A DOE-Funded Design Study for Pioneer Baseload Application of an Advanced Geothermal Binary Cycle at a Utility Plant in Western Utah

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Abstract

Funded in 2000 by an R&D grant from the U.S. Department of Energy (DOE), POWER performed a conceptual design and pilot testing effort to determine the feasibility of applying an advanced high-efficiency binary heat recovery cycle – the Kalina Cycle™ – to recover energy from 171° C silica-rich geothermal brine being injected from an existing geothermal power plant tapping Roosevelt Hot Springs in Utah's remote western desert. A crucial issue in the work was the suitability of pH modification (acid injection) treatment to prevent or delay destructive silica precipitation in the power cycle components and downstream injection lines. The work also included an updating of the computer model of the Roosevelt Hot Springs underground reservoir, to verify that it could sustainably support additional power generation. The study confirmed the suitability of the Kalina Cycle and pH modification for application to a bottoming cycle at the site, which will be a pioneer utility-scale application of a fresh and conspicuously efficient binary heat recovery technology to a significant resource – a 171° C [340° F] reject stream being reinjected into the reservoir – that is now essentially wasted because of historic fear of complications due to silica scaling.

An Underutilized Thermal Resource

Uncertainty about the application of binary energy recovery systems to silica-rich geothermal resources has impeded energy harvest from these resources because binary cycle plants are typically complex, relatively expensive and (at least in conjecture) susceptible to degradation from scaling. Binary plants also tend to be most cost-effective precisely in low-temperature operation regimes where such scaling is more likely to occur due to temperature drop and resulting drop in silica solubility below critical levels. The relevance of the work outlined here lies in its determination of the practicality of applying the pH modification/Kalina Cycle combination to such a resource, and its indication of material selections that would increase the robustness and reliability of such a power plant. The work effectively confirms the applicability of the Kalina Cycle to a particular significantly under-used thermal resource in Utah, U.S.A., and may usefully apply to other underutilized energy-rich – but also silica-rich – resources elsewhere.

The work concerned a proposed addition to an existing PacifiCorp/Scottish Power geothermal power plant, the Harry Blundell Geothermal Power Plant, which entered service in 1982. POWER's study work for DOE had three avenues of approach. A Kalina Cycle bottoming plant was sized, designed and computer-modeled to determine potential power output and cost. A pilot plant was designed and operated at the plant site, using the actual resource, to assess the likely hazard of silica scaling occasioned by a drop in resource temperature to 63° C, and to determine the efficacy of pH modification treatment to retard scaling in power plant and injection system components. The pilot plant tests were also used to identify scale- and corrosion-resistant power system component materials. Finally, an existing computer simulation of the geothermal reservoir was updated with new well and production data to determine the potential for increased sustainable resource production from the field.

Background of the Project

In mid-2000, POWER and Scottish Power/PacifiCorp prepared an R&D grant application for a newly announced U.S. Department of Energy (DOE) R&D program for enhanced geothermal systems. POWER proposed to perform conceptual engineering and investigation to specifically study the pilot application of the Kalina Cycle and pH modification technology for service as a bottoming cycle at the Harry Blundell plant. If the pH mod process can be used to ameliorate the scaling likely to be occasioned by the temperature drop across the highly efficient Kalina Cycle, the potential for energy extraction from the Blundell resource would be significantly increased. DOE issued POWER grant no. DE-FG07-00ID13991 to perform the work proposed and described here. POWER's final report was delivered to DOE in February 2001.[1]

Study Objectives

1. The study evaluated the feasibility of applying a Kalina Cycle system to recover additional energy from hot fluids being presently injected into the Harry Blundell Plant's source reservoir. The feasibility evaluation effort involved development of conceptual designs and estimates for a nominal 13 MW bottoming cycle plant suitable for the available fluid conditions. The flash plant now in operation at the Harry Blundell Geothermal Plant is rated by PacifiCorp with a current capacity of 20 MW.
2. The study determined, using a pilot plant, the suitability of component metals and the applicability of pH modification technology that could allow the plant to recover energy from a hot waste stream currently injected, without occasioning scaling problems in the bottoming cycle's heat exchanger and injection system. (The Blundell resource fluid is famously rich in dissolved silica; concern for scaling problems triggered by a fluid temperature and solubility drop has historically blocked recovery of this energy.) The pilot plant tested three candidate tube metals for heat transfer degradation due to silica scale and other deposits: carbon steel, stainless steel, and tubes coated with an experimental tube coating developed by Brookhaven National Laboratory.
3. The study undertook, using existing well and production data, to develop and calibrate a computer model of the Harry Blundell Plant's source reservoir, as a basis for identification of its capacity to sustainably serve a production enhancement of the plant. A secondary objective of this focus was to investigate several EGS modifications, including fracturing and relocated injection points, to enhance production, injectability, and reservoir recovery.

Report on Objective 1 – Kalina Cycle™ Plant Design

POWER Engineers identified a suitable plant configuration – a Kalina Cycle bottoming cycle plant – for the production enhancement at PacifiCorp's Harry Blundell Plant. The engineering deliverables developed in the study include a process flow diagram for the proposed plant, a plot plan showing the layout of bottoming cycle and interconnection components at the existing Harry Blundell Plant, an electrical one-line diagram, and a control system description/controls architecture diagram. (See Figure 1 below for the process loop portion of the process flow diagram.)

Following is the process summary provided in the DOE grant report: “To better understand the Kalina Cycle, which is essentially a modified Rankine cycle using a two-component mixture of ammonia and water, it is probably easiest to start at the feed pump. This pump receives saturated liquid from the upstream hotwell and pumps the fluid up to cycle pressure. The discharge goes to a low-temperature recuperator and is heated by a two-phase mixture from the high-temperature recuperator. After the low-temperature recuperator, the feed stream is split; part goes to the high-temperature recuperator and part to the low-level geothermal exchanger. In the high-temperature recuperator, the feed stream receives energy from the expander exhaust stream while in the low-level geothermal exchanger it receives energy from the geothermal fluid. The feed stream, which is partially vaporized at this point, is recombined downstream of these exchangers and fed to the high-level geothermal exchanger where it is completely vaporized and slightly superheated. From there it goes through a demister vessel and is fed to the turbine-generator set for energy recovery. The turbine exhaust, as noted earlier, first goes to the high-temperature recuperator and then to the low-temperature recuperator for energy recovery. In the recuperators the turbine exhaust is partially condensed through the back-exchange with the feed stream. From the low-temperature recuperator, it goes to an air-cooled condenser where any remaining vapor is condensed and the fluid then flows to the hotwell to complete the cycle.”

Insert Figure 1

The plant will include the heat exchanger and turbine generator array, resource circulation pumps, interconnection piping with the existing waste fluid and reinjection lines, acid injection skids for pH modification, controls interconnection with the existing plant control system, electrical distribution to interconnect with the existing transmission facility at the plant, and capacity upgrade additions to an existing substation at the nearby town of Milford. The Kalina Cycle plant engineered for Blundell would use a dry cooling tower to avoid competition with other water uses.

The Kalina Cycle was selected as a basis for the recommended plant because analyses have suggested that the Kalina Cycle can provide significantly more net power generation than typical binary Rankine cycle designs, using comparable geothermal heat sources. (The first geothermal Kalina Cycle plant, at Húsavík, Iceland, was successfully completed in 2000 and finished performance tests in November 2001.)

Note: A comparative modeling of a Kalina binary cycle plant at this resource (whereby it would be directly compared to conventional binary Organic Rankine Cycle binary plants applied to this resource) was not within the scope of the work commissioned by DOE. In an earlier project undertaken by POWER for Scottish Power/PacifiCorp, a preliminary analysis and technical approach assessment for a Blundell plant expansion was undertaken. The results of that effort suggested that the Kalina Cycle would offer a substantial plant efficiency advantage over a conventional ORC approach to a Blundell bottoming cycle. Those earlier results were the underlying basis for the selection of the Kalina Cycle for consideration in the DOE-funded study. As noted in the DOE grant report, “Preliminary analyses have suggested that the Kalina Cycle can provide from 15 to 40 percent more net power generation than Rankine cycle designs, using comparable geothermal heat resources.”

The proposed Blundell design, when (and if) built, is expected to confirm the effectiveness and reliability of commercial, off-the-shelf components (including heat exchangers, pumps, and power turbines) for designing and constructing ammonia-water based utility-scale power cycles. The installation of the Kalina Cycle bottoming cycle expansion will make the optimal use of PacifiCorp’s existing power production infrastructure – including the wellfield piping and pumps, the T&D interface, and the existing Blundell topping cycle, for which PacifiCorp recently bought a new turbine rotor.

Anticipated Financial Performance: As part of the feasibility analysis of the recommended Kalina Cycle plant, POWER used GT Pro software to model the technical and economic performance of the Kalina plant. (See Table 1, below.) The model showed a break-even electricity price for the Kalina plant of 3.14¢ per kWh. (Incidentally, a model run showed a break-even electricity price of 4.29¢ per kWh for a gas-fired 7FA combustion turbine at the same site, assuming a gas price of $5/mm BTU. Though the gas turbine plant can boast of initially lower cost per MW, the advantages of no fuel costs allow the bottoming plant to take a decisive advantage over the project life span in terms of cost per kWh.) The Kalina economic evaluation did not, by the way, take into account any increased market value for green power or possible implementation of production tax credits.

TABLE 1
LIFE CYCLE PLANT PERFORMANCE COMPARISON ANALYSIS OF A KALINA PLANT AT THE BLUNDELL SITE

	Blundell Kalina Bottoming Cycle
Annual Electricity Exported (10^6 kWh)	105
Total Investment	$28,073,000
Specific Investment	$2,245.5 per kW
Initial Equity	$8,422,000
Cumulative Net Cash Flow	$81,3126,000
Internal Rate of Return on Investment (ROI)	16.15%
Years for Payback of Equity	3.76 years
Net Present Value	$10,295,000
Break-even Electricity Price	3.14 ¢ per kWh

***Assumptions:** first year of operation is 2003; annual operating hours of 8,410 for the Kalina plant; project life of 20 years; straight-line depreciation life of 15 years; debt term of 15 years; depreciable percent of total investment, 90%; debt percent of total investment, 70%; debt interest rate, 9%; overall tax rate, 35%; first-year electricity price, 0.05 $/kWh; discount rate for NPV calculation, 15%; escalation rate, 4.5%.

Report on Objective 2 – Pilot Plant Operation and Evaluation of Suitability of pH Modification to Impede Silica Scaling

Precise tube fouling tests were performed by POWER's subcontractor, Thermochem, Inc., using a pilot plant to determine if a bottoming cycle would be feasible at Blundell. The pilot test unit was used to evaluate heat exchanger tube fouling rates and the subsequent heat transfer degradation due to silica scale and other deposits, and determine the efficacy of pH modification to control scale deposition. In addition to carbon steel and stainless steel, a new heat exchanger tube coating developed by Brookhaven National Laboratory was evaluated in terms of fouling resistance, heat transfer and corrosion resistance to the pH-modified brine.

Insert Figure 2

The pilot test unit consisted of individual heat exchanger tubes made of the candidate metals, a cooling jacket for tube bundles, cooling jackets for individual tubes, instrumentation and metering pump for acid injection, etc. The equipment was set up at the Blundell brine surge tank site. The inlet brine was taken from the brine injection pump discharge and the outlet brine was disposed of into the 82-33 injection well pipeline. During December 2000 and January 2001, the pilot plant was operated in a number of test runs testing the comparative performance of the tubes made of the candidate metals in exposure to untreated (pH ~8.2) and pH-modified brine (pH ~5.0) in a test regime in which the brine temperature was reduced from about 154° C [310° F] to 82° C [180° F]. The tube samples were evaluated for heat exchange capacity, silica scaling, and corrosion.

pH Modification Testing Conclusions: With sufficient over-design in capacity, it likely that a binary cycle heat exchanger can be operated under these conditions at Blundell using pH-modified brine with a reasonable clean-out schedule. Carbon steel heat exchanger tubes should be acceptable with pH modification of the brine if the pH is properly controlled at ~5.0. The acid required for pH modification can be injected downstream of the first flash vessel. This eliminates any risk of acid corrosion damage to the high-pressure two-phase piping and HP separators. The PPS-coated carbon steel tubes supplied at the time of the test were not found to be suitable. The tubes with prototype coatings performed poorly with low initial heat transfer coefficients and the greatest relative reduction in capacity over time. The coating bond completely failed within the tubes and had the potential to cause serious plugging of downstream components. The pH modification assessment report, "Blundell Plant Expansion Heat Exchanger Test," is contained in POWER's report.[1]

Note: NREL has recently commented that the tubes supplied for these tests represented a very early attempt from the coating manufacturer, and since the manufacture of the tubes used in these tests, the manufacturing method has been changed. The manufacture now applies a powder coat; these powder-coated PPS tubes have been installed on two new vent stacks at the nearby Cove Fort geothermal project. [2]

Report on Objective 3 – Reservoir and EGS Modification Evaluation

GeothermEx, Inc. was retained to assess the capability of the geothermal resource of Roosevelt Hot Springs to support an increase in plant capacity above the current level of 25 MW gross and to evaluate the potential of Enhanced Geothermal System (EGS) techniques to improve field performance. The EGS techniques considered in GeothermEx's study were augmented injection within the reservoir, and improving permeability in and around an existing unproductive well.

The Roosevelt Hot Springs has been thoroughly examined and modeled in the past. Using past work and well flow data, GeothermEx updated and calibrated a computer model of the reservoir system and used numerical simulation to forecast the performance of the field under each of the following expansion scenarios:

- Addition of a bottoming cycle to the existing plant
- Expansion of plant capacity
- Expansion of plant capacity using fracture simulation.

The results of the numerical simulation indicated that:

- Operation of the field at the current steam production rate and the current injection configuration is sustainable for the foreseeable future.
- Addition of a bottoming cycle and a reduction in injection temperature to 82° C [180° F] has no appreciable impact on reservoir performance.
- Some expansion of the field could occur with the existing injection scheme but the reservoir performs better and would allow a higher level of development with a new injection scheme which would better support the production reservoir.

A numerical wellbore simulation of an existing nonproductive well was performed. According to the analysis, fracture stimulation for the purpose of putting this hot but insufficiently permeable well into production is unlikely to be economically justified. The resource assessment report, "Assessment of Expansion Potential at Roosevelt Hot Springs, Beaver, Utah," is contained in the POWER's report to DOE.[1]

The contents of the summary report to DOE have also been reported in the *Proceedings* of the World Renewable Energy Congress 2002[3].

Summary of Study Results

The updated computer model for the Roosevelt Hot Springs geothermal reservoir indicates that production could be sustainably increased to handle another 15 MW of topping capacity in addition to the 13 MW bottoming cycle. The pilot plant testing indicated that scaling in the proposed Kalina Cycle plant could be acceptably managed or retarded by pH modification treatment, and that carbon steel heat exchanger tubing could be used. The modeling and design for the Kalina Cycle resulted in an innovative and eminently constructible and cost-effective plant design which is ready for implementation at the Roosevelt Hot Springs site. The preliminary plant design and modeling indicated that the Kalina Cycle bottoming plant would produce electrical power over its life span at a break-even cost of 3.14¢ per kWh.

Conclusions:

A 13 MW Kalina Cycle power plant can be feasibly installed at the Roosevelt Hot Springs site to extract additional energy from the existing silica-rich brine stream. The resulting plant will be the pioneer application of the advanced Kalina Cycle to a utility-scale baseload plant, and the most advanced binary geothermal plant to date. The plant will also generate power at a high availability (>95%) and at, for a geothermal plant, a spectacularly low cost.

References

[1] Lewis, B. and Ralph, M., 2001, U.S. Department of Energy, Enhanced Geothermal Systems Conceptual Definition Study for the Harry Blundell Geothermal Power Plant Production Enhancement Project, DE-PSO7 00ID13913, including “Assessment of Expansion of Power Capacity at Roosevelt Hot Springs Geothermal Field, Beaver County, Utah,” GeothermEx, Inc., and “Blundell Plant Expansion Heat Exchanger Test,” Thermochem, Inc.

[2] Chuck Kutcher, NREL, comments to draft paper, 2002.

[3] Lewis, B. and Ralph, M., 2002, “A Stream in the Desert,” *Proceedings*, The World Renewable Energy Congress VII, Cologne, Germany.

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