LOW TEMPERATURE STIRLING ENGINE FOR GEOTHERMAL ELECTRICITY GENERATION

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Introduction

Oilfield operations have multiple opportunities to recover wasted thermal energy to generate electricity. While technologies currently exist to do so, improved efficiency at smaller scale would improve the economics and performance, and open additional opportunities for waste heat recovery (WHR). Cool Energy is building a 25kW (peak output at 400°C) heat recovery module based on a Stirling cycle process. This engine is currently under assembly and should begin testing in July 2015. One of the important heat sources for its application is WHR from co-produced fluids from oil wells in geothermally active areas. Based on prior work during Phase I in which 880 wells were sampled for temperatures and flow rates, it has been estimated that 470MW of generating capacity could be supported by the thermal energy from geothermally heated co-produced fluids. It is for this application and other low-temperature hear recovery opportunities that Cool Energy has scaled its successful 3kW electricity generators to the 25kW scale.

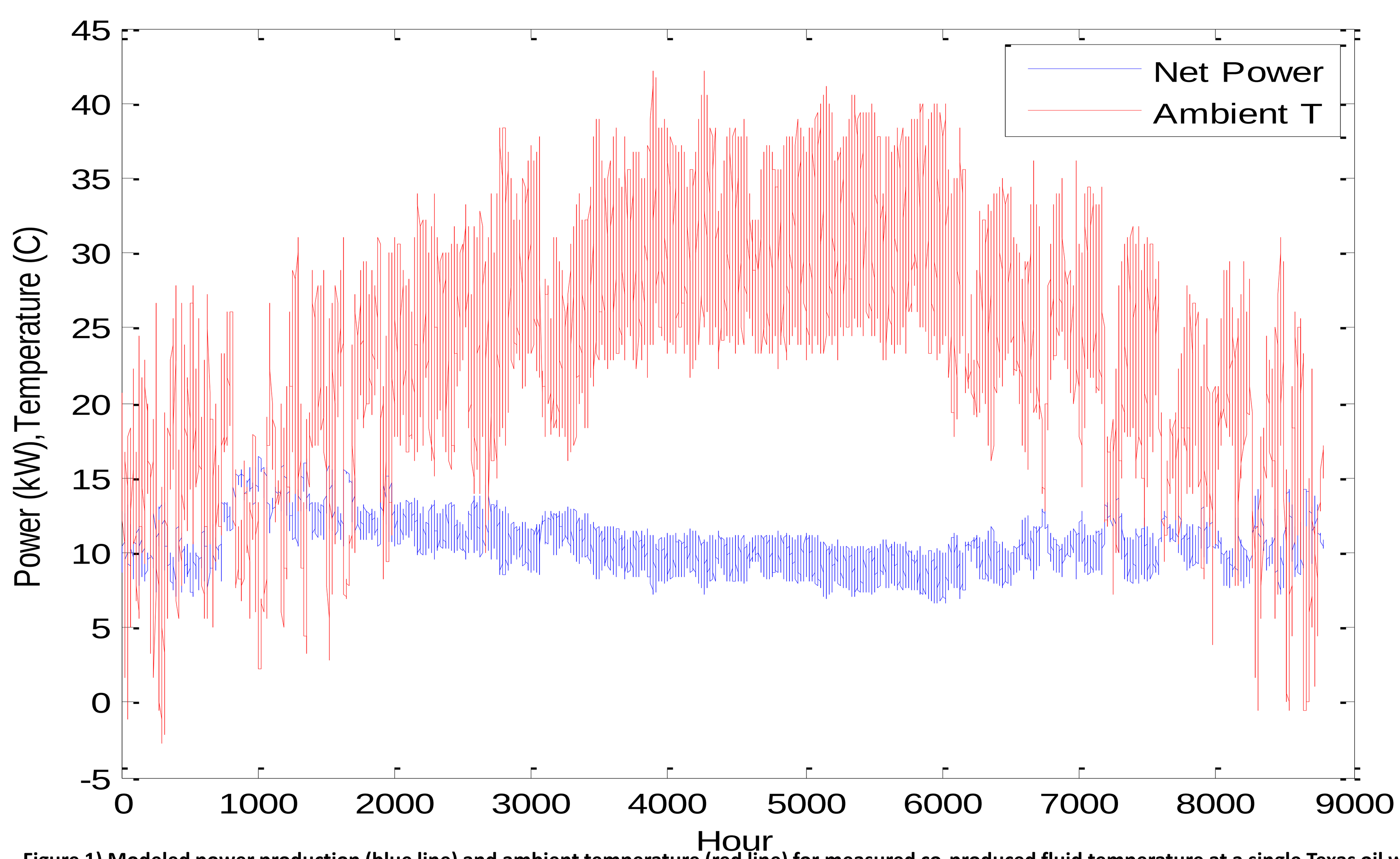


Figure 1) Modeled power production (blue line) and ambient temperature (red line) for measured co-produced fluid temperature at a single Texas oil well.

Methods

In order to design a module capable of economically generating electricity from small-scale, low-to-medium temperature applications, two main options were developed in the Phase I work. Both options were configured for a vertical orientation (tall and relatively narrow for the most economical pressure envelope). The two options considered in the early design in Phase II were similar in their heat transfer and power generation components, but different in their kinematic lower transmission linkages. The engine's thermodynamic configuration is a 4-cycle single-acting alpha arrangement, with separated hot and cold piston/cylinder pairs in each thermal cycle. Thermal energy is delivered to the hot side heat exchangers using a circulating heat transfer fluid such as Therminol, and thermal energy is rejected from the cold-side heat exchangers into a water/glycol solution which circulates through a heat rejection device such as a fan-coil radiator. The two kinematic linkage options studied were a barrel-cam and carriage option and a Watt-linkage/cam-wedge option. After initial design studies, the latter approach was selected to minimize reciprocating mass. Subsequent to that down-selection, parallel thermal system and mechanical system design efforts commenced, which employed proprietary thermodynamic and mechanical models implemented in Excel macros.

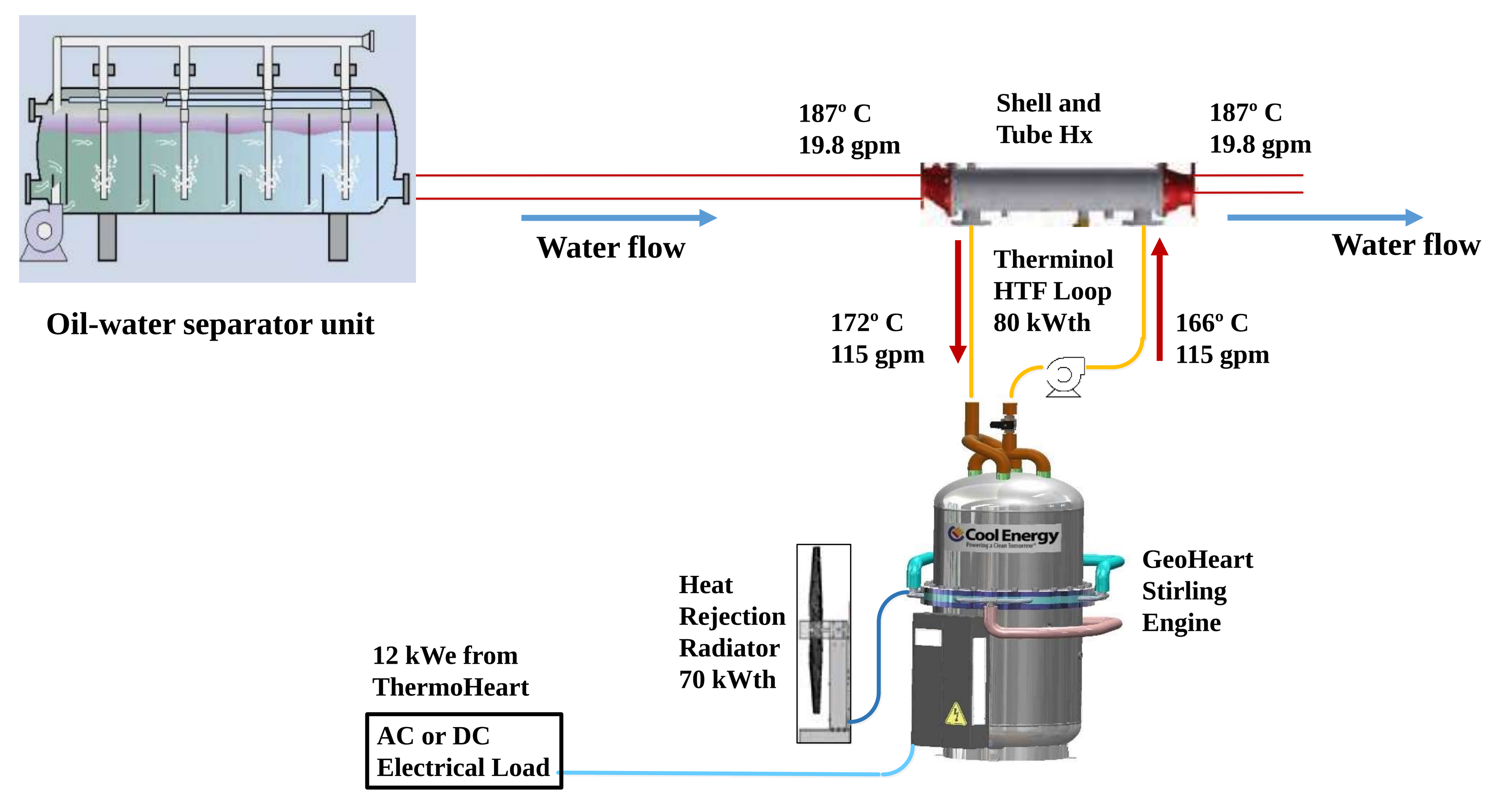


Figure 2) Schematic diagram of WHR system from an oil-water separation unit. Temperatures and flow rates and power flows are shown for each interface.

Thermodynamic and Mechanical Dynamics Results

In order to generate the target output power levels for the scale of engine module desired, two models were updated: the thermodynamic model and the mechanism dynamics model. The thermodynamics model allows designers to optimize thermal to electrical conversion efficiency at the specific operating conditions, and produces design outputs such as the dimensions of heat exchangers, number of heat transfer tubes in heat exchangers, regenerator screen mesh and dimensions, and operating speed. This is a necessary design step, but is insufficient to complete an engine design because it does not incorporate mechanism dynamics, which impose the strength requirements on the mechanical transmission components within the Stirling engine. In order to derive the mechanism performance, the output pressure waves in the engine working gas which drive the reciprocating pistons are first produced. These piston forces are then imported into a separate model focused on the transmission system that turns the linear motion of the engine pistons into rotary motion to drive an electrical generator. The mechanism model enables the calculation and optimization of component characteristics such as bearing sizes and types, mechanism component strength requirements, counter-mass weight requirements, and the interaction of the operating pressure of the gas within the engine with the operating speed of the engine.

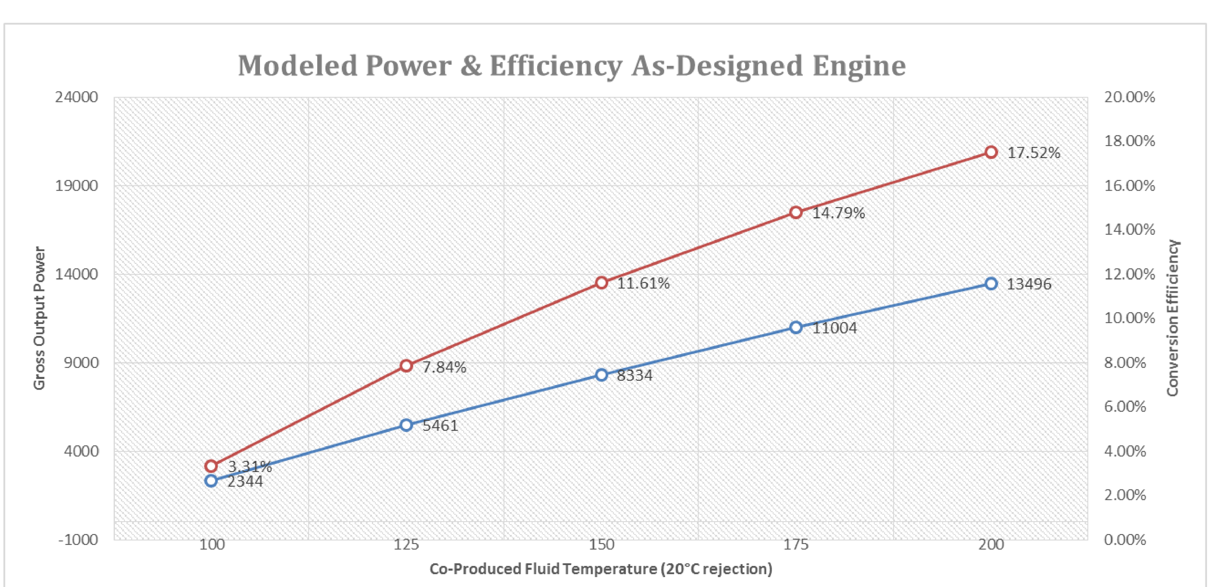


Figure 3) Modeled power output (blue line) and efficiency (red line) for the GeoHeart Stirling engine over the co-produced fluid temperature range. This is the type of performance modeling provided by the thermodynamic modeling tool developed by Cool Energy.

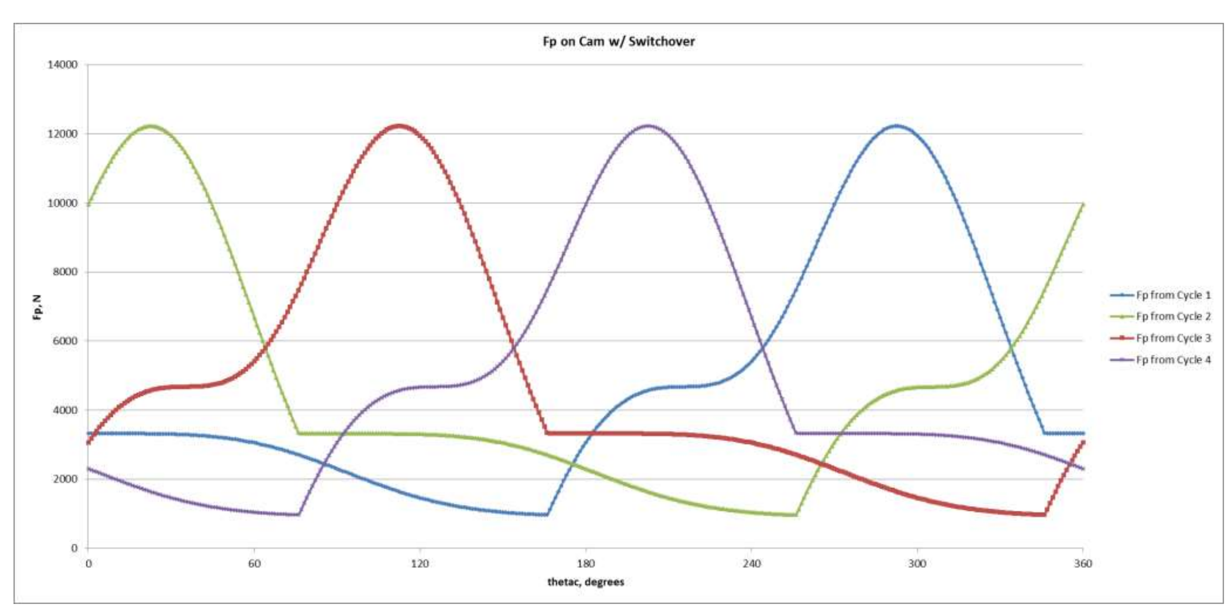


Figure 4) Forces on the cam of the kinematic linkage mechanism for each of four cam followers. This is the type of component development requirement provided by the dynamic mechanism modeling tool developed by Cool Energy.

Conclusions

As a result of the iterative, integrated engine modeling approach, a few conclusions were reached. The engine could be successfully designed for the target of 20,000 hours of operation between services even at the most extreme temperatures for which it is designed in this application (-30C rejection temperature, 200C hot side temperature). As additional fidelity was brought to the loss models in both the thermodynamic models as well as the mechanism models, the expected performance of the engine went down somewhat in the produced water application. A second conclusion, which was unexpected, is that the operating pressure of the engine couples with the engine operating speed to have impacts on the bearing lifetime. In other words, for each combination of hot side temperature, cold side temperature, and engine charge pressure, there is a speed that the engine can be operated at which will maximize bearing lifetime. For the expected operating conditions in the co-produced fluid application, operating at 600rpm will produce an average service interval on engine internal components of 30,000 operating hours, or almost 4 years.

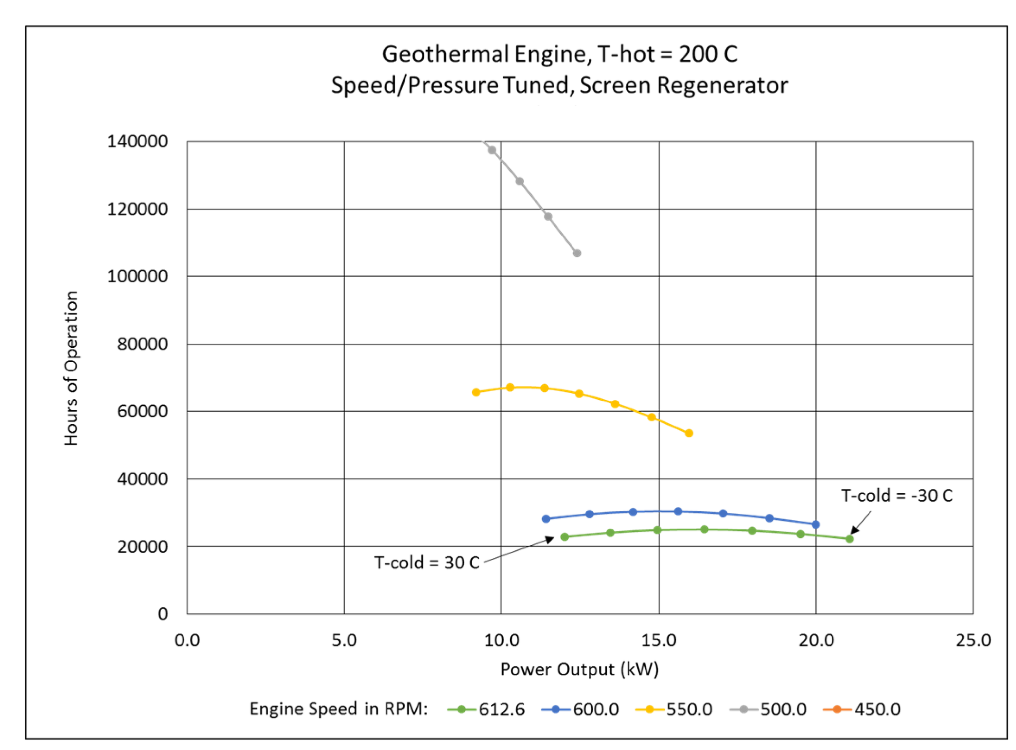
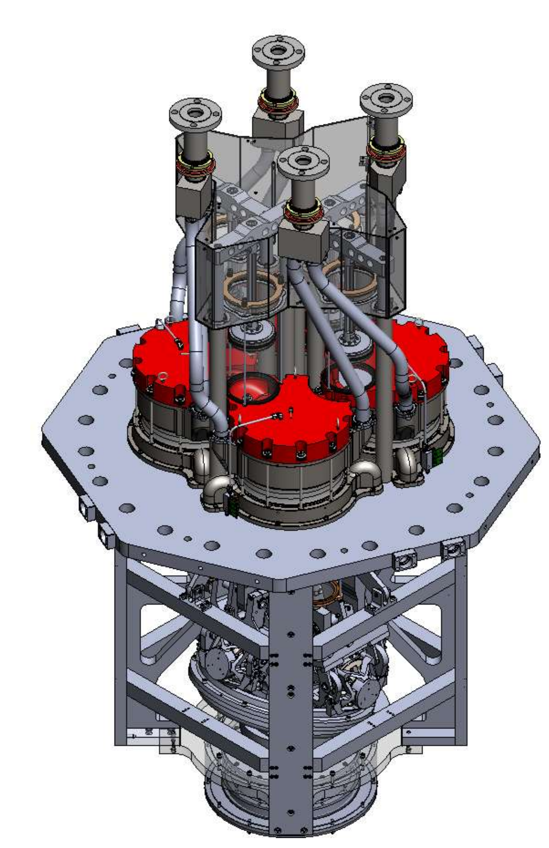
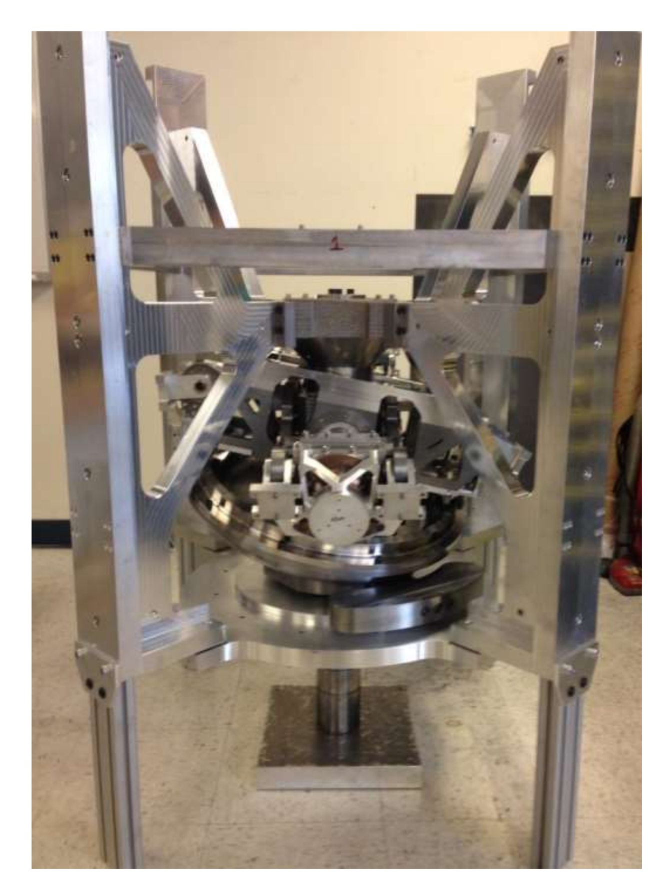


Figure 5) Chart of combined bearing lifetime and output power as a function of rejection temperature and engine speed. This leads to a speed requirement based on charge pressure.

Summary of Results and Findings

- Detailed thermodynamic design complete, specifying all aspects of the designs of the heat exchangers, regenerators, piston stroke and bore, cylinder lengths, engine speed and heat transfer fluid flow rates
- Detailed mechanical design complete, specifying all aspects of chassis, frame, rotating mechanical components, bearings, Watt linkage, and connection to the hot and cold pistons.
- Engine successfully designed to eliminate need for a kinematic mechanism on hot side of engine. A single kinematic mechanism provides proper phasing for both hot and cold pistons through offset thermal cycles and common cam follower mounting points.
- Low-cost high-surface-area heat exchanger fabrication method prototyped at small scale, and final heat exchangers fabricated at full scale
- Electrical alternator specified and procured
- Control and electrical power-handing system specified and ordered
- Thermal testbed designed and ordered
- Initial engine assembly in process



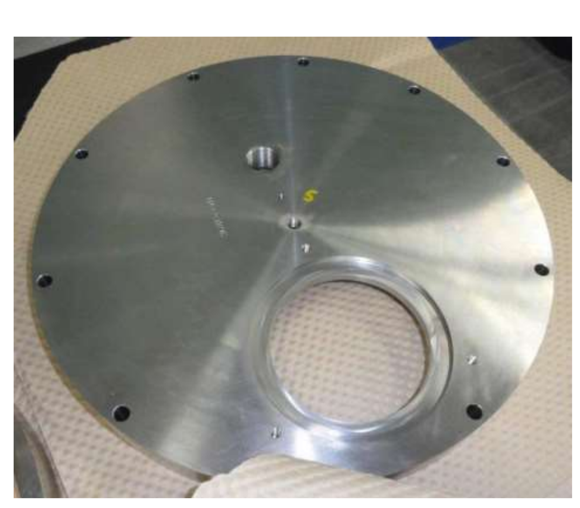


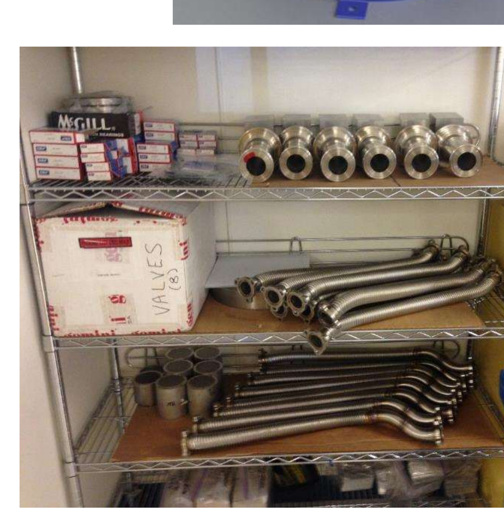
Tools Developed During Project

- Enhancements to existing thermodynamic computer modeling and design tool
- New computer model for kinematic mechanism, including mechanism dynamic positions, speeds, forces, and acceleration at all rotating positions
- Enhancements to computer models for co-produced fluid application, including ability to automatically simulate available production from a range of engine modules

Future Work

Under the Phase II grant, Cool Energy will complete assembly of the 25kW engine and begin testing. In parallel, Cool Energy has joined a business accelerator with a group of companies focused on improving sustainability in oil and gas operations, as well as contacted several suppliers to the oil and gas industry whose equipment produces waste heat. Cool Energy will work with those groups to find pilot sites on which to deploy heat recovery power generation systems for co-produced fluids or other heat recovery opportunities.





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