2019 UTSR Project Review Meeting

Novel Modular Heat Engines with sCO_2 Bottoming Cycle Utilizing Advanced Oil-Free Turbomachinery DOE FE0031617: Phase 1

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EXTENDED PROJECT TEAM

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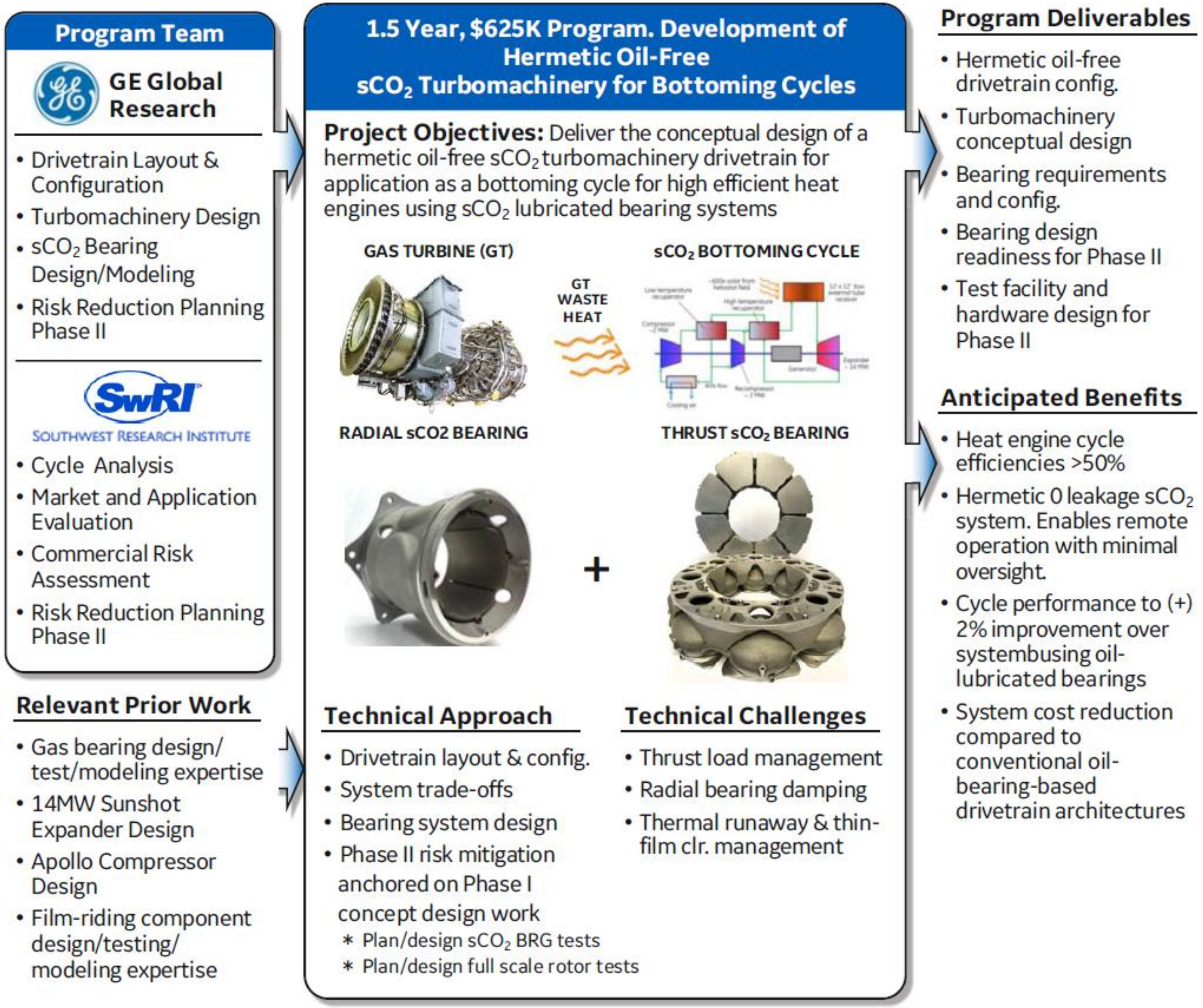
Motivation and Objectives

- Currently compressor station underutilize WHR
- sCO_2 WHR bottoming cycle
  - 40% simple cycle → (+) 50% combined cycle
  - Savings in fuel costs/CO_2 emissions
  - Improve compressor station profits
- Perform Conceptual Design of Turbomachinery
  - Define bearing requirements
  - Perform Bearing Conceptual Design
  - Identify risks with immersed generator
  - Perform economic analysis of sCO_2 WHR unit

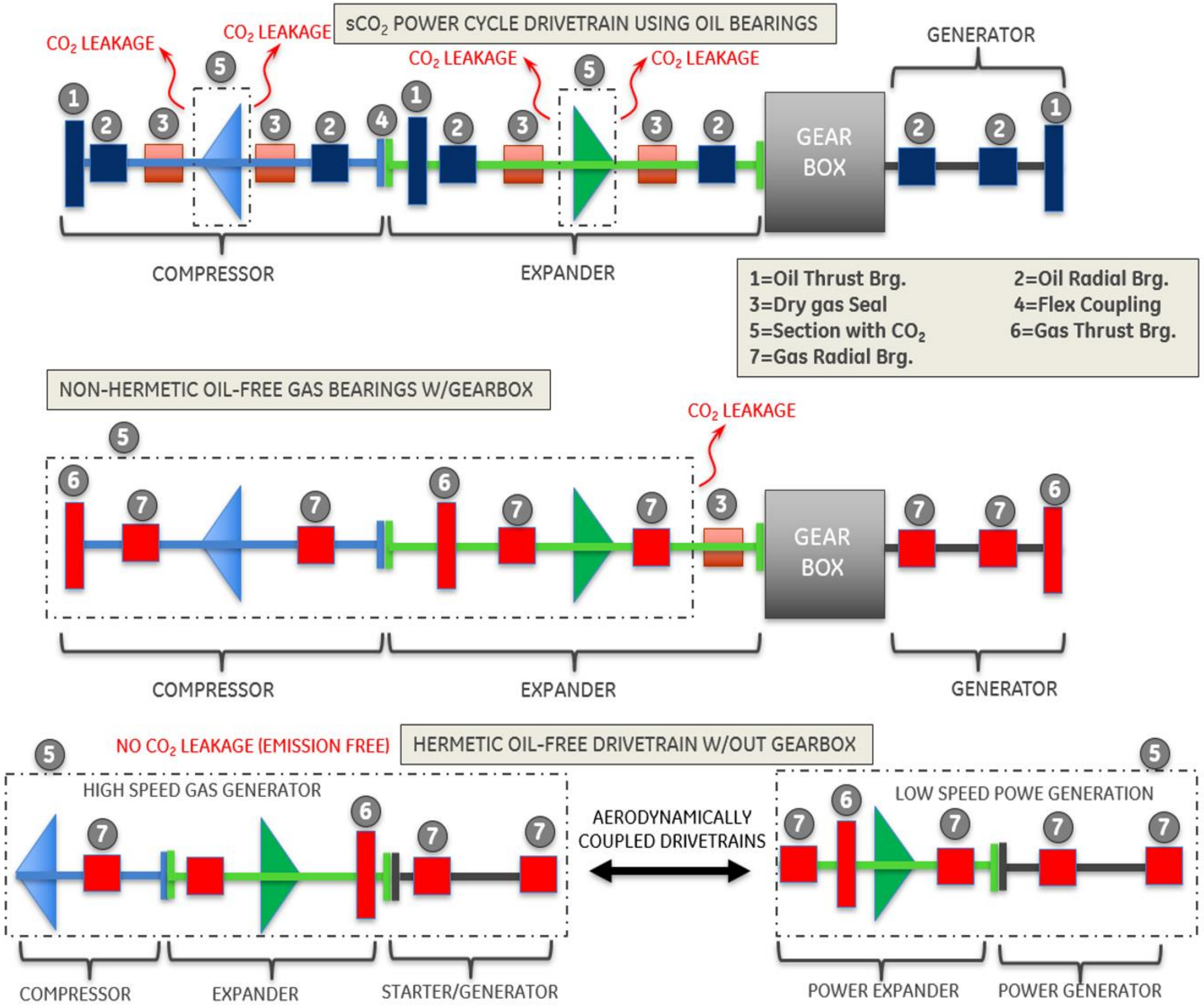


WHR Turbomachinery Drivetrain Concepts

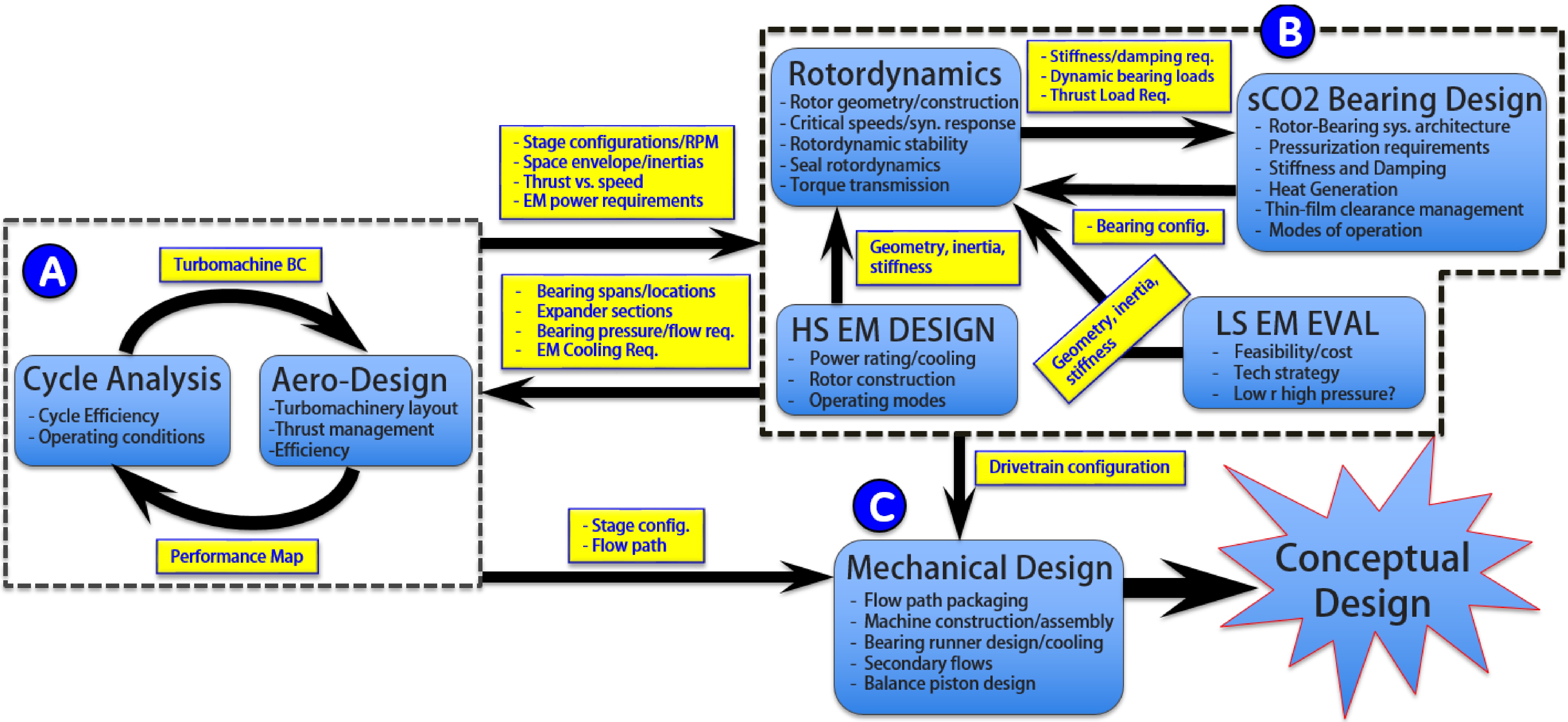
- Current high-power drivetrain configs.
  - Oil-bearings for shaft support
  - Gearbox for high-speed to low-speed power transmission
  - CO_2 leakage

- Oil-Free non-Hermetic Concept
  - All bearings → gas bearings → lower power loss→ design simplification
  - Still requires oil system for gearbox
  - CO_2 leakage

- Oil-Free Hermetic Concept
  - All bearings → process gas bearings
  - Mechanically decoupled system → No GB
  - No CO_2 leakage → completely hermetic
  - Requires a high speed line and low speed line
  - Low speed line has 2 modes
    - 60Hz power generation → grid
    - >60Hz NG compressor drive



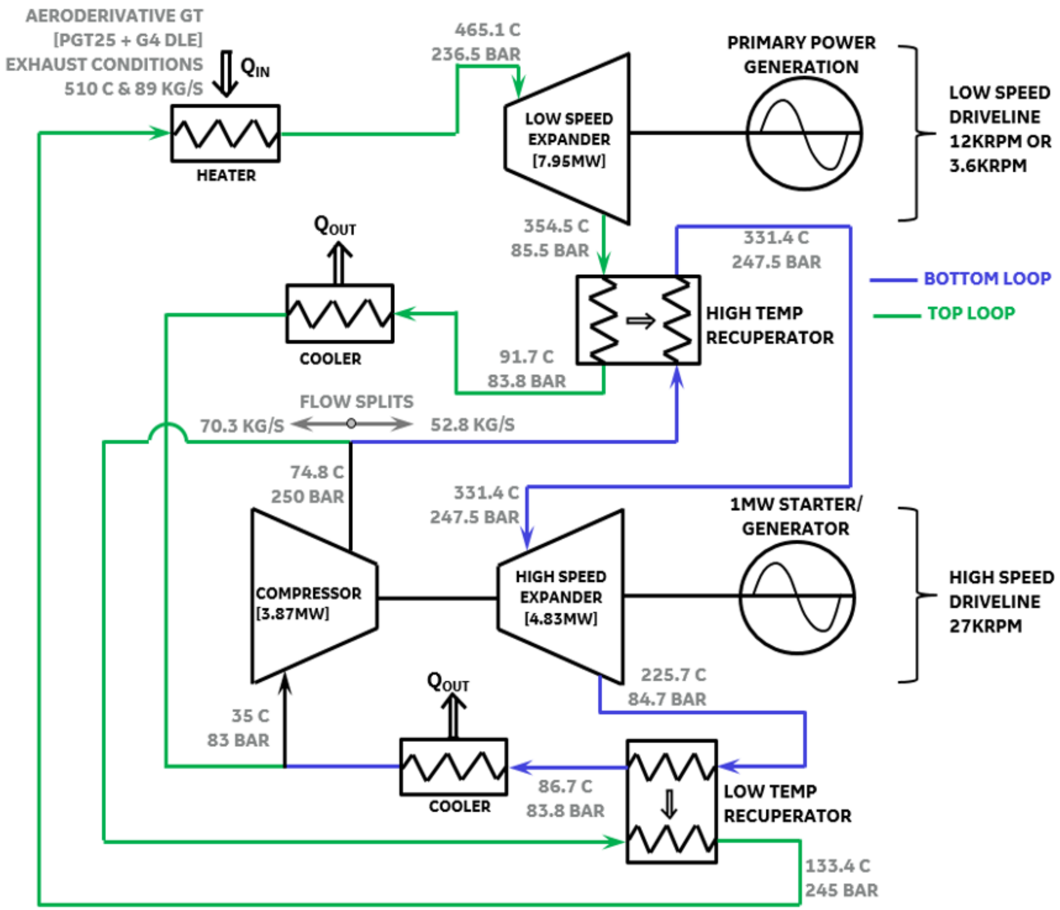
Conceptual Design Process



Thermodynamic Cycle

- Cascaded Brayton Cycle
  - PGT25+G4 GT used for study (LM2500 engine platform)
  - ~34MW @ ~40% simple cycle efficiency
  - Max GT exhaust temperature → 510 C @ 89 kg/s
  - Efficiency debit from WHR system accounted for

- Cycle has two distinct loops
  - High temp loop → low speed line
  - Low temp loop → high speed line
  - High/Low temp recuperators

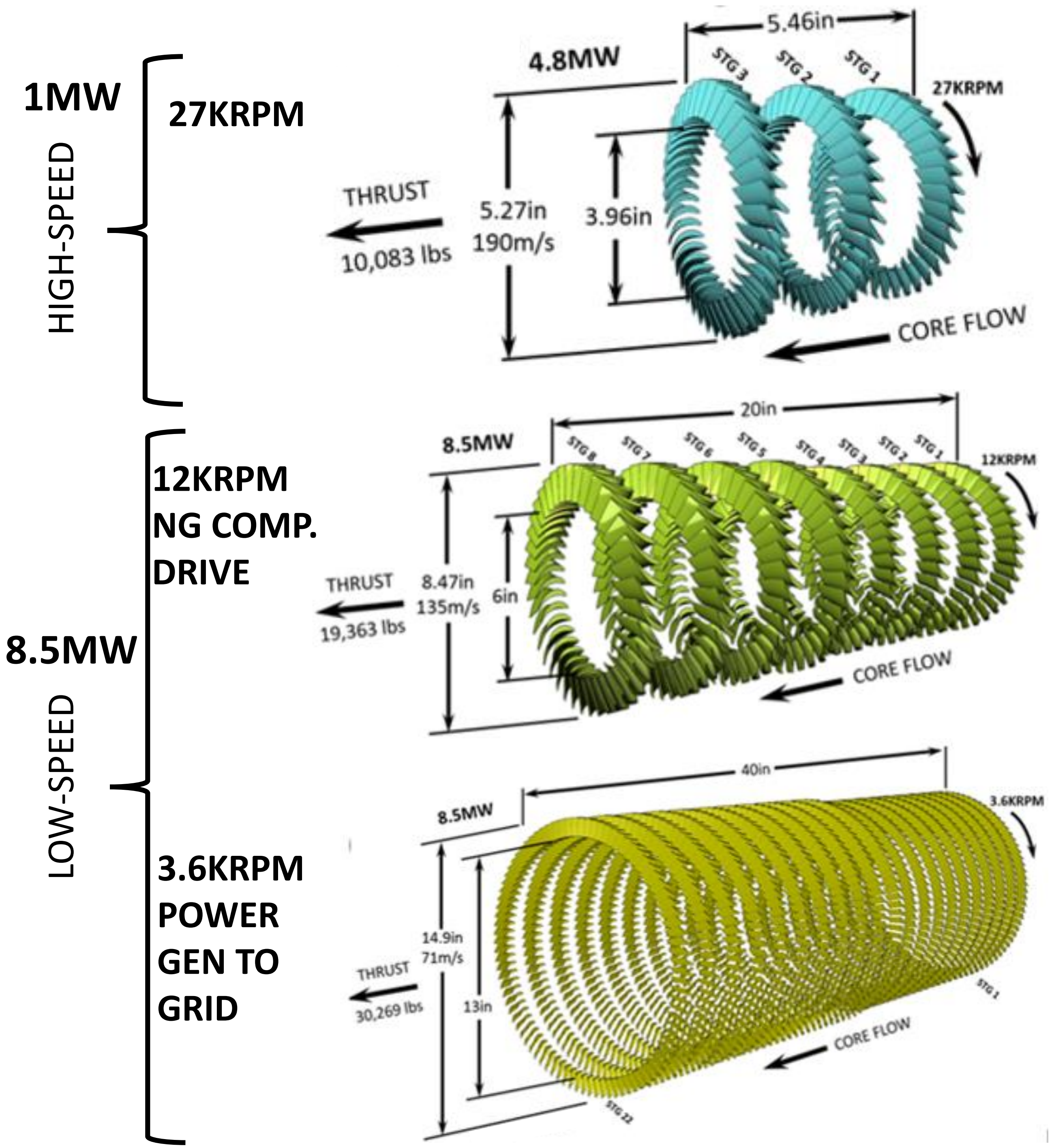


	PGT25+ G4	PGT25+ G4 with sCO_2 WHR
Output (kW)	34,000	33,252
Efficiency (%)	41	40.6
Heat Rate (kJ/kWh)	8700	8867
Fuel Consumption (kg/s)	1.730	1.724

Turbomachinery Aero-Design

- Trade-Off Analysis
  - Flow path root diameter
  - Number of stages
  - Stage height
  - Speed
  - While checking rotordynamics

- Low speed Expander speeds
  - NG centrif. compressor survey
  - 60Hz power generation



Electromagnetic Design

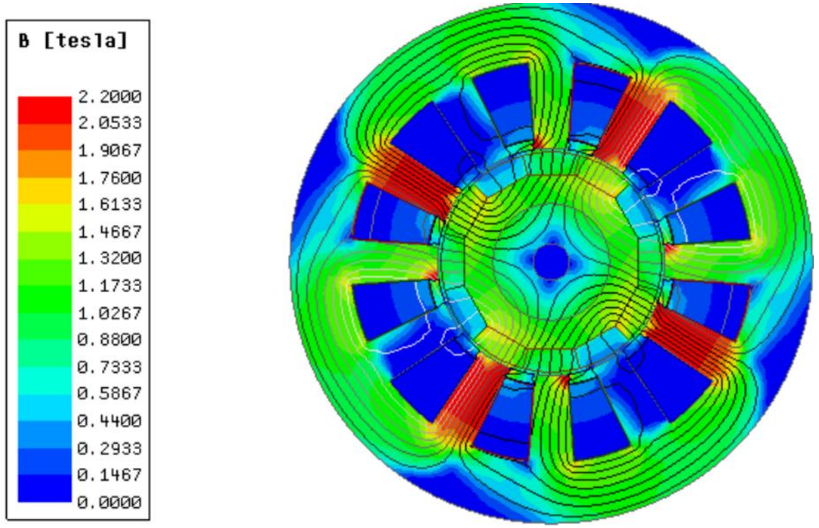
- PM Synchronous machine
  - High torque density and efficiency
  - 3 Phase electric power generation
  - Samarium-Cobalt PM; 160M/s surface speed
  - Torque correlation used to initially get L

$$T = \sigma L \pi D^2 / 2$$

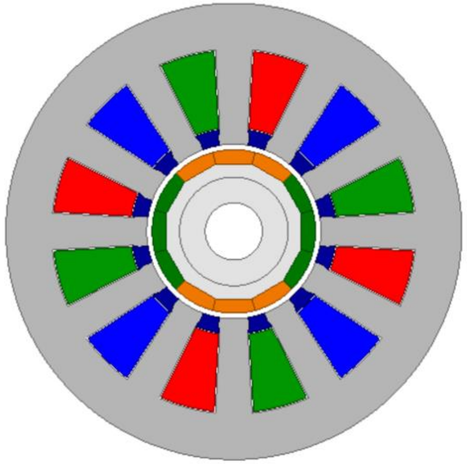
Magnetic Gap Shear stress (13kPa-300Kpa)

  - FEA used for electromagnetics/thermals

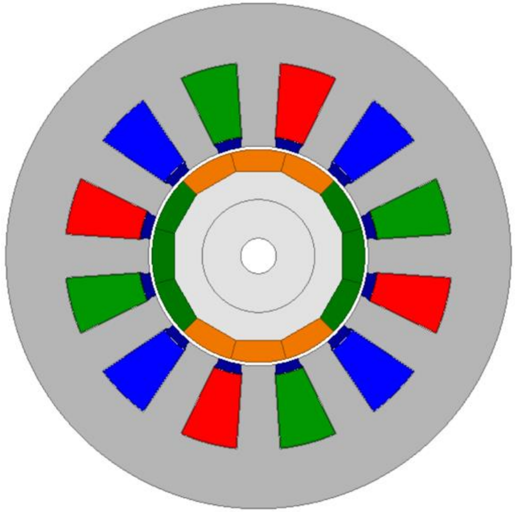
- Analysis Output
  - Losses
    - Stator and rotor core
    - Copper losses
    - Windage



27KRPM

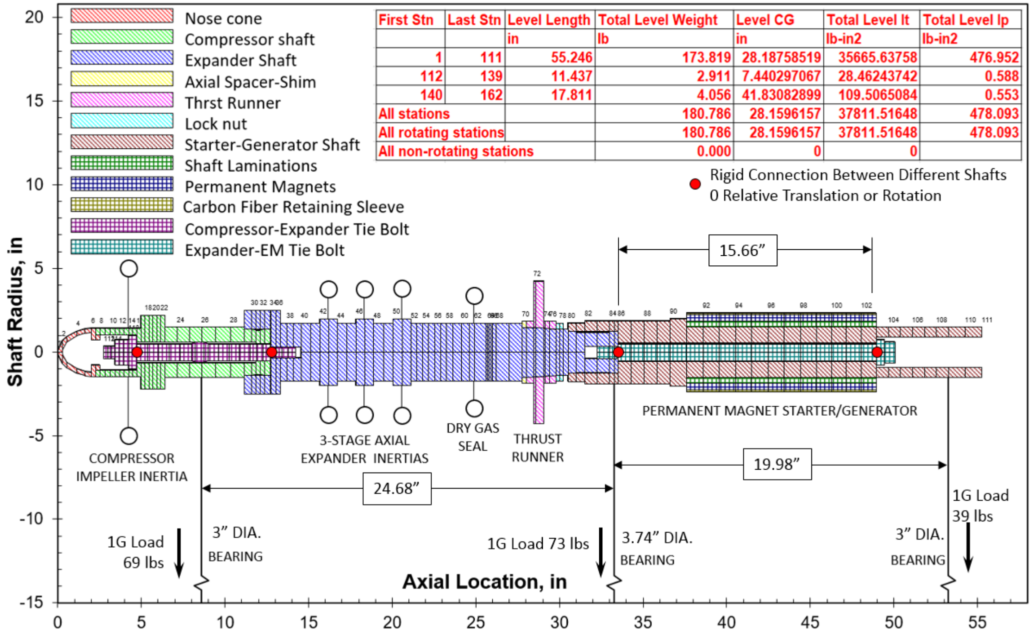


12KRPM



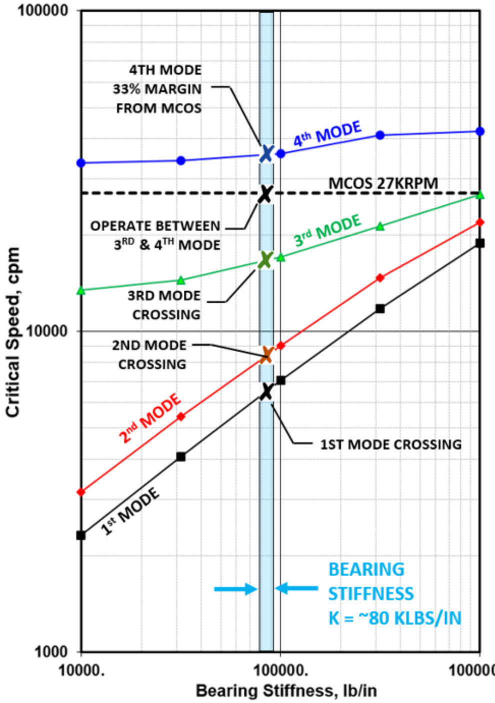
High-Speed Drivetrain Rotordynamics

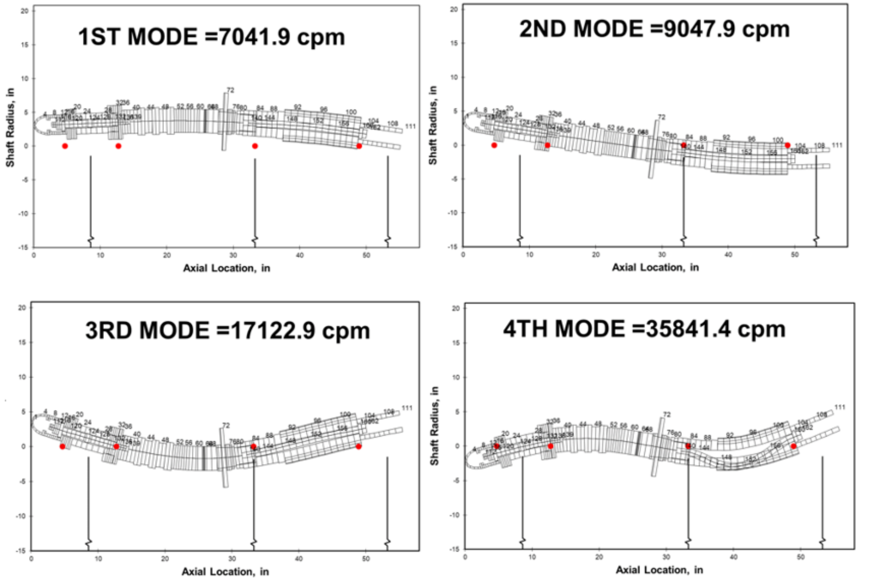
- Lateral Rotordynamic Model
  - 3 bearing machine architecture
  - Stacked-tie-bolt rotor construction
  - Single stage overhung centrif. compressor
  - 3 stage axial expander (integral to shaft for stiffness)
  - Direct drive/rigidly coupled PM starter/generator



First Stn	Last Stn	Level Length	Total Level Weight	Level CG	Total Level It	Total Level Ip
		in	lb	in	lb-in2	lb-in2
1	111	55.246	173.819	28.18758519	35665.63758	476.952
112	139	11.437	2.911	7.440297067	28.46243742	0.588
140	162	17.811	4.056	41.83082899	109.5065084	0.553
All stations			180.786	28.1596157	37811.51648	478.093
All rotating stations			180.786	28.1596157	37811.51648	478.093
All non-rotating stations			0.000	0	0	

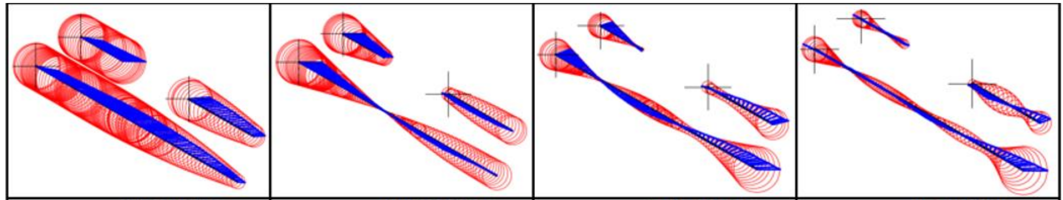
- Undamped Critical Speed Map
  - Used to position critical speeds
  - Anchoring of bearing stiffness values
  - Ensuring tie bolt frequency > MCOS
  - Cross-check 1G shaft deflections
  - Operation above 3rd critical speed below 4th critical speed



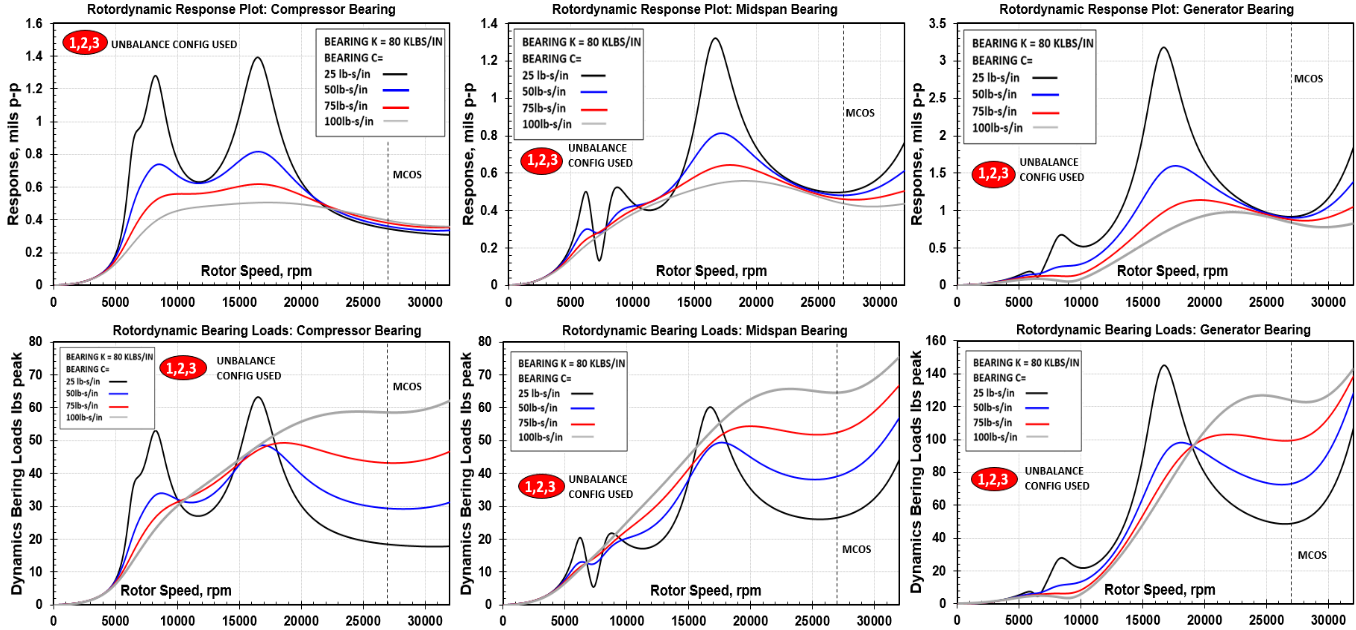


Damped Rotordynamic Eigenvalues & Unbalance Response

- Calculation of damped forward whirl mode eigenvalues
- Log dec and Frequency calcs for varying bearing damping values
- Complement w/synchronous response to rotor unbalance
- Diminishing return for vibration response with damping increase
- Balance log dec values with dynamic bearing loads

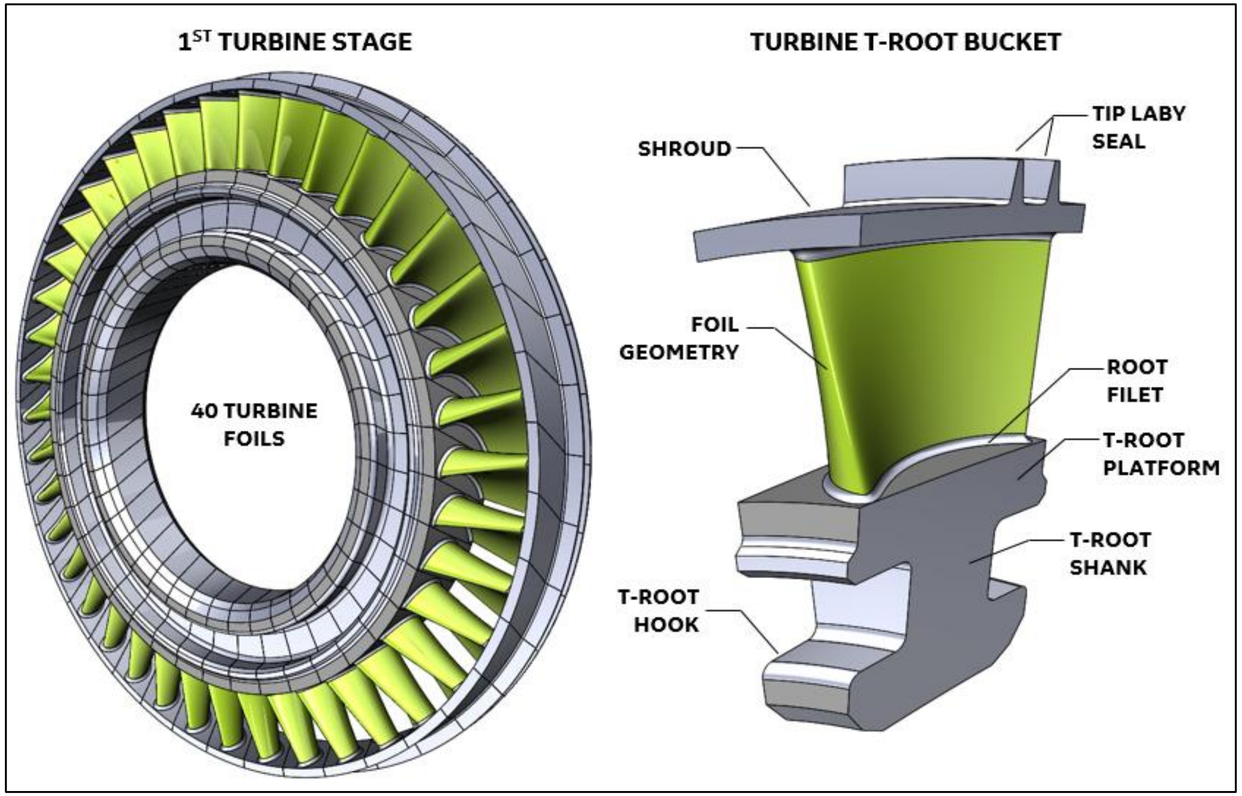


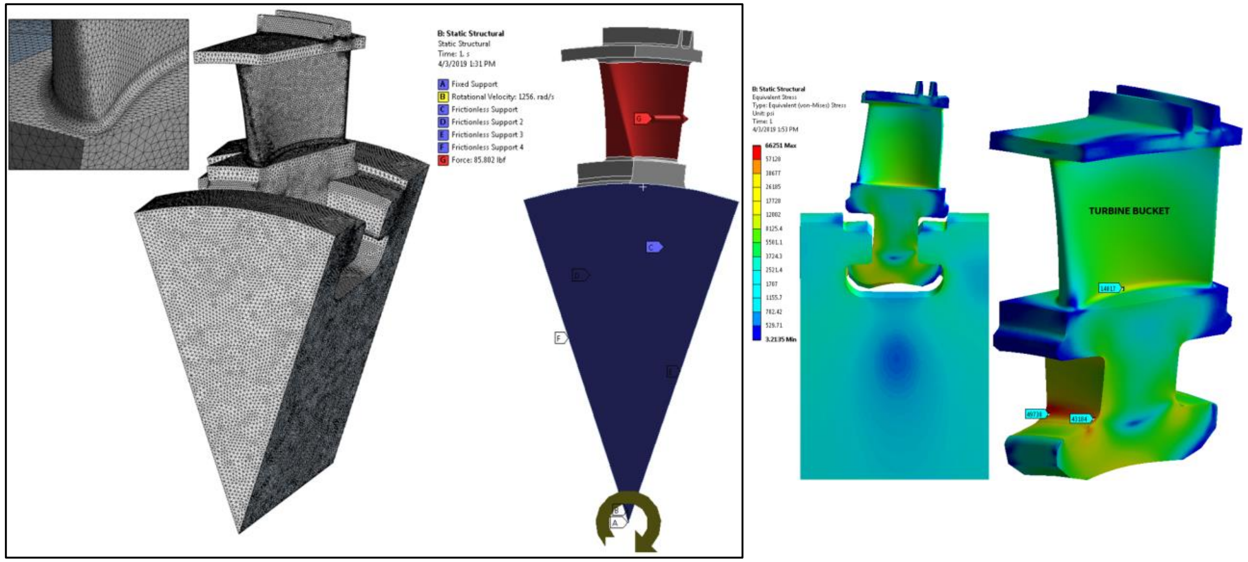
BEARING K = 80 KLBS/IN ROTOR SPEED = 27KRPM	1ST MODE		2ND MODE		3RD MODE		4TH MODE	
DAMPING VALUE (LB-S/IN)	LOG DEC	FREQ (KRPM)	LOG DEC	FREQ (KRPM)	LOG DEC	FREQ (KRPM)	LOG DEC	FREQ (KRPM)
25	0.6167	6.333	0.7342	8.31	0.5798	16.726	0.4096	34.671
50	1.255	6.262	1.4992	8.22	1.2111	16.859	0.8574	33.871
75	1.9405	6.139	2.3293	8.08	1.9908	17.16	1.383	32.067
100	2.7102	5.955	3.2575	7.923	3.3386	17.797	1.9106	28.151
150	4.8175	5.318	4.8123	8.1412	N/A	N/A	1.1133	25.231



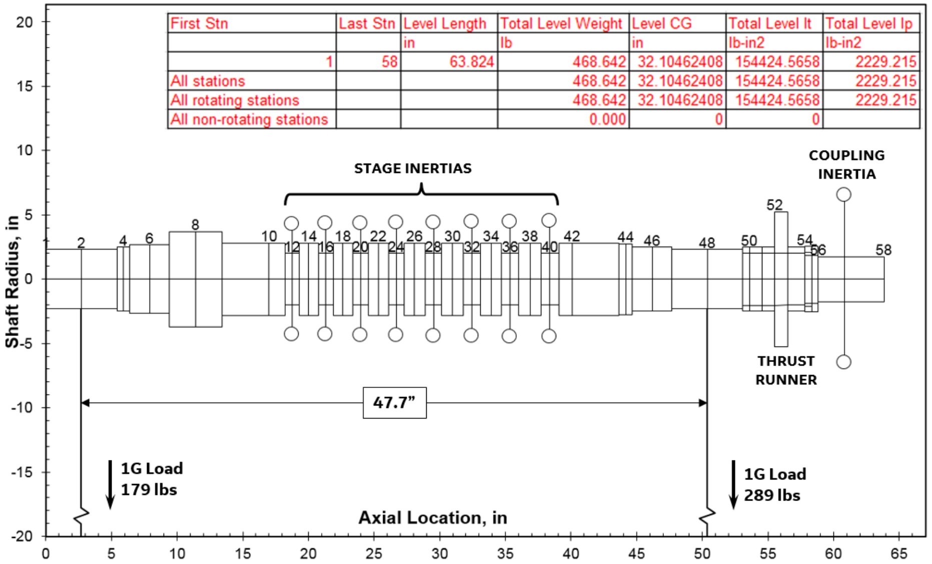
Low Speed Expander Turbine Foil Design

- Low temps from WHR application advantageous
- Low cost material selection
- Can consider dove-tailed foil designs
- T-Root bucket design
- 1st Stage worst case FEA model
- Stiffness diameter of shaft defined through this analysis→ feeds into rotordynamics

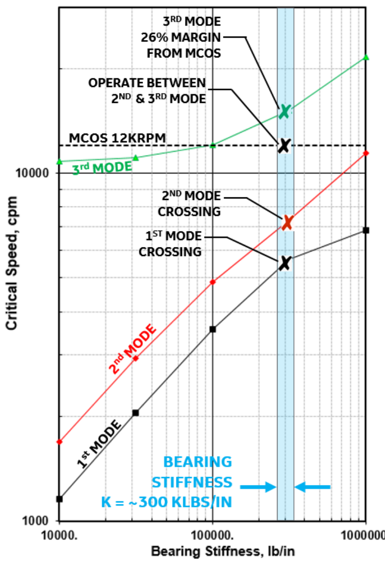


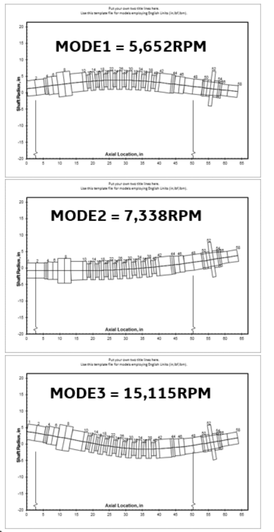


Low Speed Drivetrain
12krpm Expander

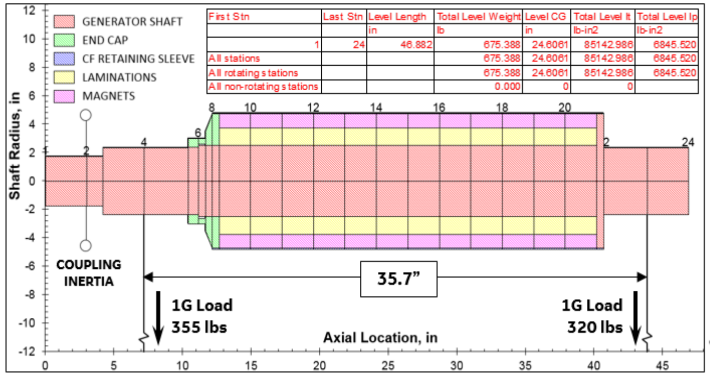


First Stn	Last Stn	Level Length	Total Level Weight	Level CG	Total Level It	Total Level Ip
		in	lb	in	lb-in2	lb-in2
1	58	63.824	468.642	32.10462408	154424.5658	2229.215
All stations			468.642	32.10462408	154424.5658	2229.215
All rotating stations			468.642	32.10462408	154424.5658	2229.215
All non-rotating stations			0.000	0	0	

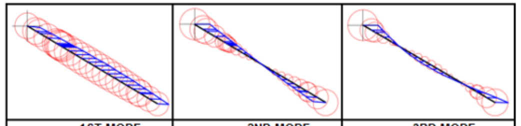




Low Speed Drivetrain
12krpm PM Generator

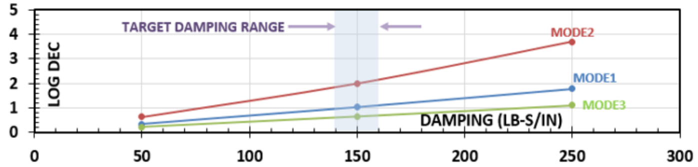


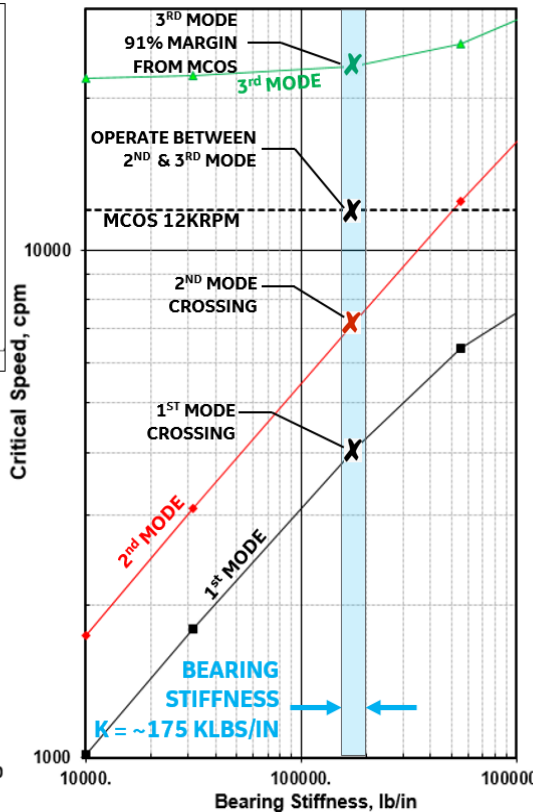
First Stn	Last Stn	Level Length	Total Level Weight	Level CG	Total Level It	Total Level Ip
		in	lb	in	lb-in2	lb-in2
1	24	46.882	675.388	24.6061	85142.986	6845.520
All stations			675.388	24.6061	85142.986	6845.520
All rotating stations			675.388	24.6061	85142.986	6845.520
All non-rotating stations			0.000	0	0	

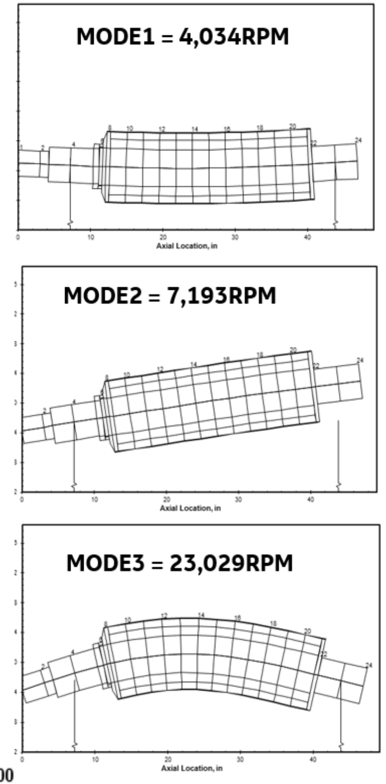


BEARING K = 175 KLB/IN
ROTOR SPEED = 12KRPM

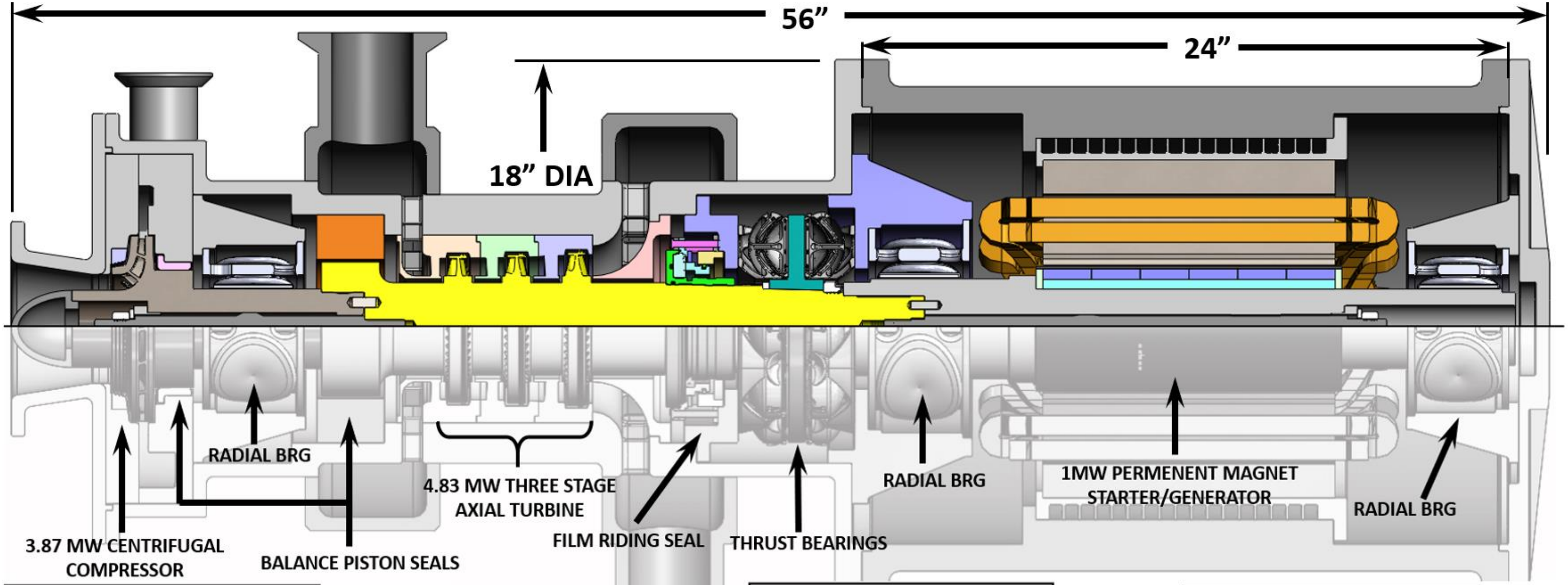
DAMPING VALUE (LB-S/IN)	1ST MODE LOG DEC	1ST MODE FREQ (KRPM)	2ND MODE LOG DEC	2ND MODE FREQ (KRPM)	3RD MODE LOG DEC	3RD MODE FREQ (KRPM)
50	0.34	4.03	0.63	7.36	0.21	19.77
150	1.03	4	1.99	7.1	0.64	19.59
250	1.77	3.95	3.69	6.53	1.1	19.2







Oil-Free Hermetic High-Speed Drivetrain: 27KRPM



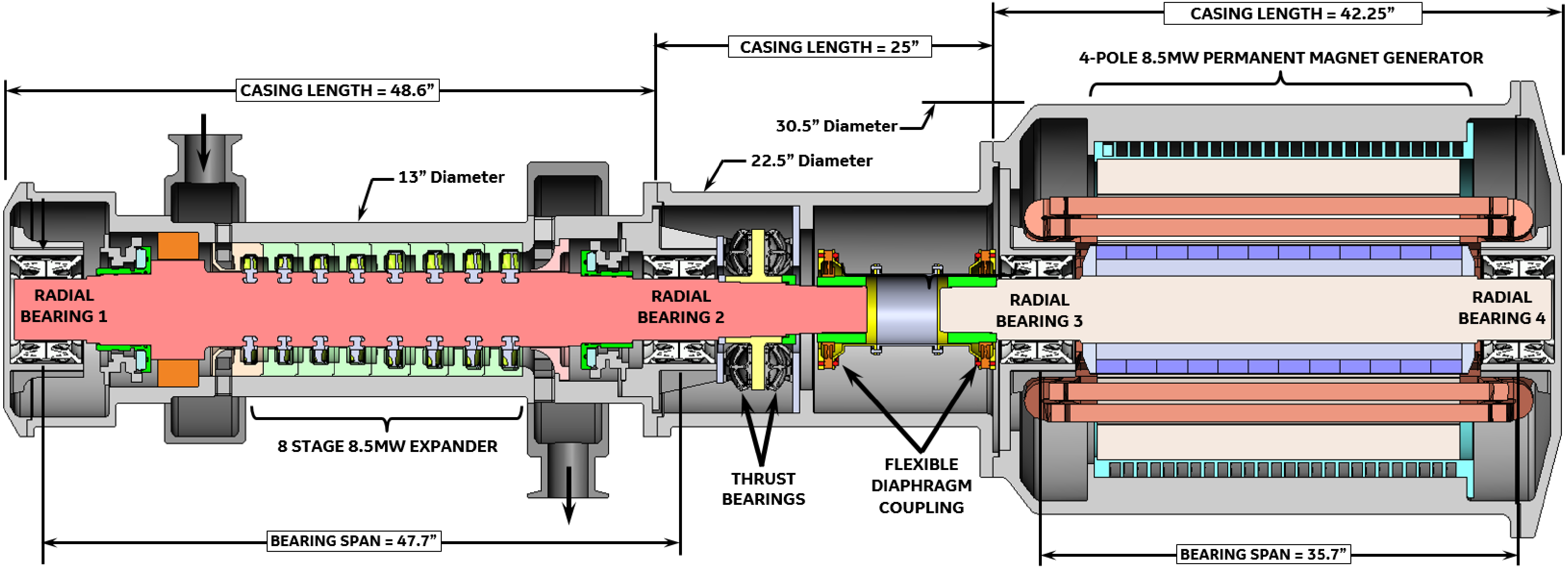
COMPRESSOR RADIAL BEARING	
MANUFACTURING METHOD	DMLS
DIAMETER	3 in
L/D	0.8
PAD LENGTH	2.4 in
NUMBER OF ORIFICE GAS DELIVERY HOLES	12
1G REACTION LOAD	69 lb
MAX SPEED	27000 rpm
PRESSURE BOUNDARY CONDITION	83 bar
BEARING STIFFNESS	80000 lb/in
1G BEARING DELFECTION (ROTOR SAG)	0.0008625 in
DAMPING REQUIREMENT	75 lb-s/in
UNIT LOAD	9.583333333 psi
SURFACE SPEED @ MCOS	107.6706 m/s
MAX DYNAMIC LOAD THROUGH CRITICAL SPEEDS	49 lb peak
DYNAMIC LOAD @ MCOS 27000 RPM	43 lb peak

THRUST BEARING	
OUTER DIAMETER	7.4 in
INNER DIAMETER	4 in
REQUIRED LOAD CAPACITY	2000 lb
MAX SPEED	27000 rpm
UNIT LOAD	65.732 psi
SURFACE SPEED @ MCOS	265.587 m/s

MIDSPAN RADIAL BEARING	
MANUFACTURING METHOD	DMLS
DIAMETER	3.74 in
L/D	0.8
PAD LENGTH	2.992 in
NUMBER OF ORIFICE GAS DELIVERY HOLES	12
1G REACTION LOAD	73 lb
MAX SPEED	27000 rpm
PRESSURE BOUNDARY CONDITION	15 bar
BEARING STIFFNESS	80000 lb/in
1G BEARING DELFECTION (ROTOR SAG)	0.0009125 in
DAMPING REQUIREMENT	75 lb-s/in
UNIT LOAD	6.52363522 psi
SURFACE SPEED @ MCOS	134.229348 m/s
MAX DYNAMIC LOAD THROUGH CRITICAL SPEEDS	55 lb peak
DYNAMIC LOAD @ MCOS 27000 RPM	52 lb peak

GENERATOR RADIAL BEARING	
MANUFACTURING METHOD	DMLS
DIAMETER	3 in
L/D	0.8
NUMBER OF ORIFICE GAS DELIVERY HOLES	12
PAD LENGTH	2.4 in
1G REACTION LOAD	39 lb
MAX SPEED	27000 rpm
PRESSURE BOUNDARY CONDITION	15 bar
BEARING STIFFNESS	80000 lb/in
1G BEARING DELFECTION (ROTOR SAG)	0.0004875 in
DAMPING REQUIREMENT	75 lb-s/in
UNIT LOAD	5.416666667 psi
SURFACE SPEED @ MCOS	107.6706 m/s
MAX DYNAMIC LOAD THROUGH CRITICAL SPEEDS	104 lb peak
DYNAMIC LOAD @ MCOS 27000 RPM	96 lb peak

Oil-Free Hermetic Low-Speed Drivetrain: 12KRPM



RADIAL BEARING 1	
DIAMETER	4.6 in
1G LOAD	179 lbs
MCOS	12000 rpm
SURFACE SPEED	73.4 m/s
L/D	0.85
BEARING AXIAL LENGTH	3.91 in
PROJECTED AREA	17.986 IN^2
UNIT LOAD	9.9522 psi

RADIAL BEARING 2	
DIAMETER	4.6 in
1G LOAD	289 lbs
MCOS	12000 rpm
SURFACE SPEED	73.4 m/s
L/D	0.85
BEARING AXIAL LENGTH	3.91 in
PROJECTED AREA	17.986 IN^2
UNIT LOAD	16.068 psi

THRUST BEARING	
OUTER DIAMETER	10.5 in
INNER DIAMETER	5.1 in
REQUIRED LOAD CAPACITY	3500 lbs
MCOS	12000 rpm
SURFACE SPEED	167.5 m/s
L/D	0.85
APPROX AXIAL WIDTH	2.5 in
PROJECTED AREA	66.128 IN^2
UNIT LOAD	52.927 psi

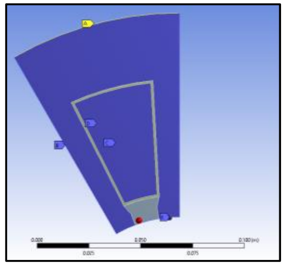
RADIAL BEARING 3	
DIAMETER	4.6 in
1G LOAD	354 lbs
MCOS	12000 rpm
SURFACE SPEED	73.4 m/s
L/D	0.85
BEARING AXIAL LENGTH	3.91 in
PROJECTED AREA	17.986 IN^2
UNIT LOAD	19.682 psi

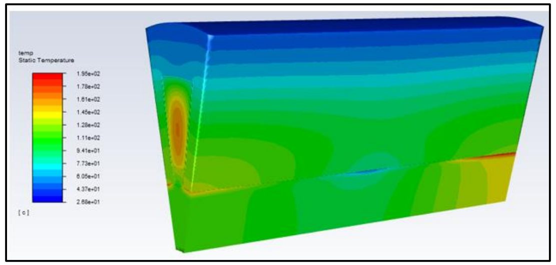
RADIAL BEARING 4	
DIAMETER	4.6 in
1G LOAD	320 lbs
MCOS	12000 rpm
SURFACE SPEED	73.4 m/s
L/D	0.85
BEARING AXIAL LENGTH	3.91 in
PROJECTED AREA	17.986 IN^2
UNIT LOAD	17.792 psi

Immersed CO_2 Generator Cavity Thermal Stability

- Heat generation from PM EM needs to be addressed
- CFD thermal analysis; 1/12 stator-rotor sector
- Weak link →electrical insulation
- Mitigated using: Stator (H2O) cooling jacket and Magnetic gap cooling (CO2),

	Per 1/12th section for 27k RPM machine		Per 1/24th section for 12k RPM machine	
Water jacket cooling	-517	W	-1205	W
Stator heat generation	546	W	2088	W
Rotor heat generation	8	W	33	W
Windage 1/12th	641	W	1708	W
Difference	678	W	2624	W
CO2 flow needed	0.0056	kg/s	0.0216	kg/s
Total CO2 flow	0.0672	kg/s	0.5184	kg/s

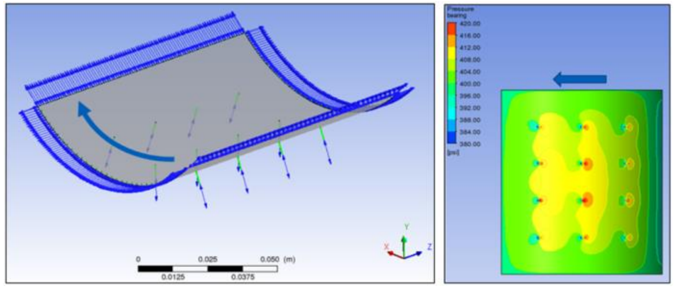




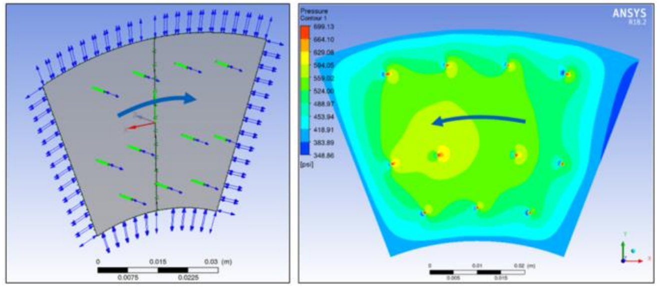
Gas Bearing DOE: Windage Leakage, Load Capacity

- Bearing CFD analysis using real gas props. includes
  - Setting desired running gap under load
  - Use orifice map DOE and inlet pressures
  - Calculation of leakage and windage
- Gas bearing show an order of magnitude less heat generation compared to oil-bearings

RADIAL BEARING PAD



THRUST BEARING PAD

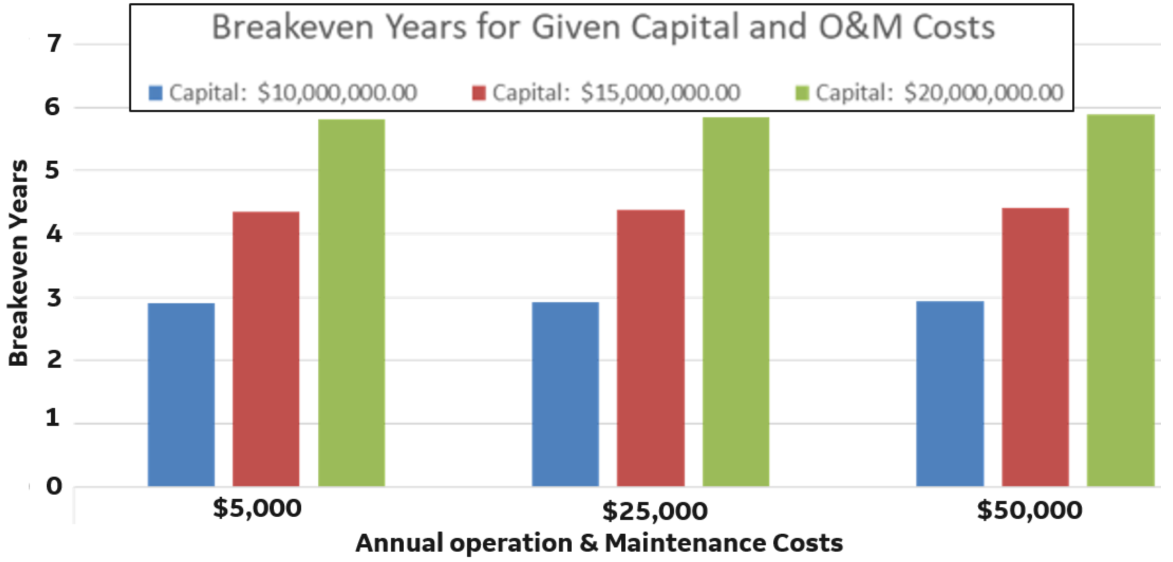


Compressor Station WHR Economics

- sCO2 WHR performance
  - 41% → 51.3% cycle efficiency increase
  - Fuel consumption/MWh reduction by 20%
  - CO2 emissions/MWh reduction by 20%
  - System cost 10-15M; 3-4 breakeven years
  - Emission-free WHR
    - EPA's New source review: stations in non-attainment areas hesitant to upgrade
  - WHR concept offers compressor stations options: 60Hz power gen or compressor drive

- Comparison to ORC*
  - Power conversion rate ~2X
  - Break even years cut by half

Configuration	Net Power	Cycle Efficiency $\eta = \frac{Net\ Power}{\dot{m}_{fuel} * LHV}$	Heat Rate $\frac{1}{\eta} * 3600$	Normalized NG Fuel Consumption: metric tons per MWh	Normalized CO_2 Emission: metric tons per MWh
1. Baseline: Single PGT25 +G4	34 MW	41%	8700 kJ/kWh	0.183	0.494
2. Baseline + Oil-Free Hermetically sealed bottoming cycle	42.0 MW	51.3%	7019 kJ/kWh	0.148	0.400

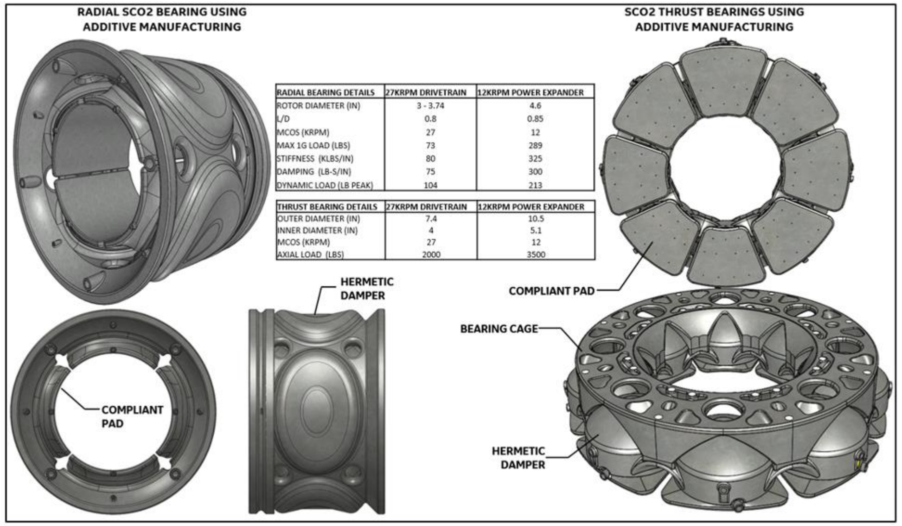


* Sweetser, M., Leslie, N., "Subcontractor Report: National Account Energy Alliance Final Report for the Basin Electric Project at Northern Border Pipeline Company's Compressor Station #7, North Dakota." ORNL/TM-2007/158. Oak Ridge National Laboratory, Oak Ridge, TN (2007)

Conclusions

	ORMAT ORC	sCO_2 WHR Hermetically Sealed
WHR Conversion %	15%	28%
Recovered Energy	5.5 MW	8.75 MW
Annual kWh	43 million kWh	69.0 million kWh
Capital Cost	$13.75M	$10-15M
Annual O&M	$250,000	$5,000-50,000
Capital Costs/kW	$2500/kW	$1142-1714/kW
Breakeven Years	7 years	3-4.2 years

- sCO2 WHR unit shows to increase efficiency from 41% → 51.3% with investment break even years = 3-4
- sCO2 Compared to ORC WHR: Power conversion rate increase nearly 2X and break even years cut in half
- Risks:
  - High-speed drive train: lightly loaded bearings but required t traverse third critical speed (bending mode)
  - Low-speed drive train: Highly loaded bearings but operates below third critical speed (bending mode)
  - Generator cavity thermal balance/stability



RADIAL BEARING DETAILS	27KRPM DRIVETRAIN	12KRPM POWER EXPANDER
ROTOR DIAMETER (IN)	3 - 3.74	4.6
L/D	0.8	0.85
MCOS (KRPM)	27	12
MAX 1G LOAD (LBS)	73	289
STIFFNESS (KLBS/IN)	80	325
DAMPING (LB-S/IN)	75	300
DYNAMIC LOAD (LB PEAK)	104	213

THRUST BEARING DETAILS	27KRPM DRIVETRAIN	12KRPM POWER EXPANDER
OUTER DIAMETER (IN)	7.4	10.5
INNER DIAMETER (IN)	4	5.1
MCOS (KRPM)	27	12
AXIAL LOAD (LBS)	2000	3500