# Leveraging loss analysis to explore novel attributes and critical features for maximum efficiency in spool compressors


**Craig R. Bradshaw, Ph.D.**
Assistant Professor
Oklahoma State University
ASHRAE Member


Seminar 19: What’s Loss Got to Do with It? Analysis of Indicator Diagrams of Positive Displacement Compressors

# Learning Objectives

1. Describe the data collection and reduction process for producing positive displacement compressor indicator diagrams
2. Describe the process for estimating compressor losses from indicator diagrams
3. Define the relationship between indicated power and compressor mechanical efficiency and explain how to estimate possible efficiency improvements using indicator diagrams
4. Illustrate the impact of operating conditions on internal compressor losses

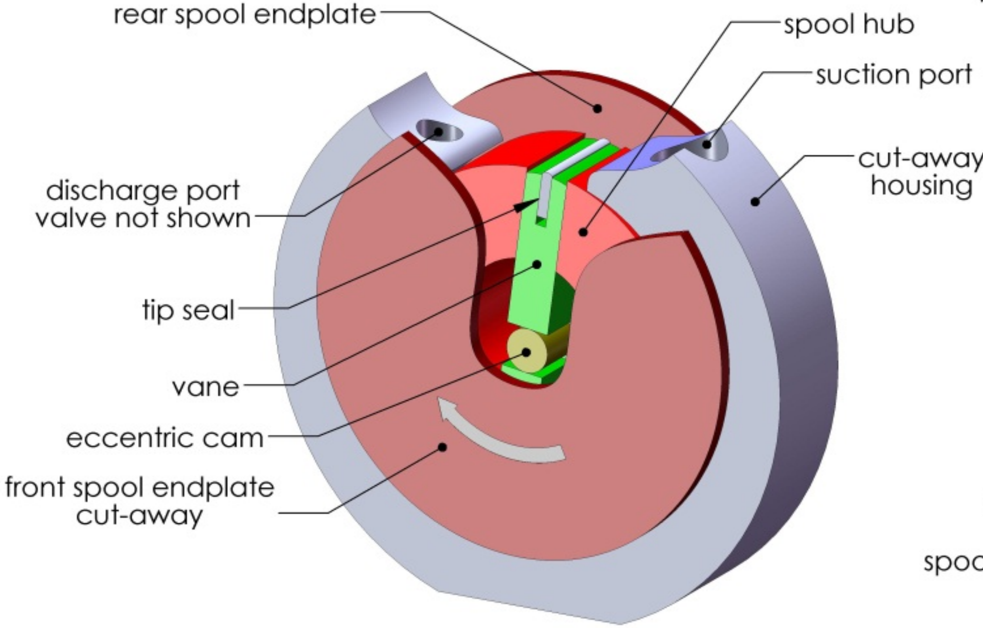
# Acknowledgements

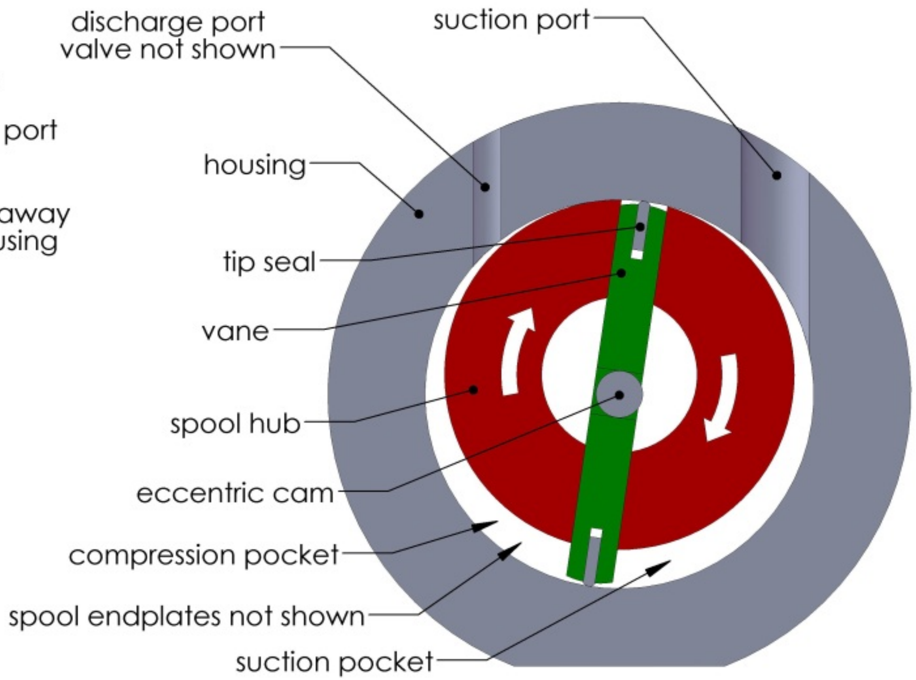
- Joe Orosz, Torad Engineering
- Greg Kemp, Torad Engineering
- Eckhard Groll, Purdue University

# Overview

- What is unique about the spool compressor?
- Holistic loss pareto of 5$^{th}$ gen. spool compressor
  - Experimental methodology
  - Loss analysis
  - Loss pareto
- Indicated losses of 7$^{th}$ gen. spool compressor
  - Updated methodology
  - Loss analysis at multiple operating conditions
- Conclusions

# What is unique about the spool compressor?



# What are indicated losses?

$$\eta_{o,is} = \frac{\dot{W}_{is}}{\dot{W}_{total}} = \frac{\dot{W}_{is}}{\dot{W}_{is} + L_{total}}$$

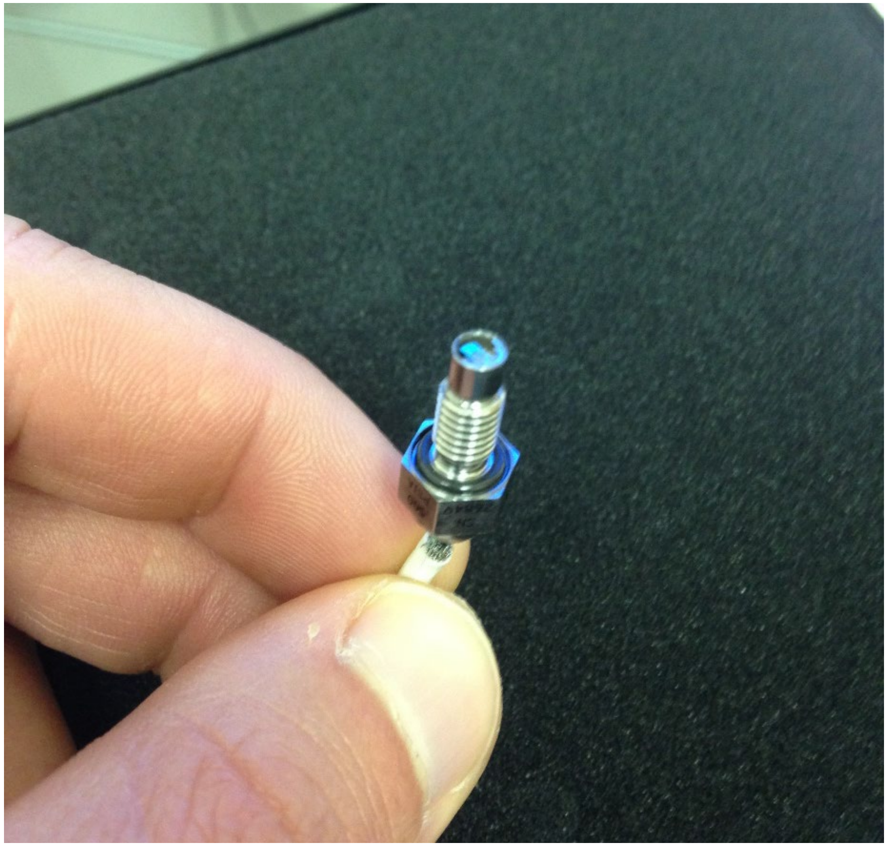
- The isentropic efficiency includes all compressor losses

$$L_{total} = L_{ind} + L_{mech}$$

- Indicated losses - “flow” losses or “internal” losses
- Frictional/mechanical losses - mostly independent

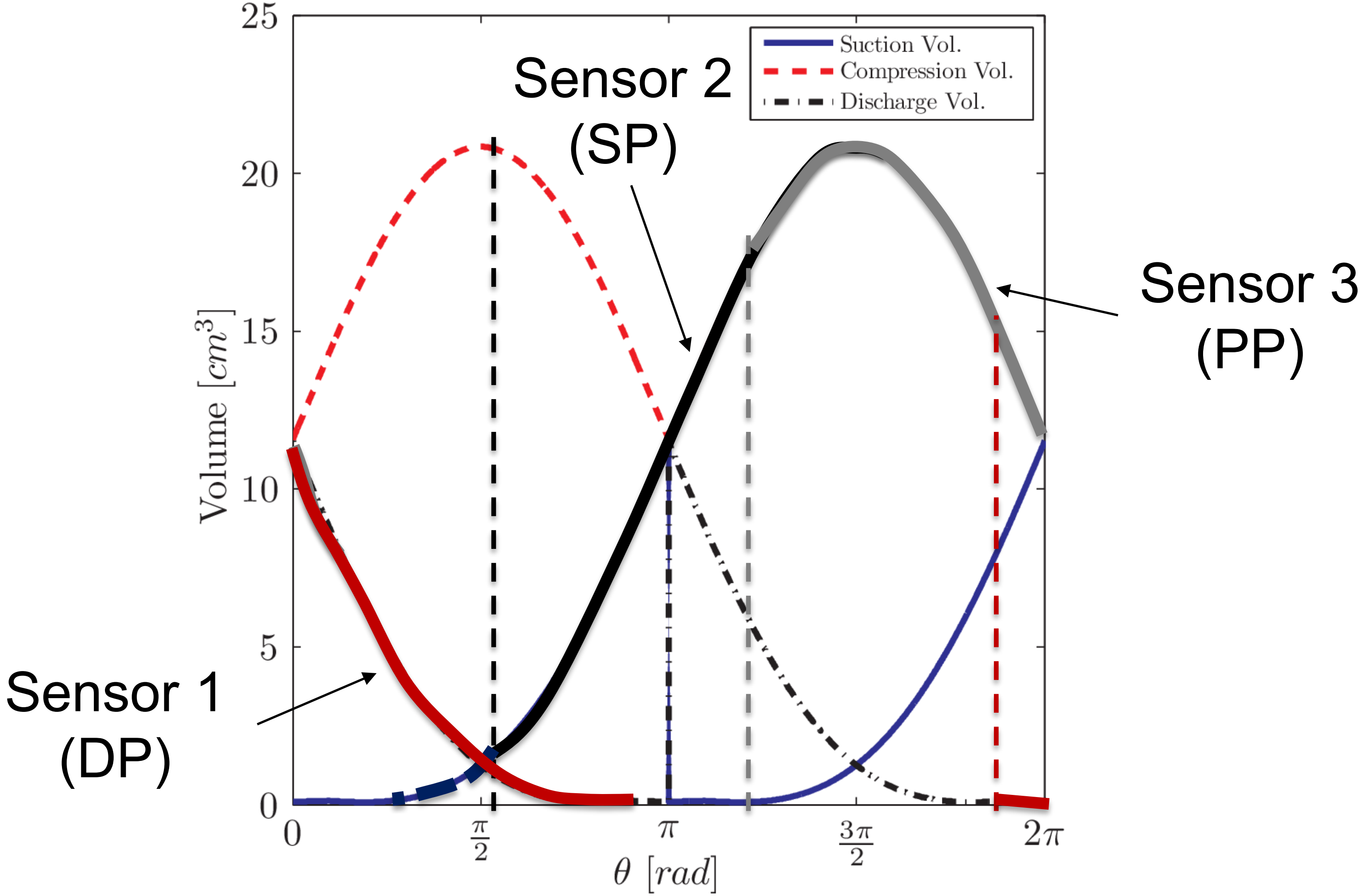
# Experimental Methods – 5th Gen. Spool Prototype[1]

- Instrumented using Endevco 8530B-500 high-speed pressure sensors
  - Sampled at 30,000 samples per second
  - Roughly 20 cycles averaged per cycle
  - 95% confidence interval presented as uncertainty

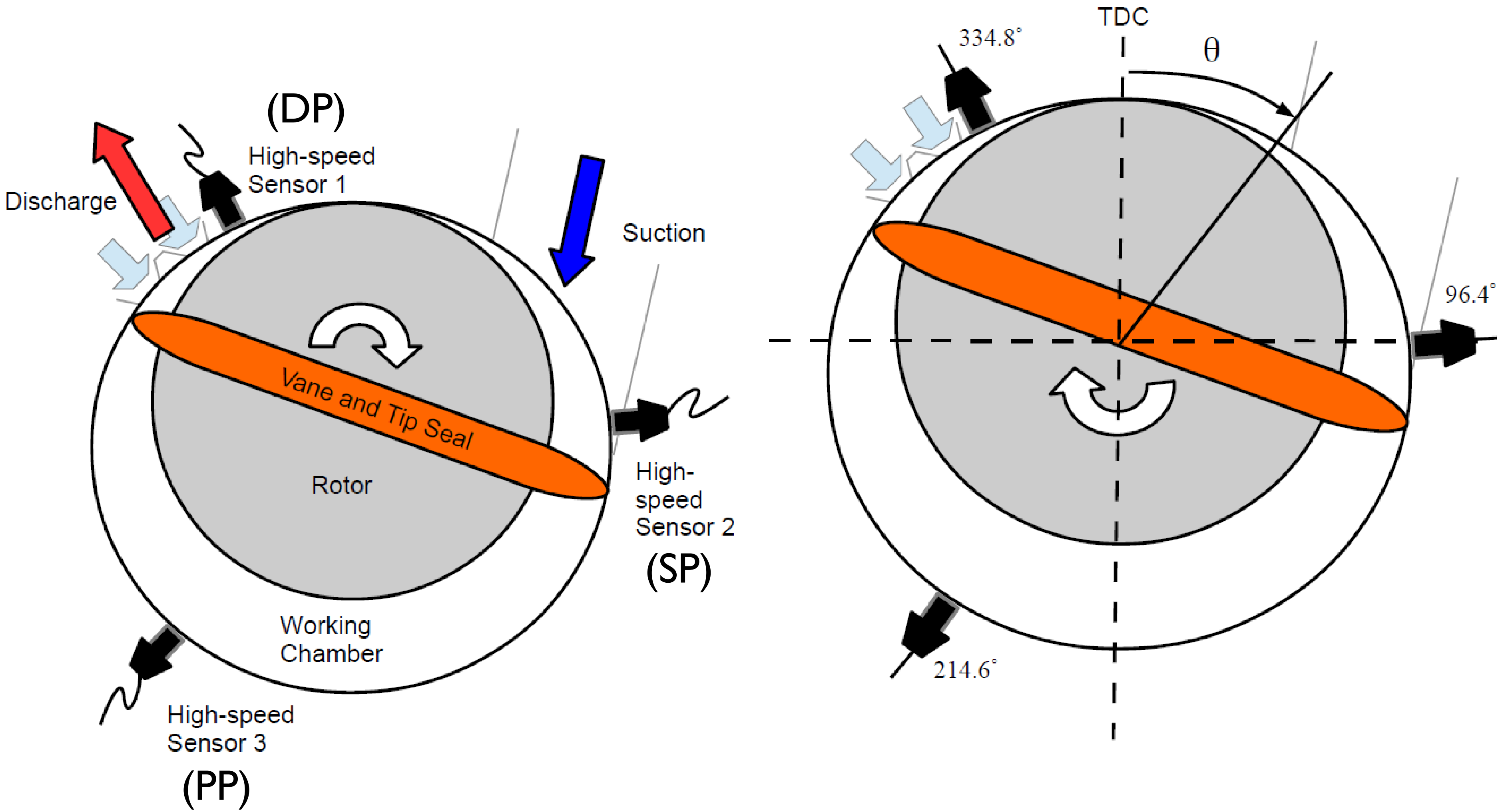


[1]Bradshaw et al. (2016). Development of a Loss Pareto for a Rotating Spool Compressor…*App.Thm. Engr.* 99, 392-401.

# Experimental Methods - Placement

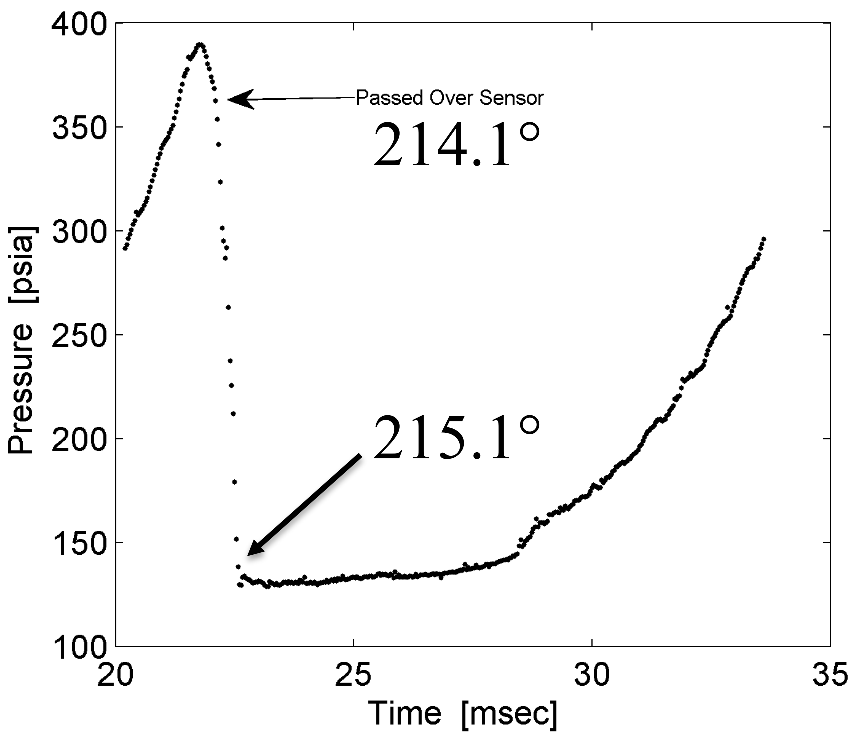


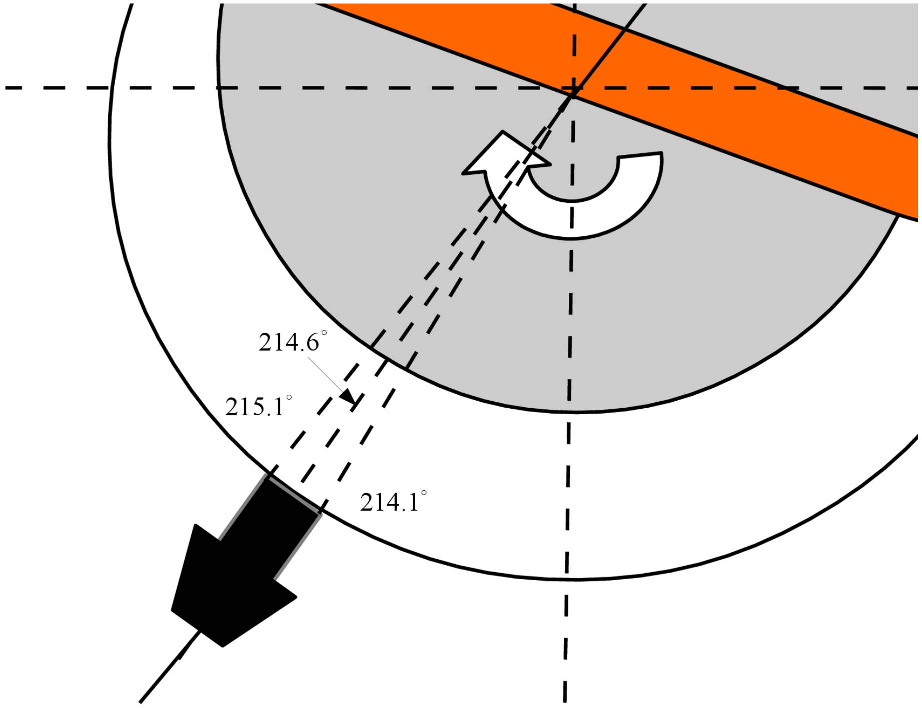
# Sensor Locations and Orientation



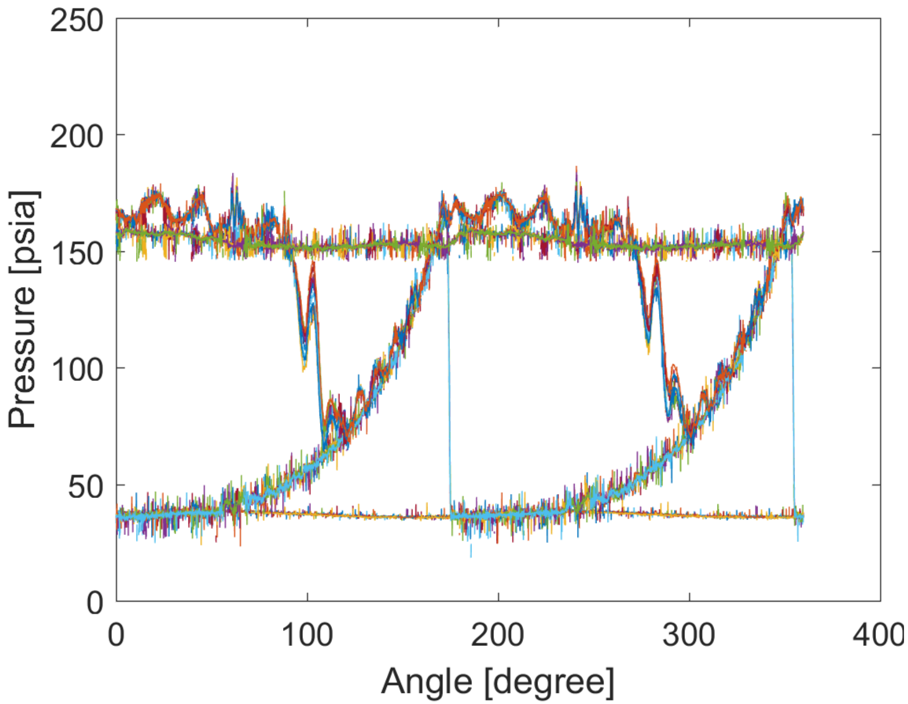
# Correlating Volume Curves to Pressure Data

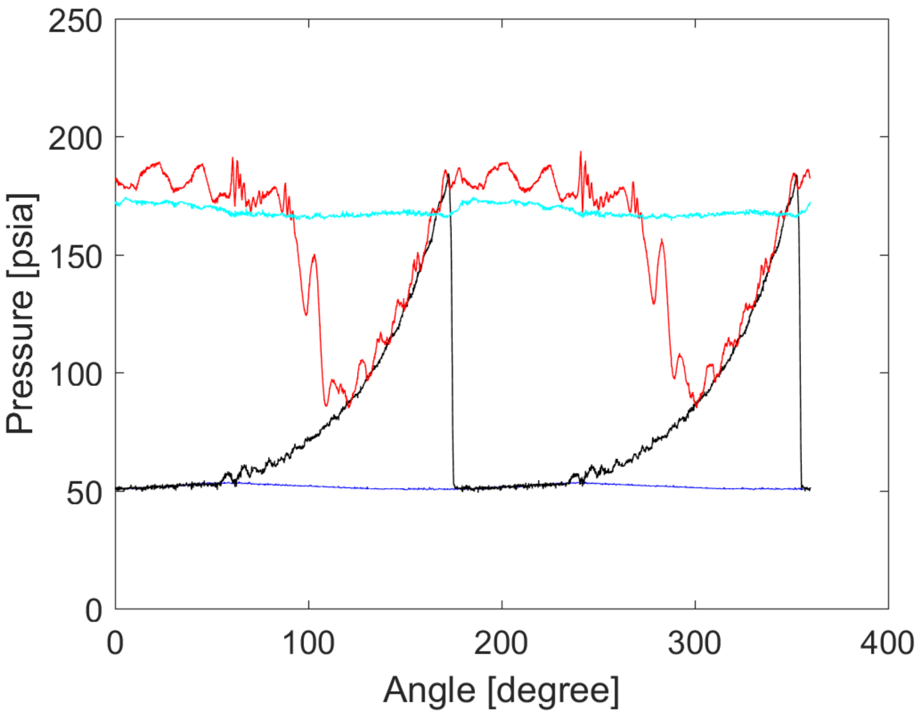
- Vane position is inferred from pressure data
- An algorithm to filter, determine inflection point, and assign vane position is developed



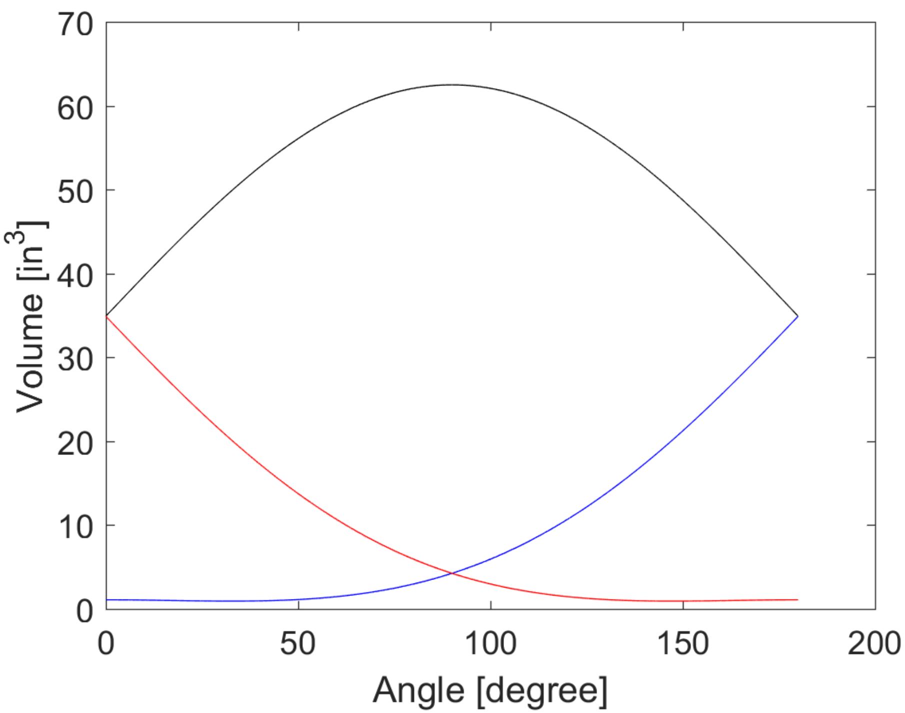
# Average Multiple Samples of Data

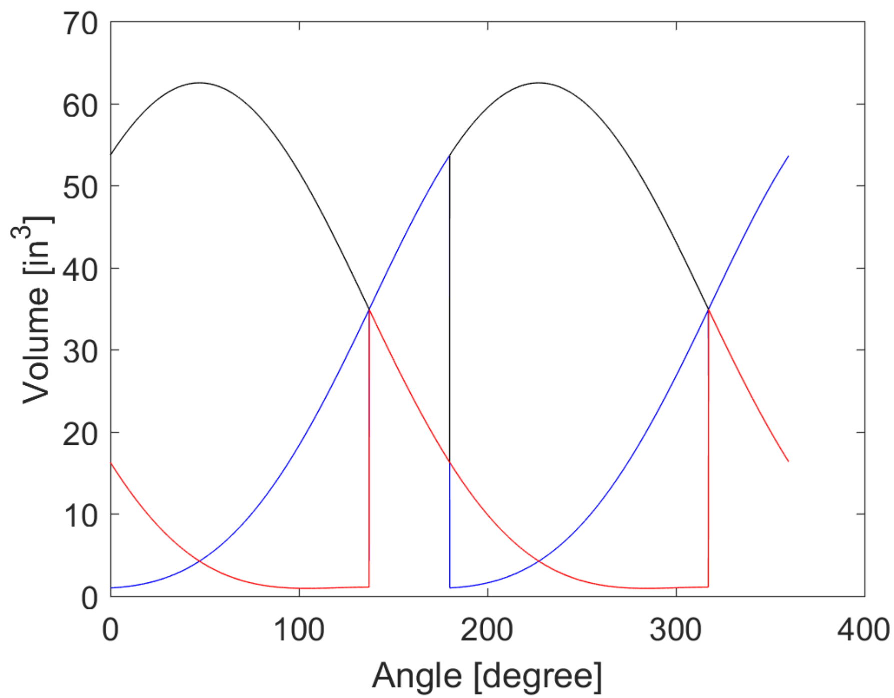



Multiple samples → Averaged final sample

# Align volumes




Model[2] volumes → Final aligned volumes

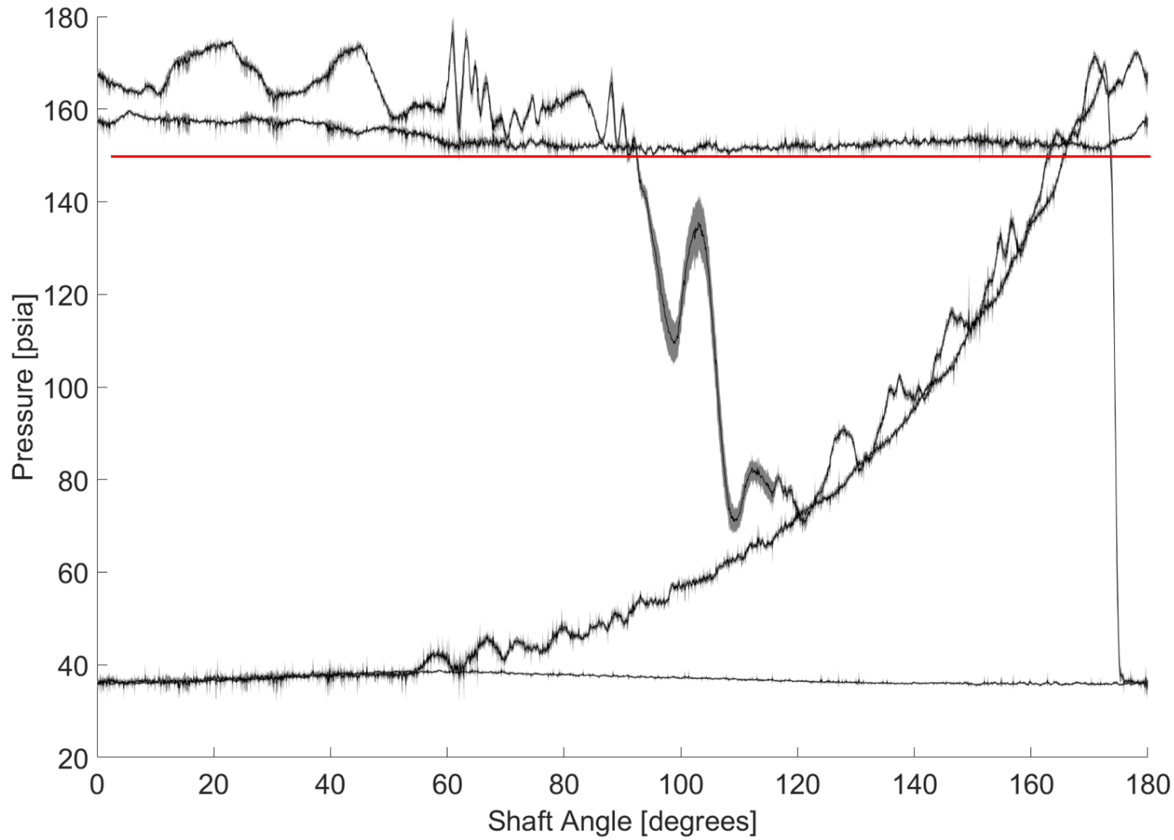
Collect volumes using model, stack two sets next to each other and shift to align with encoder position on compressor

[2]Bradshaw and Groll. (2013). A Comprehensive Model of a Novel Rotating Spool Compressor…*Int. J. of Ref.* 36, 1974-1981.

# Uncertainty analysis

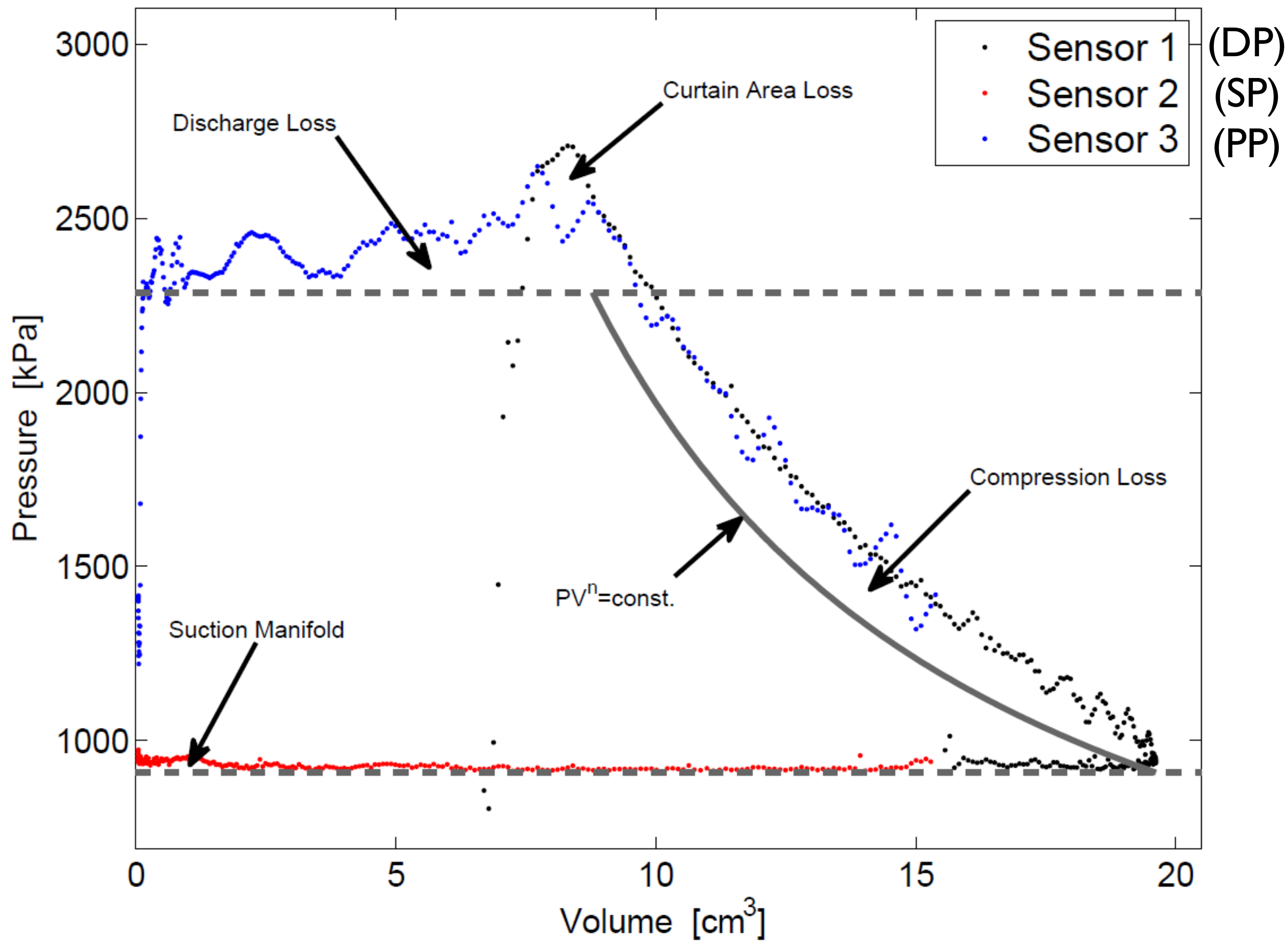
95% confidence interval (CI) based on average of data points

Average CI for each test used in propagated uncertainty




$$u_{L_{dis}} = \sqrt{\left(u_{P_{HS}} \Delta V_{dis}\right)^2 + \left(u_{P_{dis}} \Delta V_{dis}\right)^2}$$

# 5th Gen. Spool Prototype Indicator Diagram[1]

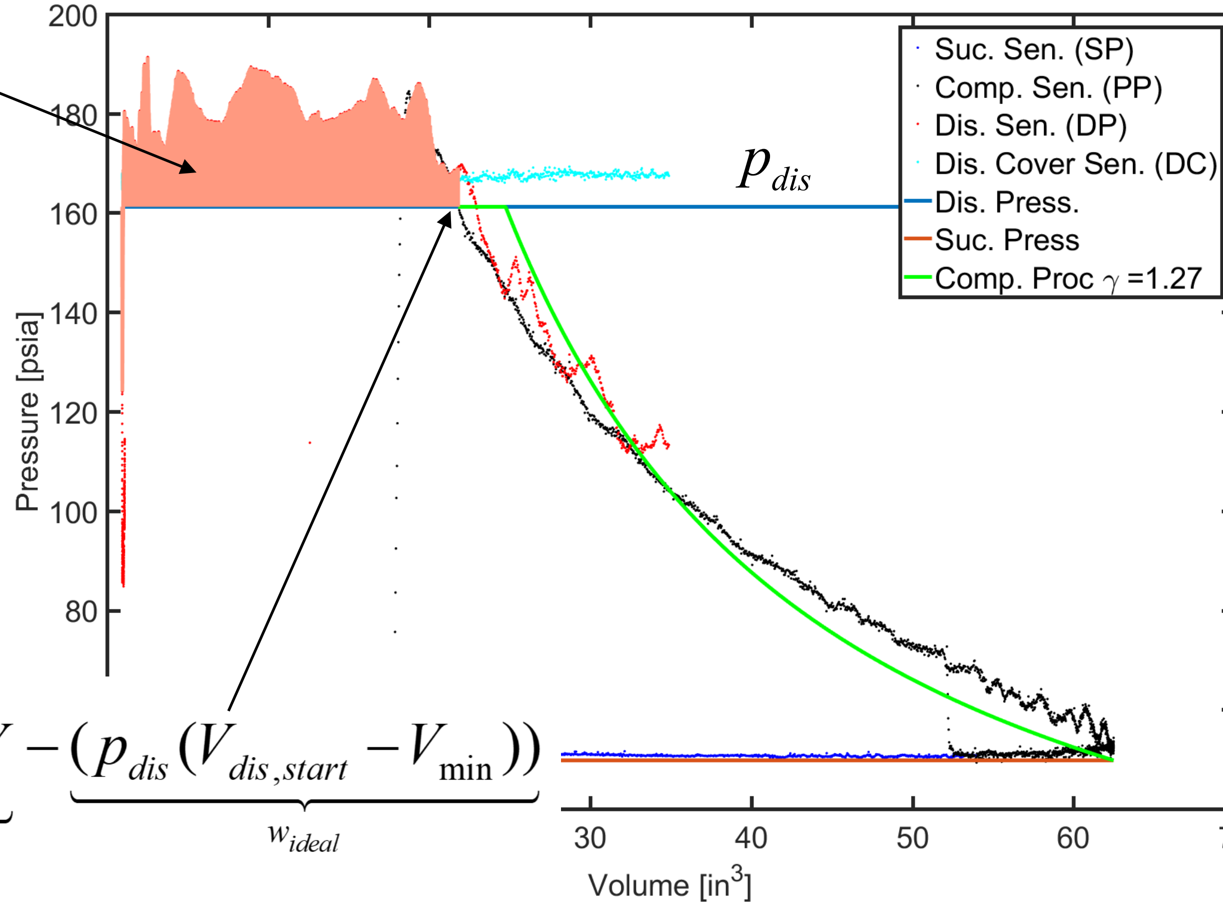



[1]Bradshaw et al. (2016). Development of a Loss Pareto for a Rotating Spool Compressor…*App.Thm. Engr.* 99, 392-401.

# Calculate Discharge Loss[3]

Red shaded area represents total discharge losses

This is the boundary work required to do this process subtracting the boundary work of an ideal process




$$L_{\text{discharge}} = \underbrace{-\int_{V_{\min}}^{V_{dis,start}} p_{DP}\, dV}_{w_{BW,dis}} - \underbrace{\left(p_{dis}\left(V_{dis,start} - V_{\min}\right)\right)}_{w_{ideal}}$$

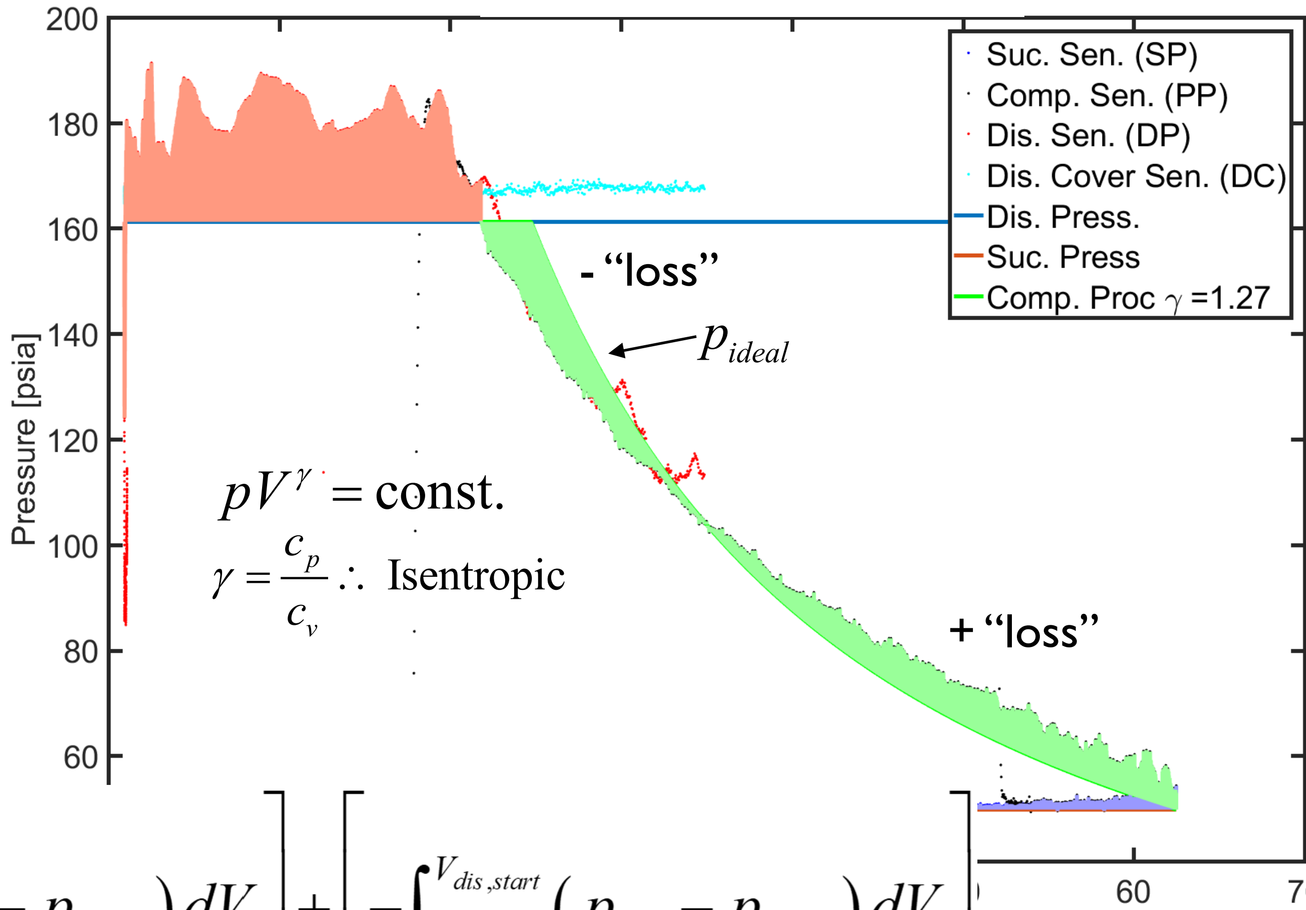
Calculated via numerical integration

[3] Bradshaw et al. (2018). An indicated loss analysis of a light-commercial spool…*In: Purdue Conference Proc.*. No. 1247.

# Compression Loss Calculation[3]

Green shaded area represents compression processes losses

This is the boundary work required for this process relative to an **isentropic compression** process

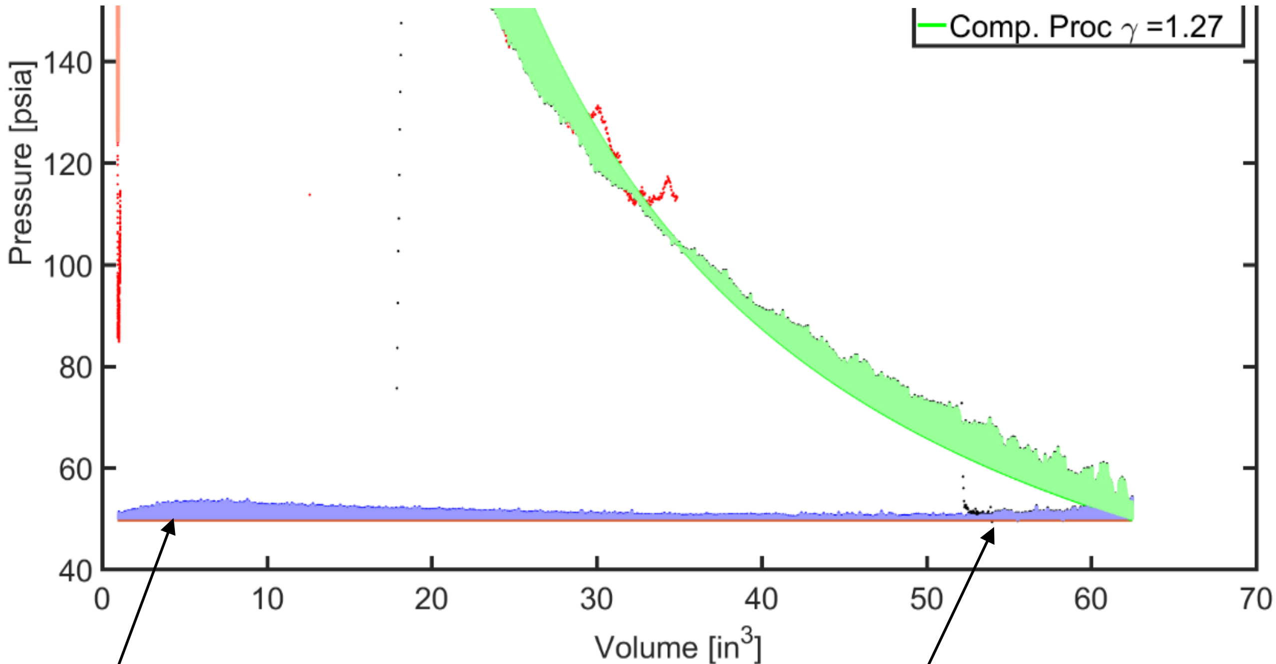



$$L_{comp} = \left[ \underbrace{-\int_{V_{\max}}^{V_{trans.}} \left( p_{PP} - p_{ideal} \right) dV}_{\text{Under PP Curve}} \right] + \left[ \underbrace{-\int_{V_{trans}}^{V_{dis,start}} \left( p_{DP} - p_{ideal} \right) dV}_{\text{Under DP Curve}} \right]$$

# Calculate Suction Loss[3]

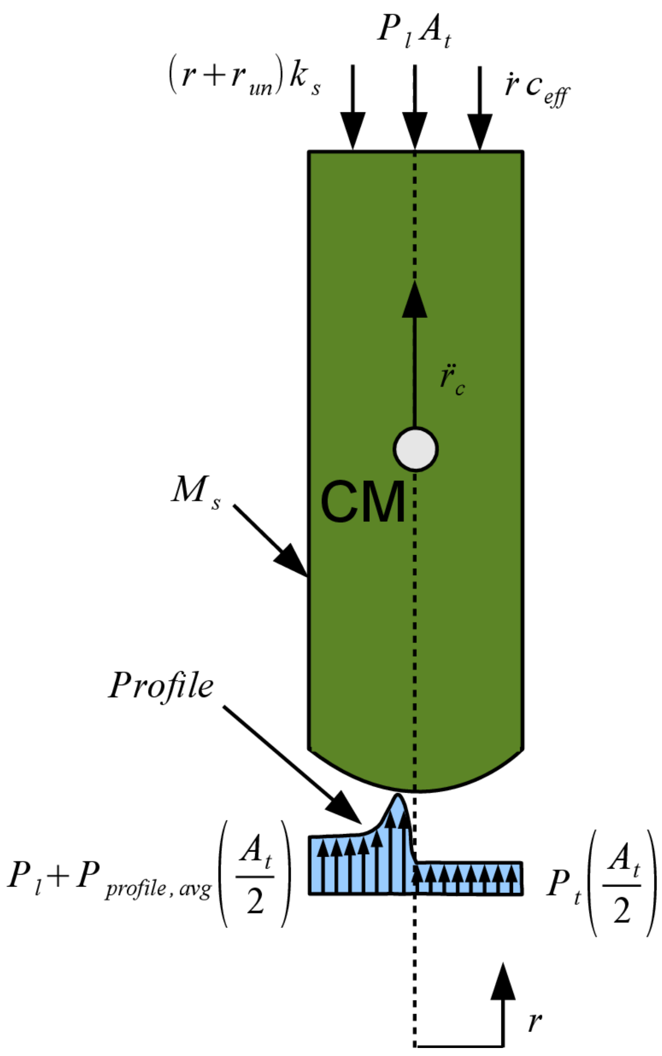
Blue shaded area represents suction process losses

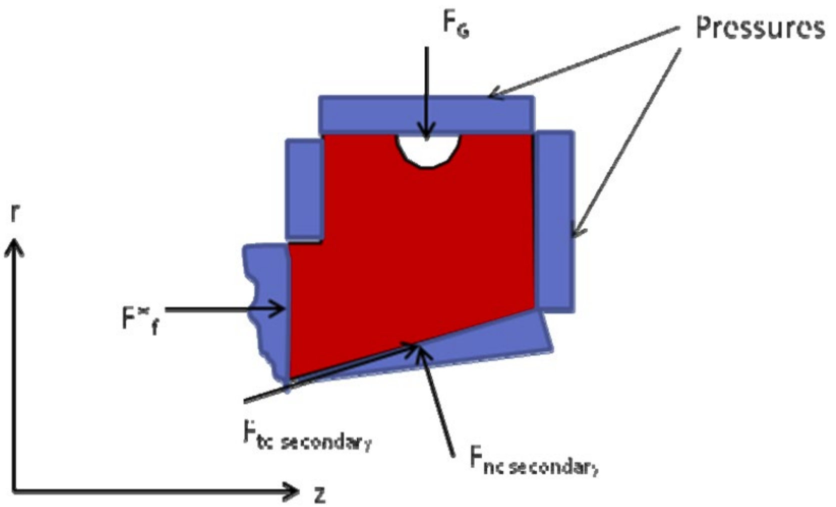
This is the boundary work required compared against an ideal suction processes



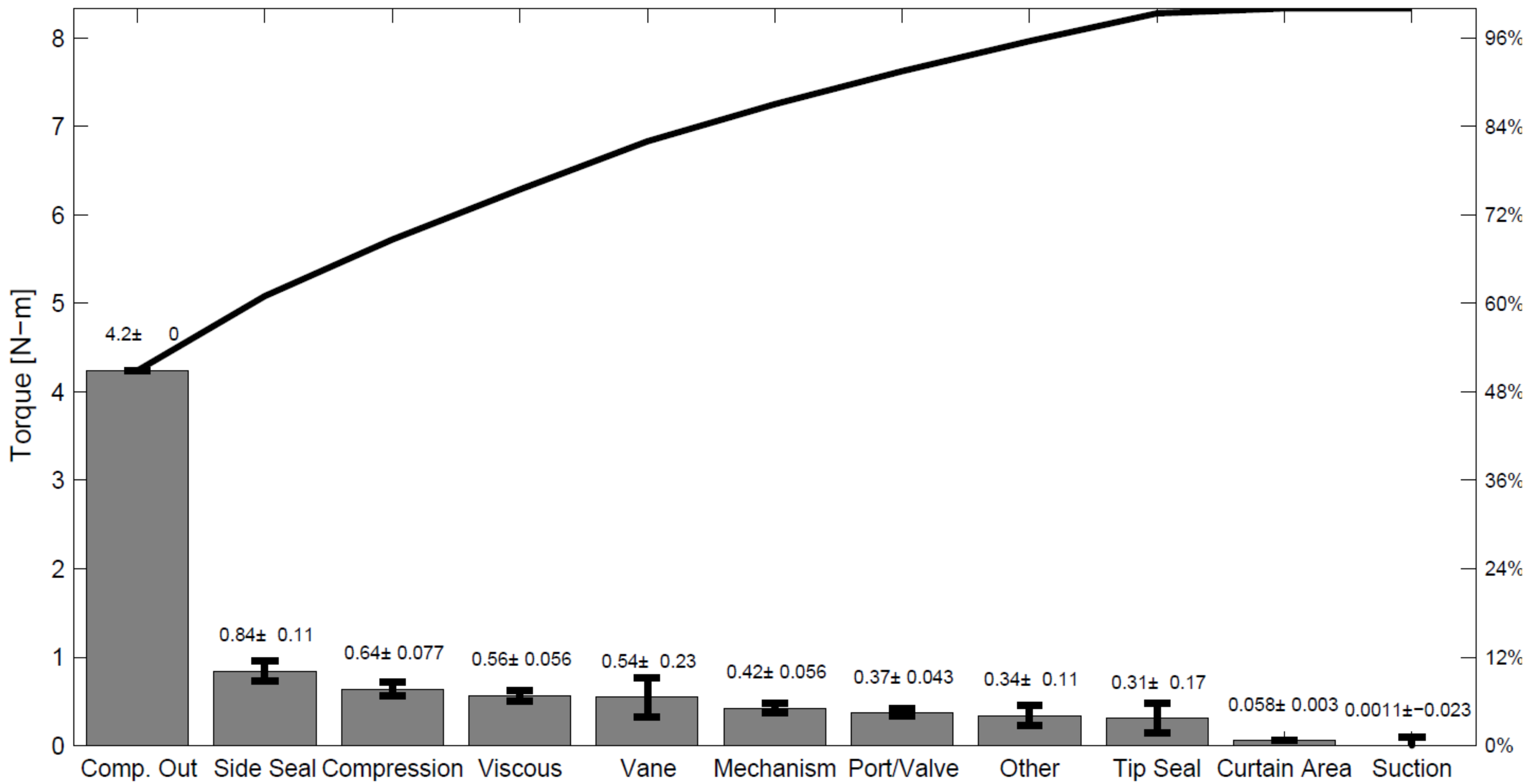

$$L_{suction} = \underbrace{\left[ \underbrace{-\int_{V_{min}}^{V_{trans}} p_{SP}\, dV}_{w_{BW,suc,1}} + \underbrace{\left(p_{suc}\left(V_{trans} - V_{min}\right)\right)}_{w_{ideal,1}} \right]}_{\text{Under SP pressure curve}} + \underbrace{\left[ \underbrace{-\int_{V_{trans}}^{V_{max}} p_{PP}\, dV}_{w_{BW,suc,2}} + \underbrace{\left(p_{suc}\left(V_{max} - V_{trans}\right)\right)}_{w_{ideal,2}} \right]}_{\text{Under PP pressure curve}}$$

# External Losses - Tip and Side Seal Friction



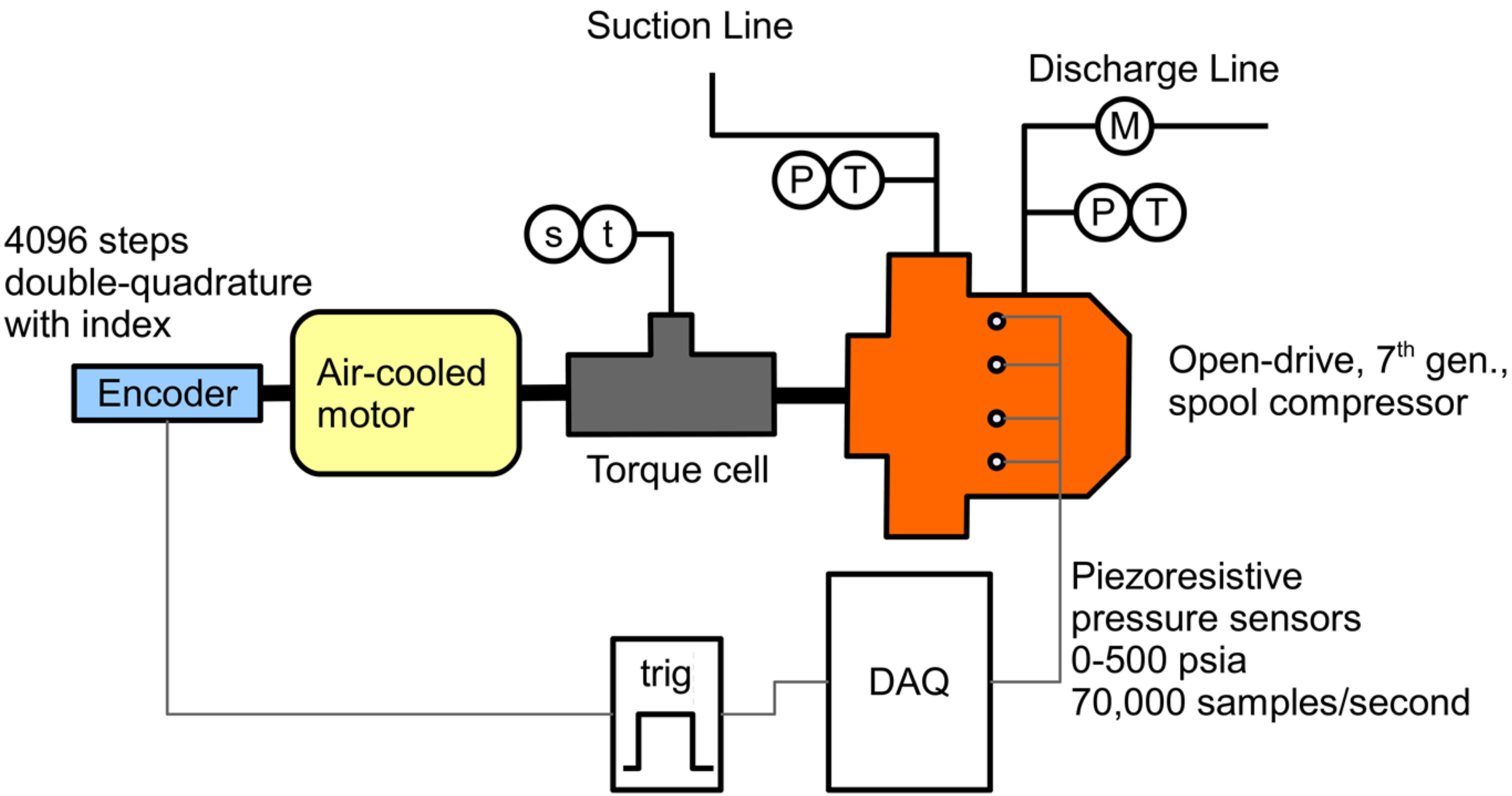



# Loss Pareto – 5th Gen. Spool Prototype[1]




[1]Bradshaw et al. (2016). Development of a Loss Pareto for a Rotating Spool Compressor…*App.Thm. Engr.* 99, 392-401.

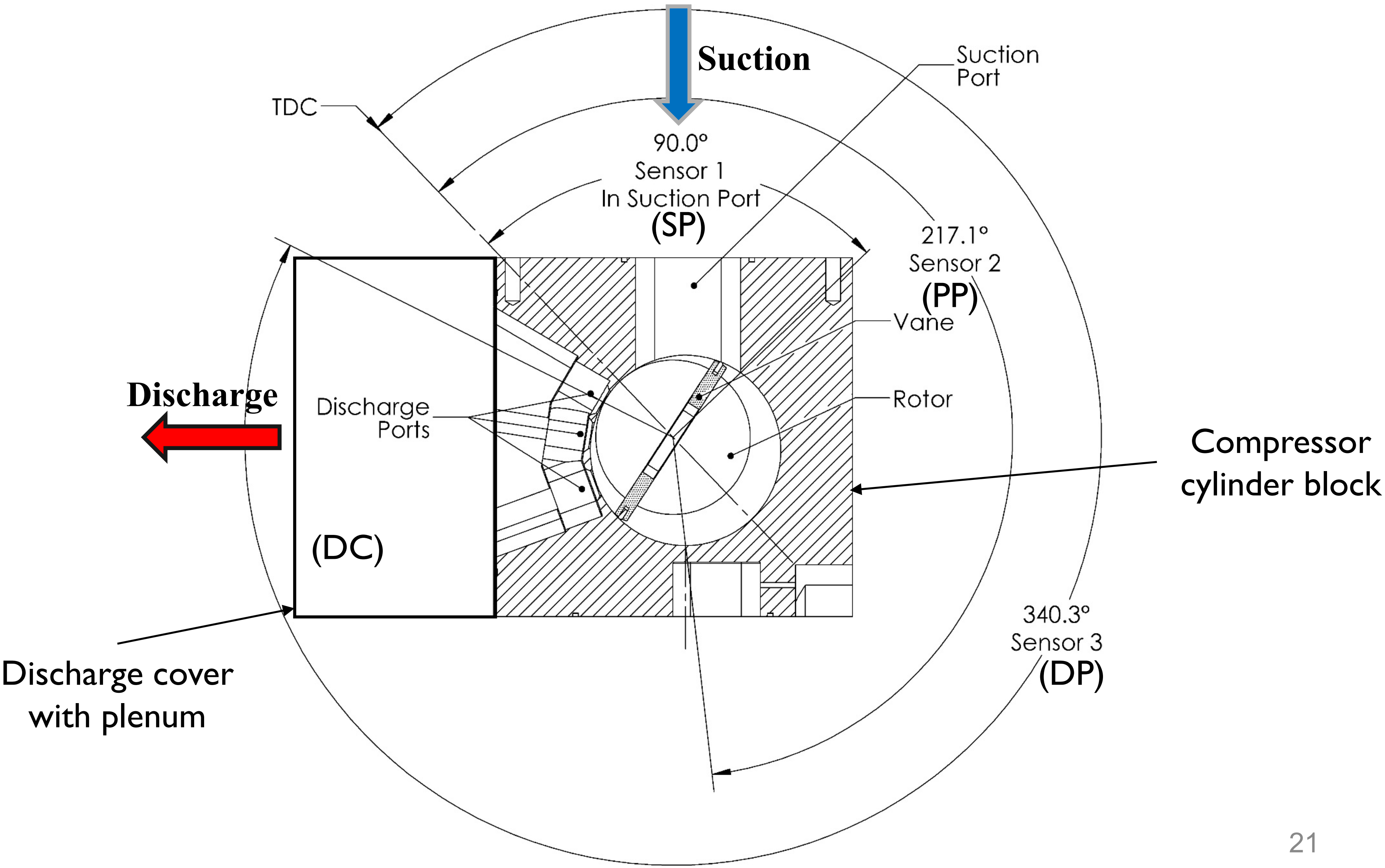
# Alternative Methodology – 7th Gen. Spool Compressor[3]




10 series of data collected, sequentially, at steady state operation

[3]Bradshaw et al. (2018). An indicated loss analysis of a light-commercial spool… *In: Purdue Conference Proc.*. No. 1247.

# Methodology - Sensor Placement

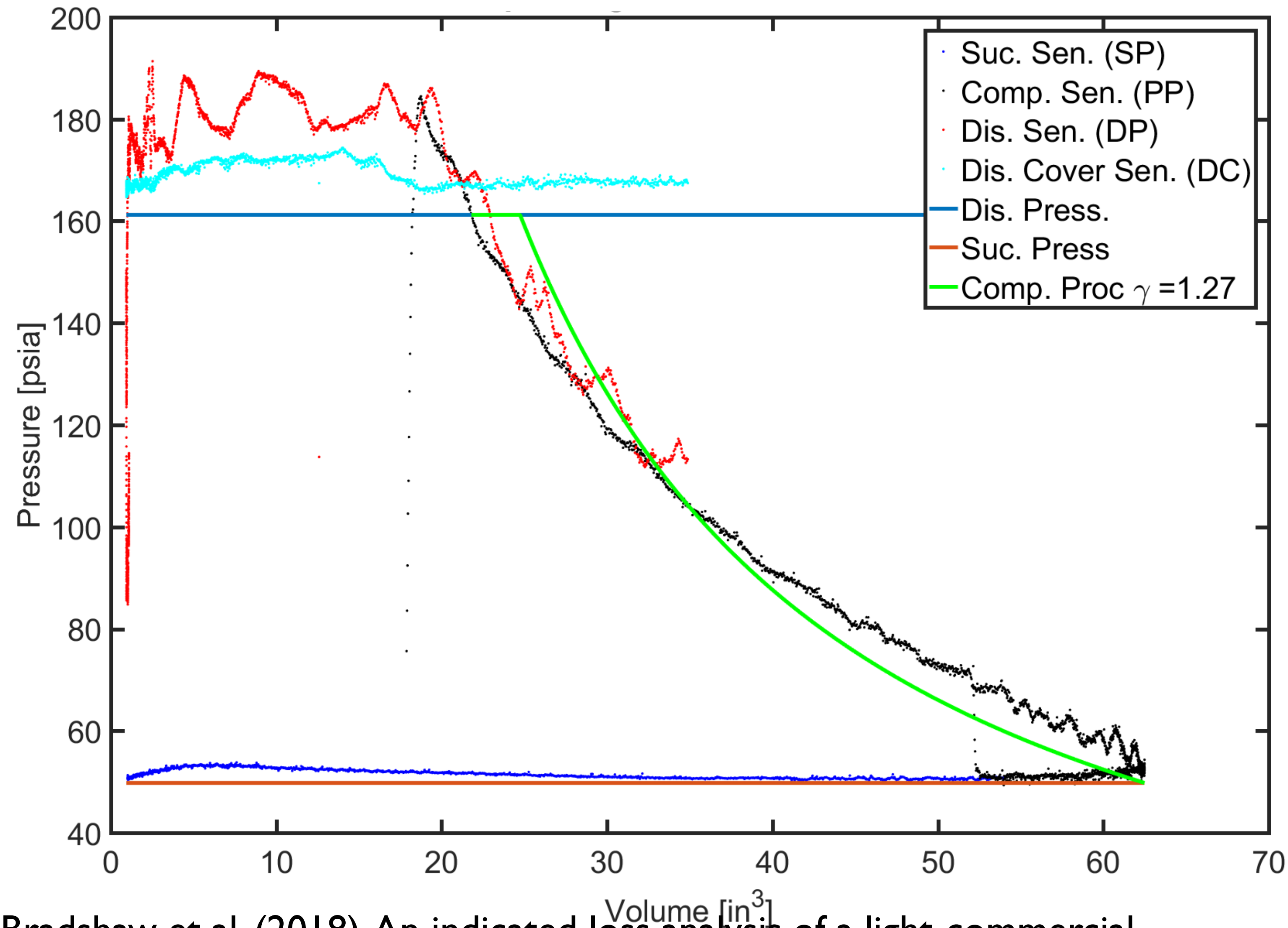


# Methodology - Final Test Matrix

39 Data points, 3 shaft speeds and sat. discharge temperatures (SDT), fixed superheat of 30°R, and various sat. suction temperatures (SST)

| Speed | SST | Test # | SDT | Test # | SDT | Test # | SDT |
|---|---|---|---|---|---|---|---|
| rpm | °F | - | °F | - | °F | - | °F |
| 900 | 25 | 1 | 100 | 9 | 110 | 17 | 120 |
| | 30 | 2 | 100 | 10 | 110 | 18 | 120 |
| | 35 | 3 | 100 | 11 | 110 | 19 | 120 |
| | 40 | 4 | 100 | 12 | 110 | 20 | 120 |
| | 45 | 5 | 100 | 13 | 110 | 21 | 120 |
| | 50 | 6 | 100 | 14 | 110 | 22 | 120 |
| | 55 | 7 | 100 | 15 | 110 | 23 | 120 |
| | 60 | 8 | 100 | 16 | 110 | 24 | 120 |
| 1300 | 25 | | | 25 | 110 | | |
| 1620 | 25 | 26 | 100 | 28 | 110 | 33 | 120 |
| | 30 | 27 | 100 | 29 | 110 | 34 | 120 |
| | 35 | | 100 | 30 | 110 | 35 | 120 |
| | 40 | | 100 | 31 | 110 | 36 | 120 |
| | 45 | | 100 | 32 | 110 | 37 | 120 |
| | 50 | | | | | 38 | 120 |
| | 55 | | | | | 39 | 120 |

# Final Reduced Data – Test #12[3]

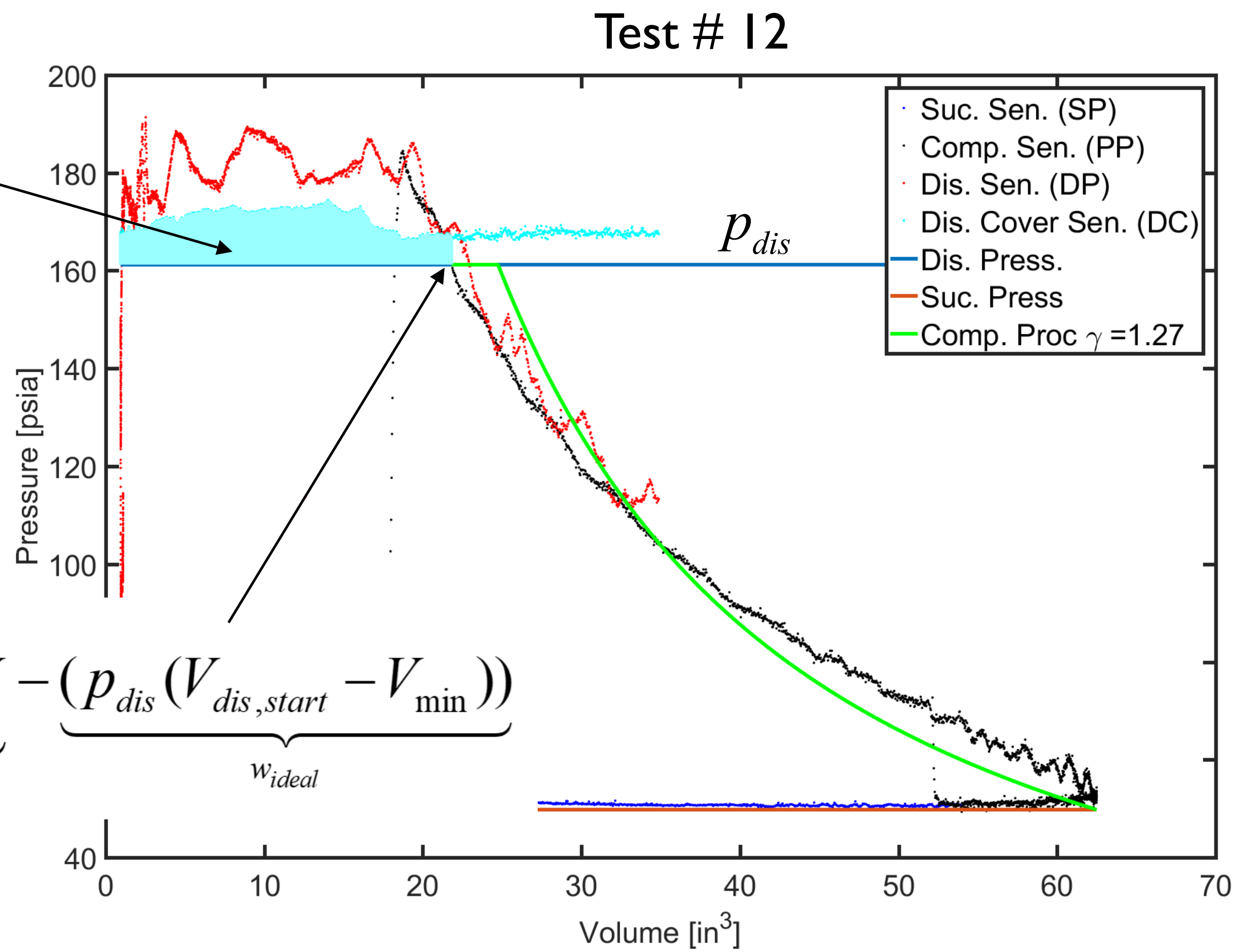



[3]Bradshaw et al. (2018). An indicated loss analysis of a light-commercial spool…*In: Purdue Conference Proc.*. No. 1247.

# Cover and Valve Losses

Cyan shaded area represents plenum (cover) losses

This is the boundary work required to move fluid from discharge plenum to system



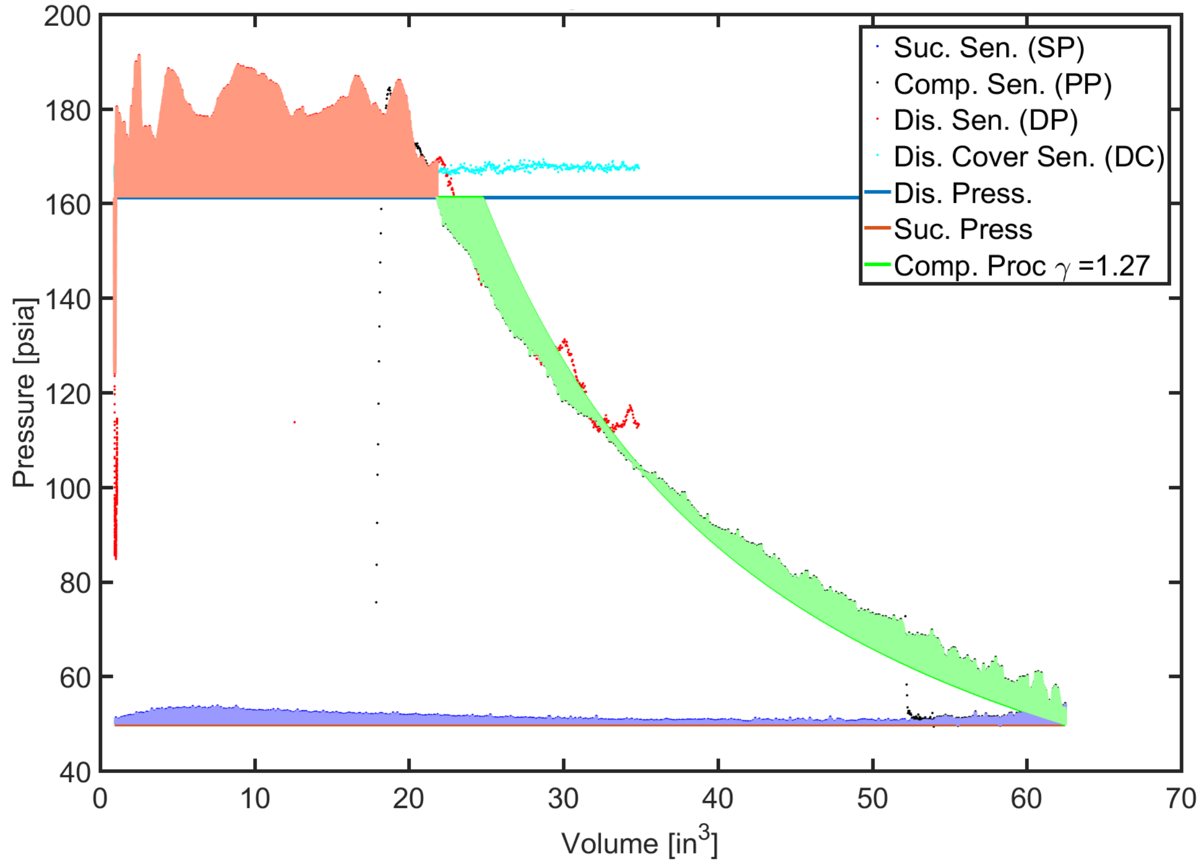

$$L_{\text{dis,cover}} = \underbrace{-\int_{V_{\min}}^{V_{dis,start}} p_{DC}\,dV}_{w_{BW,\text{dis,cover}}} - \underbrace{\left(p_{dis}\left(V_{dis,start} - V_{\min}\right)\right)}_{w_{ideal}}$$

$$L_{\text{valves}} = L_{\text{discharge}} - L_{\text{dis,cover}}$$

# Summary of Losses – Test #12

| Discharge Losses | Cover Losses | Valve Losses | Suction Losses | Compression Losses |
|---|---|---|---|---|
| % | % | % | % | % |
| 11.70 | 5.50 | 6.20 | -3.30 | 1.48 |

Losses compared to measured steady state shaft torque at each operating condition

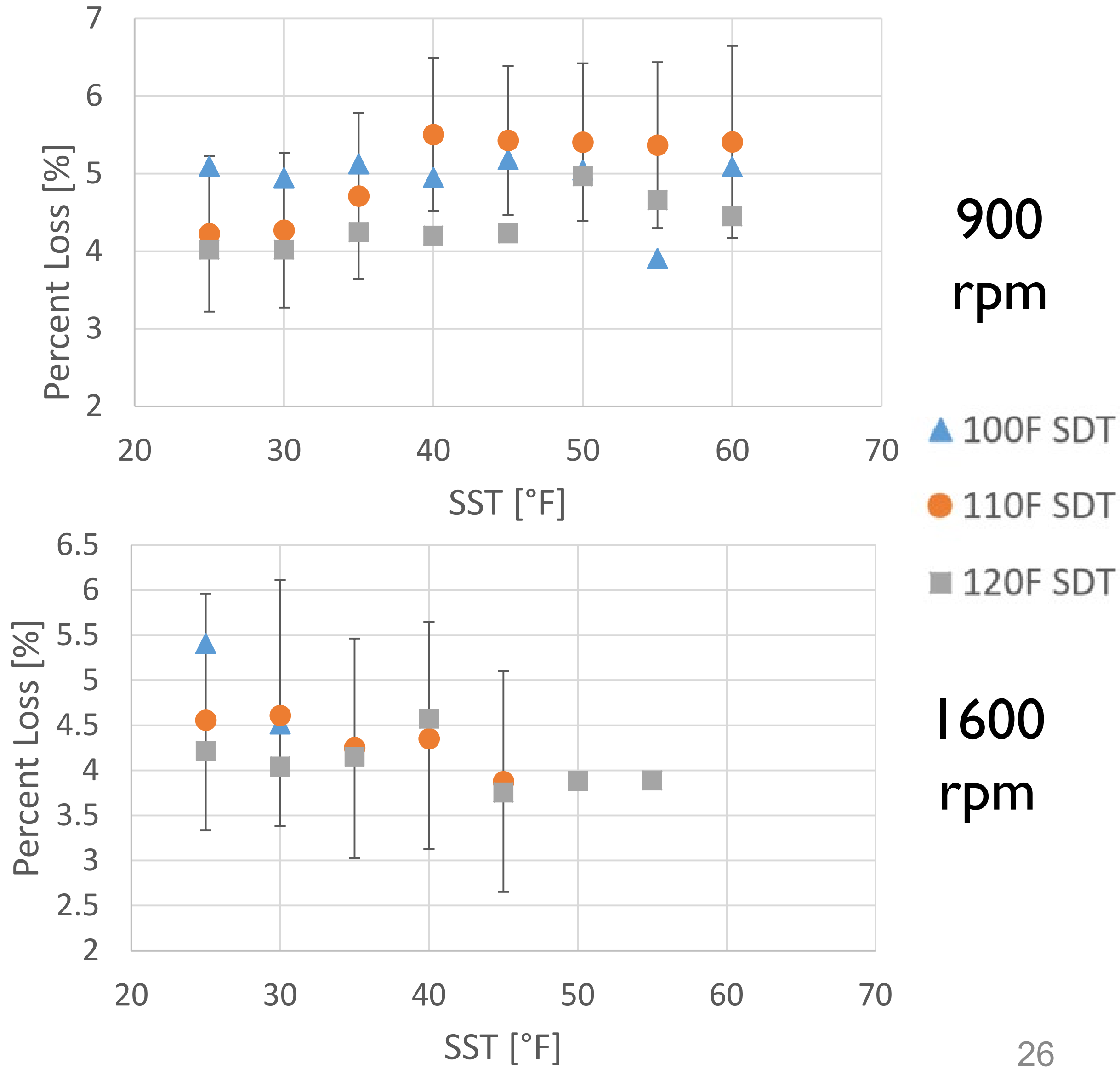


# Cover Losses

Presented as a function of sat. suction temp (SST) and sat. discharge temp (SDT)

Magnitude consistent between speeds

Independent of sat. suction and discharge temperatures



# Summary and Conclusion

- Experimental methodologies and select results were presented for two spool compressor prototypes
- Indicated loss analysis were shown to be effective at identifying more precise loss mechanisms within a compressor

**Craig Bradshaw, Ph.D.**
craig.bradshaw@okstate.edu