ISSN 0276-1084

Vol. 22, No. 4 DECEMBER 2001

GEO-HEAT CENTER *Quarterly Bulletin*

OREGON INSTITUTE OF TECHNOLOGY -KLAMATH FALLS, OREGON 97601-8801
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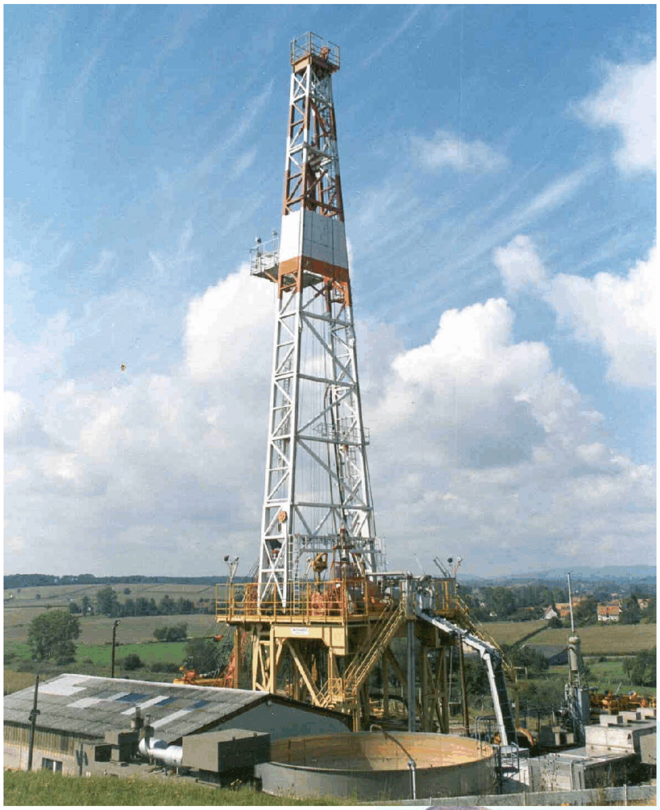
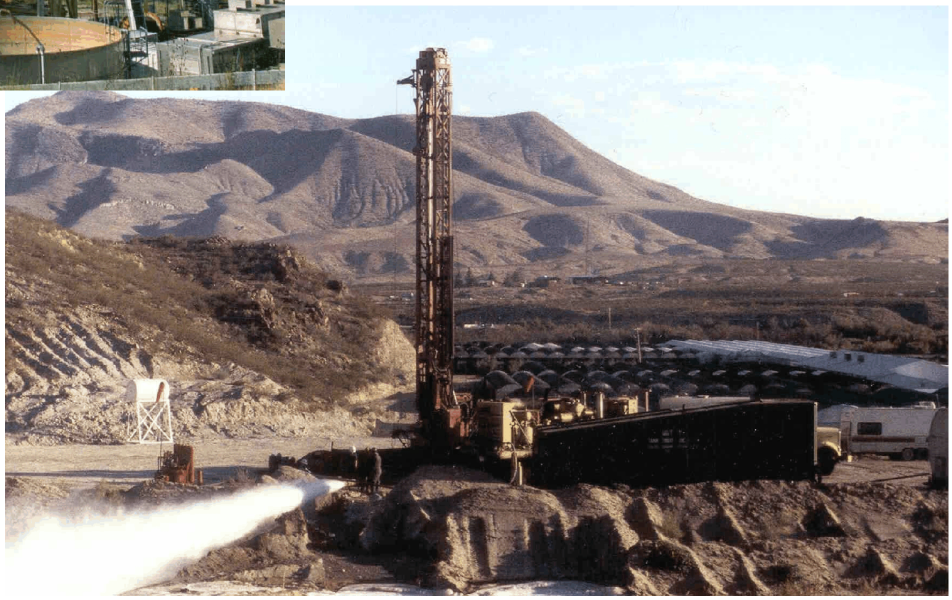


GEOTHERMAL DRILLING



GEO-HEAT CENTER QUARTERLY BULLETIN

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

CONTENTS

Cover: Top - Drill rig at Soultz-Forêt, France (European Hot Dry Rock Project) (Photo courtesy of John Lund). Bottom - Drilling at Radium Springs, NM (Masson Greenhouse Project) (Photo courtesy of James Witcher).

PUBLISHED BY

GEO-HEAT CENTER
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All articles for the Bulletin are solicited. If you wish to contribute a paper, please contact the editor at the above address.

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FUNDING

The bulletin is provided compliments of the Geo-Heat Center. This material was prepared with the support of the U.S. Department of Energy (DOE Grant No. FG01-99-EE35098)> However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the view of USDOE.

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GEOTHERMAL DIRECT-USE WELL FOR COMMERCIAL GREENHOUSES RADIUM SPRINGS, NEW MEXICO

James C. Witcher
Las Cruces, NM

Editor's Note: This report is a condensed version of the Final Report of a U.S. DOE cost-shared contract submitted by Alex R. Masson, Inc., of Linwood, KS, to the Idaho Operations Office, February 2001, titled: "Deep Production Well for Geothermal Direct-Use Heating of a Large Commercial Greenhouse, Radium Springs, Rio Grande Rift, New Mexico." This project is part of the cost-shared direct-use drilling program that also funded a well for a district heating project in Canby, CA, reported in Vol. 21, No. 4 of the *GHC Quarterly Bulletin* (December 2000), titled: "Drilling Geothermal Well ISO."

INTRODUCTION

Background

Expansion of a large commercial geothermally-heated greenhouse is underway and requires additional geothermal fluid production. This report discusses the results of a cost-shared U.S. Department of Energy (DOE) and A. R. Masson, Inc. drilling project designed to construct a highly productive geothermal production well for expansion of the large commercial greenhouse at Radium Springs. The well should eliminate the potential for future thermal breakthrough from existing injection wells and the inducement of inflow from shallow cold water aquifers by geothermal production drawdown in the shallow reservoir. An 800-ft deep production well, Masson 36, was drilled on a U.S. Bureau of Land Management (BLM) Geothermal Lease NM-3479 at Radium Springs adjacent to the A. R. Masson Radium Springs Farm commercial greenhouse 15 miles north of Las Cruces in Dona Ana County, New Mexico, just west of Interstate 25 near the east bank of the Rio Grande. (Figure 1). The area is in the Rio Grande rift, a tectonically-active region with high heat flow, and is one of the major geothermal provinces in the western United States (Seager and Morgan, 1979; White and Williams, 1975).

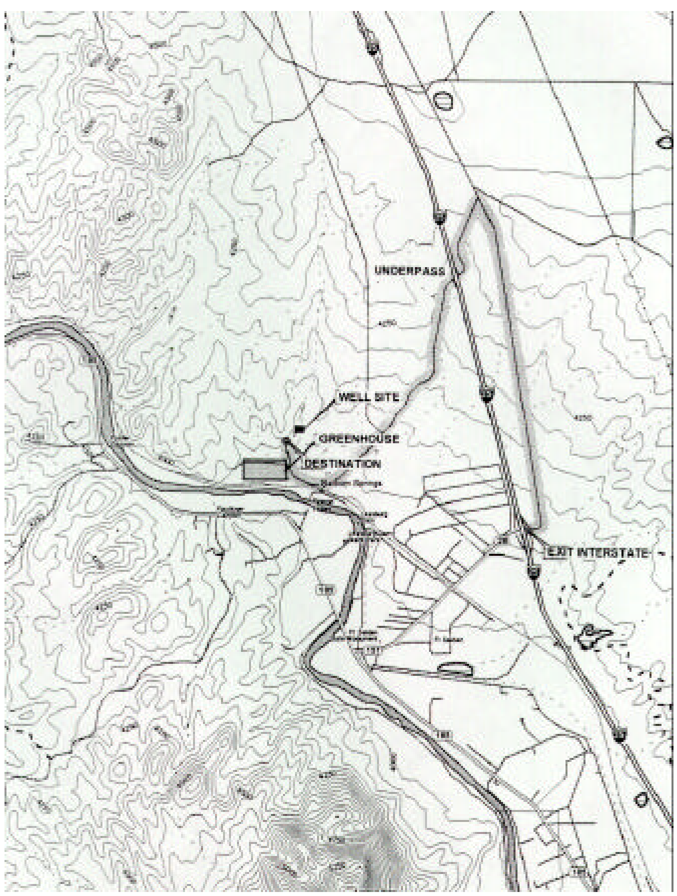

Figure 1. Location map of the Masson 36 Well.

Objectives

The major objective of the Masson 36 well was to obtain 190ºF fluids at 1,500 gallons per minute (gpm) from a deep-confined reservoir. The objective of producing from the deep reservoir which is confined by a thick, clay-rich aquitard, is to practically eliminate direct communication with the shallow cold water aquifers and the Rio Grande from geothermal production pumping in the future. Current geothermal production and injection forms a probable flow couplet that is contained in a shallow and fractured rhyolite intrusion. The couplet and intrusion are hydraulically-connected with nearby shallow cold water aquifers. Therefore, the third primary objective is to avoid drilling across the shallow rhyolite reservoir or seal it off during well construction, if it is encountered, so that only deeper water is produced. All of these objectives were apparently achieved with the Masson 36 well.

Site Selection and Well Design Considerations

The currently produced shallow reservoir at Radium Springs is a fractured rhyolite intrusion of Oligocene age and of limited areal extent and volume. The rhyolite intrudes a thick Eocene aquitard, the Palm Park Formation (Seager, 1975). The fractured rhyolite is in hydraulic communication with nearby cold alluvial aquifers (Gross, 1987).

With the current shallow production-injection well couplet, decreases in temperature are experienced in late winter and early spring as the greenhouse facility has grown from four acres to about 17 acres since 1987. This decrease in temperature is probably from the combined affects of drawdown that encourages infiltration of cold water from the Rio Grande and sub-adjacent aquifers and from cool injected fluids via the injection wells.

The shallow reservoir contains 150 to 162ºF sodium chloride water with a variable total dissolved solids (TDS) of around 3,300 milligrams per liter (mg/L)(Witcher, 1988). Current production is from two wells less than 300 feet depth, completed in fractured rhyolite. These wells were drilled by rotary air hammer. Two injection wells, approximately 1,000 feet distance from the production wells, accommodate about 400 gpm of 100ºF water. The injection wells are located in the local outflow plume of the fractured rhyolite host, while the production wells are located over the local upflow plume. The upflow plume is a "geohydrologic window" of rhyolite that acts as a conduit across the Palm Park aquitard and allows upflow out of a deeper much larger reservoir (Witcher, 1988; Ross and Witcher, 1998).

Two (8,000- and 9,000-ft) wells drilled by Hunt Energy north of the Masson greenhouses in the early 1980s, provide insight into the nature of the deep reservoir. A fractured, composite Precambrian granite and Paleozoic carbonate reservoir is capped or confined by the Eocene Palm Park Formation aquitard. Laramide Orogeny compressional (Late Cretaceous to early Eocene) and Rio Grande rift extensional (Oligocene to present day) fault zones and fractures host the deep-seated reservoir in Precambrian and Paleozoic rocks (Seager, et al., 1984 and 1986).

Temperature gradient information in the area indicates a broad area of 12.6 to 14.3ºF /100-ft temperature gradients over the area from Hunt well 53-27 and southward to the Masson greenhouse facility (Witcher, unpub. data). These temperature gradients are likely to continue into the Palm Park aquitard cap to the top of fractured and possible karst Paleozoic carbonate units. The carbonate rocks were first encountered at 675 to 960 feet depth in the Hunt wells 25-34 and 53-27, respectively (files, New Mexico Bureau of Mines and Mineral Resources). A temperature log of well 53-27 shows that the well becomes isothermal below 1,000 feet at a temperature of about 185ºF (Witcher, unpub data). If the top of the deep reservoir is about 175 to 190ºF over a broad area, then the temperature gradients also broadly define the depth to the top of the reservoir between 600 and 1,000 feet depth, provided the Palm Park aquitard has no large lateral variations in thermal conductivity.

A north-northwest trending Quaternary normal fault delimits the western surface extent of the shallow rhyolite reservoir host at Radium Springs and the westward extent of the highest temperature gradients to the footwall side of the fault zone (Seager, 1975 and Witcher, unpub data). This fault crosses the eastern part of the Masson greenhouse complex.

The final site selected for drilling is on surface land owned by Masson that has an associated BLM geothermal lease that is held by Masson. This site is about 500 feet east of the northwest-striking fault zone on the foot wall and is situated in an area with no rhyolite outcrops. The selected site is closest to the fault zone, has the best access, and is just north of the greenhouse complex in an area with good security.

Participants

The Masson 36 production well project was administered by the Idaho Operations Office of the U.S. Department of Energy. The project was cost-shared by A. R. Masson, Inc. and the U.S. Department of Energy. The drilling contractor for the project, K. D. Huey Drilling of Capitan, New Mexico, was selected on the basis of sealed competitive bid. Well site geotechnical services, permit coordination, and reporting was performed by Witcher and Associates of Las Cruces, New Mexico. The Resource Group, Palm Desert, California provided engineering assistance. Permitting and regulatory oversight was with the New Mexico State Engineer Office (NMSEO) and the BLM.

DRILLING AND SITE OPERATIONS

Drill Site Layout

The Masson 36 well is within the Radium Springs Known Geothermal Resource Area (KGRA) and is located on private surface, owned by Masson, adjacent a local arroyo flood control dike, trending east to west about 600 feet north of the Masson greenhouse complex.

Drill Rig Specifications

A truck-mounted Mobile Equipment Service SR35 rig was used for constructing the Masson 36 well. The SR35 is a top drive rig that is equipped with a 1,350 cfm/350 psi Sullair air compressor. An auxillary 1,150 cfm/350 psi Ingersol Rand air compressor was also used in tandom with the rig compressor as needed. The SR35 utilizes hydraulic drives for the drill motors, pumps, and hoist, allowing excellent variable controls. The rig has a 110,000 pound pullback with the hoist, a rotary torque of 12,000 pounds, and a 700-hp diesel engine on the deck.

Well Control

In the event that pressured fluids, gas, or rapidly boiling or flashing super-heated water entered the Masson 36 well while drilling, several steps were taken to insure that well discharges would be controlled. Well control consisted of blowout prevention (BOPE) equipment, valved flow and kill line ports, an auxiliary water tank with a minimum of 275 bbls (11,550 gallons) of water on site, and the monitoring of bottom-hole temperatures (BHT) and blooie line temperatures. The BOPE stack consisted of a Hydril GK 13 5/8 -3M annular preventer installed on a 13-5/8 in. wellhead spacer spool with flow and kill line ports. A rotating head was installed over the annular BOPE. The kill line port was connected to the auxiliary water tank via a pump. The BOPE was activated by a pneumatic accumulator and was function tested to 2,700 psi. The BOPE and casing was tested to 500 psi for 15 minutes with only 10 psi bleed off. The pressure tests were witnessed by Masson and BLM representatives.

Well Site Geology and Operations Monitoring

Well site geotechnical operations included making field geologic logs of cuttings and archiving cuttings for future reference or study. Samples were taken at the blooie line over 10-ft intervals. Cuttings will be sent for storage and archival at the New Mexico Bureau of Mines and Mineral Resources in Socorro, New Mexico.

Geophysical and temperature logs completed the geotechnical operations. Several temperature logs were taken after overnight breaks in drilling in order to gain information on the temperature gradient and bottom hole conditions. Because cement is exothermic as it cures, an additional temperature log was obtained several hours after the surface casing was cemented. Determination of the cement top in the annulus, facilitated calculation of how much cement to order to fill the backside of the casing to the surface. Geophysical logs were run prior to running surface casing and after reaching total depth (TD), but prior to running the production casing string.

Operations monitoring included daily report log, daily cost tabulation, and a well history log. The daily report log was used to document footage per shift, blooie temperature measurements, all drilling activities, and materials used in drilling. A well history log complemented the daily report log. The well history log was used to record chronologically important events at the well site such as visitors, drilling miles-tones, or any other events not recorded by daily report log.

Drilling Summary and Analysis

Drilling and casing depths in this report are referenced to the drill table (DF) at 4-ft elevation above the ground surface (Table 1). All drilling was done with air foam, using either an air hammer above 672 feet depth or rotary tri-cone bit below 672 feet depth.

On the basis of a competitive bid, the Masson 36 drilling contract was awarded to K. D Huey Drilling a water well driller from Capitan, New Mexico in May 2000. The Huey drill rig did not move on to the site until August 2000. On August 7, the borehole was spudded. The drilling assembly included 17-1/2-in. stabilizers for a straight and gauge hole along with the air hammer and bit. Drilling progressed smoothly until August 9, when the air hammer bit was shanked or in other words broken at the splines inside the air hammer and left at the bottom of the hole when the drill string was tripped or brought out of the hole. On August 22, the "fish" or air hammer bit was recovered. Options were discussed and geophysical logging was performed. It was decided to run and cement surface casing. On August 28 and 29, 465 (DF) feet of 13-3/8-in. surface casing was run in the hole. On August 31, Dowell/Schlumberger arrived on site from Artesia, New Mexico, and ran 144 bbls of cement. Cementing across the ryholite zone was done in stages to insure that fractures and washout zones were sealed. A temperature log ran several hours after Schlumberger demobilized showed the cement at the top of the rhyolite interval. A backside cement job by a local contractor was performed on September 1, to complete the cementing of the surface casing annulus to the surface. This additional 17 bbls of cement filled the hole with overflow at the surface. Between September 2 and 16, the drilling rig top drive was overhauled and the BOPE was installed and tested. Pressure testing was witnessed by the BLM and Masson's consultants on site. On September 16, drilling operations resumed with a 12-1/4-in. drilling assembly. It took an additional ten days to drill a 12-1/4-in. hole to 800 feet, and run and hang a 9-5/8-in. production casing string. A drilling assemblage change was necessary due to formation fluid production at 672 feet. The air hammer and bit was replaced with a tricone bit and rotary air operations resumed and the hole reached total depth (TD) of 800 feet on September 22.

All operations from start to finish were daytime only and usually with only a two man crew. Analysis of drilling operations time indicates that only about 40 hours was actually spent drilling. A nearly equal amount of time or 37 hours was spent tripping in and out of the hole. Installing and uninstalling the BOPE took 47 hours. A much larger amount of time was spent repairing equipment or recovering the 17-1/2 in. air hammer bit at the bottom of the hole. However, the bulk of time between the contract award and the completion of the well involved waiting on drilling personnel, equipment and supplies.

Well Completion

A total depth of 800 feet was reached on September 22, 2000, within the Permian Hueco Formation, a mostly limestone unit with some interbedded shale. The Hueco Formation was an important drilling target. However, the hole only encountered 12 feet of this unit. Much greater production and possibly 10 to 15°F higher temperatures are likely within this unit and underlying carbonate units at a few hundred feet greater depth. However, the well construction and completion provides a contingency for re-entering the hole at a later time in order to drill at least to 2,300 ft depth if desired (Table 2).

Table 1. Daily Footage and Activity Log of the Masson 36 Well

Date	Footage (ft/day)	Remarks
6/29	24	Auger conductor hole, run conductor casing and cement
6/30-8/6	0	Construct cellar and begin moving equipment on site
8/7	120	Finish rigging up, drill 17 1/2 in surface hole with air hammer
8/8	180	Continue 17 1/2 in surface hole with air hammer and foam
8/9	150	Ran temp log, continue 17 1/2 in surface hole with air foam
8/10	0	Ran temp log, trip out, shanked bit in air hammer, bit fish on bottom
8/11-8/21	0	Attempt to recover fish
8/22	0	Ran BHT (186 °F), successfully recovered fish, decide to run casing
8/23	0	Ran geophysical logs
8/24-8/27	0	Casing delivered
8/28	0	Begin to run surface casing with shoe and float collar
8/29	0	Finish run of 461 ft 13 3/8 in surface casing, haul water
8/30	0	Haul water, prepare for cementers, rig maintenance
8/31	0	Cement surface casing, ran temp log to evaluate cement job
9/1	0	Top job cement backside and WOC
9/2-9/5	0	Repair rig top drive
9/6	0	Clean cellar, cut top surface casing, prepare to install BOPE
9/7-9/11	0	Continue repair of rig top drive
9/12	0	Ran temp log, installed rig top drive, wait on BOPE
9/13	0	Unload BOPE, installed well head flange and set spool with side ports
9/14	0	Nipple up annular, rotating head, accumulator and test, install H_2S monitor
9/15	0	Install kill and choke lines, install blooie line, make up drill tools
9/16	51	Trip in, tag cement at 423 ft, drill out cement and float collar, drill ahead
9/17	0	Repair auxiliary air compressor
9/18	147	Drill ahead using 12 1/4 in air hammer with foam
9/19	0	Trip out, wait on 12 1/4 in tricone bit
9/20	0	Wait on 12 1/4 in tricone bit
9/21	68	Make up drill tools, trip in, drill air rotary foam
9/22	60	Drill ahead, TD 800 ft, producing 1175 gpm 196 °F water while drilling air
9/23	0	Trip out, break down BOPE
9/24	0	Unload casing, run geophysical logs
9/25	0	Finish removing BOPE, prepare to run 9 5/8 in production liner
9/26	0	Ran 9 5/8 in production liner to 793 ft, turn off hanger, trip and laydown rig

Table 2. Masson 36 Well Completion Specifications

Item	Hole Size (inches)	Top (ft)	Bottom (ft)	Type (grade)	ID (inches)	Weight (lbs/ft)	Cement (bbls)
conductor casing	24	surf	28	H-40	20	78	3
surface casing	17 1/2	surf	465	N-80 btc	13 3/8	72	157
production liner	12 1/4	395	793	N-80 btc	9 5/8	47	(hung)
production perf	12 1/4	562	793	3/8 rnd	9 5/8	40 h/ft	(punch)

Geophysical and Temperature Logging

The Masson 36 was geophysically logged several times before the well was completed (Table 3) (Figures 2, 3, 4 and 5). A suite of temperature logs was performed with the New Mexico State University (NMSU) temperature logging system. Southwest Geophysical Services of Farmington, New Mexico was contracted to perform additional temperature logs and various other geophysical logs to include caliper, gamma, neutron and electric logs. The NMSU and Southwest Geophysical Services temperature logs were performed with wireline tools that were outfitted with thermister probes which have an accuracy of between 0.005 and 0.05°F.

A caliper tool was run in the open hole prior to installing surface casing. The caliper log shows variation in borehole size which allows calculation of the amount of cement needed to insure a good surface casing seal. The gamma and neutron logs were also obtained. Maximum sampling radius for the gamma and neutron logs is about 1 to

2 feet into the formation. A logging rate of 20 feet per minute is used. As with temperature logs, the wireline signal is digitally converted into ASCII files for analysis and interpretation.

The gamma log measures gamma radiation from naturally occurring uranium, thorium, and potassium. Because different rock types have different radioactivity levels, the gamma log is a very useful lithology correlation tool. For instance, shales and clay may have higher natural radioactivity than sandstone and sand. The neutron tool contains an active radioactive source that emits neutrons and a detector that spaced on the tool about two feet from the neutron source. Neutrons emitted by the tool are principally slowed to low energies by hydrogen (i.e., water and hydrocarbons) in the formation, resulting in less signal for the detector if porosity is high. Where hydrogen content is low (low porosity) the neutrons diffuse much greater distances (closer to the detector) before slowing to low energies. Because of hydrogen sensitivity, the neutron log has use as an indicator of relative formation porosity.

Electric logs can also measure the amount of porosity. Because salty water is a good conductor of electricity compared to rock or drilling mud, electric logs can have much value in well evaluation. The electric logs measure voltage potential and they are reported as a difference as in the SP log or resistance as in the single point "resistance" log or as resistance per unit length as in the normal (long 64 inch - short 16 inch) "resistivity" logs.

CONCLUSIONS AND RECOMMENDATIONS

The Masson 36 well is completed in the top of a deep confined reservoir at Radium Springs. Production temperatures of 210 to 212 ºF are likely. It is believed that the well will sustain long-term production in excess of 1,500 to 2,000 gpm.

A long-term flow test should be performed to determine production and final pump design. The pump test should begin as a step-test and end with a steady-state drawdown test for at least 48 hours. As important as measuring drawdown in Masson 36, drawdown should also be

Table 3. Summary Geologic Log of Masson 36 Well

4 to 14 feet **ALLUVIUM**	Unconsolidated fluvial sand and gravel; arroyo deposits and drill pad base.
14 to 120 feet **PALM PARK FM**	Altered and slightly-to moderately indurated purple brown and blue green, clayey andesitic volcanolitharenite and volcanolithrudite; mostly interbedded andesitic breccia mudflow or lahar deposits.
120 to 222 feet **ROBLEDO RHYOLITE**	Grey porphyritic rhyolite. Highly fractured with brown and red brown oxidized fracture and breccia fragment surfaces. Rhyolite dike with shallow north dip.
222 to 495 feet **PALM PARK FM**	Altered and indurated brown andesitic volcanolitharenite and volcanolithrudite with intervals of strong blue green chlorite, epidote and clay alteration; mostly interbedded with andesitic breccia mud flow or lahar deposits.
495 to 635 feet **PALM PARK FM**	Altered purple brown, maroon and brown, indurated andesitic volcanolitharenite and volcanolithrudite with intervals of strong blue green chlorite, epidote, and clay alteration; mostly interbedded with andesitic breccia mud flow or lahar deposits.
635 to 710 feet **PALM PARK FM**	Interbedded light gray to brown arkosic litharenite and purple brown andesitic volcanolitharenite with some strong blue green alteration; very minor disseminated hydrothermal pyrite mineralization below 690 feet.
710 to 788 feet **LOVE RANCH FM**	Granule, fine to medium arkosic lithic sandstone with some clastic chert and minor disseminated hydrothermal pyrite mineralization.
788 to 800 feet **HUECO FM**	Limestone with gray sticky clay.

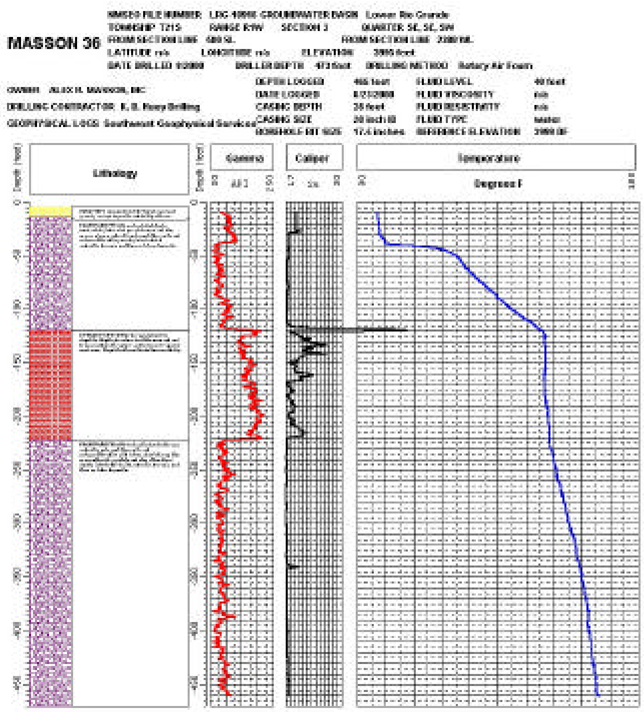

Figure 2. *Pre-surface casing temperature and geophysical logs.*

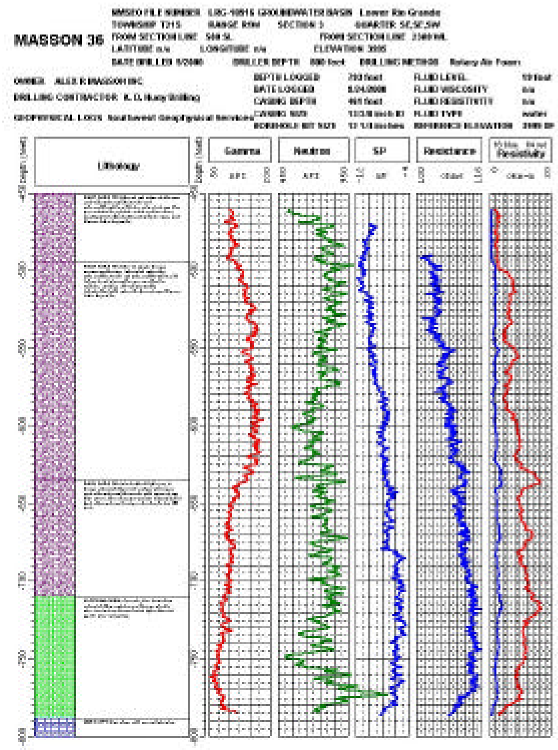

Figure 4. *Electric logs of the 460- to 793-ft interval.*

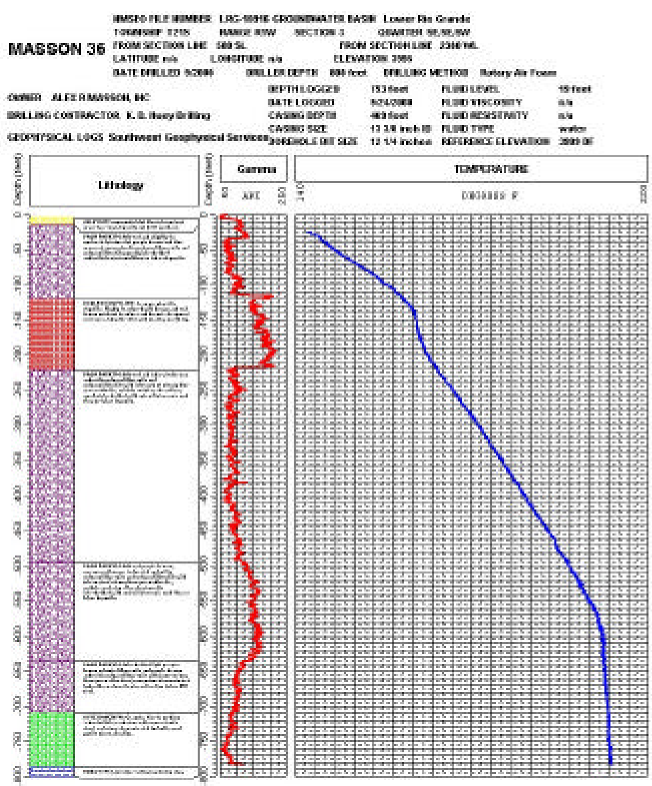

Figure 3. *Post-drilling gamma and temperature logs.*

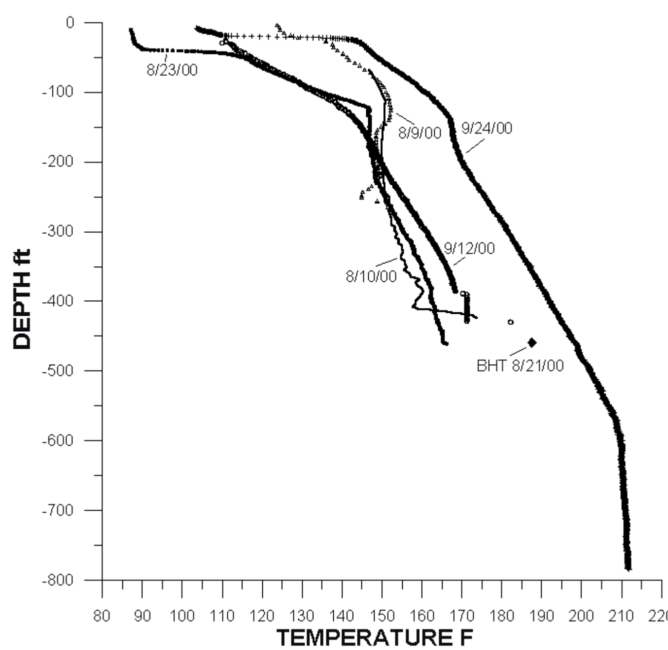

Figure 5. *Composite graph of temperature logs and BHT measurements.*

measured in several of the current shallow production wells. Drawdown should also be observed in at least one nearby cold wells. Ideally, drawdown should also be monitored in the Hunt 25-37 well while the pump test is conducted. This will require BLM approval. If step-tests indicate it is possible, Masson 36 should be pumped at 3,000 gpm for the steady-state drawdown test in order to stress the reservoir and determine any hydraulic connection with shallower reservoirs or with the deep reservoir to the north where the Hunt wells were drilled. The test should be planned and managed by a qualified engineer or geologist and not by a local southern New Mexico water well driller.

This well is configured in such a way that a very large pump can be installed. Also, the well could be deepened several thousand feet in the future if higher temperature or additional production is desired for either the greenhouse or for small-scale binary electrical power generation or both.

It is also recommended that Masson undertake a disciplined and regular monitoring of selected wells including the Masson 36 well. This would include chemistry, temperature, and water level measurements taken at regular and periodic times. As a part of such an effort, all of the wells to be monitored should be surveyed so that a precise elevation is known. If any shallow production or injection wells are to be abandoned, I would also recommend modifying the well constructions to create dedicated monitor wells or piezometers rather than plugging and abandoning the wells. This would require BLM and or NMSEO approval; but, I believe the agencies would be supportive of a proper monitor well design and use plan.

Without a monitoring program, the reservoir will probably not be understood. Monitoring also provides baseline data and procedure that can provide a measure of foresight into reservoir behavior and also "early warning" of impacts from any overly aggressive development on the Radium Springs KGRA immediately north of the greenhouse.

ACKNOWLEDGMENTS

This report was prepared with the support of the U.S. Department of Energy (DOE) under contract DE-FG07-99ID13747 to Alex R. Masson, Inc.

Michael Henzler, manager of the Masson Radium Springs greenhouse, is thanked for all of his assistance and enthusiasm. Michael Henzler's assistant Cindy is most thanked for her assistance with daily reports to the BLM by helping with the FAX and copy machine in the greenhouse office. Bill Richard and Wendell Howard of the Resource Group provided key well site and engineering support for the project, and played important roles in the success of the Masson 36 well. Dick Hahman is thanked for his geologic assistance. Russ Jentgen, Joe Torres, Russ Lummus and Rich Estabrook of the BLM are thanked for their assistance with the Environmental Assessment, and constructive discussions on drilling permits and Sundry Notices. Calvin Chavez of the New Mexico State Engineers Office also provided valuable input on permitting issues and water data. Don Pearson and Mick Peterson of Southwest Geophysical Surveys are thanked for their scheduling patience and subsequent coordination of timely borehole geophysical surveys. Comments and review by Ray Fortuna and Jay Nathwani, USDOE, are much appreciated.

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USE OF GEOTHERMAL ENERGY FOR FOOD PROCESSING INDIAN STATUS

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PRESENT STATUS OF FOOD INDUSTRY

One of India's proudest accomplishments has been achieving self-sufficiency in food production and that the country produces a wide variety of agricultural products at prices that are at or below world values in most cases- states the office of the agricultural affairs of the United States Department of Agriculture (USDA). The country's food industry's sales turnover at the end of the year 2000 was at US$ 31 billion. India's food processing industry covers fruit and vegetables (onions, garlic, tomatoes, potatoes, peas; pineapples, bananas, apples, papaya, grapes and oranges); meat and poultry; milk and milk products, alcoholic beverages, fisheries (prawns, shrimps, tuna, cuttlefish), plantation, grain processing and other consumer product groups like confectionery, chocolates and cocoa products, soya-based products, mineral water, high protein foods and other products.

According to the official statistics of the Ministry of Food Processing (MFP,2001), India exported processed vegetables and fruits worth US$ 2 billion in 1999-2000. India's food exports is about US$ 6 billion whereas the world total is about US$ 440 billion. Thus, India is one of the world's major food producers but accounts for less than 1.5 percent of international food trade. Foreign investment, in food processing sector, after the economic liberalization stood at US$ 2 billion. In recent years, processed food demand has grown considerably--especially from the middle-east countries.

In the case of fisheries sector (prawns, shrimps, tuna, cuttlefish, squids, octopus, mackerels, lobsters and cat fish), there is a growing demand for canned and processed fish from India. India's 8,041 km of coastline, 28,000 km of rivers and millions of hectares of reservoirs and brackish water have large marine product base and variety of fish that can be processed. During the last few years, India invested to the tune of US$ 0.7 billion in this sector with a foreign investment of the order of US$ 0.2 billion. The fish production potential in the exclusive economic zone is 4 million tonnes while the actual production is 3 million tonnes. This excludes the inland production which is of the order of 3 million tonnes.

FUTURE OF FOOD PROCESSING INDUSTRY AND GEOTHERMAL PROJECTS

Realizing the potential of this industry, the government of India accorded top priority and announced several financial incentives to attract investors. They are: a) No industrial license is required for almost all of the food and agro processing industries, b) Use of foreign brand names is now freely permitted, c) Capital goods can now be freely imported, including the second hand machinery in the food-processing sector and d) Excise as well as import duty has been substantially reduced and export linked duty free imports is also allowed. Hence, there is large scope for U.S. companies to invest in food processing and packaging sector which is growing annually at 15 to 20 percent. Increased literacy, changing pattern of life-styles, mass media promotion has all contributed to a change in demand for processed food. India's total food market is estimated at US$ 70 billion and value added food products would be worth US$ 22 billion. To minimize the pre/post harvest wastage, the Indian government is encouraging investment in this sector and has approved several proposals for joint ventures/foreign collaborations. Foreign investment in this sector was about US$ 2.2 billion during the last decade and is expected to increase substantially in the future. India is keen on maximum utilization of agricultural products, which are demand through out the year, and restricting the wastage of vegetables like onions. These products become scarce only due to perishability and lack of storage and handling facilities. Investment opportunity worth US$ 30 billion will be available across the food chain to strengthen the procurement, processing and storage and distribution infrastructure. All these condition in processing and handling various food commodities offer excellent opportunities for U.S. firms in the food processing and packaging equipment sector. (MFP 2001; EoI, 2000; FAO, 1996; EoUS, 2000).

Thus with economic liberalization, India has become one of the prime countries for investment. The total local production in the food processing sector in the year 2000 is estimated at US$ 1,240 million. India's total imports is estimated at US$ 400 million of which US$ 120 million are the imports from the U.S. because the food processing sector is lucrative for investment. India's diverse agro climatic conditions and also wide-ranging and large raw material availability throughout the year are suitable factors for the growth of food processing industry.

If such is the situation, then why India is not able to cash it and be the world's best processed food exporter? The problem lies in inadequate infrastructure like cold storage, dehydration facility etc. About 75-80 percent of vegetables and fruits in India perish due to high water content. This industry requires about US$6 billion in investment in the next five years to create necessary infrastructure, expand production and storage facilities using state-of-art technology to match international standards. Because of lack of such facilities products worth US$2.5 billion is wasted yearly out of which the farm products accounts for US$ 1.5 billion.

Using conventional energy to minimize wastage is expensive today and is going be the same or more expensive in future with ever increasing cost of conventional fuels. For example, 250 gm of dehydrated onions costs US$0.5 (processed in Gujarat) in the Indian market today while the price of 1 kg of raw onion from the producer is available at US$ 0.1/kg. Even if 100 percent profit margin is given, the cost of 1 kg of dehydrated onions costs US$ 0.26 which is expensive for 300 million middle class population. The cost of conventional fuel makes the finished product very expensive. To compete with international market and to promote the product in the local market, the amount spent in such process should be minimum. This can be accomplished by using the country's available geothermal energy resources. To give an example, the table below gives a comparative statement of cost involved in dehydrating fruits using conventional energy and geothermal energy.

Product	Capacity (kg)	Time (hr)	Geothermal	Conventional
Pineapple	817	18	90	4950
Apple (slices)	771	16	810	4500
Apple (cubes)	907	16	810	4500
Banana	817	24	1350	5625

Courtesy: M/s Eco-Fruit Agro Industry, Guatemala, Central America: cost in Rs.(48 Rupee - 1 US$)

Most food-processing and greenhouse operators over the world estimate that using geothermal resources instead of traditional energy sources saves about 80% of fuel costs– about 5% to 8% of total operating costs. Worldwide, the installed capacity of direct geothermal utilization is about 9000 MW and the energy used is about 31,200 GWh/yr distributed among 38 countries (Lund, 1999).

Geothermal reservoirs of low-to-moderate temperature water (20 to 150°C) provide direct heat for industrial and commercial uses. This resource is large and widespread in India and can be used to support food-processing industry to minimize the cost of finished product and wastage. Directly using geothermal energy in commercial operations is much less expensive than using traditional fuels. It is also very clean, producing only a small percentage (and in many cases none) of the air pollutants emitted by burning fossil fuels. A majority of the thermal manifestation are in rural areas and utilizing this resource will benefit the rural India and improve the socio-economic status of the rural population.

WHERE IS "GEOTHERMAL" IN INDIA?

Low–medium temperature geothermal resources exist at seven geothermal provinces in India in the form of 400 thermal springs with surface temperatures varying from 47 - 98°C. These provinces are, at present, the centers of pilgrimage (Chandrasekharam, 1999). Considering the geographic location and climate and agricultural activity and fishing, two provinces are most suitable for initiating food-processing industries in India. They are the west coast and the Himalaya geothermal provinces.

The West Coast Geothermal Province

The west coast geothermal province extends over a length of about 800 km and includes more than 25 thermal manifestations (Figure 1). The surface temperature varies from 47°C (North of Bombay) to 90°C (Tuwa, Gujarat) (Chandrasekharam, 2000; Minissale et al., 2000) with flow rate of 48 L/min (surface)(Ravi Shanker 1987) to 1000 L/min (borehole flow)(Muthuraman, 1986). The heat flow value and geothermal gradient in this province varies from 93-129 mW/m^2 and 59-70°C/km respectively (Ravi Shanker 1988). The estimated minimum reservoir temperature is 120°C (Minissale et al., 2000). All the springs are located in rural India well connected by road and railways and many are close to areas with agricultural activity.

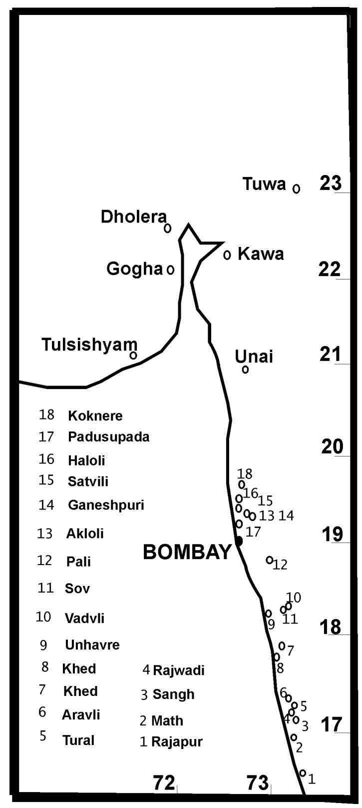
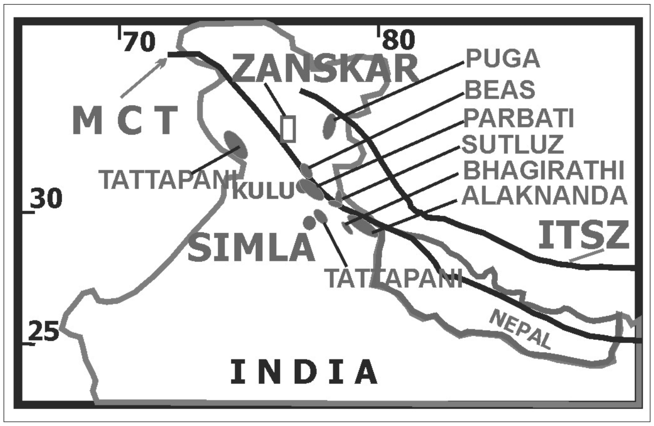


Figure 1. West Coast thermal springs.

The Himalaya Geothermal Province

This province, spreading over an area of greater than 1500 sq.km, includes about 100 thermal springs. This province is bounded by the main central thrust (MCT) on the south and the Indo-Tibet suture zone (ITSZ) on the north (Figure 2). The surface temperature of the thermal springs varies from 57 - 98°C. The estimated reservoir temperature is more than 260°C (GSI, 1991). This province record the highest heat flow value and geothermal gradient (>100 mW/m^2 and 100°C/km, respectively (Ravi Shanker, 1988). The flow rate measured from the bore wells vary from 200 L/min to more than 1000 L/min (GSI, 1991). The presence of younger granite intrusives (22-5 Ma)(Schneider, et al., 1999) and ongoing shallow magmatic processes makes this region an excellent site for any geothermal related activity.



Geothermal Areas of Himalaya

Figure 2. Northwest India.

Himachal Pradesh, where all the geothermal areas of the Himalaya province are located, has varied agro-climatic conditions suitable for growing different varieties of fruits. The state is successfully growing apple, pear, peach plum, almond, walnut, citrus, mango, raisin grapes, etc. The total area under fruit cultivation in Himachal Pradesh is about 2000 km^2 with a production of about 5000 tonnes of all kinds of fruits. Apple is the major fruit accounting for more than 40% of total area under fruits and about 88% of total fruit production in the state. The present two fruit processing plants has a combined capacity to process about 20,000 tonnes of fruit every year. But, then the region has to depend on other farm food from other parts of the country. If local geothermal resources are put to use, this region can be one of the major food producing and processing regions in the country.

Greenhouses, dehydration of fruits and vegetables and aquaculture (fish farming) are the three primary uses of geothermal energy in the agribusiness industry which are most suited under the existing Indian conditions. The relatively rural location of most geothermal resources in India also offers advantages, including clean air, few disease problems, clean water, a stable workforce, and low taxes. The Himalaya geothermal province is best suited to initiate state-of-art technology in food processing (dehydration and greenhouse cultivation) using geothermal energy. Beside the agro-based industry, large cold storage facilities can be commissioned along the west coast geothermal province where fishing is a major business.

HOW TO TAP THE RESOURCE?

Direct–use systems are typically composed of three components:

a. A production facility – usually a well – to bring the hot water to the surface;
b. A mechanical system – piping, heat exchanger, controls – to deliver the heat to the space or process; and
c. A disposal system – injection well or storage pond – to receive the cooled geothermal fluid.

These systems can be bought off-the-shelf and can further be modified to suit specific sites. Geothermal projects require one time capital investment and the annual operational cost is minimum. While in the case of conventional projects, the capital cost includes the cost of the boiler and distribution lines and a large annual operational cost which is continuous and fluctuates depending on the cost of (ever increasing cost of oil, gas and low ash coal) fuel. Depending on the available resources, direct-use projects can operate for over 20 years with low down-time period.

At present, nearly 70% of India's power production is based on coal due to the availability of huge coal reserves in the country. Excessive use of this source, without the use of strategies to mitigate its effects, will have deteriorating effect on the quality of human life. In another decade, emission of CO_2, SO_2 and NOx will exceed 1500 million tonnes, 1900 kilo tonnes and 1200 kilo tonnes respectively (World Bank Report 1999). This means CO_2 emissions will be 775 million metric tonnes per year as compared to 1000 million metric tonnes per year produced in the entire European Union! No doubt the cost of electricity produced from coal is far less expensive compared with other fuels. The present day cost of one kWh of power is less than a rupee in the case of coal based power while liquid fuel based power costs about Rs. 2 per kWh (Mehta, 1999) and hydro power costs about Rs. 1.50 (World Bank Report, 1999)(approx. US$0.04 and $0.03, respectively). But the expenditure spent to meet the consequences (like disposal of fly ash; treating the coal with high ash content, etc.) is high which automatically increases one rupee per kWh to several rupees. Now a time has come to look into those alternate energy sources which were not viable a decade ago due to non-availabilities of advanced technical know how. At present, 1.5 percent of total power generation capacity come from non-conventional energy sources like wind, solar and bio-mass. In the next fifteen years, according to the World Bank Report (World Bank report, 1999), this energy supply could increase by seven times and above.

CONCLUSION

The Ministry of Non-Conventional Energy Source and the Ministry of Food processing, Govt. India encourage use of non-conventional energy resources and provides funds for industries to initiate such projects with attractive financial incentives mentioned above. At present, the Himachal Pradesh depends on hydroelectric power; while, the rest of the country depends on coal based power. Considering the problems created by the coals based power projects and environmental degradation caused by the hydro-electric power projects, the future for geothermal energy resources is quite attractive and bright. India is the only country in the world which has not serious at utilizing its huge geothermal resources. With the present economic globalization process and attractive incentives given to foreign investors in food processing industry, geothermal energy resource utilization in food-processing industry should make a mark in India economy.

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INTERNATIONAL GEOTHERMAL DAYS "GERMANY 2001" Bad Urach, Germany

John W. Lund
Geo-Heat Center

Kiril Popovski
International Summer School
Skopje, Macedonia

The International Summer School program for 2001 was organized by the Germany geothermal organization "Geothermische Verinigung GtV" (Prof. Dr. Burkhard Sanner, Geeste, Germany) and the International Summer School on the Direct Application of Geothermal Energy (Prof. Dr. Kiril Popovski of Skopje, Macedonia). The meeting was held in Bad Urach, Germany, a small geothermal spa community in Southern Germany on the edge of the Black Forest. The site was at the Graf Eberhard hotel and conference center adjacent to the Thermal Baths. The International Summer School is an official activity of the International Geothermal Association (IGA) education program.

Bad Urach is located in a narrow valley in the heart of the Schwabian Alps, with a delightful downtown consisting of a market place surrounded by older typical beam and mortar walls and tile-roof buildings. Overlooking the town is Hohenurach peak with the ruins of a middle-age castle. The Thermal Baths have both indoor and outdoor pools that are geothermally heated, and the city also has an "Aquadrom" and large outdoor swimming pool. A hot dry rock project was started in 1977/78 and by 1983 a 3488 m deep well was drilled obtaining 147ºC water. Finally the well was extended to 4395 m where 170ºC temperature was obtained. This resource has the potential for 3 MW electric and 17 MW thermal.

The International Geothermal Days was attended by 118 participants from 26 countries (Argentina, Austria, Denmark, France, Germany, Hungary, Iceland, India, Iran, Israel, Italy, Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Russia, Slovakia, Slovenia, Switzerland, Tunisia, Turkey, UK, USA, and Yugoslavia).

The meeting covered three separate geothermal areas: (1) The International Workshop on Direct Application of Geothermal Energy for Balneology and "Water" Tourist Centers convened by Mr. Werner Bussman (D) and Dr. John W. Lund (USA); (2) The International Course on Geothermal Heat Pumps, convened by Dr. Ladislaus Ryback (CH) and R. Burkhard Sanner (D); and (3) The International Seminar on Hot Dry Rock Technology, convened by Mr. Helmut Tenzer (D) and Mr. Markus Haring (CH). Field trips were taken to see the spa at Bad Urach, a heat pump project at Bad Schussenried, the spa community of Baden-Baden, and the European hot dry rock project at Soultz-sous-Forêts, Alsace, France.

Even though balneological uses are the earliest applications of geothermal waters, the medical and recreational benefits have been neglected at geothermal conferences, and often ignored in the development of geothermal resources. However, in the past ten to fifteen years the situation has changed, particularly in Central Europe and the USA. Renewed interest in this applications, especially in concert with other geothermal uses, such as space heating, has made balneology and recreation more attractive to developers. Thus, the workshop on this subject was particularity appropriate and received with interest by the participants.

Geothermal heat pumps, even though using marginal ground and groundwater temperatures, has become the fastest growing development of geothermal resources during recent years. However, this use is characterized by major installations in a limited number of developed countries (Switzerland,

Figure 1. Participants at one of the sessions.

Figure 2. Thermal Bath indoor pool with exercise class.

USA, Germany and Sweden) with minor uses in 24 other countries (see overview article in *GHC Quarterly Bulletin*, Vol. 22, No. 1 - March 2001). Because of the increased awareness of this use, the heat pump course was well attended and stimulated lively discussion.

Hot dry rock technology has been much promoted in the EC countries and the USA, but is almost unknown in other parts of the world. It has been treated as "futuristic" technology which is only of interest in other countries probably in 50 years. However, the field trip to the Rhine Graben project at Soultz was of interest to the participants and may stimulate interest in other countries.

Figure 3. Thermal Bath outdoor pool.

Figure 4. Downtown Bad Urach - City Hall.

Hard copies of the two proceeding volumes along with a CD, edited by B. Sanner and K. Popovski, are available from the International Summer School Office at %Dr. Kiril Popovski, ul. "Dame Gruev" br. 1-3/16, 1000 Skopje, Macedonia. Orders can also be made via the Internet at <isskiril@soros.org.mk>. The two following papers by R. Curtis on heat pumps and H. Tenzer on hot dry rocks, are from the proceedings and are reprinted courtesy of the International Summer School.

Figure 5. Graf Ebenhard hotel and ruined castle.

Figure 6. Baden-Baden spa (Caracalla Therme).

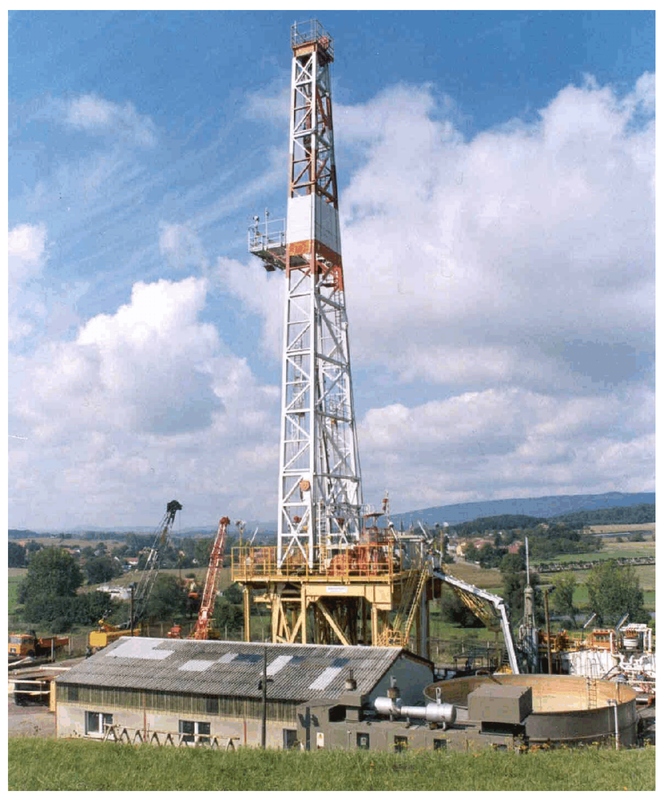

Figure 7. Hot dry rock project at Soultz, France.

DEVELOPMENT OF HOT DRY ROCK TECHNOLOGY

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INTRODUCTION

Hot-Dry-Rock (HDR) for a long time has been a synonym for heat, extracted from deep hot crystalline rock (> 5,000 m). 25 years ago, during the first oil crisis this idea was presented for the first time by atomic physicists and technicians from the Los Alamos Scientific Laboratory (New Mexico) at energy discussions. The aim of this concept was to use the inexhaustible and widely available energy for electricity production by so-called "Man-Made-Geothermal-Systems (MAGES)." This concept rarely agrees with present day systems for the use of geothermal energy and had been termed as "far future technology" even by sustaining geothermal pragmatists .

The situation has changed: first HDR projects as well as deep and very deep scientific drillholes of past years have shown, that crystalline rock in the deep underground is not dry. Even at great depth fluids and open flowpaths in the shape of joints and faults were detected. Therefore, the underground system is not exclusively "Man-Made," but natural conditions, especially if discontinuities are to be taken into consideration. In 1978, the International Energy Agency (IEA) commissioned the Kernforschungsanstalt Jülich GmbH to act as operating agent for conducting a feasibility study on the possible use of geothermal energy from so-called "Man - Made - Geothermal -Energy – Systems" (MAGES) on the basis of available experiences. Objectives of the study was a first systematic analysis of all single components of such a complex system, identify the problems, suggest possible solutions, and to evaluate the economics for using HDR geothermal energy. The database was increased by experiences from several HDR- projects during the last 25 years. The technology was adapted to the conditions underground.

Geology and natural conditions are becoming more important and should be taken into consideration in the design of a HDR system. There will be no single HDR technology but several concepts adapted to the regional conditions.

The development of HDR technology is well described in Rummel, et al. (1992); Jung, et al. (1997) and Baumgärtner & Jung (1998). The following compilation is based on these publications.

THE HDR CONCEPT

The first Hot Dry Rock concept was based on the assumption that deep crystalline basement rock formations are nearly dry and impermeable for fluids due to the pressure of the overburden rock. Therefore, it was suggested to induce artifical fractures acting as heat exchange surfaces, through which fluid is circulated via boreholes penetrating these fractures. In comparison to hydrothermal systems, the fluid circulation is performed in a closed loop where the fluid pressure is maintained at such a level to prevent boiling. Steam for electric energy production is only produced in the secondary loop at low pressure or by using a secondary fluid with low boiling temperature. Originally electric energy production was the main objective, which only can be achieved economically at temperatures above 140ºC. Today a com-bined use of heat and electricity is considered as being more attractive.

Model estimates demonstrate that a HDR system has to produce a thermal capacity of 10 to 100 megawatts over a period of at least 20 years to be economical. Such size of a system requires heat exchange surfaces of 3 to 10 square kilometers and circulation rates of 50 to 100 liters per second. The critical fluid pressure for subsurface system operation is a function of the stress field at a depth which varies from site to site. For a HDR reservoir of a depth of 5 kilometers, the minimum pumping pressure required is about 40 megapascals. In addition, economics limit the operation pressure. Today it is estimated that the flow impedance in a HDR system (the difference between inlet and outlet pressure divided by the flow rate at the outlet) should be in the range of 0.1 megapascal-seconds per liter (MPa s/L). Larger impedance values require a much higher pumping capacity for fluid circulation. It is evident, that circulation on a pressure level higher than the hydrostatic rock pressure are associated with enormous fluid losses. Such losses may occur by fluid penetration into the rock matrix.

During the past, different types of systems had been proposed and were experimentally tested to some extent.

The initial concept that was investigated and proposed by the Los Alamos Scientific Laboratory conceives the crystalline rock of the deep underground as a homogeneous impermeable block. The idea was to connect two boreholes by artificially created fractures. This fracture system was to be created by hydraulic fracturing which would lead to approximately planar vertical fractures evoked by strain processes. The heat would be extracted in a closed loop system: water pumped from an injection borehole to a production borehole, and the required pressure keeping the fracture surfaces open.

The concept of the Camborne School of Mines (Cornwall), which was proposed some years later emphasizes the fracture network in the underground: the existing joints preventing the extension of huge artificial fractures. However, the existing joints are sheared and widened during the frac-experiments thus causing a fracture network with increased permeability. This process is called stimulation. The advantage of this idea compared to the single- and multiple-fracture concept is a more intensive volumetric flow through the rock formation resulting in a more regular cooling effect.

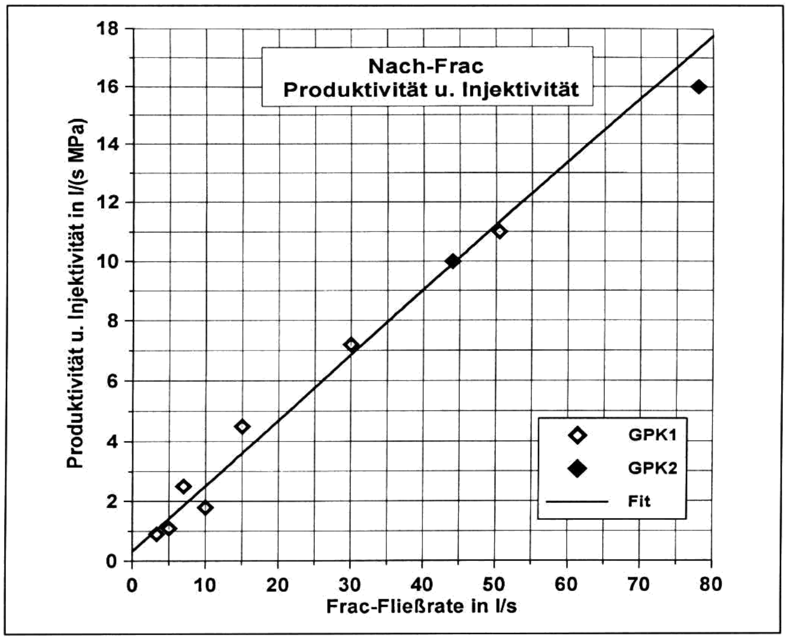

Figure 1. Conceptual models of HDR systems.

The recent concept of the European Research Project Soultz uses natural extensive fracture- and fault-systems, which show a relatively high permeability. The aim of frac-experiments according to this concept is to connect the discontinuities to the boreholes. The main advantage of this concept is, that it is not necessary to directly connect two or more drill holes by an artificially created or stimulated fracture system, which has turned out to be one of the most chal-lenging problems. Each single borehole only has to be hydraulically connect to the extensive fault-zone.

Moreover, by integrating natural fault zones an extensive circulation systems can be created. Such a system, which normally is peripherally open, cannot be operated with an over-pressure, because this would result in a large fluid loss. As a prerequisite, it is, therefore, necessary, that the stimulated fractures are sufficiently permeable at hydrostatic pressure conditions. This concept has been shown to be very successful under the conditions of the Upper Rhine Graben, where natural fault zones are present.

In each concept, the circulation occurs within a closed loop at a pressure level, which avoids boiling of the fluid. Steam for generating electrical power arises first in the secondary cycle. This operating systems guarantees that no toxic material, fluids or gas are released.

Due to good results from experience during the last years, the generation of multiple fracture systems was suggested. In such a model several parallel vertical fractures are connected by two deviated boreholes. To avoid thermal interaction between adjacent fractures, the distance between the fractures should be in the order of 200 meters. The vertical distance between the fractures boreholes may be in the order of 300 meters. The economic operation of such an HDR system requires about 10 single fractures to be induced during separate hydraulic fracturing operations.

Results in the European HDR project enable the system to run with submersible pumps using the natural fracture network after massive hydraulic stimulation. This avoids/reduces the water losses from high injection pressure during circulation.

GENERATION OF FRACS BY HYDRAULIC STIMULATION

The aim of a HDR system is to create a large heat exchanger fracture systems. Presently, the only method by which such fractures can be generated is the method of hydrau-lic fracturing. This was first used in the oil industry. Frac-turing is achieved by injection of fluid into the borehole by high capacity pumps. When the fluid pressure reaches a criti-cal value an axial tension fracture will originate at the borehole wall and will propagate into the rock with an orientation per-pendicular with respect to the minor principal stress direction. Results show that the induced fractures reach a length of several hundred meters and have a vertical orientation.

In comparison to sedimentary rock formation of oil and gas reservoirs, crystalline rocks of HDR systems are characterized by extensive natural joints and fractures which certainly may play a dominant role in the fluid circulation system. Results of experiences from hydrofrac operations show that in the case of crystalline rocks, water can be used as stimulation fluid to enhance rock mass permeability. The use of propants is not necessary.

IMAGE TOOLS FOR FRACTURE DETECTION

The development of borehole logging tools allows measuring the orientation of single fractures on the borehole wall and determining the fracture network in the rock mass.

Most common high resolution tools are the Acoustic Borehole Televiewer (BHTV) and the Formation Imager

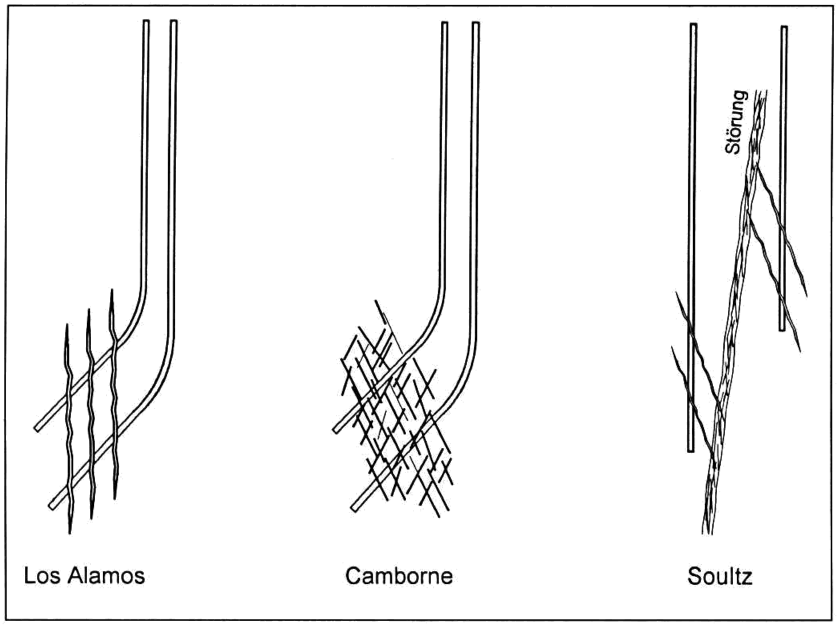

Figure 2. Seismic cloud.

(FMI). The BHTV produces an acoustic image of the entire borehole wall. The borehole wall is a good reflector. Fractures intersecting the borehole absorb acoustic energy and show a reduced reflectivity.

The FMI measure the joints with electrical sensors on four pads. While the intact rock mass is an electric insulator, fluid filled joints show low electric resistance. In hydrothermal altered zones, the FMI tool shows large dark sections. The BHTV tool is more advantage in these zones.

The development of high temperature tools (>200°C) is needed.

SEISMIC MONITORING

A comprehensive understanding of the fracture distribution and hydro geomechanical processes occurring during operation provides valuable information for reservoir development and optimization of production. Some of this information can be obtained from well logs, but they only provide direct information about conditions near the well. Microseismic (MS) monitoring techniques can be the primary methods for obtaining detailed information about reservoirs and fracture systems as far as 1 km from boreholes (Fig. 2). The opening of fractures during hydraulic stimulation induce micro-earthquakes. The origin of these events can be located.

The events are frequently distributed as a seismic "cloud" and it is possible to visualize a blurred image of the seismically active region from this cloud.

New processing methods like "collapsing" enables improved absolute and relative locations of microseismic events. Collapsing uses the existence of neighboring seismic events to obtain better locations of all events. The collapsing method is based on the observation that a cluster of points occupies more volume when each point is perturbed by random errors than it does if no errors are present. This method was developed in a international collaboration known as "MTC - More than Cloud" – Project. Using the collapsing method after stimulation tests and microseismic observations at Soultz, it can be shown that the volume of rock with seismic activity is experiencing critically elevated pressures during stimulation from each well (intersection) as shown in Figure 2.

Additionally seismic waveforms from active seismic sources are used extensively for seismic imaging. The reflection method and multi-component signal processing were improved.

Improved measurements of the overall distribution and relative location of induced seismic events will allow construction and testing of models that include locations of potentially permeable fractures that are seismically active. Such models will help make quantitative predictions about the relation between seismic events and reservoir performance.

HDR - HISTORY

The table show the technical milesones of the development of HDR systems

1970	Proposal of the Los Alamos Scientific Laboratory in New Mexico, USA to use heat from the hot dry rocks of the crystalline crust.
1973	First HDR experiments at Fenton Hill on the east - side of the Valles Caldera near Los Alamos.
Until 1979	Phase 1 of the LASL - HDR project with circulation experiments at 3 km depth at temperatures of about 195°C.
Since 1980	Phase II of the LASL - HDR project at a depth of 4.5 km at temperatures of 330°C with circulation experiments at about 3.6 km depth.

1980-1986	Participation of Germany and Japan in the LASL - HDR project.
1974-1977	HDR feasibility studies in Japan.
1975	Start of preparations for the Urach research drillhole (Germany).
since 1977	HDR feasibility studies at shallow depth (500 m) in Falkenberg, Germany (until 1986), Cornwall, Camborne School of Mines (CSM), UK and Massif Central, France. Start of the Urach geothermal drillhole Urach 3 to a depth of 3,334 meters (143°C) and hydraulic testing program.
1978-1979	The MAG ES - study ("use of man – made - geothermal - energy - systems") initiated by the International Energy Agency, operated by KFA Jülich and carried out by Preussag A.G.
1977-1981	HDR studies in the former German Democratic Republic at Mellin, Altmark.
1980	Deepening of the Cornwall drill holes to 2.6 km depth (80°C).
1980-1986	Deepening of the Urach borehole to 3,488 km (147°C) in Phase III and hydraulic testing program (single borehole system).
1984-1989	Fundamental investigations in the Le Mayet de Montagne - project in France at a depth of 800 meters (University of Paris).
1986	Start of the German - French HDR project at Soultz - sous - Forêts in Northern Alsace (F).
1987	Phase 1 of the Soultz project by drilling a first 2-km deep hole (140°C) and investigation of the crystalline basement in the Rhine-Graben.
1986-1991	HDR experiments in Japan in Hijion (NRIPR) and other locations (Sendai University).
1989	The Camborne School of Mines (the English HDR project group) joins the Soultz HDR project. Formation of an industrial consortium to organize planing and technical operation of an European HDR - project.
1990-1993	Phase II of the Soultz project: drilling a second 2-km deep drillhole and deepening the first drillhole to 3.5 km depth to a temperature of 160°C and geothermal reservoir identification. The second drillhole was used as a seismic observation hole.
1994-1995	Phase III of the Soultz project: Drilling of the second main hole to a depth of 3,876 m (170°C). Production tests, first steam production in Middle Europe from crystalline rocks. Massive stimulation and circulation tests with seismic monitoring, development of the heat exchanger stage I, thermal power of 8 MW was achieved.
1991-1996	Phase III of the Urach Project. Extension of the drillhole to a depth of 4,445 m (172°C) and intense borehole measurement program.
1996-1997	Development of the downhole heat exchanger by massive hydraulic testing ; worldwide the largest HDR system was created. Hydraulic long-term four month circulation test; thermal power of 11 MW was achieved.
1998-2000	Extension of the second main hole at Soultz to a depth of 5,060 m (201°C). Hydraulic stimulation and seismic monitoring.
2001	Planning and preparation of a first scientific HDR pilot plant at Soultz-sous-Forêts. Planning and preparation of a first HDR research pilot plant at Urach.

EXAMPLES OF VARIOUS HDR PROJECTS: MILESTONES OF HDR DEVELOPMENT

The First HDR Project -Los Alamos Scientific Laboratory (LASL), USA

The first proposal to use geothermal energy from deep hot rocks of the crystalline basement came from physicists at the LASL in 1970. The active phase started in 1973; at certain times, about 110 scientists and engineers were employed. The total financial expenditure until 1990 is estimated at DM 300 million (US$150 million). Germany and Japan contributed to the project financially and personnel with an amount of about DM 60 million (US$30 million).

Fenton Hill project is located east of a caldera about 40 kilometers west of Los Alamos on the west side of the Rio Grande Graben in New Mexico. Due to volcanism, the thermal heat flow is about 250 milliwatts per squaremeter or about three times the average heat flow at the Earth's surface.

During the first phase of the project (1973 - 1979) LASL tested the basic HDR concept: connecting two boreholes by a single fracture at a depth of 3 kilometers in granodiorite rock at a bottom hole temperature of 195ºC . The fracture was generated in the first drillhole (GT-2) by hydraulic fracturing, and was identified by seismo-acoustic measurements. The subsurface flow path system consisted of several natural fractures in addition to the induced hydrofrac. The distance between inlet and outlet was about 90 meters. Circulation experiments were carried out over a total period of 100 days and demonstrated rather low water losses and low flow resistance of the system. This first result was beyond previous expectations and also showed that propants are not required to keep fractures open in crystalline rock. This propping effect due to rough and uneven fracture surfaces is of great significance for HDR technique.

The mean thermal capacity of this first small circulation system was about 3 megawatts. Based on the data from the circulation experiment, the effective sub-surface heat exchange area was estimated as only 8,000 squaremeters, an area much smaller than the induced or stimulated fracture area. During the experiments a geothermal energy of 5 gigawatt hours was extracted from the rock mass, an amount to cover the yearly energy consumption of several hundred households.

After these first promising tests, the two boreholes were connected by a large fracture over a distance of 300 meters. A one-year circulation test phase followed; which however, only yielded a production rate of 6.4 liters per second due to a much higher flow resistance. This was a rather poor result, although the water loss again was small. The effective heat exchange area was estimated as 50,000 square meters, confirming the previous result that the effective flow path is limited to the direct connection between the two boreholes. It is interesting to mention that a part of the thermal capacity of 2.3 megawatt was used to drive a 50 kilowatt turbine generator to produce electric energy.

The second phase of the LASL- HDR project started in 1980. The objective of this project was to test the multifrac HDR concept. The system consists of two 4,500 meter deep boreholes, which were deviated on the last 1,000 meters to an angle of 30 degrees with respect to the vertical. The bottom hole temperature was 327°C. This high temperature in the vicinity of the Valles Caldera; however, induced various problems for drilling and borehole measurements, and hydraulic tests. A hydraulic connection between the two boreholes could not be achieved in the deeper part. Therefore, it was decided to fill this part of the boreholes with sand, and to carry out hydraulic fracturing experiments at a depth of 3,600 meters. This test was the largest hydrofrac operation ever conducted in the U.S., but failed with respect to connecting both boreholes hydraulically. The spatial distribution of microseismic events monitored during the injection test shows that a large complex fracture system was stimulated over an extension of 800 meters and with a thickness of about 150 meters. Instead of being vertical, the system is inclined by about 30 degrees. According to this information, the second borehole was directionally deviated to penetrate this fracture zone. Thus, in 1986 - seven years after the start of the project phase - the second HDR circulation system could be completed. A one-month circulation test indicates that the system can be characterized by rather favorable hydraulic properties. The thermal system capacity was in the range of 10 megawatts

In 2001, the U.S. Department of Energy (DOE) closed its Fenton Hill Hot-Dry-Rock project. In order to be more responsive to U.S. industry, DOE now has the Enhanced Geothermal Systems (EGS) program that will provide near term benefit to the geothermal electric power generation industry, and a long term benefit to the Nation's electric power consumers. Initial focus of the EGS program is on transitioning from a national lab-based R&D Program (HDR), to a highly industry-responsive program. Short-term objectives will seek to increase steam production from a commercially developed hydrothermal field, while longer term objectives will seek to create a man-made reservoir that can produce steam, and electrical power, at competitive rates. The knowledge achieved from the Fenton Hill experiments should now be transferred to The Geysers field in northern California.

The HDR Project at the Camborne School of Mines (CSM), UK

The second large HDR research project was carried out by the Camborne School of Mines in Cornwall. The first experiments in shallow boreholes drilled to a depth of 300 meters started in 1977. Since 1980, experiments have been conducted at a depth of 2,000 meters, at a rock temperature of 80ºC. The objective within this project phase was, first, to solve HDR - related drilling, hydraulic and rock mechanical problems, before attacking the problem of rock temperatures, by drilling to great depth during a third project phase scheduled for 1992.

The location was the Rosemanowes quarry near Penryn in Cornwall, in the middle of the Carmenellis granite massif which is characterized by the highest heat flow in England (120 milliwatt per square meter). The average geothermal gradient is about 35ºC per kilometer.

The English scientists intended to create a multi-fracture system by stimulating the network of existing fractures both by blasting and hydraulically. Since natural fractures are essentially vertical, boreholes were planned as inclined holes at depth in order to intersect as many as possible.

In 1980, two 2,000-m deep boreholes were drilled with the inclined sections 300 meters apart. During the subsequent circulation test over a period of half a year, only a poor hydraulic connection between the two boreholes could be achieved. Therefore, a third borehole was drilled to a depth below the other boreholes. In 1984, the borehole drilled by directional drilling technology reached the target area with high precision. Hydraulic connection with the existing borehole could only be created by a massive hydraulic fracturing stimulation test - the largest ever conducted in Europe. Over the following 3 ½ years, the three-borehole system was intensively investigated by hydraulic circulation tests from one borehole (injection hole). After about three years of circulation in one of the flow path, a thermal short circuit occurred (i.e., the circulating water was not heated any more along this flow path). Although only 20 per cent of the total flow passed through this channel, it resulted in a drastic reduction of the water temperature at the outlet. Presently, this short circuit is explained by assuming channel flow instead of water flow over a wide heat exchange area. This is a problem which must be generally considered in future HDR system planning.

HDR Research in France

After the first preliminary investigations in the Massif Central since 1978, from 1984 to 1986, more fundamental investigations related to the HDR concept were carried out at a granite location near the village Le Mayet de Montagne in the Massif Central. The project was funded by the European Community, the Agence France pour la Maitrisse de l'Energy, and the Centre National de la Recherche Scientifique. Besides several shallow boreholes for seismo-acoustic observations, two 800-m deep vertical boreholes were drilled. Different in comparison with other HDR drilling projects; where, borehole sections of several hundred meter length were stimulated, in Le Mayet single existing fractures were selected and then hydraulically opened and propagated by the use of borehole packers. During circulation tests over a period of several months, the hydraulic properties of the fracture system and the heat exchanger were investigated. An important technical innovation was the development of an electrical borehole imaging device which allows observation of the generation of fractures during hydraulic fracturing in the pressurized borehole interval.

HDR Activities in Japan

In Japan, the development of HDR systems has been systematically pushed ahead since 1970. At present, four HDR projects exist; with field experiments essentially carried out in the following three projects:

Hijiori - Project (Yamagata Province):

Since about 1980, the Ministry of International Trade and Industry (MITI) supports a technical feasibility study of the HDR principle in four boreholes of about 2,000–2,200 meter depth and rock temperatures of about 250°C at Hijiori. A multi-well system was developed. Short-term hydraulic tests were performed in 1991, 1995 and 1996. Two reservoirs at 1,800 and 2,200 m in the hot granite basement were created. In 1991, a three-month circulation test was conducted in the upper reservoir. At the end of 2000, a long-term (two-year) circulation test was started in the lower reservoir. The main objective is to investigate the lifetime of the artificial reservoir. Unexpected high impedance of injection at the beginning was observed. A higher recovery and a very low pressure of the shallow reservoir were determined.

In the second year, active control of the shallow reservoir is planned.

The scientific responsibility is with the New Energy and Industrial Technology Development Organization (NEDO) and with the National Research Institute for Pollution and Resources (NRIPR).

Yunomori Experimetal Field (Iwate Province):

Following the more fundamental - oriented Gamma - project at the Tohoku University the so-called "Hot - Wet - Rock" (HWR) project was started with an experimental field in Yunomori in 1988. Objective of the project is to study the water rock - interaction at a depth of 1.5 kilometers at a rock temperature of 200°C. The project is funded by the Ministry of Education and by several private institutions.

At Yunomori, also the in-situ experiments of the TIGER project are carried out scientifically operated by NEDO and funded by MITI.

Ogachi - Project:

The Ogachi project is supported by the electric power industry and is operated by the Central Research Institute of Electric Power Industry (CRIEPI). Subsequently to numerous fundamental research works in the Akinomiya experimental field between 1986 and 1988 (Phase I), circulation tests at shallow depth were performed. The reservoir at about 1,000 m depth was developed with two new bore holes between 1990 and 1992. A large-scale hydraulic fracturing and circulation test has been conducted since 1990 in Phase II at temperatures of 228°C. In Phase III in 1993, a circulation test of 22 days was conducted. In the following year of 1993, a five-month circulation test was performed and in 1995, a one-month circulation test followed. A production temperature of 160°C and a fluid recovery of 25% were achieved. Acoustic emission monitoring and tracer tests were carried out.

In addition to its own HDR research activities, Japan also participated in the HDR project of the Los Alamos Scientific Laboratory in the U.S. during 1980-1986. Also, sci-entific cooperation with the European projects is in progress.

Summarizing, it may be concluded that in Japan HDR technology and its related scientific and technical research is supported on a large-scale financial basis. In addition to governmental funding, the development of HDR technology is either partially funded by the electric power industry, or directly carried ahead like in the Ogachi project. In the so-called TIGER project, all HDR research groups collaborated with industry. Japan also seeks exchange of know-how with European HDR research groups.

Australian HDR Activities

A large potential for HDR geothermal energy exists in Australia. Investigations started around 1995. A commercial company was formed in 2000 called "Geodynamics Limited." The mission of the company is to develop Australia's unique potential for the profitable generation of clean and renewable geothermal energy from known Hot Dry Rock resources.

Several regions in the central, southern and eastern part of Australia will be investigated. In significant parts, the estimated subsurface temperature at 5 km depth is >250°C. This was extrapolated from a database of temperatures recorded on 3,291 wells. The deepest well is 5,594 m, while the average is 1,669 m.

Studies started to investigate some potential sites. An excellent economic potential was estimated - operating costs of 1¢-2¢/kwh and total costs of 6¢-8¢kWh. A study of a 360 MW (electric) power plant with 25 injection wells and 36 production wells is under way.

HDR Activities in Germany

Several German researchers were actively involved in the first HDR activities at Los Alamos since 1972. Such associations automatically resulted in the formulation of their own concepts and contributions related to HDR research:

- The **Falkenberg Frac Project** had the objective to investigate hydraulic fracturing in a tectonically rather intact crystalline rock at shallow depth (boreholes to 500 meters depth);
- The **Urach Geothermal - Project** intented to explorate the geothermal anomaly Urach by a borehole drilled to 3,500 meters depth and to test the possibility of geothermal energy extraction by one borehole only;

- Participation in the **HDR - Project of the Los Alamos Scientific Laboratory** (1980-1986);
- Participation in the German - French **HDR - Project at Soultz-sous-Forêts** in the French Alsace since 1986;
- Conducting the **MAGES - study** for the International Energy Agency (IEA) during 1978 to 1980.

In the following, only the projects conducted at Falkenberg and Urach are presented in more detail.

Falkenberg in North East Bavaria

Considering the enormous technical expenditures for deep drilling at high temperature convinced some of the German research groups to conduct a common HDR research project at shallow depth to study some principal problems of fracture growth in a natural jointed rock mass and fluid transport in hydraulically induced fractures in shallow experiments. The Falkenberg project was conducted during 1977 to 1986 and was funded with about 15 million marks (US$7.5 million) by the German Federal Ministry of Research and Technology and--to some extent--by the European Community.

The test site was about two kilometers west of the village of Falkenberg in the northern part of the Falkenberg granite massif in northeast Bavaria. The test site seemed to be suitable due to a low density joint network and due to rock homogeneity. Seven boreholes were drilled on 100 by 100-m surface area and gave an excellent opportunity to conduct a subsurface investigation of the joint network by geophysical borehole explorations prior to a generation of a large artificial fracture. In comparison to massive hydrofrac operations for oil exploitations and also used in other deep HDR projects, the Falkenberg fracture stimulation work was limited to small injection rates and only small fluid injection volumes. In spite of this, an artificial fracture plane of an area of 15,000 square meters was induced which also connected all seven boreholes over a distance of about 70 meters.

Numerous hydraulic and rock mechanical tests were conducted on this fracture. For the first time, the relation between fracture width and fluid pressure within the fracture was systematically investigated. The measurements demonstrated that fractures can be kept open without the use of propants due to their natural uneveness. The fracture was intersected by several boreholes drilled to 450-m depth. Subsequently its hydraulic behavior was tested. These tests demonstrated that the actual fracture surface had to be several square kilometers and its transmissivity was much larger than required for an HDR system. This result demonstrated that crystalline basement rock may contain large natural fracture zones suitable for extraction of geothermal energy.

Research Work at Urach Spa

The first phase of the Hot Dry Rock (HDR) Project in Urach Spa began in 1977/78 with the Urach 3 drill hole. A depth of 3,334 m within a metamorphic gneiss rock was achieved. An extension of the drill hole to 3,488 m depth followed in a second phase in the year 1982/83, where a temperature of 147°C was attained. A single hole circulation system was tested.

Basic results concerning the temperature field, joint system, stress field and hydraulic behavior of the rock were achieved. Due to high flow impedance, the concept was turned back to a doublet system. To reach higher temperatures for realizing a HDR pilot plant, further investigations had to be obtained. The Urach 3 drill-hole had to be extended from 3,488 m to higher depths, where the required rock temperature of >170°C was expected. The final depth was reached in a third phase, at 4,445 m. The bottom hole temperature at true vertical depth of 4,394 m,72 m was determined at 170°C. It can be proved that the temperature gradient is constant with 2.9°K/100 m depth. Temperatures expected at 4,500 m depth are in the range of 175°C. As main lithological units, meta-morphic rocks such as biotite-gneiss, anatexite and diatexite were determined in the extended drill hole. The different crystalline units are effected by brittle deformation. The resulting fracture system is sealed by hydrothermal products (clays, carbonates, sulphates). The aperture of the fractures is in the range of some tenth to ten millimeters. Sub-vertical sinistral strike-slip shears and faults which correspond to the most intense cataclastic structures, strike N 170° E. Televiewer and FMI logs show a general North-South orientated joint system and borehole breakouts around N 80-120° E. The orientation of maximum horizontal stress direction was determined at N 170° E. Wireline Hydrofrac stress measurements at 3,352 m depth yields values of $S\ h_{min}$ between 41-50 MPa. Estimated stress magnitudes of Anelastic Strain Recovery (ASR) measurements on cores from around 4,425 m depth yields values of S h = 63 MPa. In a study (1990-1996), local boundary conditions, infrastructure, user potential and a preliminary utilization concept (3 MWe), (17 MWth) were evaluated. Due to the results of the investigations, it is proposed that the Urach site located in a widespread tectonic horizontal strike-slip system is suitable for a HDR demonstration project. The results can be applied in Southern German and Northern Swiss regions and in other areas of Europe. Many potential consumers of geothermal energy produced by the HDR concept are situated close around the Urach 3 drill site. In 2001, it is planned to continue the research work and to develop a research pilot plant.

The European HDR Research Project at Soultz-sous–Forêts, Alsace (F)

In 1986, some of the German and French research groups conducting HDR research joined to concentrate on an HDR research project in the Upper Rhine Graben.

The project was funded by the European Community, the German Ministry of Research and Technology, (followed by the Ministry of Environmental Affairs), and the French Maitrise de I'Energie.

Soultz is located about 50 kilometers north of Strasbourg in the centre of the highest heat flow anomaly of Central Europe. Old oil boreholes indicate a temperature gradient of 60ºC per kilometer or nearly 100ºC per kilometer at Soultz for the subsurface. The geological conditions are typical for most locations in the Rhine - Graben (e.g. the Landau area).

During the first project phase (1987-1989), the objective was to test the crystalline basement for its suitability for HDR energy extraction. First, a two-km deep well penetrating the subsurface granite to a depth of 2,000 meters was drilled. The borehole was used for numerous geophysical logging and hydraulic tests. Preliminary results demonstrate, that the subsurface granite, in spite of the existence of natural fracture systems, is suitable for the planned HDR experiments. The rock temperature is 120ºC at a depth of 1,000 meters, but increases much less at greater depth. At 2,000 m depth, the temperature is only 141ºC. This is less than the 40°C expected from extrapolations from the subsurface gradient. This suggests that the geothermal anomaly originates not by a high heat flow from the crystalline basement, but rather from water circulation in the overburden sediments. The temperature gradient and the heat flow values are high in the sedimentary cover (10.5°C/100m, 176 mW/m^2) and quasi normal in the granite basement(2.8°C/100 m^2; 82 mW/m^2).

The hydraulic tests also demonstrated that east - west oriented stresses are extremely low due to the graben tectonics of the Rhine-Graben. The favorable north - south oriented natural joint systems therefore offer good conditions for hydraulic circulation experiments.

In the Phase 1 by stimulation tests, a fracture was opened with an area of more than 10,000 square meters. Hydraulic tests demonstrated that the induced fracture intersected a natural fracture zone where great water losses occurred and the fracture growth was stopped. This interconnection opened the possibility to produce hot water from this fracture zone at significant rates. Therefore, today, the possibility for geothermal heat extraction from such natural fracture systems at graben conditions (like in the Upper Rhine Graben) becomes possible.

During 1989-1991, a continuous cored well was drilled to 2,280 m depth. The well gave useful information on the joint network and mineralogy, and provided the basis for subsequent interpretation of cuttings and geophysical logs.

The main objective of the second project phase starting in 1992-1993 was to deepen the first main hole into a reservoir depth from 2,000 m to 3,590 m depth with a temperature of about 160°C.

Large-scale hydraulic tests were carried out to characterize the rock mass. Supporting activities during the injection tests included microseismic monitoring, production logging, and fluid sampling.

The existing information available was then used to target a second well to a depth of 3,890 m approximately 450 m south of the first well.

In 1995 and subsequently 1996, this borehole was stimulated with a maximum flow of 78 L/s to improve the injectivity as a function of flow rate. During the test in 1995, a total of 30,000 m^3 of fluid was injected and during the 1996 injection a total of 28,000 m^3 of fluid was injected between 3,200 and 3,600 m in three flow steps (24, 45, and 78 L/s) with a maximum well head pressure of 13 MPa for 78 L/s.

Productivity (and injectivity) of both drill holes is proportional to the applied injection rate during the frac-experiments (Fig. 3). This result is essential, especially because it makes the effect of frac experiments predictable. Despite of turbulent flow in the fracture system the post-frac-productivity was abundant attaining a production rate of more than 10 L/s. This was achieved solely by using a low artesian pressure and buoyancy effect without active production. The production rate could be increased to more than 20 L/s by a downhole pump and simultaneous reinjection.

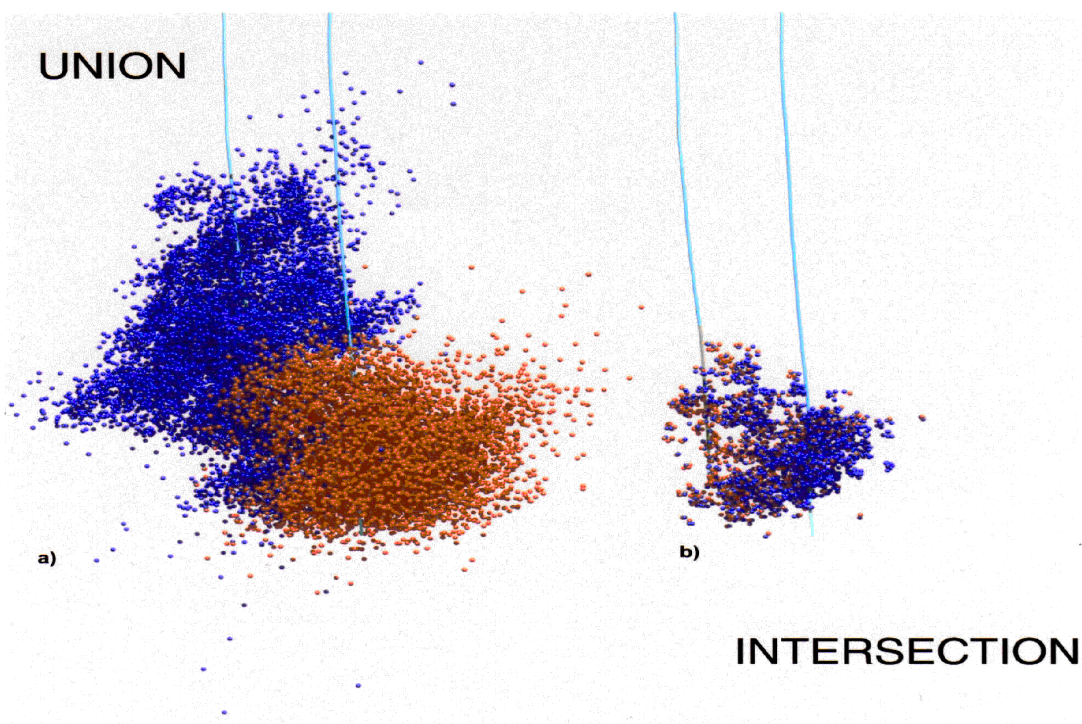

Figure 3. Fracture - production vs. injection.

During a four-month circulation test in 1997, 8 MW thermal power were extracted continuously and the general functioning of a HDR could be determined.

The circulation test was carried out between the two deep wells at around 25 L/s. The result of the test showed that brine can be circulated through the enhanced fracture rock mass at great depth with a separation in excess of around 450 m, with low power consumption for circulation, no geochemical problems and no water losses. A total of 244,000 tonnes of hot brine were produced

In 1999, the second drill hole was extended to 5,060 m depth with temperatures of 201°C. Injection tests and seismic observation indicates that a reservoir independent from the testing zone of 3,200 –3,600 m was reached. The first hydraulic tests showed very promising results for the development of a heat exchanger and a scientific pilot plant at depth around 5 km.

Results of the last years made Soultz the most successful HDR-project worldwide concerning size of fracture system, flowrate, flow impedance and fluid loss. The goal of the next project phase is to construct a HDR-pilot-plant with a thermal power of 30 MW, a final depth of 5,000 m and a rock temperature of 200°C, which seem to be feasible. This project phase will be carried out with a stronger industrial participation especially together with electrical energy supplying companies. According an agreement has been made.

OUTLOOK

During the last 25 years of worldwide HDR research, the initial idea to develop a method for tapping geothermal energy from deep crystalline rocks, which can be used for power generation at any localities, has not been successful. However, not only one HDR method, but several different methods will be realized, which will use and improve the individual local conditions thus enabling an economic heat production. Scientific tools to achieve this goal were developed and can be applied in all depth- and temperature-ranges which can be drilled.

Extensive experience of the effectiveness of these methods under varying local conditions is lacking. Therefore, in addition to basic research in HDR projects, which has to be continued in the future, HDR-technology should now be realized. Possibilities and demand exist in the marginal high enthalpy storage field and low enthalpy systems as well as in the tapping of hot water from fractured and porous-permeable aquifers that show a deficiency of an adequate flowrate.

ACKNOWLEDGMENT

This article is an edited version from the "Proceedings of the International Summer School, Skopje, Macedonia - International Geothermal Days - Germany 2001"–used with permission.

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EARTH ENERGY IN THE UK

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EARLY UK HISTORY

Delving back in the archives, seeking some (or even any) evidence of contributions that our individual countries might have played in the development of this technology, the writer has come to the conclusion that the UK story follows the classic British pattern viz: in at the beginning, good theoretical contributions, limited practical deployment by obsessed individuals with no follow through to widespread commercial success! We are now fervently trying to address the last of these, at least in the area of ground-coupled heat pumps for delivering heating and cooling to buildings.

Clutching at straws, Sumner (1976) notes "that the first mention of a 'heat multiplier' (or heat pump) is associated with William Thompson (later Lord Kelvin).... As one of the world's first conservationists, he therefore outlined and designed a machine which he called a Heat Multiplier. This machine would permit a room to be heated to a higher temperature than the ambient temperature, by using less fuel in the machine than if such fuel was burned directly in a furnace." Suffice to say that in a fossil fuel rich Britain, there was little interest in such a device at the time (i.e., 1852). Sumner reports that the only interest that was shown was for the possible cooling of public buildings and British residences in India. The notion of heat pumps for heating and cooling buildings was born.

Some readers will know that Cornwall has been prominent in UK geothermal activity over recent decades through its Hot Dry Rock programme. It is opportune to offer a historical plug for the region. Earlier this year, a full-scale replica of the first steam-powered vehicle, built by the Cornish engineer Trevithick, ran up Cambrone Hill–200 years after its first run. I mention this because the current interest in Trevithick's prodigious technical innovation reveals that his thinking ranged right across the steam cycle and into the refrigeration air cycle (Burton, 2001). Next week (Oct. 2001), there will be an international conference in Cornwall discussing the steam and air cycles. While the self-taught Trevithick was trying to find a cheaper method of producing ice, the search for replacement refrigerants for heat pumps is of immediate concern to our technology. There is active research on the topic in British universities–unrelated to ground-source heat pumps per se–but related to heat pump refrigerants in general (e.g., Butler, 2001).

Moving forward in time, the following is an extract from a 1981 publication:

> *"Taking heat from the ground by digging a hole of twice the area of the house and burying a pipe in it works well, and is widely used in Germany, Scandinavia and other places that have very low winter air temperatures. This has been tried in Britain. It is not significantly more efficient than an air-source installation and if you feel like digging a hole that is twice the size of your house, this may be of interest. If not, read on...."*
>
> *"...none of this is criticism of those who put forward these proposals, whether in the media or in experimental housing. They do an important job, but in this book, we are concerned with proven pump technology that is commercially available now, it is essential to differentiate between the two approaches"......!! (Armor, 1981).*

Let us hope that we are now in a position to avoid "digging" quite such large "holes" and that we can now offer the technology on a "commercial" basis, or we will not have moved forward significantly from this somewhat cynical view of ground-coupled technology.

This was the view of the technology at the time, despite information printed in a small booklet (Sumner, 1976) produced by the same publisher in 1976, concerning a closed-loop ground-source heat pump installed and used by the earliest known UK champion of the technology John Sumner. This was installed in 1960 using a horizontal copper coil in the garden of a small bungalow and ran continuously and successfully thereafter. A trade journalist recently revealed that he had the privilege to meeting John Sumner, but that his house was "one of the coldest heat had ever been in?" This probably says more about the appalling low level of insulation in British houses built in the 50s and 60s, than anything to do with the ground-coupled heat pump.

Sunmer, a vigorous proponent of heat pump technology for buildings, clearly demonstrated the benefits of using the ground as the ambient energy source in UK climatic conditions. His booklet also hints at research work "carried out 30 years ago" on ground coils by a Miss Griffiths (Griffiths, 1946). The author has yet to obtain a copy of this paper.

A comprehensive book on "Heat Pumps in Buildings" (Sharrat, 1984), which was based on a significant UK conference on the subject in 1983, has only passing references to the use of the ground and groundwater as the energy sources.

In 1995, the writer reported on the evidence found to-date at that time of ground-coupled heat pumps in the UK (Curtis, 1995). Apparently in 1948, Sumner had been commissioned by the philanthropist Lord Nuffield to install 3-kWe ground-source heat pumps in 12 houses. Even in those days, a seasonal performance factor (SPF) of 3 was reported.

Since 1995, in the light of current interest and activity in the UK, evidence of a limited number of one off, open and closed-loop ground-source applications have been brought to the writer's attention. In some cases, the systems are no longer in use for a variety of reasons. In others, they have only come to light because, after many years of faultless operation, a minor problem has forced owners to make contact. As an example, a Scandinavian resident who had imported a complete horizontal loop system from Sweden, had to make a service call for the first time in seven years of operation. The reason for the fault eventually proved to be that his plumber, knowing nothing about heat pumps, had unwittingly released all the refrigerant through attempting to replenish the ground- loop brine circuit using the wrong set of valves!

It is thought that in the period 1970 - 1994, perhaps a dozen or so other horizontal closed-loop systems were installed–all domestic. A number are believed to be in the south coast area due to the presence of an installer importing Swedish heat pumps.

It should be mentioned that there is considerable technical potential for open-loop heat pump systems in the UK (Day and Kitching, 1981). This arises because accessible groundwater is present under a very large proportion of the UK landmass. The barriers are primarily the necessity for licensing, well testing and proof of resource prior to being able to confirm availability to any potential user. Again, in the period 1970 - 1994, there is evidence of a handful of installations, from small domestic, to larger commercial build-ings, using open-loop heat pumps. Difficulties with reinjection and heat exchanger corrosion problems afflict a number of these. Nonetheless, it is likely that more of these systems will be installed–but probably in connection with fairly high profile, high cooling-demand projects, or those where the groundwater resource has already been proven and licensed.

UK BACKGROUND AND IMPLICATIONS FOR GROUND COUPLING

For any country or region involved in the deployment of ground-coupled heat pumps, several natural and man-made factors play significant roles in the rate of adoption of the technology.

Climate

The UK (currently) has a moderate climate, considerably influenced by the warming effect of the Gulf Stream. This has positive and negative effects–extremes of temperature rarely arise; but as a result, we have traditionally constructed buildings with poor levels of insulation compared to countries with severe winters.

Geology

A minor nightmare for ground-coupled installers in the UK, is the extensive range of geology that exists within such a small regional area. Almost all known geological sequences exist within the UK. We can be drilling with air hammers in granite in Cornwall, contending with pure sandstone in areas of the midlands, and have to case and operate with drilling mud for running sands in areas of the southeast. This means that there can be a significant range of drilling and trenching costs across the UK, as well as a wide range of thermal conductivities and hence, variations in the required sizes of closed-loop systems to meet given thermal demands. On the positive , side, a very large proportion of the UK landmass (probably >75%) has a shallow water table, most of our boreholes will be in "wet" or at least "damp" conditions. For larger commercial installations, it has already become established practice to carry out thermal conductivity testing. As well as obtaining data for sizing, the exercise confirms the anticipated geology, the appropriate drilling method, and the quantity of water that might be encountered.

Building and Level of Insulation

Because of the mild climate, and an abundance of fossil fuel (i.e., coal initially, oil and gas subsequently), a large proportion of the UK housing stock was built with what many other northern European countries would regard as appallingly low levels of thermal insulation. In recent decades, the building regulations have been slowly tightened to improve this situation; but, housing stock turnover is slow and it will take many years to rectify this situation. On the other hand, the UK climate is generally (some would say always!!) damp and condensation, due to poor ventilation, is prevalent. Modern buildings, both in the housing and non-domestic sector built to much better standards, are more suitable for heat pumps.

In general, there is limited demand for cooling in UK houses; although, there is growing evidence of luxury housing offering heating and comfort cooling. As a consequence of higher levels of insulation and a warming climate, the possibility of providing cooling, and in particular passive cooling, it is becoming a more commonly request. In the commercial and institutional sector, new buildings in the UK are now very often cooling-dominated. This arises from better levels of insulation, coupled to high internal gains due to lighting, office and IT equipment.

Fuel Supply and Distribution–Heating Methods

Traditionally, UK housing was heated with coal. Coal gasification then emerged and town-based gas grids evolved. From the late-fifties onward, gas and oil fired, wet central heating systems became the preferred method of heating houses. With the advent of North Sea gas, an extensive national gas grid was installed which is now connected to about 75% of the UK housing sector, primarily covering all urban areas. Thus, the dominant and currently lowest cost method of heating in the UK domestic sector is provided by natural gas boilers. In off-(gas) grid areas, oil and LPG are used to fire the central heating boilers. Off peak electric storage heating supplies the remaining domestic heat demand–with coal fires still present in some areas. The unfor-tunate consequence of the preponderance of the existing wet central heating systems is that they are designed to operate at flow and return temperatures typically in the 70 - 80°C range.

Population/Building Density

The UK has a very high population density and consequently, relatively high land values. This results in most buildings, both domestic and non-domestic, usually having very limited areas of land surrounding them. Obviously, there are exceptions–rural areas, out-of-town retail centres, hospitals, schools with playing fields for example. Thus, ground-coupled installations will probably be dominated by more expensive borehole based, rather than trenched systems.

Electricity Supply

The UK has an all pervading, robust and long established national electricity grid. However, practically all domestic premises are (only) supplied with single-phase 230 V, 50 Hz. Without soft start capability, this limits compressor sizes to between 2 and 3 kWe and therefore, has consequential effect on the size of electrically-driven heat pump that can be installed. This is in contrast to many northern European countries where 3-phase domestic supplies are common place.

To some extent, most of the factors listed so far have acted as constraints on the evolution of ground-coupled heat pumps in the UK. On the positive side, the following factors are going to act in favor of heat pump growth.

Improved Building Regulations

Revised building regulations are leading to the construction of more thermally-efficient buildings. This results in significant reductions in peak heat losses. In the domestic sector, this means that single-phase heat pumps will be able to meet the total heating and domestic hot water requirements. In commercial and institutional buildings, reduced, but balanced requirements for heating and cooling will make reverse-cycle ground-coupled heat pumps more affordable and manageable in terms of ground requirements. Revisions to Part L of the building regulations will stipulate total annual energy requirements per square metre, which may be difficult to achieve with conventional systems.

Underfloor Heating and Cooling

For a number of reasons, the underfloor heating market is about to expand very rapidly in the UK, displacing the traditional wet radiator systems, and offering underfloor cooling in some instances. The lower heating temperature and higher cooling temperatures required by underfloor systems, are ideal for the efficient operation of water-source heat pumps.

Improvements in UK Generation Mix

Over the last 10 years, the CO_2 emitted per kWe generated on the UK grid has steadily fallen due to a change in the mix of power stations. Increased use of natural gas and nuclear power to displace oil and coal stations, has resulted in overall figures of -0.49 kg CO_2/kWe. Thus, a ground-coupled heat pump exhibiting an SPF in the region of 3.5 offers substantial reductions (>40%) in CO_2 emissions compared to the best fossil fuel boilers currently on the market. The arrival of "green" or renewable electricity on the UK grid means that clients can choose to connect heat pumps to this supply and have virtually zero CO_2 emissions associated with the heating and/or cooling of their buildings. Two recently completed commercial building in the UK have adopted this approach.

RECENT UK DEVELOPMENTS

Against this background, ground-coupled heat pumps have made a slow start into the UK building sector.

For several years, a Scottish utility promoted the introduction of small DX-based systems (i.e., ground loops containing refrigerant). These were installed in remote housing, off the national gas grid, that would have been electrically heated. The first 1.4-kW units were installed in the Lerwick, Shetland in late-1994. After satisfactory operation, a further 40 units were installed using two sizes of DX heat pumps, 1.4-kW and 2.5-kW respectively, during the period 1998 - 1999. The early installations all used horizontal, refrigerant-filled copper ground loop collectors. The later installations used boreholes in a range of ground conditions–rock, boulder clay and sand/gravels (Millar, 2001).

The first of the modern, borehole based, closed-(water) loop systems was installed in 1994 in Devon in a new built house being constructed by an architect for his own use (Figure 1). The configuration consisted of a single closed-loop borehole connected to an American reverse-cycle water-to-air unit. Warm or cool air is distributed around the house via ductwork that is also connected to a fresh air/heat recovery unit (Curtis, 1996).

Figure 1. Domestic installation Devon.

Since then, progress has been slow, with a variety of different sizes and types of systems being installed. A list of these "modern" ground-coupled systems that the author is aware of in the UK is provided in Table 1. Sizes range from 4-kW to approximately 200-kW thermal. Borehole arrays, single pipe trenches, Slinkies and pond loops have all been used as the heat sources/sinks. Building distribution systems have ranged through wet radiators, underfloor heating and cooling, distributed console systems, central water-to-air plant, providing ducted air, and central water-to-water plant coupled to four pipe fan coils. Heat pumps from America, Sweden, France, Italy, Ireland and the UK have all been used in a variety of sizes. Heating only, reverse-cycle and cooling only, have all been utilized. One or two the commercial systems are hybrids working in conjunction with traditional boiler and chiller systems.

Table 1. Recent UK Geothermal Closed-Loop Heat Pump Installations (this list primarily covers non-domestic installations)

Metropolitan Housing Trust - Office Headquarters, Raleigh Square, Nottingham - 30-hole array coupled to two heat pumps mounted in the roof of a new build four-story office block. One heat pump for heating, one for cooling. The heat pumps are coupled through a common buffer tank, which supplies four pipe fan coils distributed throughout the building. Boreholes drilled Autumn 2000. Commissioned July 2001.
Ascom UK Headquarters, Croydon - A 30-hole closed-loop borehole array is part of a hybrid system supplying reverse-cycle console units distributed thorugh this new multi-story office block. These particular console units incorporate economizers that provide passive cooling. Installed and commissioned during 2000.
Dunston Innovation Centre, Chesterfield - 32-hole array coupled directly to reverse-cycle console units distributed throughout this newly- built, three-story, low-energy office block building, housing fully-serviced startup units. Each office unit has its own heat pump and metering arrangement. The common conference facility has a water-source heat pump supplying fan coils. The ground loop installation was completed in Winter 2000 and commissioning took place in early-2001.
Cotswold Water Park near Cirencester - The visitor centre is using pond loop system to provide heating and cooling. The pond loop heat exchanger has been installed in the adjacent lake and is connected to eight reverse-cycle console-type heat pump units. The system was commissioned in November 2000.
National Forest Millennium Discovery Centre, Moira, Leicestershire - 32-borehole based hybrid system. The ground heat exchanger is coupled to a heat pump, which feeds hot and cold buffer tanks that are also serviced by supplementary boilers and chillers. Borehole array installed Spring 2000. System commissioned early-2001.
Nature's World Visitor Centre, Middlesborough - The centre incorporates a coupled solar/geothermal system. An array of 30 metre deep, concentric heat exchangers, supply individual reverse-cycle water-to-air heat pumps installed around the building. Commissioned during 2000.
Stover Country Park - Newton Abbot, Devon - A shallow pond loop heat exchanger provides heating and cooling to the visitor centre. The pond loop system is coupled, through 100-metre headers from the lake, to a reverse-cycle heat pump. The heat pump delivers energy to an underfloor system via a buffer tank. This is believed to be the first example of a closed pond loop system in the UK.
Bryce Road - Phase 2A, Dudley, Nottingham - Four high profile eco-friendly terraced houses have had a small borehole-based system installed to provide partial heating and cooling to a wet underfloor system. Commissioned in November 2000.
Minehead Community College, Minehead, Somerset - A Slinky-based system is installed in a new IT teaching block. The ground heat exchangers are installed in horizontal trenches in the adjacent sport field and are coupled to a reverse-cycle heat pump and supplied connected to a separate air handling unit. Loops installed during Summer 2000. Commissioned during 2001.
Charlestown J&I School - St. Austell, Cornwell - This 1960-school building has been retrofitted with a 10 borehole-based system with the ground loop array installed in the school grounds. A fully-integrated roof-mounted air handling unit has replaced the original air handling system that used direct electric heater batteries and a chiller. The new roof-mounted heat pump unit incorporates twin reverse-cycle water-source heat pumps supplying the integrated DX-to-air coils. System installed in Summer 1999.
Health Centre - St. Mary's, Isles of Scilly - The new health centre on St. Mary's uses a 4-borehole closed-loop array to supply heating and cooling, using a reverse-cycle water-to-water heat pump to the underfloor system and to provide domestic hot water using a desuperheater. Commissioned in December 1998. This is thought to be the first non-domestic closed-loop installation in the UK.
The Royal Zoological Society Millennium Project, London - The new Invertebrate House at the London Zoo in Regents Park is designed as a high-profile, low-energy building. The small closed-loop system provides cooling to the air supply being used to control the temperature of the high mass TermoDeck floors and ceilings. The boreholes were drilled and completed in early-July 1998 and the system was commissioned in early-1999.
Sheltered Housing Development, Marazion, Cornwall - These four small bungalows, developed by a housing association, use Slinky coils connected to individual heat pumps to provide domestic hot water and heating via conventional radiators. Commissioned 1998.
Botallack Count House, Pendeen, Cornwall - The National Trust restored this old mining Count House. A closed-loop borehole system provides underfloor heating for the main exhibition hall and warm air heating for the warden's office. Commissioned 1999.
Millennium House, Building Research Establishment, Garston, Watford - This futuristic, low-energy house is fitted with a small two-hole closed-loop system to supply the heating and cooling to the convective underfloor system in this Intelligent House of the Future.
Note: About 20 private domestic installations have taken place in the last five years ranging in size from 4 to 30 kW. These are in addition to the 30 or so small DX systems installed in the North of Scotland. There are possibly up to 10 or 20 other trenched-based closed-loop systems that have been installed in the last 20 years by various individuals using a variety of imported heat pumps. There are also a small number of open-loop, borehole, river, lake and pond systems that have been custom designed and installed over the last 20 years.

The first non-domestic borehole-based system was installed in 1998 for a new health centre on St. Mary's in the Isles of Scilly (Figure 2). Four closed-loop boreholes supply an American water-to-water reverse-cycle heat pump that services a multi-zone underfloor slab. The high thermal performance of this building allows the floor slab to "heat charge" overnight using low-rate electricity, resulting in very low running costs. Figures 3 and 4 show two of the larger commercial buildings that have recently been commissioned with closed-loop ground-coupled installations. The systems have been predominately installed in new build projects, but there have been retrofits to older houses, National Trust properties, and in one case, a school once serviced by air handling plant fitted with direct electric heater batteries and a conventional chiller (Figure 5). The latter is an excellent example of where dramatic cost and CO_2 savings have been achieved by displacing electric heating.

Figure 2. Isles of Scilly Health Centre.

Figure 3. Dunston Innovation Centre.

Figure 4. National Forest Discovery Centre.

Figure 5. Charlestown Junior and Infant School.

Three recently completed commercial buildings demonstrate relatively novel internal plant solutions. In Cryodon, the Ascom office project carried out by Clivet/ Groen Holland utilizes a hybrid system connected to the newly developed Geothermic console units. These units offer an "economizer" option that delivers passive cooling directly from the water circulating in the ground loops. In the shoulder seasons (spring and autumn), significant levels of total cooling requirements can be met from this source due to the ground loop temperatures having been reduced in the building preheat phase. At the National Forest visitor centre, use is made of a uni-directional, heating only, heat pump to service hot and cold buffer tanks. In conjunction with additional chillers and boilers, heating and cooling can be delivered simultaneously to different parts of the building. In balancing the demands of the buffer tanks, heat is moved to and from the ground loop array as required. At the new headquarters of the Metropolitan Housing Trust in Nottingham, two central heat pumps are used to service distributed four-pipe fan coil units. One heat pump provides heating, the other cooling, with the two being con-nected via a buffer tank. This also allows for simultaneous de-livery of heating or cooling to different sections of the building as required. The buffer tank acts as an energy transfer store– with the ground loop supplying or rejecting heat as required.

The outcome of this limited, slow and somewhat painful progress has been the distillation from both American and (mainland) European practices of design methods, installation methods, equipment and heat pump technology that can be used in the UK environment. The direct importation of American systems is limited to some extent by the requirement for metric systems, CE-rated equipment, refrigerant restric-tions, UK electrical requirements and in the domestic sector, the need for water-to-water heat pumps as opposed to water-to-air units. The ability to supply domestic hot water at all times of year is also a factor–with American-style desuperheaters not always providing a satisfactory solution. Conversely, it is difficult to obtain European closed-loop water-to-water heat pumps that go above 4-kW thermal output on single phase. Very few European ground-coupled units offer cooling.

IGSHPA (International Ground-Source Heat Pump Association) offers a great deal of educational material, design software, specifications and training for closed-loop systems related to the North American experience–while, Europe has more relevant standards but offers little in the way of training and English language documentation or specifications. It has been a case of having to pick and choose the various elements that are required from both continents to evolve systems suitable for the UK.

In the heat pump arena, three UK heat pump manufacturers have recently become involved in the development of closed-loop ground-coupled equipment devised specifically for the UK market. Clivet (ex Temperature Ltd.) have evolved their Verstamp water-loop console system into the Geothermic range. Kensa Engineering are offering a range of closed-loop reverse-cycle units in the 4 to 48 kW range, complete with DHW (domestic hot water) options. This range can also be serviced by single-phase electricity supplies up to the 16 kW size. A third, well known UK heat pump manufacturer, will shortly announce a small, low-cost, heating only unit that also offers high-temperature DHW service.

THE ASSOCIATED ACTIVITY - "SUPPORTING MEASURES"

In addition to the (slow) growth of the number of actual installations, the UK is beginning to see developments in terms of the supporting infrastructure that will be required before these systems can be widely applied. BSRIA (Building Services Research and Information Association) has commissioned and published two reports (BSRIA, 1998 & 1999) that address the potential UK market and the technology of ground-source heat pumps. The Buildings Research Establish-ment will shortly begin to monitor a number of installations with the aim of reporting on them under the Best Practice Program. This should provide guidance to designers and installer, and some comfort to potential purchasers of the systems.

The UK Heat Pump Network has been established to address all issues related to heat pumps. However, it has specialist sub-committees looking particularly at the use of ground-source systems in the domestic sector. To this end, a number of UK energy rating schemes will need modification to incorporate the appropriate efficiency factors for ground-coupled systems.

There has been very limited assessment of the potential for ground-source systems in the UK. An EU SVE study looked at the potential market for all heat pumps in several European countries including the UK and made considerable reference to ground-coupled systems (Scoitech, 1998). More recently, a resource assessment for all renewables in one UK county was carried out. For the first time, this included a section on ground-coupled systems (REOC, 2001). In addition, the activities of a very limited number of UK designers and installers has begun to raise the awareness level such that there is an order of magnitude increase in interest in ground-coupled heat pumps.

There has been limited training activity. One company briefly ran the unadulterated IGSHPA training course, primarily for drillers. This left a number of frustrated drillers around the UK who are still looking for the market that they were assured was about to take off. There is a proposal that an OPET scheme will be established to train installers in Scotland using the internet as the training delivery mechanism, with material supplied from Sweden. It is important that UK relevant standards, particularly for drilling practices, grouting, and antifreezes are established before large numbers of systems are installed.

Currently, there is practically no government support for the technology in the UK–either in terms of developing technology awareness or research and development. It is only in the last two years that the UK joined the IEA (International Energy Agency) Heat Pump Programme. While the UK is heavily committed to increasing its proportion of renewable electricity to 10% by 2010, there is currently little discussion on the role of renewable thermal energy.

Two of the electricity utilities (SWEB and Scottish Hydro-Electric) have lent their support to the early systems, and a third is about to start playing a promotional role particularly in the social housing sector.

ECONOMICS - THE MAIN DRIVER

Although there are growing pressures to deliver technologies that can utilize renewable energy and offer reductions in CO_2 emissions, it will always be fiscal, or legislative incentives that will dominate the rate at which new products penetrate a given market. Ground-source heat pumps for heating only in the UK market cost about two to three times the price of conventional fossil fuel boilers, and many times the cost of a resistive electrical installation. They offer reductions in running cost against direct electric heating, oil and LPG at 2001 tariffs for these fuels. In some new build houses with an element of thermal mass and with underfloor heating, it is now possible to demonstrate potential running cost savings against mains gas; especially when, maintenance costs are included. While there will always be an advantage against direct electric heating, the relative tariff levels of oil, gas and LPG electricity will affect the potential for heat pumps to offer running cost advantages.

In the commercial and institutional sector, it is currently easier to demonstrate cost benefits for ground-source heat pumps. For new low-energy buildings that require both heating and cooling, it has been possible in some recent projects to offer complete ground-coupled systems that lie within the capital cost range of conventional alternatives. This can require the inclusion of cost savings related to reduced plant space, absence of flues, fuel tanks, and gas supplies. Given a mix of heating and cooling, reduction in maintenance costs, and long lifetimes, running cost benefits can be demonstrated immediately even against mains gas heating and conventional electric cooling systems.

CONCLUSION

The UK proponents of this technology agree on one point–the market for ground-source heat pumps is definitely developing in the UK. The debate is about how large it is and how fast it will grow. At the moment, the number of installations is minuscule, and predictions are notoriously difficult at this stage. In total, there are approximately 70 closed-loop installations, including the 40 or so very small DX installations in northern Scotland. Sizes range from 1.5 kW to 200 kW thermal. A surprisingly wide variety of closed-loop heat pump configurations have been used–controlled partly by heat pump availability and different methods of distributing heating and/or cooling within UK buildings.

Domestic

For heating-only applications in the domestic sector, the competition against main-fed natural gas, the dominance of high-temperature wet radiator central heating systems, and high-density urban housing conditions will probably preclude widespread adoption of ground-coupled heat pumps for many years. The new build, self-build, out of town, off mains gas sectors are where the immediate future probably lies in UK housing. Delivery of attractively priced systems, using appropriate heat pumps for the UK market, across a wide range of geological conditions has to be the focus for would-be suppliers and installers in the UK. Increasing interest by end users in environmental offerings, and a number of limited drivers from government and/or the utilities should see a modest increase in the rate of domestic installations in the next few years.

In the domestic sector, there will be a requirement for suitable water-to-water equipment capable of operating on single-phase electricity supplies with starting current characteristics that are acceptable to the UK electrical distribution network. These heat pumps will need to address domestic hot water requirements, possibly provide cooling (either active or passive), and will need to offer higher temperature outputs if they are to penetrate the retrofit market dominated by the wet radiators as fitted today.

Non-Domestic

It is expected that there are drivers in this sector of the market that should accelerate the adoption of ground-coupled systems. Firstly, the presence of the recently commissioned larger systems should increase the exposure of the technology to end users, and professional alike. Environmental requirements, mandatory requirements for CO_2 and energy reduction in new buildings, and cost effectiveness in buildings that require heating and cooling are expected to lead to many more systems being installed–particularly in out-of-town locations.

It is likely, therefore, that John Sumner was far ahead of his time–and the few systems that he managed to install were a false start for closed-loop systems in the UK. It is expected that with growing environmental pressures, improvements in the performance and delivery of the technology, the UK will slowly, but irrevocably join the growing number of countries where this technology is no longer a novelty.

ACKNOWLEDGMENTS

The author would like to thank GeoScience Ltd. for its long suffering endeavors and continuing financial support to haul ground-source heat pumps into the UK marketplace. Thanks are also due to the small band of co-conspirators who have contributed to both the understanding of how to implement this technology in the UK and who have participated in the actual design and delivery of UK installations. The views expressed here are those of the author alone.

This article is reprinted with the permission from the International Summer School, "International Geothermal Days - Germany 2001," Bad Urach, 2001, Skopje, Macedonia.

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