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GEOTHERMAL POTPOURRI





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A Quarterly Progress and Development Report on the Direct Utilization of Geothermal Resources

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DISTRICT HEATING ON THE HIGH PLAINS OF PAQUIMÉ

Susan F. Hodgson
California Department of Conservation
Division of Oil, Gas, and Geothermal Resources

INTRODUCTION

For a brief 56 years, around 1205 to 1261 A.D., Paquimé, Mexico (also called las Ruinas Casas Grandes) was in its prime, a city about 280 km northwest of Chihuahua in a basin on the vast high plains of northern Mexico. Paquimé relied upon many innovative hydrological systems—perhaps including a geothermal district heating system begun around 1060 A.D. If this proves true, the Paquimian system is the oldest geothermal district heating system in the world.

How the city came to be as it was—and why its golden era was so brief—are integral parts of a complex hydrological story that includes geology and cultural history.

GEOLOGY

As late as Eocene time, northern Mexico was cut by the Laramide orogeny. Large fault blocks of Mesozoic and Paleozoic rock—including rugged volcanics—became mountain ranges stretching northwest-southeast, usually between 1,000 and 2,000 meters above sea level, their bases hidden in basins of Cenezoic sediment where hot springs sometimes bubbled up.

The parallel pattern of basins and ranges formed a great corridor, a north-south frontier passage where animals and humanity ebbed, flowed, and intermingled through millennia, including mankind who arrived about 10,000 B.C. in the shadow of Pleistocene megafauna.

CULTURAL HISTORY

Paquimé, Mexico, is near the center of what is called the Casas Grandes Archaeological Zone in northern Mexico and the southwestern United States (Figure 1). Vast and inexact, the zone equals about 170,521,470 sq km.

The zone was populated by Chichimecans, rugged individualists from all accounts. They included several mixtures of Mexican peoples, depending on the chronicler, so the exact composition is unsure. The Chichimecans lived in small hunting groups for hundreds of years longer than their southern neighbors, unable to risk agrarian communal living without irrigation in a climate such as theirs.

The great art and urban architectural traditions of Mesoamerica, including skills such as irrigation, evolved in the highly organized, agrarian cultures in southern Mexico, where between 1900 and 1500 B.C., people became full-time agriculturists.

PAQUIMÉ: THE BEGINNING

Chichimecans began living together at the site we call Paquimé between 700 A.D. (±50 years) and 1060 A.D. (Figure 2). This may have been inspired by contacts with

Figure 1. ***Paquimé, Mexico, at the center of the Casas Grandes Archaeological Zone (after Di Peso, 1974a).***

southern merchants, for by now long trading caravans moved throughout southern Mexico and then northward, exchanging products and ideas. Highly civilized southern Mexico had reached its *Classic Period*. In general, this was a time of change in both southern and northern Mexico—destruction of civilizations and power shifts in the south and growth of communities in the north. Gradually life in Paquimé altered, and architecture and artifacts became more complex. By the mid-11th century, the dominion of Paquimé had grown to include over 220,150 sq km of land and several thousand satellite or culturally associated villages.

These socio-cultural interrelationships were created and nurtured by southern merchants based on their own direct economic ties to one or more older southern cities. The merchants, called *puchtecas*, were commoners—chosen as advisors and war captains to kings, merging military and trading activities in southern Mesoamerican society. A merchant in a frontier post was under the direct control of a home merchant with military, religious, and mercantile responsibilities. The *puchtecas* provided information about new areas, new customs, and trails and raw materials. They negotiated trade treaties and guided conquering armies.

Archaeologists assume *puchtecas* came to Paquimé from a relatively complex hydrological culture (or cultures) in Mesoamerica. The first sent were—naturally—in disguise to gather data about the town. Turning Paquimé into a major trading center was a major undertaking, and *puchtecas* carefully calculated risks and benefits. They considered the amount of exploitable raw materials available; the hydrological potential—at least one major water source was

Figure 2. ***Paquimé, Mexico. The letter "A" is by the fork of the acequia madre and the acequia lateral 1, and "B" is by Reservoir 1. Compare the photo with Figure 6 to trace the paths of the acequias. Courtesy of The Amerind Foundation, Inc., Dragoon, Arizona.***

needed to feed a hydrological system; the climate—a complete plant growth cycle was critical; the acreage of fertile soil accessible to irrigation; and geography in terms of transportation. Paquimé was near the center of all the Chichimecans, on the southern edge of a turquoise-producing area and in an important north-south corridor with enough people to support economic growth. The *puchtecas* negotiated "rights-of-passage" treaties with enemies on all sides of the city, safely linking Paquimé to both the raw materials needed to make goods and the markets to sell them.

PAQUIMÉ: ITS PRIME

Under the helm of the *puchtecas*, Paquimé was rebuilt from the ground up. It became a dazzling planned, model city that reached a pinnacle of prosperity from 1205 to 1261 A.D. Influenced by its merchant "professional rulers," the city "…changed from a conglomerate of single-storied, ranch style house-clusters to a massive, multistoried, high-rise apartment house covering some 36 hectares (Figure 3). The former were either razed, remodeled, or abandoned; the earlier city water system was revamped to accommodate the remodeling; and the city planners surrounded this new housing complex with a ring of ceremonial structures including effigy mounds, ball courts, a market place, stately open plazas, and other specialized edifices. Obviously, the Paquimian authorities had not only the power to relocate the inhabitants, but control of the required labor and building materials to carry out this change" (Di Peso, 1974b).

Figure 3. ***Looking eastward across a portion of the dwellings at Paquimé (the walls were once several stories high).***

In 1584, Obregón described Paquimé in its prime, writing, "…this large city…contains buildings that seemed to have been constructed by the ancient Romans. It is marvelous to look upon. There are many houses of great size, strength, and height. They are of six and seven stories, with towers and walls like fortresses for protection and defense against the enemies who undoubtedly used to make war on its inhabitants. The houses contain large and magnificent patios paved with enormous and beautiful stones resembling jasper. There were knife-shaped stones which supported the wonderful and big pillars of heavy timbers brought from far away. The walls of the houses were whitewashed and painted in many colors and shades with pictures of the building" (Hammond and Rey, 1928, *in* Di Peso, 1974a). The name "Paquimé" may come from the Náhuatl language: pa ("big"), ki ("house"), mé ("s").

Thousands of hours were probably spent rebuilding the city, cutting and transporting timbers and gathering construction mud and other supplies. Probably this fascinating architectural rebirth occurred only at Paquimé, not in surrounding areas. However, hundreds of mountain and valley satellite villages around Paquimé helped supply its needs, freeing Paquimians to create "…architectonics, ceramics, jewelry, and lithic [objects]" (Di Peso, 1974b). City life now meant exciting daily markets, busy workshops for pottery and other trading goods, ball games, and ceremonial pomp.

PAQUIMÉ: THE FALL

By the mid-13th century times had changed again, and in the city itself "…two and one-half generations sat idly by and watched the magnificent city of Paquimé fall into disrepair. Artisan-citizens continued to produce an abundance of marketable goods, but civil construction and public maintenance all but ceased. The populace crudely altered public and ceremonial areas into living quarters. The walls of the city crumbled and, apparently unconcerned, people laid rude ramps over the rubble to reach still usable upper rooms" (Di Peso, 1974b).

"The city water and reservoir system was no longer maintained, but left choked by debris and used as a burial area. More hopeless were the cistern drains, which emptied the enclosed plazas of rainwater. These, too, were permitted to go out of commission. The remaining population stole the capstones of the drains and buried their dead in them" (Di Peso, 1974b).

Were these last years ones of economic depression when export markets were lost? Were there natural calamities like earthquakes? Were Paquimians characteristically casting off social oppressors, retrenching to better survive (Di Peso, 1974b)? No one knows.

Whatever the cause, the bitter end for Paquimé came around 1340, when unknown enemies attacked the city. Igniting the first-floor master beams, they destroyed Paquimé, collapsing it upon itself like a house of cards. Hundreds were killed inside the houses and in the public areas. Objects on altars were defiled and thrown into the walk-in well, part of the abandoned city water system. Breeding macaws and turkeys were left to die in their pens and boxes. Only scavenging animals cleaned the slaughter. Through the years, earthquakes, desertion, and ruin have left Paquimé an abandoned, one-storied maze of brown adobe walls.

Some suggest the end was part of a chaotic and widespread frontier revolt against sophisticated Mesoamerican overlords and their practices, possibly triggered by a long drought (Di Peso, 1974b). In any event, the destruction coincided with the general collapse of established centers throughout the Gran Chichimeca.

THE WATER SYSTEMS OF PAQUIMÉ

The city of Paquimé included two innovative water systems—both with multiple parts: one outside the city and one inside.

These systems supported a city built in reverse of most in southern Mesoamerica, which typically had ceremonial and public architecture at their centers and dwellings around the edges. The style chosen for Paquimé, with dwellings in the center and public and religious areas on the periphery, certainly maximized hydrological efficiency in dwelling areas.

That the city was torn down deliberately and rebuilt just before its prime explains a fundamental puzzle about the amazing water systems at Paquimé. Clearly, they were preplanned and in place before structures covering them were built. Yet, the systems themselves are so sophisticated, they came late in the culture.

Outside the City: Surface Water- and Soil-Retention—Plus Irrigation

Paquimé, wrote Obregón in 1584, "… is located in some fertile and beautiful valleys surrounded by splendid and rich mountains and small mountain ridges. It is situated on the shores of the river. This is the most useful and beneficial of all the rivers we found in those provinces. It can readily and at little cost be utilized for irrigating the fertile shores" (Di Peso, et al., 1974).

On the slopes around Paquimé, *puchtecas* designed an elaborate, effective, surface water- and soil-retention system, finishing as an irrigation system. The public project enhanced, protected, and irrigated the land, especially the 750 to 800 sq km of deep, rich bottom lands in the lower Casas Grandes Valley, one of the finest valleys in the northern frontier" (Bartlett, 1854, *in* Di Peso, 1974b). An unforeseen benefit was increased agricultural land on the upper slopes because so much moisture and soil were retained there. Some 12,000 sq km of a dendritic hydrological system were involved, an area of 80,000 hectares once subject to violent runoffs from high mountain thunderstorms.

The system controlled "…every raindrop which fell upon the mountainous southern and western borders [of the city]" (E.L. Hewett, 1908, *in* Di Peso *et al.*, 1974). To do this, stones were arranged in linear borders, terraces, check dams, and grid borders (Figure 4) (Herold, 1965, *in* Di Peso *et al.*, 1974). Slope angles and erosive features determined placement. Some stones were piled in tiers and some aligned in single rows. The complex system, built as a unit, delivered clear water to irrigation canals that ran through fields in the rich lower valley—and to the river itself.

The interlocking system so safeguarded the rich valley-bottom farmlands from erosion and annual flooding that satellite farming villages were built there. Today, such a choice is out of the question for people living around Paquimé, as the entire water- and soil-retention system is in disrepair. Angle by angle and rock by rock, it was custom-made to the terrain. Each part depended on the rest, and once maintenance ended, the system failed.

City Water and District Heating—the Oldest System in the World

The people who lived in Paquimé from about 700 A.D. (±50 years) to 1060 A.D. were first to collect domestic water from Ojo Vareleño, the nearby thermal spring. Archaeologists believe the first city water system channeling domestic water into Paquimian houses was built around 1060 A.D., and I believe the water warmed the rooms it flowed through, the world's first geothermal district heating system (Figure 5).

Figure 5. ***Thermal domestic water flowed through this channel lined with flagstone-like rock in the dwelling area of Paquimé. The small pit has been identified as a tub for bathing. (Photo by Susan Hodgson)***

From 1205-1261 A.D., as *puchtecas* rebuilt and ran the city in its prime, the original city water system was expanded and improved—along with the *de facto* geothermal district heating system (Figures 6 and 7).

The district heating theory depends on the waters of Ojo Vareleño in the low-lying volcanic foothills of the Cerro Prieto Mountains. The spring is 3.65 km northwest and up slope of the northern edge of Paquimé, as measured from the fork of the *acequia madre*, the main water channel of the city system, and the *acequia lateral 1*, the first lateral channel. The fork is visible on all photos and maps of the site. The spring had a flow rate of 11,400 liters per minute in 1960 and is about 1501 m above mean sea level (Di Peso, 1974b).

In 1960, a concrete dam at the spring ran "…north-south across the mouth of the Ojo de Vareleño arroyo below the spring's source, forcing the water to rise to the level of the *acequia madre* outlet, located 1.75 m above and on the southern side of the Ojitos Arroyo. A similar contrivance, perhaps made of earth and destroyed by the modern dam, must have been used originally to perform this hydraulic action" (Di Peso, 1974b).

How hot was the water? Spring water temperatures, sometimes described in the literature as "hot" and sometimes as "warm," today are about 82°F. The water is no longer from

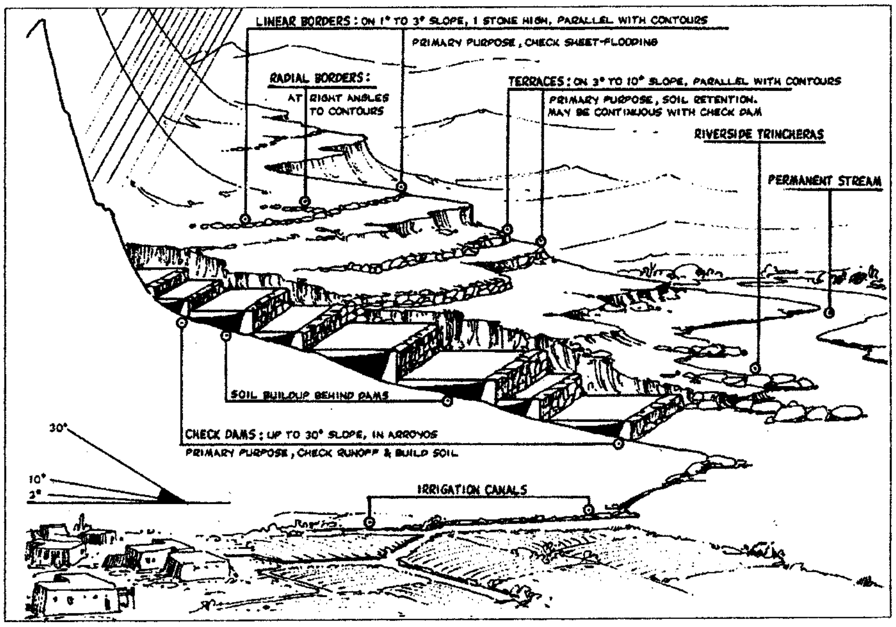

Figure 4. ***Schematic view of the water-control and soil-retention system on the slopes around Paquimé, Mexico. Courtesy of The Amerind Foundation, Inc., Dragoon, Arizona.***

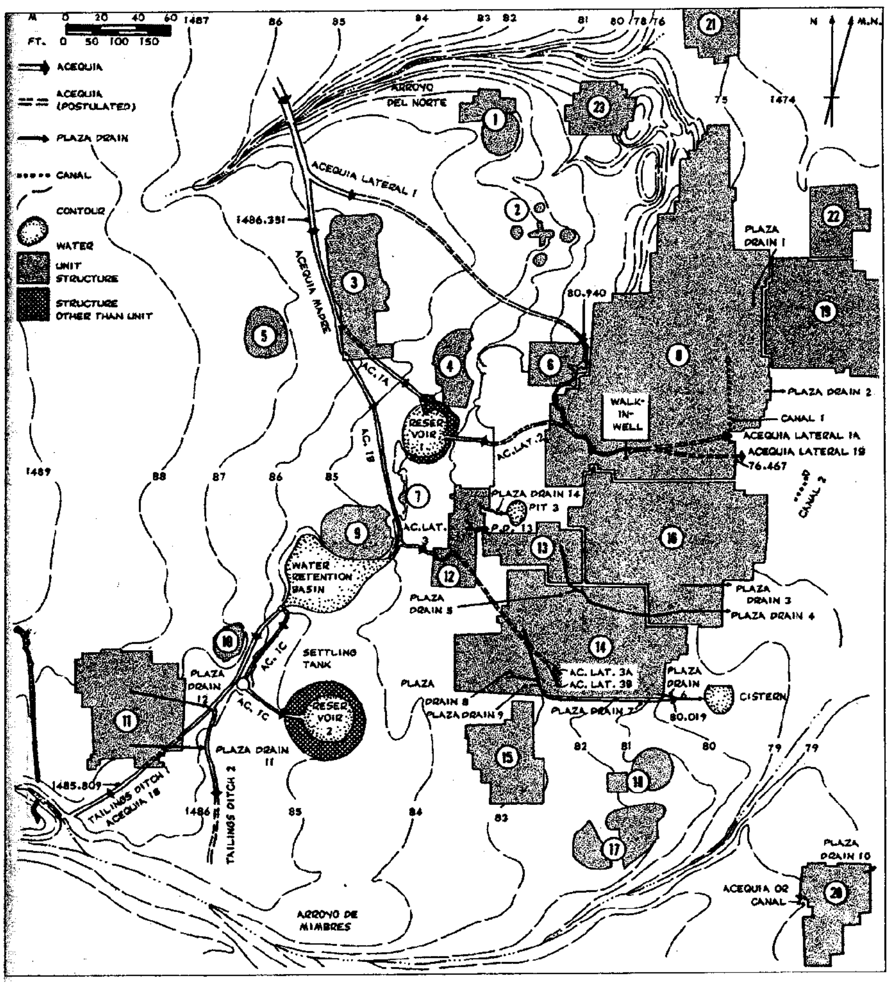

Figure 6. ***Sketch of the city water system at Paquimé, Mexico. The domestic water flows from a hot/warm spring 3.65 km northwest of the fork at the upper left, where the acequia madre meets the acequia lateral 1. Water reaches the housing areas through the acequias laterales 1, 2 and 3. Courtesy of The Amerind Foundation, Inc., Dragoon, Arizona.***

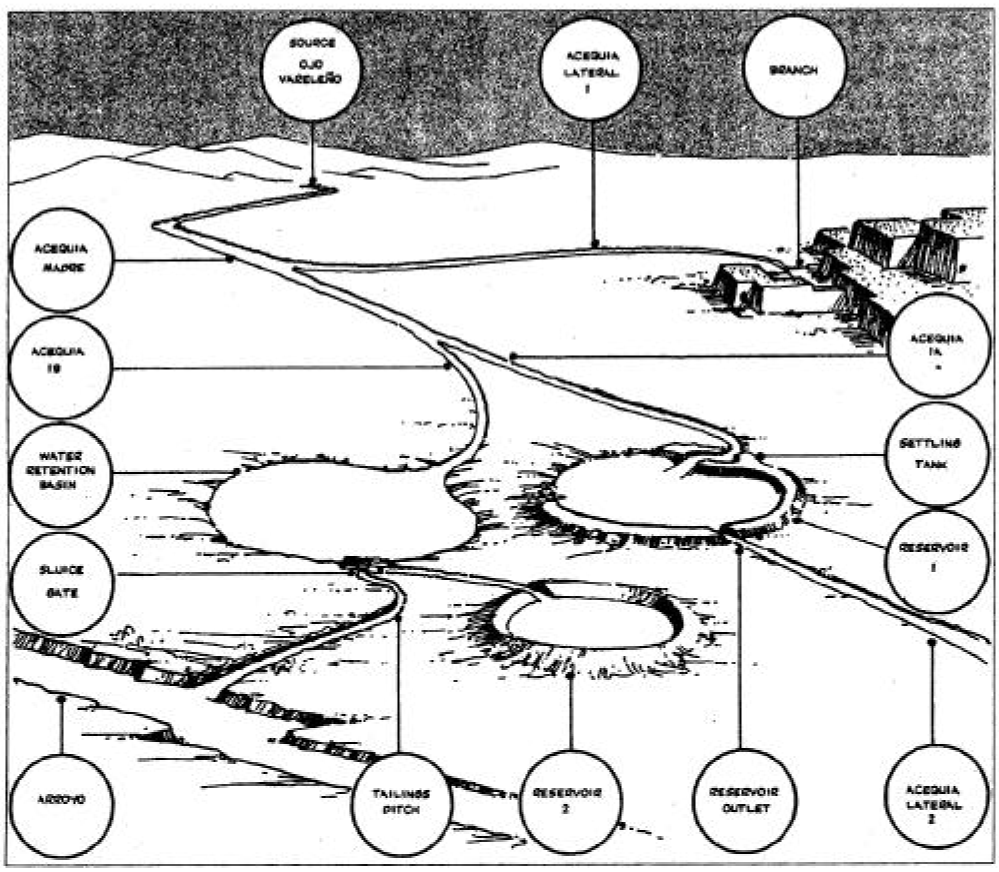

Figure 7. Schematic view of the city water system at Paquimé, Mexico. Not all Figure 6 elements are included. Courtesy of The Amerind Foundation, Inc., Dragoon, Arizona.

one large spring but from a cluster of smaller ones in the same area. Today, the water is collected, filtered and piped to nearby Viejo Casas Grandes, a town abuting the eastern edge of Paquimé. The thermal water is hot enough when it arrives here to make further heating unnecessary for much of the year. True, the thermal spring temperatures may have changed over the last 900 years or so, but experts say this is rare.

Stable isotopic analyses—or other geochemical tests run on spring water deposits on the rocks lining the *acequias* and channels at Paquimé—may tell us the water temperatures in the spring when the domestic water/district heating system was operating. Such analyses are made on sea shells to find the water temperatures of their natural habitats (Churchill, 2001).

At Paquimé, all the *acequias* were empty of water from about 1854 on in the literature I read. (A search of Spanish accounts from the end of the 1500s might prove otherwise for earlier times.) Much information about the *acequia madre* was noted by famed archaeologist Adolph Bandelier, who wrote in 1892, "The *acequia* is best preserved on the terrace northwest of the ruins. There its course is intercepted by gulches, and the section is therefore very plain. It seems that at a depth of about four feet below the present surface, a layer of calcareous concrete (caliche) formed the bottom of the shallow trough through which the water was conducted. It was carried on a steady and very gradual incline by means of artificial filling. The calcareous concrete forming the bed of the *acequia* may be artificial" (Di Peso, et al., 1974).

In 1890, Bandelier said portions of the *acequia madre* near the spring were 10 feet wide, and "...show traces of filling and of cutting. It is no longer the primitive method of slavishly following sinuosities of the ground in order to avoid obstacles. The ditch…runs almost straight…It rests on a bed of stones" (Di Peso, 1974b). Di Peso himself called the *acequia madre* "stone- and adobe-lined" (1974b). The *acequia madre* was graded with a "delicate drop" of 0.4 cm per meter.

Water reaching the city flowed east from the *acequia madre* through three lateral *acequias* to various housing clusters, there passing into narrow channels incised in various ground-floor rooms (Di Peso, 1974b)(Figure 8). (Not all ground-floor rooms have channels and naturally none of the upper story rooms did.) In the Paquimé museum, an archaeologist showed an exhibit of a channel about 25-30 cm wide, made of flagstone-like rock on all four sides. All stones but those on top were cemented, possibly with caliche. If the water channels were like this and people inside rooms lifted loose stones at floor level to extract water for domestic use, I suggest they did so to adjust heat in these areas, as well.

Figure 8. ***A channel for thermal domestic water cut in the floor in the dwelling area of Paquimé. The door at the top of the photo has the typical shape used in the city. Note the smaller door shape incised in the wall, photo right. (Photo by Susan Hodgson)***

This was possible because water flowing from the spring probably retained its heat for the distance to the dwellings. Hydrologists designing systems for Paquimé were too brilliant to have disregarded the heat, and a few heated rooms in the winter would be too welcomed to ignore. If this is true, Paquimé was the first city in the world to develop a geothermal district heating system.

New geologic and archaeological studies, combined with modern hydrological calculations, can help verify this. New measurements are needed of the flow rate; ancient and current spring temperatures; length of the *acequia madre* from the spring to the city; *acequia madre* width and gradation—a grade is given, but I don't know how much of the *acequia madre* was measured to find it; grades of the *acequias laterales* and channels in the rooms; and annual air tempera-tures at Paquimé. Other data may be necessary, as well.

The city water system included three more features attesting to the hydrological genius of the city builders. One was a sewer system and one an extensive plaza-drainage system, built to empty water from the completely enclosed plazas after torrential cloudbursts. Drainage systems are not unknown in ancient Mesoamerican and southwestern sites, but they are not common (Di Peso, et al., 1974).

The third was a "walk-in well," a large multistoried room built under Plaza 3. The only such structure in the Americas, the room is well shored and vented for good air circulation. Stairways wind down to the water table at the bottom—a second urban water supply completely apart from the *acequias*. Halfway down is a detour to a secret room, perhaps built for religious reasons.

CONCLUSIONS

People with great hydrological imagination and skill developed the effective and innovative water systems at Paquimé. Outside the city, these included a surface water- and soil-retention system, and inside the city a "walk-in well" unique to the Americas and what may be the world's first geothermal district heating system.

At Paquimé, channeling thermal spring water for domestic use through dwelling floors meant channeling heat. Housing residents could get water and change the air temperature by adjusting rocks over the channels. Thus, the geothermal district heating system and the domestic water system may have worked together. New geological and archaeological studies may help prove this is so.

Most people are unaware of geothermal district heating systems. The possibility of finding one probably didn't occur to archaeologists studying Paquimé, and I didn't find the topic mentioned in the Di Peso volumes. Although the volumes discuss the *acequia madre* and *acequias laterales*, the large channels bringing water to the city from the thermal springs—these are not studied in the same detail as many other aspects of city life. There was no reason to do so if a geothermal district heating system was not at issue.

Studies by geothermal and geological experts are underway to pinpoint the nature of the geothermal waters enjoyed so long ago at Paquimé.

ACKNOWLEDGMENT

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REFERENCES

Note: Except for comments on geothermal district heating systems, information about Paquimé comes from the volumes by Di Peso, and Di Peso *et al.*

Churchill, R., 2001. Personal communication.

Di Peso, Charles C., 1974a. *Casas Grandes, A Fallen Trading Center of the Gran Chichimeca*, Vol. 1. The Amerind Foundation, Inc., Dragoon, AZ.

Di Peso, Charles C., 1974b. *Casas Grandes, A Fallen Trading Center of the Gran Chichimeca*,. Vol. 2. The Amerind Foundation, Inc., Dragoon, AZ.

Di Peso, Charles C.; Rinaldo, J. B. and G. J. Fenner, 1974. *Casas Grandes, A Fallen Trading Center of the Gran Chichimeca*, Vol. 5. The Amerind Foundation, Inc., Dragoon, AZ.

GATORS IN THE SAGE

Ted Clutter
Geothermal Resources Council
Davis, CA

Sagebrush rustled as 400-lb. prehistoric beasts rose up on strong legs and thundered past us into a steaming pond. After the dust settled, eerie reptilian heads rose through the translucent water until only jewel-like eyes and domed snouts poked above the surface. The high-desert country of the Snake River Plain is a far cry from the lush subtropical swamps of the U.S. Gulf Coast, but a with a perfect combination of sparkling geothermal water and abundant food from local fish farms, captive American alligators thrive in the harsh climate of southern Idaho.

For 50 miles along southern Idaho's Thousand Springs Scenic Byway, life-giving geothermal water reaches the surface in scores of seeps along the Snake River. It is here, near Buhl, where Leo Ray started his successful Fish Breeders of Idaho with his first geothermal well over 25 years ago. His pioneering efforts brought geothermal fish farming to Idaho in the early 1970s, and now promise to usher in a unique growth industry in alligator meat and hides.

A tall, lanky outdoorsman, Ray was born and raised on a farm in Oklahoma. He earned a BS degree in zoology at the University of Oklahoma in 1963, and has continued his studies with more than 100 hours of courses in the sciences and fisheries. By the late 1960s, Ray was running a successful aquaculture operation for African tilapia at the Salton Sea in southern California. It was there that he first learned about the advantages of geothermal waters for aquaculture.

After seeing the wealth of geothermal springs along the Snake River on a trip to Idaho in the early 1970s, Ray quickly realized its potential for raising high-grade fish for market. He looked at various properties for six months during 1972 and 1973 before deciding to buy the site of an old auto junkyard along the breaks of the Snake River Canyon. There he found not only the volume of hot water he needed, but an excellent supply of cold water as well. The hillside site and its fluid resources have proven perfect for his vision of the future.

Ray's Fish Breeders of Idaho, Inc. is located on 170 acres in the Western Snake River Plain geologic province, slashed by the Snake River Canyon from central Idaho west to the Oregon border. The region is thought to be the trace of a "hot spot" now found at Yellowstone National Park, hundreds of miles to the east. Thick lava flows and volcanic deposits are characteristic. It's western portion consists of late Tertiary silicic volcanic rocks and clastic sedimentary rocks, and includes 32 individual low-temperature geothermal systems. The region's geothermal resources have been extensively developed over the past 100 years for aquaculture, greenhouses, and space/district heating.

Upon drilling his first well and raceway for catfish in 1973, Ray gained the distinction of Idaho's first geothermal fish farmer. His first year of production netted 100,000 lbs, and over the next five years he built ponds and additional raceways, fed today by eight geothermal wells. Cascading the water downslope through his raceways makes efficient use of this free heat from the earth, and lowers fish production costs by simplifying operations.

Figure 1. ***Leo Ray standing on one of the raceways.***

Ray's geothermal fish farm is unique. "Most geothermal aquaculture operations are characterized by pumped wells for geothermal water supply," explains Geo-Heat Center (Klamath Falls, OR) Associate Director Kevin Rafferty. "The limited flows from most low-temperature geothermal wells, coupled with the electrical energy necessary to operate the pumps, makes these operations more expensive to build and more complex to operate." But the substantial natural flow of Ray's geothermal spring—coupled with his downslope raceway design—creates excellent economics and provides top quality water conditions for his fish. "Ray's fish farm successfully took advantage of an excellent geothermal resource and a site favorably situated for a raceway aquaculture operation," Rafferty concludes.

Geothermal wells are easy in this part of the world. "Five-hundred foot holes with cable tool hit the water," says Ray, who drilled one well to 1,100 feet, but achieved little additional flow. His eight wells intersect and follow fault-line rubble zones. Faults accessible from his property were indicated to Ray by bends in the river from west to north, natural seeps (3 to 4 gpm) along the river below his property, and large geothermal springs nearby that heat resorts and commercial greenhouses.

Ray's geothermal water flows at a wellhead temperature of 90E to 95EF, with total flow of 4,500 gpm. "To be successful in raising fish, it's good to be able to mix-and-match your hot water with cold," says Ray. "That way you control your oxygen content (hot water holds less) and achieve the optimum temperature for the fish." Ray mixes his geothermal flow with cold well water at a rate of 1,000 gpm during the winter, and between 4,000 and 5,000 gpm during the summer.

That's enough water to run his operations, but he has lost 2,500 gpm in geothermal flows during the last 15 years. "The decline came with hundreds of wells drilled in the area for irrigation and hot water wasted in swimming pools," says Ray, whose property now lies within an Idaho Water Management Area where no new commercial wells are allowed. "Now you can't remove water faster than recharge," says Ray, who claims "1st-in-time" water rights that guarantee his flows.

Ray raises U.S.-native blue and channel catfish, and African tilapia, one of the fastest growing food fish. The catfish enjoy the purest water at the top of his cascading raceways, with more tolerant tilapia at the bottom of the system. With special pellet food devised by Ray and year-round warm water, his catfish grow at more than double their natural growth rates. Respective annual production is 500,000 lbs. and 100,000 lbs. from Ray's geothermal operations.

Figure 2. ***A typical channel catfish.***

Fish Breeders of Idaho also raises a million pounds of rainbow trout and 200,000 lbs. of sturgeon annually at coldwater fish farm on an additional 200-acre property. Ray has 2,000 adult sturgeon at an average 120 lbs. and up at his coldwater operation that he hopes to begin spawning soon. "Caviar from Snake River white sturgeon is said to be second only in quality to that from beluga sturgeon in the Caspian Sea," he says. Ray plans to use a portion of his geothermal operation to quickly "grow out" his sturgeon, but like catfish, they cannot produce eggs at an elevated temperature. For that, Ray lowers their water temperature by 20EF to prompt spawning.

Ray maintains 25 full-time employees, with eight working at the company's hatchery and rearing operations, and the remainder at its processing facility where fish are cleaned and filleted for market. "It takes one to grow it, and two to clean it," says Ray, explaining that much of each processed fish is waste, totaling over 200,000 lbs. each year that must now be landfilled. Though he has plans to begin composting the material, he says, "That's a lot of protein that could be used for another cash crop."

The solution? Alligators. Ray's interest in the ancient reptiles was piqued in the late-1980s as he watched the market for their meat and hides resurge in the South. With his supply of geothermal water, he said, "I knew I had a natural." Ray brought 200 alligator hatchlings from Louisiana to Idaho in 1994. Since then, he has expanded his alligator operation to satisfy a growing market for their succulent meat and superb hides.

Ray imports up to 1,500 hatchlings from Louisiana and Florida every year, raising them to market maturity in dark indoor concrete buildings that suit their largely nocturnal habits. Meanwhile, his hand-picked breeding stock kept in outdoor enclosures has grown to between 10 and 14 feet and 1,000 pounds! He is working to breed these 30 large alligators, to provide a self-sustaining supply of hatchlings and hundreds of new, toothy mouths hungry for his fish processing waste.

Figure 3. ***Juvenile alligators with their bright yellow cross-bands.***

In their natural habitat, alligators retreat to burrows when seasonal temperatures fall. But with geothermal water in southern Idaho, Ray's breeding stock often bask in the sun even after winter temperatures fall below freezing. Only when the mercury falls below 0EF do they retire to their ponds. "They're one of the toughest animals around, and haven't changed for 70 million years," Ray explains. "Alligators can stay underwater for two hours on one breath, live for two years without food, withstand low temperatures, and they feed on carrion—that's how they survived the great extinction of the dinosaurs."

Figure 4. ***Typical alligators ready for harvest.***

Even so, he continues, "If any of these critters did get loose up here in Idaho, they wouldn't survive long outside the artificial environment we provide with geothermal water." To ensure against escape and potential problems with human contact, Ray worked out a plan with the Idaho Department of Fish & Game that encloses his breeding stock with deep-set concrete walls topped with chain-link fence and barbed wire.

Ray currently feeds his alligators with dead fish from his coldwater and geothermal aquaculture operations, and provides free disposal of dead fish from the local fish farming industry. With scores of fish farms in the area (mostly coldwater operations), he has no problem providing his leathery livestock with the food they need to stay in top condition. Ray's alligators are also a local attraction, with neighbors and busloads of school kids regularly visiting his farm. "Kids are fascinated with dinosaurs, and alligators are just small dinosaurs," says Ray, who also provides alligators to zoos in Boise and Pocatello every spring.

Since 1995, Ray has processed 3,500 alligators at an average length of over seven feet. Timing is paramount for Ray's alligator operation. He enters the market each year for January, after southern stocks are depleted. His crew kills eight to 10 alligators per day to maintain continuous processing of meat and hides. The meat is kept frozen for sales throughout the year, but Ray gets top dollar for their hides in late-spring when the market is hungry for leather. "The smallest hides are used to make wallets, gloves and watch bands," he explains. "A three-foot alligator makes a cowboy boot, and larger hides are used for coats and luggage."

Ray isn't the first geothermal fish farmer in the United States to raise alligators. In Mosca and Lamar, CO, Erwin Young has raised and bred alligators to eat dead fish and processing waste from his tilapia farming operations since 1985. And with publicity about Young's operation, Husavik, Iceland is now considering a "Krokodil Plan" that would raise alligators with water from its geothermal power plant and district heating system for an environmentally sound solution to disposing of the town's fishing industry waste.

Today, there are 150 licensed aquaculture farms (mostly coldwater) within a 30-mile radius of Ray's geothermal operations, that raise over 40 million lbs. of fish annually for market. Of those, four (including Fish Breeders of Idaho) use geothermal water to raise tilapia and catfish. Idaho now claims 10 geothermal fish farms, many of which Ray helped get their start. And with a concerted effort toward education, he sees the potential for far more high-value, geothermal aquaculture in the region.

"This area's got the best geothermal potential, but some of the poorest farm land in the state," says Ray, who laments the fact that most owners of geothermal wells in the area consider its heat a nuisance. Indeed, most of geothermal water produced around Ray's operations is used for irrigation and livestock, demanding that it be cooled before it can be used. But with over 800 geothermal springs and wells in the state," he continues, "farmers could switch from low-value irrigated crops to high-value aquaculture crops that thrive in hot water."

According to Ray, demand is growing among American ethnic and regional populations for exotic aquatic foods, from fresh tilapia to alligator and other potential products yet to be explored. Yet the limiting factor in southern Idaho for such new industries is not knowledge about the science and geology of geothermal energy, but lack of readily available information on how to use it to grow high-value, niche aquaculture products. "I couldn't have my farm without geothermal water," says Ray, "but I couldn't make it work without knowledge about how to raise, process and market my crop."

ACKNOWLEDGMENT

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THERMAL EXPANSION IN ENCLOSED LINESHAFT PUMP COLUMNS

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INTRODUCTION

In a well pump handling hot water, when the pump is not in operation, those components above the static water level (SWL) are typically at a temperature substantially lower than when the pump is in operation. At start up the pump fills the column with hot water resulting in a lengthening of the column and shaft due to the thermal expansion. The difference in the change in length between the shaft and column resulting from the thermal expansion and other forces is a significant factor in pump design and selection.

In a vertical turbine pump, the shaft is attached to the driver (usually an electric motor) at the ground surface and to the impellers in the pump (or bowl assembly). Forces acting on the shaft tend to lengthen it when the pump is in operation. These forces, due to the weight of the shaft and the impellers, the thrust imposed by the impellers (when in operation) and the thermal expansion when the shaft is exposed to hot water all act in the downward direction. Since the shaft is suspended from the motor, the shaft tends to grow downward when these axial forces are exerted upon it. Though the shaft is supported in bearings attached to the column, it is free to move axially independently of the column. Vertical movement of the shaft manifests itself as vertical movement of the impellers within the bowls. Sufficient clearance (for vertical movement of the impellers) must be available in the housings to accommodate that portion of the thermal expansion and impeller thrust that occurs after pump start.

The impeller housings are attached to the pump column and together these components are suspended from the pump pedestal at the well head. As in the case of the shaft, the forces exerted by the weight of the column, the water in the column and thermal expansion, tend to cause the column to lengthen downward. This causes a movement of the impeller housings relative to the impellers (which are suspended on the shaft).

The thermal expansion resulting from the pump being submerged in hot water (the portion of the column and shaft below the water line) and the stretch of the shaft and column resulting from the weight of these components can be adjusted for and essentially "zeroed" at installation. When the pump is started and hot water fills that portion of the column above the static water level, additional change in length of the column and shaft occurs. This change in length in the column is due to thermal expansion for the most part but also due to the added weight of the water in the column as it fills with pump operation. Change in length of the shaft is due to thermal expansion and down thrust exerted by the impellers on the shaft. The net change in length between the shaft and column resulting from these forces, plus any allowance for manufacturing tolerances, is the clearance (lateral) required in bowl assembly.

In an open line shaft pump, with all components in the column exposed to the hot water directly, all of the forces tend to act at the same time as the pump is started thus resulting in a net length change calculation that is fairly simple. Consider the example of a pump producing 400 gpm of 190 ºF water with a static water level of 360 ft. The pump is equipped with a 1 ½" stainless steel shaft and 6" column and the pump suction is located at 400 ft. Impeller thrust for this pump is 6.7 lb/ft of pump head. Once operating, the following changes in length would occur:

Shaft (impeller thrust) - 400 ft x 6.7 lb/ft = 2680 lb
Expansion of 1 ½" SS shaft at above load - 0.254 in

Shaft above SWL (thermal exp.) - 360 ft x 12 in/ft
x 0.0000055 in/in ºF x (190 -100) = 2.14 in

Shaft below SWL (thermal exp.) 70 ft x 12 in/ft
x 0.0000055 in/in ºF x (190-130) = 0.277 in

Column (due to added weight of water) - 360 ft
x 1.41 gal/ft x 8.3 lb/gal = 4213 lb
Expansion of 6 " column due to above load = 0.126 in

Column above SWL (thermal exp) - 360 ft x 12 in/in
x 0.0000063 in/in ºF x (190 - 100) = 2.45 in

Column below SWL (thermal exp) 70 x 12 in/ft
x 0.0000063 in/in ºF x (190 -130) = 0.318 in

Net expansion = (2.45 + 0.318 + 0.126) - (2.14 +
.277 + 0.254) = 0.233 in

The net expansion is small in this case (relative to the 0.75" standard and up to 1.375" machined lateral available in pumps of this size)and would be accommodated in most vertical turbine bowl assemblies. The key issue controlling the net expansion in this case is the fact that all of the change in length in shaft and column, particularly the thermal expansion, is occurring at the same time. In an open lineshaft pump this is the case since all of the components are directly exposed to the hot water.

In an enclosed lineshaft pump, the situation is quite different with respect to the thermal expansion occurring after the pump is in operation. In enclosed column assemblies, the shaft is located in the enclosing tube (Figure 1). This configuration protects the shaft from exposure to the

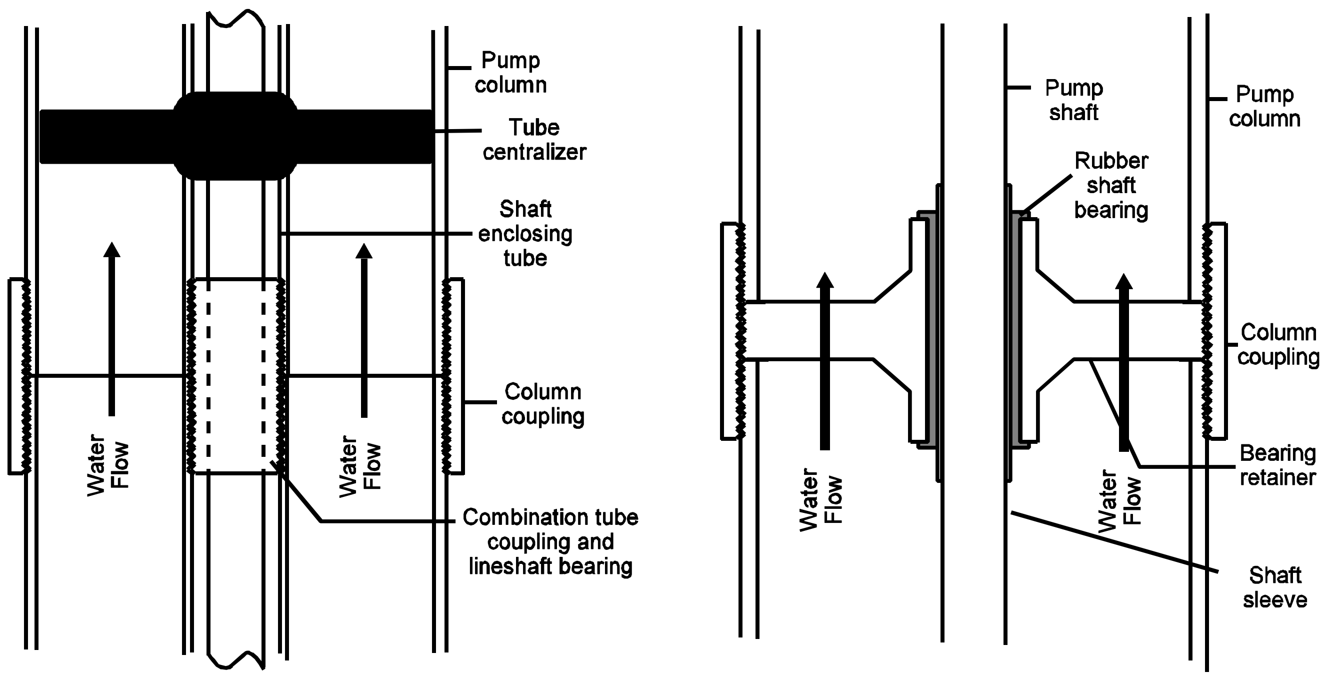

Figure 1. Details of lineshaft pump column types

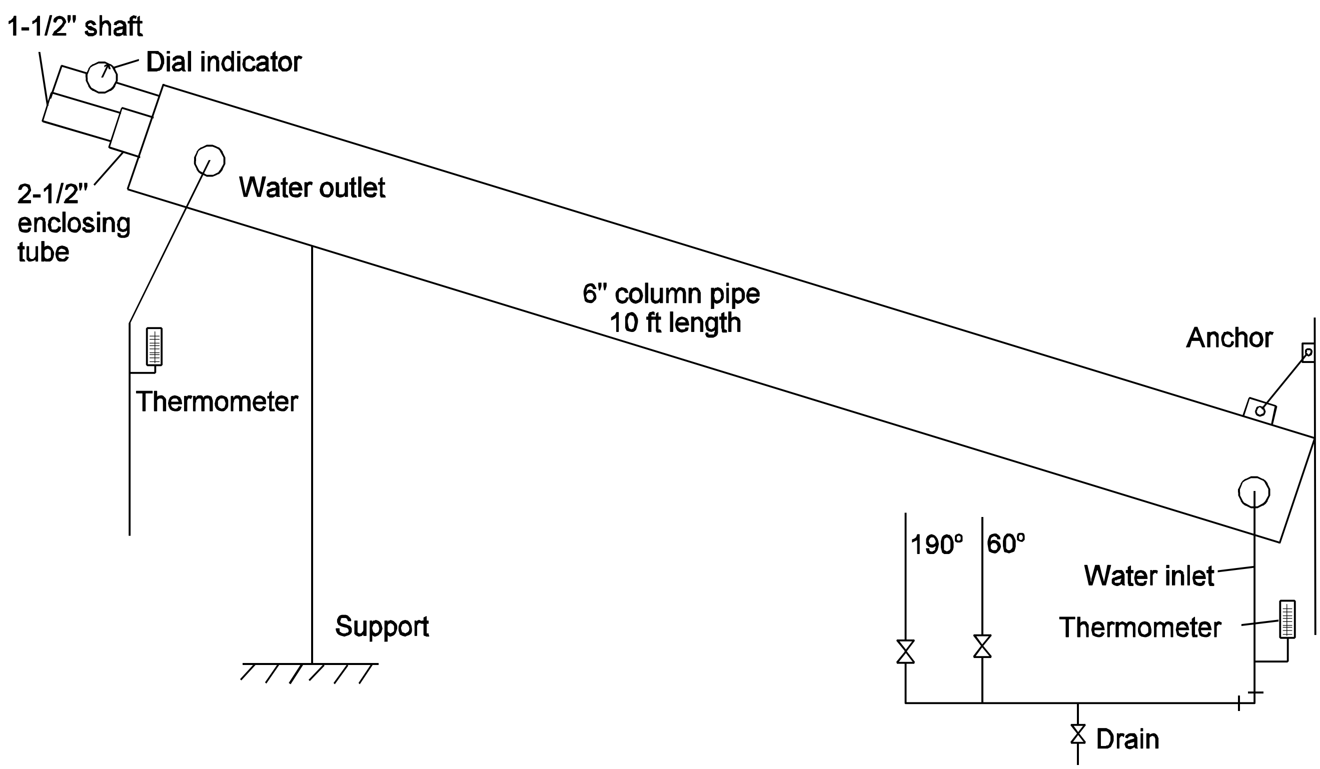

Figure 2. Diagram of experimental setup.

geothermal water and allows the use of oil for bearing lubrication. At the same time, the location of the shaft (inside the enclosing tube) also "insulates" it from the water flowing up the column. At some point after the pump has been operating, the shaft does come to thermal equilibrium with the hot water - but at a much slower rate than does the column. This results in the column reaching it's full thermal expansion prior to the shaft. The unresolved question is - to what extent does the shaft lag the column in a typical application? Current treatment of this topic in one existing text (Culver and Rafferty, 1999) assumes that all of the column expansion occurs before any of the shaft expansion. This assumption results in the requirement for very large impeller-to-housing clearance (also sometimes referred to as lateral), essentially equal to the total gross thermal expansion (roughly 2.5" at the above example conditions). In most cases of static water levels of >150 ft and water temperatures of > 180ºF, a conservative calculation such as this would result in a required lateral in excess of that which could be accommodated with machining of the impeller housing.

Considering the situation from the opposite extreme, the assumption could be made that the shaft heats at the same rate as the column resulting in a zero net thermal expansion. Given the configuration of the column assembly, this seems an unlikely circumstance since the insulating effect of the air space between the ID of the enclosing tube and the shaft will undoubtedly result in some lag in the heat transfer to the shaft relative to the column. The importance of this lag in heating of the shaft relative to the column is that it translates directly into bowl assembly lateral requirements. Although the column and shaft, owing to their construction of similar materials (enclosed line shaft pumps typically employ a carbon steel shaft and column) may ultimately experience the same change in length due to thermal expansion, the rates at which the change occurs in the two components heavily influences lateral requirement in the pump. The maximum difference (relative expansion) in length that occurs between the rapidly expanding column and the more slowly expanding shaft contributes substantially to the lateral necessary in the bowl assembly for deep (> 150 ft)static water level applications.

TEST PROCEDURE

To evaluate this issue, a section of column was instrumented and configured in such a way as to allow the measurement of the maximum difference in thermal expansion between the column and shaft. The test apparatus is illustrated in Figures 2 and 3. It consists of a 10 foot section of 6 inch column equipped with a 2 ½ inch enclosing tube (5 ft bearing spacing) and a 1 ½ inch carbon steel shaft. The assembly was initially tested using 190ºF water from a geothermal system. Using a dial indicator to measure the differential expansion between the column and shaft, the results summarized in Figures 4 and 5 were obtained.

As indicated in the figure, the column reaches maximum thermal expansion at approximately 90 seconds after water flow is initiated. At that point, little if any thermal expansion has occurred in the shaft and this is the point of maximum relative expansion between the column and shaft

Figure 3. Experimental setup.

Figure 4. Details of expansion measurement.

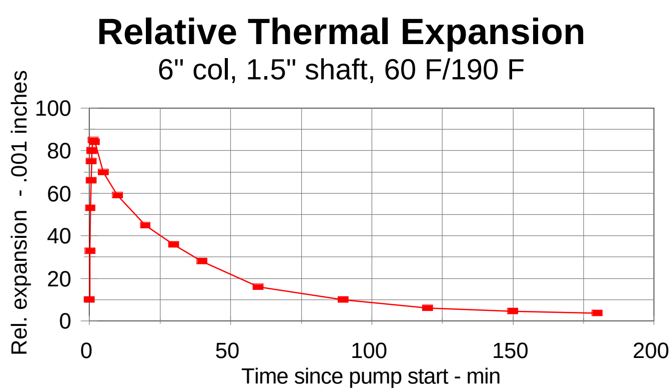

Figure 5. Relative thermal expansion.

under the test conditions. After this point, heat transfer to the shaft results in it's slow change in length, gradually closing the difference in length to zero after some time of operation (approximately 2 to 3 hours in our test). Based only on this data, it would appear that the conservative calculation method mentioned above would be confirmed. However, this test was characterized by several parameters that tend to over estimate the relative expansion which occurs in an actual application. The initial temperature of the test section was equal to the room temperature (55º to 70ºF in our tests) - much lower than the 100 ºF average temperature of the air in the well above the static water level. More importantly, the temperature of the water passing through the test section, while equal to the production temperature of our wells was much higher than what would initially be experienced in service. In reality, the temperature of the water passing through the pump and column in the first few minutes of operation is substantially less than the temperature of the water produced after the well bore has reached thermal equilibrium. Due to the gradient that exists in the well under static conditions, much of the water in the well bore is less than the production zone temperature. As a result, the water produced initially is lower in temperature. The response of two of OIT's production wells is illustrated in Figure 6. Both of these wells produce approximately 193 ºF water after sustained production, yet the temperature of the water produced in the first 30 minutes after the wells have been out of production for some time is substantially lower.

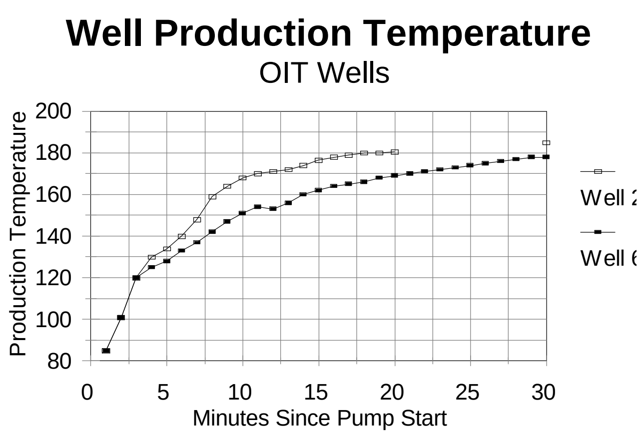

Figure 6. Well production temperature.

The curves indicate production temperature at the well head versus time since the pump was started. It is apparent that the two wells behave differently in terms of the temperatures produced and the time to reach thermal equilibrium. Though more data from other wells is necessary to confirm it, the difference may be related to the volume and surface area of the well bore. Well #2 is shallower (1288 ft, SWL 355 ft) and smaller in diameter than well #6 (1717 ft, SWL 360 ft). The relationship between the capacity of it's pump and the well volume (below the SWL) is such that the entire volume of the well can be produced by the pump in approximately 10 minutes. For well 6 this requires approximately 13 minutes. With the production zone in the bottom of both wells, the time required for the hottest water to reach the pump and the heat losses occurring between the water and the lower temperature casing between the pump and the bottom of the well result in an extended period before steady state is reached. The greater the well volume to pump capacity ratio the longer this "heat up" time will be.

RESULTS

To determine the impact of this initially lower temperature water, several additional runs were made on the test section with varying water temperature. Figure 7 presents the typical results of these tests.

These tests were run with exit water temperatures (from the test section) that mirrored those indicated in Figure 4. Adjustment of water temperature was less than optimum and excursions of up to 10 ºF from those in Figure 4 occurred in the course of the experiment. The test section was preheated to approximately 100ºF prior to each test to simulate the temperature of the air in the well above the static water level. It is apparent that the maximum relative expansion that occurs in an actual well capable of a steady state production of 190ºF water(as reflected in Figure 5) is much lower than that indicated in the initial test using 190ºF water .

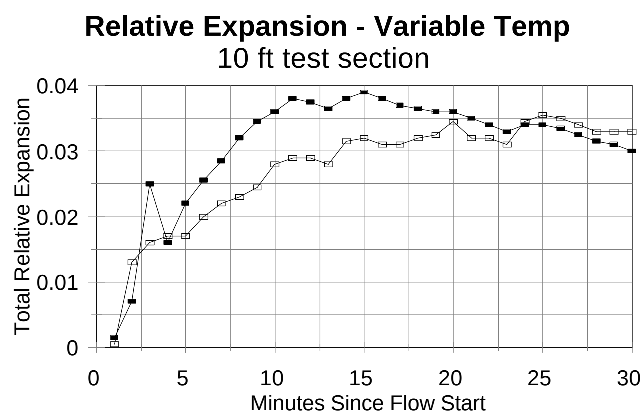

Figure 7. Relative expansion.

The maximum relative expansion of the 10-ft test section using the 190ºF water (and adjusting for a 100ºF pre test equilibrium temperature) is approximately 0.060 inches. Using the more realistic temperature response based on that measured in the OIT wells, the maximum relative expansion is reduced to the range of 0.033 to 0.038 or about 37 to 45% lower than the 190ºF test.. The slower rise in temperature of the water produced from the well effectively allows the shaft thermal expansion to "catch up" to the more rapidly expanding column, greatly reducing the lateral requirements in the bowl assembly. It may be possible to reduce lateral requirements further by slowly "ramping up" the well pump flow using a variable speed drive though this was not investigated in the work reported here.

Results of the testing of the 6-inch column equipped with a 1 ½-inch carbon steel shaft and 2 ½-inch enclosing tube confirm that approximately 90% of the thermal expansion in the column occurs before any of the expansion in the shaft when 190ºF water is flowed through the assembly. This results in a maximum relative expansion of approximately 0.006 in/ft of column for an initial temperature of 100ºF and a final temperature of 190ºF.

Using water temperatures reflective of the performance of the wells tested in this work, the maximum relative expansion was reduced to 0.0033 to 0.0039 in/ft of column for an initial temperature of 100ºF and a final temperature of 190ºF. The lower values was applicable to the initial temperature rise experienced in OIT well #6 and the higher value applicable to the temperature rise in OIT well #2 (see Figure 4)

CONCLUSIONS

Calculations found in the existing literature (Culver and Rafferty, 1999) regarding thermal expansion in enclosed lineshaft pump applications are largely correct with the exception of the consideration of the impact of well dynamics on the production temperature during initial start up.

The temperatures encountered by the well pump/column during the initial 30 minutes of operation are critical to the relative expansion that occurs between the shaft and the column. Well dynamics play an important role in the determination of these temperatures. Based on findings in the work reported here, the actual performance of the two wells measured indicates that the time to reach steady state temperature may be as much as 2 to 3 hours. The impact of this reduced temperature operation reduces the maximum relative thermal expansion in the example case by approximately 37 to 45% compared to that calculated using steady state production temperature.

For the bowl assemblies of the size considered in this test (nominal 9" bowl diameter), it appears that applications characterized by static water levels of less than 350 ft and steady state water temperatures of less than 190ºF, can be specified with machining to achieve the lateral required. This is contingent upon the rate of increase in temperature of the water produced being limited to a maximum of approximately 2ºF per minute for the first 30 minutes of operation. This may be achieved though the natural dynamics of the well or through speed control of the well pump. In some cases in which the well volume below the water line is very small relative to the pump capacity, it may not be possible to achieve this rate of increase.

The key parameters in the determination of the maximum relative thermal expansion are:

Static water level - determines the total length of column exposed to the maximum relative expansion. Deeper static levels result in greater lateral requirements.

Well production temperature increase rate - determines the maximum relative expansion. A pivotal parameter. Faster rates of increase result in greater lateral requirements.

Steady state production water temperature - determines the maximum temperature of system. Lower steady state production temperatures reduce relative expansion and total expansion.

Air temperature above the static water level - determines the initial temperature of the system. Higher air temperatures reduce the total expansion occurring in the system.

ADDITIONAL RESEARCH

A key finding of this work was the critical influence of the well production temperature rate of increase on the maximum relative expansion in the pump column. In the course of this work only two wells were available for data on this rate of increase. Due it's strong influence on the relative expansion, the collection of data from other wells would be valuable. In addition, more data from the two wells used in this work using gradually increasing flows at start up would also help to characterize the correlation between flow, temperature and well volume.

REFERENCES

Culver, G and K. Rafferty, 1998. "Chapter 9 - Well Pumps," *Geothermal Direct Use Engineering Design Guidebook*, Geo-Heat Center, Klamath Falls OR.

GEOTHERMAL HEATING AT THE CALIFORNIA CORRECTIONAL CENTER, SUSANVILLE. CALIFORNIA

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Susanville, CA

INTRODUCTION

Since the early-1980s, there has been significant geothermal development in the Honey Lake Valley of northeastern California. Surveying in the late-1970s by the U.S. Bureau of Reclamation indicated the potential for geothermal development in the area, spurring the interest of public and private agencies (Templeton, 2002). Since then, the city of Susanville has taken advantage of a 23-67ºC geothermal reservoir for a sizable district heating system, the California Correctional Center (CCC) near Litchfield (Figure 1) has installed a 72-74ºC geothermal heating system and greenhouse, and two small binary flash steam power plants have been constructed in Wendel and Amadee using a 95-107ºC resource (Culver, 1990; Majmundar, 1983; Nichols, 1999; Short, 2002).

In 1980, the state of California and the city of Susanville collaborated to install a geothermal heating system to supplement the existing diesel-powered system at CCC (Short, 2002; Templeton, 2002). Two wells, approx. 460 m deep, were installed on a tract of land some 3.2 km east of the prison site by the Carson Energy Group, Inc. of Sacramento. Temporary funding was provided by the Bank of America (Templeton, 2002). Geothermal heat is used for 50-80% of the prison's space and domestic water heating, as well as for a medium-sized greenhouse. CCC houses around 5,800 minimum custody inmates, and some 1,100 custodial and support staff are employed at the 4.5 km^2 site (CDC, 2002). The geothermal heating is used for inmate dormitories, but generally not for staff areas (Cantrell, 2002). While the system experiences occasional problems, it has proven to be cost-effective, clean and low-maintenance. Moreover, both the Susanville and CCC geothermal systems have provided substantial savings when compared to the alternative of fossil fuels (Cramer, 2002; Cantrell, 2002; Short, 2002; Templeton, 2002).

Figure 1. ***CCC in foreground, Honey Lake Valley and Diamond Mountains to the south (photo: CDC, 2002).***

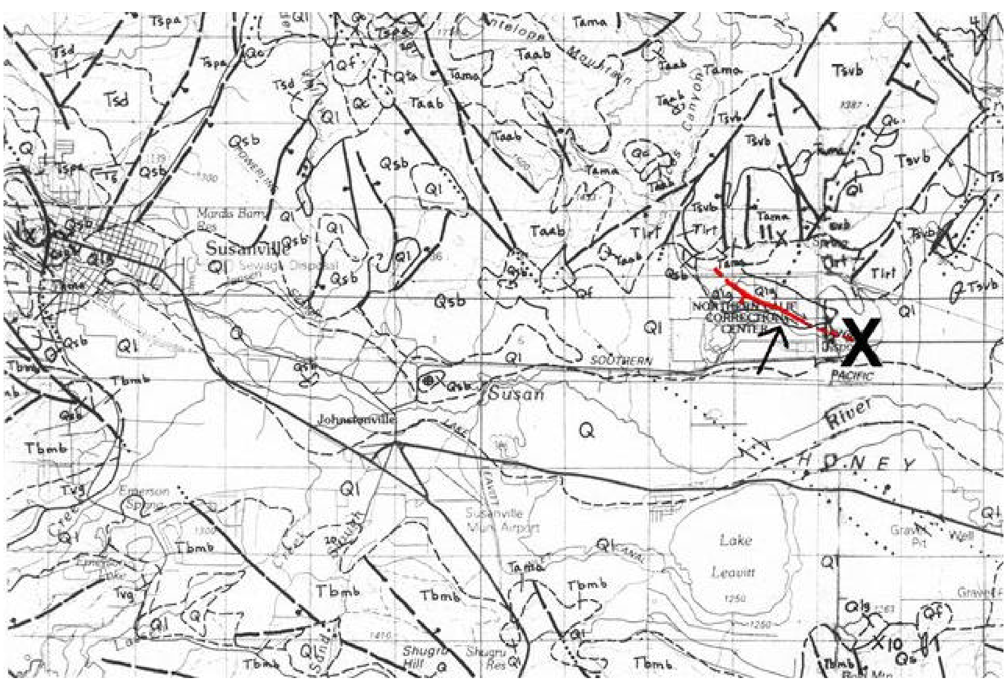

Figure 2. ***Geological map of Susanville area. Well and transverse fault marked with "X" and arrow, respectively (Grose, et al., 1990).***

GEOLOGY

The California Correctional Center is located just to the south of the widespread Tertiary to recent basalts, mafic andesites, and tuffs of the extension- and subduction-induced Modoc Plateau volcanic region (Donnelly-Nolan, 1988; Hirt, 1998). The wells themselves are located on lacustrine gravels and near-shore deposits of pluvial Lake Lahontan, cut by a small west-northwest striking right-lateral fault (Figure 2) that correlates directly with the geothermal reservoir (Grose, Saucedo, and Wagner, 1990). The recent work of Colie, Roeske, and McClain (2002) indicates that shearing associated with the Walker Lane in Nevada and eastern California extends beyond the Honey Lake fault zone northwestward through Eagle Lake and beyond (Figure 3).

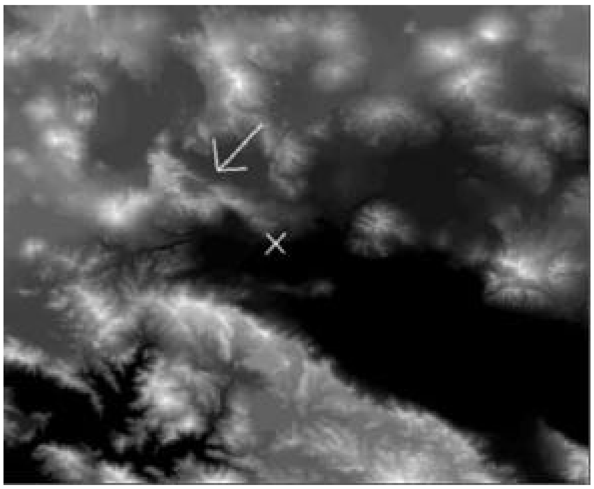

Figure 3. ***Digital elevation model of Honey Lake Valley and Eagle Lake area. Apparent transverse zone marked by arrow. CCC area marked by "X" (USGS, 2002).***

Available mapping (Grose, et al., 1990) suggests that the transverse fault associated with the prison's geothermal reservoir is directly related to the relative motion between the North American plate and the Pacific plate, causing the region between the San Andreas fault and the Walker Lane to rotate counterclockwise, with faulting on the northeast margins (Colie, Roeske, and McClain, 2002). The crustal thinning and high thermal gradients associated with Basin and Range extension, Walker Lane transverse faulting and fracturing, and the nearby subduction-related volcanism of the Cascades all appear to contribute to the presence of a viable geothermal reservoir at the CCC site. From a geologic viewpoint, the discovery and use of yet other geothermal reservoirs in the region seems likely.

SYSTEM DESCRIPTION

CCC's geothermal system consists of two production wells, several heat exchangers linked to a closed heating loop, an application area, and an evaporation pond. The wells are owned and operated by the city of Susanville, while the well area is owned by the state and used by the prison for agriculture and water resources (Short, 2002). For contingency, two wells were drilled during the initial construction of the system, one producing water around 76ºC, and the other delivering 72-74ºC water. Unfortunately, in 2001 the casing on the hotter well collapsed and was deemed too costly to repair, and the cooler well has been used since then (Cantrell, 2002).

Use of the thermal water is "take-or-pay," meaning that the water is paid for whether it is used for heating or not (Cantrell, 2002; Cramer, 2002). According to Rice (2002), the city collects a minimum of $17,062/month, based on the calculated use of 525,000 therm/year, and working out to a cost of $0.39/therm. Compare this with the $1.22/therm rate that the city charges residents and property owners for natural gas heating (Susanville, 2002). A portion of the fees collected are paid to the former owner of the well property as royalties (Templeton, 2002). If measured usage exceeds the standard 525,000 therm threshold, $0.39/therm in addition to the contracted fee is billed to the state. However, payment is not collected if geothermal water is not produced for more than 30 consecu-tive days by the city (Cantrell, 2002; Rice, 2002). This has happened several times in the past, in which case 162ºC steam from the diesel boilers is pumped through a heat exchanger adjacent to the geothermal equipment (Cantrell, 2002).

The currently operating 72ºC well (Figure 4) uses a 75 hp oil-lubricated pump to produce about 1130 L/min for an underground supply line to the prison boiler room. After passing through a sand filter, the supply water is routed to one of two plate heat exchangers (Figure 5) for space heating, and a smaller heat exchanger (Figure 6) for domestic hot water (Cantrell, 2002; Short, 2002). Incoming water on the closed-loop system is at about 21ºC, and outgoing water on the domestic loop is heated to about 51ºC using a stainless-steel plate heat exchanger (Cantrell, 2002). Water going out to the space heating loop is usually heated to 60-66ºC when needed in the wintertime (Cantrell, 2002). Three 30-hp pumps produce flow in the space heating loop as needed (Cantrell, 2002).

Figure 4. ***72ºC well, 3.2 km east of prison (photo: Mark A. Miller).***

After being passed through the heat exchangers, the now 60-66ºC geothermal water is sent to a medium-sized greenhouse half a kilometer to the east (Short, 2002). Here a portion of the hot water is diverted and passed through a

Figure 5. ***Space heat exchanger, located in prison boiler room (photo: Mark A. Miller).***

Figure 6. ***Domestic heat exchanger (photo: Mark A. Miller).***

manifold heating system underneath two lengths of plant trays (Esparza, 2002). This heating is used during cool periods to maintain a fairly constant temperature of 22-26ºC in the greenhouse (Esparza, 2002).

After the geothermal water is passed through the greenhouse, it is hypochlorinated and returned to a dispersion area between the wells and the prison, consisting of a 20-acre application area and an evaporation pond of approximately 81 ha (Short, 2002). The application area uses 20 lengths of 120 m aluminum runners, with 18 sprinklers spaced about every 6 m (Short, 2002). When in use, the geothermal water is sprinkled over the application area to either evaporate or drain to the overflow pond through a small diversion ditch (Short, 2002). Water that is not sprinkled on the application area flows directly into a privately-owned pond (Figure 7) that reportedly supports populations of bass, waterfowl, deer, and antelope (Short, 2002). The author estimates incoming pond water to be approximately 50ºC. Several cottonwood trees and other riparian species have established themselves around the perennial pond (Short, 2002).

Figure 7. ***Evaporation pond, located on private land just northwest of production wells (photo: Mark A. Miller).***

PROBLEMS ENCOUNTERED

The failure of the higher-temperature well was a disappointing occurrence that is apparently too costly for repair (Short, 2002). From time to time, sand and mineral deposits clog the heat exchanger, bringing the system down for anywhere from a few days to a few weeks for cleaning (Cantrell, 2002). Also, occasional well failures have caused other periods of downtime (Cantrell, 2002; Cramer, 2002; Short, 2002). According to Templeton (2002), these problems are routine and can be expected with any well, whether geothermal or not.

In the greenhouse, minor repairs have had to be made to the manifold heating system, in which the standard piping was replaced with high-temperature piping, and the gate valves replaced with ball valves (Esparza, 2002). However, according to Esparza, in the past nine years, the greenhouse heating system has never been down for longer than three days (2002).

While the lack of an injection well could cause reservoir depletion, it has apparently not caused any problems to date. Templeton (2002) states that the city's prior experience with attempts at injection led developers to view an evaporation pond as the best option. It may also be difficult to find a suitably distant injection zone with equal or lesser water quality, as demanded by the Lahontan Regional Water Quality Control Board (Culver, 1990). The application of the alkaline water to the 20-acre area of sagebrush and bunchgrass has caused some damage to plant life, but otherwise no serious environmental concerns have been observed or mentioned.

As a precaution for workers and inmates, the water is hypochlorinated before it is released (Short, 2002). Water dispersed by the geothermal system meets all requirements imposed by the Lahonton Regional Water Quality Control Board, according to Short (2002).

The released water contains dissolved sodium and boron, and the aluminum laterals in the application area warrant replacement about every five years due to corrosion (Short, 2002).

CONCLUSION

The CCC direct-use geothermal system has proven to be a clean, cost-effective, and efficient method for supplementing its institutional heating system. While the system does not have an industry-standard injection well, the environmental impact is by all appearances minimal. Use of this geothermal resource is expensive but still cheaper than the use of diesel fuel to power its boilers. The recent installation of a state-owned natural gas pipeline in the area, however, is expected to replace many of the area's current geothermal operations, including that of the prison. The current contract with the city will expire in 2007, and nearly all involved expect that both CCC and the city of Susanville will retrofit most of their facilities and switch to natural gas equipment (Cantrell, 2002; Cramer, 2002; Short, 2002; Templeton, 2002). Templeton (2002) predicts that for the time being the cost of geothermal energy will not be able to compete with natural gas because of the need for electricity to run the well pumps. The primary drawback, of course, to burning natural gas is the emission of carbon dioxide, methane, and nitrous oxides (EPA, 2002), practically absent from geothermal applications.

Although the future looks grim for the next few years of geothermal development in the Susanville area, the applications currently in operation can serve as real-life examples of the successful use of a non-polluting, economical, and renewable resource. For geothermal developments in the future, it is hoped that the system described herein can serve as a prototype and as a useful precedent.

ACKNOWLEDGMENTS

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REFERENCES

California Department of Corrections (CDC), 2000. "California Correctional Center (CCC)," URL: http://www.cdc.state.ca.us/facility/instccc.htm

Cantrell, Gene, 2002. Personal interview.

Colie, Erin M.; Roeske, Sarah; and McClain, James, 2002. "Strike-slip Motion on the Northern Continuation of the Late Cenozoic to Quaternary Honey Lake Fault Zone, Eagle Lake, Northeast California," The Geological Society of America, Cordilleran Section, 98th Annual Meeting, 13-15 May, 2002, Abstract. URL:http://gsa.confex.com/gsa/2002CD/finalprogram/abstract_34838.htm.

Cramer, Daryl, 2002. Telephone interview.

Culver, Gene, 1990. "Case Histories of Vale, Oregon & Susanville, California," Symposium on Subsurface Injection of Geothermal Fluids, Underground Injection.

Practices Council (UPIC) Research Foundation, Oklahoma City, OK.

Donnelly-Nolan, J.M., 1988. "A magmatic model of Medicine Lake volcano, California," Journal of Geophysical Research, v. 93, no. B5, p. 4412-4420

EPA (Environmental Protection Agency), 2002. "Emissions," EPA Global Warming Site, URL: http://www.epa.gov/globalwarming/emissions/.

Esparza, Tony, 2002. Personal interview.

Grose, T.L.T, Saucedo, G.J., and Wagner, D.L., comp., 1990. "Geologic Map of the Susanville Quadrangle, Lassen and Plumas Counties, California, 1:100,000 scale," California Department of Conservation, Division of Mines and Geology.

Hirt, William, 1998. "Geology of the Medicine Lake Volcano, California," College of the Siskiyous, Weed, CA. URL:http://www.siskiyous.edu/class/geol42/handout98.html

Lienau, Paul. 1997. "Geothermal Direct Heat Utilization Assistance," U.S. Department ofEnergy, Geothermal Energy Technical Site, URL:http://wastenot.inel.gov/geothermal/fy95/dir-use/use01.htm

Majmundar, Hasmukhrai, comp., 1983. "Technical Map of the Geothermal Resources of California,Geologic Map #5," California Department of Conservation, Division of Mines and Geology,

Nichols, Ken. 1999. "Case Histories, Barber-Nichols Small Geothermal Power Plants," Barber-Nichols, Inc. URL: http://www.barber-nichols.com/Papers/geothermal.pdf

Rice, Jay, 2002. Personal Interview.

Short, D.J., 2002. Personal interview.

Susanville, City of, 2002. "Public Utility Information," URL:http://www.cityofsusanville.org/Economic/Utility%20Information.pdf.

Templeton, Louis, 2002. Personal Interview.

USGS, 2002. "Examples of 1:250,000 Digital Elevation Models," EROS Data Center, Sioux Falls, SD. URL:http://edcwww.cr.usgs.gov/geodata/examples.html.

GEOTHERMAL RESOURCES OF THE GREAT ARTESIAN BASIN, AUSTRALIA

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INTRODUCTION

There is a little resemblance between world geothermal hot spots and the Australian landscape pictured in Figure 1. However, vast parts of the Australian continent have considerable reserves of geothermal energy stored in deep artesian groundwater basins in the form of warm groundwater.

Figure 1. ***Typical landscape of inland Australia.***

Artesian groundwater was discovered in central and eastern inland Australia around 1880. Further extensive geological investigations and water-well information helped to outline the shape and size of a large confined groundwater system, now known as the Great Artesian Basin (GAB). The GAB extends across four Australian states underlying 22% of the Australian continent (Habermehl, 1980, 2001). Temperatures of the artesian groundwater (which is generally of a very good quality) range from 30º to 100º C at the well heads. As the groundwater is too hot for town water supply and for stock to drink, it needs to be cooled down before consumption. That is why cooling towers can be seen throughout the region. Some cooling towers are equipped with electric fans, in which the case electric power is spent to remove the thermal energy of the groundwater (Figure 2).

The efficiency of power generation from fluids of temperatures not exceeding 100º C is known to be low. However, there are some factors that may outweigh relatively low efficiency of electricity production from the GAB groundwater. One of such factors is a high cost of fossil-fuel electricity in remote locations of the GAB due to high transportation costs. Other factors, which one may need to consider, are the quality of the GAB groundwater and the flow rates of artesian wells.

Figure 2. ***Cooling tower in the Borefield B of the Olympic Dam Mine, SA.***

In what follows we overview geothermal resources of the Great Artesian Basin and discuss prospective geothermal applications and their potential benefits for the region.

OVERVIEW OF THE RESOURCE

The Great Artesian Basin is a confined multi-layered groundwater system, which underlies 1.7 million km^2 of arid and semi-arid land across Queensland, New South Wales, South Australia and Northern Territory. Most artesian wells in the area tap the Cadna-owie-Hooray aquifer, the uppermost artesian aquifer of the multi-layered sequence. The aquifer consists of highly permeable sediments, mainly continental quartzose sandstones of horizontal permeability of around one darcy. (Detailed information on hydrogeology of the Cadna-owie - Hooray aquifer can be found in Habermehl, 1980 and Radke *et al.*, 2000.)

Groundwater Development

Somewhat 4700 artesian water-bores have been drilled in the Basin over the last 120 years, of which about 3100 remain flowing. Water-bores are up to 2000 m deep, although the average water-bore depth is about 500 m. Artesian flow rates from individual wells exceed 100 L/s, but the majority have smaller flow rates between 10 L/s to 50 L/s. The accumulated discharge of the GAB wells is about 1200 ML/day.

Groundwater in the Cadna-owie-Hooray aquifer is of good quality, containing between 500 mg/L to 1000 mg/L total dissolved solids. It is suitable for domestic, town water supply and stock use, though unsuitable for irrigation in most areas. The water is of the Na-HCO_3-Cl type, and these ions

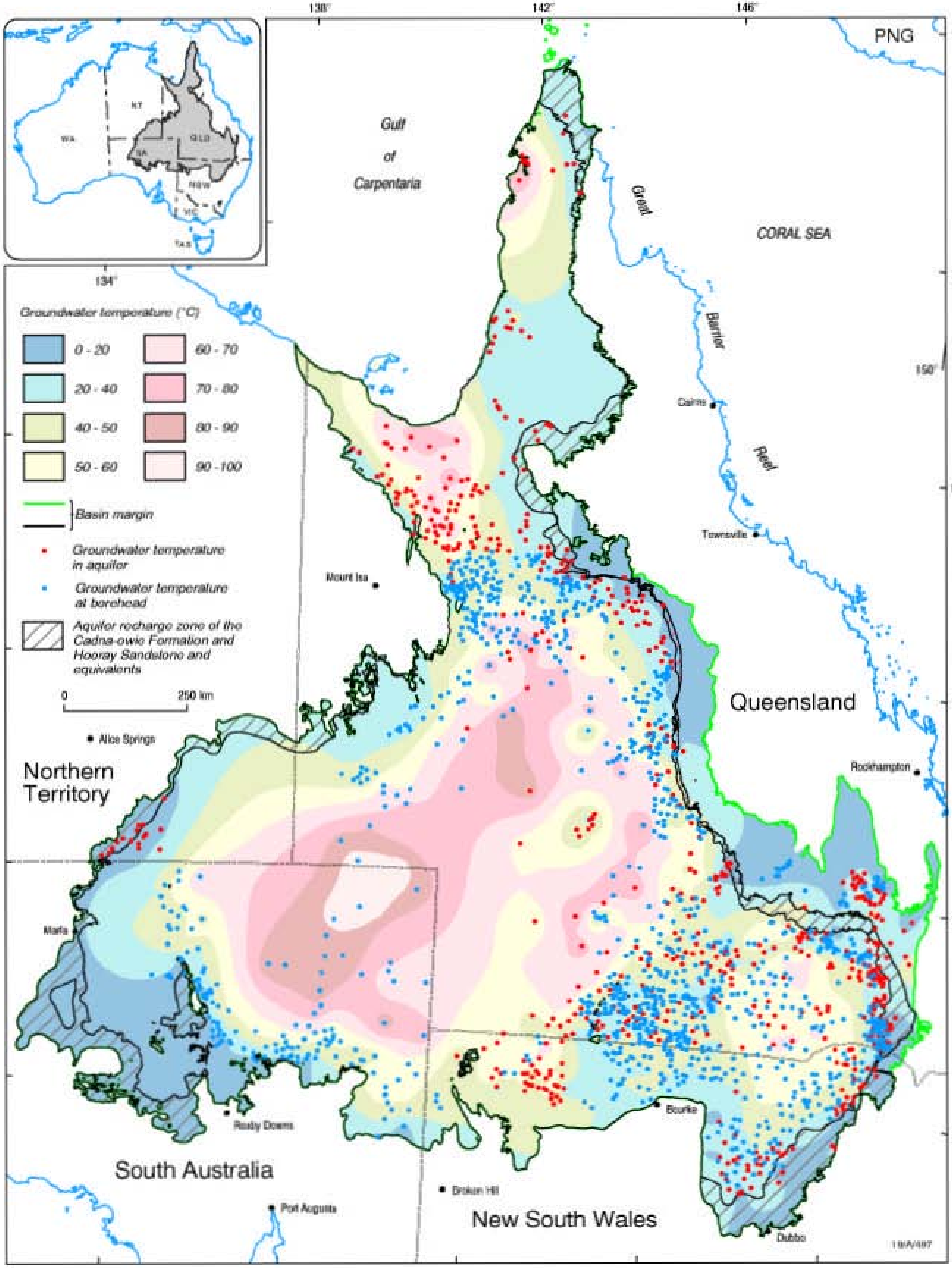

Figure 3. GAB groundwater temperatures (after Habermehl, 2001b).

contribute more than 90% of the total ionic strength of solutes in the main Basin area. In the south-western part of the Basin the groundwater is characterized by Na-Cl-SO_4 type water (Habermehl, 1980, 2001a,b; Habermehl and Lau, 1997).

Groundwater Temperatures

Groundwater temperatures at the well heads range from 30º to 100º C. Spring temperatures range from 20º to 45ºC, with the highest temperatures having been measured in the Dalhousie Springs group in northern South Australia. Figure 3 shows groundwater temperatures of the Cadna-owie - Hooray aquifer derived from measurements taken from 1880 water-bores. The density of observation data is high except for the central part of the Basin where the bore distribution is sparse.

The shallow parts of the Basin near the margins, in particular the eastern and western recharge margins and the areas basin-wards from these margins contain relatively cool water with temperatures not exceeding 40ºC. The deepest parts of the Basin in northeastern South Australia and southwestern Queensland, the southwestern and central parts of the (geological) Eromanga Basin (the western and central parts of the hydrogeological Great Artesian Basin) have highest groundwater temperatures between 70º and 100ºC (Habermehl, 2001a). For example, the Muloorina water bore has a groundwater temperature of 80ºC (Figure 4). A groundwater temperature at Goyder Lagoon (SA) is 100ºC (Figure 5). The Birdsville town bore has a temperature of 98º C. Near Quilpie (Qld) groundwater temperatures are between 70º and 80ºC.

Figure 4. ***80ºC groundwater discharging from the Muloorina water-bore (SA).***

Geothermal Gradients

In general, a correlation exists between groundwater temperatures and aquifer depths. However, there are regions in the GAB, where warm groundwater is located at a relatively shallow depth of a few hundred meters. The map of geothermal gradients given in Figure 6 shows where warm groundwater comes close to the surface.

Figure 5. ***Uncontrolled water-bore in Goyder Lagoon (SA) with a 100ºC groundwater.***

Groundwater is heated by the heat flow attributed to the burial depth of aquifers and the heat produced in the earth crust by radio-active minerals, uranium and thorium (Torgersen, et al., 1992). In some parts of the Basin higher heat fluxes are attributed to the presence of young granite (Tony Hill, private communication). Thermal anomalies in some areas might be generated by vertical groundwater flow along geological faults. However, no thermal anomalies coincide with major faults, such as the Canaway Fault system (Habermehl and Lau, 1997).

The geothermal gradient surface of Figure 6 was developed by Tim Ransley from temperature log data of the GAB water-bores. The mean and maximum values of geothermal gradients for the Basin are 49.5 K/km and 120 K/km, respectively. In the most of the GAB geothermal gradients exceed the global average. Higher geothermal gradients occur in the south-central, northwestern and northern parts of the Basin. Some of these areas are underlain by igneous and metamorphic rocks. Highest geothermal gradients of 100 K/km and more are present in several isolated areas in the southwestern, south-central and northern areas of the GAB, and correlate with the location of hot springs (e.g., Dalhousie Springs group in northern South Australia). The central part of the Eromanga Basin and the Surat Basin are underlain by older sedimentary basins and have lower values of geothermal gradients. Geothermal gradients shown in Figure 6 are consistent with data given in previous works (cf. Polak and Horsfall, 1979; Cull and Conley, 1983; Pitt, 1986).

Effects of Temperature Variations

The effects of temperature variations on the hydrodynamics of the Great Artesian Basin have long been recognized, and attempts have been made to incorporate temperature-corrected heads into computer-based groundwater models. In some cases, however, such a correction may not be sufficient. According to Pestov (2000a), a head error due to the assumption of isothermal flow is not significant (less than 6%); whereas, an error in velocity calculations can be much

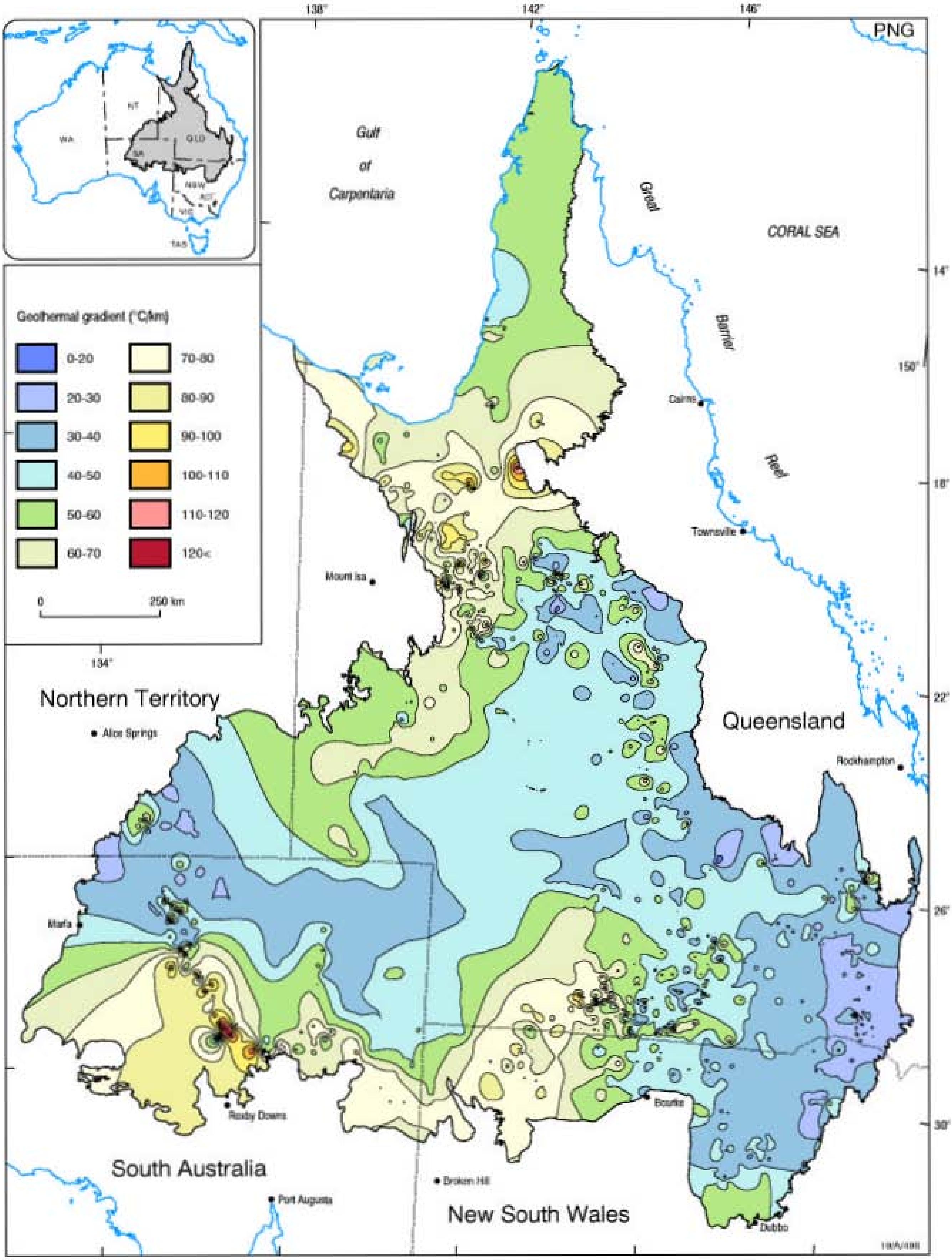

Figure 6. GAB geothermal gradient (after Habermehl, 2001b).

higher. Pestov (2000a) has shown that dynamic viscosity of groundwater varies by a factor of four within a temperature range typical of the GAB. As groundwater velocity is inversely proportional to dynamic viscosity, viscosity variations of such a scale need to be incorporated into groundwater models. Both viscosity and density variations with temperature may result in completely different flow patterns compared to those predicted by isothermal groundwater models.

As demonstrated in computer experiments by Pestov (2000b), temperature variations similar to those found in the GAB are sufficient to trigger convective circulation in some parts of the Basin. There are six large-scale convective regions within the Cadna-owie-Hooray aquifer (see Figure 1 of Pestov, 2000b). The horizontal extent of convective regions is of the order of 100 km and more. The largest of convective regions, Eastern-Downs/Coonamble region, coincides with an important water management zone where most of the water-bores are located. In the Eastern-Downs/ Coonamble region the groundwater flow is likely to exist in the form of a giant convection cell with groundwater flowing in the opposite directions in the aquifer layers above and below the dividing aquitard, the Orallo formation (Pestov, 2000b). This conjecture is supported by field observations reported in Radke, et al. (2000). In other parts of the Basin, the groundwater flow is likely to form convection cells bounded to a single aquifer layer (Pestov, 2000b). Pestov (2000b) does not exclude the existence of thermal convection throughout the multiple aquifer sequence of the GAB.

Incorporating non-isothermal effects into groundwater models is important for sustainable management of geothermal resources in the GAB. Non-isothermal numerical models are discussed in Pestov (2000a, b). The importance of non-isothermal effects for transport of hydrocarbons and other chemicals in the GAB is discussed in Pestov (2000c).

PROSPECTS OF GEOTHERMAL DEVELOPMENT

The Great Artesian Basin has significant reserves of warm groundwater suitable for a variety of geothermal applications. Perspective applications include space heating, bathing, aquaculture, air conditioning and electric power generation. Heating requirements for the above applications are within the temperature range of the GAB groundwater.

Space Heating, Geothermal Bathing and Aquaculture

The GAB is largely located in tropical and sub-tropical Australia (see Figure 3). Annual average temperatures throughout most of the region range between 18° and 24°C. However, winter nights in inland areas of the GAB can be quite cool. The utilization of thermal energy of groundwater for space heating during winter will be an added benefit for inland Australia.

Bathing and aqua-culture are most promising geothermal applications at the low temperature end of the GAB groundwater. In spite of this, only one example of direct use is known in the area. In Moree, NSW a 40°C artesian groundwater is used in spa baths and swimming pools (Figure 7). With modern re-injection technologies, the GAB groundwater can be used at a significantly larger scale for both geothermal bathing and aquaculture. Benefits will include improved leaving standards of remote communities as well as new opportunities for tourism in the area. Geothermal bathing and a use of warm groundwater for seafood growing will make the area a more attractive tourist destination.

Figure 7. Geothermal hot spa in Moree, NSW.

Air Conditioning

Absorption refrigeration is another prospective geothermal application in the GAB. It works at the high temperature end of 80° C and above, "converting" geothermal heat into cold. This technology can be employed for comfort cooling in houses and other buildings in towns and individual homesteads during hot summer months. As it is not practical to transmit high-temperature water over large distances, geothermal technologies are at their most efficient when implemented close to the resource.

Very dry warm to hot climates predominate in the GAB area. In the central and western parts of the region maximum air temperatures often exceed 50°C. During summer months, the lion's share of electricity generated by diesel power stations is spent on air conditioning. Multiple benefits from an introduction of the absorption refrigeration technology in the region will include a reduction of green-house gas emission from diesel power stations that currently operate in the region.

Power Generation

Binary Rankine cycle geothermal plants successfully operated for a number of years in Mulka (SA) and in Birdsville (Qld). A small 20 kW facility at the Mulka cattle station in South Australia generated electricity for domestic needs using a 70°C to 100°C groundwater (Figure 8). Since the plant was equipped with an old type generator containing a Freon-based working fluid, it had to be shut down in the mid 1990s (Cam Douglas, personal communication; also see CADDET link below). The 150 KW geothermal plant in Birdsville was shut down in 1996 for the same reason. In 1999-2000 the Birdsville plant has been re-equipped with a hydrocarbon-based working fluid (isopentane). It is currently

Figure 8. ***Geothermal plant at the Mulka Cattle station, SA.***

capable of generating 120 KW electricity from a 98ºC groundwater (Bob Collins, personal communication; also see link to the Birdsville geothermal plant web page below). As demonstrated by the Mulka and Birdsville examples, geothermal resources of the GAB are capable of supporting electric power generation at a considerable scale.

The efficiency of power generation from low-enthalpy fluids largely depends on the resource temperature (Rafferty, 2000). Lower groundwater temperatures will require higher heat input due to lower efficiency of the plant. Although the groundwater temperatures in the GAB do not exceed 100ºC, the flow rates from the GAB artesian wells are generally very good.

We have calculated the flow rates, which will be required to support a 100 kW binary (Rankine cycle) plant at different resource temperatures. The results of our calculations are shown in Table 1. Note that the highest flow rate of 3383 m/day is still within the range of the flow rates of the GAB wells. Our calculations are based on the net plant efficiency for different temperature as given in Figure 2 of (Rafferty, 2000).

Table 1. **Geothermal Flow Rates for a 100-KW Binary Plant at Different Resource Temperatures**

T (deg C)	Efficiency (%)	Heat Input (kJ/h)	Flow Rate (cubic meter/day)
82	5.5	1818	3383
88	6.25	1600	1984
93	6.8	1471	1368
99	7.25	1379	1026
104	7.5	1333	827

The Kalina technology makes a better use of the heat input through improved efficiency compared to that of the binary plant. According to Spinks (1994) the efficiency of the Kalina cycle could be 10% to 25% higher than that of the Rankine cycle. In addition, Kalina plant's installed cost per kilowatt could be substantially lower (e.g., 40% lower) compared to that of the binary plant (Spinks, 1994).

It should be noted that the geothermal plant efficiency is considered to be low when compared to fossil-fuel power generation not to other renewable energy sources. It is very likely though that the cost of electricity generated from local geothermal resources will be competitive with the cost of fossil-fuel and power-grid electricity due to high transportation expenses for remote locations of the GAB. "Off-grid" remote communities will particularly benefit from a reliable electricity supply of small easy-to-operate geothermal plants. Binary plants of 100 kW capacity or less will be suitable for small-scale applications such as electricity supply to townships, homesteads and cattle stations. Note that about half of urban centers in the GAB area have a population of less than 2,500 (Habermehl, 1980).

CONCLUSIONS

Geothermal energy of the artesian groundwater in the Great Artesian Basin is a valuable natural resource suitable for a variety of useful applications. Prospective applications include direct-use applications, such as space heating, bathing, aquaculture and air-conditioning, as well as electric power generation.

Bathing and aquaculture are most promising geothermal applications at the low temperature end of the GAB groundwater (30º - 40ºC). Absorption refrigeration, which works at the high temperature end of 80ºC and above, is another prospective geothermal application for the hot climate of the region.

Although the groundwater temperatures in the GAB do not exceed 100ºC, the flow rates from the artesian wells are generally very good. Our calculations show that the flow rates from the GAB wells are capable of supporting heat inputs required for electric power production (see Table 1).

With modern re-injection and numerical simulation technologies thermal energy of the artesian groundwater of the GAB aquifers can be utilized in a sustainable way to the benefits of remote communities. "Off-grid" communities will particularly benefit from a reliable electricity supply of small easy-to-operate binary plants. The Kalina technology has a potential to improve efficiency of power production from the GAB groundwater.

The cost of electricity generated from local geothermal resources is not expected to be high compared to the costs of other types of electricity including fossil-fuel and power-grid electricity. Reduction of greenhouse gas emission will be an added benefit of geothermal developments in the Great Artesian Basin.

ACKNOWLEDGMENTS

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INTERNET LINKS

CADDET, Australia: www.isr.gov.au/resources/netenergy/domestic/caddet/caddet-home/index.html

Birdsville geothermal plant: www.env.qld.gov.au/sustainable_energy/qseif/projects/birdsville_geothermal.htm

REFERENCES

Cull, J. P. and D. Conley, 1983. "Geothermal Gradients and Heat Flow in Australian Sedimentary Basins." *BMR J. Aust. Geol. Geophys.*, 8, 329 - 337.

Habermehl, M. A., 1980. "The Great Artesian Basin, Australia." *BMR J. Aust. Geol. Geophys.*, 5, 9-38.

Habermehl, M. A.,2001a "Hydrogeology and Environmental Geology of the Great Artesian Basin, Australia." In: V.A. Gostin (ed) *Gondwana to Greenhouse - Australian Environmental Geoscience.* Geological Society of Australia Inc., Special Publication 21: 127-143, 344-346.

Habermehl, M. A., 2001b. *Wire-Line Logged Waterbores in the Great Artesian Basin, Australia - Digital Data of Logs and Waterbore Data Acquired by AGSO.* Bureau of Rural Sciences publication, Canberra, Australia; also: Australian Geological Survey Organisation, Bulletin 245.

Habermehl, M. A. and J. E. Lau, 1997. Hydrogeology of the Great Artesian Basin, Australia (Map at scale 1 : 2 500 000), Australian Geological Survey Organisation, Canberra.

Pestov, I., 2000a. "Modeling Non-Isothermal Flows in Porous Media: A Case Study Using An Example of the Great Artesian Basin, Australia." In: *New Methods in Applied and Computational Mathematics* (R. Melnik, S. Oliveira and D. Stewart, eds.), Center for Mathematics and its Applications, Australian National University, Australia, 59-65.

Pestov, I., 2000b. "Thermal Convection in the Great Artesian Basin, Australia." *Water Resources Management*, 14, 391-403.

Pestov, I., 2000c. "Thermal Convection and Mass Transfer in Sedimentary Basins: Implications for Management." *Proc. Int. Hydrology and Water Resources Symposium*, Institution of Engineers, Australia, 980-984.

Pitt, G. M., 1986. " Geothermal Gradients, Geothermal Histories and the Timing of Thermal Naturation in the Eromanga-Cooper Basins." In: Gravestock, D.I., Moore, P.S. and Pitt, G.M. (eds) *Contributions to the Geology and Hydrocarbon Potential of the Eromanga Basin.* Geological Society of Australia Inc. Special Publication No. 12, 323-351.

Polak, E. J. and C. L. Horsfall, 1979. "Geothermal Gradients in the Great Artesian Basin, Australia. " *Bull. Aust. Soc. Explor. Geophys.*, 10, 144-148.

Radke, B. M.; Ferguson, J.; Cresswell, R. G.; Ransley, T. R. and M. A. Habermehl, 2000. *The Hydrochemistry and Applied Hydrodynamics of the Cadna-owie-Hooray Aquifer, Great Artesian Basin, Australia.* Bureau of Rural Sciences publication, Canberra, Australia.

Rafferty, K., 2000. " Geothermal Power Generation: A Primer on Low-Temperature, Small-Scale Applications." Geo-Heat Center electronic publication.

Spinks, A. H., 1994. "The Commercial Development of the Kalina Cycle and A 30-Megawatt Design for Wairakei." *Proc. 16th NZ Geotherm. Workshop*, 269-274.

Torgersen, T.; Habermehl, M. A. and W. B. Clarke, 1992. Crustal Helium Fluxes and Heat Flow in the Great Artesian Basin, Australia." *Chemical Geology (Isotope Geoscience Section)*, 102, 139-152.

GEOTHERMAL UTILIZATION IN AGRICULTURE IN KEBILI REGION, SOUTHERN TUNISIA

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INTRODUCTION

The use of geothermal energy is limited to direct utilization in Tunisia, because of the low enthalpy resources. The resources are localized mainly in the southern part of the country in the regions of Gabes, Kebili and Tozeur and utilized mostly for agricultural purposes (irrigation of oases, greenhouses). The government's policy in the beginning of the 1980's was oriented to the development of the oasis' sector and the main aim was to supply oases with geothermal water for irrigation. Therefore, in the Kebili area, about 35 boreholes are operating mostly for irrigation of 15,500 ha of oases after cooling the water in atmospheric towers. Fifteen years ago (1986) the State started using geothermal energy for greenhouse farming, by planting an area of one ha. The results of this experiment were very encouraging and thus, the areas today have increased to 40 ha.

Figure 1. A well used for oases irrigation.

GEOTHERMAL RESOURCES IN TUNISIA

The geothermal resources in Tunisia have been described by Ben Dhia and Bouri (1995). They divide the country into five geothermal areas. This division is based on the geological, structural and hydro-geological features of the different regions. A very coarse classification of the geothermal resources would be to distinguish only between two areas, the northwest part and the remaining part of the country.

The northwest region is characterized by a complex geological setting where volcanic rocks are more common than in other regions. The density of thermal manifestations is higher here than in other parts of the country. This region is greatly affected by the over thrust of the alpine napes, dated as upper Miocene, and thick deposits of sandy layers ''Numidian formations.'' In southern Tunisia, the flow rate from the hot springs is usually higher (Stefánsson, 1986). Outside the northwest region, the geothermal aquifers have been found in well-defined geological formations (sedimentary rocks), which in some cases are mapped over large areas (basins). These reservoir rocks have very high permeability and many of the wells drilled in the south have artesian flow rates of the order of 100 L/s (Figure 1). The geothermal gradient is in the range of 21EC/km to 46EC/km. These values are in the same range as the world average values for thermal gradient. In general it is, therefore, expected that the geothermal resources in Tunisia are the result of normal conductive heat flow in the crust. This means that, in general, high-temperature geothermal resources are not expected to be found in Tunisia, the only exception or question mark is the northern part of the country (Stefánsson, 1986).

The region of Kebili, with a total area of 2.2 million hectares, is located in the southwestern part of the country and characterized by two aquifers, the largest in Tunisia (the medium aquifer or CT: Complexe Terminal, and the deep aquifer or CI: Continental Intercalaire). These aquifers are the most important resources for the development of agriculture in the region, but they are rarely considered as renewable resources.

GEOTHERMAL UTILIZATION

About 1,500 L/s are exploited from geothermal resources; 95% is utilized for agricultural purposes: 78% for oases and 17% for greenhouses. The remaining part (5%) is used for bathing (hammams)(Figure 2), tourism (hotels and pools), washing and animal husbandry. Figure 3 shows the different direct geothermal uses in the area.

Figure 2. The swimming pool at Ras-Elaîn locality.

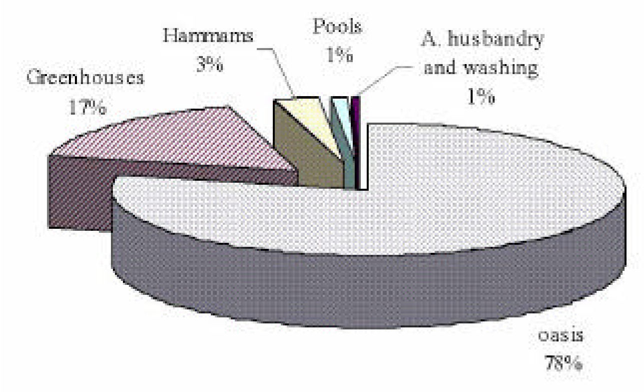

Figure 3. Direct geothermal uses in Kebili area.

IRRIGATION OF OASES

The region of Kebili, located in the southwest of the country, is characterized by desert climate (arid). The annual precipitation is irregular and generally less than 100 mm. The maximum temperature is about 55EC (July) and the temperature range (the difference between maximum and minimum temperatures) is very high. These difficult conditions require a large amount of water to maintain the humidity inside the oases system. The oasis area is estimated at 15,500 hectares (51% of the total area in the country) and the oasis system is classified into three levels: (a) the first level which is called the upper level is composed of date palms, the second one or the middle level is composed of trees under date palms (apple, fugue, grape, apricot, grenade, etc.) and the third one or the open field is composed of grass and vegetable cultivation. These three levels constitute the oasis system and are generally managed at the same time and irrigated with the same water. The cultivation of these three levels together makes a microclimate, commonly called "oases' microclimate." People go there in the summer time for relaxation.

Date Palm Importance

In recent years, large quantities of hot water have been identified in the country by drilling. This discovery is mainly a spin off from groundwater drilling, and in other cases related to exploration drilling for oil. Due to climatic conditions in the country, clean water is one of the most valuable substances, at least in the southern part (desert). The groundwater is mainly used for agricultural purposes (95%) and principally for the irrigation of oases (78%). All the resources taken from the Complexe Terminal (CT) are used for irrigation. Geothermal resources were exploited for the first time to provide a complete water supply for old oases, which have a high density and low productivity, in order to create new ones. The main target was to develop the oases sector in the south of the country by means of the rehabilitation of old oases and the installation of new ones (new farmers). The government's policy in the beginning of 1980's was oriented to encourage farmers. In that way, the operation consisted of pulling up the non-productive date palms to replace some of them by another more productive variety with good quality, intended for export. This was expected to generate more income for the farmer (micro-economy) but a large quantity of old varieties disappeared (Figure 4).

Figure 4. Dates production (Deglat Nour variety intended for export).

Date palms occupy the first place in the agricultural activity of the region due to their social and economical interest. The social interest is due to the large number of farmers depending directly on this activity (about 30,000 farmers) and also families that are depended directly or indirectly. More than 80% of the population lives on this sector. The government policy for a stationary population has been reached. It is important to acknowledge the high level of employment generated by this sector. The economical interest is related to its profitability and the good income for its farmers and consequently the favorable contribution to the commercial balance. Indeed, the dates' sector occupies the third place in the total agricultural export of the country after olive oil and fishing. In the year 2000, the total production of dates in Tunisia was estimated at 100,000 tonnes. The region of Kebili produced 58,000 tonnes. Generally, the region contributes on average, more than 55% of the total product. About 31,000 tonnes were exported mostly to the European countries producing an income of 78 million dinars (US$52 million or 59 million Euros).

Water Cooling and Irrigation

The water temperatures varies from 27EC to 73EC. Generally, water less than 40-45EC is used directly for irrigation or cooled by means of multiple ponds (five ponds in the region) or cascaded as shown in Figure 5. By this cooling system we can lower the temperature by only 3-4EC.

The maintenance operation is limited to the removal of soil deposited by wind. When the temperature exceeds 45EC, the water is cooled by means of atmospheric towers before being used for irrigation (Figure 6). In normal conditions, we can drop the temperature to 30-32EC, but when the ventilation doesn't function properly, the water is dropped to only 40EC. However, these towers have the disadvantage of losing water via evaporation, estimated at 2-6% of the total flow rates and are expensive to operate (10,000-15,000 dinars annually [US$6,700 to 10,000, or 7,600 to 11,400 Euros]) which is includes the costs of electricity, maintenance and gardening.

Figure 5. The water cooling system (Cascade of Oum Elfareth)

Figure 6. The water cooling system (Atmospheric tower)

The irrigation in the region is by the submersion method and all the area is irrigated (no localized irrigation). In this case, water is transported through a ditch to parcels causing high water wastage caused by evaporation and infiltration due to the physical characteristics of the soil (light soil, sandy, salty soil). For economic purposes, the government encourages farmers to install and utilize PVC pipelines for irrigation by subsidizing 40-60% of the total investment. Since 1994, the beginning of the water management project, over 5,000 ha were equipped for more than 7,000 farmers and 22 water organizations. The Tunisian policy in the agricultural field and especially in its hydraulic aspects was oriented in the beginning of 1990's to give more importance, responsibilities and decision making to the local organizations. In that way, 98 organizations involved in the use of water resources, called GIC, are operating in the region and they contribute effectively to the management and the distribution of water. In the same policy of water management, a project called APIOS (to improve the irrigated areas in south oasis) started in 2001 by the installation of concreted canals for the irrigation and drainage systems. The project covers 7,500 ha of oases with a total cost of 30 million dinars (US$20 million or 22.5 million Euros) co-financed by a Japanese company. The objectives of the project are to improve the irrigation frequency, to increase the oasis's efficiency and productivity, and to enhance the value of the water resources.

HEATING AND IRRIGATION OF GREENHOUSES

In addition to irrigation of the oasis, the geothermal water is used for heating plastic greenhouses. The utilization of geothermal energy recently started in the country as an experiment conduced by the National Agronomic Institute (INAT) in Mornag and in Chenchou localities. The results of this experiment were very encouraging and led to the idea of a geothermal utilization project in agriculture (PUGA-project, TUN/85/004) financed by the UNDP. In comparison with unheated greenhouses, the geothermally heated greenhouses generate better quality and higher yields. It also resulted in earlier ripening of crops.

In 1986, the government started to use geothermal energy in greenhouses in southern Tunisia. After one year, many demonstration projects in several places had been established with the collaboration of the Energy Agency (AME) and the Rural Development Programme (PDRI). The locality of Limagues, in the region of Kebili was the first place where plastic houses were implemented (1 ha). At the same time, the company ''5th Season'' stocked the first part of a large project (5 ha). Furthermore, in 1991 a second project for greenhouse development was begun in cooperation between the governments of Belgium and Tunisia. The exploitation of geothermal resources for heating and irrigating greenhouses on the edge of the desert seems to represent a promising alternative for the development of this sector.

Starting with one ha as an experiment in 1986, the total area of geothermally heated greenhouses in Tunisia has increased considerably. Indeed, the area reached 21 ha in 1988 and 33 ha in 1989 in which 51 and 54% were respectively in the region of Kebili. In 1992, the total area covered was 67 ha in which 43% were located in this region. The total area continues to increase, reaching 75 ha in 1996 and near 80 ha in 1998, in which the region represents, respectively, 38% and 40% of the total. Today, the total area is 102 ha, in which 40% are located in the Kebili area. Figure 7 shows the evolution of the greenhouse area in the country and in the region.

It is very clear that the significant increase was from 1987 to 1990. Plastic houses were attributed in the beginning to small farmers with two units of houses allocated for social aspects and financed by the PDRI programme. The first experience was in the Limagues zone where one ha was planned in 1986. Further, the areas reached 11 ha in 1988 and 18 ha in 1989. Since 1990 this sector has stagnated in the range of 28 ha, but started increasing again in 2000 and reach 40 ha. The development of the greenhouse sector was very

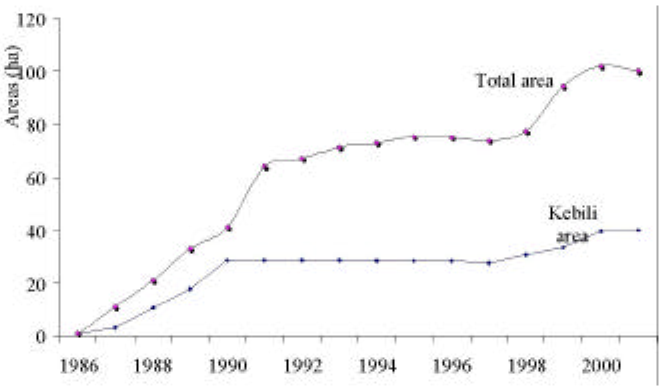

Figure 7. The evolution of the greenhouse area.

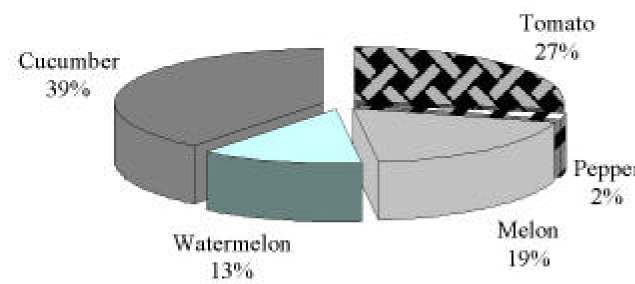

Figure 8. The crop composition (2001).

fast, at least for some farmers starting with two houses, holding now 5-6 greenhouses and sometimes 10 greenhouses. In some cases, outside the greenhouse project, farmers have parcels in which they practice oasis cultivation.

The utilization of the geothermal resources will, without a doubt, increase in the near future by the application of the remaining part of the greenhouse strategy. By the end of 2002, 14 ha (280 greenhouses) will be added in the region reaching a level of 54 ha, which represents an increase of 35%.

The Utilization of the Areas

Utilization of the greenhouse area in the Kebili region is based on three cultivations, the first, from late August to December, the second from late December to June and the third from late August to June (continuous). Harvesting takes place more than once per year and lasts over a nine-month period. The crops produced in 2000 were composed of cucumbers and tomatoes representing, respectively, 40 and 29%, melons (21%), watermelons (8%) and peppers only 2%. In 2001, cucumbers and tomatoes were also the main vegetables crops (66%) due to their commercial value and their marketability. Figure 8 shows the composition in 2001. Inside a greenhouse, several types of crops can be raised simultaneously. Growers, in this way, try to diversify their production in order to minimize the risk.

The Evolution of Productions

Despite some problems handicapping the greenhouse sector in the beginning, such as lack of qualification and poor practices of some farmers, production increased from year to year. This is not always a result of good productivity but sometimes generated by the expansion of areas as mentioned above. But, in comparison with unheated greenhouses, the geothermally heated greenhouses generate better quality and higher yields (see Figure 9).

In the season 2000/2001, the total production from heated greenhouses in the country reached 10,142 tonnes (see Table 1). The region of Kebili contributed with 37% of the total production, after Gabes with 46%.

The production in Kebili region grew from 210 tonnes in 1988 to 1,120 tonnes in 1990 and reached 1,939 tonnes in 1995. From 1996 to 2001, it varied as shown in Figure 10 with an average of 2,830 tonnes per year.

Figure 9. Example of greenhouses production.

Table 1. The Total Production in the Country

Regions	Area (ha)	Production (tonnes)	Contribution (%)
Kebili	39.5	3,7402	36.9
Tozeur	18.25	1,700	16.8
Gabes	41.6	4,657	45.9
Nabeul	3	45	0.4
Total	102,35	10142	100

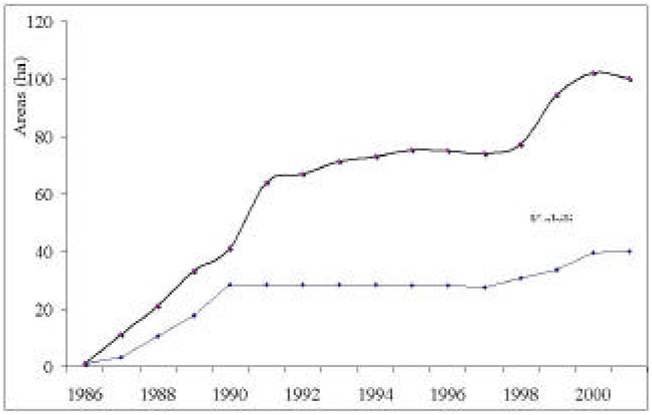

Figure 10. ***The evolution of production in the Kebili region.***

Heating of Greenhouses

Continuous low temperatures at 10-12EC during two successive days disturb the physiological behavior of plants. Paradoxically, temperatures higher than 30-38EC can provoke irreversible damage to crops. Normally, temperature variation should not exceed 5-7EC. In the south this is difficult to obtain, as the risk of temperature variation is frequent. In order to solve this problem, the use of geothermal water is a good solution, which can improve the climate inside green-houses principally during the night. The heating is through pipes lying on the ground between the plants (Figure 11).

Figure 11. ***A typical greenhouse heating system.***

Several types of pipes have been tried and polypropylene pipes were selected (Mougou et al., 1987). Generally, an average of 8-10 loops are used per house and they are connected to the system by an easily operated valve. During the last years, an economic approach became predominant in Tunisia: the use of simple constructions and heating installations in order to minimize the investment costs. Greenhouse heating in Mediterranean countries is a typical example of an economic approach. The task is not the total conditioning of the inside climate of the greenhouse, but its optimization (Popovsky and Popovska-Vasilevska, 2001).

For heating greenhouses in the Kebili region, 12 wells are operating to supply 17 different sites. An area of 40 ha (800 greenhouses) is heated with a total flow rate of 258 L/s and a water temperature varying from 45 to 73EC.

As mentioned above, the greenhouses in the region consume 17% of the total geothermal water, and about one - third of the total flow rate of the wells supplying the sites is intended for the greenhouse heating. The rest is mainly used for oases irrigation. In the region and during the cold period, the need for heating is estimated to be 6.45 L/s per ha, which corresponds approximately to the recommended flow rate (6 L/s/ha or 0.3 L/s per greenhouse), but this amount depends strongly on the temperature of the water and the climate conditions. The need for greenhouse heating is only six months, mostly during the night. Farmers start heating in November-December and stop it in April. The duration lasts 14 hours per day. This means that they open the heating system in the afternoon when they finish working and stop it the next morning when they reach the farm (Ben Mohamed, 1995). Similarly, the total volume of water needed per season for heating is approximately 58,500 m^3/ha.

Irrigation of Greenhouses

After the thermal water has been used for heating it is collected in concrete ponds for subsequent use for irrigation. These ponds need to be large to store all the cooled water until it is used for irrigation. In some projects, farmers utilize very small and simple ponds with plastic linings, which are cheaper and very practical. Their dimension varies from 40 to 80 m^3. Generally, these ponds are used for the irrigation of an open field area close to greenhouses. The need for water irrigation during the growing period is very low (0.6 L/s/ha or 5,500 m^3/ha) compared to heating. In the region, only 10% of the total heat flow rate is used for irrigation (30 L/s). In that way, farmers utilize a local system. Water circulates inside a perforate pipeline lying on the ground. The chemical composition of the geothermal water used in irrigation must be monitored carefully to avoid adverse effects on plants because of the high salinity in the region (from 2.3 to 4.4 g/L).

The Return Water

Geothermal water is used both for heating and irrigation. From the borehole, water goes directly through pipes lying on the ground inside the greenhouse for heating. After that, it is cooled in ponds outside, and then used for irrigation. As mentioned above, only 10% of the total amount of water is used for irrigation. The need for heating and irrigating a greenhouse is respectively estimated at 0.3 and 0.03 L/s. The rest or the return water which represents 90% (0.27 L/s) should supply the oases surrounding the area, but this is often difficult to achieve.

Greenhouse heating occurs during the night, while irrigation occurs during the day. Therefore, it is necessary to store the return water in ponds to be used later for irrigation purposes. This is why two types of ponds should be installed in a greenhouse project. The first is a big one to store the return water from greenhouses for oasis irrigation. The storage capacity should be at least equal to the total volume of return water for two or three nights (Saïd, 1997). The second pond is smaller and used for irrigation of crops inside the greenhouses. In order to facilitate the water supply to the oasis, the storage pond should be located a relatively high level. Otherwise, water must be pumped and farmers will pay an additional cost. It is important to note that the location of a greenhouse project near the oasis is preferred and a combination greenhouse-oasis must be considered in the future for using return water. Figure 12 shows the proposed connections between a greenhouse project and an oasis.

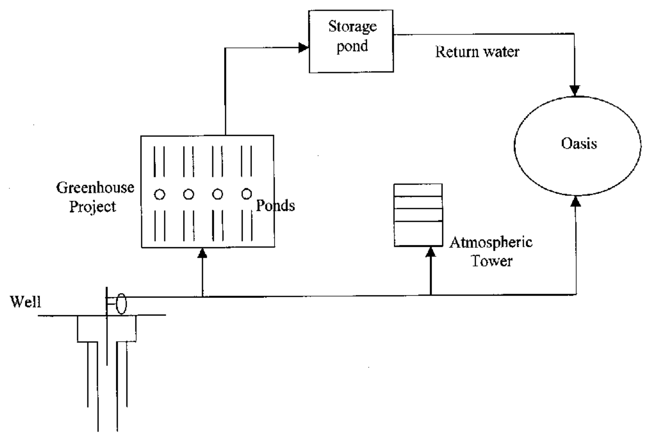

Figure 12. Proposed configuration for using the return water.

Due to poor design of some greenhouse projects, hot water sometimes cannot reach the ponds. Therefore, farmers dispose of the water close to the fields and often in the drainage system producing a large waste of water resources. Normally the return water should supply the old oases or the new ones close to the greenhouses project, but, generally, there are conflicts between users. The total amount of water returned from the greenhouses to the oases is estimated at 129 L/s, which represent 57 % of the available water.

SOIL DISINFECTION'S

Crops grown under greenhouses can cause infection by nematodes such as *Meloidogyne,* which are parasite on the roots of vegetables. Several methods are used to resolve this problem and they are classified as agronomical, chemical, physical and biological treatments. Resolving this problem chemically has negative aspects, due to:

- Environment (percolation of chemical products), and
- Residues of chemical products in fruits.

In the Kebili area, the physical method is utilized by some farmers. The geothermal water is combined with solar radiation (solarisation) and used to disinfect the soil. The idea is to irrigate the total area of the greenhouse in summer time. The techniques consist of three different steps. The first is to divide the greenhouse area into several small basins to be submerged by hot water. The second is to cover the area irrigated by geothermal water by plastic films. The third is to add a solution of formol 1‰. The plastic keeps the soil temperature as long as possible without any heat losses and improves the efficiency of solar radiation (Saïd, 1997). The experience conduced in the region showed that temperatures of 44EC and 39EC are obtained in the soil at 30 cm depth with a flowrate of 1.33 and 2.03 L/s respectively (Belkadhi, et al., 1993).

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REFERENCES

Belkadhi, M. S.; Joost, V. D. and F. Aoun, 1993. "The Effect of the Geothermal Energy and Soil Solarisation on the Nematodes," Revue des Régions Arides, NE 1, I.R.A., Medenine, pp. 91-101.

Ben Dhia, H. and S. Bouri, 1995. "Overview of Geothermal Activities in Tunisia." Ecole Nationale d'Ingénieurs de Sfax, Tunisia, 5pp.

Ben Mohamed, M., 1995. "Analyses and Perspectives of Development of the Greenhouse Production Systems in Kebili Region," Centre International de Hautes Etudes Méditerranéennes, Institut Agronomique de Montpellier, Montpellier, M.Sc. thesis (in French), 145pp.

Mougou, A.; Verlodt, H. and H. Essid, 1987. "Geothermal Heating of Greenhouses in the South of Tunisia. Proposals for a Simple Control," *Plasticulture*, 75, pp. 41-50.

Popovsky, K., 1993. "Heating Greenhouses with Geothermal Energy," International Summer School, Skopje, Macedonia, 326 pp.

Popovsky, K. and S. Popovska-Vasilevska, 2001. "Feasibility of Geothermal Agricultural Projects at the Beginning of XXI Century." *Geo-Heat Center Quarterly Bulletin*, Vol. 22, No. 2, Klamath Falls, OR, pp. 38-46.

Saïd, M., 1997. "Geothermal Utilization for Heating, Irrigation and Soil Disinfection in Greenhouses in Tunisia," Report 13 in : *Geothermal Training in Iceland 1997*, UNU GTP, Iceland, 311-338.

Stefansson, V., 1986. "Report on an Advisory Mission 1986 in Tunisia," United Nations, New York, report, 24 pp.

LOLO HOT SPRINGS, MONTANA

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INTRODUCTION

Lolo Hot Springs is located southwest of Missoula in the Bitterroot region of Montana next to the Idaho border. The hot springs were well know to the Indians, as it was a mineral lick for wild game, and an ancient meeting place and bathing spot for the Indians. Lewis and Clark visited here in 1805 and again on their return trip in 1806. The hot, mineralized springs became a land mark and rendezvous point for early explorers, trappers, and prospectors. By 1885, it had become a favorite vacationing spot for local families and hunters. Today, there is a large outdoor swimming pool, and indoor soaking pool, both heated by the geothermal springs. There is also a hotel, restaurant, saloon and a RV park, camping and picnicking area. An extensive trail system is available for hiking and horseback riding in the area, and since it is located at over 4,000 feet elevation, there is snowmobiling in the winter.

GEOTHERMAL USE

Originally, seven to eight hot springs flowed out of the ground through glacial deposits. Today, the springs produce 275,000 gallons per day between 104 and 117EF. The hot water is collected in a 35,000 gallon holding tank which is used to supply drinking and shower water for the restaurant, hotel, swimming pool and the other establishments in the area. Water from the springs is used directly for filling the pool and for heating the decks and floors of the pool area. The swimming pool uses water at 92EF and the indoor soaking pool 104EF. The waste water from these areas is piped across the highway to bumper boat pond at the RV park. From here the water is disposed of to a local stream The use of the geothermal water saves the swimming pool between $500 and $600 per month during the winter. The swimming pool holds about 100,000 gallons of water with a complete change about every 1.5 days, and the soaking pool of 35,000 gallons has a complete change every four hours. Due to the long retention time for the pool, the water is chlorinated. It is estimated that the peak energy use is around 200,000 Btu/hr and the annual energy use around 800 million Btu.

LEWIS AND CLARK

The Lewis and Clark expedition stopped at Lolo Hot Springs on both legs of the journey, in September of 1805 and in June of 1806. William Clark suggested the name Boyles Springs, but the first Lolo post office was registered as Lolo Hot Springs and the name endured. The trip over Lolo Pass took the Corps of Discovery 11 days to cross. On the crossing, since there was no game, they were forced to eat candles, bear oil, horsemeat, and packaged "portable" soup they'd brought from the east.

Figure 1. Outdoor pool.

Figure 2. Indoor pool.

Journal entries by members of the Corps were made on September 13, 1805 as follows:

Lewis:

"At the distance of two miles we came to several springs issuing from large rocks of a coarse, hard grit, and nearly boil hot. These seem to be much frequented, as there are several paths made by elk, deer, and other animals, near one of the springs hole or Indian bath, and roads leading in different directors. These embarrassed our guide who, mistaking the road, took us three miles out of the proper course, over an exceedingly bad route."

Sergeant Gass:

"...we came to a most beautiful warm springs, the water of which is considerably above blood-heat, and I could not bear my hand in it without uneasiness. There are so many paths leading to and from this spring that our guide took a wrong one for a mile or two..."

Journal entries made by the Corps on June 29, 1806 are as follows:

Clark:

"Those Worm or Hot Springs are Situated at the base of a hill of no considerable hight - these springs issue from the bottom and through the interstices of a grey freestone rock, the rock rises in irregular masy clifts in a circular range - the principal springs is the temperature of the warmest baths used at the Hot Springs in Virginia. In this bath which had been prepared by the Indians by stopping the river with Stone and mud, I bathed and remained in 10 minits it was with dificuelty I could remain this long and it causd. A profuse swet. Two other bold Springs adjacent to this are much warmer, their heat being so great as to make the hand of a person Smart extreemly when immerced. Both the Men and indians amused themselves with the use of the bath this evening. I observed after the indians remaining in the bath as long as they could bear it run and plunge themselves into the creek the water of which is now as cold as ice can make it; after remaining her a few mintis they return again to the worm bath repeeting the transision several times but always ending in the worm bath. Saw the tracks of 2 bear footed indians."

Sergeant Gass:

"...in the evening we arrived at the warm springs; where we encamped for the night, and most of us bathed in its water."

Authors note: the original spelling and grammar of the journals have been maintained. Their description of the temperature of the springs, verifies that they were approximately the same temperature as today (104E to 117EF), as this is the range of temperature that the human body can only stand for short periods of time - and the upper limit can be painful. The reference to Virginia probably refers to the resort at Hot Springs, VA - described in Vol. 17, No. 2 of the Geo-Heat Center Quarterly Bulletin (May, 1996). The spring temperature at this resort, commercialized in the middle 1700s, is at 102E to 106EF.

Additional information on Lolo Hot Springs and the Lewis and Clark route through Montana can be found at the following website: http://lewisandclark.state.mt.us/ and www.lolohotsprings.net. Much of the information in this article came from these two sites.