A New High Efficiency Binary Expander Design: Low Temperature Geothermal Application Bottoming Beowawe Geothermal Flash Plant

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ABSTRACT

Through the development of a range of new high efficiency binary expanders applied to the Organic Rankine Cycle, lower than traditionally thought of as "commercially viable resource temperatures" can now be utilized for geothermal and waste heat applications. Generally not considered viable for utility scale deployment, the project demonstrates the technical and economic feasibility of electricity generation from nonconventional geothermal resources of 205°F, utilizing the first commercial use of a low temperature bottoming cycle at a geothermal flash power plant.

In May of 2009, the U.S. Department of Energy's (DOE) Geothermal Technologies Program (GTP) issued a Funding Opportunity Announcement (DE-FOA-0000109) to promote the development and commercial application of energy production from Low-Temperature Geothermal Fluids, between 150-300° Fahrenheit. Terra-Gen Power, LLC successfully received an award to demonstrate the technical and economic feasibility of geothermal energy production from these non-conventional geothermal resources.

This paper intends to highlight; 1) the successful development of a new design axial turbine family for geothermal and waste heat applications, applied to 2) the successful utilization of a low temperature resource in a commercial utility power sale setting, and finally 3) the successful demonstration of flash bottoming binary cycle technology.

Introduction to a New ORC Turbine Family

In conjunction with Barber Nichols Inc (BNI), TAS has successfully developed an axial turbine – gearbox family for ORC applications. The turbine design is focused mainly on geothermal and waste heat applications using R134a and R245fa and as the primary working fluid, to cover gross power output from 500 kW – 5.0 MW output with temperatures from 200 – 500°F (97 - 260°C) designed to work with both water cooled and air cooled heat rejection.

The Design Challenge

The first step in achieving the desired result was to identify and establish the key design goals and current market limitations / barriers:

- Recognition that a customized one off approach to equipment design is not aligned with the majority of market needs, and
- At these low power levels, high turbine-gearbox costs (on a $/kW basis) can challenge plant economics.
- Develop a family of pre-engineered turbines with suitable modularity to allow use of common parts as the general architecture, with a
- Market changing design with a result that would improve the customer value proposition; by both reducing lead-time, and maximizing NPV.
- Design objective was to minimize production unit cost while maintaining high reliability and good performance.
- Achieve the widest application (ORC fluid selection, source temperature and output range) using a minimum number of configurations.

The Design Process

Design for manufacturability and assembly (DFM/DFA) is the classic method for creating good product design via reduced part count, simplified manufacturing techniques, and standardize parts and materials with the ultimate goal of developing a quality product at the lowest cost while saving time. The primary advantage of the design for assembly (DFA) methodology is that it ensures a good design early in the design process further reducing the detailed design effort and cost. DFM/DFA methodology was used throughout the process:

- The design is simple with a low parts count See Figure 1
- Different turbine configurations use most of the same parts w/ different trims
- Simple castings incorporate key design features
- The small size of the turbines allows the use of low cost radially split housings
- Two piece turbine plenum/bearing housing design provides effective, low cost thermal isolation between turbine inlet stream and seal and bearing assemblies
- The need for piping expansion joints is minimized with a strong, stiff plenum that will handle piping stress loads in excess of API requirements
- Rotor blades are Electro-Chemically Milled (ECM) on the rotor disk and the shroud is electron beam welded to produce a low cost, robust rotor
- Turbine speeds are limited to enable the use of manufacturer's standard industrial (pre-engineered) gearboxes, reducing cost and lead time
- Turbine thrust is limited to enable use of off-the-shelf rolling element bearings
    - Bearing scheduled maintenance interval is 2 years
    - Ball bearings limit shaft deflections and improve seal life
    - Turbine thrust bearing capacity eliminates the need for thrust bearings in the gearbox which improves gearbox efficiency to greater than 98%
    - Turbine bearing lube oil demand is minimized, favorably impacting oil sump and pump size
- Figure 2 shows CFD results for the turbine flow path:
    - The design achieves high performance with a high stage loading (to reduce the number of stages) and limits reaction to maintain low thrust
    - Resulting blades and vanes can be manufactured with cost effective ECM and flank milling processes respectively

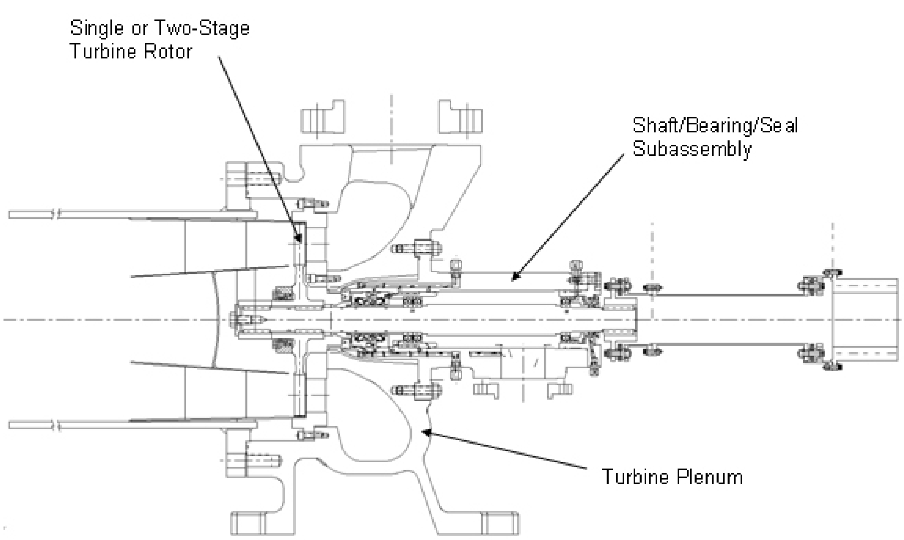

Figure 1. Turbine Design Concept.

- The design facilitates rapid field maintenance:
    - Access to turbine internals only requires removal of piping spool piece
    - Turbine rotors are slip-fit and locked to the shaft with tapered locking devices to allow rapid removal / replacement without the need for heat
    - The shaft/bearing/seal subassemblies are interchangeable and a preassembled spare can be stocked at a service center to eliminate the need for a complete field disassembly

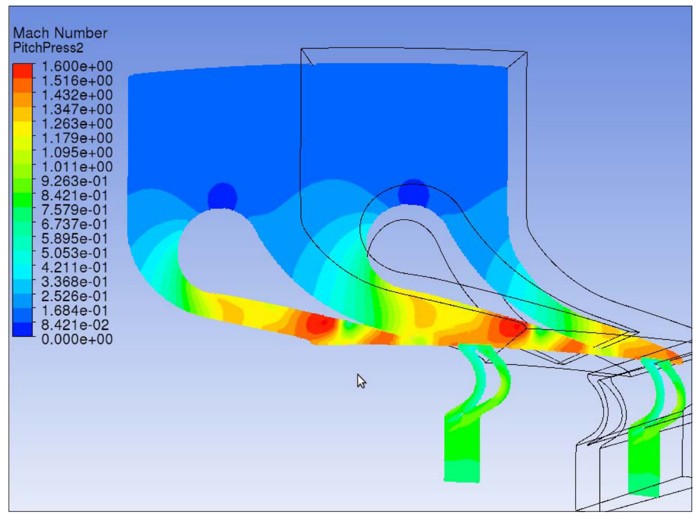

Figure 2. Turbine Flow Path CFD Results.

The Results

The results speak for themselves. Figure 1 shows the basic design concept for the axial flow turbine family. The power range is covered with two cast turbine plenums – one for low flows and one for high flows. The temperature range is covered with a single-stage or two-stage turbine; a single-stage for lower to moderate temperatures, and two-stage for higher temperatures. Figure 1 shows single-stage configuration. The second stage is simply mounted on the shaft extension.

The single stage unit is expected to be applied to lower temperature applications, mostly geothermal in the 200-350°F range, where there is a lower enthalpy drop and R134a is the preferred refrigerant. The range of output is expected to be in the 2.5 to 5MW range which represents the lower end of the geothermal applications. See Figure 3.

All configurations use the same shaft-bearing-rotor assembly. A symmetric design allows for either direction of rotation and application in dual drive configurations. This provides for a standard design having the same skid foot print for all applications throughout the entire 500kW – 5.0MW range, applicable to geothermal, solar thermal, and waste heat recovery to power, with either R134a or R245fa..

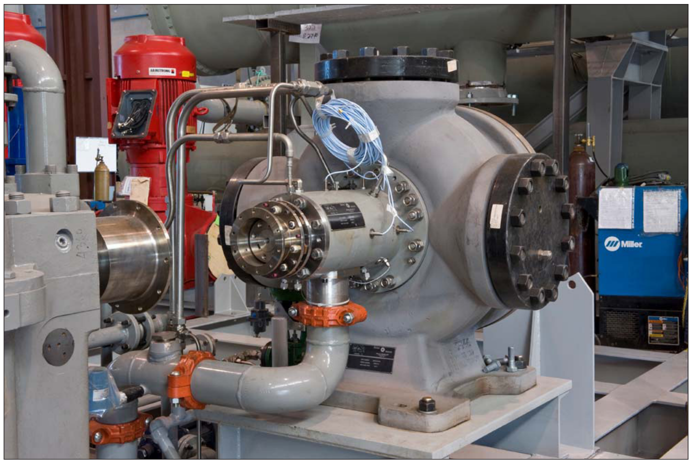

Figure 3. Manufactured Turbine in the TAS Shop.

Cost Effective Low Temperature Design – Health and Safety Benefits

This application utilizes R134a, an environmentally friendly working fluid that is well known and proven. The thermodynamic properties of R134a provide the highest practical cycle efficiency given the low temperature of the resource. Further, the high molecular weight allows for a smaller number of turbine stages to reduce cost of the power turbine equipment.

The safety and environmental impact of the TAS equipment provides a significant advance in binary cycle power plants over the working fluids used in isopentane (flammable and explosive) and ammonia (toxic) cycle technologies.

R-134a is non-flammable, unlike conventional hydrocarbon-based binary systems that use pentanes, butanes, propanes, or their derivatives. Consequently, no fire protection system is required, with a resultant capital reduction.

R-134a is non-toxic and non-corrosive, unlike the ammonia which is proposed for use in some high-efficiency binary power cycles. R-134a eliminates a safety hazard for plant personnel, reduces or eliminates permitting costs and delays with state and federal agencies, and the concerns of those communities adjacent to large ammonia-using facilities.

The elimination of safety and environmental hazard leads directly to capital cost and operating cost reductions:

- R134a is not listed by or subject to the State of Nevada, Division of Environmental Protection, Chemical Accident Prevention Program (CAPP) - Permitting Requirements, eliminating cost and time delays.
- R134a is non-flammable. This eliminates the need for the fire protection system which is required for the use of hydrocarbon based binary power plants. As a result, insurance costs will be less since the plant has no flammable materials.
- As of January 2009, all employees working in facilities with flammable fluids are required to be provided with and wear non-flammable cover garments.
- R134a is non-toxic and non-corrosive, unlike the ammonia which is proposed for use in other high-efficiency binary power cycles. R-134a eliminates a safety hazard for plant personnel, permitting costs and delays with state and federal agencies, and the concerns of those communities adjacent to facilities with a large ammonia inventory.
- The overall higher environmental and safety benefits of the R134a have a benefit beyond the reduced capital cost and permitting effort. With no flammability and no toxicity, the prospect of reduced staffing is presented.
- For a simple process design with few rotating components, the potential for reduced staffing and cost savings is a reality.

DOE Low Temperature Project Application

In May of 2009, the U.S. Department of Energy's (DOE) Geothermal Technologies Program (GTP) issued a Funding Opportunity Announcement (DE-FOA-0000109) to promote the development and commercial application of energy production from Low-Temperature Geothermal Fluids, between 150-300° Fahrenheit. Terra-Gen Power, LLC successfully received an award to demonstrate the technical and economic feasibility of geothermal energy production from these non-conventional geothermal resources at their operating geothermal flash plant at Beowawe, near Battle Mountain, NV.

The FOA provided for the demonstration of the technical and economic feasibility of electricity generation from nonconventional geothermal resources of 205°F using the first commercial use of a low temperature bottoming cycle at a geothermal power plant, with an inlet temperature of less than 300°F. The proposed two-year project supports the DOE Geothermal Technology Program's goal of promoting the development and commercial application of energy production from low-temperature geothermal fluids, i.e., between 150°F and 300°F. The successful award was based on Terra-Gen Power's ability to:

- Perform a study to determine the technical and economic feasibility of a power generation expansion at the existing Beowawe Geothermal Power Plant utilizing binary technology which derives its heat source from the existing low pressure, low-temperature (205°F) brine, which is currently injected into the geothermal reservoir.
- Obtain the necessary permits related to the expansion, including water rights for a new fresh water well which will provide makeup water for the new cooling system.
- Engineer, procure, construct, test, and commission a 2.5 megawatt electric (MWe) binary plant.
- Operate and maintain the new binary plant, providing non-proprietary data to the National Geothermal Data System (NGDS) and the Department of Energy Geothermal Technologies Program (DOE GTP) for a minimum of two years.

Benefits and Outcomes:

- Proving the technical and economic feasibility of utilizing the available unused heat to generate additional electric power from a binary power plant from the low-temperature brine at the Beowawe Geothermal Power Plant.
- Providing non-proprietary data to the NGDS and DOE for two years.

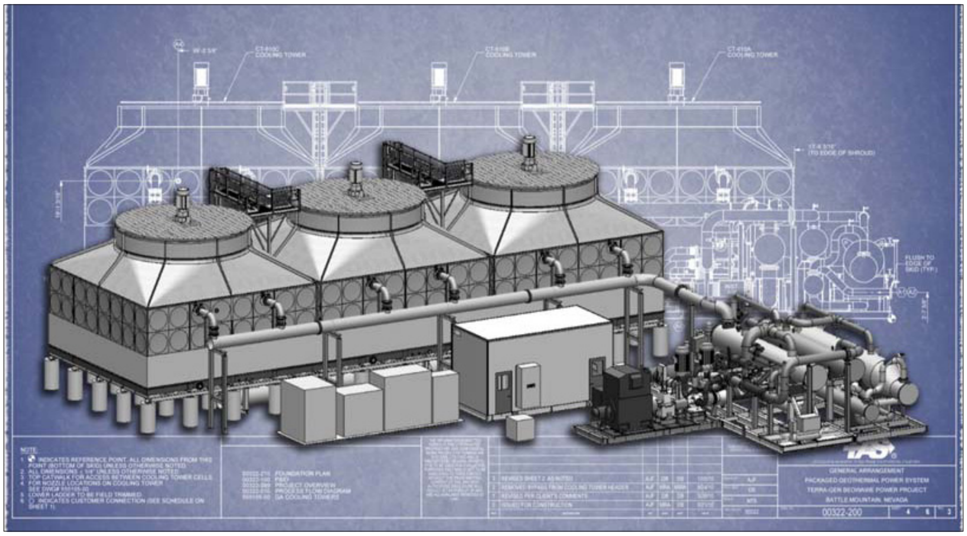

Figure 4. Beowawe Modular Plant Design.

- Increased economic benefits in terms of job creation, income generation, and increased tax and royalty payments.
- Decreased greenhouse gas (GHG) emissions.

Impacts

- Innovative application new to low temp geothermal, potentially adding 10% additional power.
- Good economics in high price region.

Beowawe Flash Plant

Located in Eureka County, NV, the Beowawe geothermal power station is owned by Terra-Gen Power, LLC. The geothermal area at Beowawe Geysers straddles the Eureka-Lander County line in Whirlwind Valley, about 10 km west of the small community of Beowawe, Nevada. It is one of the largest geothermal fields in Nevada with some of the highest reported subsurface temperatures in the state (reservoir temperatures of 213-216°C), making it an ideal area for the development and production of geothermal power.

Figure 5. Beowawe Modular Skids in shop.

The Beowawe flash power plant came on line in 1985, producing 16.7 MW from a 200°C resource. During the first year of plant operation, injection of spent brine outside of the Beowawe reservoir caused the reservoir pressure to reduce, which allowed cold ground water to flow into and cool the geothermal reservoir. The cold water inflow stabilized the reservoir pressure but over eight years it reduced the temperatures of the production wells by as much as 21C. A large new production well was drilled, which temporarily restored full plant output but accelerated the decline in reservoir pressure, causing a reduction in the power plant output. The problem was resolved over the next two years, and full production resumed.

In 2005, Sierra Pacific Power Company signed a 20-year contract to purchase geothermal power from Beowawe Power. Operated by Caithness Operating Company, the Beowawe plant will supply Sierra Pacific 17.7 MWe in January 2006.

- The Beowawe plant has experienced resource decline over its life and had a reduced output, well below the design output.
- The engineer, procure, construct, test, and commission of a new advanced design 2.5 MWe gross binary plant was completed by Terra-Gen Power, LLC. See Figures 2, thru 6.
- The plant was constructed through the end of 2010, and commission in January of 2011.
- The turbine is over-performing and exceeding the performance guarantee, currently producing in excess of 2.0 MWe.

Summary

This paper demonstrates how this project application benefits the geothermal industry worldwide by:

Figure 6. Beowawe Modular Bottoming Plant operating in field.

- Proving the technical and economic feasibility of utilizing typically available unused flash tank brine heat to generate additional electric power.
- Delivering increased economic benefits in terms of job creation, income generation, and increased tax and royalty payments.
- Decreasing greenhouse gas (GHG) emissions.
- Demonstrating how this innovative application can potentially add 15% additional power to a geothermal flash plant.
- Still delivering good economics even in high price region.
- Introducing a new market changing expander design that is now currently available as a standardized commercial product with performance guarantees, and offers the ability to improve a customer value proposition by reducing lead-time and maximizing NPV.
- Substantiating the commercial viability and utility use of low temperature heat sources from below 200°F on up.
- Establishes that rapidly deployable commercical technology is available to be applied to bottom cycle existing flash plants and low temperature, lowere enthalpy resources.
- Establishes the BNI design allowing geothermal and low heat applications up to 5.0 MW with a geared axial expander.
- Yields a flexible design capable of operating on R134a from extremely low temperatures to 350°F or higher, which is also capable of switching to R245fa above beyond the capabilities of R 134a, without any change in manufacturing design.
- Employs an innovative application of existing technology using a novel configuration and a new application. Consequently, a large efficiency improvement is accomplished with minimal technology risk.
- Results in a 15% increase in efficiency over existing binary geothermal power plants (on a power plant only basis), and thereby reduces the barrier to application, as well as a 20% reservoir capacity increase (MW of installed capacity for the same total fluid extraction) compared to existing geothermal binary power plants when the geothermal fluid pump parasitic loads are subtracted from the plant net output.
- May allow daily operations with fewer staff, enabling small geothermal resources to meet economic hurdles, obtain financing for development, and be added to total installed U.S. geothermal capacity.
- Shortens the time and risk to construct a power plant by 3 – 6 months, resulting in reduced financing costs during construction, and provides earlier commercial operations, all of which improve risked NPV.
- Employs proven manufacturing approach of prefabrication packaging allows 90% of the total plant construction inside the controlled environment of the TAS Energy Houston factory.
- Modularization of the packages results in rapid field assembly and the ability to match standard modules to various reservoir sizes.
- Has high U.S. content and opens a path toward export of the technology to globalize low to moderate temperature renewable resources.