Polygon Expansion Engine Waste Heat Energy SCO2 Recovery Cycle Thermodynamic Analysis and Component Design

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Outline

- Introduction
- Design Concept
- Thermodynamic Modeling
- Manufacturing Methodology
- Component Stress Analysis
- Conclusions
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Introduction

- Approximately 280 GW of waste heat is estimated to be expelled annually by
  - Could result in $70-$150 billion in savings if salvaged
  - On this scale, any efficiency increase will result in large savings
- SCO_2 offers unique properties as a working fluid for a cycle
  - Relatively low temperatures for supercritical state
  - Unique challenges for pressures and viscosities
    - High pressure ranges, 4-5 times max pressure in typical diesel engines
    - Viscosity poses problems for sealing, dry gas mechanical seals needed
- Relatively recent hardware innovations and green energy initiatives have sparked interest in applications

Introduction

- It has recently been recognized that a large quantity of waste heat is generated annually, and thus represents a large opportunity for energy savings
- With burgeoning research in cycles which utilize super critical carbon dioxide as a unique working fluid; herein an optimized thermodynamic cycle development was proposed that would center around a novel expansion device for extracting power from the SCO_2 working fluid

Introduction

- Passive and active components in the system
- Passive: Heat exchangers
  - Well formulated design criteria readily available, especially for single phase flow
- Active: Pump/Compressor and Expander
  - Pump/Compressor technology has existed for 20 years for dealing with super-critical carbon dioxide
  - Expander design has become an industry goal for such processes
- Expander design
  - High specific power goals
  - Compatibility with SCO2

Design Concept

- The original engine design stemmed from a Polygon engine project sponsored by Butte Industries, Inc. [1,2] while the current evolution of the design stems from the works published in [3-5]

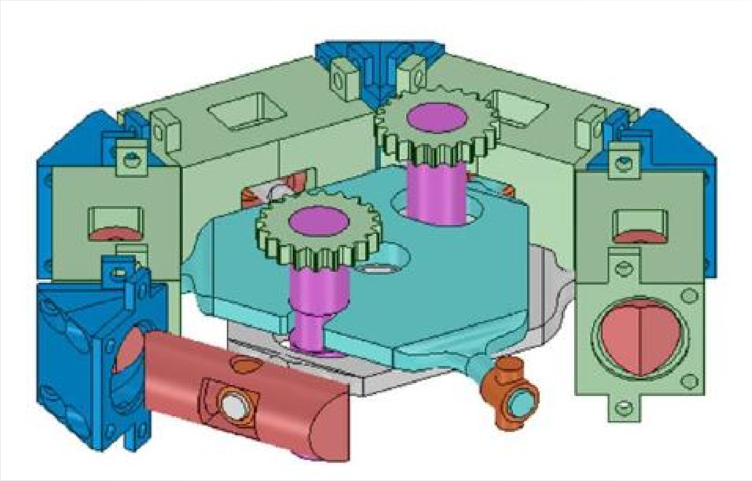


Figure 1a. Polygon Expansion Engine Design Concept [2]

Figure 1b. Polygon Expansion Engine Design Concept [2]

Design Concept

- The Mollier diagram for the expansion process in conjunction with the waste heat recovery cycle is shown below in Figure 2

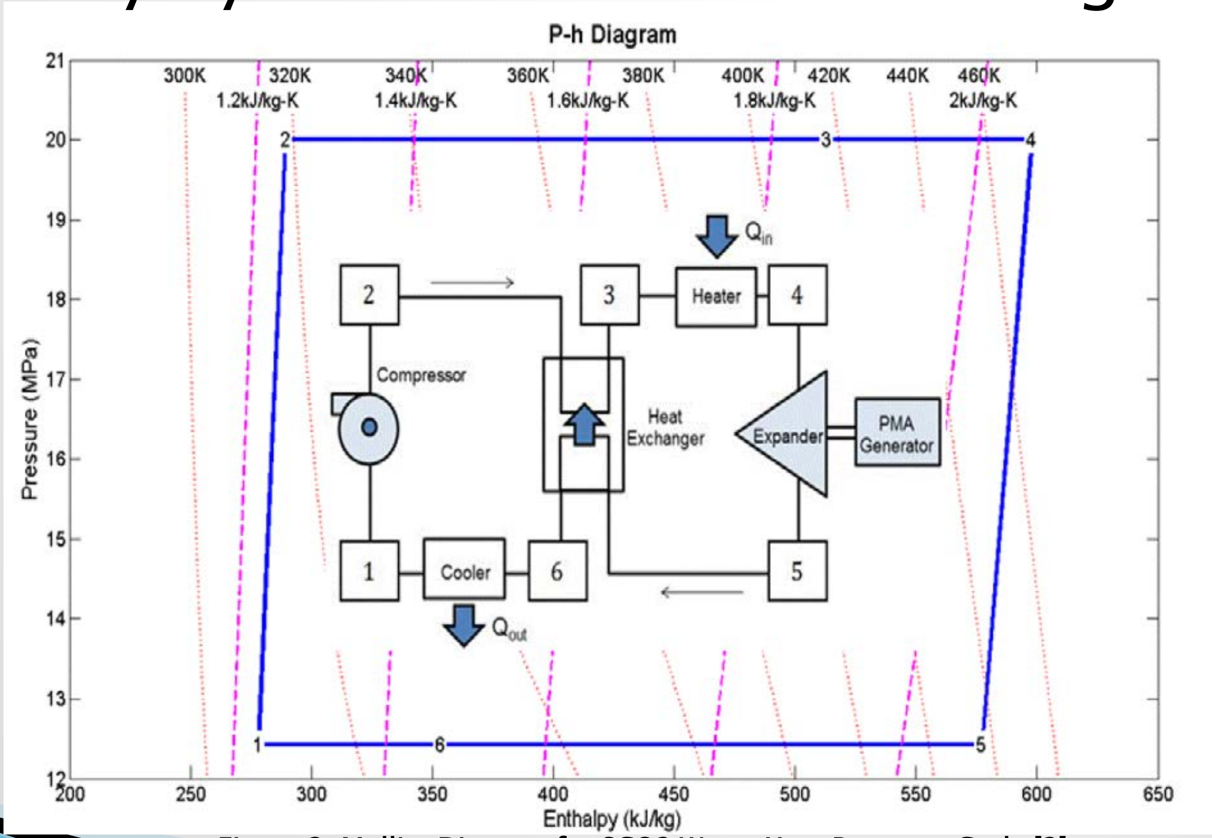


Figure 2. Mollier Diagram for SCO2 Waste Heat Recovery Cycle [2]

Design Concept

- The pertinent thermodynamic state points for the expansion engine are summarized in Table 1

Table 1. Pertinent Thermodynamic State Points for SCO2 Waste Heat Recovery Cycle [2]

	State Points (cf. Figure 2)	T (K)	P (MPa)	Density (kg/cu m)	Enthalpy (kJ/kg)	Entropy (kJ-kg-K)
	1	308	12.4	776.61	278.19	1.23
	2	319	20.0	810.49	289.38	1.24
	3	417	20.0	338.83	413.32	1.86
EXPANSION PROCESS	4	473	20.0	258.82	597.79	2.05
EXPANSION PROCESS	5	436	12.4	176.78	577.23	2.08
	6	328	12.4	537.76	353.29	1.47

Design Concept

- Cycle efficiency analysis

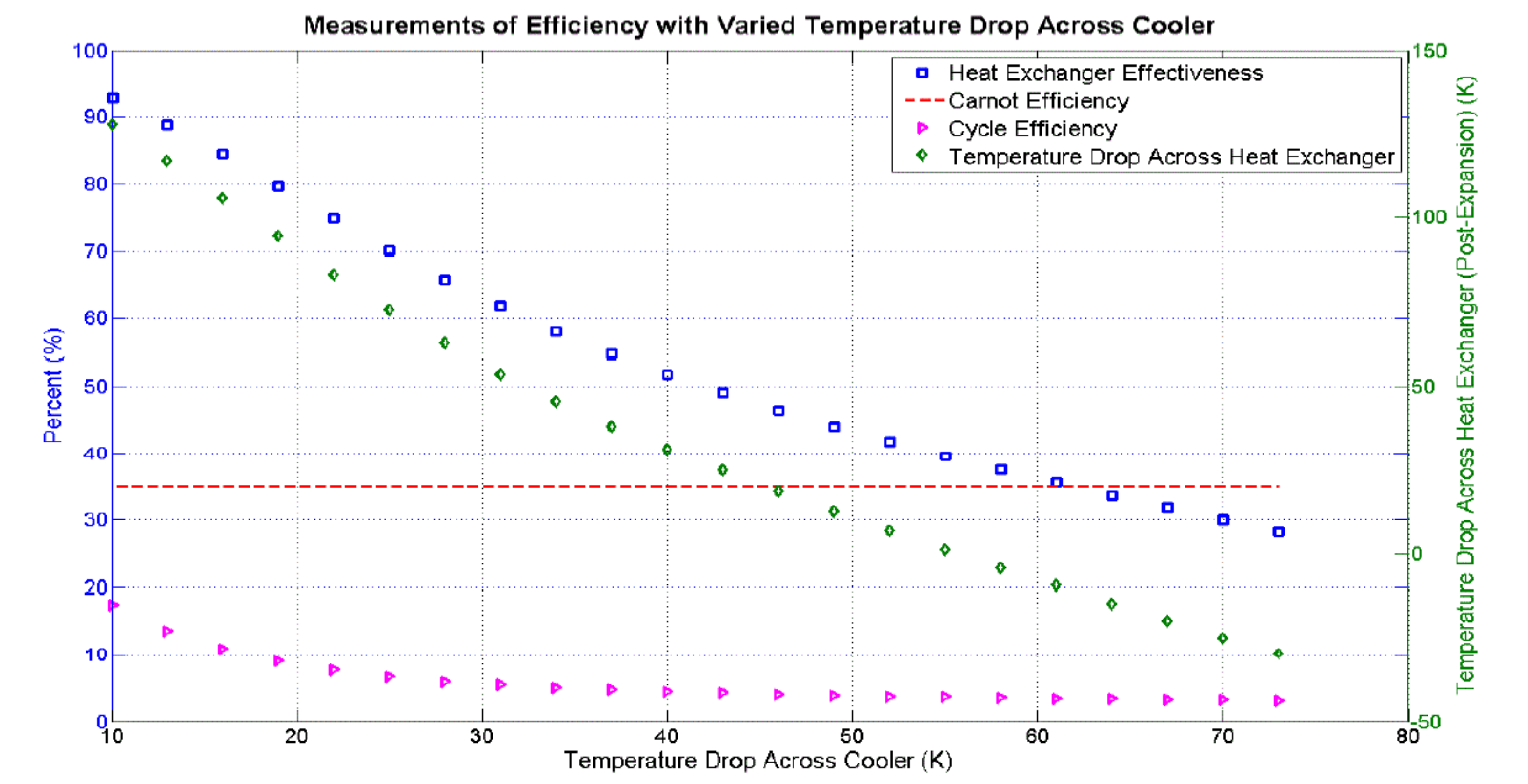


Figure 3. Cycle efficiency based on temperature drop over heat exchanger [2].

Design Concept

- Specifications
  - SCO2 Mass Flow Rate approx. 30 gm/s = 238 lb/hr
  - 300 RPM operating speed
  - 0.8~1.1 kW power generation
- The modular design shown in Figure 1 allows the ability to have multiple engines stacked in series as shown below in Figure 4

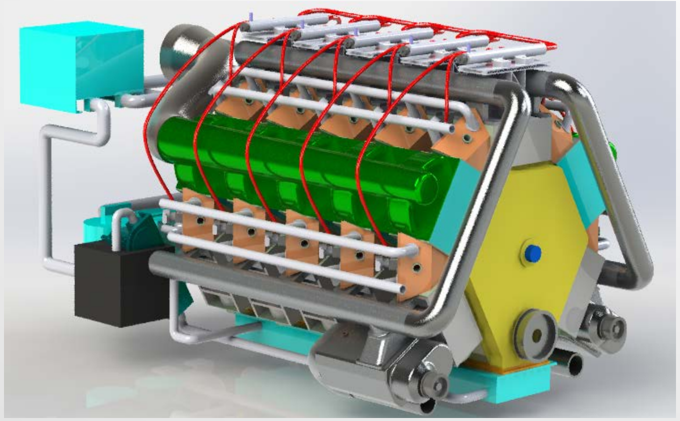


Figure 4. Stacked Polygon Expansion Engine Design Concept [3,4].

Thermodynamic Modeling

- A key component of the system design was the modeling of chamber pressure as this would drive all design modifications
- The modeling was centered around a polytropic model which spurred a new methodology for determining the polytropic index as detailed in [5]
- The chamber thermodynamic behavior is detailed in Figure 5 through Figure 7 below

Thermodynamic Modeling

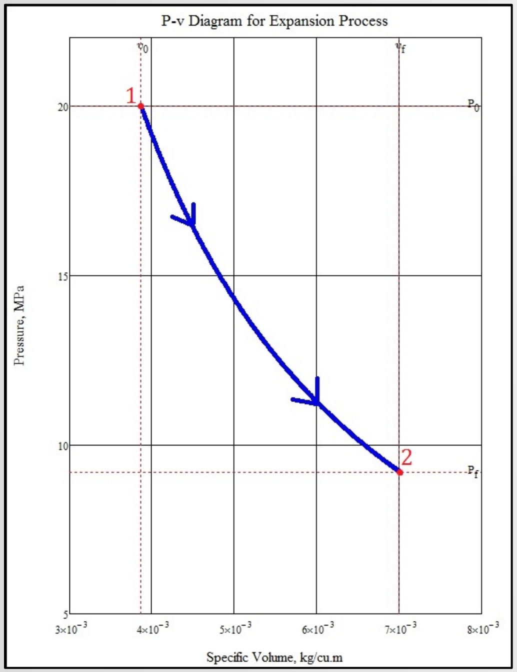


Figure 5. Pressure Volume Diagram of Expansion Process [5].

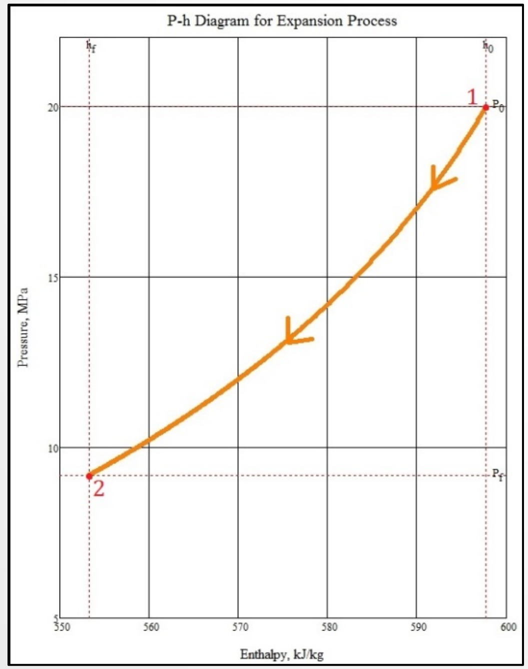


Figure 6. Pressure Enthalpy Diagram of Expansion Process [5].

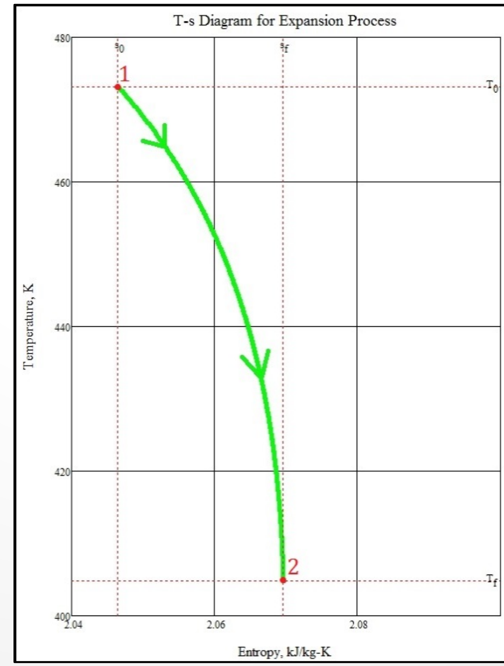


Figure 7. Temperature Entropy Diagram of Expansion Process [5].

Thermodynamic Modeling

- P,T, ρ as a function of stroke during expansion process
  - Note: SCO2 ρ remains below critical state during expansion, while p & T remain above critical state

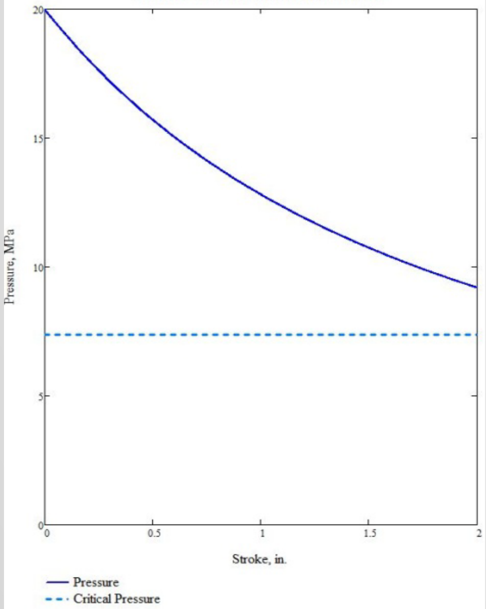


Figure 8. Pressure vs. Stroke [5].

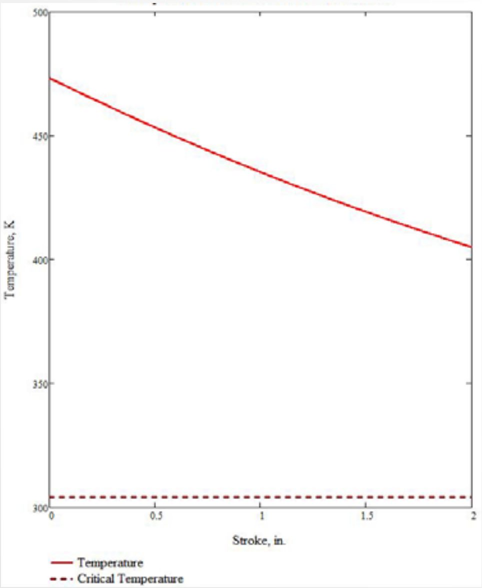


Figure 9. Temperature vs. Stroke [5].

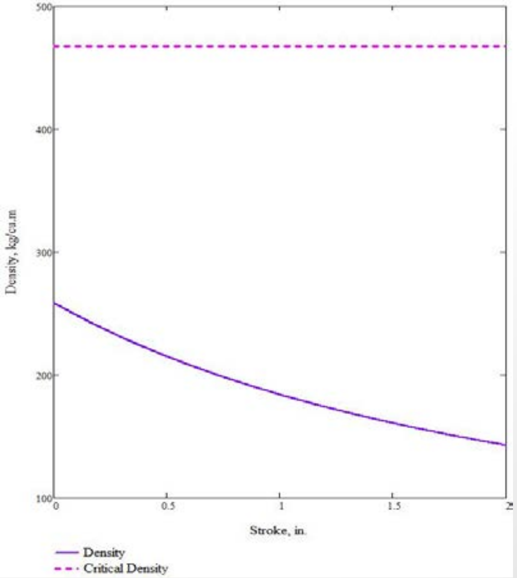


Figure 10. Density vs. Stroke [5].

Thermodynamic Modeling

- The nominal polytropic index was found per [5]

$$\frac{\left(n-2k_{avg}+1\right)}{(1-n)}\left[\left(2\zeta x_f+1\right)^{1-n}-1\right]=\frac{2\rho_o\left(u(\rho,T)-u_o\right)\left(k_{avg}-1\right)}{P_o}$$

k = Ratio of specific heats

n = Polytropic Exponent

$u(\rho,T)$ = Internal Energy of SCO2 per NIST REFPROPS

Table 2. Nominal Polytropic Index Iteration Procedure [5].

Iteration	T (K)	P (MPa)	T_{error} (%)	P_{error} (%)	k_{avg}/n
1	436	12.4	8	35	1.580/1.302
2	420	11.0	4	20	1.600/1.304
3	405	9.2	0.02	0.02	1.615/1.306

Manufacturing Methodology

- The manufacturing process selection was crucial to obtaining a design that could be produced
- An initial trade study was performed to determine the feasibility of using silicon carbide (SiC) due to low material costs, availability, and potential mechanical properties but was ultimately turned down due to lack of material standardization and machining costs involved when produced with the required strength specifications

Manufacturing Methodology

- Due to the relatively low operating temperatures, various steels were chosen to meet loading requirements and provide thermal expansion uniformities
- The present design is shown in Figure 11 as an assembly rendering

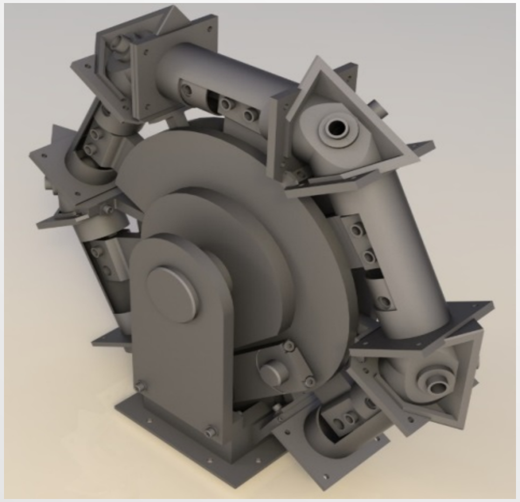
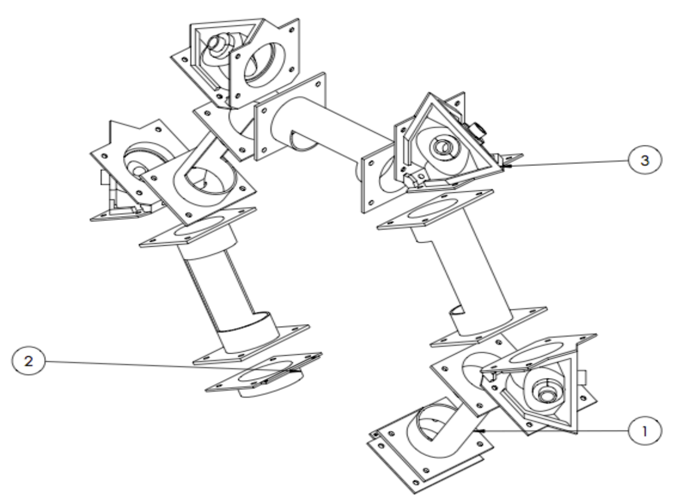


Figure 11. Assembly Rendering of SCO2 Expansion Engine

Manufacturing Methodology

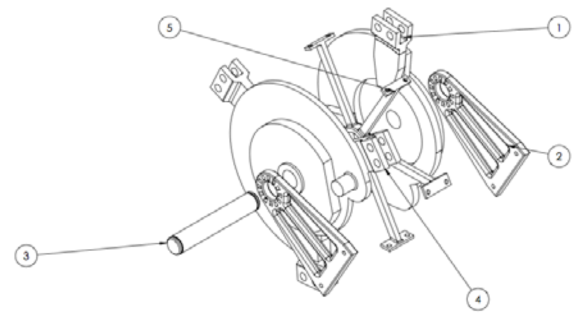
- Figure 12 through Figure 16 show detailed drawings of the primary components comprising the expansion engine design



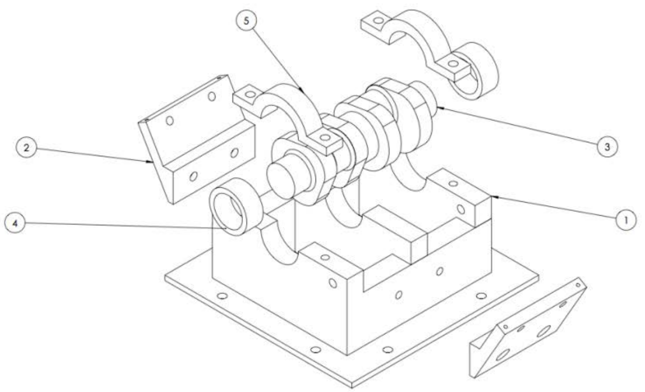
ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-802_B_exhaust-sleeve-standard_V2	EXHAUST_SLEEVE	AISI 1020	SAND CASTED/POST MACHINED	5
2	2500-701_A_end-piece_V2	END_PIECE	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	2500-206_A_corner-combustion_V2	CORNER_COMBUSTION_CHAMBER	AISI 1020	SAND CASTED/POST MACHINED	4

Figure 12. Detailed Drawing and Bill of Materials for Combustion Chamber Subassembly

Manufacturing Methodology



ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-604_A_back-disk	BACK_DISK	AISI 1020	SAND CAST/POST MACHINED	1
2	Main Shaft Support^Full Assembly	MAIN_SHAFT_SUPPORT	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	-1		AISI 1045 Steel, cold drawn	CNC MACHINED	1
4	2500-603_A_front-disk	FRONT_DISK	AISI 1020	SAND CASTED/POST MACHINED	1
5	-1		AISI 1020	SAND CASTED/POST MACHINED	1

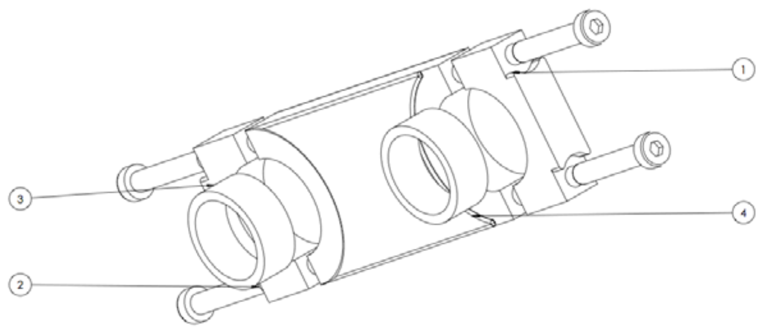


ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-501_B_crank-bearing-support_V2	CRANK_BEARING_SUPPORT	AISI 1045 Steel, cold drawn	SAND CASTED	1
2	2500-601_A_external-case_crank-support_V2	EXTERNAL_CASE_CRANK_SUPPORT	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	2500-515_A_crank-shaft	CRANK_SHAFT	AISI 1020	SAND CASTED/MACHINED	1
4	-1		AISI 1045 Steel, cold drawn	CNC MACHINED	3
5	2500-505_A_crank-bearing-cover	CRANK_BEARING_COVER	AISI 1045 Steel, cold drawn	CNC MACHINED	2

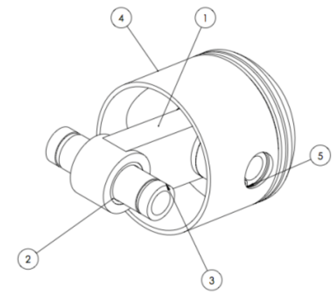
Figure 13. Detailed Drawing and Bill of Materials for Disc Subassembly

Figure 14. Detailed Drawing and Bill of Materials for Disc Crankshaft Subassembly

Manufacturing Methodology



ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-609_A_push_rod_end	PUSH_ROD_END	AISI 1045 Steel, cold drawn	CNC MACHINED	2
2	2500-608_A_Bolt_.38	BOLT_3/8"	STEEL	COATED	4
3	2500-516_A_neddle_bearing_cam	NEDDLE_BEARING_CAM	AISI 1045 Steel, cold drawn	CNC MACHINED	2
4	2500-610_A_push_rod_center	PUSH_ROD_CENTER	AISI 1045 Steel, cold drawn	CNC MACHINED	1



ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-614_A_piston_rod	PISTON_ROD	AISI 1045 Steel, cold drawn	CNC MACHINED	1
2	2500-220_A_piston_bearing	PISTON_BEARING	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	2500-219_A_piston_rocker_pin	PISTON_ROCKER_PIN	AISI 1045 Steel, cold drawn	CNC MACHINED	2
4	2500-205_A_piston_end-piece-dome	PISTON_END_PIECE_DOME	AISI 1045 Steel, cold drawn	CNC MACHINED	1
5	99142A390	INTERNAL_RETAINING_RING	STEEL	BLACK-FINISH	2

Figure 15. Detailed Drawing and Bill of Materials for Pushrod Subassembly

Figure 16. Detailed Drawing and Bill of Materials for Piston Rod Subassembly

Component Stress Analysis

- Finite element analysis using NX software was employed to predict the stresses in the major components of the SCO2 Polygon Expansion Engine
- Figure 17 through Figure 19 show typical results

Component Stress Analysis

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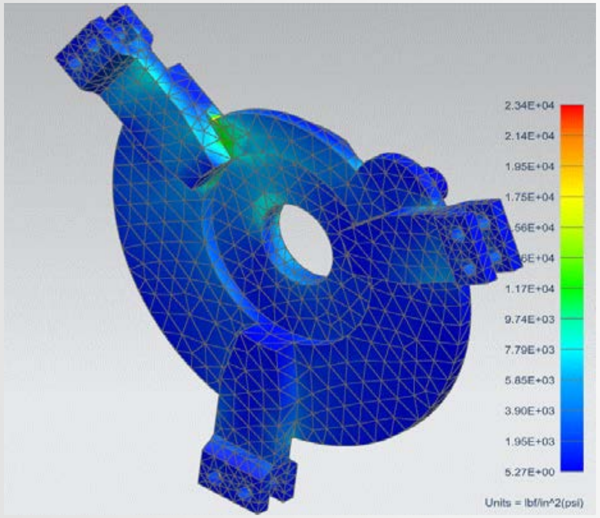

Figure 17. FEA Stress Analysis for Disc Assembly

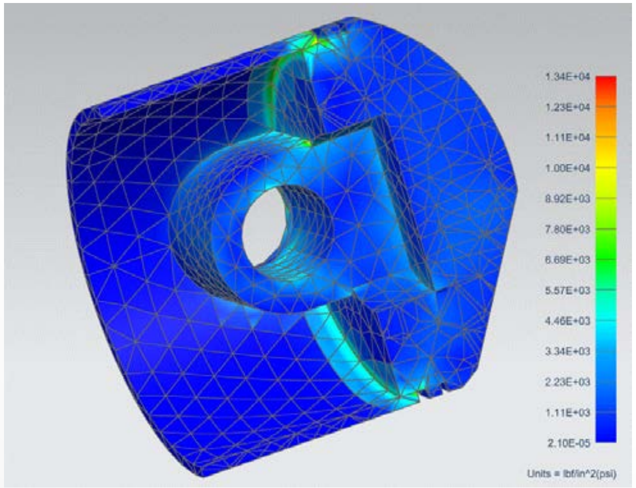

Figure 18. FEA Stress Analysis for Crankshaft Assembly

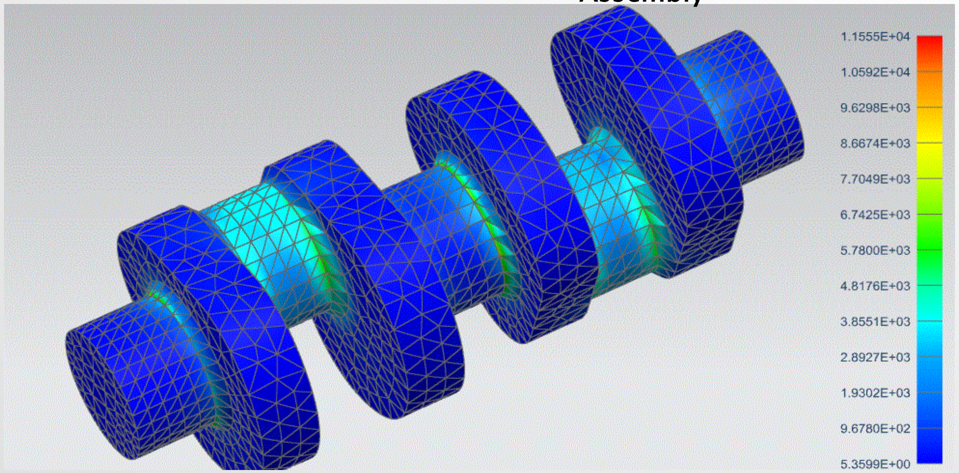

Figure 19. FEA Stress Analysis for Piston-head Assembly

Component Stress Analysis

- Detailed precision hand calculations were also performed at the machine component level based on the practices outlined in Shigley and Mischke [6]. Relevant findings are highlighted below in Table 3.

Table 3 – Relevant Stress Analysis Results

Engine Component	Stress Mode	Max. Stress (ksi)	F.S. (Static/Fatigue)
Wrist Pin	Bending	98	2.04/1.53
Connecting Rod	Compression	27	2.90/2.53
Center Shaft	Compression	48	2.93/1.50
Disc	Bending	16	4.57/4.95

Conclusions

- This paper summarizes the thermodynamic modeling, machine deign layout and component level stress analysis of a Polygon Expansion Engine for use in a SCO2 Waste Heat Recovery Cycle
- Working design
  - High specific power
  - Modular design for expandability
- Issues
  - Appropriate bearing choices
  - Good lubrication but unbounded by appropriate bearings
- Bottom line: Viable design with a few unbounded issues
- Future work will include
  - Analysis and design of lubrication system for the engine
  - Engaging venture capitalists and National Labs in order to sponsor the funding required to fabricate a proto-type working engineering model of the engine

References

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6. Shigley and Mischke, 1989, "Mechanical Design", McGraw-Hill, 5th ed., New York