2014 GMRC Gas Machinery Conference
Nashville, TN – October 6-8, 2014

Design and Field Test of a Full Scale Performance Augmentation Network (PAN)

2014 GMRC Research Project

W. Norman Shade, PE & John J. Bazaar, ACI Services, Inc.
Kelly Eberle & Mehdi Arjmand, Beta Machinery Analysis
Glen F. Chatfield & Dale K. Wells, OPTIMUM Pumping Technology
Scott Schubring, Williams

End User Interest and Objectives

- Support advancement of new technology
- Significant commercial benefit from
  - More flow from compressors for given driver size & rating
  - Higher efficiency reduces fuel cost & specific exhaust emissions
  - Reduce no. & size of multiple parallel drivers at a station
- Such advancements may become mandatory in future
  - Recently announced DOE efficiency initiative
  - EPA GHG reduction initiatives

PAN & Bottle Systems Are Fundamentally Different

	Bottle Systems	PAN Systems
Pulsation energy	95% dissipated	95% recovered
Throw phasing	Individually	<u>all</u> throws Interleaved
Pressure & HP losses	can be large	Insignificant
Components	expansion bottles baffles choke tubes orifice plates	tuned pipe lengths tuned pipe diameters primary Y or W junctions secondary Y junctions

Brief PAN Technology Development History

- **1994 engine technology development begins with Univ. of Belfast**
- **2006 modeled 1st compressor cylinder**
- **2007 GMC paper on 1st PAN compressor model**
- **2008 GMC paper on lab air compressor PAN testing**
- **2009 GMC paper on TGT Ellisburg station PAN field test**
- **2010 El Paso sta. 96 PAN conversion designed; project suspended**
- **2011 GMRC project - PAN conversion at El Paso Batesville station**
- **2011 GMC paper on efficiency increase with PAN tuning**
- **2012 El Paso sale cancelled Batesville host & GMRC project on hold**
- **2013 GMRC project - PAN conversion at Williams sta. 85; withdrawn**
- **2014 GMRC project – Williams Zick station (this paper!)**

Project Objectives

Primary

- Cover operating range from 450-900 suction & 1000-1200 discharge
- Maximize capacity at all conditions at rated power & speed
- Total system (line to line) pressure drop <2.0 psig at all conditions
- Control pulsations to <1.5% of line pressure level at all conditions
- Control mechanical vibrations and stress levels to API 618 M5
- 10% reduction in BHP/MMSCFD at the high flow condition (compared to existing bottle unit)

Secondary

- Validate predictive accuracy of OPT VPS software
- Demonstrate ability to create optimal PAN that simultaneously achieves all objectives
- Achieve performance with unloading limited to HE VVCPs
- Fit factory-built PAN entirely onto the compressor package skid
- Dependable operation over 1300 to 1400 rpm speed range

Compressor Package Specifications

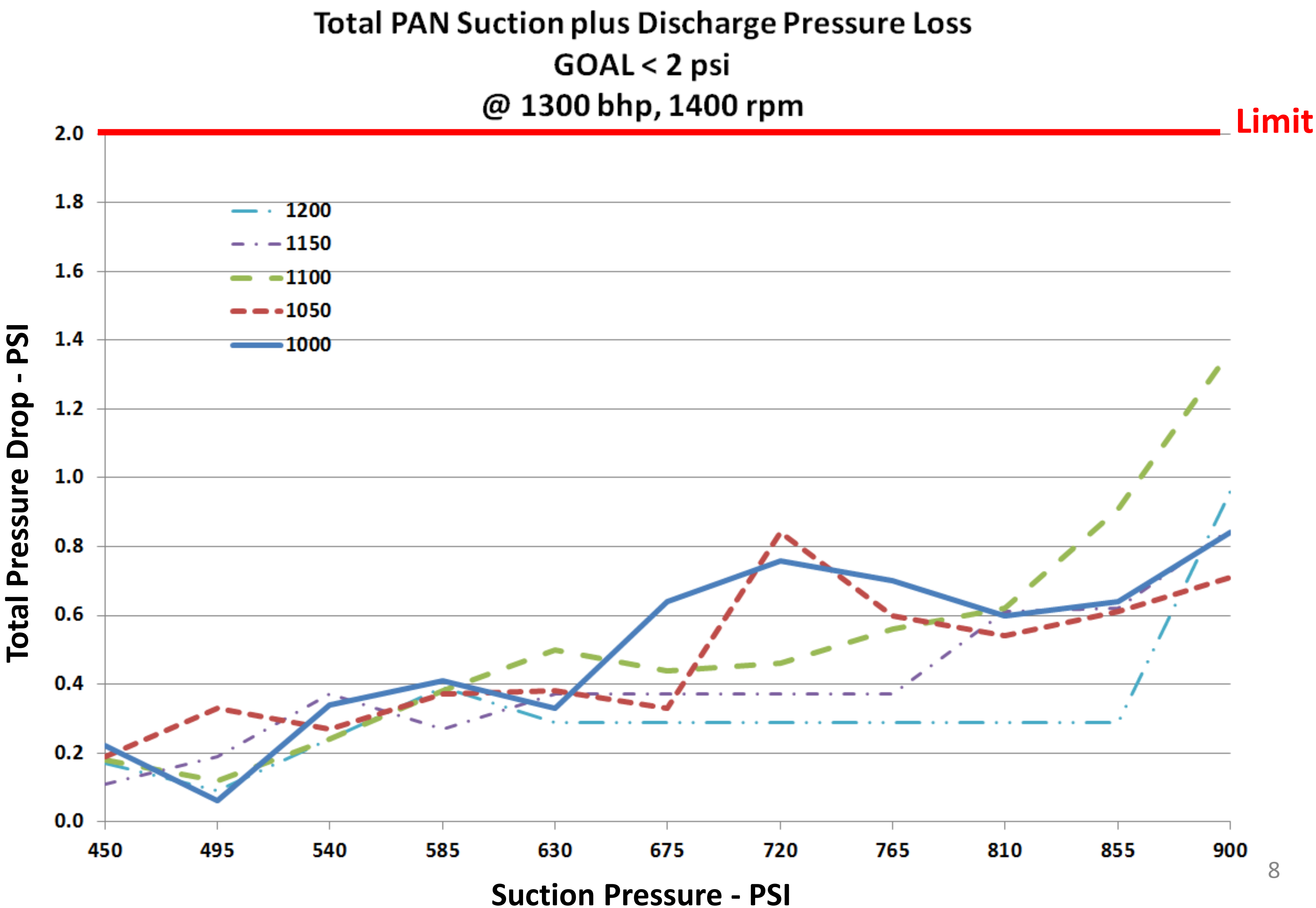
- Caterpillar G3516 gas engine driver
- 1380 BHP @ 1400 rpm
- Ariel JGT/4 4.5” stroke compressor
- (4) 6.75” cylinders with HE VVCP
- Single stage
- Suction pressure 450 to 900 psig
- Discharge pressure 1000 to 1200 psig
- Separate motor-driven cooler
- Single suction scrubber

Specified PAN System Design Points

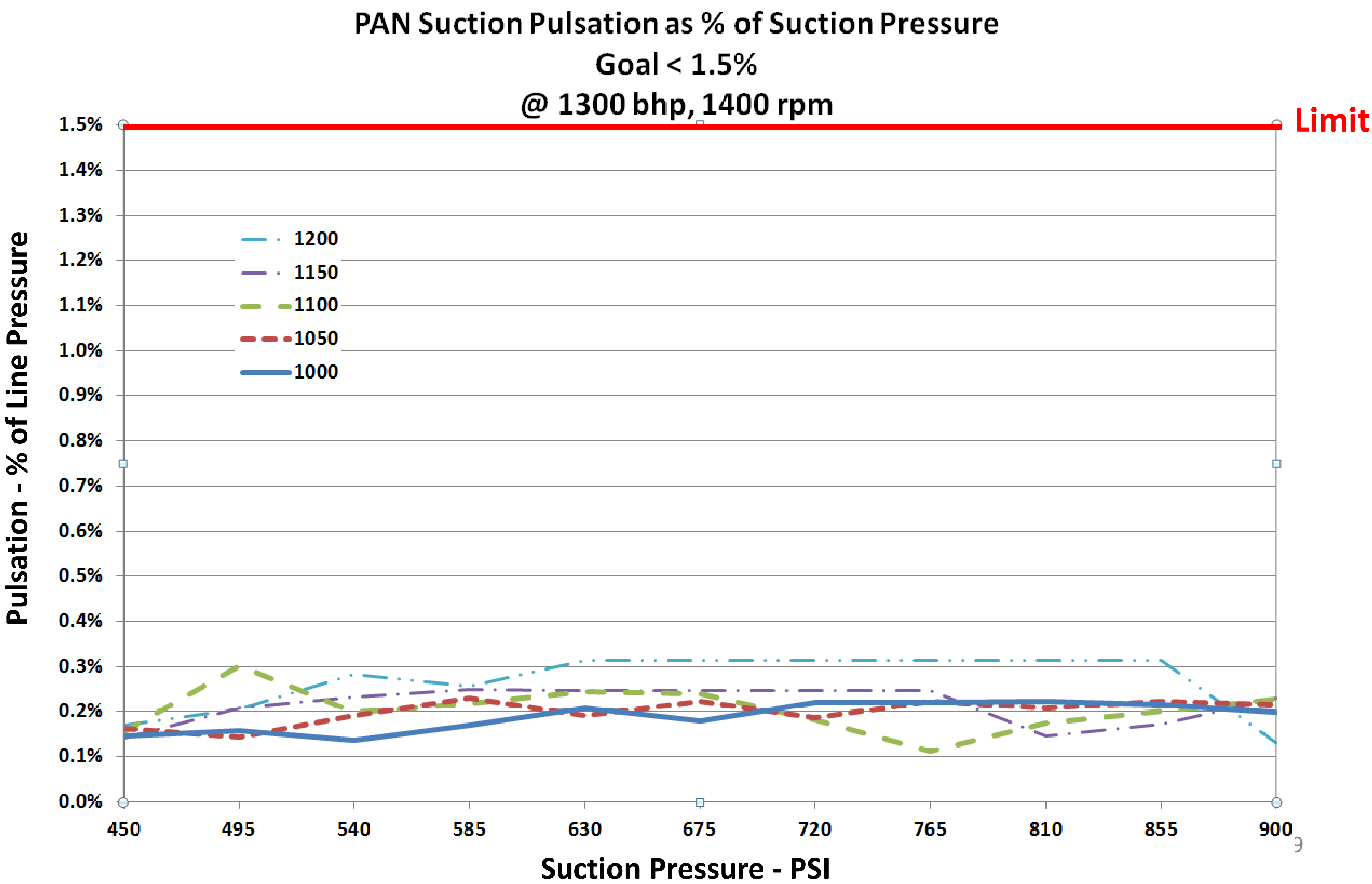
Operating Condition	Suction Pressure (psig)	Discharge Pressure (psig)
Low suct; Low disch. (low flow)	450	1000
Low suct; high disch. (high ratio)	450	1200
Center of operating map (design pt.)	675	1100
High suct; low disch. (low ratio/high flow)	900	1000
High suct; high disch.	900	1200

Predicted PAN Performance

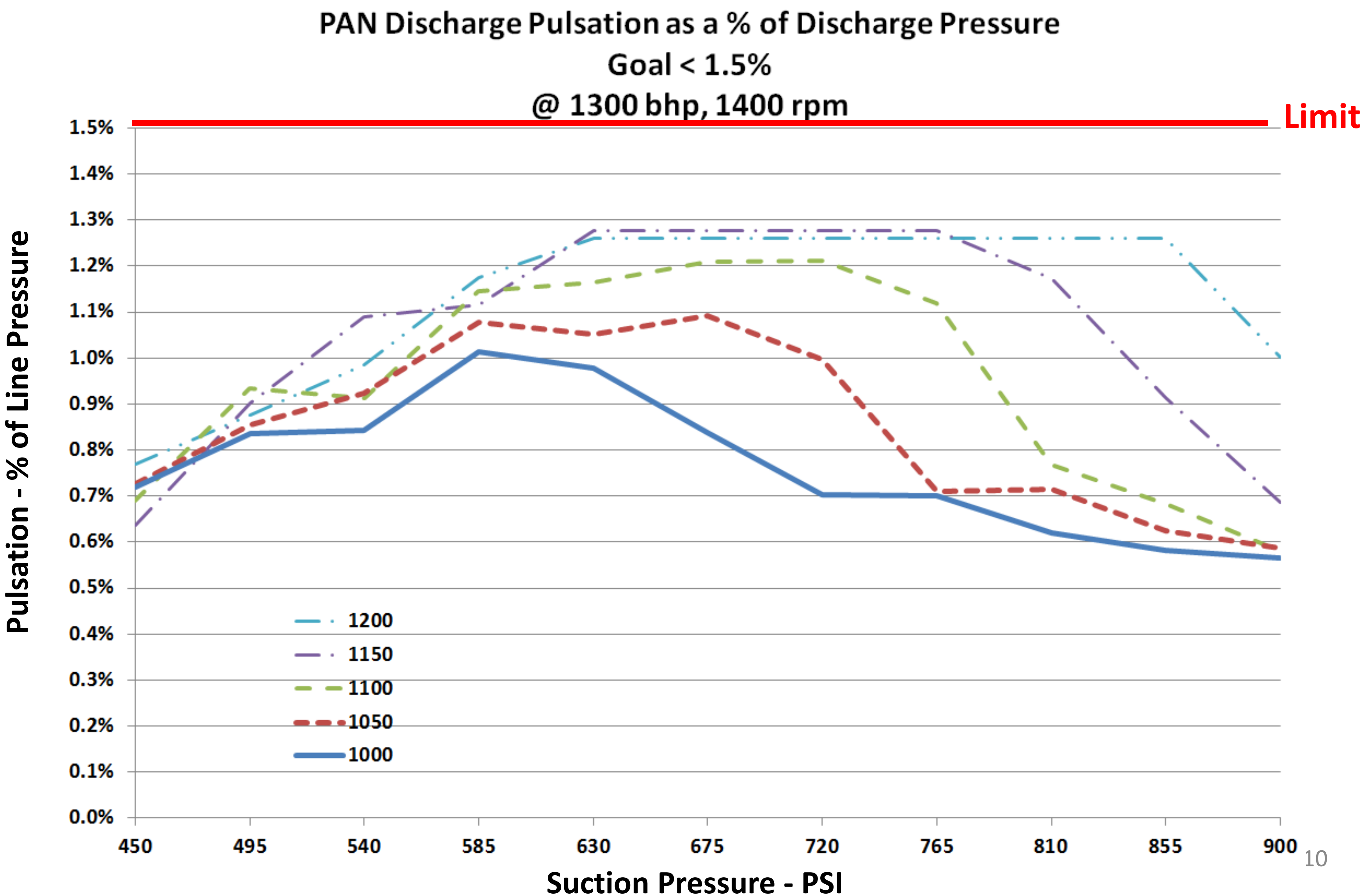
Pressure Drop



Predicted PAN Performance
Suction Pulsation



Predicted PAN Performance
Discharge Pulsation



Predicted Pressure Drop Reduction

PAN Unit vs. Baseline Bottle Unit

1300 BHP @1400 rpm

Unit #8 (PAN) vs. Unit #1 pressure drop reduction					
	1000	1050	1100	1150	1200
450	92.8%	93.1%	92.9%	96.0%	93.7%
495	98.3%	90.5%	96.1%	93.1%	96.2%
540	91.6%	92.9%	92.6%	88.4%	93.1%
585	90.9%	91.2%	88.8%	92.4%	88.8%
630	93.6%	91.8%	87.6%	89.6%	91.7%
675	89.4%	93.7%	90.5%	89.6%	91.7%
720	88.8%	86.3%	91.5%	89.6%	91.7%
765	90.6%	91.6%	91.1%	89.6%	91.7%
810	92.7%	93.3%	91.8%	90.8%	91.7%
855	92.8%	93.0%	89.3%	92.0%	91.7%
900	91.2%	92.5%	85.2%	90.6%	88.0%

Table Average – 91.5%

Predicted Flow Increase (MMSCFD)

PAN Unit vs. Baseline Bottle Unit

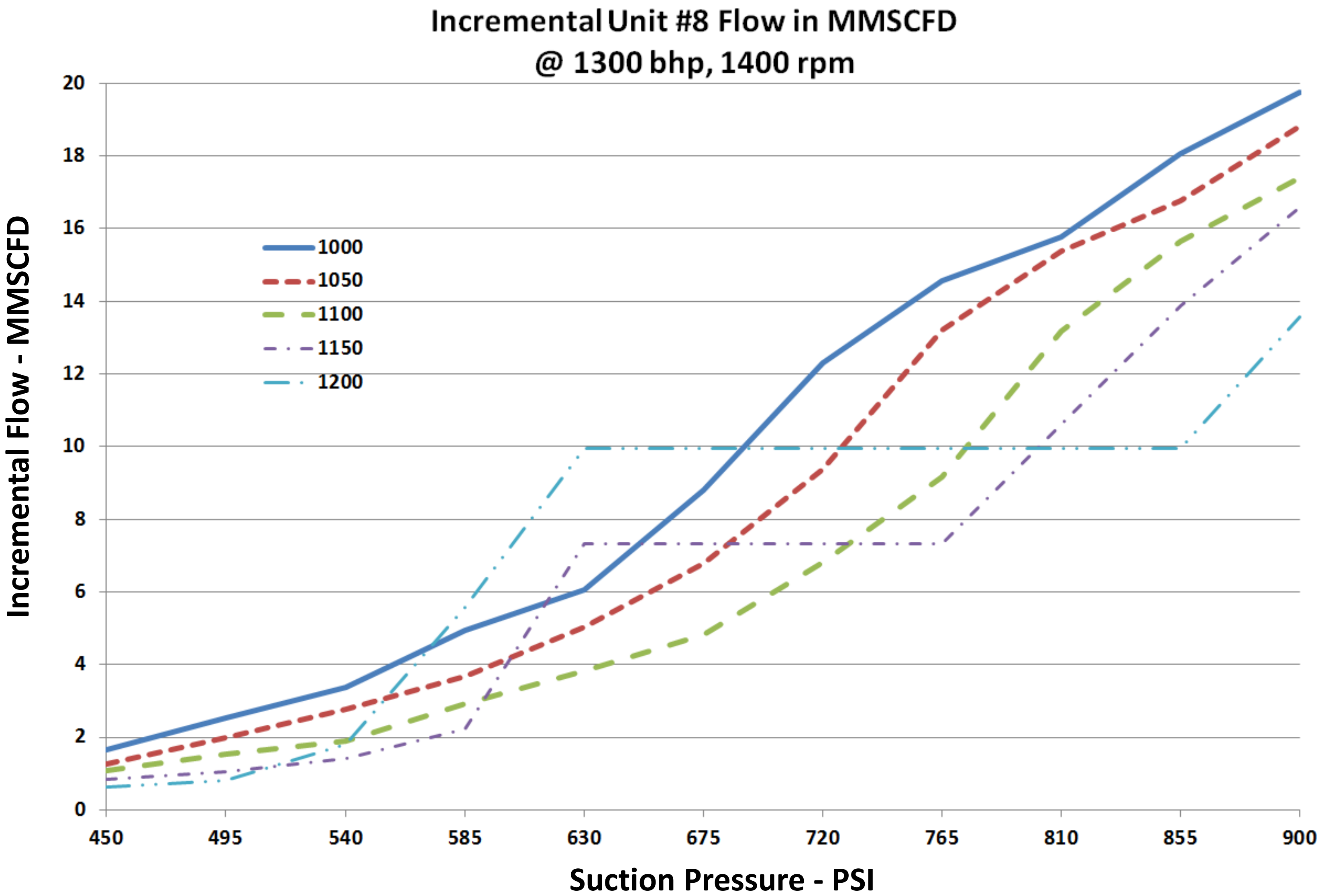
1300 BHP @1400 rpm

Unit #8 (PAN) vs. Unit #1 flow improvement (MMSCFD)					
	1000	1050	1100	1150	1200
450	1.7	1.3	1.1	0.8	0.6
495	2.5	2.0	1.5	1.1	0.8
540	3.4	2.8	1.9	1.4	1.8
585	4.9	3.7	2.9	2.2	5.6
630	6.1	5.0	3.8	7.3	10.0
675	8.8	6.8	4.8	7.3	10.0
720	12.3	9.4	6.8	7.3	10.0
765	14.6	13.2	9.2	7.3	10.0
810	15.8	15.4	13.2	10.6	10.0
855	18.1	16.8	15.6	13.9	10.0
900	19.8	18.8	17.4	16.6	13.6

Table Average – 8.0

Predicted Flow Increase (MMSCFD)

PAN Unit vs. Baseline Bottle Unit



Predicted % Improvement in BHP/MMSCFD

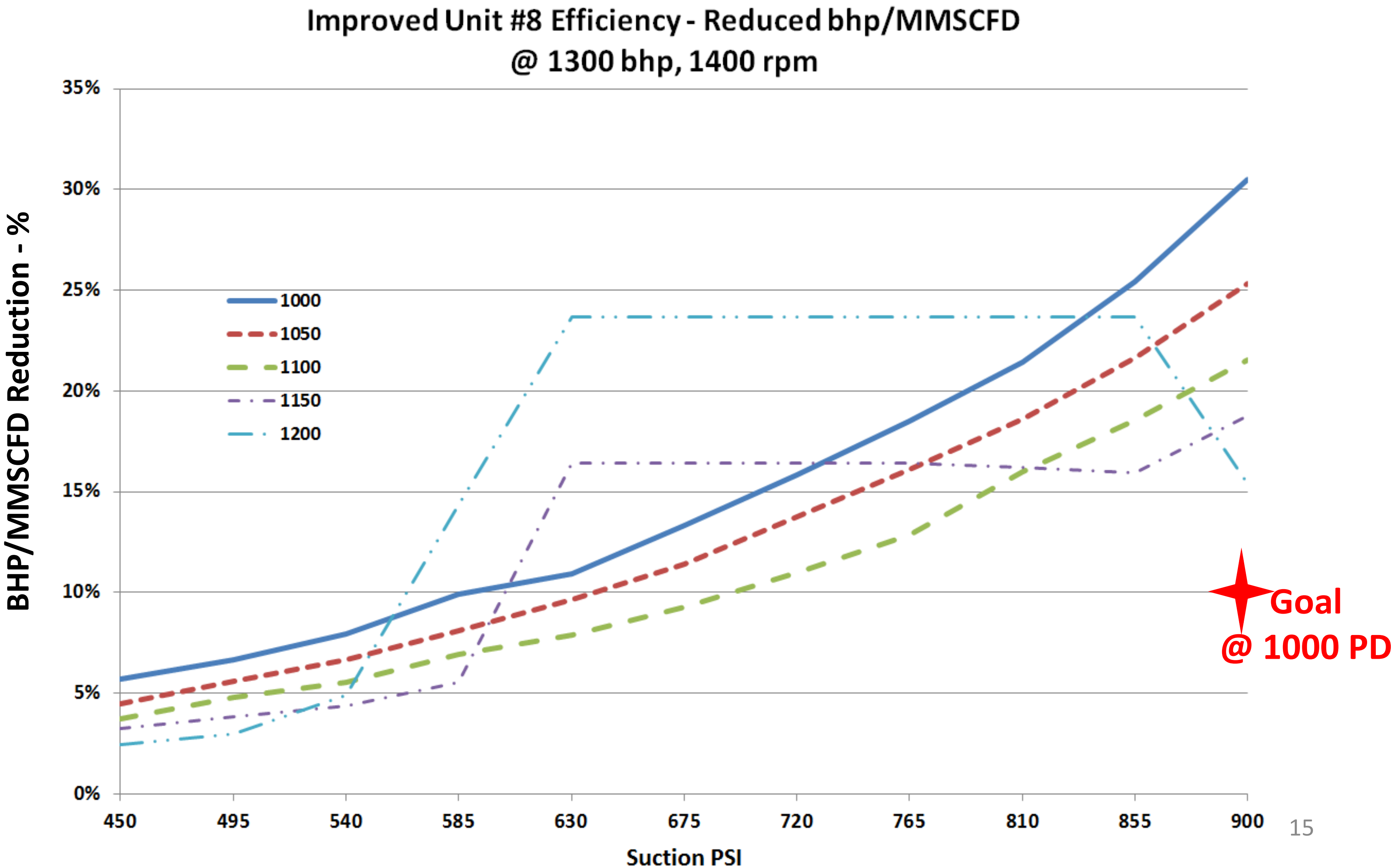
PAN Unit vs. Baseline Bottle Unit

1300 BHP @1400 rpm

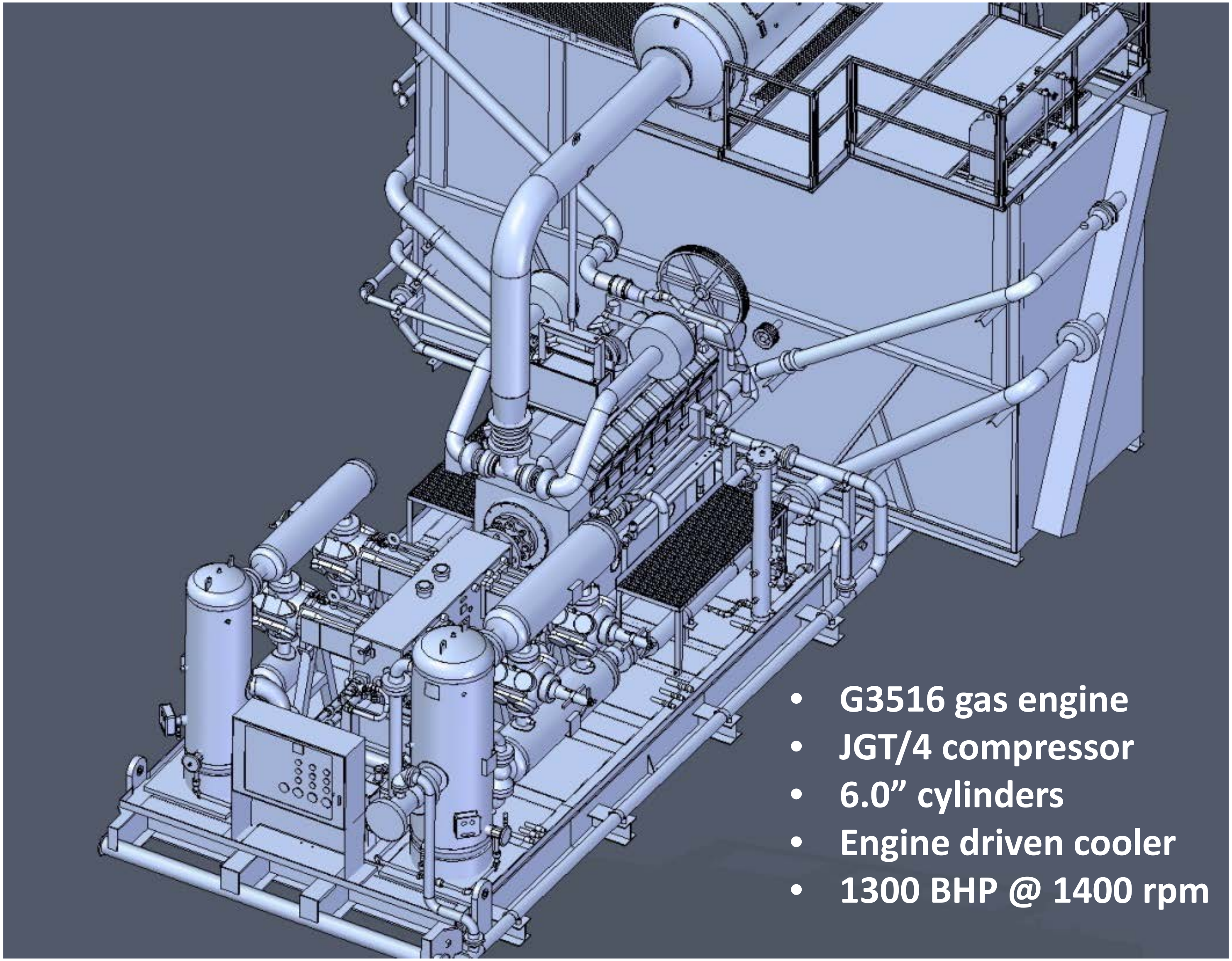
Unit #8 (PAN) vs. Unit #1 HP/MMSCFD reduction					
	1000	1050	1100	1150	1200
450	5.7%	4.5%	3.7%	3.3%	2.5%
495	6.7%	5.6%	4.8%	3.8%	3.0%
540	8.0%	6.6%	5.5%	4.4%	4.9%
585	9.9%	8.1%	6.9%	5.5%	14.4%
630	10.9%	9.6%	7.9%	16.4%	23.7%
675	13.3%	11.4%	9.3%	16.4%	23.7%
720	15.8%	13.8%	11.0%	16.4%	23.7%
765	18.5%	16.1%	12.9%	16.4%	23.7%
810	21.5%	18.6%	16.0%	16.2%	23.7%
855	25.5%	21.6%	18.6%	15.9%	23.7%
900	30.5%	25.3%	21.5%	18.8%	15.4%

Table Average – 13.5%

Predicted % Improvement in BHP/MMSCFD
PAN Unit vs. Baseline Bottle Unit

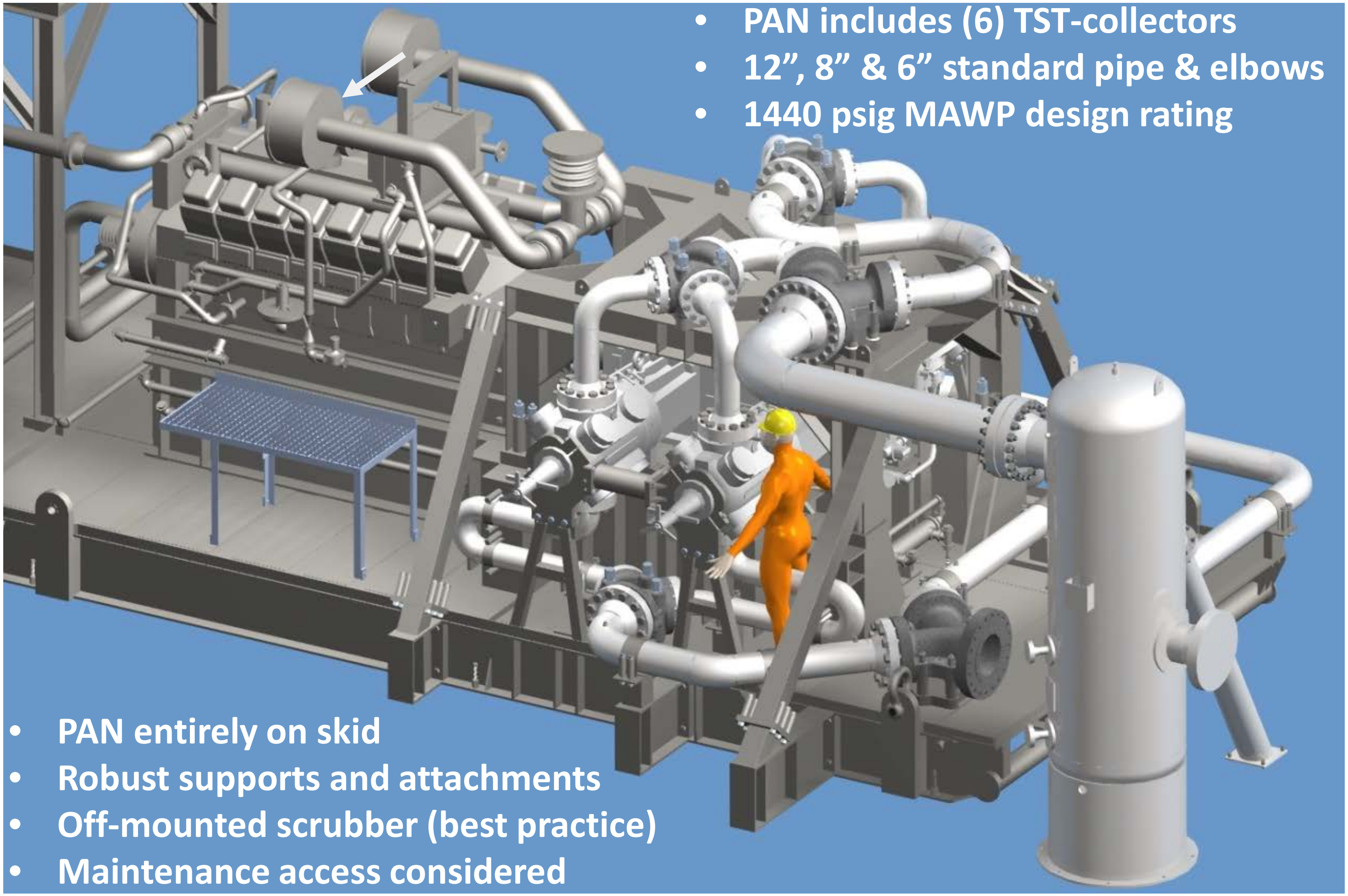


Existing Bottle Unit



- G3516 gas engine
- JGT/4 compressor
- 6.0” cylinders
- Engine driven cooler
- 1300 BHP @ 1400 rpm

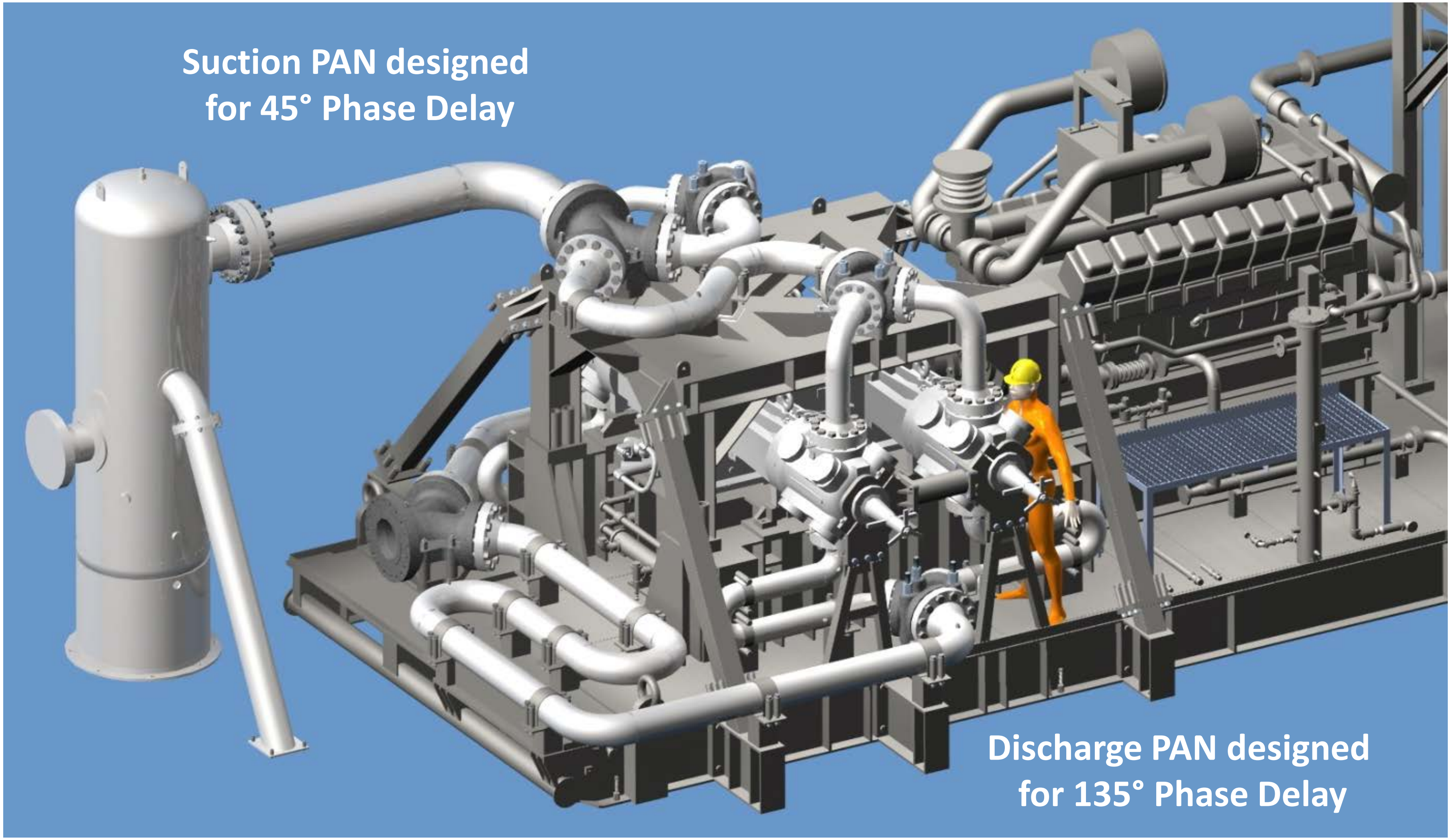
PAN Mechanical Design
3-D CAD Model



- PAN includes (6) TST-collectors
- 12”, 8” & 6” standard pipe & elbows
- 1440 psig MAWP design rating

- PAN entirely on skid
- Robust supports and attachments
- Off-mounted scrubber (best practice)
- Maintenance access considered

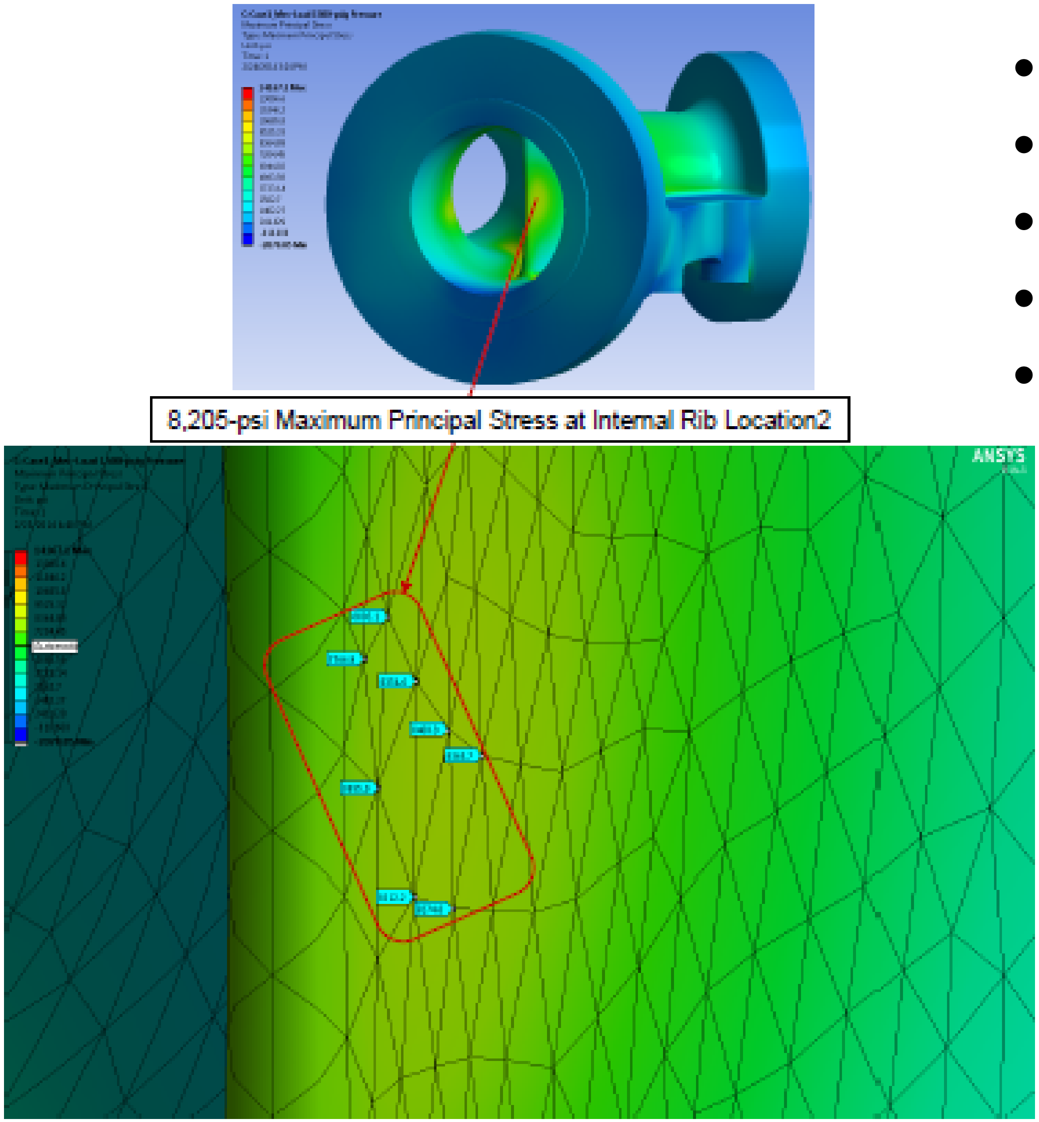
PAN Mechanical Design
3-D CAD Model



PAN Mechanical Design
Completed Package

PAN Mechanical Design
Completed Package

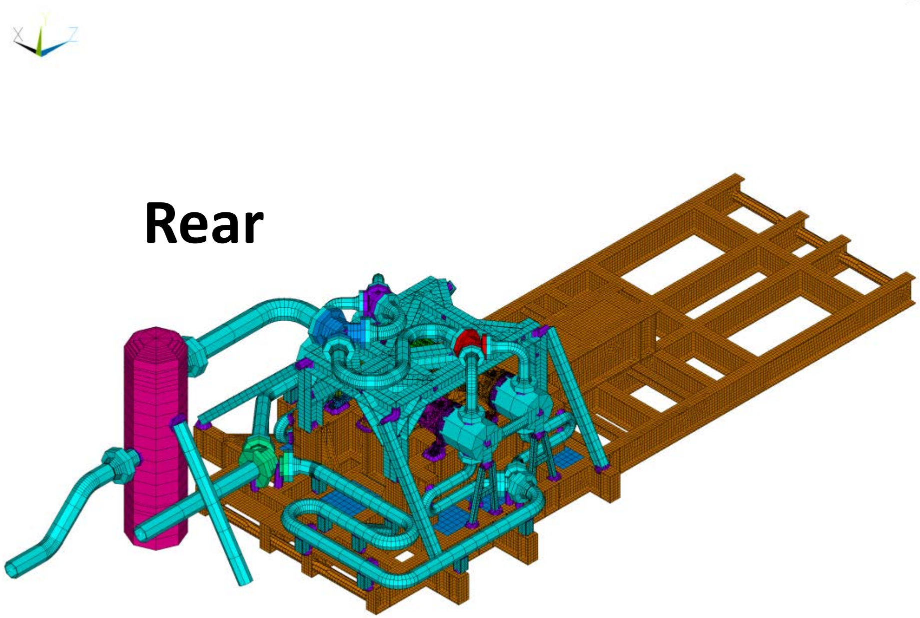
PAN Mechanical Design
TST-Collectors



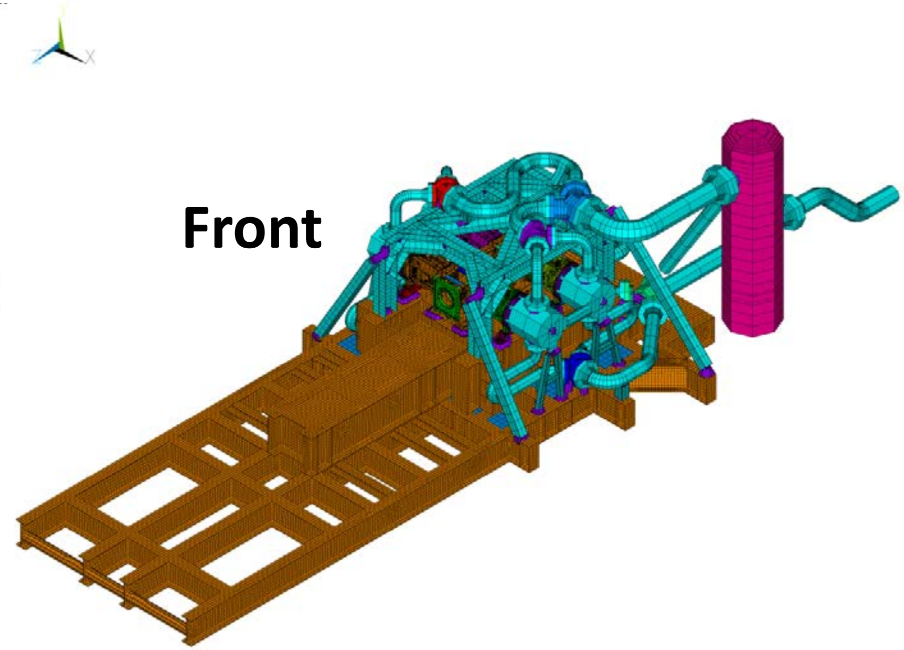
- **(4) 8x6x6 Y-collectors**
- **(2) 12x8x8 Y-collectors**
- **ASTM A395 Cast DI**
- **1500 psig MAWP**
- **Serialized Items**

PAN Mechanical Analysis
FEA Model

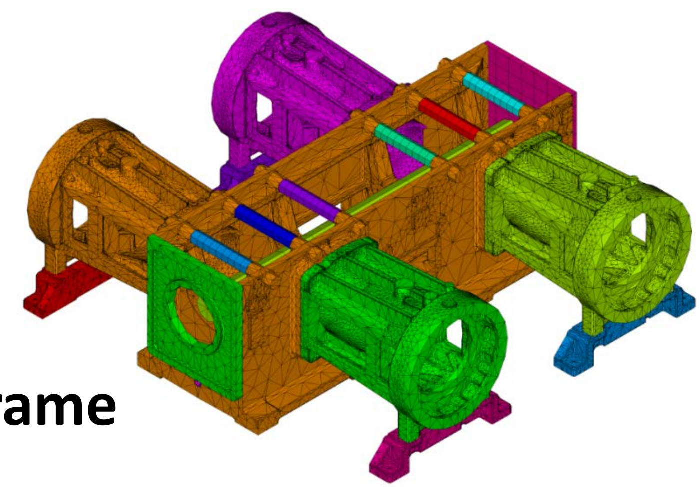
Rear



Front

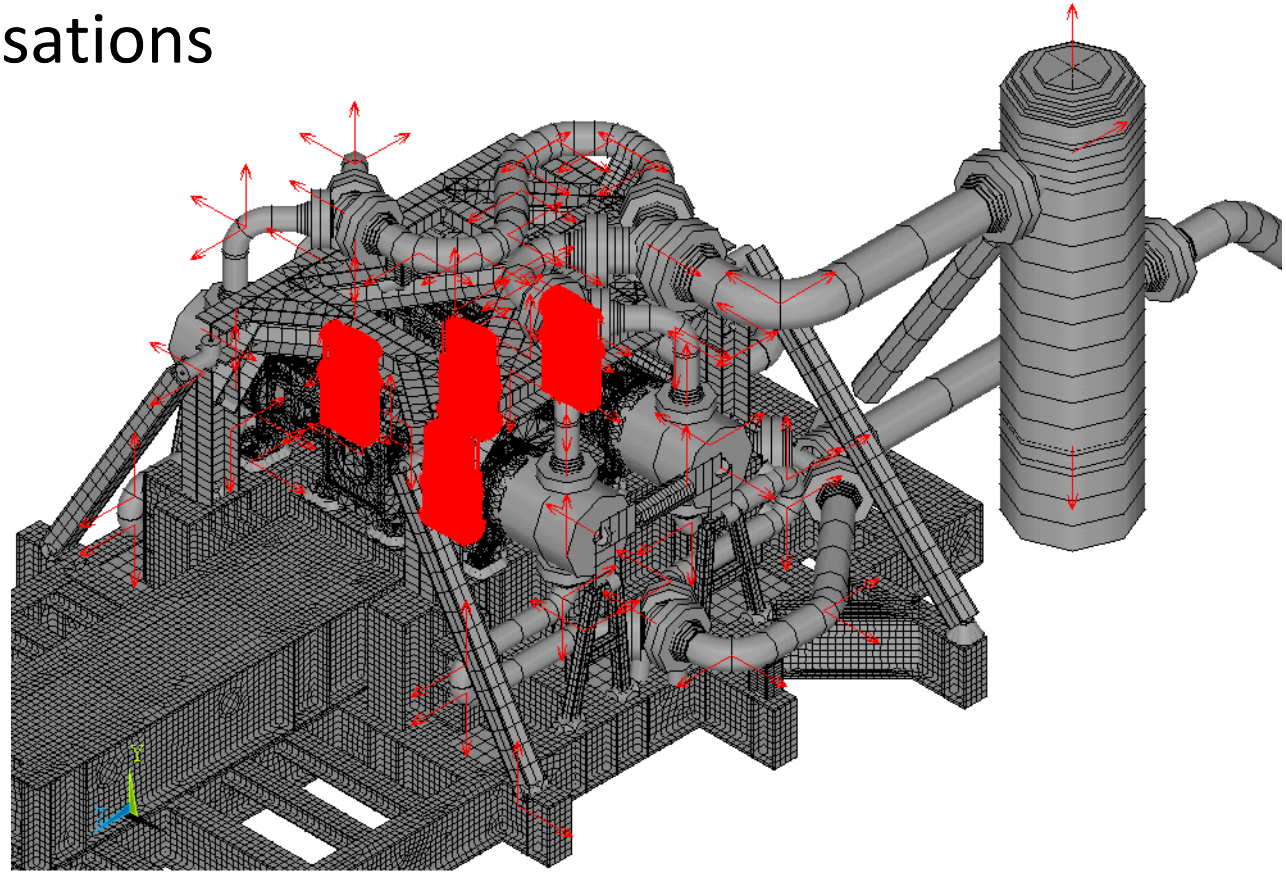


Frame

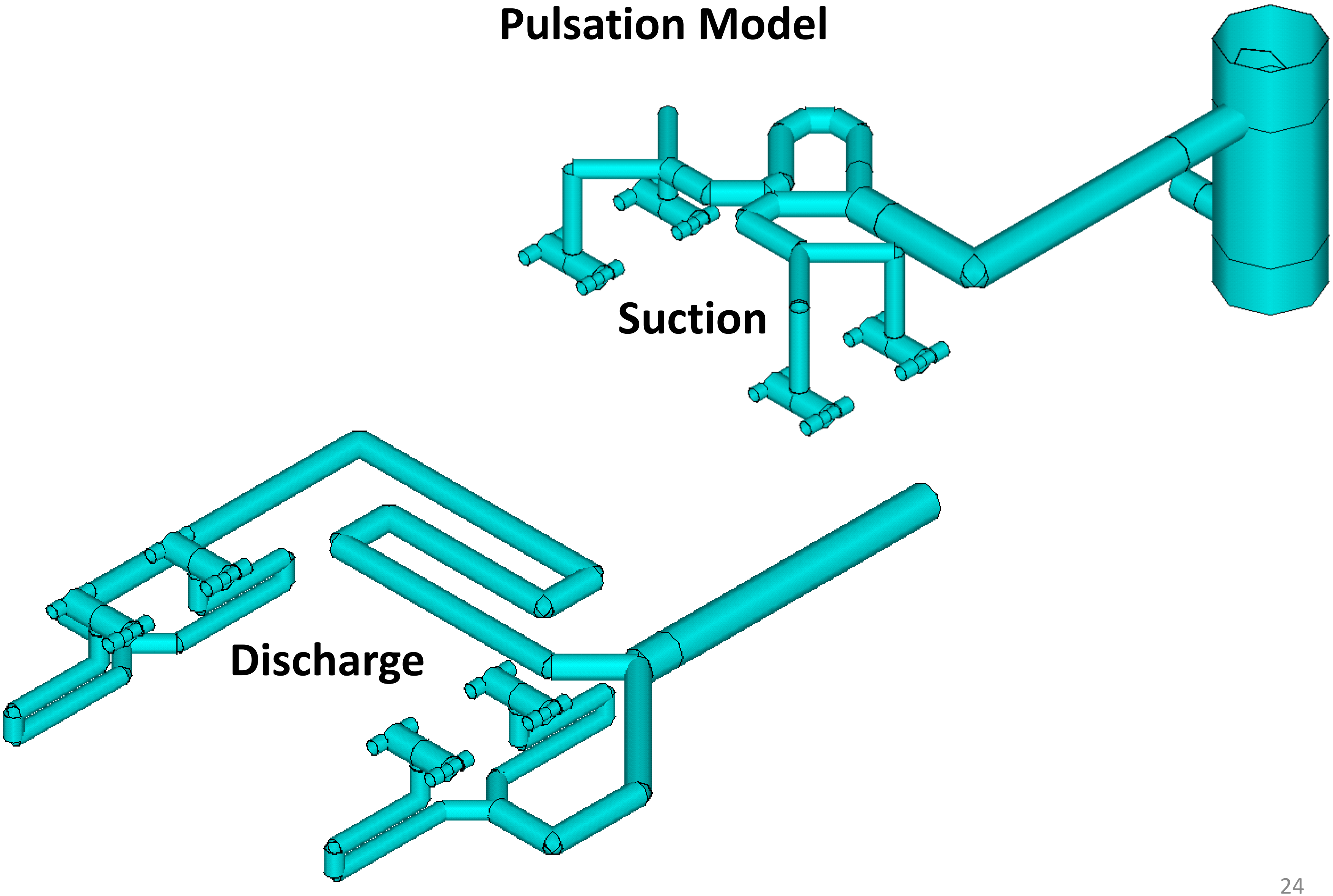


Dynamic Loads

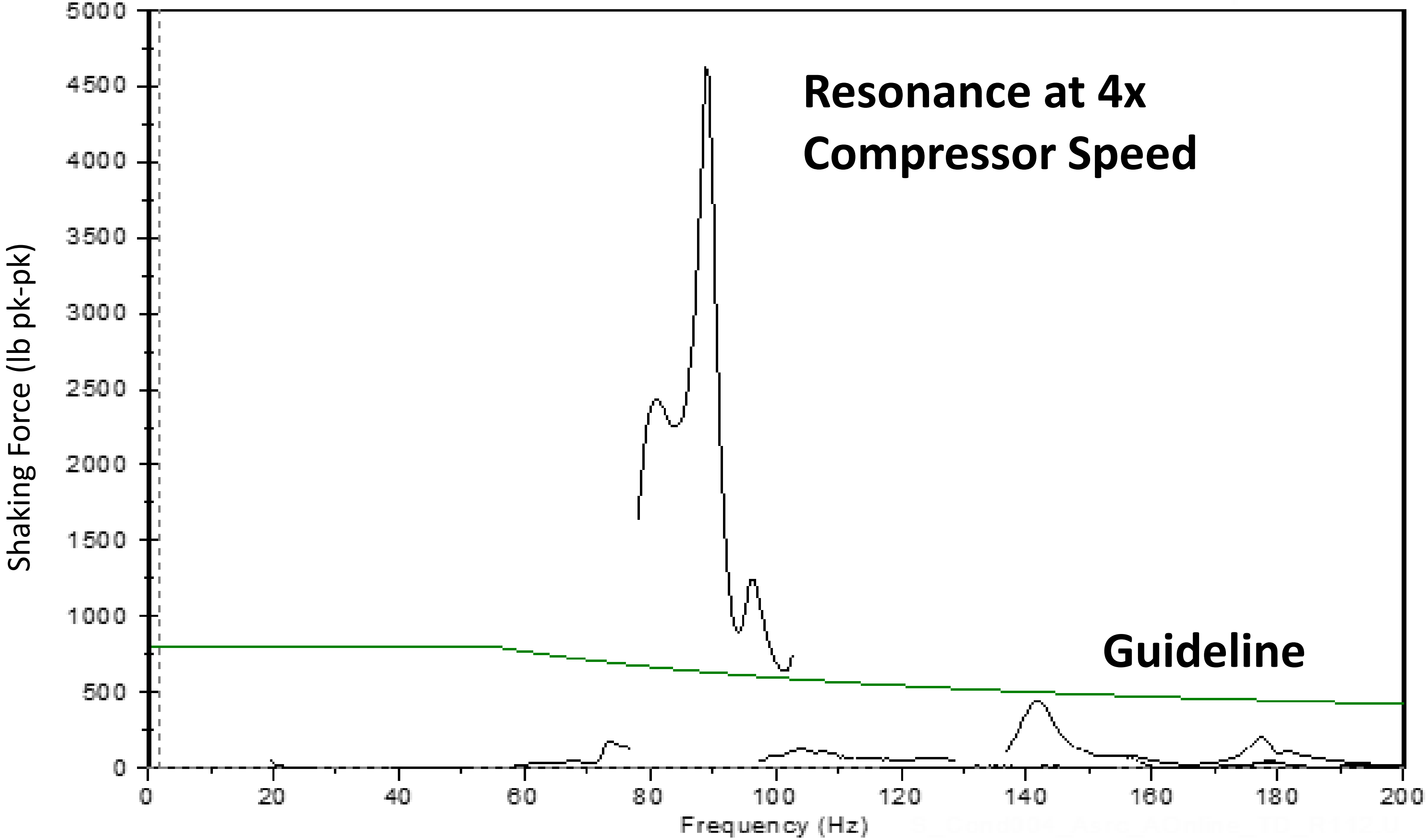
- Compressor reciprocating and rotating inertia
- Cylinder gas force (stretch force)
- Crosshead guide force
- Pressure pulsations



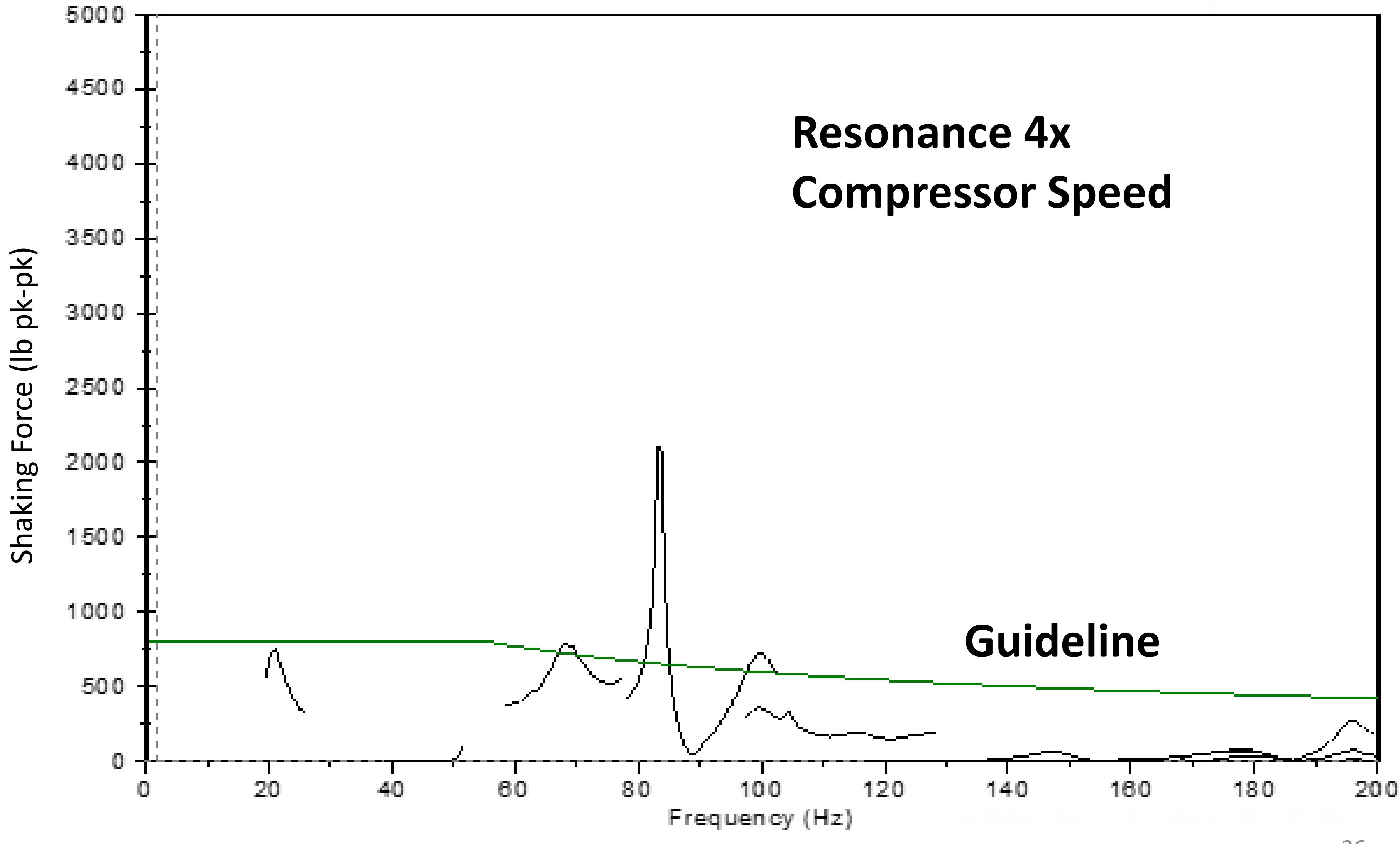
PAN Mechanical Analysis
Pulsation Model



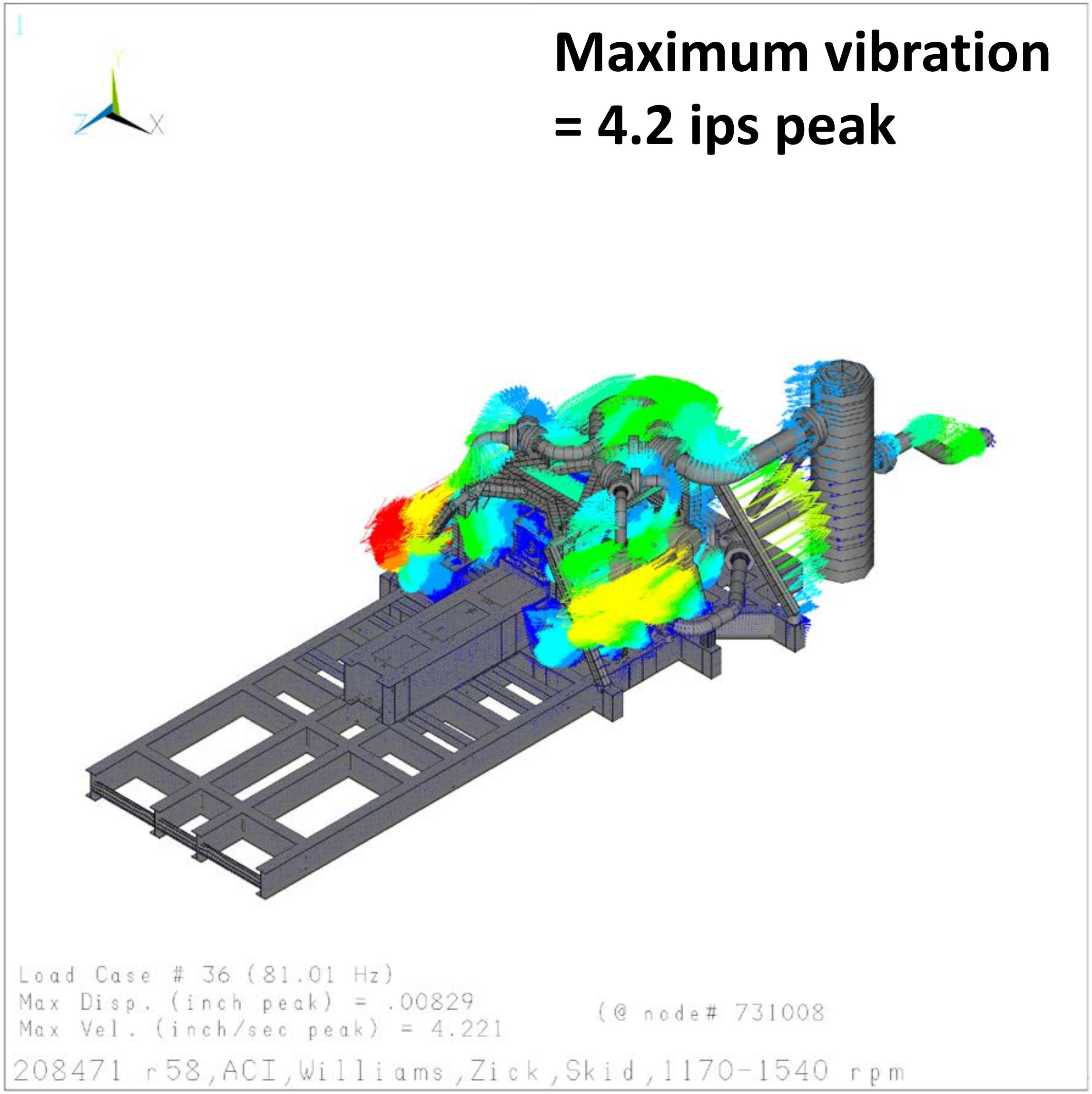
PAN Mechanical Analysis
Maximum Shaking Forces - Suction



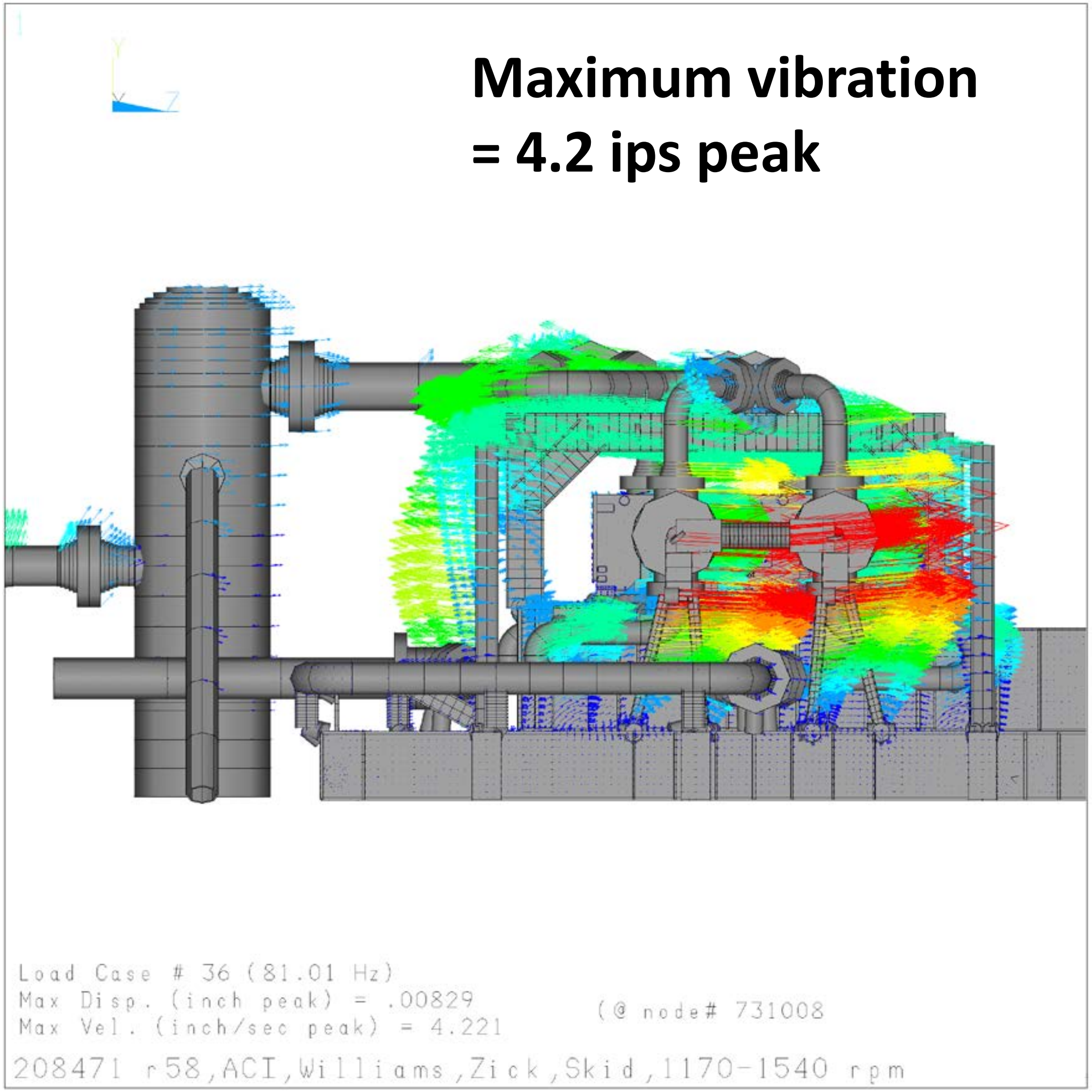
PAN Mechanical Analysis
Maximum Shaking Forces - Discharge



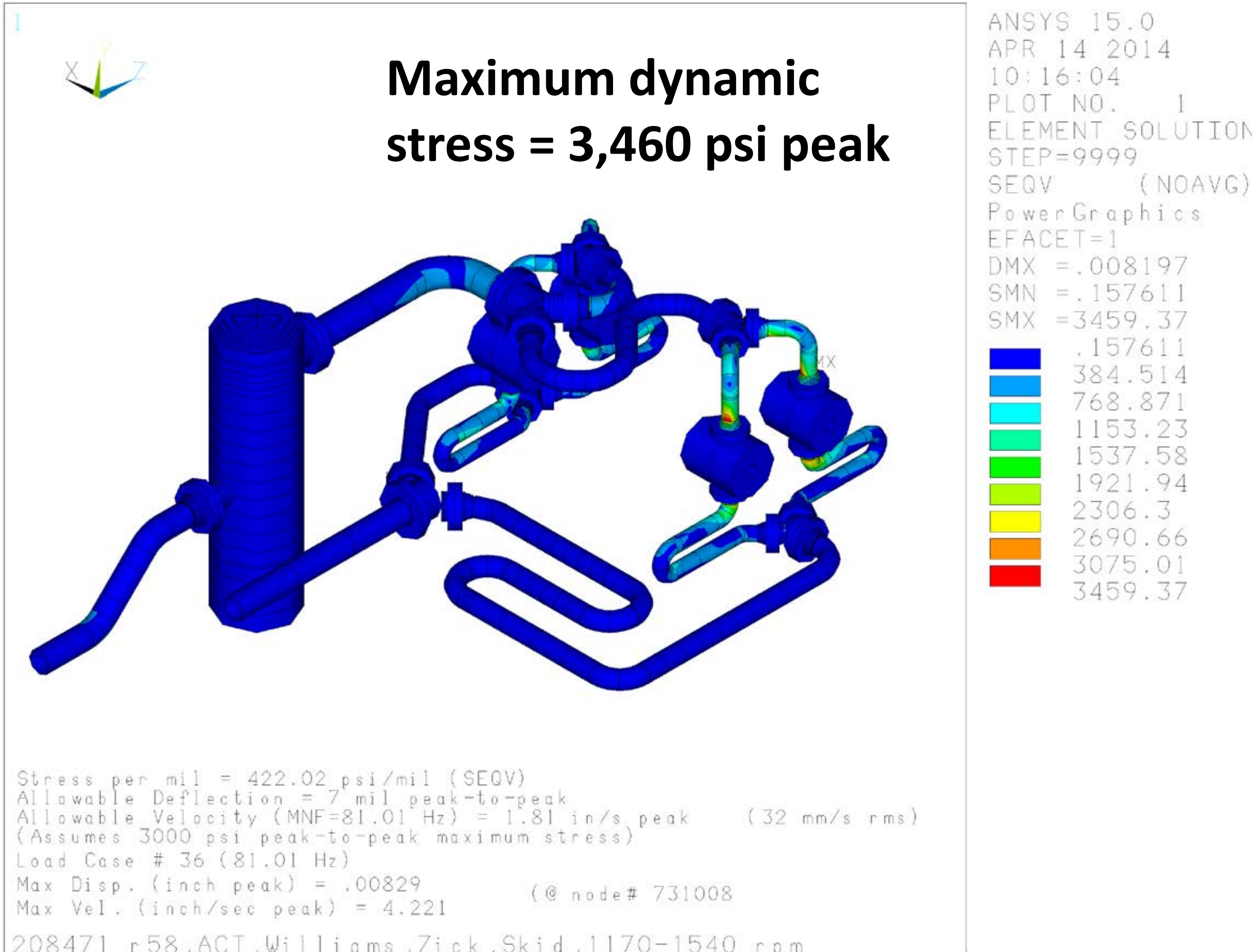
PAN Modal Analysis & Mechanical Forces Response Analysis
Vibration Result at 81 Hz



PAN Modal Analysis & Mechanical Forces Response Analysis
Vibration Result at 81 Hz – Cyl. 1 & 3 Side View



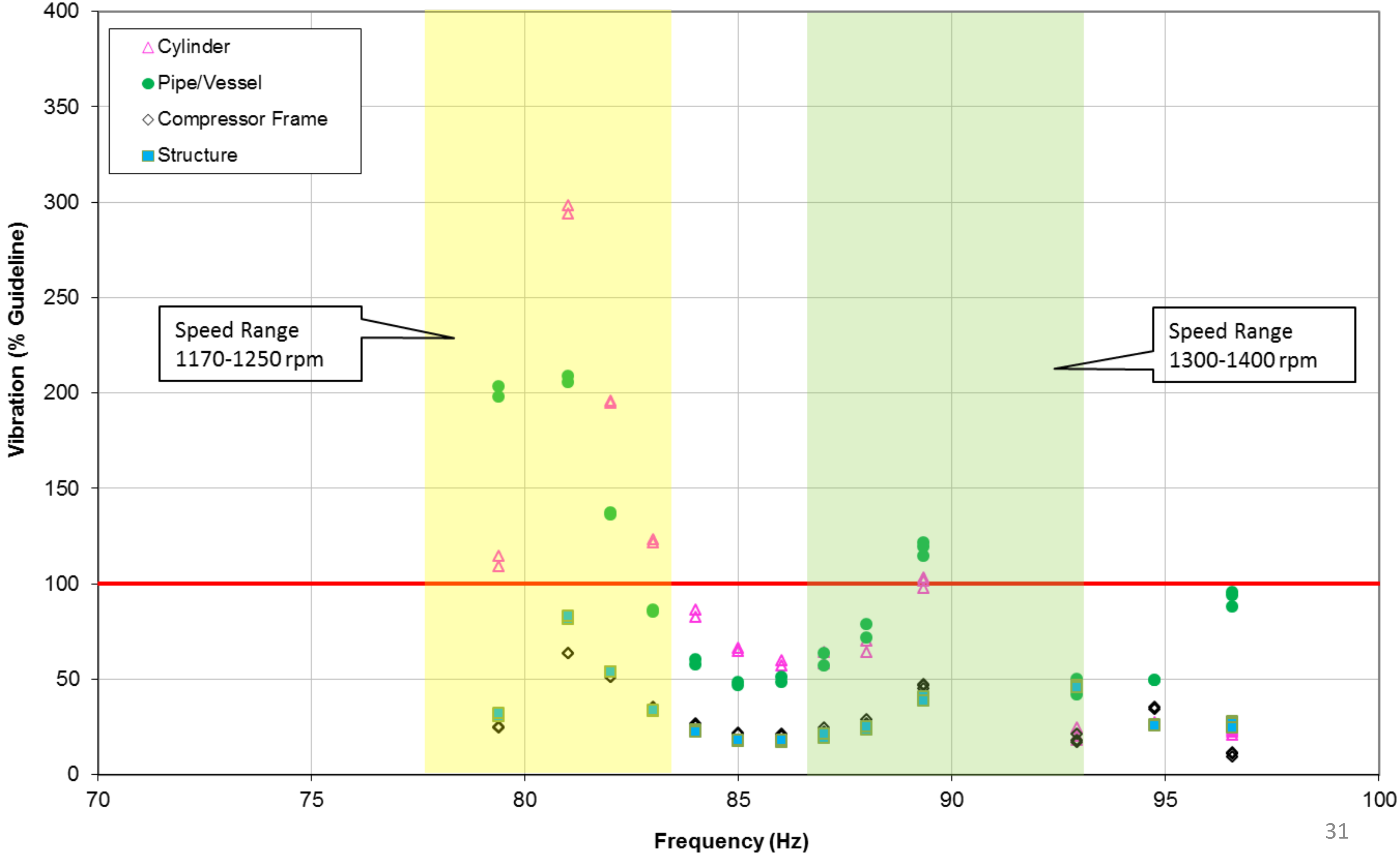
PAN Modal Analysis & Mechanical Forces Response Analysis
Dynamic Stress at 81 Hz



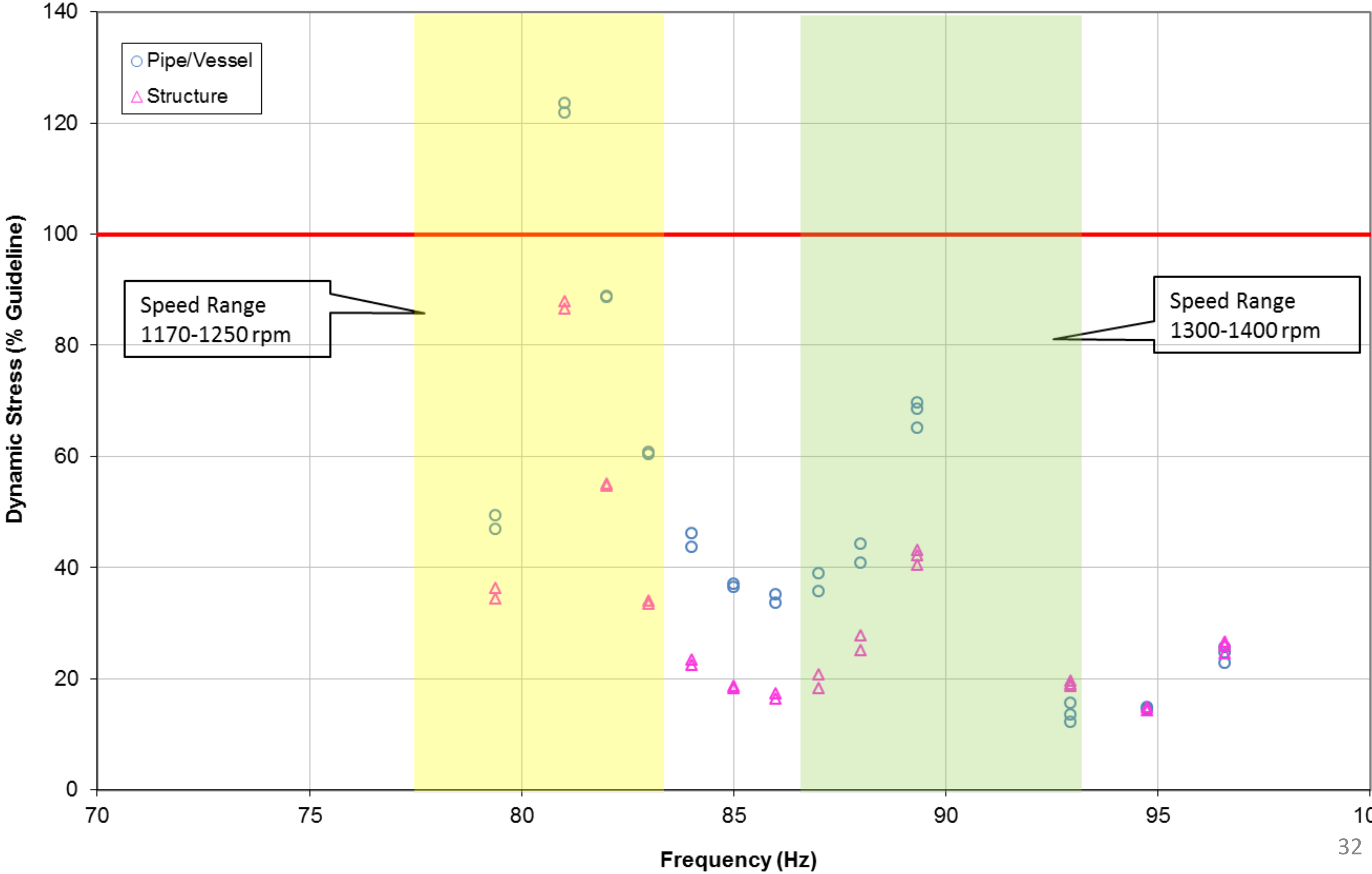
Preliminary Results

- Vibration = 4.1 ips peak at 81 Hz
  - Guideline is 1 ips peak
- Dynamic stress = 3,460 psi peak at 81 Hz
  - Guideline is 1,500 psi peak
- Assumptions
  - 81 Hz resonance occurs (81 Hz at 4x = 1215 rpm). Normal operating speed is 1300-1400 rpm.
  - Damping ratio is 1%. Typical damping ratio for this mode is 2% to 4%.
- Vibration and dynamic stress will be lower at normal operating speed and higher damping

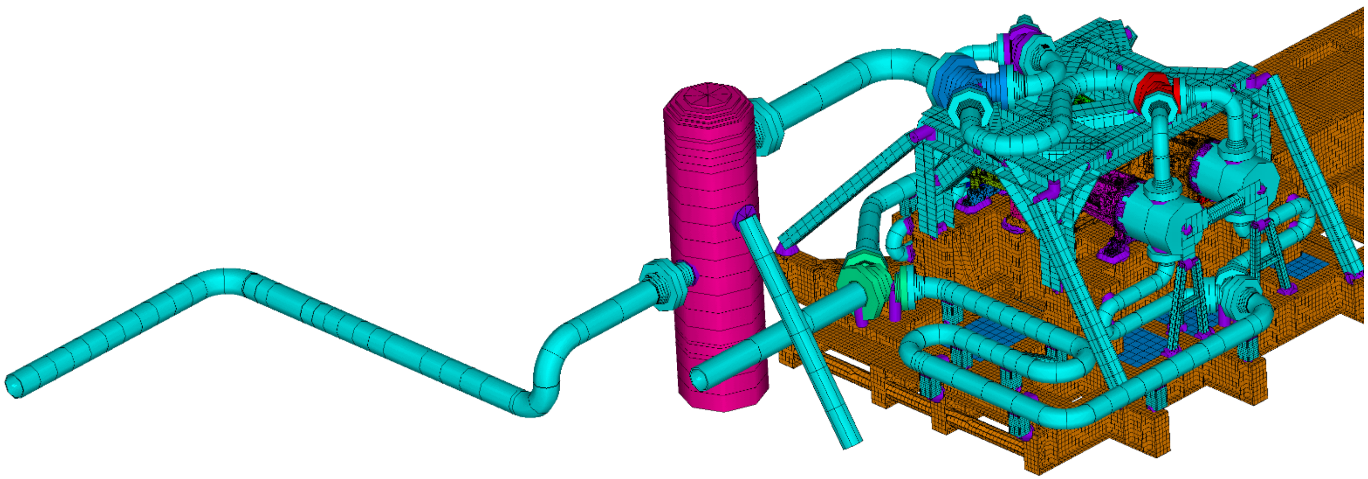
PAN Modal Analysis & Mechanical Forces Response Analysis
Vibration Summary for Condition 4 Assuming 2% Damping



PAN Modal Analysis & Mechanical Forces Response Analysis
Dynamic Stress Summary for Condition 4 Assuming 2% Damping



PAN Modal Analysis & Mechanical Forces Response Analysis
Scrubber Detuning



Recently scrubber inlet piping design was finalized. Potential scrubber resonance.

Proposed Solution: Skirt Cut-out

12" to 18" diameter cut-out in skirt

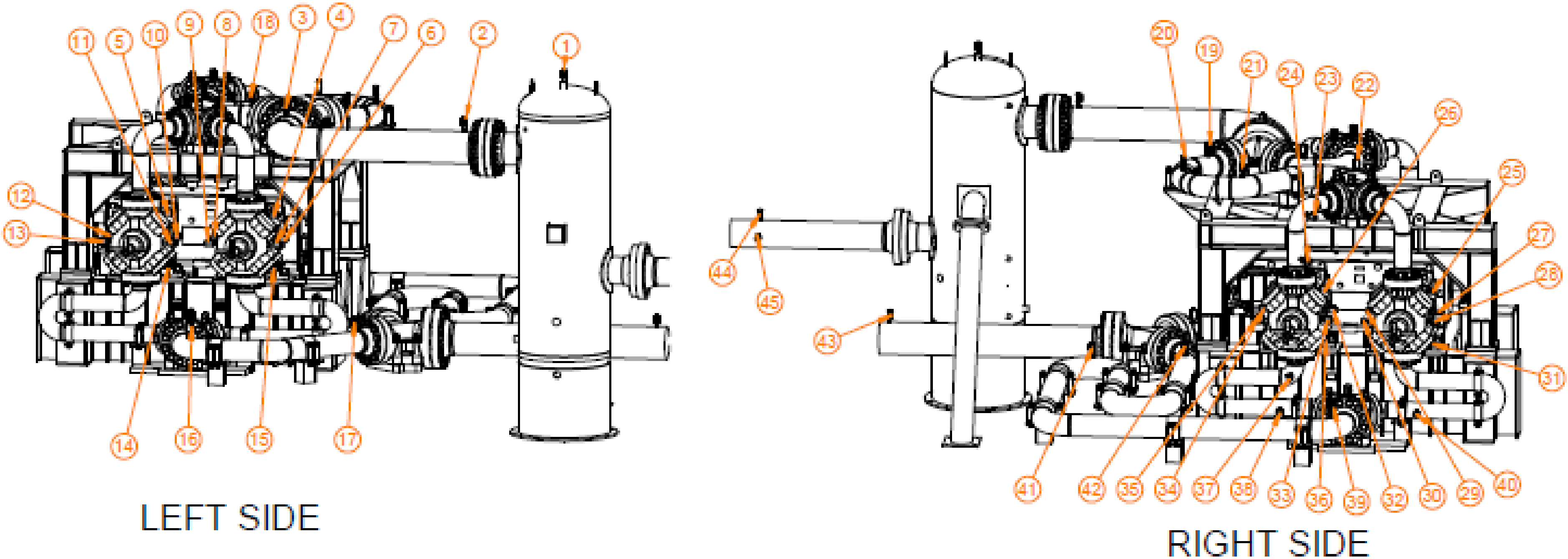
PAN Modal Analysis & Mechanical Forces Response Analysis
Mechanical Recommendations

- Design & assembly care to avoid pipe strain
- Small bore piping natural frequency testing
- Shop bump testing to verify model MNF predictions
- Shop bump testing to verify damping ratio assumptions
- Field bump testing to verify MNF placement & response
- Running test to verify acceptable vibration limits at first start-up
- Inspect pipe clamps, flange studs & other critical fasteners at regular intervals to ensure there is no vibratory loosening.

Field Performance Testing

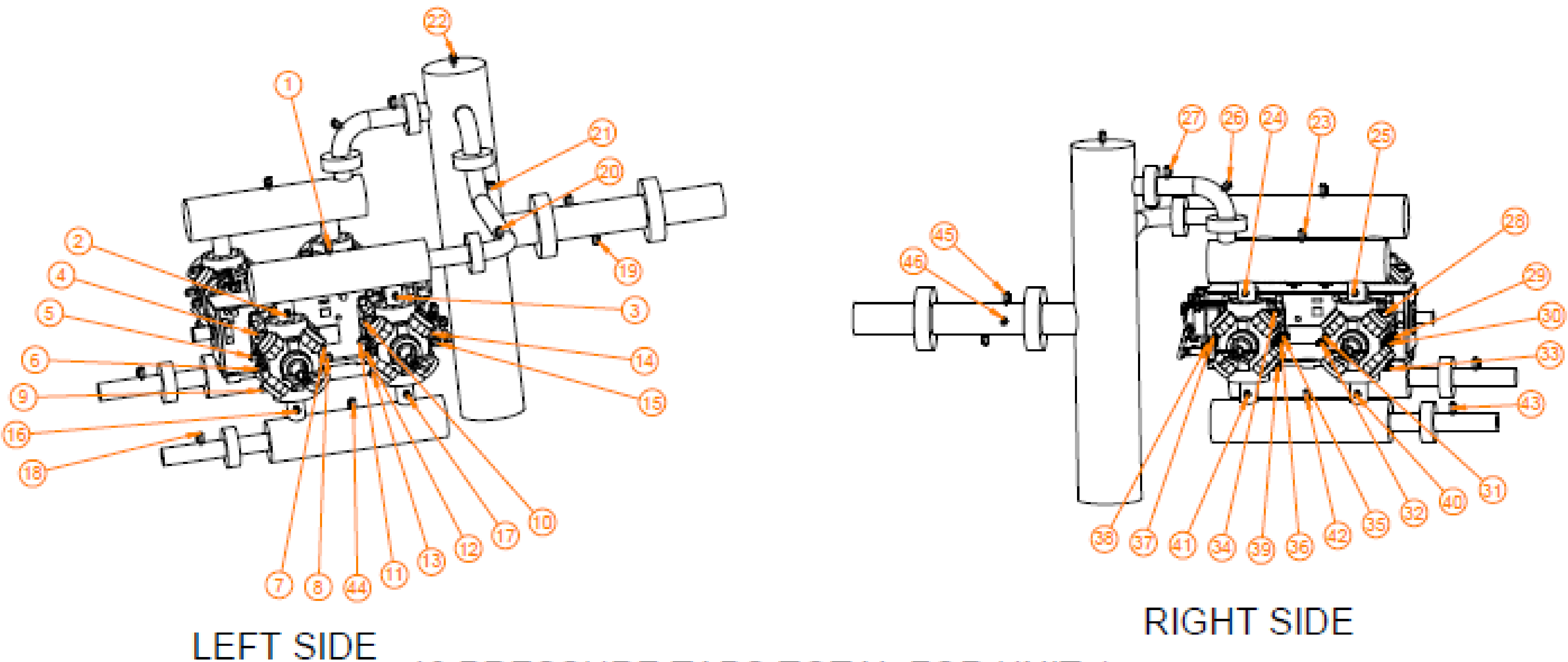
- Steady state tests at 5 specified points – 1300 BHP @ 1400 rpm
- Data also recorded during speed and pressure transient sweeps
- Multiple pressure points on both PAN & existing bottle unit
- Both units will be tested simultaneously at each operating point
- Enthalpy rise measured between system suction & discharge
- AGA flow meters on each unit suction
- Laboratory grade instrumentation and (3) data acquisition systems
- All cylinder ends indicated with (3) Windrock analyzers
- Valve losses indicated
- Crosshead ODC measured for accurate phasing
- Engine & panel data recorded for reference only
- Pulsations measured throughout both systems (full port valves)
- All recording systems time synched
- Gas sample at each suction each day
- Downstream gas chromatograph log obtained for each day

Field Performance Testing
PAN System Test Points



45 PRESSURE TAPS TOTAL FOR UNIT 8

Field Performance Testing
Bottle System Test Points



46 PRESSURE TAPS TOTAL FOR UNIT 1

Field Performance Testing

- Test team of 13-14 people with detailed protocol established.
- Calculation methods pre-established.
- VMG and NIST gas data.
- Data adjusted for differences in cylinders (based on predictions).
- Comparison of measured and predicted results for both units.
- Unfortunately, construction delays prevented test data for paper.
- Mechanical testing this week.
- Performance testing late October awaiting higher gas flows to reach high end of suction pressure required for test points.

Conclusions

- Simulations confirm optimized PAN can cover large range of operating conditions (to be verified by field test).
- Higher PAN efficiency mandated choice of larger cylinders to load unit and maximize flow (conflicting end user requirement that complicates the pure research comparison with bottle unit).
- Predicted system pressure drop less than 1.0 psig over most of operating range.
- Predicted pulsation less than 0.3% of line pressure at all conditions.
- -30.5% BHP/MMSCFD predicted improvement at high flow point.
- Control of pulsation induced forces within the PAN is challenging.
- PAN structural design to avoid MNFs is challenging, but doable.
- Fixed speed applications much easier to design.
- More to follow in report and paper after field tests are complete.

Testing currently planned for wk. of Oct. 27


Thanks for your attention.
Questions???