Turbo-Machinery Considerations Using Super-Critical Carbon Dioxide Working Fluid for a Closed Brayton Cycle

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Machinery Discussion

- Large Scale ~300 Mwe Rotating Equipment Design
  - Compressors
  - Turbine
  - Seal Options
  - Bearing Options
  - Generator Option
- Small Scale ~ 280 kWe System Design
  - Compressors
  - Turbine
  - Seal Options
  - Bearing Options
  - Generator Option

Cycle Design Is the Input to the Turbomachinery Design

MIT Cycle ***(V. Dostal, M.J. Driscoll, P. Hejzlar, and N.E. Todreas, 2002 (MIT-ANP-TR-090)***

Turbine-
Mass Flow=3485 kg/sec
Pin=19.83 MPa
Tin=550 deg C
Pout=7.90 MPa

Main Compressor-
Mass Flow=2091 kg/sec
Pin=7.69 MPa
Tin=32 deg C
Pout=20 MPa

Re-Compressor
Mass Flow=1349 kg/sec
Pin=7.70 MPa
Tin=69.69 deg C
Pout=20 MPa

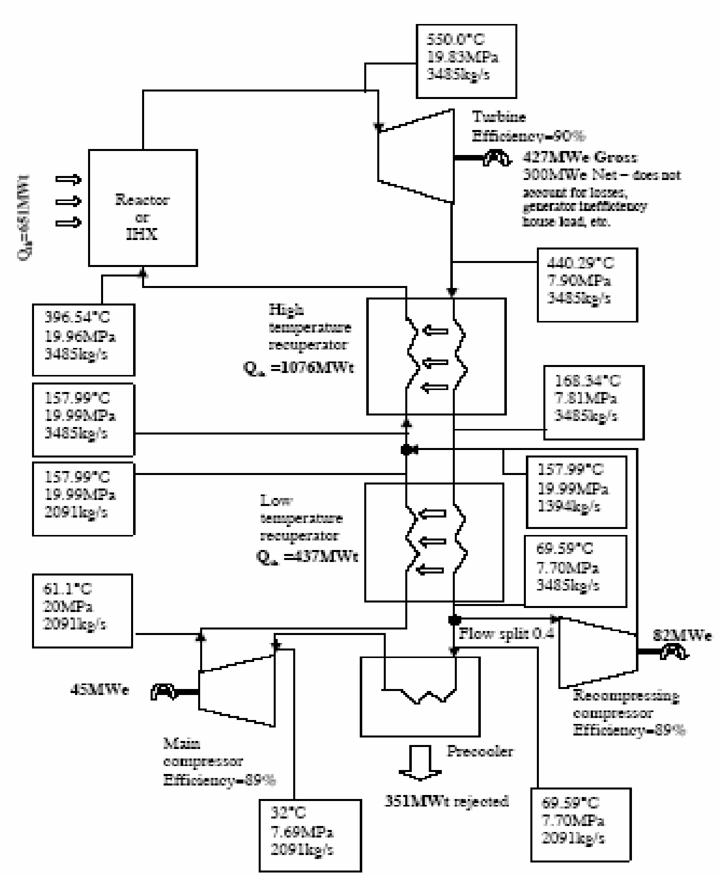
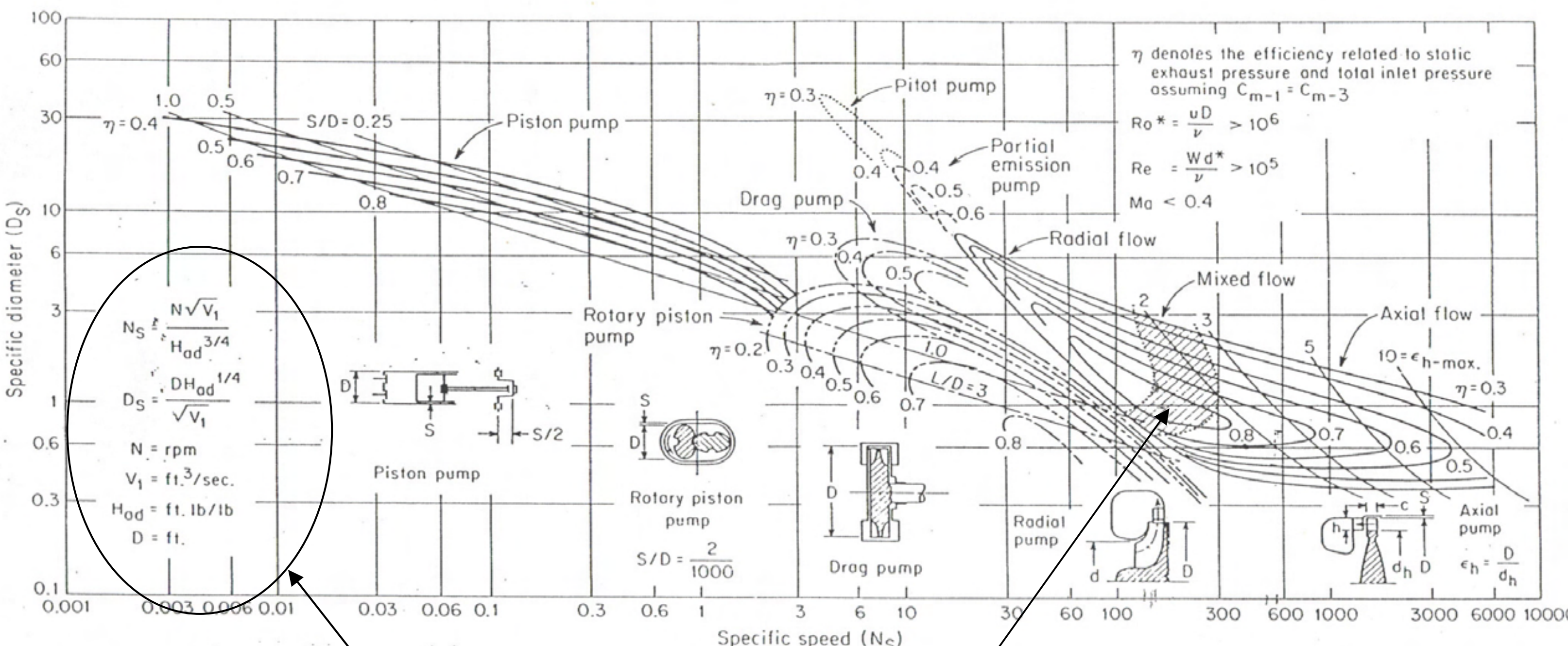


Fig. 1.2 Reference Cycle State Points for 300MWe
3

Ground Rule: Industry Acceptance Is Important

- **Make the Machinery Look Like Conventional Power Plants If Possible (Generate Industry Interest)**
  - 3600 RPM (GE Makes a 3600 RPM Hydrogen Cooled Generator @ ~300 Mwe)
  - Single Shaft
  - Oil Lubricated Hydrodynamic Bearings (Tilt Pad or Elliptical)
  - Seals (Acceptable on Steam and Gas Turbines)
  - Horizontal Shaft

Ns-Ds Diagram Compressors (English Units)



Highest Efficiency
Speed and Diameter

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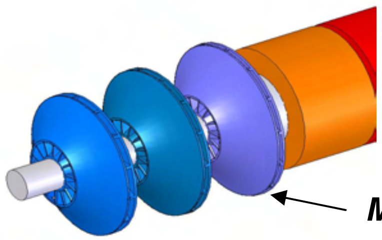
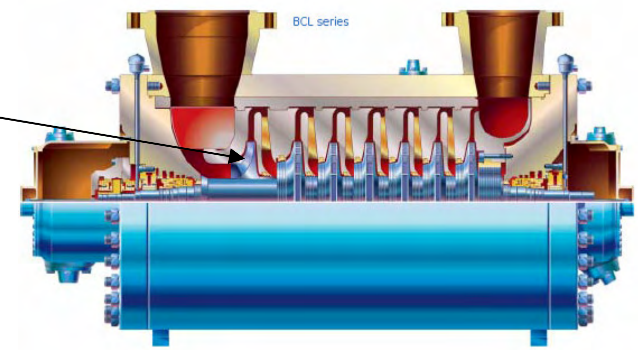
Large System



My Model

From General Electric Site BCL Series Compressor



Main Compressor (Large System)

3-Stage Radial Efficiency is 87%

MAIN COMPRESSOR PERFORMANCE Wdot 2091kg/s Mit 300MW cycle
THREE STAGE RADIAL *Stage enthalpies need to be corrected
3600 RPM Stage eff 0.87 but are OK for concept study

Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)	Stage Ns	US Ns	Efficiency Overall	Stage U2 ft/s Dia inches
32	7.69	598.81	306.81	1.3483	15.813	1.20	154		343.53
41.649	10.766	647.38	311.74	1.3483	4.7145				21.87
41.803	10.766	644.8	312.48	1.3506	4.7558	0.99	128		361.03
51.164	14.803	684.11	318.53	1.3506	3.1544				22.98
51.447	14.803	681.47	319.43	1.3534	3.1672	0.82	106		371.98
60.965	20.014	717.81	326.88	1.3534	2.5125				23.68
61.405	20.014	715.02	327.99	1.3567	2.5179				
60.286	20.014	722.1	325.18	1.3483	2.5041		*	0.87	

3-Stage Radial (Mixed Flow) Compressor Meets Target Efficiency

3-Stage Overall Efficiency

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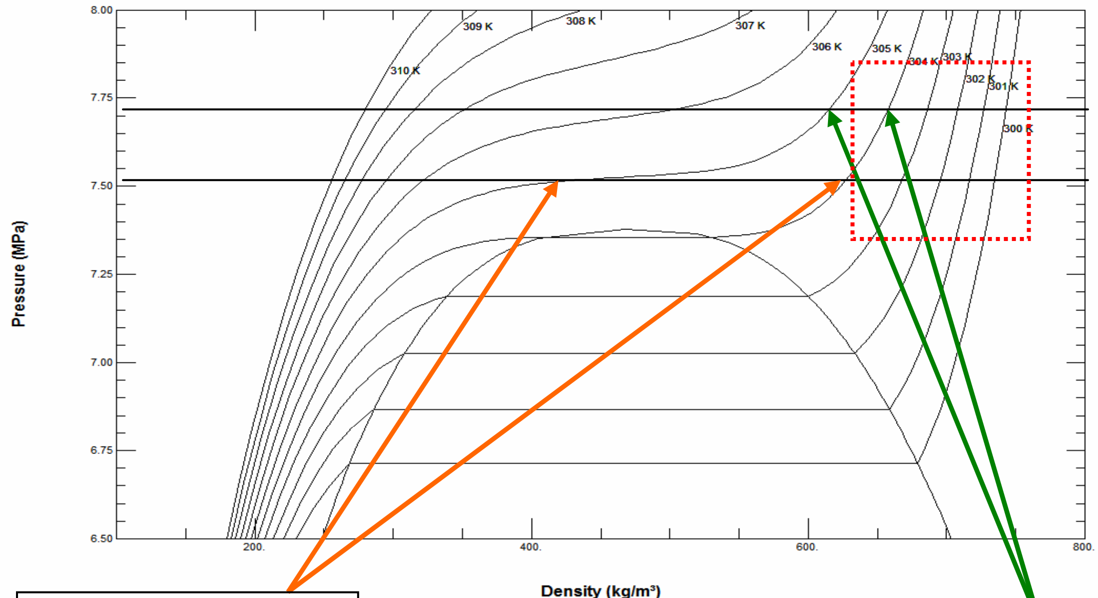
Large System

Large Density Variation for Main Compressor Makes for a Difficult Design

Large Scale System

CO2 Pressure-Density from NIST



At 7.5 MPa
1 deg K Change
304K to 305K
=2X Density change

At 7.69 MPa (MIT Cycle)
1 deg K Change
=1.1X Density change

Need to Keep Compressor Inlet Density In Small Range for Successful Operation

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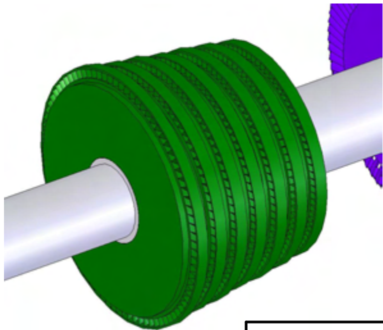
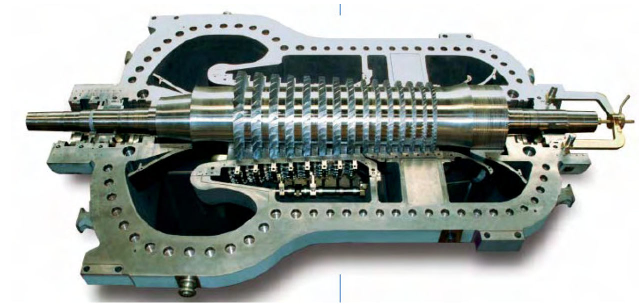
Main Compressor

Radial Type

- Close to the Dome During Startup/Shutdown/System Upset/Wet Gas Handling
- Radial Head/Flow Characteristics for Startup/Shutdown Flow/Pressure Transients
- Flat Head v Flow Characteristic Allows Maintenance of Head over a Wider Flow Range
- Reduced Number of Stage for Overhung Configuration (Rotordynamic Consideration)
- Shrouded Design for Best Efficiency



Re-Compressor Axial Type



	Axial Re-Compressor 7-Stage						
	Stage						
	1	2	3	4	5	6	7
Pressure Ratio	1.226	1.2033	1.18	1.146	1.1126	1.0914	1.0711
P in psia	1116	1369	1647	1945	2228	2480	206
P out psia	1369	1647	1945	2228	2480	2706	2899
Specific Speed	144	138	134	141	157	171	194
D tip (inches)	42	40.7	39.5	38.3	37.1	35.8	34.6
D hub (inches)	39.1	37.8	36.7	35.5	34.4	33.2	32
Hub/Tip Ratio	0.930952	0.928747	0.929114	0.926893	0.927224	0.927374	0.924855

Hub/Tip Ratio is Above .9 (Needs Further Review)

Analysis Was Done For Multi-Stage Radial Compressors

Re-Compressor as Radial 84%

Difficult to Obtain High Efficiency

3070.5lb/sec

Three Stage Temperature (°F)	Pressure (psia)	Density (lbm/ft^3)	Enthalpy (Btu/lbm)	Entropy (Btu/lbm-°R)	Cp (Btu/lbm-°R)				
157.26	1116.5	10.281	205.95	0.45305	0.38367	298.6577	6690.8	84.09706	453.73
220.03	1675	13.848	214.55	0.45305	0.38935				28.89
223.98	1675	13.631	216.07	0.45528	0.3827	225.2586	5679.4	82.58789	396.58
273.68	2275	16.834	223.37	0.45528	0.38298				25.25
277.07	2275	16.641	224.66	0.45704	0.3789	184.5142	4986.98	82.40226	345.04
317.58	2900	19.46	231.07	0.45704	0.37647				21.97
320.58	2900	19.289	232.2	0.45849	0.37382	159.184			0.84
309.46	2900	19.941	227.99	0.45305	0.38413				

Wheel Diameter Inches

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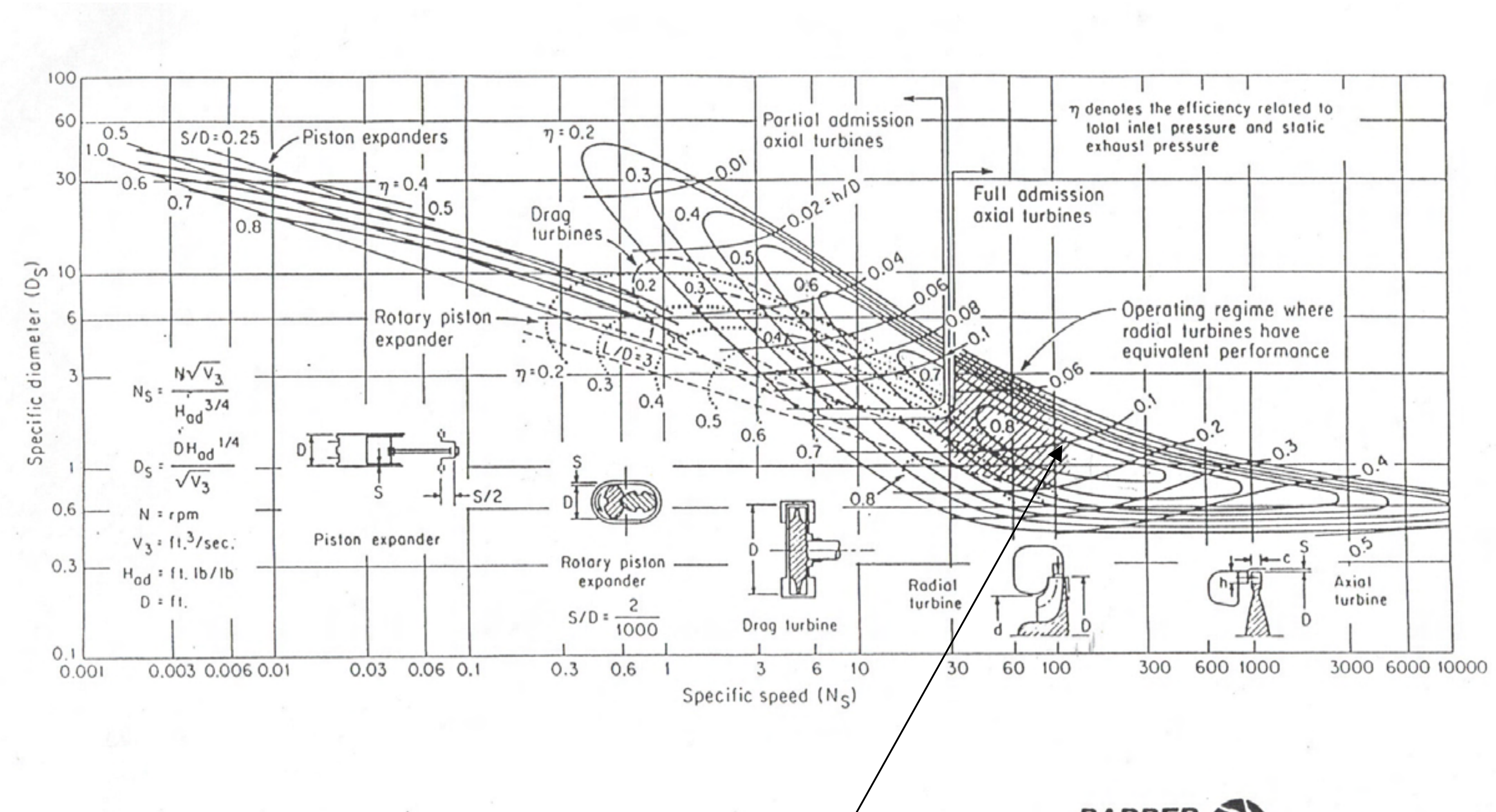
Large System

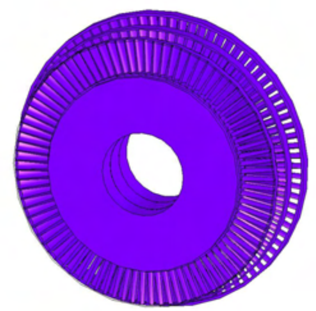
Ns-Ds Diagram Turbines (English Units)



Axial Turbine Highest Efficiency Speed and Diameter

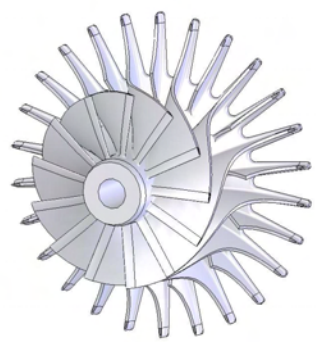
Turbine Design (3-Stage Axial)

90% Efficiency



	Axial Reaction Turbine Summary			
3-stage				
	Stage 1	Stage 2	Stage 3	
Turb In Temp F	1022	955	888	
Nozz In Temp F	972	905	839	
Rotor Out Temp F	951	883	819	
Turb Out Temp F	955	888	823	
Mass Flow lb/sec	7683	7683	7683	
Adiab. Head B/#	19.735	19.735	18.59	
Hub Dia 1 Inch	28.59	36.43	32.14	
Hub Dia 2 Inch	32.23	38.64	35.2	
Tip Diameter Inch	45.687	47.58	48.9	
Reaction	0.4	0.4	0.4	
Blade Chord Inch	2	2	2	
# Blades	85	85	85	
Specific Speed	93	105	125	

Turbine (Single Stage Radial)
90% Efficiency ~1.9 meter Diameter



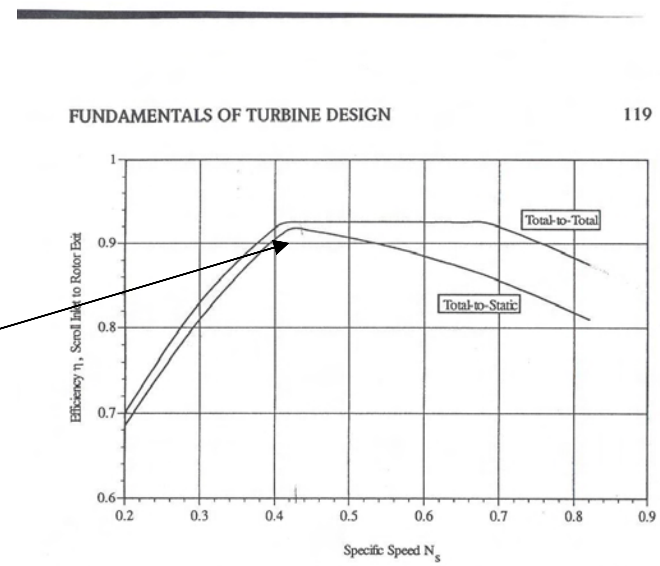


Figure 17 Effect of specific speed on radial-inflow turbine efficiency. (Replotted from Ref. 25.)

Specific Speed .41 Shows 90%+ Efficiency T-S

Radial Flow Turbine
3600RPM Wdot 3485kg/s
Single Stage

Temperature (℃)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Cp (kJ/kg-K)	Cp/Cv	delH Isentropic	Ns		Optimum U/Co	Utip m/s	Diameter Rotor m
550	19.83	123.38	1035.3	2.7429	1.2404	1.2412						
428.8	7.9	59.525	901.02	2.7429	1.1677	1.2351	134.28	0.41	53.42	0.69	357.78	1.90
440.29	7.9	58.491	914.45	2.7619	1.1712	1.2324						

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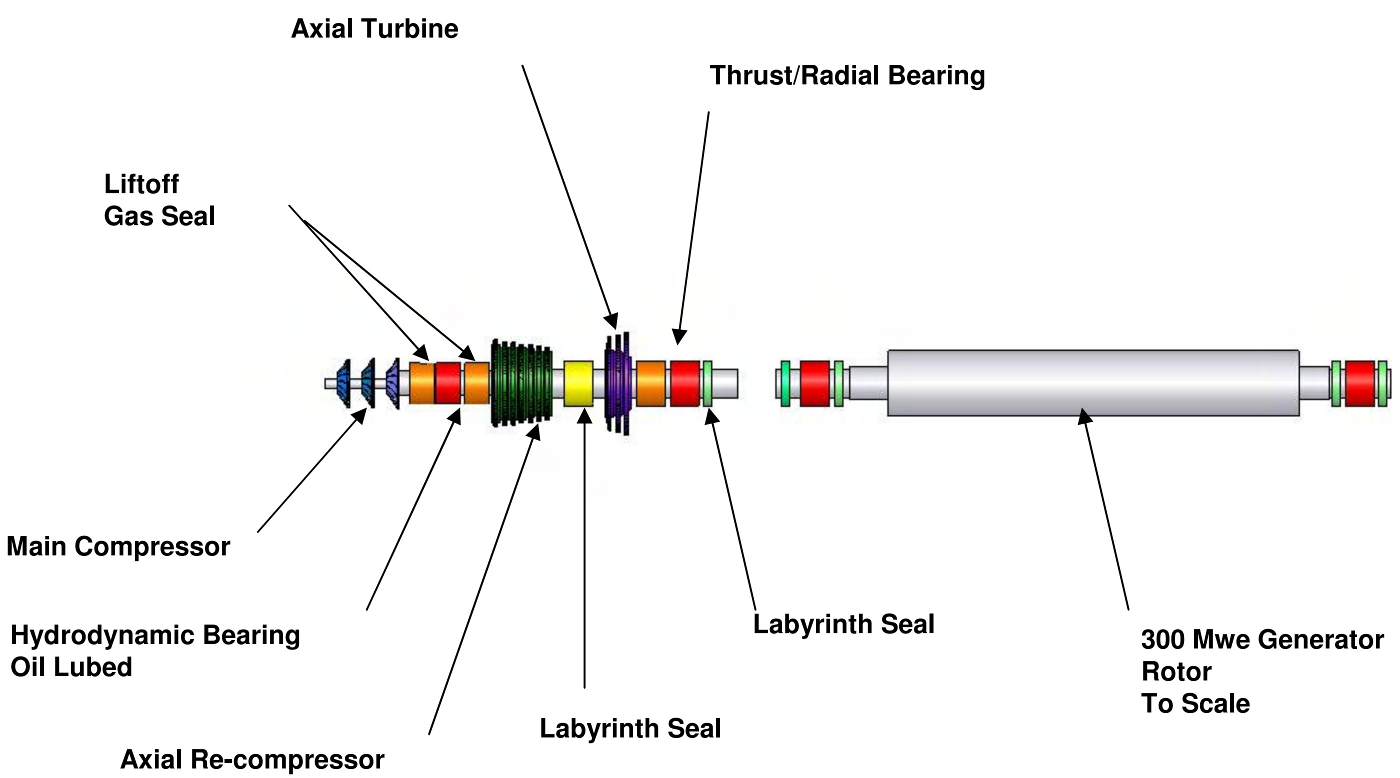
Large System

300 Mwe Super-Critical CO_2 Closed Brayton Cycle Rotating Group



~10 meters + spool + 12 meters

Overall Length ~ 22 meters

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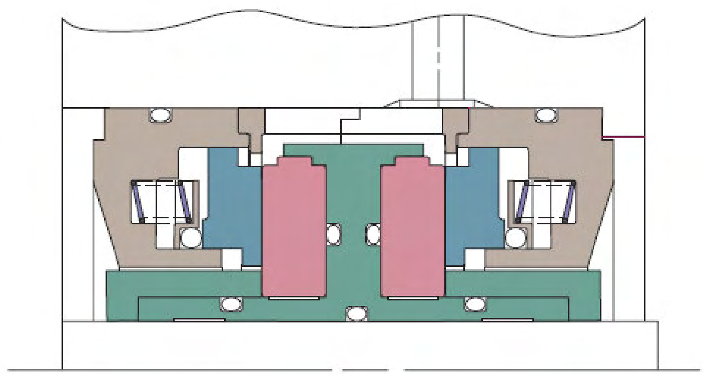
Large System

Oil Lubricated Hydrodynamic Bearings

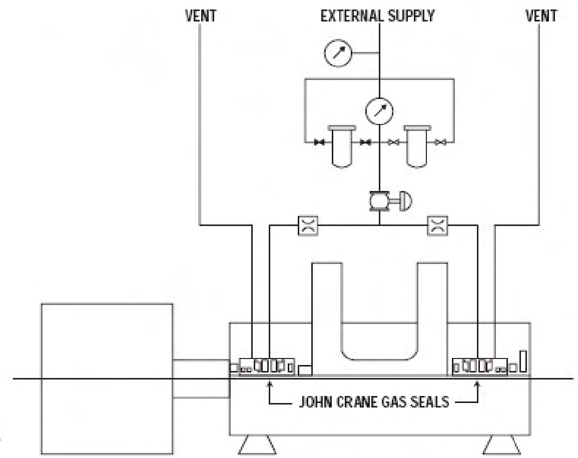
-Thrust and Journal Hydrodynamic Bearings (Industry Standard for Power Generation Equipment, Waukesha)

Liftoff Gas Seal (John Crane)
Surface Speeds/Pressures/Temperatures/CO_2 Currently Offered

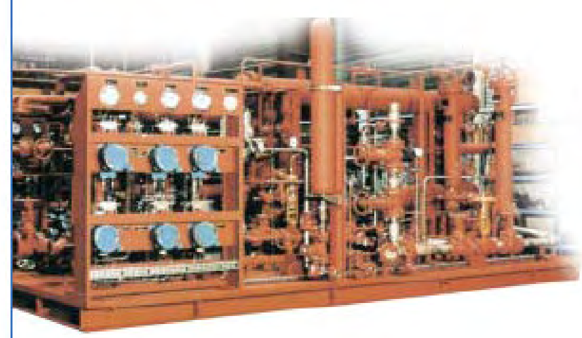
Typical Double Opposed Seal Arrangement and Seal Support System



*Double Seal Arrangement where hazardous gas is not permissible to leak into atmosphere.



Dry Gas Seal Machinery Necessary
Require Monitoring
Storage, Compression
Re-Introduction
(From GE Site)



Large System

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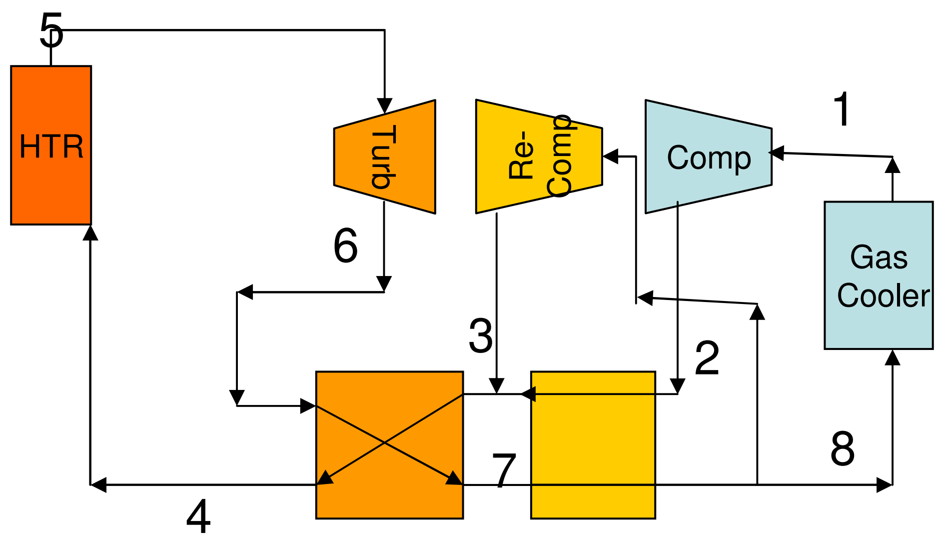
Small Scale System ~300 kWe

- Study SCO2 Closed Brayton Cycle on Small/Affordable Scale
- Same Pressures and Much Lower Flow Rate
  - Higher Speed Machinery to Gain Efficiency
  - Radial Compressors and Turbine
  - High Speed PM Motor/Generator
  - Bearings/Seals for Large System Not Optimum for Small System

Small Scale Loop (Mass Flow 5 kg/s)



Station	***T (K)***	***P (Mpa)***	***mdot (kg/s)***	***eff***	***dP/P***	***kJ/kg***
1	305	7.69	3	72	0.01	304.6
2	335.2	20	3			329.8
3	485	19.9	2	68	0.005	614.3
4	668	19.8	5		0.005	843.9
5	825	19.7	5		0.005	1037.6
6	722	7.93	5	85		924.39
7	504.7	7.85	5		0.01	675.89
8	375	7.77	3		0.01	524.07

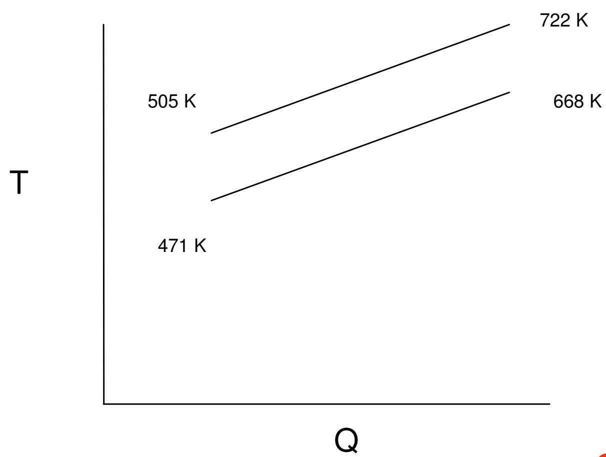
Cycle Analysis with Pressure Drops

~279 kWe Net Electric Power

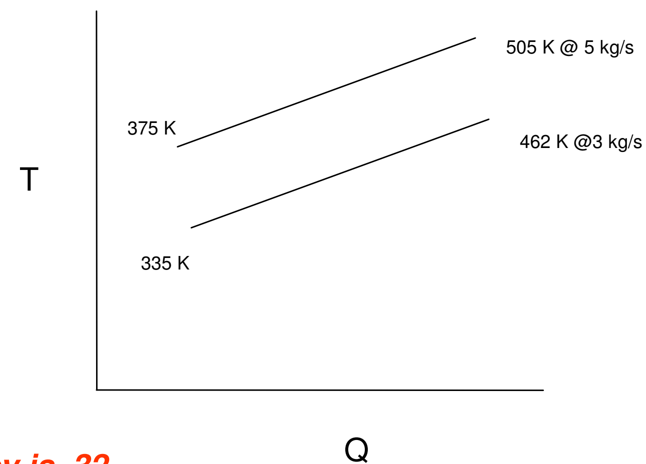
	P1 Mpa	P2 Mpa	H1	H2'	eff	H2	mdot	Power kW	Speed rpm	psi	D2 inches	Ns
Radial Main	7.69	20	304.6	322.7	0.72	329.8	3	75.6	80,000	0.58	1.66	48.5
Radial Re-Comp	7.77	19.9	524.1	585.4	0.68	614.3	2	180.4	80,000	0.58	3.06	33.8
Radial Turbine	19.7	7.93	1037.6	904.4	0.85	924.4	5	566	80,000	0.65	3.16	45.5
							Net Shaft	310				
							Net Elect	***279.93***				

Size

High Temp Recuperator



Low Temp Recuperator



Cycle Efficiency is .32

Before Electrical and Mechanical Parasitic Losses

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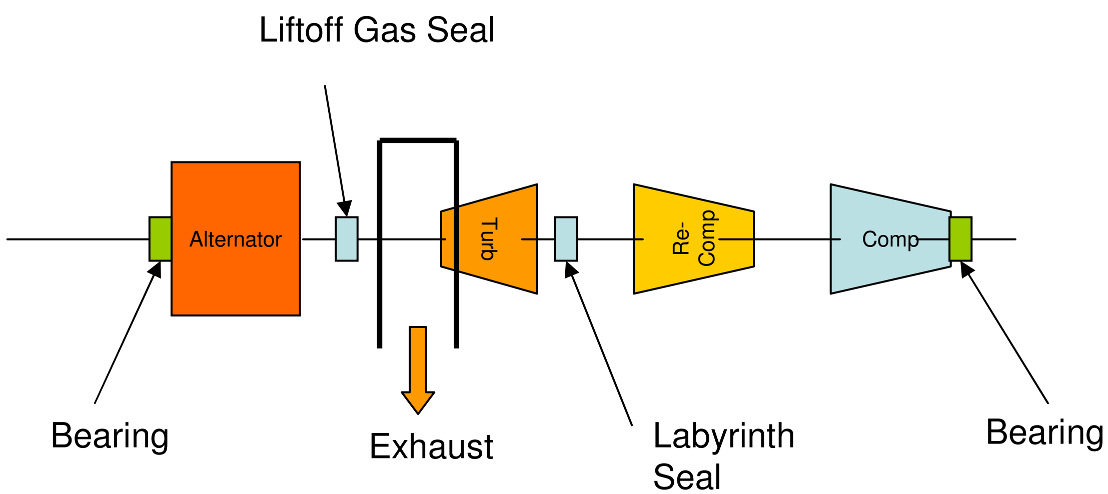
Small Scale System

Oil Lubricated Bearings with Seals to Use "Large Machine" Technology

Scaled Loop Machinery (2 bearing option)



+Thrust Loads Balanced
~Flexible Rotor vs Liftoff Seal Runout?
Detailed Design Necessary

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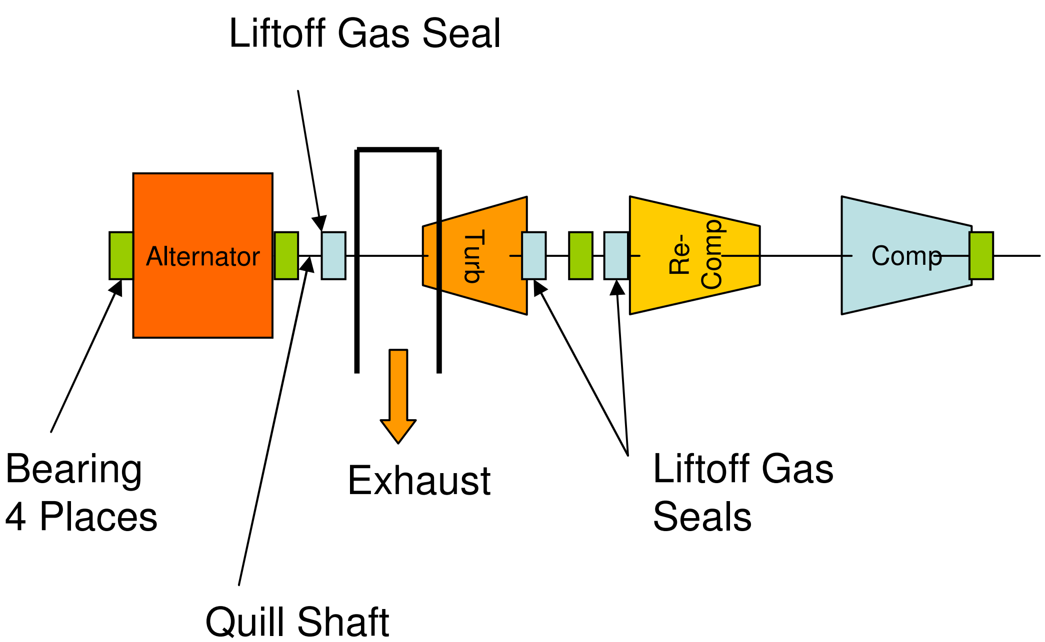
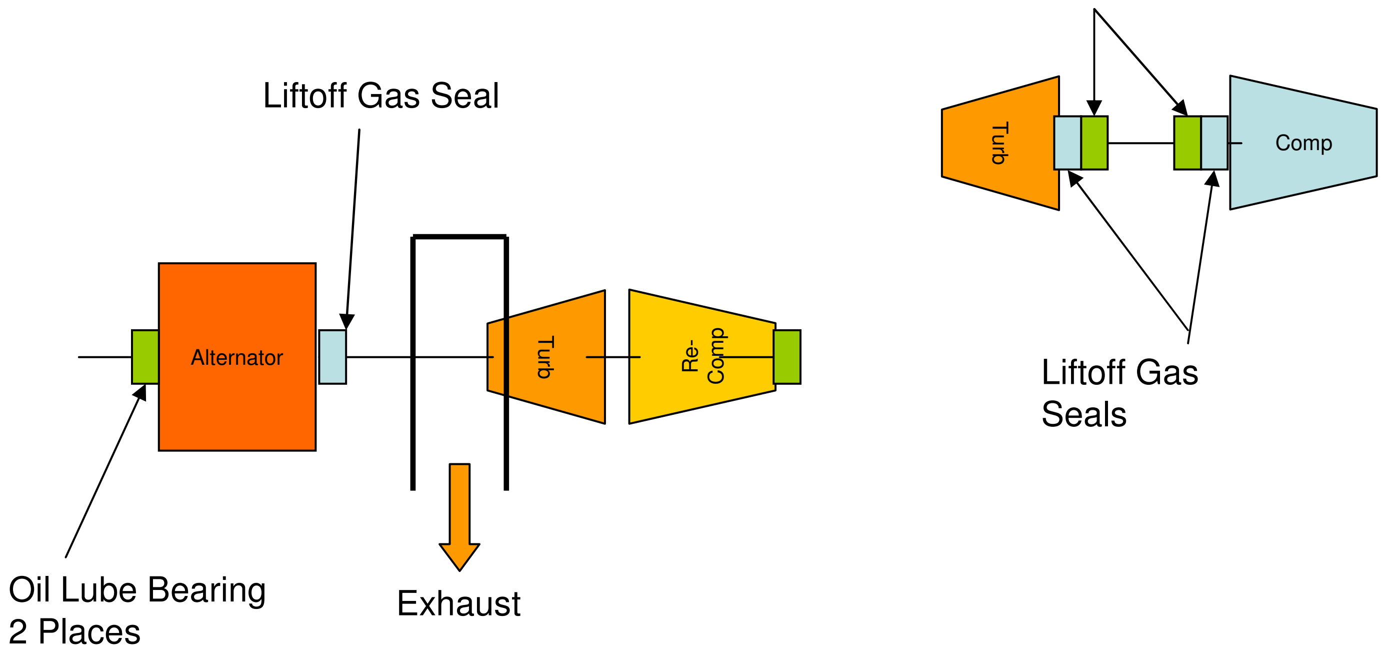
Oil Lubricated Bearings with Seals to Use "Large Machine" Technology

Scaled Loop Machinery (4 bearing option, more seals)



Oil Lubricated Bearings with Seals
to Use "Large Machine" Technology

Scaled Loop Machinery
(2 Shaft Option)



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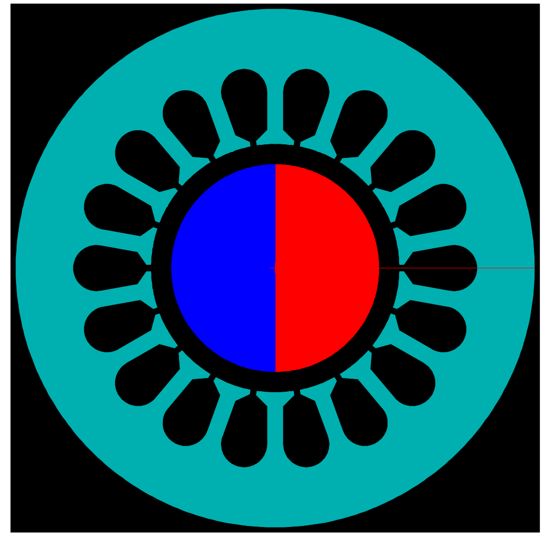
Small Scale System

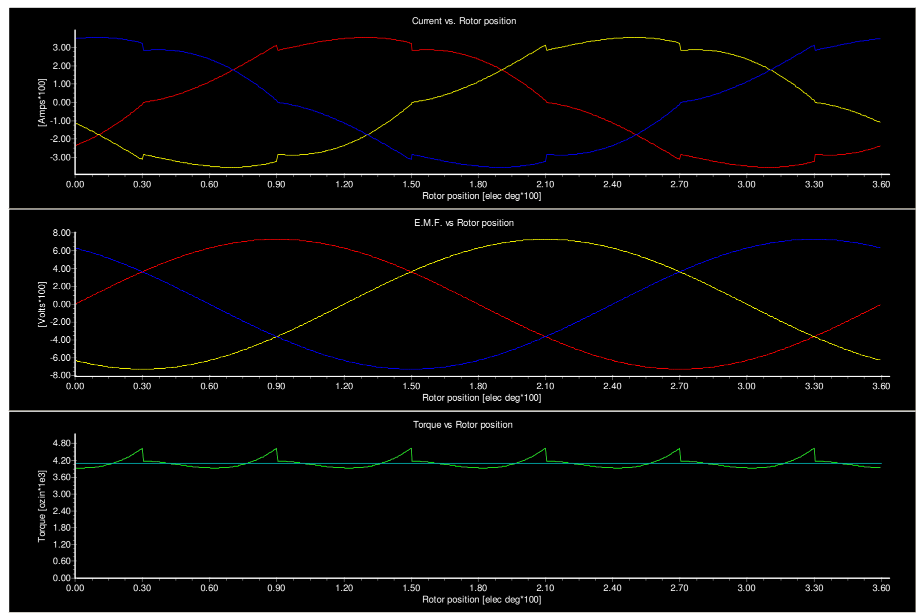
Simplified Design

- CO_2 Bearing Supply
  - Hydrostatic
  - Hydrodynamic
    - Flex Pad
    - Foil
- Generator Operating in CO_2
  - Eliminate Gas Liftoff Seals/Laby Seals OK
  - Supercritical CO_2 Degradation of Insulation
  - Windage Loss

Generator Technology
Very High Power/Speed
Compact for Rotordynamics



Permanent Magnet Generator
- -45 MGOe NIB Magnet
- -Arnon 5 Laminations
- -7” Stack Length
- -5” Outer Diameter
- -Inconel 718 Rotor Can
- -279 kWe Output at 80,000 rpm
- -98% Efficiency



-Windage in CO_2 at 170 deg F
- -62 kW @ 1100 psi
- -11 kW @ 250 psi
- -1 kW @ 14.7 psi

Need to Operate Generator at Low Pressure

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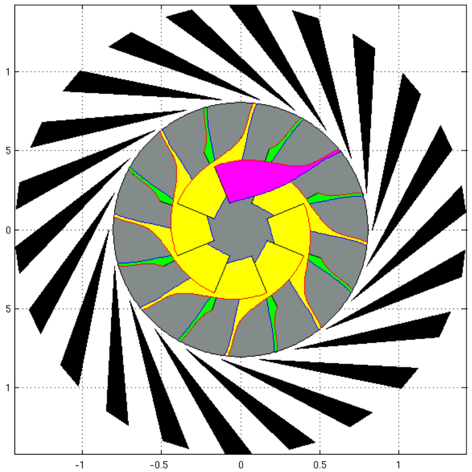
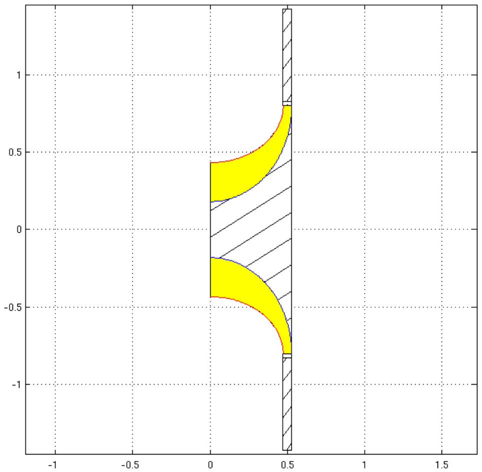
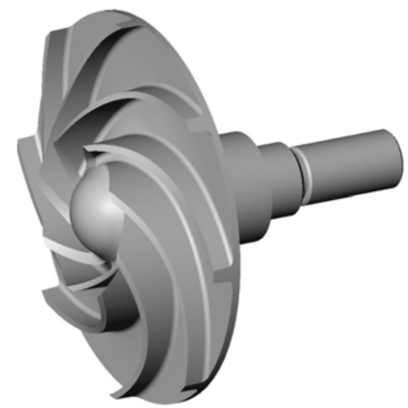
Small Scale System

Main Compressor Analysis

Looks More Like a Pump Than a Compressor







- Developed Defined Procedure
- Use Real Gas Mean Line Code
- Modify for Ideal Gas
    - Flow Path Analysis
    - Sizing
    - Input to CFD Code with Average CO2 Properties

Other Considerations To Be Considered When Designing Turbomachinery

- Rotordynamics
- Thrust Load Management
- Startup/Shutdown Transients
- Clearances
- Inlet/Discharge Diffusion etc.
- Stresses (Including Thermal/Fatigue/Operating etc)

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