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POLYGON EXPANSION ENGINE WASTE HEAT ENERGY SCO2 RECOVERY CYCLE THERMODYNAMIC ANALYSIS AND COMPONENT DESIGN

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ABSTRACT

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; an optimized thermodynamic cycle development was proposed that would center around a novel expansion device for extracting power from the sCO_2 working fluid. Following the cycle development it was determined that conversion of an experimental, existing two-stroke engine design would be modified to perform the job of an expander.

INTRODUCTION

The original engine design stemmed from a two-stroke design project sponsored by Butte Industries, Inc. [1,2] while the current evolution of the design stems from the works published in [3-5]. The Mollier diagram for the expansion process in conjunction with the waste heat recovery cycle is shown below in Figure 2. The pertinent thermodynamic state points for the expansion engine are summarized in Table 1.

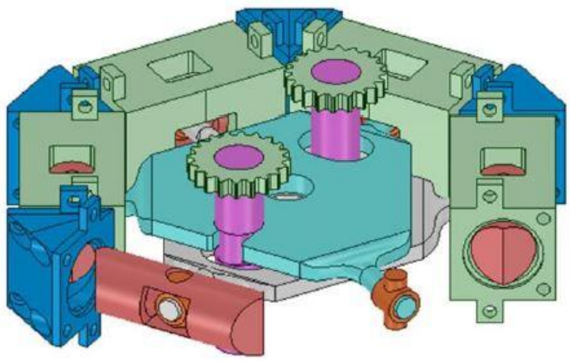


Figure 1. Polygon Expansion Engine Design Concept

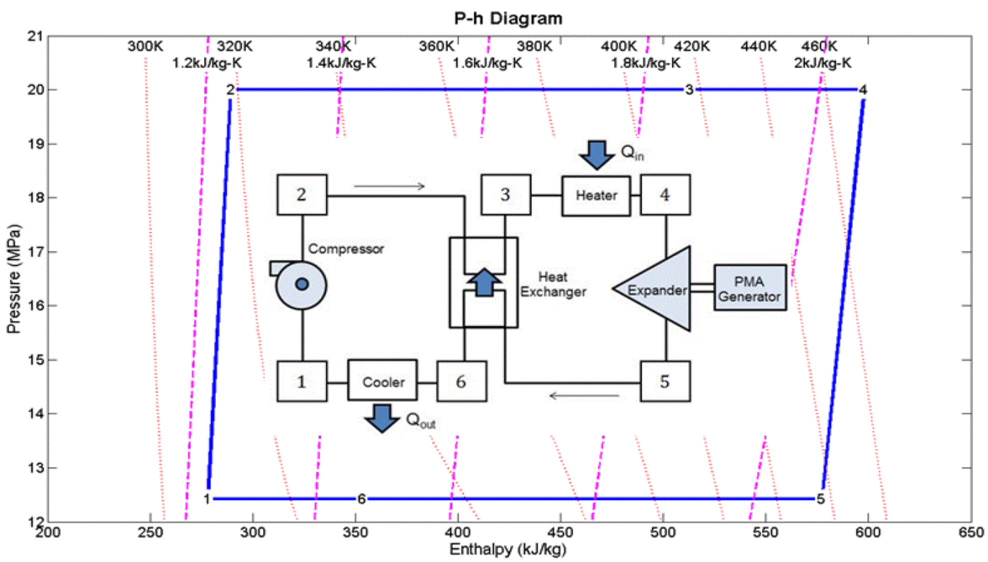


Figure 2. Mollier Diagram for SCO2 Waste Heat Recovery Cycle

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

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
4	473	20.0	258.82	597.79	2.05
5	436	12.4	176.78	577.23	2.08
6	328	12.4	537.76	353.29	1.47

The modular design shown in Figure 1 allows the ability to have multiple engines stacked in series as shown below in Figure 3.

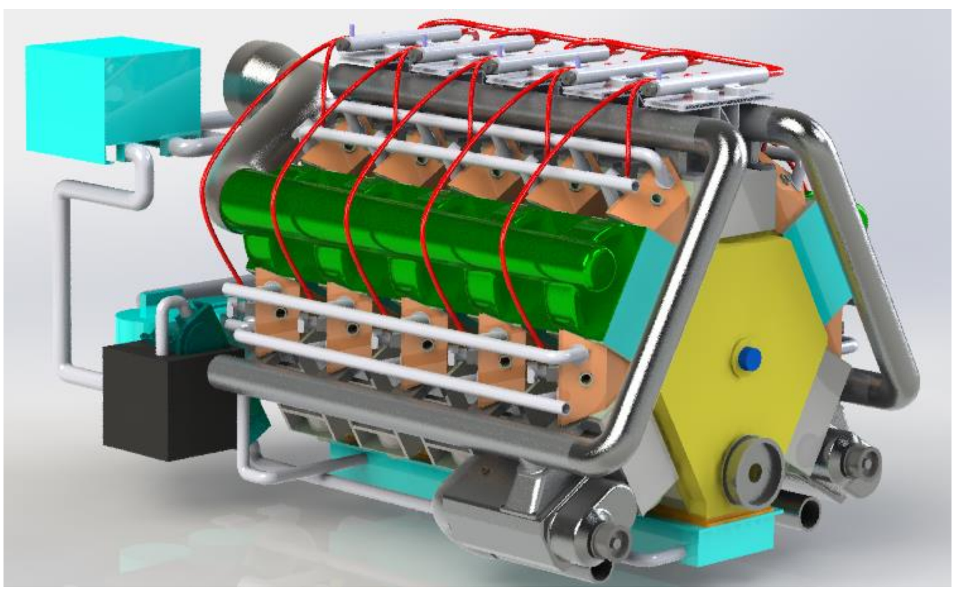


Figure 3. Stacked Polygon Expansion Engine Design Concept

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 4 through Figure 6 below.

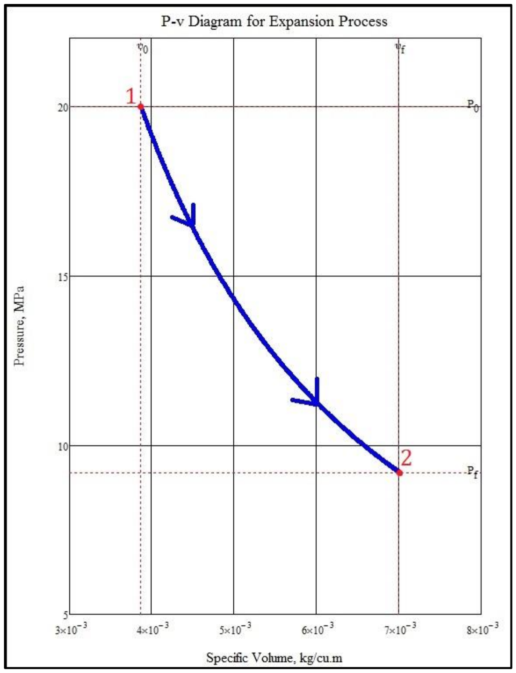


Figure 4. Pressure Volume Diagram of Expansion Process

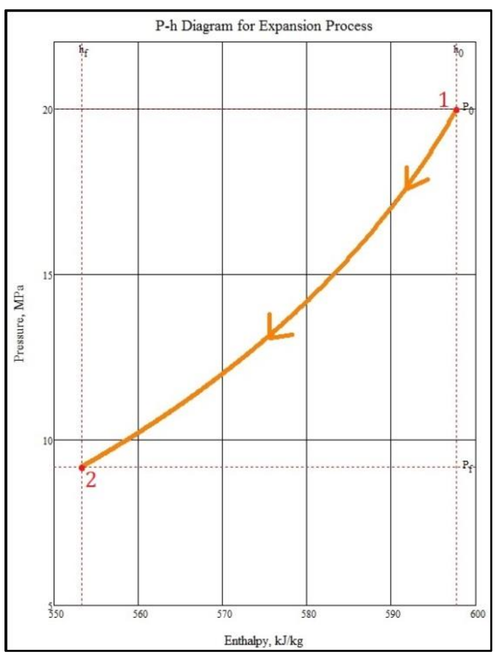


Figure 5. Pressure Enthalpy Diagram of Expansion Process

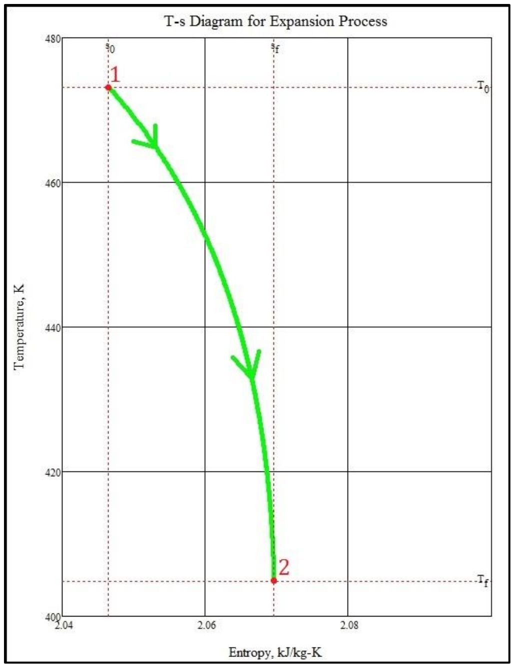


Figure 6. Temperature Entropy Diagram of Expansion Process

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 turned down due to lack of material standardization and machining costs involved when produced with the required strength specifications. 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 7 as an assembly rendering. Figure 8 through Figure 12 show detailed drawings of the primary components comprising the expansion engine design.

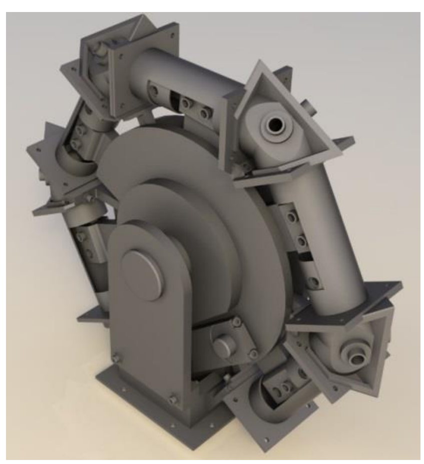
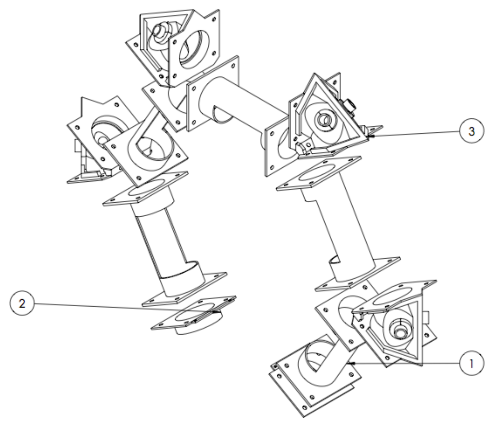
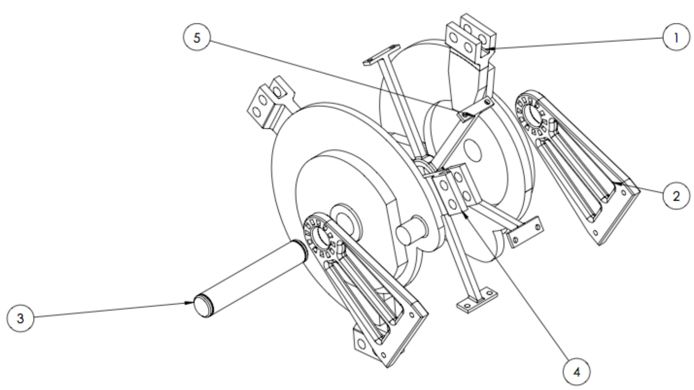


Figure 7. Assembly Rendering of SCO2 Expansion Engine



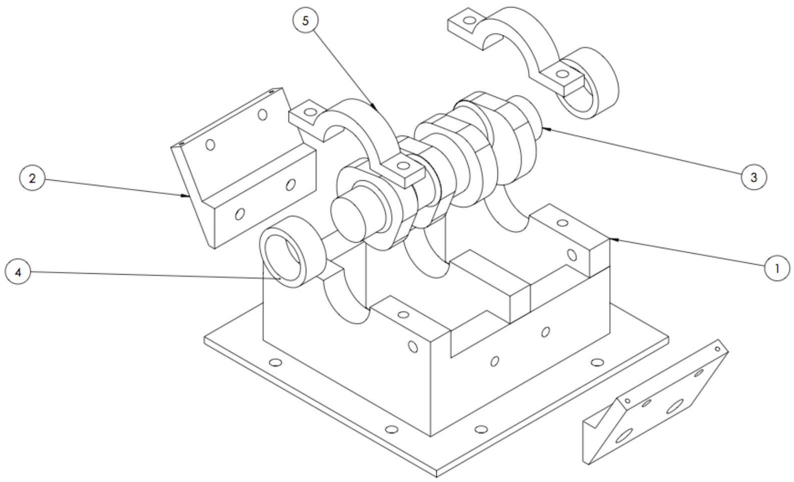
ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-802_B_exhaust-sleeve-standard_V2	EXHAUST_SLEEVE	AISI 1020	SAND CASTED/POST MACHINED	5
2	2500-701_A_end-piece_V2	END_PIECE	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	2500-206_A_corner-combustion_V2	CORNER_COMBUSTION_CHAMBER	AISI 1020	SAND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

Figure 8. Detailed Drawing and Bill of Materials for Combustion Chamber Subassembly



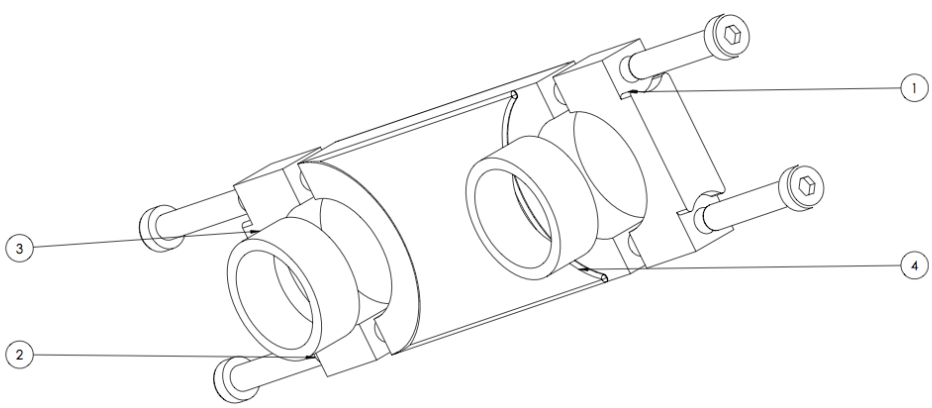
ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-604_A_back-disk	BACK_DISK	AISI 1020	SAND CAST/POST MACHINED	1
2	Main Shaft Support^Full Assembly	MAIN_SHAFT_SUPPORT	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	-1		AISI 1045 Steel, cold drawn	CNC MACHINED	1
4	2500-603_A_front-disk	FRONT_DISK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

Figure 9. Detailed Drawing and Bill of Materials for Disc Subassembly



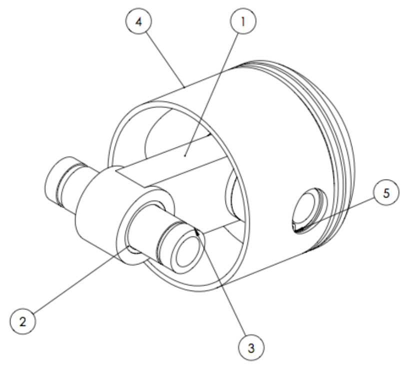
ITEM NO.	PART NUMBER	DESCRIPTION	Material	Finish	QTY.
1	2500-501_B_crank-bearing-support_V2	CRANK_BEARING_SUPPORT	AISI 1045 Steel, cold drawn	SAND CASTED	1
2	2500-601_A_external-case_crank-support_V2	EXTERNAL_CASE_CRANK_SUPPORT	AISI 1045 Steel, cold drawn	CNC MACHINED	2
3	2500-515_A_crank-shaft	CRANK_SHAFT	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 10. Detailed Drawing and Bill of Materials for Disc Crankshaft Subassembly



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

Figure 11. Detailed Drawing and Bill of Materials for Pushrod Subassembly



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 12. 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 13 through Figure 15 show the results.

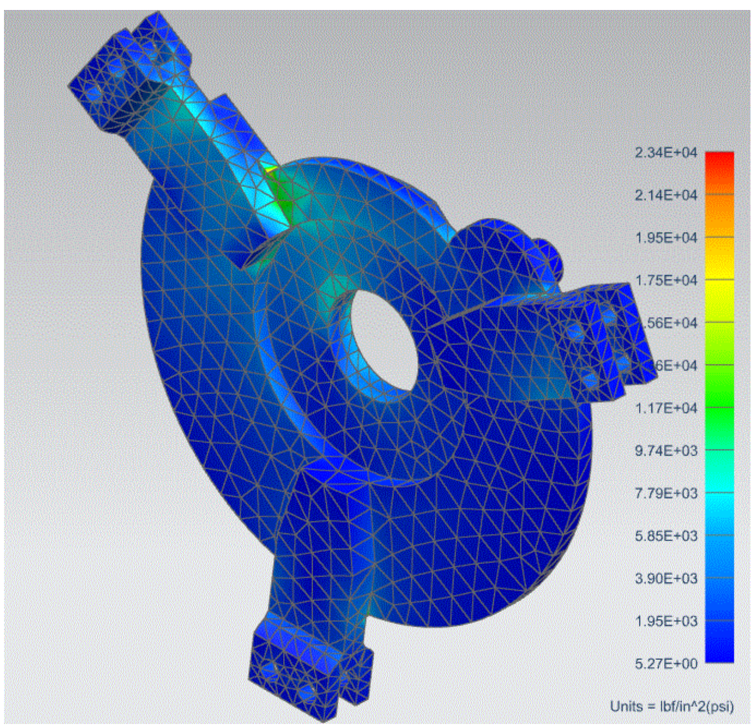


Figure 13. FEA Stress Analysis for Disc Assembly

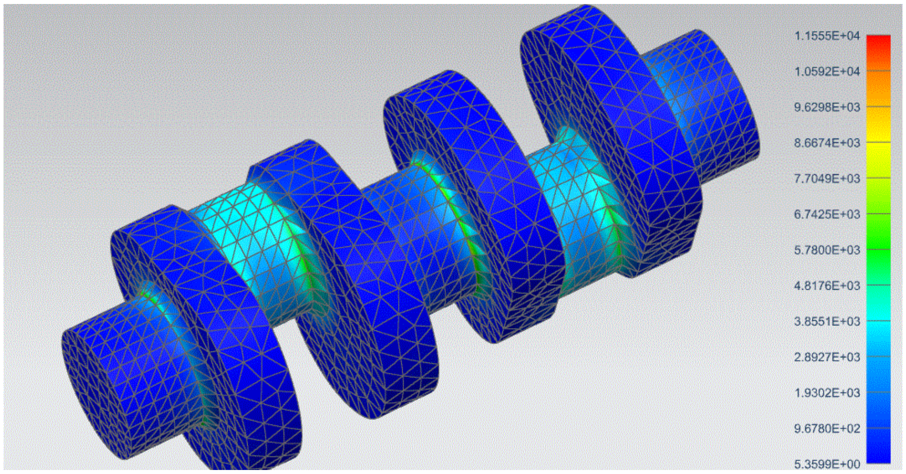


Figure 14. FEA Stress Analysis for Crankshaft Assembly

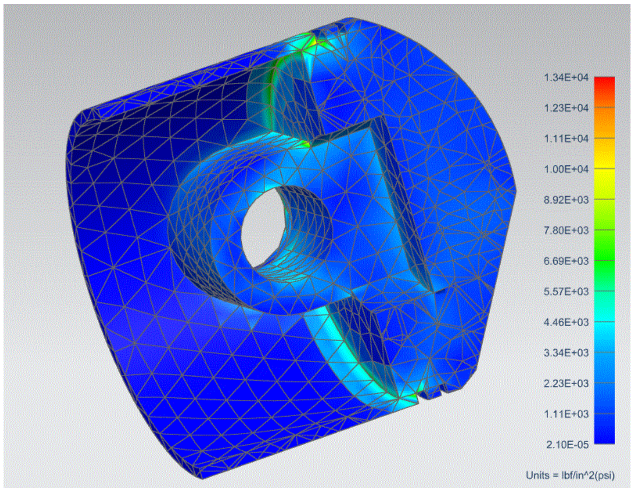


Figure 15. FEA Stress Analysis for Piston-head Assembly

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 2.

Table 2. Pertinent Machine Component 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. Future work will include engaging venture capitalists in order to sponsor the funding required to fabricate a proto-type working engineering model of the engine.

REFERENCES

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3) Yoshiba, L., Clark, A., Kirkland, R., Davison, D., Stover, S., Anderson, K.R., Cunningham, S., 2013, "System Engineering Based Design and Analysis of a Lightweight Polygon Engine" ASME International Undergraduate Research and Design Expo. Topic: 17-2 Undergraduate Design Projects. Poster Number: IMECE2013-66945, November 17, 2013, San Diego, CA.

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

ACKNOWLEDGEMENTS

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