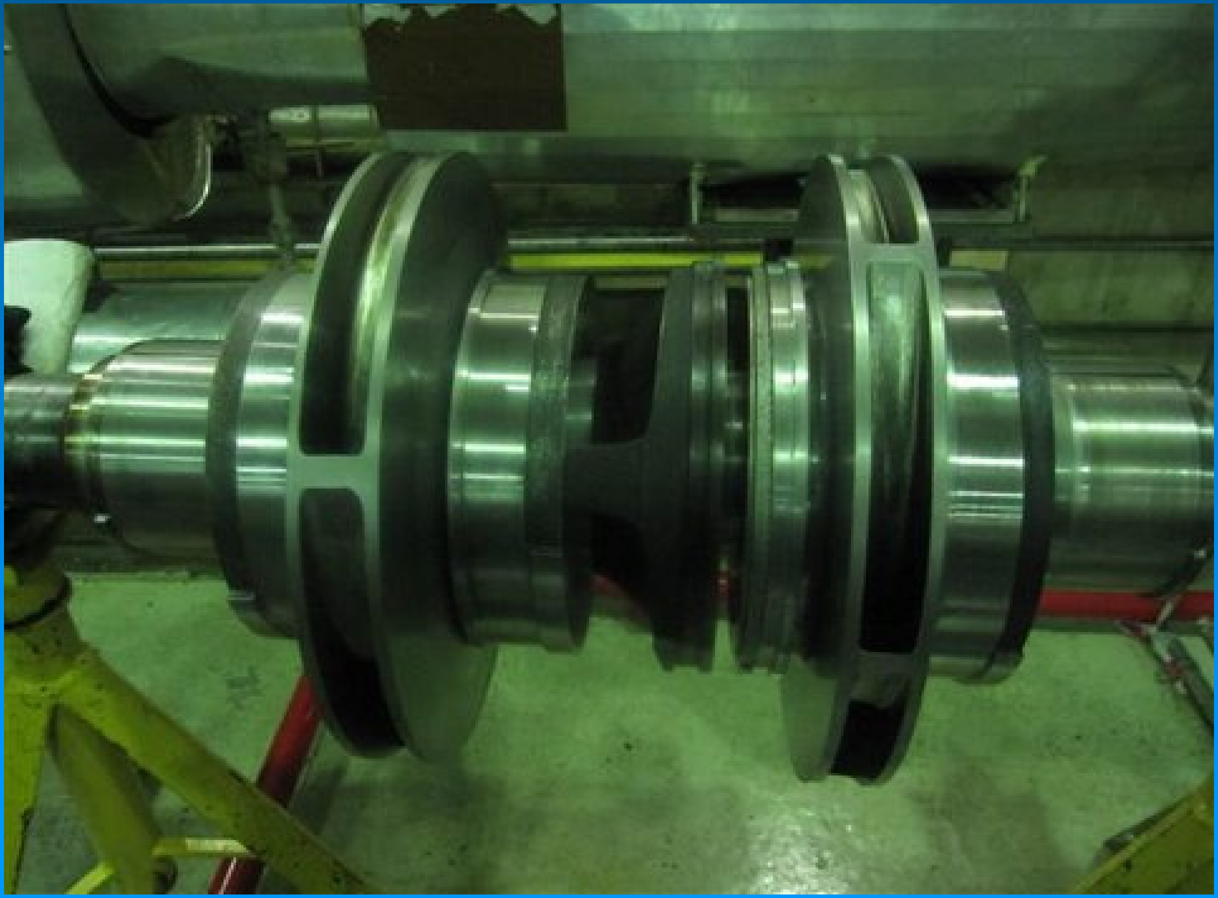
- Preliminary Conclusion: System vibrations are driven by dynamic pressure pulsations from impeller design and resulting behavior

Impeller / Rotor Inspections

- OEM discussions proved inconclusive
- Vane count: 4 and 6 (double volute case) promotes "phase resonance" or "constructive reinforcement" due to jet-wake / casing interactions: pulsations
- Concern that stage one inlet eye geometry promotes inlet recirculation
- Basic design – orthogonal vane features, no central rib / stagger on first stage etc.

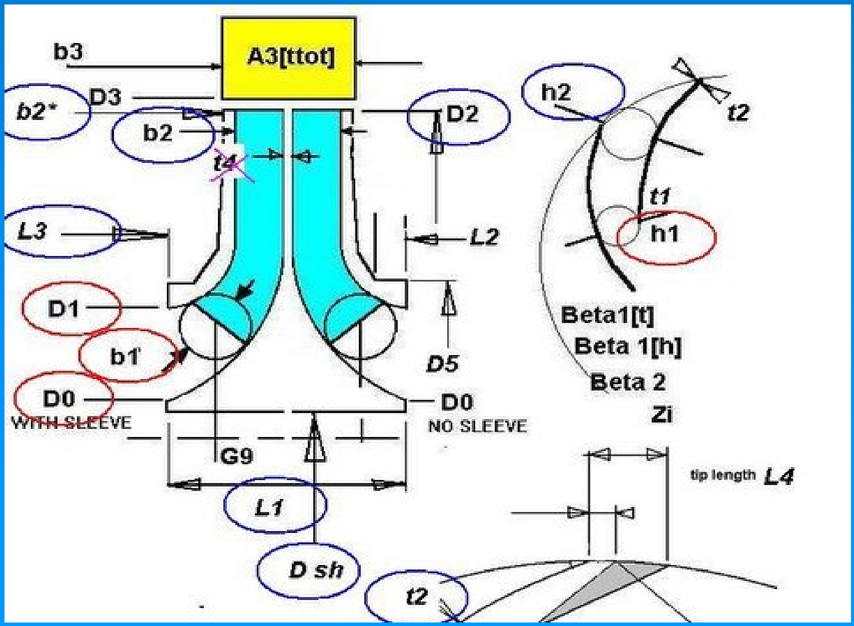
Impeller / Rotor Inspections

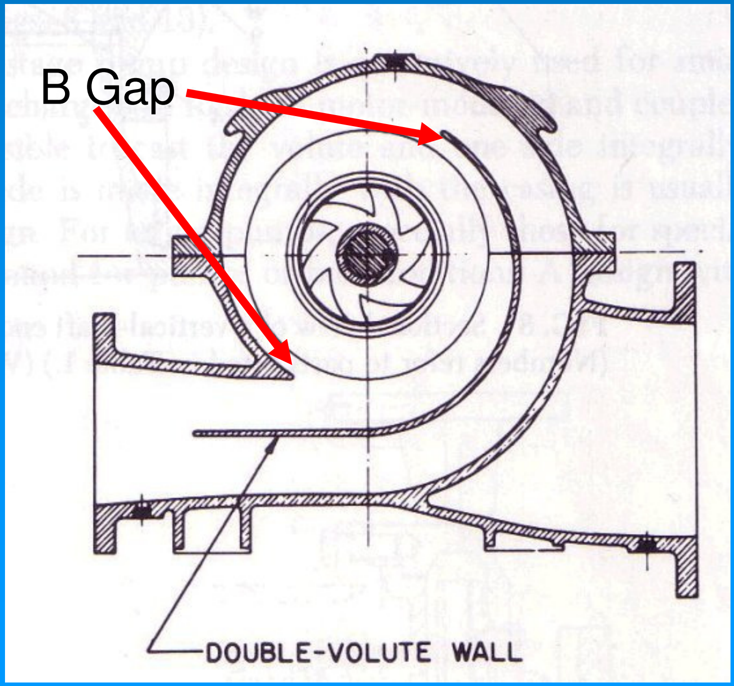
- Basic Design



Disassembly Case Inspection

- Hydraulic gap "B-Gap" smaller than industry standard and not consistent
- Cutwater locations / profiles not as expected for high-energy pump
- Volute has "tight fit" relative to impeller width – limits redesign options





Root Cause

- **Poor pump behavior due to high-energy dynamic pulsations resulting from several facets of pump design**
- Secondary causes include:
  - Poor SBC design – susceptible to vibration damage
  - Inappropriate recycle throttling device selection

Investigation Conclusion

- Four major factors contribute to excessive dynamic pressure pulsation including:
  - Constructive pulsation reinforcement resulting from impeller vane count
  - Unusually small stator / rotor tip clearance
  - Pump operation near or at inlet recirculation
  - Likely interaction with vane encounter, inlet backflow and system response frequency

New Rotor Design Requirements

- Mechanical interchangeability
- Hydraulic duplication (or better)
- Pulsation levels reduced to acceptance (4%?)
- System compatibility – seals, bearings, vibration monitors etc.
- Shaft material upgrade
- Minimal case alterations (if needed) – no spare case

New Design – Stage One Impeller

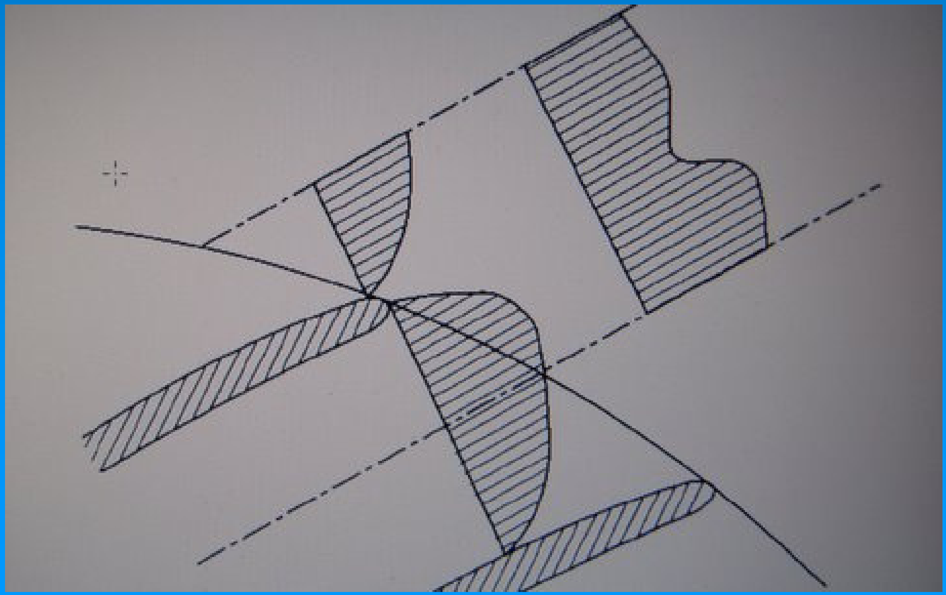
- Vane count from 4 to 5
- Vane skew from orthogonal
- Inlet hydraulic enhancements
- Casting technology improvements
- Double entry partition rib plus “stagger”

New Design – Stage Two Impeller

- Vane count from 6 to 7
- Vane skew from orthogonal
- Inlet hydraulic enhancements
- Casting technology improvements

New Design – Case Alterations

- Increased impeller tip-to-cutwater hydraulic gap
- Improved cutwater profile and location on both cutwaters – both stages & skewed stage two



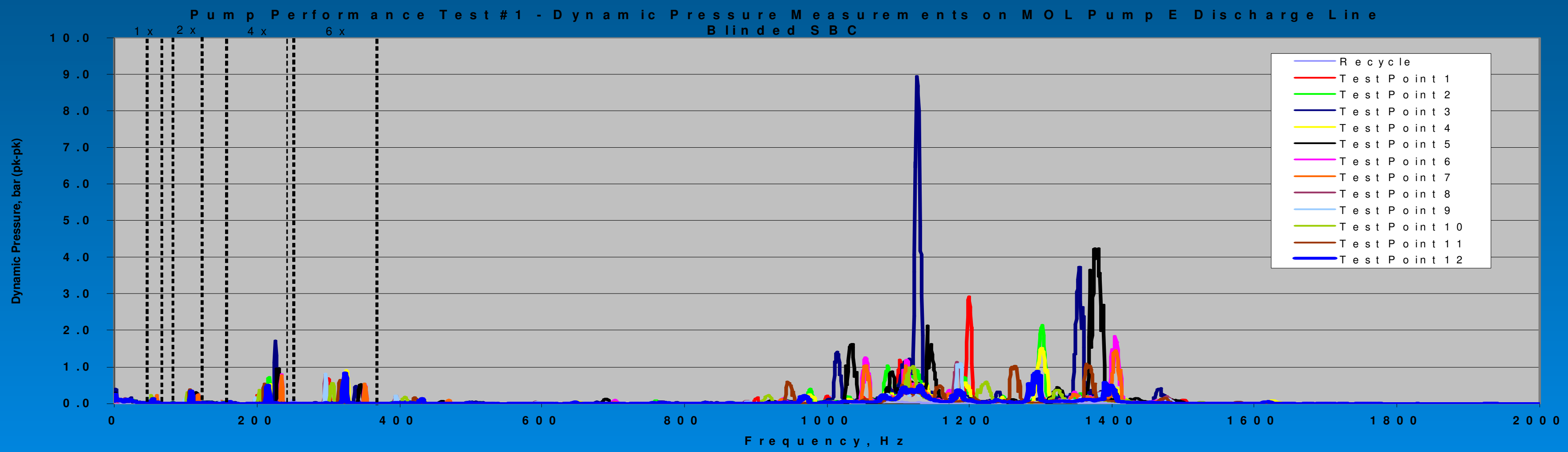
The Solution?

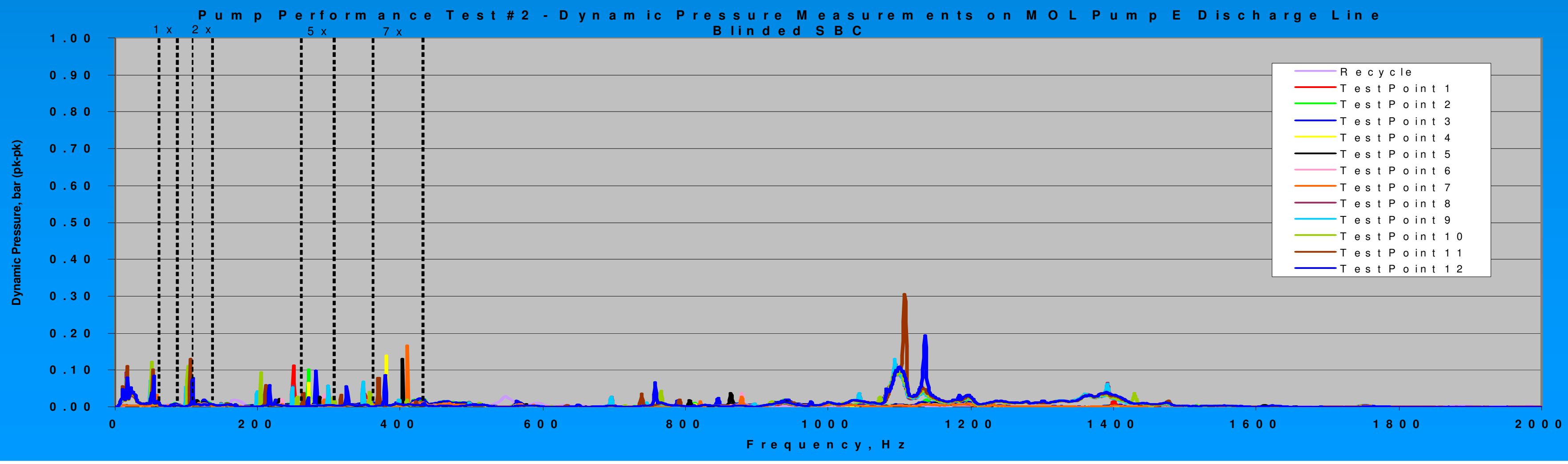
Test Program

- Duplicate test "Before" and "After" prototype installation
- Test with "single pump" operation
- Test 12 operating conditions from recycle to 100% flow and speed at 14 pumphouse locations
- Collect performance data including:
  - Dynamic pressure
  - Dynamic stress at historically troubled locations
  - Hydraulic performance; flow and head
  - Vibration
- Develop "factory" performance curve

Test Results

- Before and After Dynamic Pressure Levels





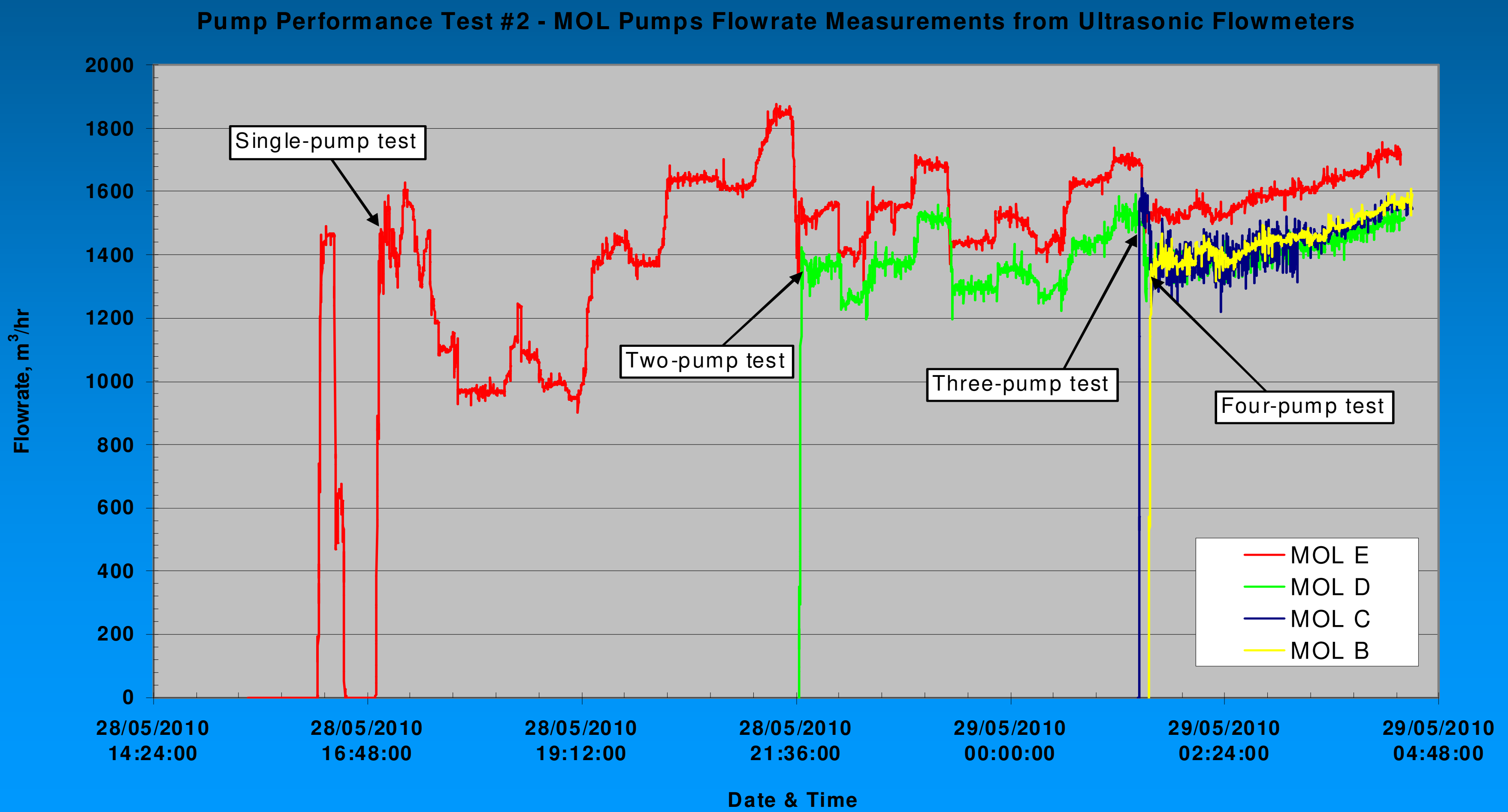
Test Results - 2

- Before and After Stress Levels

Test Point	Number of Measurement Points with Excessive Dynamic Stress Levels	
	Pump Performance Test #1	Pump Performance Test #2
Recycle	2	0
1	2	0
2	2	0
3	2	2
4	0	0
5	4	0
6	3	0
7	3	0
8	1	0
9	1	0
10	1	0
11	4	1
12	2	0

Test Results - 3

- Single and Multi-Pump Flow Rates



Conclusions

- Dynamic stress levels reduced to "acceptable" within normal operating range at all monitored locations
- Pulsation levels reduced > 50% with most locations >70%
    - Pulsation level at stage crossover location still borderline high at 100% speed although reduced >80% from original
        - Confirmed excitation of 7X acoustic resonance in crossover
        - Not normal operating speed
- Shaft movement (by proximity) and case vibrations reduced by approximately 50%
- Sound levels reduced 3 db in pump vicinity and 9 db at pump discharge
- Hydraulic output improved by 5% to 10% within normal operating range - correctable with 1% speed reduction
- Apparent pump efficiency improved about 1%

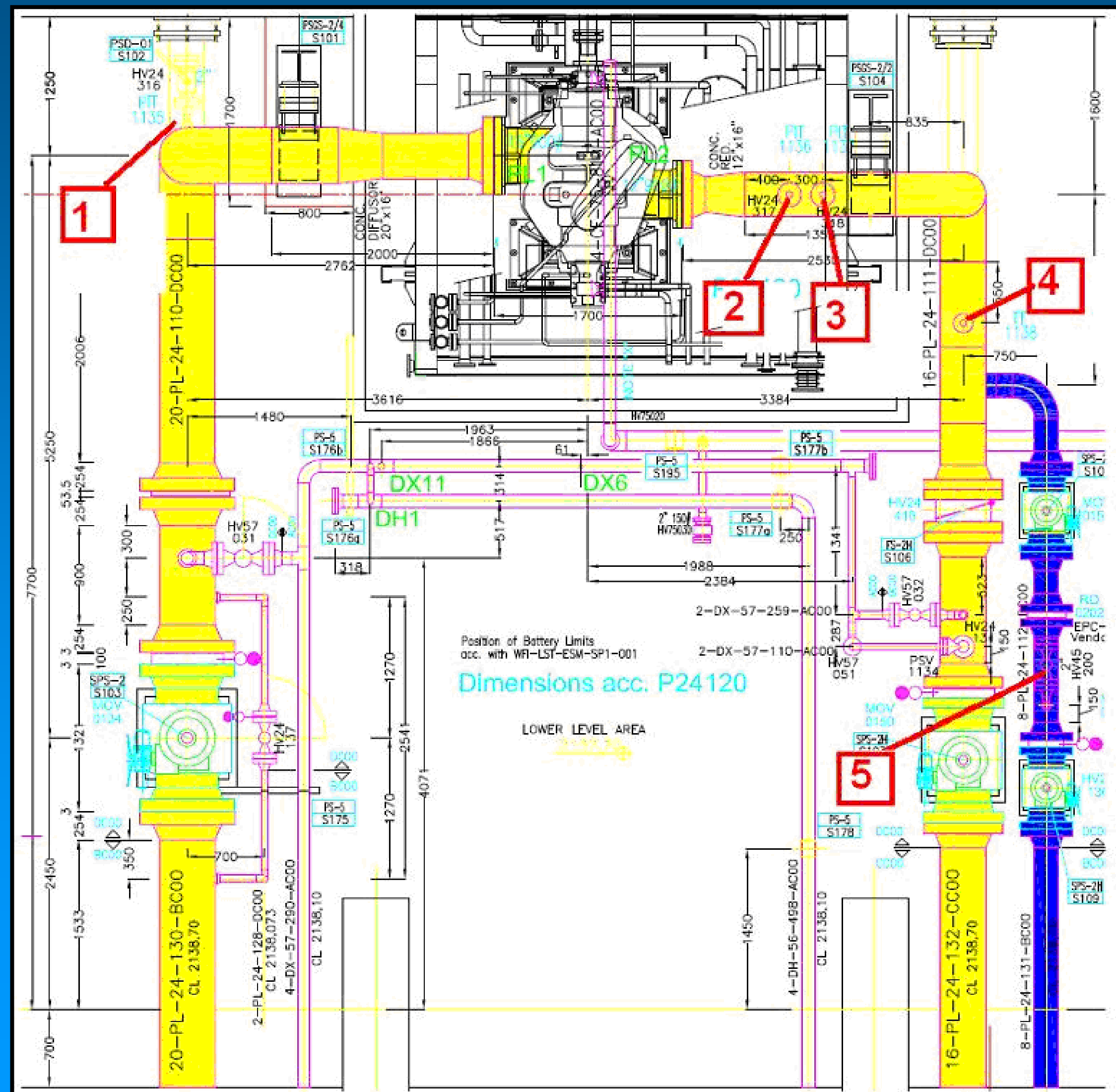
Project Completion

- Ten new rotors installed
- Instrument, drain and vent connections to pump cases replaced with new
- In-station suction, discharge and recycle piping plus recycle throttle replaced with new
- Outside-station headers repositioned and re-supported

Remedial Action

- Suction, discharge, recycle lines renewed

- Pump vents, drains, instrument taps renewed



Lessons Learned

- Original equipment design reviews are critical
  - Maintain “Global Vision” of system - not just flange-to-flange
  - Pump design review should consider all operating parameters including pulsation levels
- Process / piping design reviews are important - branch connection design is critical
- Factory acceptance tests have major limitations:
  - Different connected piping
  - Different fluid
  - Different support system
  - Different driver usually
  - Only looks at flange-to-flange compliance

Thank You!

Questions?