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Geothermal ORC Systems Using Large Screw Expanders

Tim R. Biederman
cyrq, United States of America, tim.biederman@gmail.com

Joost J. Brasz
cyrq, United States of America, syracuseturbomachinery@gmail.com

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Tim BIEDERMAN
Cyrq Energy
Salt Lake City, UT
tim.biederman@cyrqenergy.com

Joost J. Brasz
Syracuse Turbomachinery
Syracuse, NY
syracuseturbomachinery@gmail.com

ABSTRACT

This paper describes an air-cooled low-temperature Organic Rankine Cycle (ORC) Power Recovery system with a screw expander as its power unit. The screw expander is specifically designed for ORC expansion and has a unique rotor profile. Manufacturing the screw expanders at a plant which already produces screw compressor hardware has resulted in reduced development time and lower development cost. Low screw expander cost has been realized by assembling the screw expanders in parallel with the higher volume screw compressors. The net electrical output power of the system's ORC screw expander varies from 5kW to 950 kWel which is an order of magnitude larger than the output power of currently available ORC screw expanders. Following the development of a 300 kWel prototype unit and its installation and successful operation at Chena Hot Springs near Fairbanks, AK, four commercial production units were developed for geothermal power production at Lightning Dock in New Mexico. All units use R245fa as refrigerant. Initial operating experience with these ORC systems will be presented.

1. INTRODUCTION

Turbo expanders have been used commercially for low temperature waste heat power recovery ORC systems in capacities varying from 50 kWel up to multi-MWel electrical output power. Commercially available ORC screw expander power output has up until now been limited to values below 100 kWel.

A screw compressor company in Shanghai, China, produces a family of large capacity R134a screw compressors used on water- and air-cooled chillers. It has developed R245fa screw expanders for ORC duty in addition to these large capacity R134a screw compressors. This reduced the expander development time dramatically. A similar approach was followed for the heat exchanger components: the preheater module and the air-cooled condenser share a lot of communality with existing HVAC equipment. This paper will describe the procurement, field installation, start-up and system optimization of one of the four 1 MW screw expander based ORC systems.

The pure size of a 1 MW air-cooled ORC system eliminates the possibility of a factory assembled unit that could be tested and optimized before shipment to the final site. Shipment of the various modules in separate containers is required to be followed by field erection of the complete unit system. Chapter 2 describes and illustrates the various components that make up a complete ORC system such as expander, air-cooled condenser, preheater, boiler, refrigerant pump, connecting piping, oil separator, oil pump module, power generator and synchronizing equipment. Chapter 3 shows the plant layout of the four 1 MWel units with respect to the geothermal production well and the reinjection well with the temperatures of the entering and returning heat source temperatures. Contrary to packaged equipment that is optimized at the factory, field erected equipment has to be optimized on site. Chapter 4 describes system optimization with respect to condenser fan power and working fluid charge, focusing on its liquid level in the evaporator. After these system optimizations evaporator pressure was increased to reach the design capacity of 1 MWel as described in Chapter 5. The initial shortfall in net output power was attributed to the presence of non-condensables which manifested itself by a pressure in excess of the expected saturation pressure. The 1 MWel net power was achieved after removal of the non-condensables with a purge unit as described in Chapter 6. The main conclusions are listed in Chapter 7.

2. COMPONENTS, PROCUREMENT AND FIELD ERECTION

Figure 1 shows a picture of the final factory assembly of the screw expander:

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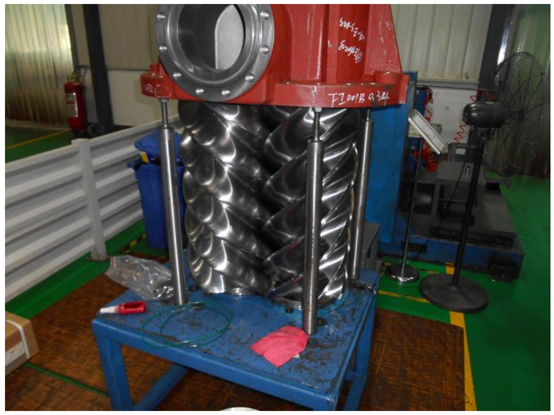

Figure 1 Screw expander assembly

The air-cooled condensers were procured from the factory in Anji, China. Forty air-cooled condenser modules were required for the four 1MWel ORC units. Figure 2 shows a completed air-cooled condenser module.

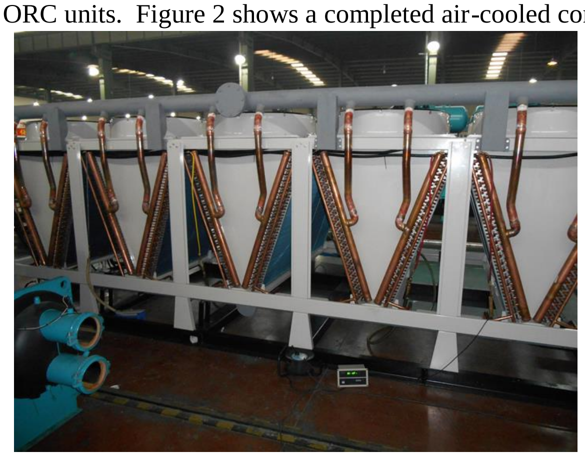

Figure 2. Condenser Module Assembly:

In the third and largest factory in Quzhou, China, the pre-heater module, evaporator module, oil separator module, and oil pump module were fabricated and assembled. The pre-heater module consists of two pairs of parallel refrigerant pumps, four motors, a liquid filter, and four heat exchanger tubes. One of the completed preheater modules can be seen in Figure 3.

Figure 3. Preheater assembly

Figure 4: Evaporator Module Assembly

Figure 5: Generator and Synchronizing Equipment

The evaporator module consists of an evaporator, expander, vapor filter, synchronous generator, and an oil recovery system designed to skim any oil that might collect in the evaporator. This module also houses the synchronization equipment and controllers. Figure 4 and Figure 5 are pictures of an evaporator module.
The oil separator skid consists of two large oil recovery tanks. These tanks have a grid filtration system in them that helps separate the oil from the refrigerant. Figure 6 shows an oil separator module under assembly. The last module required in the unit is the oil pump skid. This is the smallest module consisting only of the oil pump, oil pump motor, and an oil filtration system. Four of these modules are shown in Figure 7.

Figure 6: Oil Separator Skid

Figure 7: Oil Pump Module Assembly

In addition to the modules, the screw compressor company also produced piping for four condenser collection systems, four VFD cabinets for the refrigerant pumps, 40 VFD cabinets for the air cooled condensers, and four resistor cabinets used for unit start up. The last shipment of equipment left Shanghai on October 3rd, 2013. The equipment spent two weeks traveling by boat from Shanghai to Long Beach, CA. Once in Long Beach the equipment had to be offloaded and go through U.S. Customs. This took from a few hours to several days per container. After clearing Customs, the equipment was trucked to the power plant site in Animas, New Mexico. The total shipment included 45 containers of equipment and took about 16-20 days to be delivered from Shanghai to the construction site in New Mexico. The geothermal plant construction took two months. This included assembly of the well field piping that would carry the geothermal water to and from the units, the piping between the modules, plant grading, four blow down ponds for system evacuation, the electrical connection for the units, and the connection to the grid. There were 61 piping connections per unit, 20 well field piping connections, hundreds of feet of cable, and thousands ofterminations to complete the units and connect them to the grid. The construction was done on a unit-by-unit basis and was approached in a systematic and efficient way. First the units were completed mechanically. The units had all of their piping and field welds complete. All of the modules were mounted on their skids and buttoned up. Electricians began wiring the refrigerant pumps, oil pump, condenser fans, and communications sensors. Simultaneously, leak and vacuum tests were performed on each mechanically complete unit. The leak tests were conducted by pressurizing the unit up to 80psi and holding the pressure for 24 hrs. After the leak test, the unit was placed under vacuum and held for another 24hrs. Upon completion of the electrical connections and mechanical testing, site personnel performed instrument installation and testing. This process included testing valves, checking rotational direction of pumps and fans, and verifying sensor values. The first unit was completed and commissioned on December 4th 2013. The fourth unit was completed on December 24th 2013. Design, manufacturing, construction, and onsite testing for all four of the 1MW units were completed in less than four months.

3. PLANT LAYOUT

The layout of the plant is very simple. Currently there is only one production well and one injection well. The production well sits in the aquifer that has the 315 ^{0}F geothermal water that is the fuel source for the plant. This well sits approximately 150 ft away from the units and can flow up to 1300 gpm. The injection well is the well that the geothermal water goes down after the units have finished extracting heat from it. It is important that each well can handle the amount of flow that the units will take. If either well cannot give or receive the correct volume of water the units become limited in how much power they can produce. After coming out of the production well, the water flows to the units. The units feed off the geothermal water line in series. The flow is controlled by a valve on the injection side of the unit. The flow through the units must be maintained such that the injection temperature remains above 150^{0}F. Minerals begin to drop out when the temperature is below 150 ^{0}F. This will cause scaling in the system and reduce the plants power output. Figure 8 is a simple diagram of the plant layout.

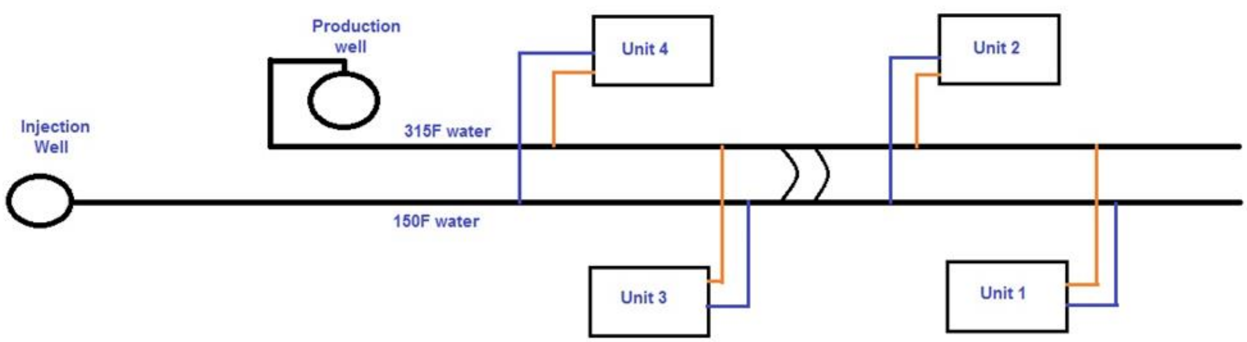

Figure 8: Lightning Dock Site Layout

4. SYSTEM OPTIMIZATION

The units have a variety of controls and set points that must work in unison for the power plant to operate at peak efficiency. For example, for a unit to perform at its peak power output, the system's differential pressure, maximum evaporator temperature, and power output set points must be aligned so that any one of them does not restrict the other two. A restriction in any one of these set points will cause to unit to fall short of its optimal efficiency and peak output. Once the set points are balanced, the unit's output can be further optimized by adjusting the air cooled condenser fan frequency and the refrigerant liquid level in the evaporator.

Optimization of the air cooled condenser fans was done by testing various fan frequencies at a given ambient. Since the ambient temperature is the cold side of the system, it has tremendous effect on the condensers. In all heat exchangers, the rate of exchange is defined by the temperatures of the hot and cold sides as well as the mass flow rates of both sides. Increasing the fan frequency does not reduce the temperature of the air crossing the condensers, but does increase the mass flow. In order to determine which fan frequency provided the optimal mass flow, a number of frequencies were tested with an ambient temperature of 62^{0}F. The frequency range tested was from 25-40Hz and the optimum was found to be 30Hz. Figure 9 is a plot with the results of the testing.

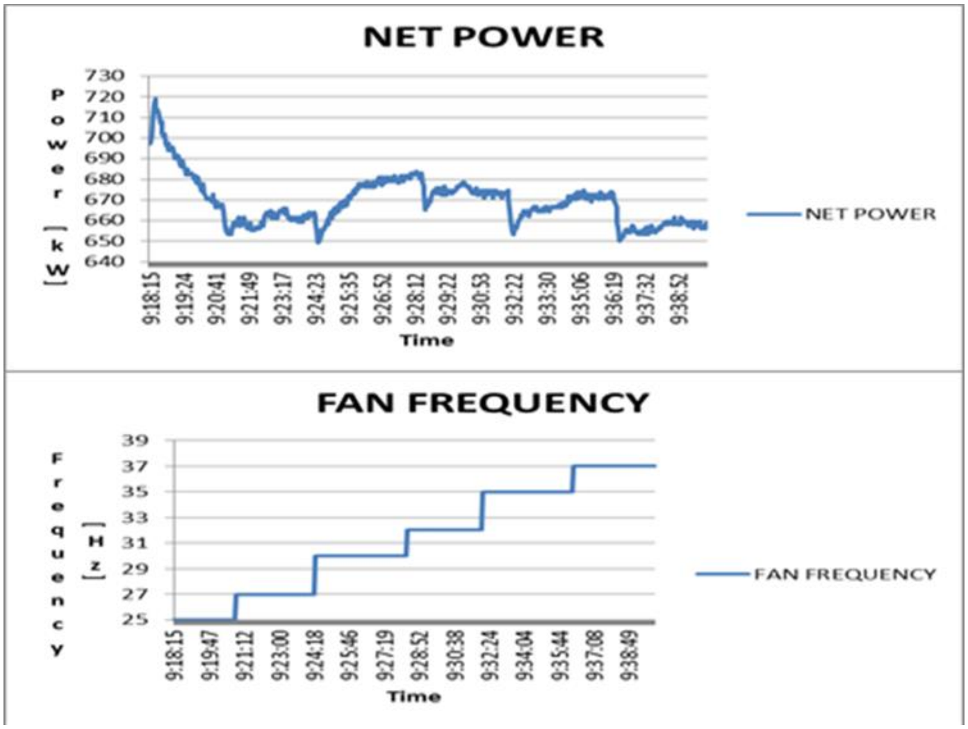

Figure 9: Condenser Fan Frequency Optimization

The optimization of the evaporator level was a more lengthy process that required several iterations. The evaporator level controls the temperature and pressure of the refrigerant as it goes into the expander. The screw expander runs optimally right on the saturation line. To optimize this, the evaporator level was varied by controlling the refrigerant pumps. The was done over a 24 hour period and the results showed peak evaporator pressures and temperatures around a 575 mm evaporator level. The results of the test are plotted in Figure 10 and Figure 11.

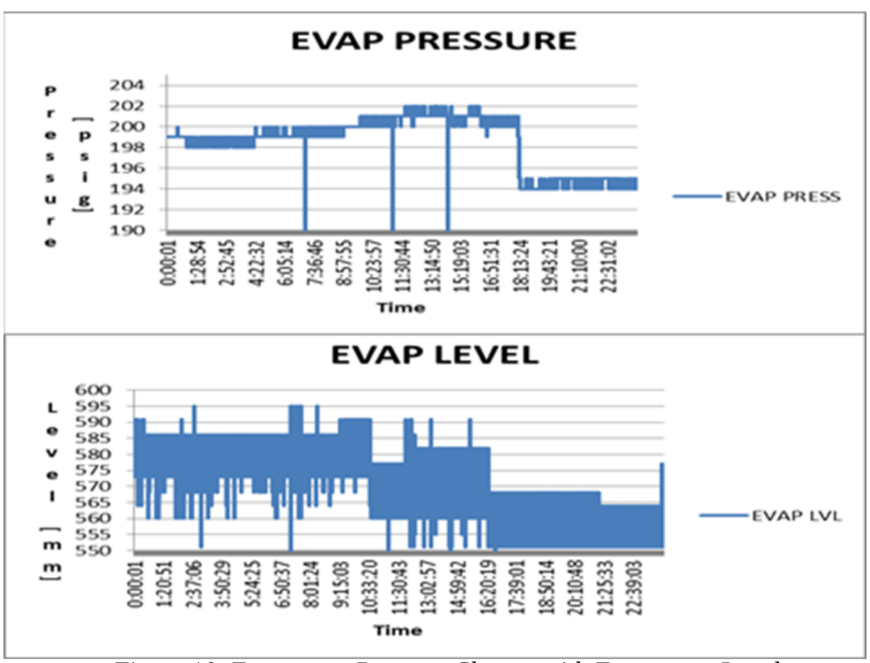

Figure 10: Evaporator Pressure Change with Evaporator Level

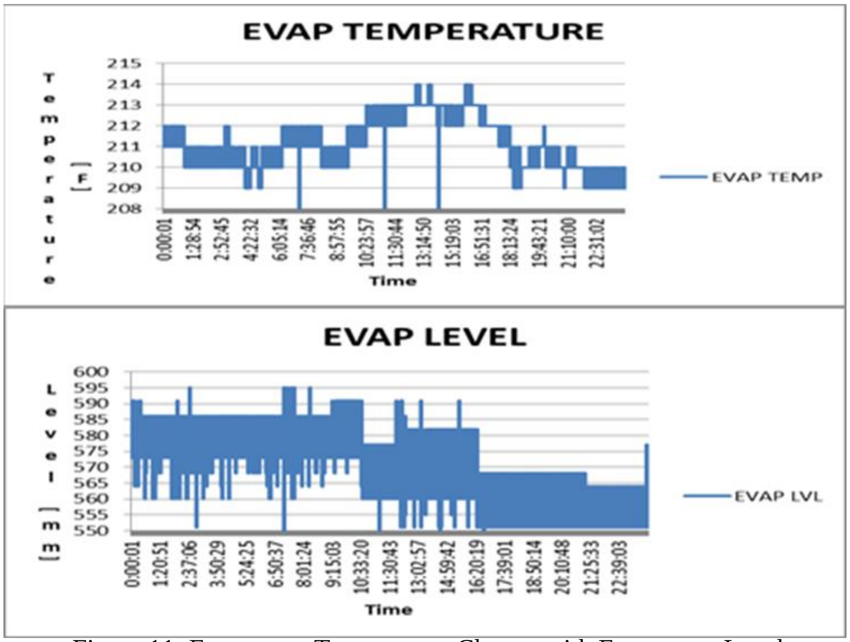

Figure 11: Evaporator Temperature Change with Evaporator Level

5. FULL-LOAD POWER CONDITIONS

Once the optimization for the units had been completed, the units were ramped up in power. Due to the current production well pump not having enough capacity to provide water to run all four units at maximum power, one unit had to be shut down and two others had to have their set points restricted to force more water through one unit for testing. Although the target flow rate was not reached by this method, it was close enough that a 1MW output can be reached. The ramp up process is shown in Figures 12, 13, and 14.

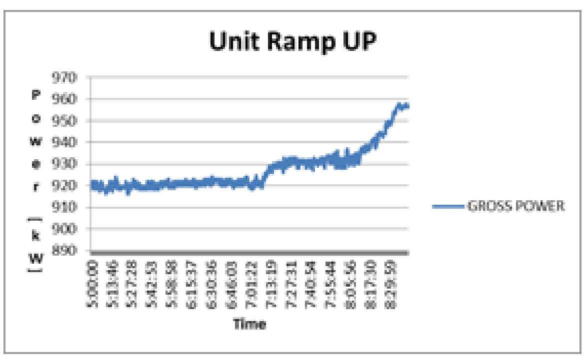

Figure 12: Power Ramp Up

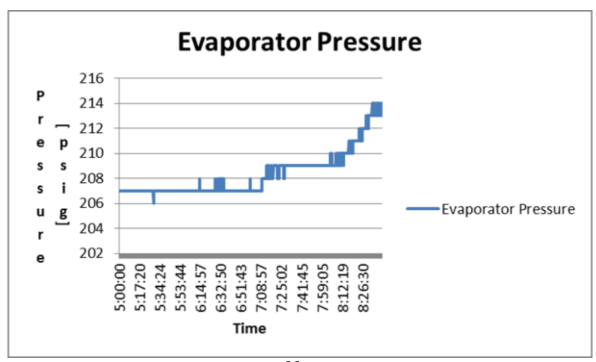

Figure 13: Ramp Up Effect on Evaporator Pressure

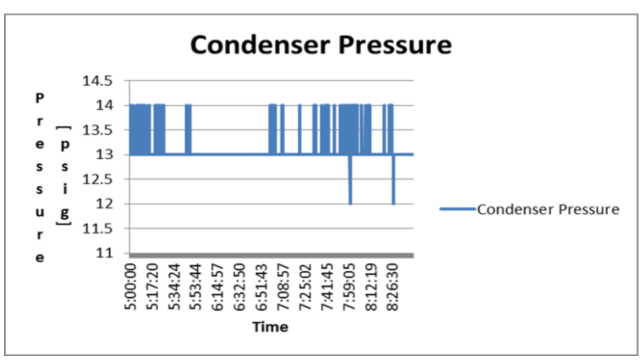

Figure 14: Ramp Up Effect on Condenser Pressure

6. PURGING OF NON-CONDENSABLES

Another factor hindering power production was non-condensables in the system. It is clearly seen in Figure 15 that there are some gasses in the condensing side of the unit. Upon further investigation, it was discovered that the condenser was approximately 8psig over the saturation curve. A high condenser pressure lowers the systems differential pressure and can cause a significant drop in output.

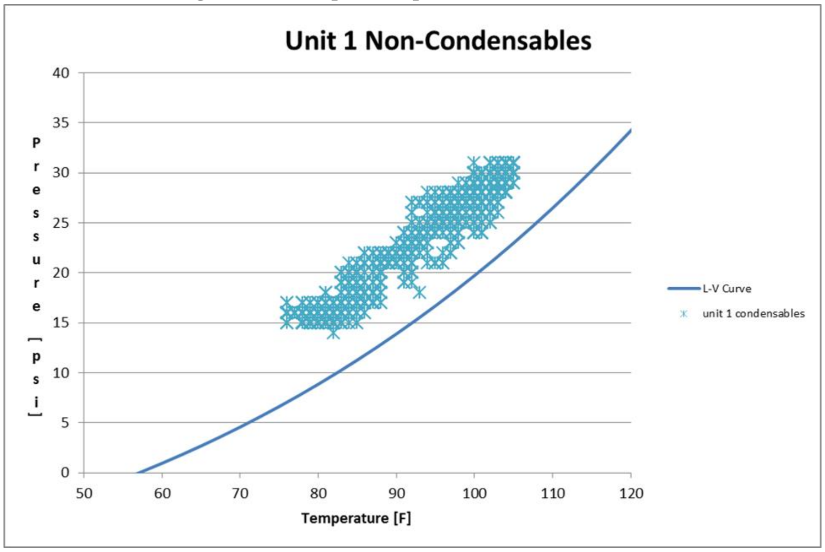

Figure 15: Original Condenser Curve

To fix this problem, a makeshift purging system was installed. This purge system pulls vapor from the top of the liquid collection tank immediately after the condenser modules. From looking at pressures across the unit, it was determined that the non-condensables were getting dragged through the system and caught in this tank. The gasses caught in this tank must collect at the top because the lower part of the tank is all liquid and the vapor cannot pass through to move on to the next step in the system. A line was connected to the top of the collector tank and the vapor was pumped into the vapor side of a liquid/vapor separating bottle. The liquid side of the bottle had another hose running to a point just before the condenser modules where it is evaporated and recycled through the system. Using a pressure gauge on the vapor side of the bottle, the pressure can be measured to determine if non-condensables are collected in the tank. When enough non-condensables collect in the bottle they are vented to the atmosphere. The following plot in Figure 16 shows the unit after the purge system was installed.

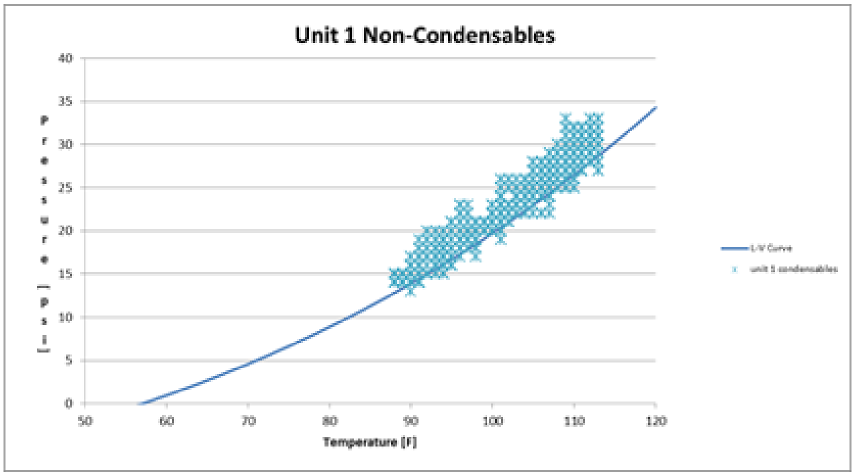

Figure 16: Unit Condenser Curve After Purging

The removal of the non-condensables in the system increased output by approximately 30-40kW. This brought the unit up to its 1MW capacity.

7. CONCLUSIONS

A total of four large capacity air-cooled ORC systems using 1 MWel screw expander units have been installed and brought on-line successfully at the Lightning Dock geothermal power plant.

The size of the ORC unit prevents the use of packaged equipment and necessitates field assembly of the complete ORC system from a large number modules containing the various system components.

System optimization in terms of working fluid charge adjustment and purging of non-condensables had to occur to reach the ORC design capacity.

Based on the positive experience, Lightning Dock's screw expander ORC capacity is expected to reach 7-8MW by 2015.