EVOLVING POWER PLANT DESIGNS PREPARE AMERICAN GEOTHERMAL INDUSTRY FOR THE 21ST CENTURY

R. Gordon Bloomquist, Ph.D.[1], B. Alexander Sifford III, M.S.[2]

[1]Washington State Energy Office, Olympia, Washington, USA
[2]Oregon Department of Energy, Salem, Oregon, USA

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ABSTRACT

Geothermal power generation in the United States of America has undergone an innovative revolution since the early 1980s. The design and operation of geothermal power plants continues to evolve, reflecting changes in power sales arrangements, legislative and performance incentives, environmental awareness, and regulation. These changes are clearly evident in plant design and operational characteristics, including redundant well field and plant equipment, non-utility ownership and operation, project financing, emission control techniques, and architectural solutions to the siting of facilities. This paper reports on current developments in North American geothermal power plant technology, with examples from plants in California, Nevada, and Utah, which provide insight into what will be required to meet the demands of the 21st Century.

1. INTRODUCTION

Geothermal power generation in the United States went through an innovative revolution beginning in the early 1980s. Prior to that, the American geothermal industry was, for all practical purposes, a single technology unique to The Geysers. The resource was dry steam at a fairly constant temperature and pressure with low amounts of non-condensable gases. Resource companies developed The Geysers steam field, and Pacific Gas and Electric Company (PG&E) was the only utility involved in design, construction, and operation of geothermal power generation facilities. Steam was purchased from the resource companies at a percentage of the selling price of the electricity. Condensate was used for cooling water with any excess sent back to the resource company for injection at an additional cost.

Since late 1979, however, "The Geysers Scenario" is no longer the norm. Resources, developers, and organizational roles have changed. New resources being developed in other geographical areas are typically hot water instead of steam, with temperatures varying from near boiling to 320°C (600°+F) or above. Hot water requires flashing to yield the valuable enthalpy in the resource. As rare, dry steam, "high grade" sources were developed, developers focused on the more abundant lower grade prospects. Water quality of these resources varied from several hundred parts per million (ppm) total dissolved solids to upwards of 350,000 PPM, requiring that much greater attention be paid to material selection, brine handling, and injection.

Resource companies are still in the business of exploring for and developing resources, but most are no longer satisfied merely to sell steam or brine. Most now construct, own, and operate power generating facilities. This leaves the utility with the sole role of power marketer. However, not all utilities have accepted this role. Some utilities now have leases containing geothermal resources, e.g., Eugene Water & Electric Board has leases in Oregon's Cascades, and others own resource lands, e.g., Sierra Pacific Power Company at Steamboat 1 in Nevada. Some utilities formed development subsidiaries, e.g., Southern California Edison's Mission Energy Company. Furthermore, condensate is no longer looked upon as a waste product with associated disposal costs. It is instead a vital commodity for prolonging reservoir life, mitigating potential land subsidence problems, and even as a means of disposal for noncondensible gases.

Changes in the geothermal industry have been prompted in large part by federal legislative initiatives, of which the passage of the Public Utilities Regulatory Act (PURPA) of 1978, the Energy Tax Act of 1978, and the 1980 Windfall Profit Act were, by far, the most important. These initiatives required electrical utilities to interconnect with geothermal plants and purchase electricity at a rate based upon their full avoided costs; allowed for the deduction of intangible drilling expenses and extended to geothermal the percentage reservoir depletion allowance traditionally allowed in oil and gas development; and provided investment tax credits and accelerated depreciation for generation facilities. Other contributing factors have been increased competition with both conventional and renewable energy resources, and greater environmental awareness.

This paper addresses innovations in new plant development and provides an overview of emerging information from the new, diverse array of projects in the western United States (Figure 1). Table 1 is a summary of selected American geothermal industry's accomplishments documented by this report.

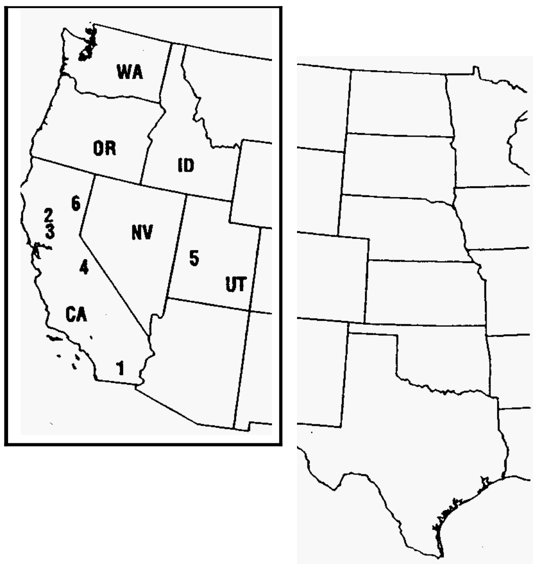


Figure I
Western States Geothermal Case Studies

Table 1
Matrix of Geothermal Plants
Pioneering Innovative Features

	1 Salton Sea	2 SMUDGE0 #1	3 Santa Fe #1	4 Mammoth-Pacific	5 Cove Fort	6 Wineagle
Innovative Feature(s)	Crystalizer/ Clarifier	Heat Rejection System	2 Turbines, Partial Arc Admission	Air Cooled	Steam-Binary Hybrid	Lowest Temperature Unmanned Oper..tion
Result	Increased ability to use high tds brines	Increased efficiency	Increased availability	Reduced environmental impacts	Increased efficiency	Economic use of low temperature resources: small production plants
Size (Net MW)	10	72	80	39	10	.62
Conversion Tech.	Triple Flash	Direct	Direct	Binary	Steam & Binary	Binary
On-Line Date	1982	19x3	1984	1984/90	1984/90	1985
Plant Designer	Unocal	SWEC	SWEC	Ben Holt Co	ORMAT. Barber-Nichols, Ben Holt	Barber-Nichols
Plant Owner	Magma	SMUD	Santa Fe	Pacific Geothermal	UMPA/Provo	Wineagle

SMUD = Sacramento Municipal Utility District
UMPA = Utah Municipal Power Agency
SWEC = Stone & Wchster Engineering Corp
Provo = City of Provo, Utah

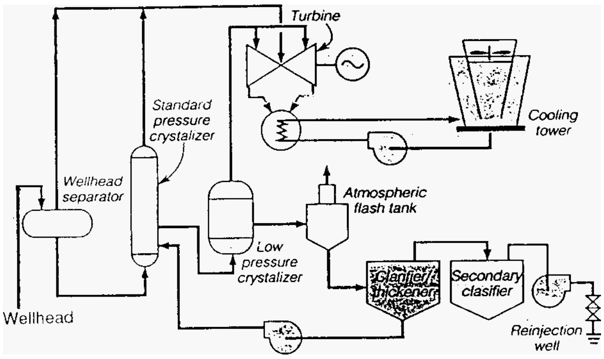
2. CASE STUDIES

2.1 Salton Sea

As companies strove to develop all available known geothermal resource sites, the ones that presented the industry with its most serious challenge were the extremely attractive reservoirs at the Salton Sea and Brawley in California's Imperial Valley. These reservoirs, known to exist since the 1850s, contain fluids with temperatures up to 320°C (608°F) and with total dissolved solids that range from 200,000 to 300,000+ ppm. These highly corrosive and scale-forming brines thwarted all attempts to use them for power generation until the early 1980s (DePippo, 1990). The problems in handling these fluids were studied during the 1970s through a joint research and development effort of Magma Power Company, San Diego Gas and Electric Company, and the U. S. Department of Energy at the Geothermal Loop Experiment Facility (CLEF).

During tests at the CLEF, engineers developed the crystallizer/clarifier process to solve the problem of silica scale build-up while processing geothermal brines. With the very high concentration of dissolved silicas, silica precipitates would eventually accumulate and clog pipes and other surface equipment and seriously interfere with injection. By 1982, UNOCAL and Southern California Edison were able to put Salton Sea Unit 1 on line using the technology developed in the 1970s at the GLEF facility. This was basically a single flash steam plant. Subsequent plants used a dual-pressure turbine. The steam is generated in a series of stages using well head separators (ws), high pressure (HPFC), and low pressure (LPFC) flash crystallizers (Figure 2). The brine from the HPFC is flashed to the LPFC, and the highly concentrated brine from the LPFC is flashed to atmospheric pressure into atmospheric flash tank (AFT). The highly supersaturated brine (with respect to silica) is directed to a reaction-clarifier (RC) that separates the heavy solids from the liquid which is then pumped to the secondary clarifier before injection. Solids are either reintroduced into the crystallizer as seed material or disposed of in an environmentally acceptable manner (DiPippo, 1990).

In 1985, Magma Power Company completed construction of the Vulcan power plant at the old CLEF site. This 34 MW (net) facility, employing the crystallizer/clarifier process successfully demonstrated that commercial scale generation was possible using the Salton Sea brines. Magma subsequently built three 38 MW (net) power plants on the Salton Sea reservoir: the Del Ranch and Elmore plants in 1989; and the J. M. Leather plant in 1990 (Figure



Dual-flash process **used** at the Salton Sea plant extracts up to 30% more power than old. single-flash units.
After Forsha and Nichols, 1991

Figure 2
Salton Sea Process

3). UNOCAL also expanded its operation in the Salton Sea, completing the 47.5 MW (net) Salton Sea Unit 3 in 1989. All of these facilities use the crystallizer/clarifier process (Signorotti and Hunter, 1992). In 1990, UNOCAL completed Salton Sea Unit 2, an 18 MW (net) facility that is the only plant not equipped with a

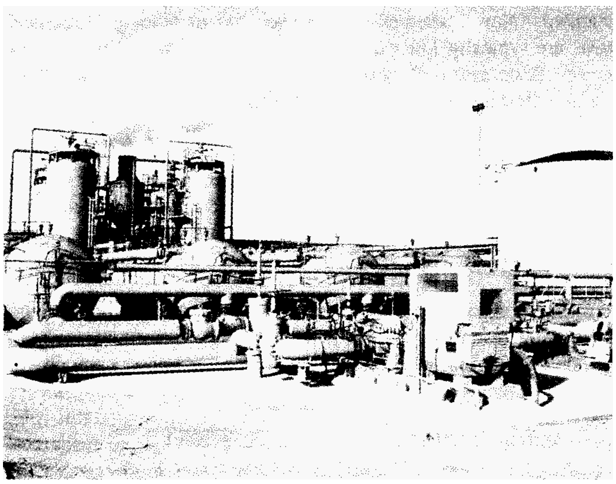


Figure 3
Commercial Crystallizer/Clarifier Plant

crystallizer/clarifier process. Instead, brine handling at Salton Sea Unit 2 is accomplished through pH modification, thus providing developers with yet another tool to deal with the complex chemistry of many geothermal reservoirs.

2.2 SMUDGEO #1

The Sacramento Municipal Utility District (SMUDGEO #1) is a Geysers plant owned and operated by the Sacramento Municipal Utility District. The 72 MW power plant went on-line in 1983, and is an excellent study of increased conversion efficiency. Its chief innovation was to purchase steam from Calpine *Corp.* on a per-pound basis (Tucker and Kleinhans, 1980). This contrasts with the "traditional" cost of steam sales based on a percentage of plant net electricity sales. A tremendous incentive therefore exists to generate as many kilowatts per pound of steam as is economically feasible.

In order to obtain maximum possible efficiency, SMUDGEO does three things, all related to efficient heat rejection. First, the plant uses a highly efficient four-flow turbine with 63 cm (25 inch) last stage blades. The 63 cm blade was the largest ever used at The Geysers. Efficiency is also increased through the use of an oversized heat rejection system. This consists of a 23,200 square meter (250,000 sq.ft.) titanium tubed, two-zone condenser and two six-cell, Class 600 wood cooling towers. The four-flow turbine with its 63 cm last-stage blades and the oversized heat rejection system allow the plant to operate at a back pressure of 3.X cm (1.5 in.) HgA. SMUDGEO's efficiency is also increased through the use of an innovative, three-stage, noncondensible gas removal system. The two first stages use steam jets while the third is composed of three 50 percent capacity liquid ring vacuum pumps.

In comparison, the Pacific Gas and Electric Company (PG&E) 110 MW Unit 16, that came on-line the same year as SMIJDGEO #1, has 17,000 square ineter (184,000 sq.ft.) of condenser area and an 11 cell cooling tower (Stone & Webster Engineering Corp., 1986). PG&E Unit 16 uses 880,000 kilograms/hour (1,940,000 lbs/hr.) to produce 110 MW net, while the SMUDGEO #1 plant utilizes only 431,000 kilograms/hour (950,000 lbs/hr.) to produce 70 MW net (Stone & Webster Engineering Corp., 1985). SMUDGEO #1 consumes 5.0 to 6.4 kilograms (13 to 14 lbs.) of steam to produce 1 kWh. PG&E Unit 16 system consumes X.2 to X.6 kilograms (IX to 19 lbs.) of steam per kWh produced. Thus a desired 25 percent improvement in conversion efficiency was achieved over previous typical steam consumption rates at The Geysers.

As a result of this innovation, the Central California Power Authority (CCPA) Units #1&2, incorporated many of the design features into its operation. And PG&E added a three-stage ejector system at its Unit 18 plant, to lower steam consumption and the operating pressure of the ejector (Ballantine, 1994).

2.3 Santa Fe #1

The Santa Fe #1 geothermal power plant, which is located less than a mile from SMUDGEO #1, is the most unique power plant in The Geysers steam field and provides an interesting example of a plant that has obtained both high capacity and availability through innovative approaches that ensure highest possible flexibility and reliability in plant operation. Santa Fe was the first company in The Geysers to control the operation of both the steam field and the power plant and sell power under a PURPA contract (80 MW net maximum output). Because Santa Fe is both steam supplier and plant operator, each pound of steam produced from the reservoir has a premium value, and thus provides a strong incentive to use that steam **as** efficiently as possible.

Initial design studies completed for the Santa Fe facility by Stone and Webster Engineering Corp. indicated (as with the SMUDGEO #1 plant) that the highest efficiency could be obtained through the use of a four-flow turbine. However, due to common ownership of the plant and well field, plus contract incentives, Santa Fe desired to obtain both highest allowable capacity and availability for maximum revenue with minimum per unit production costs. Instead of using a single four-flow turbine arrangement (which would have to necessarily operate at below maximum efficiency because of turbine fouling or experience regular shut downs for turbine blade refurbishing), it was determined that two two-flow turbines would provide both higher capacity and availability with little or no loss in efficiency. Capacity and availability are assured because each of the two turbine generators can produce the full design capacity of 80 MW by operating at increased pressure and with increased steam flow. Higher efficiency is also ensured through selection of a turbine design that incorporated partial arc admission. The use of the partial arc admission results in reduced throttling losses under normal operating conditions (two turbine operation) and improved single turbine operation. Normal operation calls for each turbine generator to operate at 48.5 MW gross at 8 kilograms per sq. cm (115 psig) inlet pressure and with 7.6 cm (3 in.) Hg exhaust pressure. However, each turbine can also operate at 88.2 MW gross with 11.6 kilogram per sq. cm (165 psig) inlet pressure and 5.1 cm (2 in.) Hg exhaust pressure (Fesmire, 1985).

The use of two turbine generators thus allows for more frequent refurbishing of the turbine blades to maintain performance at design value without significant loss of revenue and without the need to maintain two spare rotors.

The use of a large multi-pressure condenser results in a low average condenser pressure and further enhances efficiency when combined with the large cooling tower (McKay and Tucker, 1985). During single unit operation, full steam flow can be passed through the condenser and the use of the entire cooling tower allows design back pressure to be maintained (McKay and Tucker, 1985). The use of the turbine bypass allows for constant steam flow to the plant in case of a turbine trip or other disturbance, with the steam being fed directly into the condensor and through the hydrogen sulfide abatement system. The turbine bypass allows the plant to be brought back on-line very rapidly after being tripped off-line, and ensures that the plant can meet all air emission requirements without shutting in the wells. Engineers as well **as** regulators quickly recognized the value of the turbine bypass to increasing availability and reducing unabated steam emissions.

The Santa Fe facility has also provided an answer to one of the greatest challenges now facing the independent power industry—the ability to meet the increasing demands of a very competitive market. Given the competition in today's power market, utilities are much freer to demand increasing control over purchased power and to require that plants supplying power best meet the operational and economic goals of the utility. One of the major elements of many utility solicitations for power is the requirement for load following or dispatchability. The two turbine/dual pressure operational capability of the Santa Fe facility allows the plant to meet the utility's criteria for load following or dispatchability while still maintaining extremely high efficiency and availability.

The ability to effectively operate in a dispatchable mode is accomplished through the incorporation of several plant design features. Among these, partial arc admission is most significant.

Partial arc admission, as the name implies, allows for steam to enter the turbine through a portion of the full 360" arc under certain operating parameters and to the full arc during others. The stationary blade ring of the control stage is made up of sectors that may or may not be adjacent to each other. The more the area of the admission nozzle sectors is reduced, the smaller the turbine opening (Bourcier, 1988).

Under partial arc admission, the throttle control valve(s) supplying various portions of the arc are operated at an optimum flow, thus minimizing losses. In fact, when the plant is operating at the minimum output allowed by the partial arc arrangement efficiency will be only 5 percent below full output efficiency. This ensures the use of the minimum amount of steam possible for any given level of output (Manetti, 1990).

The use of partial arc admission also allows for plants to be ramped up very quickly, e.g., from partial to full output in approximately 5 minutes, thus providing a major advantage when operating in a load following/dispatchable mode.

The Santa Fe plant has more than lived up to expectations. During the first year of operation, it achieved a capacity factor of 98.6 percent of its 80 MW operating permit and an availability factor of 99.9 percent. Such performance is believed to be without precedent in commercial power plants, and the plant continues to operate with high capacity and availability.

The use of multiple turbine generators has also been incorporated into the design of the Mammoth-Pacific and Coso plants and into the design of several of the projects utilizing small modular units such as those produced by ORMAT Systems, Inc. The Mammoth-Pacific plant, for example, has had an availability of over 90 percent (Asper, 1988). None of the other plants studied, however, have the ability to operate at increased inlet pressure so as to be able to approach the operational performance that has been demonstrated by the Santa Fe plant. However, the use of multiple turbine generators does provide a high degree of flexibility in operation and the continuing production of significant amounts of power, even when some units are inoperable because of equipment failure or scheduled maintenance.

2.4 Mammoth-Pacific

A major design option, operating since 1979, minimizes all forms of pollution from geothermal power plants: the air-cooled binary system. In a Rankine cycle binary system, geothermal brine never comes into contact with the atmosphere, but is instead confined under pressure from the plant's production well back to the injection well. Heat exchangers transfer the heat from the geothermal brine to a secondary working fluid that vaporizes and drives the turbines.

An excellent demonstration of binary technology is at Mammoth Lakes, California, home of the Mammoth-Pacific 40 MW (gross) modular binary power project (Figure 4). Resource temperatures are approximately 165°C (330°F). The three plants use isobutane as the working fluid for the Magmamax binary process (patented by Magma Power Company). The project is composed of three plants, G1, G2, and G3, built in 1984 and expanded in 1990. Plants operate above design specifications and maximum gross power output has been over 40 MW while average net output exceeds 35 MW.

Figure 4
Mammoth-Pacific Plant G1

Cooling is provided through the use of four banks of dry cooling towers (air-to-air heat exchangers). Condensation of the working fluid is based upon floating cooling with the condensing temperature allowed to vary with changes in the inlet air temperature. Floating cooling results in lower than average production during the summer, and higher than average output in the winter. Since Mammoth is a peak winter load area, the increased efficiency of winter operation more than justifies the use of dry cooling (Asper, 1985). Favorable atmospheric conditions during the remainder of the year make up for the low summer production. The net result is a higher total annual power output than if a single high air temperature was chosen as the design point for year-round operation (Campbell and Holt, 1985).

In addition to eliminating cooling water use, this system also eliminates cooling tower drift and vapor plumes (Asper, 1985). Thus the Mammoth-Pacific plant is essentially free of environmental impacts. Although within a mile of the highway into Mammoth, one of the most popular ski resorts in the United States, it is unnoticed by the 40,000+ persons who visit the area each week during the winter ski season. Steamboat Springs (Nevada) plants 2 and 3, built in 1992, use the same design features for many of the same reasons. A number of other binary plants have also adopted dry cooling including Soda Lake and Stillwater, both of which are in Nevada. Dry cooling is also being seriously considered for use at The Geysers where water is at a premium and use of dry cooling would help conserve water for injection.

2.5 Cove Fort

Another innovative plant, operating since 1985, uses both direct steam and binary technologies to efficiently recover available energy. At Cove Fort, Utah, three different plants generate over 13 MW (gross) of electricity for the Utah Municipal Power Agency. The first power plant constructed was a binary system consisting of four 800 kW ORMAT binary units. The second plant, built in 1988, is a refurbished 1.8 MW marine turbine. Now operating in a topping cycle fashion, the exhaust from this turbine generator supplies the binary units. The third plant is an 8.5 MW turbine generator set using steam from three new wells (GRC, 1990). Net output averages 10 MW.

The innovative design feature of this facility is the marine turbine that acts as a topping cycle unit upstream of the binary units. This type of "cascaded" power output has been suggested informally for years, but the Cove Fort developer (Mother Earth Industries) first applied it in a geothermal operation. As a result, similar designs utilizing flash plant exhaust to feed a binary plant are under way in the Philippines.

2.6 Wineagle

The Wineagle power plant, designed and built by Barber-Nichols Inc., was the first plant in the United States to be operated entirely unmanned. It is also unique in that it uses the lowest temperature resources in a United States geothermal power plant (109°C/228°F). The 620 kW (net) faciiity, consisting of two skid-mounted binary units (Figure 5), began commercial operation in 1985, only 6 months after receipt of the order. This rapid turnaround was made possible by the modular design of the plant's two preassembled power modules. Factory assembly of all of the piping, wiring, and major components on a single skid minimized time-consuming field construction. Larger plants, consisting of multiple units, can take advantage of phased construction that improves economics by minimizing the time between the start of construction and the onset of revenue generation (Forsha and Nichols, 1991). The plant's cooling system consists of an evaporation condensor mounted on top of the power module (Figure 5). The evaporator condensor combines a shell and tube heat exchanger and a cooling tower in a single component.

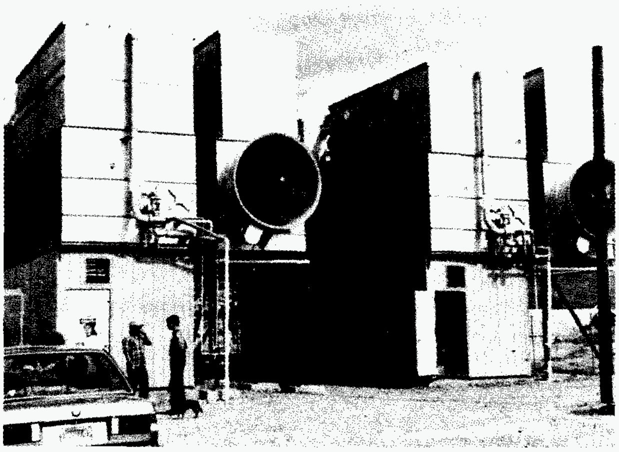


Figure 5
Wineagle Plant

The control system allows unattended operation. The plant is automatically shut down when a malfunction is detected. If the problem is with the power distribution grid, the plant is automatically restarted as the grid comes up. If the problem is in the plant, restarting is attempted once, after which the plant operator is notified through an automatic phone dialing system. Daily operation requirements are limited to approximately 30 minutes for equipment inspection. Over the period 1985-1991, the plant operated with an average avarlability of over 98 percent.

The Wineagle plant's commercial demonstration of the use of resources slightly above the boiling point opens up the possibility of power generation at a tremendous number of low-temperature sites. Our host country for this conference, Italy, has unmanned plants operating today. The factory-built modular units and unmanned operation make this technology especially attractive to remote locations where either small increments of power are needed or where skilled personnel are unavailable for either plant construction or operation.

3. SUMMARY

The design and operation of geothermal power generating facilities in the United States has undergone a major revolution since the early days at The Geysers. The majority of that revolution began during the 1980s, but continues into the 1990s.

The changes that have occurred are a result of several factors, among which the passage of the Public Utility Regulatory Policy Act (PURPA) of 1978, the Energy Tax Act of 1978, and the 1980 Windfall Profit act are probably most significant. These important pieces of legislation have resulted in a new alignment of traditional resource developer/utility roles. Resource developers are no longer satisfied nor constrained (depending upon corporate philosophy or perspective) to merely sell geothermal brine or steam to a generation utility. Instead, they often consider plant ownership and operation a natural extension of their business, with the utility serving only as the marketer of electricity. Utilities, on the other hand, have begun to consider investment in resource exploration and development to ensure competitive "fuel" prices and market positions. Utility subsidiaries are often the vehicles used to accomplish this although some utilities, such as Portland General Electric, Seattle City Light, and the Eugene Water and Electric Board, have made direct investments in leases and exploration.

Improved generation efficiency has been mandated by steam contracts that call for payment on the basis of kilograms of steam delivered rather than on a percentage of revenues from electricity sales. Similarly, when the field developer and the plant operator are the same, there is a clear recognition of the value of each kilograms of steam produced (Fesmire, 1985). Higher efficiency has been achieved through turbine bypass systems, computerized well field operation, the use of larger heat rejection systems, and more efficient turbines. Secondary benefits have been decreases in airborne pollutants, increases in available water for reservoir maintenance, and decreases in the visual effects of cooling tower plumes.

Engineering design, driven by desire to maximize economic efficiency, has also sought highest capacity and availability factors. Many of the newest plants consistently achieve these factors in the high 90 percent range. High availability has been ensured through redundancy of most active components. For example, in the case of the Santa Fe plant at The Geysers, this even goes so far as to include a redundant (i.e., "twin train") turbine generator (Fesmire. 1985). In the case of Mammoth-Pacific, Steamboat Springs, and Coso, it means multiple modular units that vary in size from 1.2 MW to 27 MW.

Thus, through innovative improvements in plant design and plant and well field operation, many of the geothermal generating plants built since 1980 operate with extremely high capacity and availability factors, optimize the use of geothermal steam or brine, and do it all with decreased environmental impact. The Mammoth-Pacific binary plant is one of the classic examples of this with benefits occurring to the developer, utility, consumers, the long-term productivity of the field, and the environment.

The cases sited above can be regarded as state-of-the-art technology. Even on low grade resources, small, modular binary systems are demonstrating technical, environmental, and economic advantages in spite of less profitable fluids. As confirmation/testing facilities, these small plants incur minimal risks and may offer significant insight into the feasibility and operating parameters of larger commercial scale plants.

Geothermal power generation is continuing to prove itself a highly reliable, cost-effective source of electricity. Comparison of cost, reliability, and environmental acceptability criteria suggest geothermal to be a source of electricity that will almost surely play a major role in meeting the demands of the 21st century.

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