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THE EVOLUTION OF POWER PLANT DESIGN AT THE GEYSERS

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ABSTRACT

It has been 67 years since John D. Grant drilled the second steam well at The Geysers utilizing steam from the first well as a source of power. This initial development led to the first generation of geothermal electrical power in the western hemisphere and helped to supply power to the Big Geysers resort. This early power plant was expensive to operate and required high maintenance owing to the lack of suitable materials to protect against corrosion and erosion. Twenty three generating sites and close to 2,000 MW of installed capacity have been added to draw upon The Geysers resource since 1960. Many of the problems of the 1920s still exist today. This paper presents the evolution of 30 years of geothermal power plant design and the reasoning behind changes in design philosophy. It covers the evolution of each plant system, steam path, condenser, gas removal, and abatement, beginning with PG&E's Unit 1, through the construction of larger facilities and ending with the recent addition of smaller plants utilizing modular construction techniques.

INTRODUCTION

The Geysers is located 100 miles northeast of San Francisco in the Mayacamas mountains. It consists of 23 plant sites operated by eight different entities. Over the past 30 years changes in plant design have been required by expanded development of the reservoir, environmental regulations and efficiency of operation considerations. The Geysers first found success in 1960 when PG&E's Unit 1, at a cost of less than $2 million, became the first commercial geothermal plant in North America. The total installed plant capital has since grownto nearly $2 billion. Power plant design is unique at The Geysers as a large number of problems exist which are not found in conventional power plant design. A list of Geysers units and systems used is shown in Table 1.

CONDENSER

The largest number of design changes at The Geysers have occurred with the condenser. The condenser and gas removal systems are the most characteristic aspect of Geysers geothermal power plants in relation to conventional power facilities since the high volume of noncondensible gases contained in the steam represents the primary obstacle around which the entire plant is designed. Without adequate gas handling capabilities the performance of the plant will suffer. Sufficient condenser capability to meet design turbine exhaust pressure requirements is important in achieving turbine design steam rate and meeting plant economic goals. Condenser heat transfer is complicated by the addition of noncondensible gas mass transport problems which are intensified by the condensing steam. The condenser also plays a key role in evaluating the type of hydrogen sulfide abatement system to be installed. Types of condenser design used at The Geysers can be grouped into three categories: barometric, low level direct contact, and tube and shell.

PG&E Units 1 through 4 utilize barometric condensers (Figures 1 and 2). Steam flows from the turbine through the exhaust duct and up into the condenser. The elevation of the condenser, inter-condenser and after-condenser is

Table 1. Power plant systems used at The Geysers.

OPERATOR	PLANT	TURBINE DEM	GROSS MW	CONDENSER	OFF GAS	PRIMARY ABATEMENT	SECONDARY ABATEMENT	YEAR COMMER-CIAL
PG&E	UNIT 1	GE	12	BAROMETRIC	2 STG JET	INCIN	FE CHE***	1960
PG&E	UNIT 2	ELLIOTT	14	BAROMETRIC	2 STG JET	INCIN	FE CHE	1963
PG&E	UNIT 3	ELLIOTT	28	BAROMETRIC	2 STG JET	ICP**	N/A	1967
PG&E	UNIT 4	ELLIOTT	28	BAROMETRIC	2 STG JET	ICP	N/A	1968
PG&E	UNIT 5	TOSHIBA	55	LLDC*	2 STG JET	INCIN	FE CHE	1971
PG&E	UNIT 6	TOSHIBA	55	LLDC	2 STG JET	INCIN	FE CHE	1971
PG&E	UNIT 7	TOSHIBA	55	LLDC	2 STG JET	INCIN	FE CHE	1972
PG&E	UNIT 8	TOSHIBA	55	LLDC	2 STG JET	INCIN	FE CHE	1972
PG&E	UNIT 9	TOSHIBA	55	LLDC	2 STG JET	ICP	N/A	1973
PG&E	UNIT 10	TOSHIBA	55	LLDC	2 STG JET	ICP	N/A	1973
PG&E	UNIT 11	TOSHIBA	110	LLDC	2 STG JET	INCIN	FE CHE	1975
PG&E	UNIT 12	TOSHIBA	110	LLDC	2 STG JET	INCIN	FE CHE	1979
PG&E	UNIT 13	GE	138	SURFACE	2 STG JET	STRET	FE CHE	1980
PG&E	UNIT 14	TOSHIBA	114	SURFACE	2 STG JET	STRET	FE CHE	1980
PG&E	UNIT 15	GE	62	SURFACE	2 STG JET	LOCAT	FE CHE	1979
PG&E	UNIT 16	TOSHIBA	119	SURFACE	2 STG JET	STRETFORD	FE CHE	1985
PG&E	UNIT 17	TOSHIBA	119	SURFACE	2 STG JET	STRETFORD	FE CHE	1982
PG&E	UNIT 18	TOSHIBA	119	SURFACE	2 STG JET	STRETFORD	FE CHE	1983
PG&E	UNIT 20	TOSHIBA	119	SURFACE	2 STG JET	STRETFORD	FE CHE	1985
NCPA	NCPA 1	FUJI	2 x 55	SURFACE	2 STG JET	STRETFORD	FE CHE	1983
NCPA	NCPA 2	ANSALDO	2 x 55	SURFACE	2 STG JET	STRETFORD	FE CHE	1985/86
SMUD	SMUDGEO	MITSUBISHI	78	SURFACE	COMP/JET HYBRID	STRETFORD	PEROXIDE	1983
SANTA FE	SANTA FE	TOSHIBA	2 x 48	SURFACE	2 STG JET	STRETFORD	FE CHE/ PEROXIDE	1984
CALIF/DWR	BOTTLE ROCK	FUJI	55	SURFACE	2 STG JET	STRETFORD	PEROXIDE	1985
SMUD	CCPA	TOSHIBA	2 x 66	SURFACE	COMP/JET HYBRID	STRET/INCIN	FE CHE/SUL-FITE	1988
CALPINE	BEAR CANYON	MITSUBISHI	2 x 11	SURFACE	2 STG JET	STRETFORD	PEROXIDE	1988
CALPINE	FORD FLAT	MITSUBISHI	2 x 17	SURFACE	2 STG JET	STRETFORD	PEROXIDE	1988
CALPINE	AIDLIN	FUJI	12.5	SURFACE	2 STG JET	INCIN	FE CHE	1989

** Low level direct contact; **Iron Chelate Caustic Peroxide; ***Iron Chelate.*

based on their design operating pressure, which provides a tailpipe water seal to maintain vacuum. The advantages of the barometric design are its simplicity, low cost and high efficiency. The cost of the barometric condenser is low because of the uncomplicated construction in comparison to surface condensers. The condenser is a relatively open vessel with water distribution created by either a cooling water spray nozzle or a series of disks and rings to aid in water and steam mixing. The design allows for a tremendous amount of plugging to occur before efficiency is compromised, which is important in geothermal applications. The design is efficient as it provides direct contact of the steam and water without the additional heat transfer resistance of tube condensers. Stainless steel clad material is used to further reduce cost.

The primary disadvantage of the barometric condenser is poor H_2S partitioning. Because of the direct contact of steam and water, a higher percentage of H_2S is scrubbed into the liquid phase, which makes this condenser less practical for the Stretford or LoCat abatement processes. Natural partitioning of H_2S into the gas phase is approximately 50 to 60 percent for barometric condensers although it is strongly influenced by the steam chemistry, in particular, changes in steam ammonia concentration.

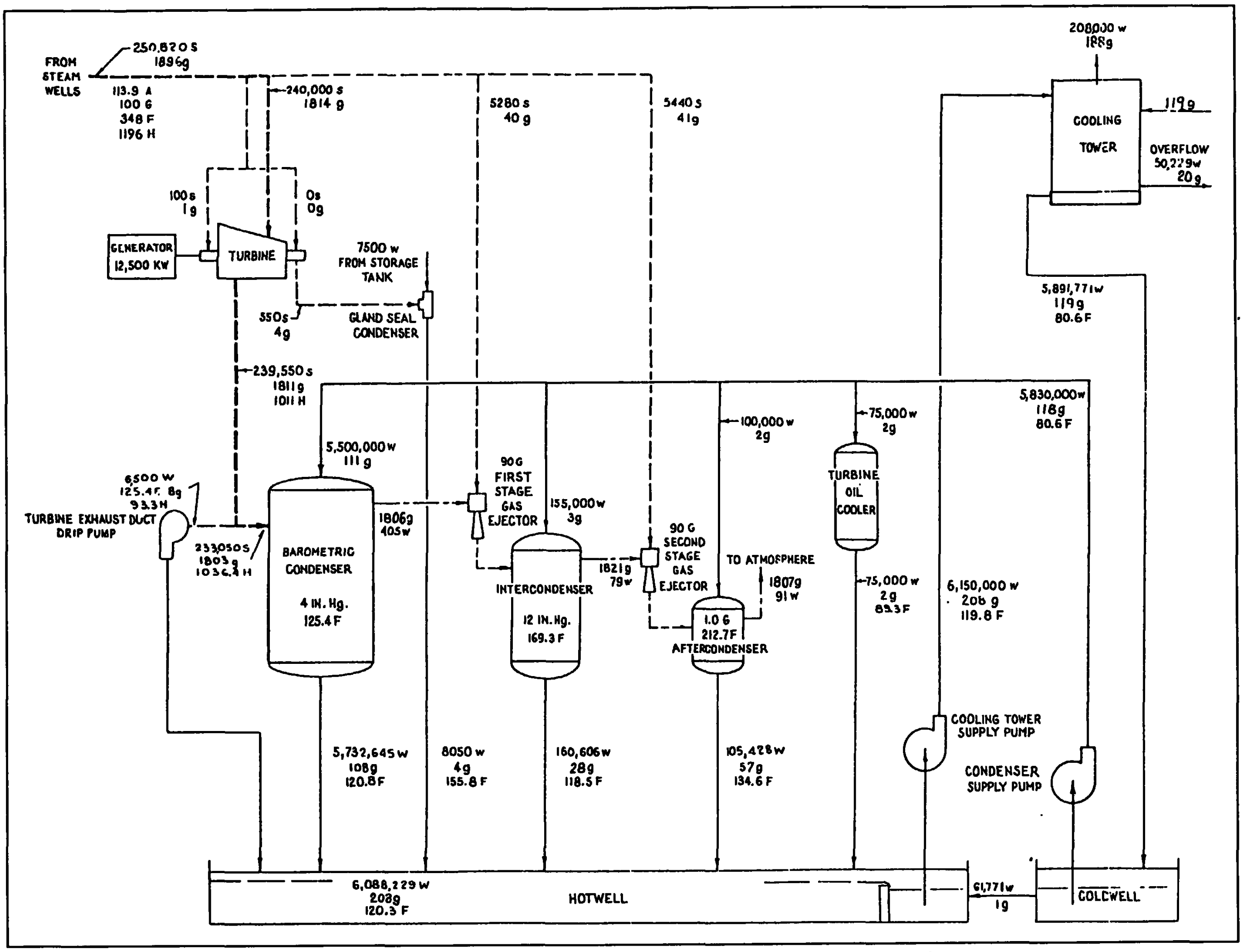

Figure 1. Engineering diagram of an early power plant (Units 1-4) at The Geysers including barometric condenser.

The barometric design and its inherent low partitioning has proven to be sufficient for H_2S incinerator applications and PG&E Units 1 and 2 have been converted. Another disadvantage is that some cold and hot water mixing occurs between the hot and cold wells to ensure the cooling tower supply pump does not outrun its water supply. Other than material changes to provide corrosion protection against abatement chemicals, no design changes have been made to the barometric condensers.

The second type of condenser installed at The Geysers was low level direct contact (Figures 3 and 4). The low level direct contact condenser has many of the advantages and disadvantages of the barometric design. This design eliminates the need for a condenser cooling water supply pump as water is drawn into the condenser by condenser vacuum and atmospheric pressure. Separation of hot and cold circulating water is better maintained in comparison to the barometric condenser. The primary disadvantage is that less plugging can be tolerated because of the perforated water distribution trays. When H_2S abatement systems were installed beginning in 1978 condenser performance decreased substantially Because of the increase in sulfur solids plugging. This problem makes the low level design well suited for incinerator application.

Several modifications to the low level design have been made to cope with rising noncondensible gas concentrations. Modifications include off gas removal manifolds to improve gas and heat distribution and gas removal rate control to minimize the amount of vapor carry over due to excessive gas removal rates. The vapor removal rate is controlled by valving or by isolation of one ejector in dual first stage ejector systems (Figure 4). One difficulty in designing modifications to improve heat transfer with direct contact condensers is that improving the heat "scrubbing" ability of a condenser will cause an increase in H_2S scrubbing into the liquid phase. This has been experienced on plants that have poorer thermal performance having superior partitioning.

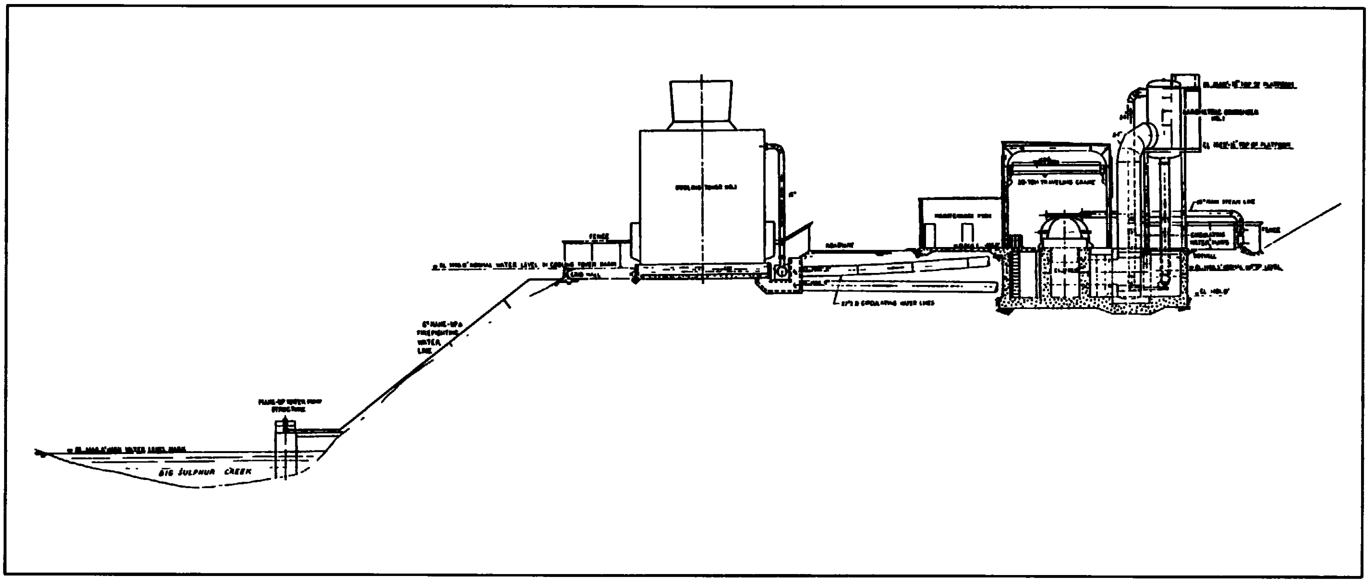

Figure 2. Cross section of an early power plant (Units 1-4) at The Geysers showing the barometric condenser in relationship with other components.

The final condenser type used is the tube and shell surface condenser. This design has been used on every plant installed since 1979. PG&E's Unit 14 was originally designed for low level direct contact application but changed to a surface design to apply a Stretford abatement system. The primary advantage of the surface design is the higher H_2S partitioning achieved in comparison to direct contact condensers. Typical partitioning is 80 to 90 percent. Partitioning performance is one of the key performance parameters evaluated when deciding on a condenser design as higher partitioning reduces the chemical requirements for treating the liquid phase hydrogen sulfide. The disadvantages of the surface condenser are the high cost and added maintenance associated with tube cleaning. Chlorine dioxide and ball cleaning systems have proven to be very effective in maintaining tube cleanliness. Titanium tubes have been used on several condensers because of the improved thermal conductivity and corrosion resistance over stainless steel. One of the most critical surface condenser design aspects is reducing the amount of heat transfer difficulties caused by the increase in noncondensible gas concentration as the steam passes through the tube bundle. Various designs have been used to compensate for this problem. Future condenser modifications will continue to be directed at increasing the condenser gas handling capability as higher gas laden steam is developed.

STEAM PATH

The main considerations for Geysers steampath design are the reliability of operation in a highly corrosive and erosive environment and steam efficiency. The steam path is susceptible to erosion damage as a result of particulate and stress corrosion cracking caused by hydrogen sulfide and chlorides. Steam efficiency is important for prolonging the reservoir life and reducing operating costs.

The first four plants installed at The Geysers utilized single flow turbines. The majority of units installed since

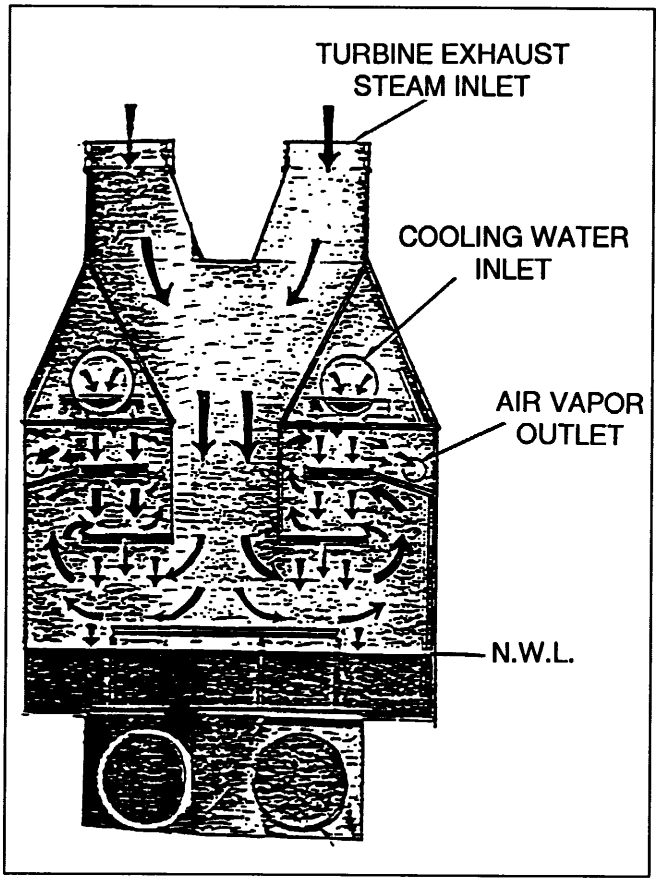

Figure 3. Cross section of a low level direct contact heat exchanger that was used at The Geysers in Units 5-12.

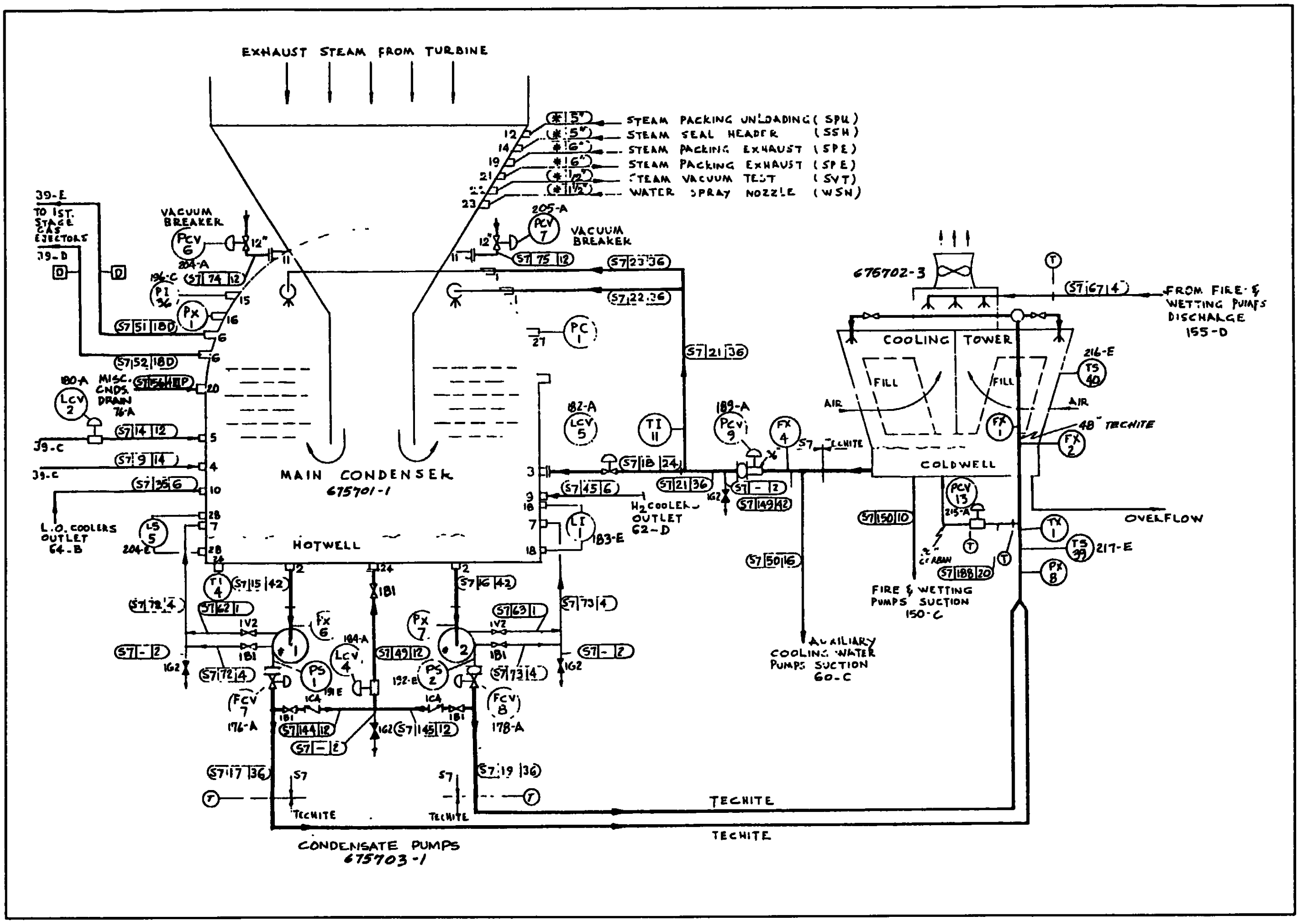

Figure 4. Engineering diagram of a power plant at The Geysers showing a low level direct contact heat exchanger and the cooling water system.

then have been double flow rotors which, in comparison to single flow ratios, reduce the size of the rotor per megawatt and reduce the possibility of thrust problems. PG&E's Unit 1 turbine generator was salvaged from a retired fossil fuel plant. This 300 psig General Electric marine rotor was manufactured in 1927 and was modified for lower pressure operation at The Geysers by removal of the first three stages. The rugged construction of this era has been beneficial in a geothermal application. Unit 1 has operated for 29 years and had a 1988 availability factor of 96 percent.

The improvement in Geysers turbine steam rates since 1960 is shown in Figure 5. The primary design change which has improved the steam rate is the lower condenser pressure design point. Lower condenser pressure operation is provided by greater cooling tower and condenser capability in plants installed in the 1980s. Improved interstage sealing has also added to the improvement.

Future steam path changes will likely be directed towards efficiency improvements to cope with the declining steam reservoir and lower quality of new reserves. Lower pressure operation requires higher steam velocities to maintain mass flow rates because of the reduced steam density. Possible modifications include rotor replacement or modification for low pressure and reducing piping restrictions such as replacing field piping, valves and strainers with lower pressure drop designs. Modifications will also include protection against corrosion and erosion through alternative steam path materials and/or protective coatings. The feasibility of all modifications will be determined by the future economics of Geysers energy.

GAS REMOVAL

The primary design used for gas removal is the two stage steam jet ejector. This design provides high reliability at low cost with sufficient ability to achieve reasonable condenser pressures. Gas compressors can sometimes be justified based on individual plant economics and have been used on two plants for second stage operation. Compressors have the advantage of reducing steam consumption, and the disadvantage of higher capital and maintenance expenses. The lower reliability of compressor trains

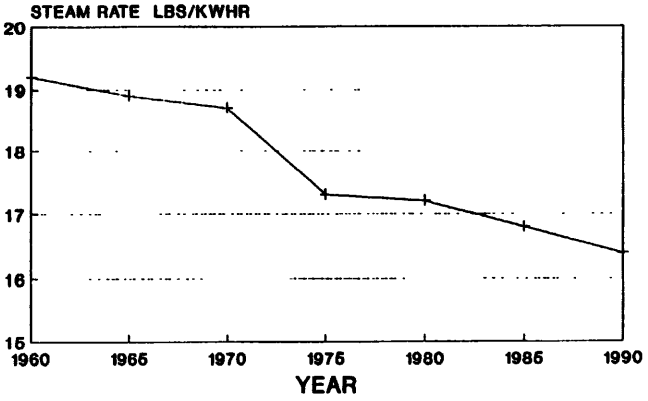

Figure 5. Chart showing average turbine design steam rate for The Geysers.

requires a parallel steam ejector train as backup. Three stage steam ejector trains with intercoolers have been designed which can improve both steam consumption and performance but require a higher initial capital expense. Future changes to gas removal systems will involve lower pressure operation and reduction of steam usage.

HYDROGEN SULFIDE ABATEMENT SYSTEMS

Environmental regulations have played a large role in influencing the type of designs used for nearly all plant systems. The abatement system represents a significant portion of the initial installed capital expense and a large maintenance and operating expense through the cost of chemicals, disposal of hazardous waste and daily maintenance. Table 1 lists the abatement system used at each Geysers unit.

The first permanent hydrogen sulfide abatement system was installed on PG&E Units 3 and 4 in 1978. This abatement system used iron sulfate, caustic soda and hydrogen peroxide (ICP) to scrub the H_2S into the liquid phase and convert it into sulfur compounds. Iron sulfate was replaced by a chelated iron in 1982 that produces lower product losses to side reactions and a more manageable sulfur product. The ICP system causes plugging of heat transfer surfaces because of the buildup of sulfur compounds in the circulating water system.

In 1979 the primary abatement system became the Stretford process. The Stretford process treats the gas phase H_2S using a vanadium salt to oxidize scrubbed H_2S to sulfur. Depending on the level of partitioning and the steam H_2S concentration at liquid phase, (secondary) abatement may also be required. An ICP type of abatement is the most common system used for secondary abatement. The disadvantage of the Stretford process is in disposal of the sulfur product which may be contaminated with vanadium or mercury. In 1988 PG&E Unit 15 was converted from vanadium based Stretford to an iron chelate based LoCat. LoCat reduced the cost of waste disposal by lowering the water content of the filtered sulfur product, but increased chemical cost. LoCat also increased the gas handling capacity over the Stretford system.

In 1981 PG&E installed a pilot plant incinerator at Unit 1. Since then, the majority of ICP systems have been retrofit with incinerators. Incineration has been an effective complement to the ICP system by reducing circulating water sulfur solids. Incinerators burn H_2S producing SO_2 which is passed to a scrubbing tower. The scrubbed SO_2 forms sulfurous acid which reacts with circulating water sulfur to form soluble thiosulfate. Two plants at The Geysers use incineration in conjunction with Stretford abatement to reduce circulating water solids formed by secondary abatement and provide added capacity for gas phase abatement.

CONCLUSION

The Geysers power plants have evolved from the conceptual phase, through the experimental, to become a major and reliable source for northern California electrical needs. The power plants have evolved through different design phases based primarily on efficiency, the best technology available during design, and changes in regulatory policies.