Geothermal Resources Council TRANSACTIONS, Vol. 18, October 1994

TURBINE-DRIVEN COMPRESSORS FOR NONCONDENSIBLE GAS REMOVAL AT GEOTHERMAL STEAM POWER PLANTS

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ABSTRACT

An innovative concept for an advanced turbine-driven compressor system is investigated as an alternative to conventional steam-jet ejector or hybrid liquid-ring vacuum pump systems for extraction of noncondensible gases at geothermal power plants. The new design eliminates the need for a motor/gear box drive, lubrication system and high speed shaft seal normally associated with centrifugal compressor units. The result is a high efficiency, reliable, low maintenance system that has significant advantages over conventional vacuum systems. The turbine-driven compressor system has a higher capital cost than the conventional systems, but savings from reduced operating costs pay back the difference in less than a year.

INTRODUCTION

The steam flow in geothermal power plants has a much higher concentration of noncondensible gas (NCG) than conventional power plants. In conventional power plants, NCG is introduced through vacuum leaks and dissolved gas in boiler make-up water and representative concentrations are 10-50 ppm (by volume). In geothermal plants, NCG flows from the geothermal reservoir and concentrations can be two orders of magnitude higher than for a conventional plant. The NCG must be removed from the condenser and compressed from condenser pressure to ambient. The NCG extraction systems have a high capital cost and require a significant amount of power. Consequently, overall plant performance and cost are sensitive to the type of NCG extraction equipment that is used.

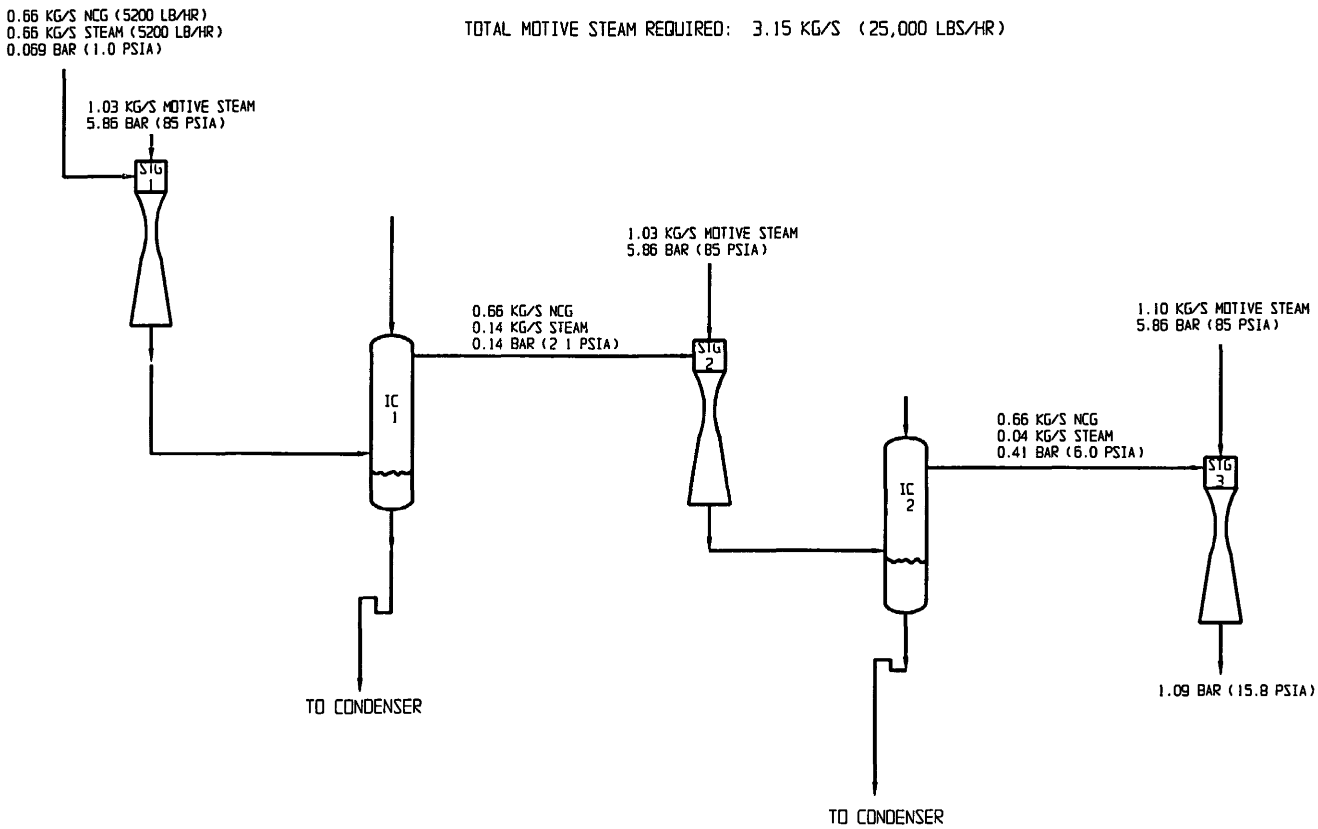
Most geothermal power plants currently use a train of steam-jet ejectors to compress the NCG to ambient pressure. Steam-jet ejectors have a relatively low capital cost and high reliability. However, they are low efficiency devices and require a high flow rate of motive steam.

To reduce the power required by the NCG extraction system, some geothermal power plants utilize a higher performance hybrid system. These systems use steam-jet ejectors for high vacuum compression and liquid-ring vacuum pumps for low vacuum compression. Since the efficiency of a liquid-ring vacuum pump is superior to a steam-jet ejector, this hybrid approach reduces the power required by the NCG extraction system. However, liquid ring pumps have a high capital cost, and a number of performance restrictions that limit their effectiveness.

Very high performance NCG extraction can be achieved by using centrifugal compressors. Centrifugal compressors have higher efficiencies than ejectors or liquid-ring pumps and they are not subject to the performance restrictions that limit liquid-ring pumps. However, these compressors have seen limited use in NCG extraction systems because of high capital cost, and maintenance and reliability concerns about the high speed rotating assemblies. This paper will discuss a new turbine-driven compressor design that incorporates a number of novel features. With this design, it is possible to utilize the performance advantages offered by centrifugal compressors and eliminate the potential drawbacks.

This paper will compare the performance and cost of the following NCG extraction systems: (1) a system using steam-jet ejectors only, (2) a hybrid system using steam-jets and liquid-ring vacuum pumps, and (3) a system using turbine-driven centrifugal compressors. The systems are all optimized for a representative 50 MWe geothermal plant with the following conditions: condenser pressure - 52 torr (1.0 psia), NCG flow rate - 0.66 Kg/s (5200 lbm/hr), NCG molecular weight - 41.5, motive steam pressure - 5.8 bar (85 psia).

FIGURE 1 - CONVENTIONAL STEAM-JET EJECTOR SYSTEM



STEAM-JET EJECTORS

In the US, steam-jet ejectors are the most widely used method for NCG extraction at geothermal power plants. A typical system is shown in Figure 1. Three-stages of ejectors are required to achieve the overall pressure ratio of 15.8 and intercondensers are used between each stage to reduce the flow rate of water vapor into the following stage.

The key components of a steam-jet ejector are shown in Figure 2. The operating principles of the ejector are as follows. (1) In the nozzle section of the ejector, high pressure motive steam is expanded to produce a flow of high velocity, low pressure steam. (2) In the mixing section, the load gas from the condenser (a mixture of NCG and water vapor) is entrained in the high velocity motive steam jet. Momentum is conserved in the mixing section, and when the mixing is complete, the motive steam and load gas flow at the same velocity. (3) In the diffuser section, the pressure of the mixture is increased by decelerating the flow and converting most of the kinetic energy into pressure head.

Steam-jet ejectors are popular because they are simple, reliable, and have very low capital and maintenance costs. The installed cost of the system shown in Figure 1 is $160,000. The only required maintenance is periodic cleaning of the steam nozzles.

Steam-jet ejectors have two major drawbacks. First, ejectors have an inherently low compression efficiency. The overall efficiency of the ejectors shown in Figure 1 is between 0.15 - 0.20. This low efficiency requires a high flow rate of motive steam. The motive steam flow to the ejectors effectively reduces the flow rate of revenue producing steam that is expanded through the power turbine. Second, ejectors are relatively inflexible to changes in the flow rate of the load gas. If the NCG load changes over time, as is the case with many geothermal resources, it is often necessary to replace the ejectors in order to maintain reasonable performance.

Table 1 shows a breakdown of the system capital cost and an estimate of the operating cost. The operating cost is estimated as the revenue that could be

NCG Extraction Systems
Cost Comparison
Table 1

	Steam-Jet Ejectors (see Fig 1)	Hybrid - Ejectors and Liquid-Ring Vacuum Pumps	Turbine-Driven Compressors (see Fig 4)
Capital Costs			
Stage 1	$30,000	$30,000	$200,000
Intercondenser 1	30,000	30,000	20,000
Stage 2	20,000	20,000	200,000 (Note 3)
Intercondenser 2	20,000	20,000	10,000
Stage 3	10,000	180,000	(Note 3)
Installation	50,000	50,000	50,000
Total Installed Cost	$160,000	$330,000	$480,000
Operating Costs			
Steam Flow Required (kg/s) (lbm/hr)	3.15 25,000	2.05 16,300	0.73 5,800
Power Required (kWe)	0	95	0
Equivalent Total Power Required (kWe) (Note 1)	1,560	1,110	360
Annual Operating Cost (Note 2)	$680,000	$490,000	$160,000

Note 1 Based on a steam rate of 7.3 kg/kW-hr (16 lbm/kW-hr).
Note 2 Assumes that plant has excess generating capacity so the cost of steam is equal to the cost of power that it could generate. Based on a cost of power of $0.05/kW-hr.
Note 3 Two-stage, (second and third-stage) turbine-driven compressor cost is entered as Stage 2.

FIGURE 2 - STEAM JET EJECTOR

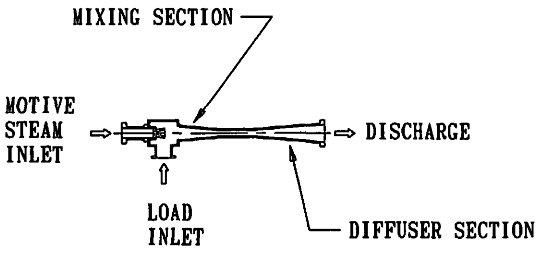
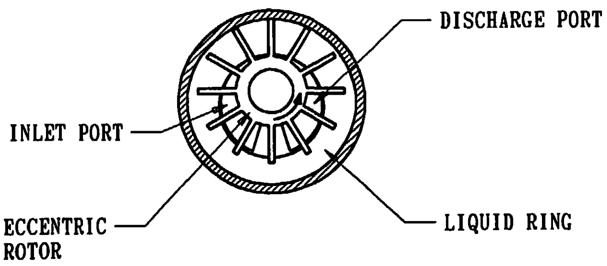


FIGURE 3 - LIQUID-RING VACUUM PUMP



produced if the motive steam was expanded through the power turbine. This assumes that there is sufficient excess capacity in the power plant equipment to handle the increased steam flow (which is the case in many geothermal plants). The low efficiency of the ejectors is highlighted by the fact that the capital cost of the system is equivalent to only four months of operating cost.

LIQUID-RING VACUUM PUMPS

To improve the performance of the NCG extraction system it is possible to use liquid-ring vacuum pumps in place of steam-jet ejectors for the higher pressure compression stages. The key components of a liquid-ring vacuum pump are shown in Figure 3. This positive displacement pumping device uses a radial blade impeller which rotates eccentrically in a ring of water. As the impeller rotates, the eccentric water ring alternately increases and then decreases the volume of the gas space that is trapped between adjacent blades. The vacuum pump ports connect the inlet flow to the arc where the gas volume is increasing and the exit port to the arc where the gas volume is decreasing.

Liquid-ring pumps have four significant advantages over steam-jet ejectors. (1) The water ring provides cooling to the load gas during the compression process which improves the compression efficiency and eliminates the need for intercondensers. (2) For inlet pressures above a certain limit, liquid-ring pumps have much higher efficiencies than steam-jet ejectors. At an inlet pressure of 155 torr (3.0 psia), a compression efficiency (isentropic) of approximately 0.45 can be achieved. At lower inlet pressures the efficiency decreases rapidly. (This will be discussed below.) At inlet pressures above 205 torr (4.0 psia), a compression efficiency of about 0.55 can be achieved. To compare these efficiencies for a liquid-ring pump to the steam-jet ejector, the liquid-ring pump efficiency must be multiplied by the efficiency of the power turbine (0.85), generator (0.96), and pump motor (0.93) in order to determine the overall steam-to-compressor efficiency. The resulting range in overall steam-to-compressor efficiency is 0.34 - 0.44. (3) The liquid-ring pump can utilize a variable speed drive that allows the pump to handle changes in the NCG flow rate as the geothermal resource matures.

There are three major drawbacks associated with liquid-ring vacuum pumps. (1) There is a limit to the minimum allowable inlet pressure. As the inlet pressure to a liquid-ring pump approaches the vapor pressure of the water in the ring, water vapor from the liquid ring will displace most of the load gas and the volumetric efficiency of the pump will deteriorate. With typical geothermal plant conditions, the minimum reasonable inlet pressure for a liquid-ring vacuum pump is about 155 torr (3.0 psia). Consequently, a liquid-ring pump cannot be used for the first or second stage compressor for the current application. (2) Due to their large size and relatively high complexity, liquid-ring pumps have a high capital cost. The steam-jet ejector system shown in Figure 1 can be converted to a hybrid system by replacing the third stage ejector with a liquid-ring pump. The liquid-ring pump and motor assembly is approximately 5 ft. high by 10 ft. long and costs $180,000. The installed cost of the hybrid system is $330,000. (3) The maintenance costs for liquid-ring pumps are higher than for steam-jet ejectors. However, since maintenance costs are difficult to estimate (they are sensitive to site conditions and maintenance practices), and for most applications, they are small compared to the operating and capital costs , they will not be included in the system comparison.

Table 1 shows the capital and operating costs for the hybrid NCG extraction system using a first and second stage steam-jet ejector and a liquid-ring pump in parallel for the third stage. The capital cost of the hybrid system is over twice the cost of the ejector system. However, for this application, the hybrid system appears to be preferable as the lower operating cost will pay back the higher capital cost in less than a year.

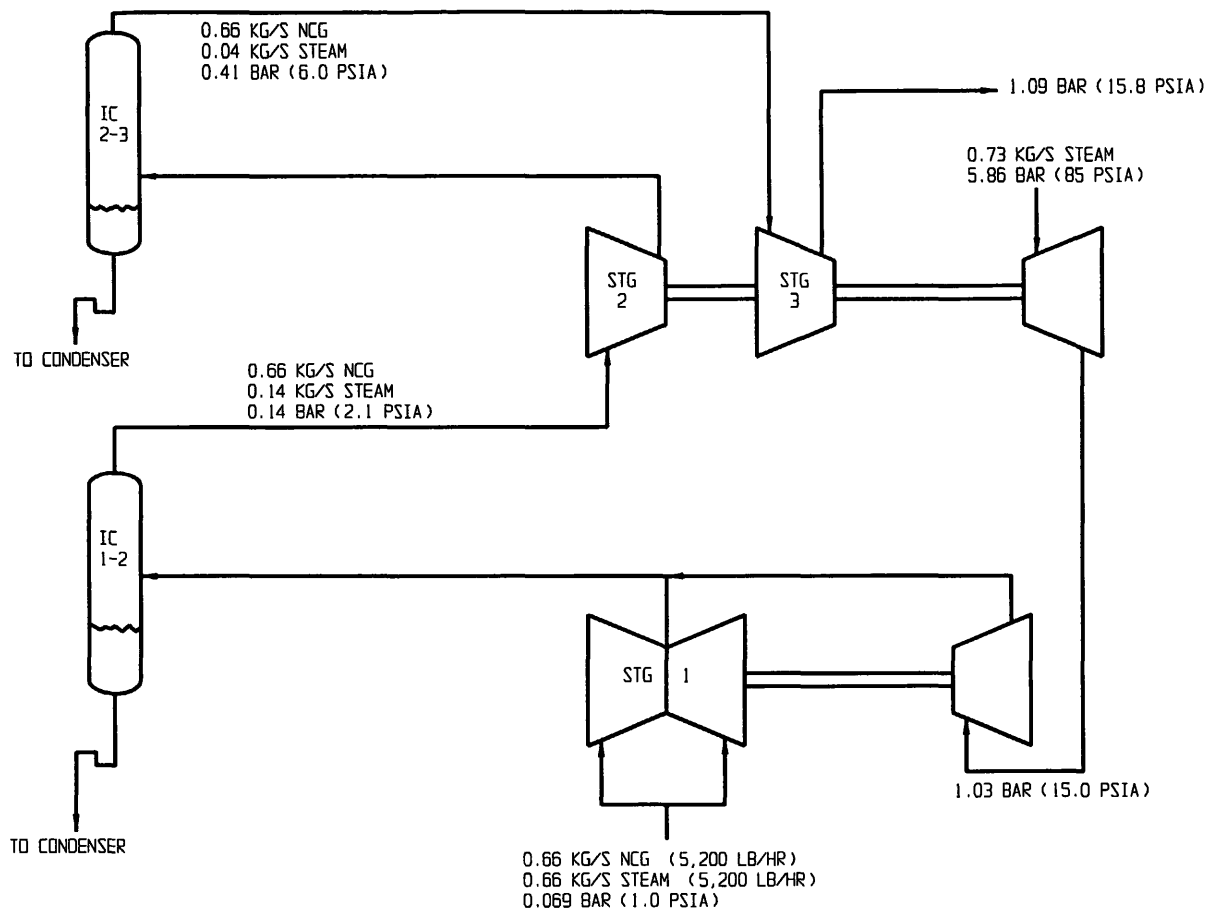
TURBINE-DRIVEN COMPRESSOR SYSTEM

NCG extraction systems with the best performance use high speed centrifugal compressors. There are a number of geothermal power plants (operating outside of the US) that use these systems. These currently in operation use a high speed gearbox to drive three stages of compressors. These systems operate at high efficiency. However, they also have a high capital cost, and maintenance and reliability concerns associated with the rotating assemblies (especially the high speed shaft seals). Since these compressor drives generally operate at fixed speed, the compressors also have little flexibility to accommodate changes in NCG flow rates.

In order to take advantage of the benefits offered by centrifugal compressors and avoid the potential drawbacks of the current systems, preliminary work is proceeding on a new system of turbine-driven centrifugal compressors. The turbine-driven compressor system is shown in Figure 4. Three compressor stages are required to achieve the overall pressure ratio of 15.8. The first stage uses a dual inlet compressor to handle the high volume flow rates. The second and third stage compressors are combined in a single housing and driven by

FIGURE 4 - TURBINE-DRIVEN COMPRESSOR SYSTEM

TOTAL MOTIVE STEAM REQUIRED: 0.73 KG/S (5780 LBS/HR)



a single turbine. Intercondensers are used between each compressor stage for cooling and to minimize the flow rate of water vapor into the following stage. The two turbines are connected in series to produce process conditions that are well matched to the compressor requirements and to allow for condensation removal with a demister between the turbines.

Characteristics of the turbine-driven compressors are listed in Table 2. The predicted efficiencies shown in Table 2 are somewhat conservative and take into account the effect of condensation in the turbine. Test data for similar compressor and turbine stages demonstrate efficiencies that are 2-5 points higher.

A first stage turbine-compressor unit is shown in Figure 5. The general design characteristics of the combined second-third stage unit are the same. The compressor is directly driven with a single-stage steam turbine. The turbine-compressor rotating assembly is supported by water lubricated, fluid film, journal and thrust bearings. Water lubricated bearings were selected because they eliminate the need for both oil seals and an oil lubrication system. Water lubricated bearings are not in common use because they operate with a smaller film thickness than comparable oil lubricated bearings. However, experience with a similar pump application suggests that a fairly conventional bearing design can be utilized to provide stable operation with a film thickness of approximately .025 mm (.001 in).

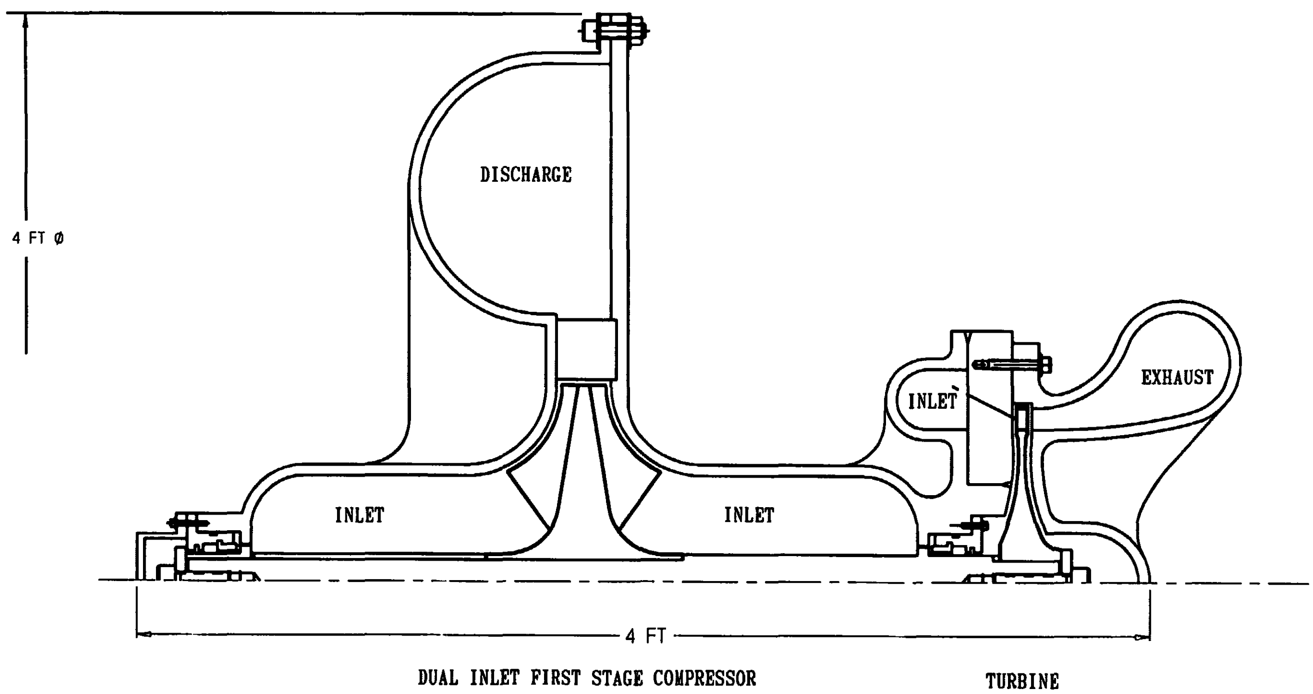
The selected design approach has the following major advantages. (1) The overall steam-to-compressor efficiency of 0.59 - first stage, 0.57 - second and third stages, is significantly better than a motor-driven liquid-ring pump and a steam-jet ejector. (2) There are no shaft seals. The water lubricated bearings eliminate the need to

Turbine-Compressor Characteristics
Table 2

	Stage 1	Stage 2	Stage 3
Shaft Speed (rpm)	17,000	27,000	27,000
COMPRESSOR			
Tip Diameter (m) (in)	0.46 18	0.30 12	0.25 10
Inlet Flow Rate (m^3/s) (ft^3/s)	9.57 338 (Note 1)	4.13 146	1.10 39
Pressure Ratio	2.20	2.94	2.60
Specific Speed	140	140	89
Efficiency	.78	.78	.78
TURBINE (Note 2)			
Inlet Pressure (bar) (psia)	1.02 15.0	5.8 85	
Exit Pressure (bar) (psia)	0.16 2.30	1.05 15.5	
Flow Rate (kg/s) (lbm/hr)	0.68 5400	0.73 5800	
Specific Speed	46	30	
Efficiency	0.76	0.73	

Note 1 Flow rate to each inlet of dual-inlet compressor.
Note 2 One turbine drives both second and third stage.

FIGURE 5 - TURBINE-DRIVEN COMPRESSOR



seal oil passages around the shaft. Also, with the internal turbine drive, the shaft does not penetrate the housing so there is no need for dynamic seals at housing penetrations. As a result, the rotating assembly can be enclosed in a hermetically sealed housing. Since shaft seals are typically the highest maintenance component for this type of high speed turbomachinery, eliminating the seals significantly enhances the reliability of the equipment. (3) The capital cost of a turbine-driven compressor is lower than a comparable liquid-ring pump. Since a turbine-driven compressor operates at a much higher speed than a comparable liquid-ring vacuum pump, the turbine-compressor is smaller and manufacturing costs are lower. The cost of the combined second and third stage turbine-compressor unit is $200,000 (based on estimated production costs). The cost of a liquid-ring pump to replace the third stage only is $180,000. (4) The centrifugal compressor system is not limited by the minimum inlet pressure conditions that restrict liquid-ring vacuum pumps. Unlike the liquid-ring pumps, centrifugal compressors can be used for the first and second stages of compression which significantly reduces the steam flow requirements as compared to a steam-jet ejector. (5) By making minor trim changes to the turbine and compressor diameters, blade heights, and shaft speeds, it is possible to cover a wide range of NCG flow rates and condenser pressures with a single set of component designs. (6) The operating speed of the turbine-driven compressors can be adjusted to accommodate changes in NCG flow rates.

There is some concern that long term corrosion and erosion effects will limit the service life of the turbine-driven compressor units. Until some operating experience is gained under actual plant conditions, the life of the unit will be difficult to predict. However, a relatively long service life is expected since all critical components will be manufactured from high strength, corrosion resistant materials that are commonly used in geothermal steam turbines. Also, since the component costs for the turbine rotor and compressor impeller are relatively low, less than $10,000 each, they can be replaced periodically with little impact to overall maintenance costs. The combination of a sealless assembly, water bearings, and replaceable rotating components all contribute to a design that will achieve high reliability with simple, low cost maintenance requirements.

Table 1 shows capital and operating costs for an NCG extraction system using turbine-driven compressors. The major performance advantage of the turbine-compressor system is the low steam flow requirements. The turbine-compressor system uses only about 25% of the steam used in the ejector system, and 35% of the steam and none of the electric power used in the hybrid system. The capital cost of the turbine compressor system is three times higher than the ejector system and 50% higher than the hybrid system. However, the reduction in operating costs associated with the reduced steam consumption of the turbine-compressor system pays for the higher capital cost in less than six months as compared to the ejector system and less than eight months as compared to the hybrid system.

CONCLUSIONS

As the geothermal industry matures, the risks and true cost of producing steam from geothermal reservoirs is being better understood. It is apparent that geothermal steam is a valuable commodity and it is critical that all plant equipment be designed to optimize the use of the resource. The new NCG extraction system described in this paper has performance and cost advantages over currently available systems. When development work is complete, it will reduce the parasitic steam flow in geothermal power plants by a factor of two to three and the reduced operating cost will pay for the higher capital cost of the new system in less than a year.