KLAMATH FALLS GEOTHERMAL FIELD, OREGON

Case History of Assessment,
Development and Utilization

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by

Paul J. Lienau
Gene Culver
John W. Lund
OIT Geo-Heat Center

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ABSTRACT

Klamath Falls, Oregon, is located in a Known Geothermal Resource Area (KGRA) which has been used by residents, principally to obtain geothermal fluids for space heating, at least since the turn of the century. Over 500 shallow-depth wells ranging from 90 to 2,000 ft (27 to 610 m) in depth are used to heat (35 MWt) over 600 structures. This utilization includes the heating of homes, apartments, schools, commercial buildings, hospital, county jail, YMCA, and swimming pools by individual wells and three district heating systems.

Geothermal well temperatures range from 100 to 230°F (38 to 110°C) and the most common practice is to use downhole heat exchangers with city water as the circulating fluid. Larger facilities and district heating systems use lineshaft vertical turbine pumps and plate heat exchangers. Well water chemistry indicates approximately 800 ppm dissolved solids, with sodium sulfate having the highest concentration. Some scaling and corrosion does occur on the downhole heat exchangers (black iron pipe) and on heating systems where the geo-fluid is used directly.

The development of the city district heating system in 1981, resulted in perhaps the most extensive and, in some ways, the most complete aquifer tests ever conducted in the United States. Hundreds of private well owners using downhole heat exchangers were concerned that pumping the reservoir would impact the performance of their wells. The geological setting, historical development, and reservoir testing that led up to this major aquifer stress test in 1983 are presented. The institutional and legal problems that resulted in the establishment of a city ordinance controlling the use of the resource and a Geothermal Advisory Committee to oversee future utilization and development are also discussed.

KLAMATH FALLS GEOTHERMAL RESOURCE

General Geologic Setting

The Klamath Basin is a northwest-southeast (N40ºW) trending structural valley approximately 50 mi (80 km) long and 10 mi (16 km) wide, extending from the southern portion of Lower Klamath Lake on the California border to the south, to the Crater Lake caldera to the north. The Klamath graben is morphologically similar to the Basin and Range terrain; however, it is transitional between the High Cascade volcanic chain and the Basin and Range Province, with Upper Klamath Lake being the largest body of water in the basin (Figure 1). The steeply dipping normal faults (60º) that form the basin have estimated vertical movements of 1,600 ft (500 m) and some as much as 6,000 ft (1,800 m), with several of the fault scarps exposed. The Cascade Range is located to the immediate west and the high desert country to the east. The city of Klamath Falls (urban population approximately 45,000) is located along the east side of the basin near the center at an elevation of approximately 4,100 ft (1,250 m).

Evidence of recent volcanic activity in the area is shown by Mt. Lassen 135 mi (215 km) to the south (erupted in 1914-1917), Mt. Shasta 70 mi (110 km) to the southwest (a composite volcano with an explosive eruption reported as recent as 1786), Crater Lake 45 mi (70 km) to the northwest (formerly Mt. Mazama which erupted approximately 6,700 years ago), and Lava Beds National Monument 45 mi (70 km) to the south (with lava flows as recent as 1,100 years ago). Surface hot springs and mud pots were present before the settlement of Klamath Falls, and have been used by Indians and sheepherders before the turn of the century. The local residents have made use of the resource, principally in the form of hot water for space heating. Approximately 400 shallow-depth wells are used to heat approximately 500 structures in the city. The Known Geothermal Resource Area (KGRA) is centered principally under the city of Klamath Falls, with smaller areas located at Olene Gap-Stukel Mountain to the southeast and at the Klamath Hills to the south near the California border (Figure 2).

Detailed Geology

The main rock units in the basin consist of an almost continuous inter-fingering depositional sequence of Pliocene-Pleistocene volcanic-sedimentary rocks that have uncertain stratigraphic boundaries (Beatty, 1956; Newcomb, 1958; Newcomb and Hart, 1958; Peterson and Groh, 1967; Peterson and McIntyre, 1970; Sammel, 1980; Sammel, 1984). Based on drillers' logs, the change from a dominantly volcanic to a dominantly sedimentary regime was a gradual one which occurred over a long period of Pliocene time.

The oldest rocks exposed in the basin are of middle-to-late Pliocene age based on meager fossil information (freshwater gastropods and a peccary jaw). This unit, referred to as the Yonna Formation (Tst on the areal geology map - Figure 3), consists of lacustrine and fluvial tuffaceous siltstone, sandstone, ashy diatomite, basaltic tuff and breccia, and a few thin basalt flows. Some of

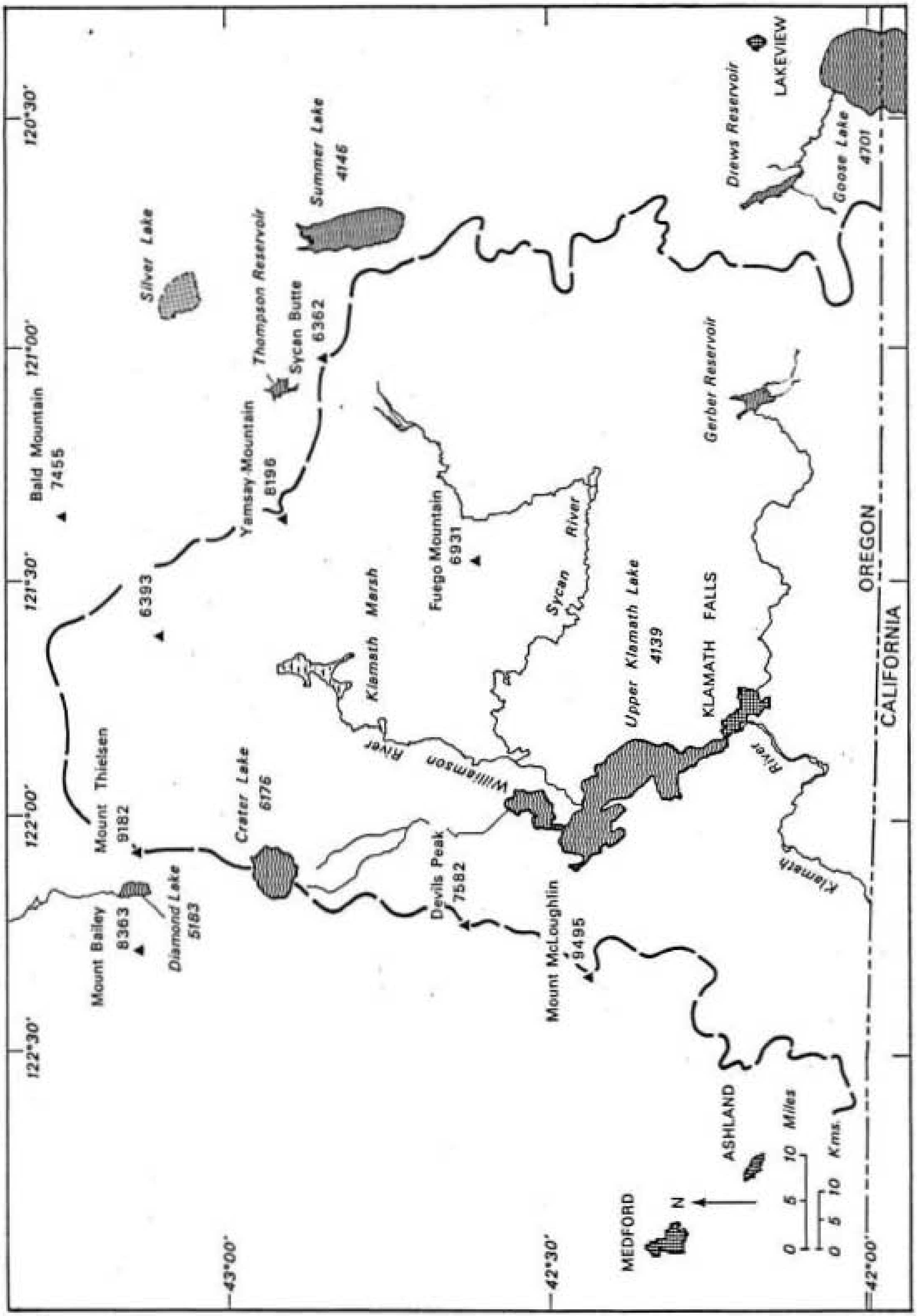


Figure 1. Klamath Basin (Stack, et al., 1979).

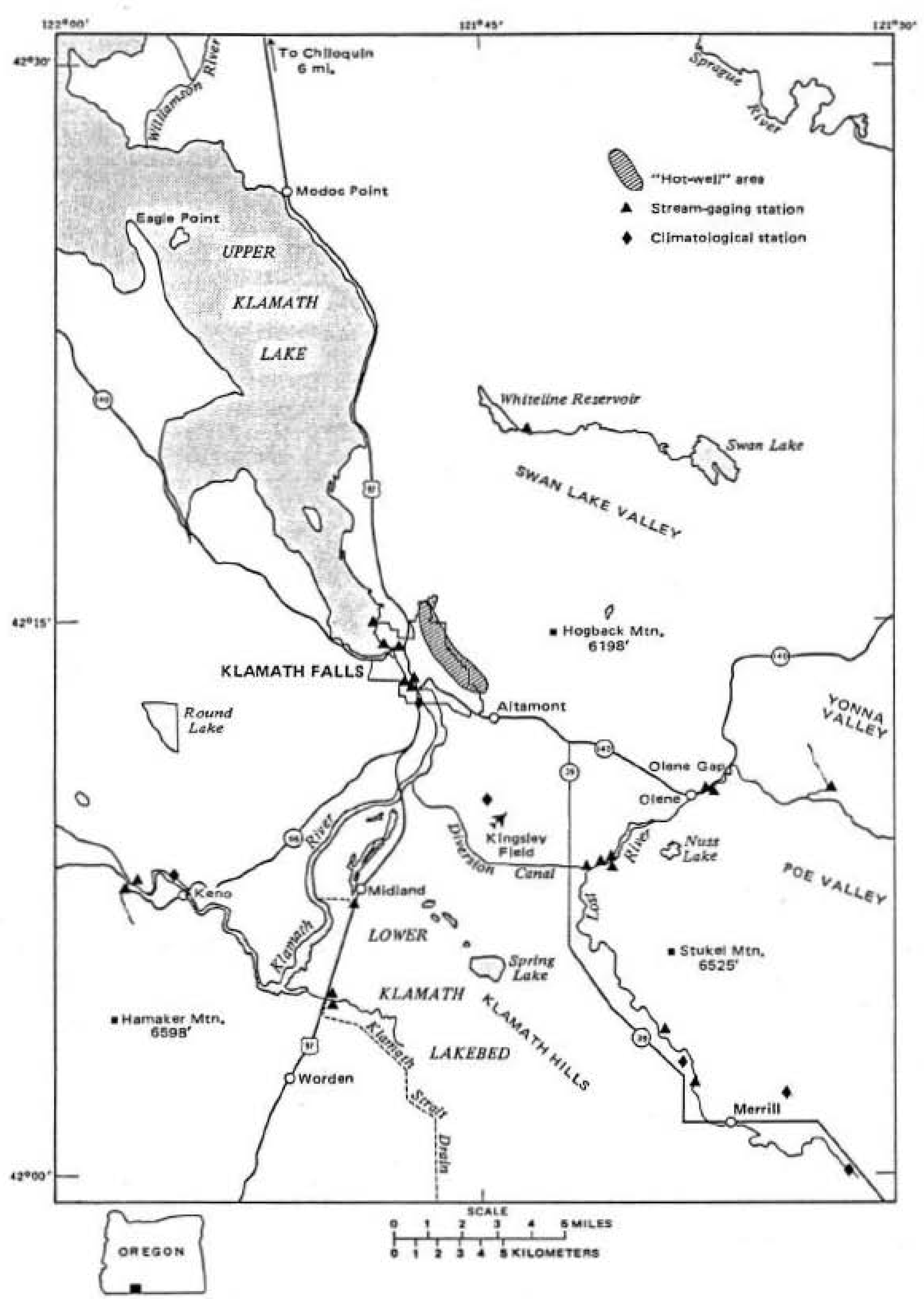


Figure 2. The Klamath Falls area, locations of "hot well" area, National Weather Service stations, and stream-gaging stations (Sammel, 1980).

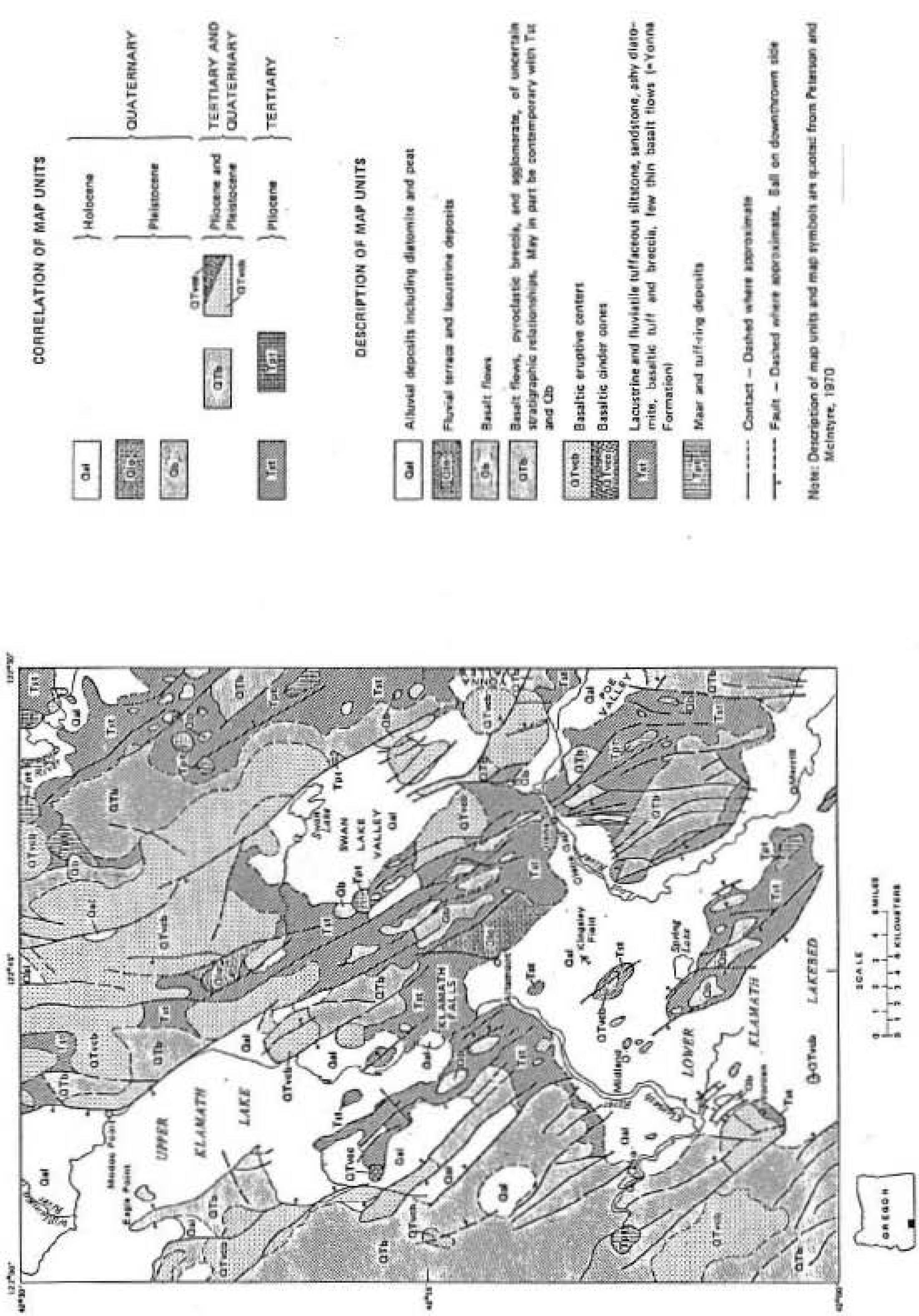


Figure 3. Areal geology of the Klamath Falls area (modified from Peterson and McIntyre, 1970).

the sedimentary deposits have been locally altered to palagonite. This formation, locally referred to as "chalk rock", is estimated to be from 200 to 1,000 ft (60 to 300 m) thick; however, being only from 30 to 150 ft (10 to 45 m) thick in the urban area. In very localized areas, such as in the vicinity of Oregon Institute of Technology (OIT) and Merle West Medical Center (MWMC), this formation has been hydrothermally altered to various silicious deposits such as porcelainite and opal breccia, locally called "hot springs agates." The ashy diatomites of the Yonna Formation have been encountered in road cuts and quarries (a good example is just north of the city on U.S. 97), and are penetrated by many wells. Most of the vesicular lava flows and pyroclastic rocks (fine grained cinders), are not clearly associated with any eruptive centers, and some of the flows are brecciated and altered due to extrusion into water or wet diatomaceous ooze. Most of the eruptive centers have been covered; however, a few maar and tuff-ring deposits have been identified (Tpt on Figure 3).

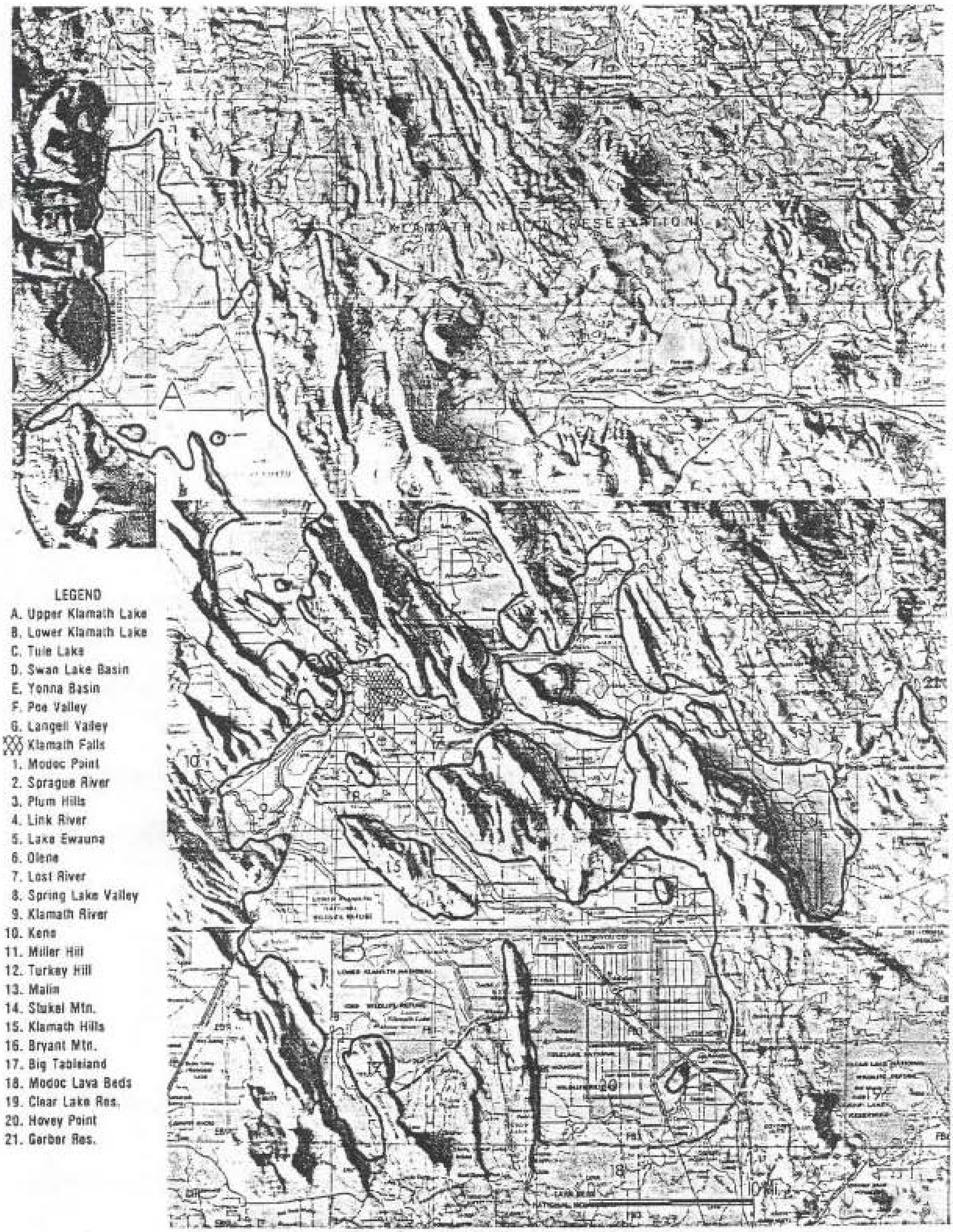
The entire areas of diatomite deposits were probably covered by numerous shallow lakes. Dicken (1980) proposes a 1,100 mi^2 (2,800 km^2) body of water called Lake Modoc, which existed in Pleistocene time. The southern end was in California, south of Tulelake and the northern end was near Fort Klamath in west-central Klamath County (Figure 4). At maximum extent, the lake was 75 mi (120 km) long with 400 mi (640 km) of shoreline at elevation 4,240 ft (1,290 m). The present Upper Klamath Lake (elevation 4,139 ft (1,262 m), Lower Klamath Lake, Tule Lake, Swan Lake and others are remanent of pluvial Lake Modoc.

Massive diatomites of the Yonna Formation have been correlated with deposits in Butte Valley in northern California. Rocks older than the Yonna Formation have been identified in wells and in mapping of adjacent areas. To the east of Klamath Falls, the Yonna Formation lies unconformable on olivine basaltic rock of probably Pliocene age. This lower unit composed of basaltic lava flows up to 800 ft (245 m) thick in sometimes referred to as the "lower lava rocks" (Figure 5).

These extensive lava flows and pyroclastics were deposited on relatively level surfaces in the region and are correlated with older basalts of the High Cascades. From drillers' logs they are described as massive gray to brown vesicular olivine basalts and tuffaceous sediments. These flows probably originated from large shield volcanoes of the High Cascades that existed on the eastern flank of the Cascade Range along north-south trending fissures. Pelican Butte and Brown Mountain to the northwest of Klamath Falls, are a classic examples of these massive shield volcanoes.

The basement rocks are unknown, but are probably Micocene andesitic and basaltic flows, volcanic breccias, and minor tuffs similar to the volcanic rocks of the Western Cascades. These lavas probably correlate with units in northern California near Butte Valley and Macdoel, and are at least 12,000 ft (3,600 m) thick near the Oregon-California border west of Klamath Falls.

During early Pleistocene time, thin basaltic lavas 50 to 200 ft (15 to 60 m) thick were extruded onto the erosional surface developed on the Yonna Formation. These are described as vesicular, medium to dark gray, diktytaxitic basalts (shown as Qtb and Qb on the areal geology map). Examples of these flows can be seen capping the fault blocks surrounding the basin and in the Williamson River Canyon near Chiloquin. The original pahoehoe surface of these flows are usually covered only by a thin veneer of soil and Mazama pumice, except in the basin where they are covered by lacustrine sediments.



Preliminary map of area covered by Pluvial Lake Modoc. Highest shoreline (solid line) is near 4,240-ft contour except in the south, where lava flows have encroached on lake bed (dashed line).

Figure 4. (Dickens, 1980).

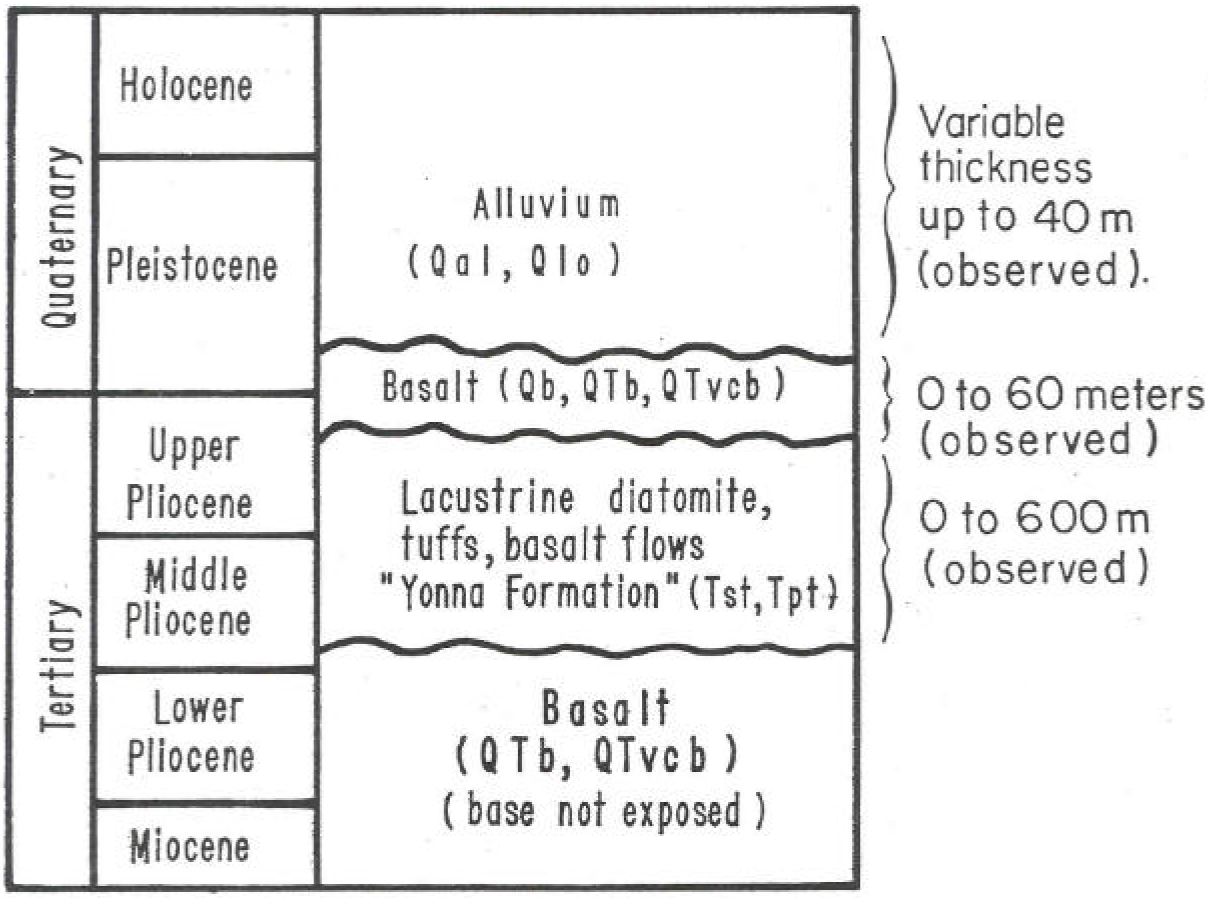


Figure 5. Stratigraphic section for Klamath Falls area (after Peterson and McIntyre, 1970).

Structural development in the basin includes anticlinal arching along with high angle normal faulting that began as early as Pliocene time. After the deposition of the Yonna Formation and related basalt flows, the basin was folded into a broad north-south axial trending anticline whose crest collapsed to form the present graben. Horst and graben faulting probably ended during Pleistocene time, producing the steeply dipping (over 60°) normal faults that gravity data indicate are displaced over 6,000 ft (1,800 m). During this time, several eruptive centers occurred in the area consisting mainly of basalt flows and basaltic cinders (QTvcb and QTvcc on Figure 3). Seismic events have occurred in historical time; but, no surface breaks have been observed. The area is located in seismic risk zone 2 - moderate damage (Uniform Building Code).

Finally, alluvial deposits covered much of the low-lying areas of the basin during late Pleistocene and Holocene time (Qlo and Qal on Figure 3). These deposits consist of the typical gravels, sands, silts and clays, but also include diatomites and peat. Some Mazama pumice has been washed into the basin from the north. The overall distribution and thickness of recent diatomite in the Klamath Marsh-Klamath Lake depression is not known; but, the deposit may be extensive.

In summary, the geology of the basin is complicated and difficult to define. To quote Peterson and McIntyre (1970):

> "The stratigraphy of the Klamath Falls area is not easily deciphered. The abundant and widespread Pliocene and Pleistocene volcanic activity in the High Cascades just to the west and within the basin, complex faulting, and sedimentation all happened concurrently have resulted in a heterogeneous sequence of volcanic and sedimentary rocks. The thickness and composition of rock types varies greatly from place to place, making it very difficult to describe a complete stratigraphic section."

USGS Geothermal Resource Assessment

The United States Geological Survey has published numerous reports concerning the assessment of geothermal resources of the United States (1975, 1978 and 1982). Extracting information on the three Klamath Falls KGRAs gives the following characteristics of the reservoir:

1. 1975 (Circular 726 - White and Williams, editors):

   Klamath Falls:

   Surface temperature = 165°F (74°C)
   Subsurface temperature = 248°F (120°C)
   Subsurface area = 93 mi^2 (240 km^2)
   Thickness = 1.2 mi (2 km)
   Volume = 115 mi^3 (480 km^3)
   Heat content = 119×10^{15} Btu (125×10^{18} J)
   (30×10^{18} cal)

2. 1978 (Circular 790 - Muffler, editor):

   Klamath Falls area mean reservoir:

   Temperature = 232°F (111°C)
   Volume = 27 mi^3 (114 km^3)
   Thermal energy = 28×10^{15} Btu (30×10^{18} J)
   Wellhead thermal energy = 7.0×10^{15} Btu (7.4×10^{18} J)
   Beneficial heat = 1.70×10^{15} Btu (1.79×10^{18} J)

   Klamath Hills area mean reservoir:

   Temperature = 255°F (124°C)
   Volume = 2.5 mi^3 (10.6 km^3)
   Thermal energy = 2.9×10^{15} Btu (3.1×10^{18} J)
   Wellhead thermal energy = 0.27×10^{15} Btu (0.78×10^{18} J)
   Beneficial heat = 0.177×10^{15} Btu (0.187×10^{18} J)

3. 1982 (Circular 892 - Reed, editor) - low temperature:

Klamath Basin:

Mean reservoir temperature = 86ºF (30ºC)
Mean reservoir area = 45 mi^2 (117 km^2)
Mean reservoir thickness = 0.15 mi (0.25 km)
Assessable resource base = 1.08 x 10^{15} Btu (1.14 x 10^{18} J)
Resource = 0.059 x 10^{15} Btu (0.062 x 10^{18} J)
Beneficial heat = 13.2 MWt for 30 years

Klamath Falls - Olene Gap:

Mean reservoir temperature = 140ºF (60ºC)
Mean reservoir area = 12 mi^2 (32 km^2)
Mean reservoir thickness = 0.15 mi (0.25 km)
Assessable resource base = 0.88 x 10^{15} Btu (0.93 x 10^{18} J)
Resource = 0.116 x 10^{15} Btu (0.122 x 10^{18} J)
Beneficial heat = 60 MWt for 30 years

Klamath Hills:

Mean reservoir temperature = 127ºF (53ºC)
Mean reservoir area = 8 mi^2 (20 km^2)
Mean reservoir thickness = 0.15 mi (0.25 km)
Assessable resource base = 0.48 x 10^{15} Btu (0.51 x 10^{18} J)
Resource = 0.087 x 10^{15} Btu (0.092 x 10^{18} J)
Beneficial heat = 43 MWt for 30 years

Note that the 1978 data greatly reduced the estimated reservoir size and thermal energy. The 1975 and 1978 data did not consider the low-temperature portion of the reservoir (<194ºF - 90ºC); whereas, the 1982 data considers only the low-temperature resource.

Geophysical Investigations

The basin has been assessed by several geophysical surveys (Stark, et al., 1979; and Stark, et al., 1980). These include remote sensing, temperature gradient measurements, gravity surveys, aeromagnetic surveys, roving dipole, electromagnetic and direct current resistivity sounding surveys, and magnetotelluric surveys. These were performed by Lawrence Berkeley Laboratory, University of California to locate potential geothermal resources.

Interpretations of the data from these surveys concluded that:

1. The Klamath graben has been offset along northeast-trending cross faults which are inferred from geologic, remote sensing, gravity, aeromagnetic, and resistivity survey data (Figure 6). These shallow hydrothermal circulation is related to these faults and their intersections with northwest-trending normal faults.

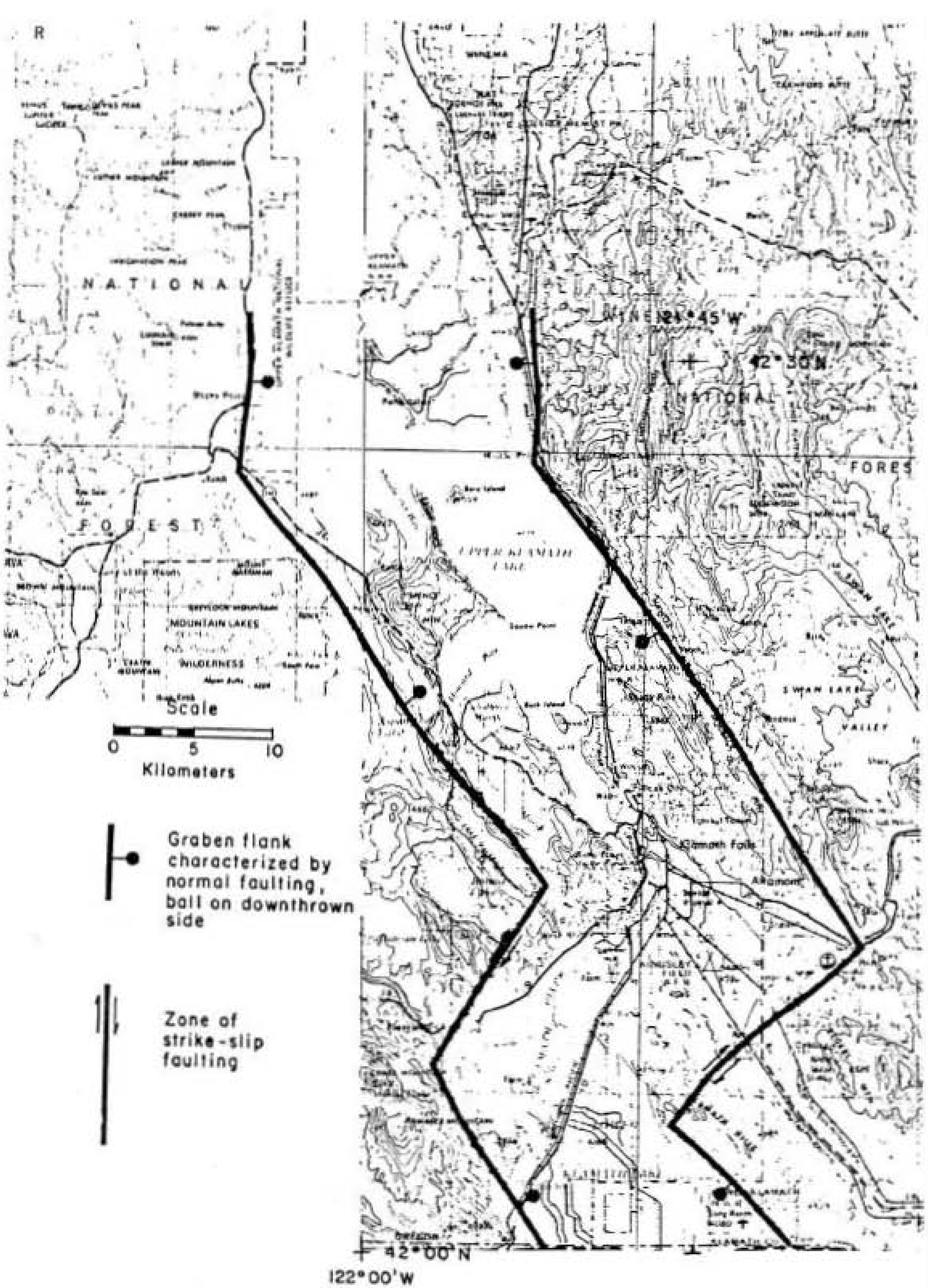


Figure 6. Schematic tectonic map of Klamath graben (Stark, et al., 1980).

2. Geochemical data indicate a reservoir temperature of about 248ºF (120ºC), but inconsistencies and the drilling of a 293ºF (145ºC) hole in Klamath Falls. Sammel (1976) proposes a deep steam reservoir producing these high temperatures. Subsequent analysis calculate the reservoir temperature to be 365ºF (185ºC) (Truesdell, et al., 1984).

3. The Klamath Falls and Olene Gap areas have high specific conductivities.

4. The resistivity data suggest that the entire area west of Upper Klamath Lake is underlain by 20 ohm-m or less conductive formations at depths ranging from 1,200 to 10,000 ft (360 to 3,000 m). Conductive formations have also been found in several other areas.

In summary, they feel that the deeper plumbing system is poorly understood. It is unsure whether the three KGRAs (Klamath Falls, Olene Gap and Klamath Hills) are supplied by the same source, or whether they result from separate circulation patterns along faults. The nature of the heat source is also unknown. It is either caused by discrete igneous heat sources cooling at depth, or by deep circulation along fault zones penetrating a hotter-than-average crust. The latter theory is accepted by other geologists (Sammel, 1984). Deep drilling is proposed to answer the fundamental questions about the nature of the resource.

Analysis of geophysical, hydrologic, lithologic and high altitude infrared photographs were performed at a later date (Prucha, 1987). These data indicated numerous fault traces in the Klamath Basin, conforming to the regional fault pattern, which trends either northwest or northeast (Figure 7). Well testing in Klamath Falls is also supportive of these proposed fault locations, as the geothermal reservoir appear to have a high degree of transmissivity and connectivity between wells, implying a highly fractured and faulted medium. The normal faults, cross-faults and contacts between lithologic layers act as high-permeability conduits, and low permeability strata within the fault blocks provide a large storage volume for the thermal fluids. It is hypothesized that the locations of once-active artesian hot springs generally coincide with the intersection of the strike-slip and normal faults. This suggests that high permeability regions are associated with the intersection of two or more faults throughout the KGRA.

A three-dimensional conceptual model was then proposed for the Klamath Falls geothermal system (Figure 8)(Prucha, 1987). Based on numerical simulations, this model appeared to represent the Klamath Falls geothermal system reasonably well. The model proposed up-flow occurring along the main normal faults and is constrained to the north and south by bounding cross-faults (2 and 9 in Figure 7). The hot waters intersect near surface permeable strata where they begin to flow laterally towards the southwest until they reach the second subsidiary normal fault. At this point, both down-flow and lateral flow occur. The primary zone of discharge from the area is through the western portion of the southeastern boundary and the southern part of the southwestern boundary.

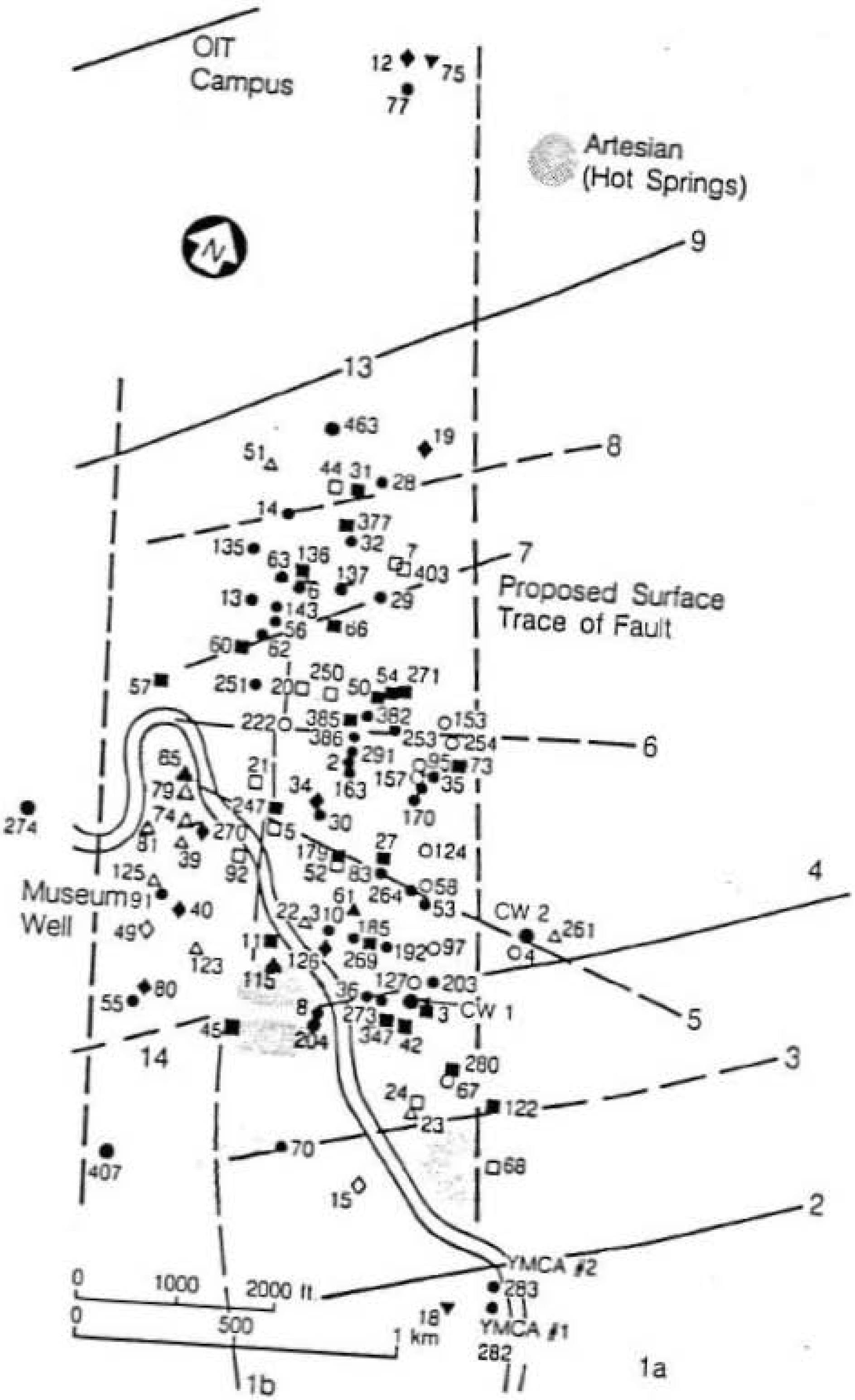


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Figure 7. Fault locations inferred form the cross-sectional temperature profiles and temperature contour plots. Solid lines indicate a higher degree of certainty (Prucha, 1987).

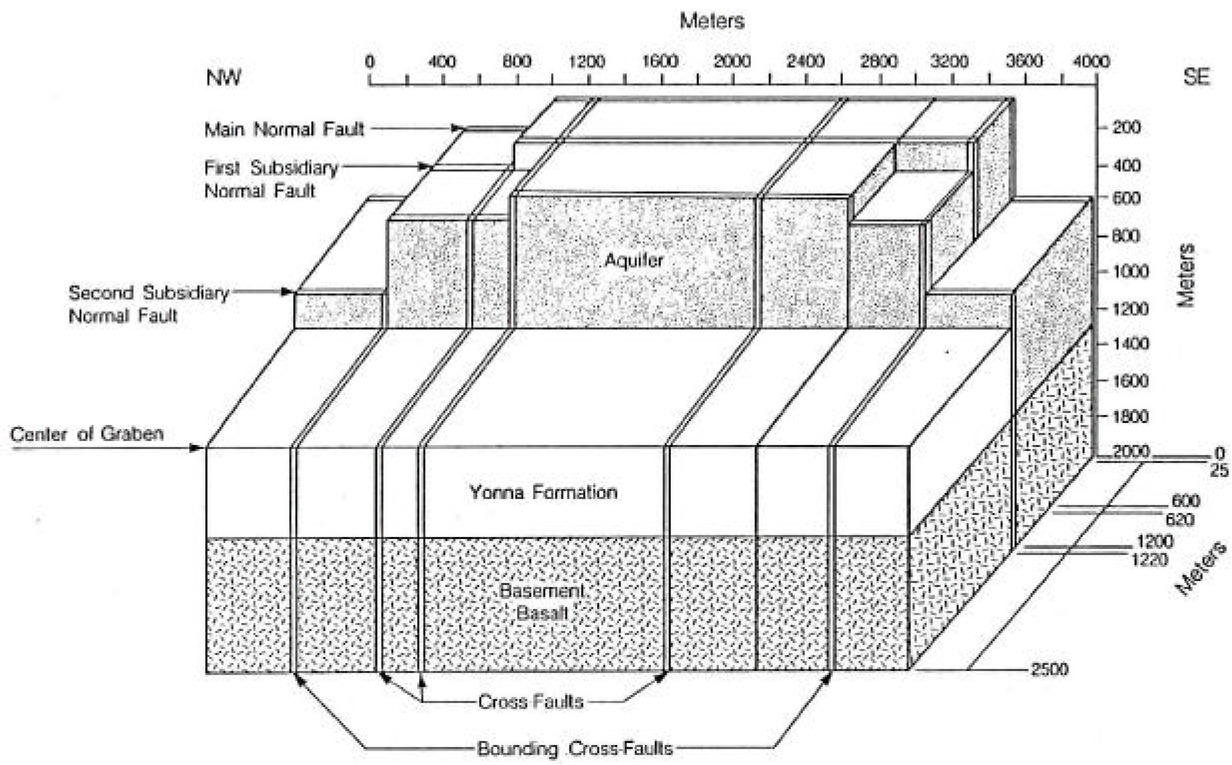


Figure 8. Three-dimensional conceptual model proposed for the Klamath Falls geothermal system (Prucha, 1987).

Regional Heat Flow and Geothermal Gradients

The average heat flow at Klamath Falls is between 2.0 and 2.8 HFU (84 and 117 mW/m^2); whereas, calculation based on the known and estimated discharge of thermal water from the 2 mi^2 area suggest that natural and induced thermal discharge would represent at least 95 HFU (4,000 mW/m^2)(Blackwell, et al., 1977; and Sammel, 1984). This convective heat flow is probably due to local structural, stratigraphic, and hydrologic conditions in the upper few hundred to few thousand feet of rock, rather than from conductive heat flow due to deep crustal conditions over a large area.

Temperature profiles from more than 40 wells in the region indicate that temperature gradients may be extremely high to depths of 600 ft (180 m) or more; but, the profiles in the three OIT wells (1,325 to 1,805 ft - 404 to 550 m) indicate that deeper wells would show temperature reversals or quasiisothermal profiles indicative of hydrothermal convection (Lund, et al., 1974; and Sammel, 1980). It is concluded that temperature profiles from hot-water wells are unreliable indicators of deep conductive heat flow; thus, no conclusions can be drawn from these profiles regarding the heat source and nature of thermal activity at great depth. Based on measurements made at the base of the sediments in Lower Klamath Lake, a lower limit for heat flow in the region is about 1.5 HFU (60 mW/m^2)(Sass and Sammel, 1976).

Temperature of the Geothermal Aquifer

Well water temperatures vary from 70°F (21°C) at the top to over 230°F (110°C) at the bottom. The low surface temperatures are generally caused by cold surface water cooling the surrounding formation. Rock temperatures in drill holes have been measured as high as 250°F (121°C); but, once water enters the hole, the temperature will drop to the 230°F (110°C) range. Average water temperatures in the hot water area vary from 86°F (30°C) to over 208°F (98°C) (Lund, et al., 1978).

The most probable source of the thermal water in the Klamath Falls area is the principal fault zone, from which the water spreads laterally toward the south and west. The maximum temperatures are highest near the fault and decrease toward the southwest. A number of "steamers" are located along the middle of Hillside Avenue (Figure 9). These are sources of natural steam that were encountered during the course of drilling at very shallow depths (approximately 90 ft - 27 m). These are in the 300 to 400 block of Hillside Avenue, and are due to the high temperature gradient in this area 20 to 35°F per 100 ft (370 to 640°C per km) boiling the local groundwater.

The thickness of the aquifer varies from place to place and in many cases, is controlled by fractured flow, as evident by some "poor wells" being drilled immediately adjacent to "good wells." Most wells in the hot-water area are artesian to some degree. The true thickness of rocks that comprises the thermal aquifer is not known, but is at least 2,000 ft (600 m) on the basis of the temperature profile in the 1,805-ft (550-m) OIT well (Sammel, 1980). This temperature profile also suggests that no well in Klamath Falls has penetrated the full thickness of the aquifer.

There is a significant change in well water level between summer and winter, as influenced by weather and use (Figure 10). During the winter months, when heat extraction is greatest, well temperatures will often increase by 5 to 35°F (2 to 20°C) and water levels may drop up to 10 ft (3 m). The water level fluctuations are somewhat erratic, influenced by the great geological variations of the reservoir. By summer, the temperature and water level will return to near that of the previous summer; however, there has been a long-term gradual decline of the water level in many wells.

A study to examine the effect of operating the city of Klamath Falls' district heating production and injection wells, along with the effect of using many of the private wells, was expanded to investigation the hydrology of the aquifer as a whole (Nork, 1985). This study found that the changes in water level of the wells have a high level of correlation with changes in average ambient air temperature, at least on a daily basis. Much of the recharge to the geothermal aquifer appears to come from snow melt, and from two distinct elevations: one where the snow melts in spring, and the other where it melts in early summer. However, the exact source and recharge connections are unknown. The geothermal reservoir is apparently large, containing fluid which is rather slow moving. At least 50% of the long-term declines observed in the geothermal aquifer over the last 15 years seems to be the result of pumping exceeding recharge. The declines in temperature that many wells with downhole heat exchangers have experienced over the past few years, appear to be related mainly to well construction, water level declines, or both. The regional decrease in temperature within the aquifer itself is apparently very small to negligible.

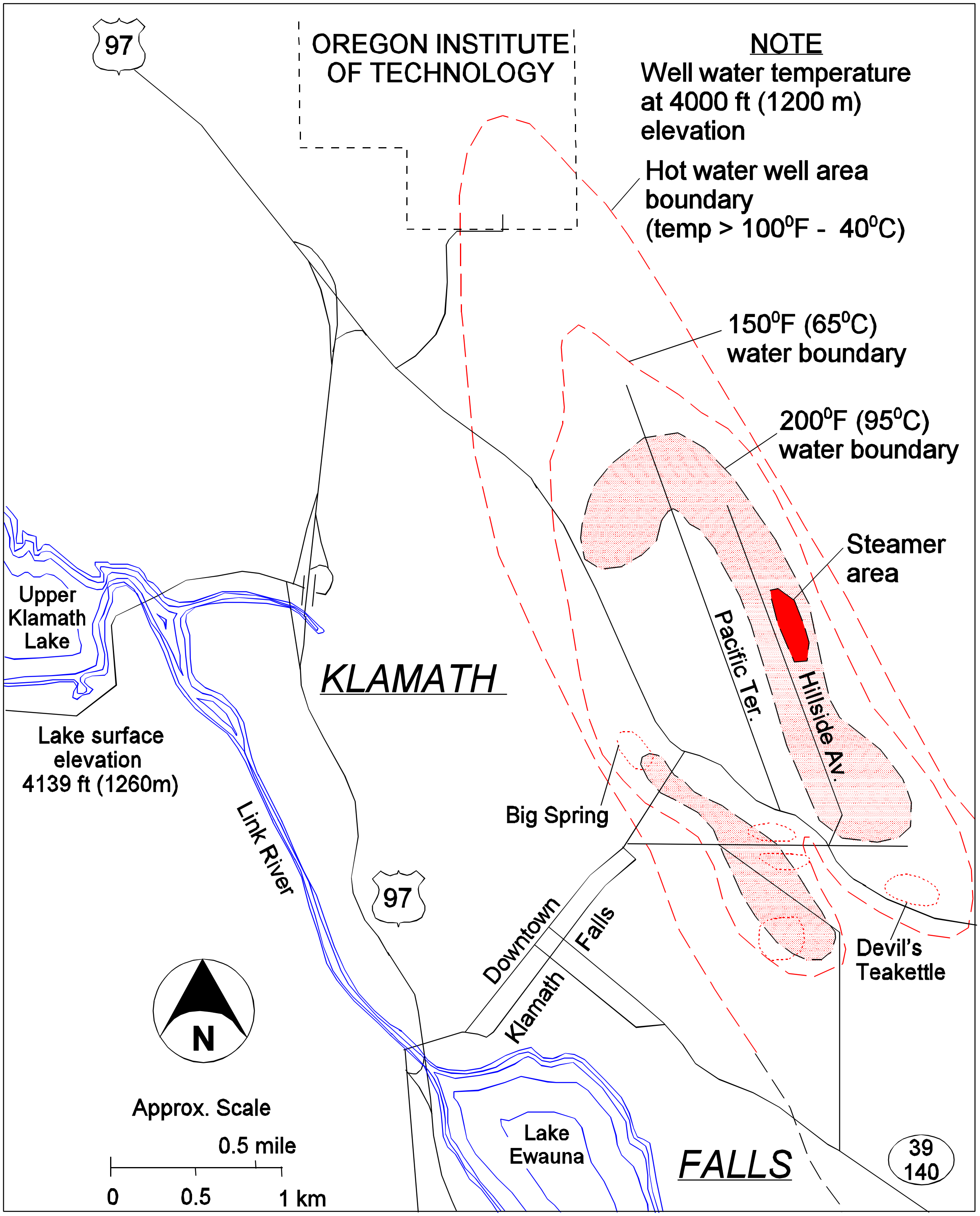


Figure 9. Well water temperature at 4,000 ft elevation.

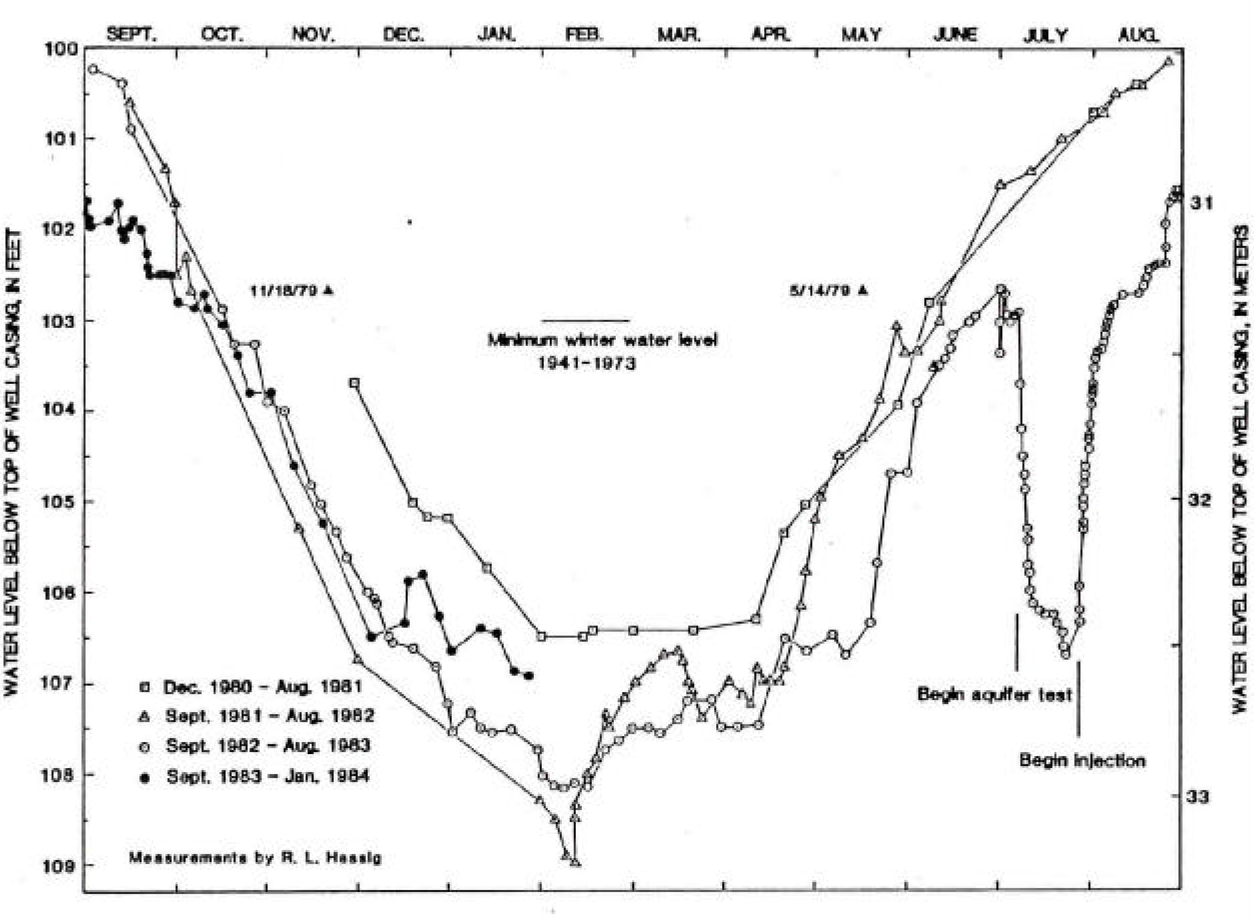


Figure 10. Annual water-level fluctuations in Well 181 (Hessig) for the years 1981-1984.

In almost all cases, the geothermal water is found in confined aquifers; thus, it is artesian and will rise in the well. In the area around Modoc Field and East Main Street, the wells and hot springs were originally surface artesian, with heads of around 20 ft (6 m) reported near the corner of East Main and Holly Street--verified by a photograph taken around 1950. Today these wells are still artesian with heads above the ground surface of from 2 to 5 ft (0.2 to 1.5 m). The artesian surface is now slightly below the ground surface at Modoc Field (Big Springs)(Lund, et al., 1978).

Water Chemistry and Corrosion

The well water is generally characterized by high concentrations of sodium and low concentrations of potassium, having Na/K mass ratio of about 42 (atomic ratio of about 71). The water hardness of these samples is generally low and results principally from calcium ion. The total dissolved solids are approximately 1,000 mg/L. On a mass basis, sulfate is the principal negative ion of these waters (approximately 500 mg/L). The alkalinity values indicate the major contributor to pH is bicarbonate ion and that these waters are highly susceptible to downward pH shift. The silica concentration typically is 70 to 90 mg/L SiO_2/L which exists principally in these waters is bisilicate ion.

Wells which are adequate heat sources for space heating have a cation/anion pattern notably different from those wells which are not adequate heat sources. All of the adequate heat sources, while having notably different sampling temperatures, each share certain chemical compositional patterns. The most noted differences are high concentration of silica, sodium, chloride and potassium, and low concentration of calcium in adequate heat sources as compared to colder water.

Water chemistry of geothermal wells varies as follows (Lund, et al., 1977):

Table 1. Summary of Geothermal Well Water Characteristics

Variable	Units	Average	Standard Deviation	Typical Cold Water Well
Ph		8.08	0.337	7.30
Potassium	mg/l	4.80	1.110	2.00
Calcium	mg/l	21.80	8.480	55.00
Sodium	mg/l	201.00	47.700	10.80
Chloride	mg/l	49.10	7.950	6.80
Conductivity	μ mhos/cm	1210.00	287.000	420.00
Silica	mg/l	91.30	21.400	45.80
Sulfate	mg/l	410.00	73.100	8.30
Water hardness	mg/l	78.50	23.100	194.00
Dissolved oxygen	mg/l	1.88	1.290	6.00
Magnesium	mg/l	0.20	0.340	13.70
Iron	mg/l	3.06	6.120	0.23
Boron	mg/l	0.78	0.100	0.16
Temperature	^oC	72.60	2.470	25.00

The Langelier Saturation Index (Lanelier, 1936; and Sisson, 1973) was determined for wells where chemical analysis was available. This index describes the tendency of natural or conditional water to either deposit calcium carbonate or to dissolve calcium carbonate on the material with which the water is brought in contact (Mashiko, 1970). A positive index indicates the tendency to deposit calcium carbonate, which is related indirectly to scaling. A negative index, indicates no calcium carbonate is present to coat the downhole heat exchanger pipes and well casing; thus, the greater the possibility for other forces to corrode the metals. Based on a study by Culver, et al. (1974), there appears to be good correlation between this index and scaling. Wells having a heat exchanger pipe repair frequency of approximately five years has a low saturation index of 0.02; while, non-artesian water with large positive index values between 0.45 and 0.75 have repair frequencies of 10 to 20 years. Artesian wells, on the other hand, having saturation index values between 0.45 and 0.75 have repair frequencies between 29 and 34 years.

Materials such as mild steel, cast iron, copper, brass and aluminum have poor resistance to corrosion when in contact with the geothermal water. Stainless steel has the highest resistance to corrosion. Hydrogen sulfate, measured at 1.5 mg/l, contributes to these corrosion problems.

Isotopic Compositions

Water from Klamath Falls cold wells and springs is isotopically similar to rainwater, but shows some effects of evaporation before infiltration (Truesdell, et al., 1984). The oxygen-18 and deuterium contents of the cold waters fall on a line parallel to the normal "meteoric water line" (MWL) at an offset of +0.5 permil in oxygen-18 (Figure 11). The thermal waters are significantly lower in deuterium and higher in oxygen-18 than the local cold water. This difference suggests that the recharge to the geothermal aquifer occurs at greater elevation than the recharge to the cold aquifer.

The tritium content of cold water gives values from 0.14 to 0.71 tritium units (TU) which is low, suggesting a residence time greater than 30 years (Truesdell, et al., 1984). The tritium content of the thermal waters range from 0 to 1.6 TU, with most <0.3 TU, indicating greater than 30-year storage in the reservoir. Tritium contents along with other chemical analysis from the 1983 pumping test (detailed later in this report) are shown in Table 2 (Truesdell, et al., 1984).

Relationships between temperature, chloride and tritium contents of the thermal waters indicate mixing. Based on these chemical compositions in the water, it is estimated that the cold water probably does not originate from modern Klamath Lake. Based on silica geothermometer, the fraction of high-temperature water in the reservoir mixture is calculated to be about 44% (assuming the cold and mixed waters contain 45 and 120 mg/l SiO_2 respectively). Using the chloride geothermometer, the fraction of hot water is calculated at 40% (Truesdell, et al., 1984).

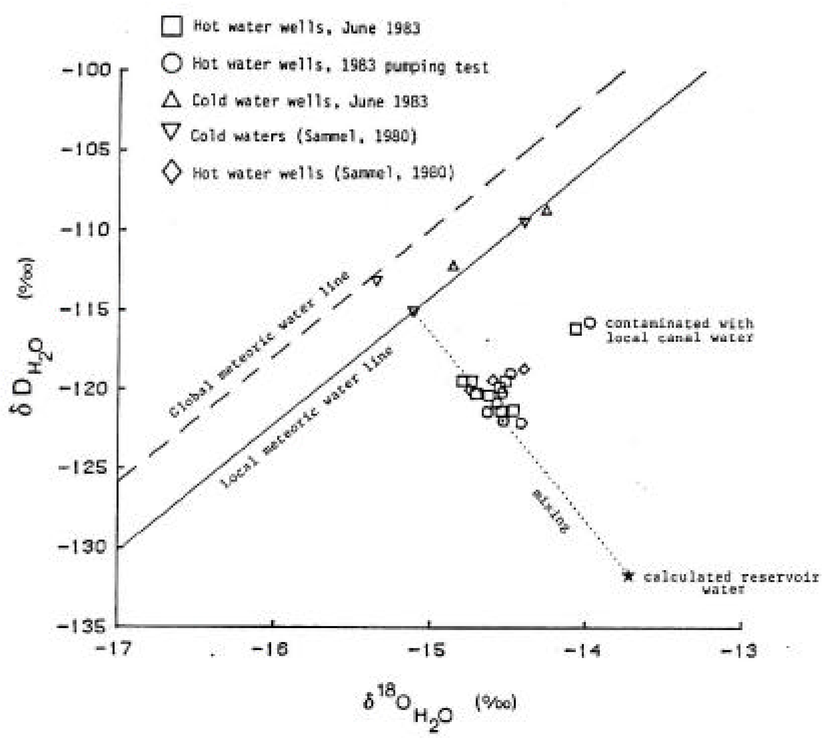


Figure 11. Hydrogen- and oxygen-isotope compositions of thermal and non-thermal waters, and calculated composition of deep reservoir water (Sammel, 1980).

Table 2. Chemical and Isotopic Analyses[1]

Sample	Date	Temperature (°C)	SiO_2	Na	K	Li	Ca	Mg	Al	Cl	F	SO_4	HCO_3	δD	$\delta^{18}O$	Tritium	$\delta^{18}O$ vs. SO_4
Hot water well sampled the month prior to 1983 pumping tests 1/																	
25	6/04/83	78	94.0	206	5.08	—	31.8	0.02	27	51.7	—	398	45.2	-119.4	-14.78	0.27 ± 0.08	-5.34
45	6/09/83	88	98.6	207	5.47	—	34.7	0.05	27	48.7	—	425	46.4	-119.4	-14.30	0.33 ± 0.08	-5.18
45A	6/09/83	80	171.0	220	6.63	—	34.8	0.12	133	49.6	—	431	47.6	-120.2	-14.69	0.06 ± 0.08	-5.37
63	6/14/83	66	83.0	194	4.30	—	29.8	0.05	27	47.7	—	383	50.0	-119.8	-14.56	1.03 ± 0.09	-5.12
76	6/07/83	78	90.7	189	5.08	—	22.6	0.02	27	41.9	—	362	46.4	-119.4	-14.72	0.23 ± 0.08	-5.44
110	6/21/83	91	96.6	213	5.47	—	16.3	0.02	27	52.8	—	423	46.4	-121.3	-14.45	0.52 ± 0.09	-5.43
216	6/29/83	72	123.2	217	5.86	0.31	15.0	0.06	22	51.7	1.2	409	43.3	-121.3	-14.23	0.36 ± 0.09	-5.38
239	6/08/83	56	89.7	205	5.08	—	18.9	0.05	27	51.7	—	—	45.8	-120.3	-14.61	0.21 ± 0.08	-5.35
304	6/08/83	56	80.2	175	3.91	—	16.7	0.02	27	40.1	—	293	86.0	-116.1	-14.05	8.23 ± 0.30	-4.36
Cold water wells 1/																	
500	6/20/83	21[a]	58.0	23.5	2.74	—	10.2	4.27	27	5.7	—	1.2	113	-112.3	-14.86	0.16 ± 0.06	—
501	6/23/83	17	56.1	20.0	3.13	—	15.8	7.75	27	7.2	—	1.8	136	-108.8	-14.28	0.71 ± 0.09[b]	—
Hot water wells sampled during 1983 pumping tests 1/																	
25	8/10/83	82	126.0	216	5.94	0.28	28.2	0.06	25	51.7	1.2	408	43.9	-120.2	-14.36	—	-5.40
45	8/15/83	86	130.7	225	6.32	0.31	28.5	0.09	30	51.1	1.3	428	43.9	-122.0	-14.53	—	-5.08
216	8/16/83	71	109.2	214	5.09	0.30	23.5	0.03	19	53.6	1.1	402	45.1	-119.0	-14.48	—	-5.49
272	7/08/83	95[c]	115.8	230	7.46	0.38	36.8	0.05	30	55.0	1.3	419	41.6	-121.4	-14.63	0.11 ± 0.08	-5.07
272	7/09/83	98[c]	130.1	228	7.17	0.38	36.1	0.03	33	53.6	1.3	441	42.9	-122.1	-14.41	—	-5.82
272	8/24/83	—[c]	120.7	228	7.32	0.36	36.1	0.05	26	53.6	1.6	450	40.3	-120.8	-14.56	—	-5.16
306	8/17/83	47	97.3	177	4.39	0.28	20.5	0.05	50	38.6	1.2	294	90.3	-115.7	-13.96	—	-4.66
Earlier analyses of hot water wells 2/																	
OIT #6	8/26/83 3/31/75	58 79	317 90	195 —	5.9 —	— 0.12	26.2 —	<.1 —	— —	58 —	1.45 —	600 —	66 —	— -118.7	— -14.6	— 1.8 ± 0.3	— -5.45
Assembly of God	8/27/76	87	110	213	4.6	—	28	0.1	—	56	—	393	61	-120.0	-14.73	—	—
Medo-Bel	1/26/55	81	81	213	4.2	—	23	0	—	56	1.2	403	32[d]	-119.6	-14.6	—	-5.45
J. E. Friesen	3/19/53	73	87	221	4.4	—	25	0	—	56	1.6	431	32[e]	—	—	—	—
L. Serruys	11/22/56	71	83	207	3.8	—	22	0	—	58	1.6	393	43[e]	—	—	—	—
Earlier analyses of cold water 2/																	
Well																	
Oregon Water Cure	9/--/71	16	27	22	—	—	16.6	9.8	—	4.3	0.08	1.2	—	-109.4	-14.4	2.6 ± 0.3	—
Cold springs																	
Paul W. Sharo (spg.)	3/06/76	18	43	19	4.0	—	13	9.6	—	2.1	0	10	110[f]	—	—	— —	— —
Shell Rock (spg)	8/09/72 3/06/75	12 7	32 58	5.9 —	1.5 —	— —	8.1 —	3.9 —	— —	<1 —	0.1 —	<2 —	50 —	-113.1 —	-15.25 —	— — — —	— —
Hummingbird Spg.	7/26/72 3/06/75	12 10	21 42	7.0 —	1.2 —	— —	10.9 —	8.2 —	— —	1 —	0.1 —	<2 —	96 —	— —	— —	— — — —	— —
Barkley Spg.	7/26/72 4/02/75	11 11	18 —	8.0 —	1.2 —	— <0.02	9.2 —	6.3 —	— —	1 —	0.1 —	<2 —	86 —	-115.0 —	-15.11 —	— — — —	— —
Neubert Spg.	8/05/72 8/06/75	17 10	24 48	7.6 —	1.3 —	— —	12.1 —	7.2 —	— —	1 —	0.11 —	<2 —	94 —	— —	— —	— — — —	— —

1/ Janik and others (1984), tables 4-2, 4-3. New Ca data from A. White and A. Yee of Lawrence Berkeley Laboratory, Berkeley, Calif.; new Cl data from Analytical Chemistry Branch, U.S. Geological Survey, Menlo Park, Calif.

2/ Sammel (1980), tables 5, 8.

[a] City of Klamath Falls reports a constant temperature of 18°C.
[b] The value of 0.17 TU reported in Janik and others (1984) is a transposition error.
[c] Wellhead temperature reported (Benson and Sollen, 1984) to have remained constant at 100°C for entire pumping test.
[d] CO_3 = 8 [e] CO_3 = 6 [f] CO_3 = 1

(Chemical analyses in mg/kg except for Al, which is µg/kg; isotope analyses in permil relative to VSMOW; tritium in Tritium Units)

The silica mixing calculations indicate an average temperature of 365° +/- 32°F (185 +/- 18°C) for the reservoir based on 1983 silica data; however, the 1983 pumping test data indicated a calculated temperature of 378°F (192°C). Sulfate isotope chemistry calculations at 372°F (189°C) are consistent with these values. A summary of the various geothermometer calculations are shown in Table 3. Using the 365°F (185°C), value and an average of the two mixing fractions (42%), the reservoir water is calculated to have an oxygen-18 value of about -13.7 and a deuterium value near -132 (assuming no oxygen shift for the cold end member).

Based on carbon-14 dating, the age of the hot water is calculated to be between 11,438 and 11,130 ybp (personal communication, C. J. Janik, USGS).

Table 3. Reservoir Temperatures Calculated from Geothermometers, in °C

Sample	Date	Measured T°C	Qtz 1/	Chalced. 2/	SiO_2 Amorph. 2/	Na/K 3/	Na-K-Ca 4/	SiO_2 mixing 5/	SO_4-H_2O 6/ $\delta^{18}O$	X(hot) 7/
Hot water wells sampled the month prior to 1983 pumping tests										
25	6/04/83	78	136	108	16	74	78	175	186	0.38
45	6/09/83	88	137	108	16	78	82	165	189	0.48
45A	6/09/83	80	170	146	47	87	89	271	188	0.25
65	6/14/83	66	127	98	8	68	70	168	187	0.32
76	6/07/83	78	132	103	12	79	81	165	189	0.41
110	6/21/83	91	137	108	16	76	81	162	194	0.51
216	6/29/83	72	149	123	28	79	85	221	191	0.26
259	6/08/83	56	131	103	12	74	76	201	187	0.20
304	6/08/83	56	125	96	6	68	78	180	186	0.23
Hot water wells sampled during 1983 pumping test										
25	8/10/83	82	151	124	29	81	83	206	191	0.34
45	8/15/83	84	148	121	27	84	86	196	186	0.37
216	8/16/83	71	142	115	21	81	86	203	194	0.28
272	7/08/83	95	148	121	26	91	86	182	184	0.47
272	8/09/83	98	153	126	31	89	84	189	198	0.47
272	8/24/83	*	148	121	27	93	86	178	187	0.52
304	8/17/83	47	136	107	16	77	79	256	189	0.12
Earlier analyses of hot water wells										
OIT #6	3/31/75	79	132	103	12	62	71	154	195	0.51
Assembly of God	8-27-76	87	143	115	22	66	74	180	—	0.43
Medo-Bel	1/24/55	81	126	96	7	61	75	148	191	0.48
J.E. Friesen	2/19/55	73	130	101	10	61	76	165	—	0.37
L. Serruys	12/22/54	71	127	98	8	57	73	161	—	0.37

* 100°C assumed for calculations.

1/ Fournier and Potter, 1982. Assumed conductive cooling.

2/ Fournier and Rowe, 1966; Fournier, 1977. Assumed conductive cooling.

3/ White 1970.

4/ Fournier and Truesdell, 1973.

5/ Mixing model based on quartz equilibria and a cold-water component having a SiO_2 concentration of 45 mg/kg and a temperature of 20°C (Truesdell and Fournier, 1977; Fournier and Potter, 1982).

6/ McKenzie and Truesdell, 1977. Assumed conductive cooling.

7/ Fraction of hot end-member water in the SiO_2 mixing model.

HISTORICAL DEVELOPMENT

General

Surface hot springs and mud pots were present before the settlement of Klamath Falls, and had been used by Indians and sheepherders before the turn of the century. Five specific spring areas were known during this time, the most noted ones being the "Big Springs" located in present-day Modoc Field (adjacent to the high school) and "Devil's Tea Kettle" located in the present Ponderosa Field (behind the city school administration buildings)(Figure 9). Other locations were one on either side of Main Street in the vicinity of the present city swimming pool and Klamath Medical Clinic on Main Street, and one between Mills School and the railroad passenger depot. The latter area was a swamp and excellent duck hunting area for many years. Today, these areas are the location of artesian or near-artesian wells. These natural spring areas were used by residents for scalding hogs and poultry and as temporary residence by many transients.

In the 1890s, local sheepherders dug holes in the ground to obtain hot water in areas adjacent to the artesian springs. In 1925, residents started drilling wells using cable drilling methods in the area near the lower end of Pacific Terrace and Hillside Avenue. During the period from 1920 to 1932, plunger pumps were used on the dug and drilled wells due to the lack of knowledge concerning principles of "thermo-syphoning" (the natural convection movement of hot water in heat exchangers). The last plunger pumped well (at Alameda and Esplanade) was abandoned in 1937. The first downhole heat exchanger was placed at 519 Pacific Terrace in 1929. In 1928, Butler's Natatorium was constructed on the location of the present-day high school swimming pool. It had a swimming pool and hot mineral baths. Greenhouses have also been used since the early 1900s, but only to a limited extent (personal communication with Charles Leib)(Fornes, 1981).

The original Big Springs around 1910
(Courtesy of Klamath County Museum).

An outing at the Big Springs (Courtesy of Klamath County Museum).

A residence on Modoc Field. Note the heating pipes.
(Courtesy of Klamath County Museum)

<u>Big Springs</u>

Much of the geothermal history of Klamath Falls centers around Big Springs, the present site of Modoc Field, an athletic field for Klamath Union High School (Lund, 1978). Big Springs was natural hot springs, producing artesian geothermal water at temperatures near the boiling point. Water from a dozen or more steaming springs flowed to the southwest.

The Indians recognized the value of the hot water long before the early settlers made use of it. As reported in the Oregon Sunday Journal, January 8, 1939, Lizzie Schonchin, wife of Peter Schonchin, and Indian survivor of the Modoc War, told of one use of the water. "Long time back, Indian hunt rabbit, porcupine, geese, ducks", she said. "He tie on string, let down in hole. Pull 'em up, skin come off easy. He boil meat, cook fish that way too." The Indians also placed great value on the healing powers of the hot water, by bring their aged and crippled from long distances to be cured of their ailments. They would soak themselves in the cooler overflow pools of Big Springs. After the Natatorium was built on the field (1928), the Indians would still come to soak in the tub baths.

An early account of the hot springs, reported in the Ashland Tidings, August 10, 1876, and printed in the Klamath Echo, a local historical publication, describes a visit to a local ranch having boiling springs (Big Springs or in the nearby Hot Springs Addition to the east). The report stated, "Mr. Brooks has erected a comfortable bathhouse, supplied with water from one of these springs. In order to reduce the temperature within the limits of human endurance, he has erected a large tank, which he fills with water and lets it stand until it cools." "...By drinking and bathing in these waters, great relief and in some instances perfect cures have been effective to those troubled with kidney diseases." "...Use of the teakettle and boilers are entirely disperse with, they draw their boiling water direct from the hydrant. Eggs, and even meat are cooked by placing a vessel containing them, under a flowing hydrant." "...We had congratulated Mr. Brooks on the favorable location of his place when he comes to die; for it is evident that the distance to that other country must be very short, and he would, therefore, be saved a long, and perhaps, tedious journey."

The early settlers followed the traditions of the Indians, using the hot springs for cooking and scalding meat, cooking vegetables, bathing, and just to keep warm. Picnic parties held at the hot springs were a favorite outing for the local residents, where eggs and wieners were boiled in the hot water. The Lioness Club of the city built a dam across a large irrigation ditch near the present high school so that the area could be flooded in the winter and used for ice skating. Benches were placed around the skating area and warmed underneath with hot water piped from a nearby spring. In the summer, these pools were used for swimming.

Butler's Natatorium

The open ditch and ponds served its purpose; but, bigger and better things were due Klamath Falls. Several bathhouses were constructed either on or adjacent to the field, and in 1928, Mrs. R. M. Butler built the modern Klamath Mineral Hot Springs Natatorium at the Big Springs, known locally as Butler's Natatorium. Her both swimming and bathing were available, where 10,000 gallons (38,000 liters) of geothermal water were used daily during the summer months, as the water in the swimming pool was changed daily. Natural steam baths and mineral water tub baths were also available.

In 1905, the hot spring water was analyzed... "to show its fitness for use by a camp of the U.S. Geological Survey." In a letter from Mr. C. H. Stone, Assistant Analyst of the Reclamation Service in Berkeley, California, to Mr. T. H. Humpherys, Engineer for the USGS, Klamath Falls, he stated, "I see nothing in this water to render questionable its use as a drinking supply. The sulphates are rather high, but are mostly present in the form of sodium sulphate, which would not render the water hard. The silica in a way is an interesting feature, as we do not, as a rule, find this element present in any great amount, except in exceptional cases. The total solids are quite within the limits of safety, and in fact, considering the analysis as a whole, I should say the supply is very safe and good one for domestic use." Mr. Stone's analysis has proven out, as even today there are residents in Klamath Falls who still use the cooled geothermal water for drinking. The high silica content is typical of geothermal water and is related to temperature.

It appears that an attempt was made to use the water for medicinal purposes in 1911. A letter from Mr. H. V. Tartar, Acting Chemist of the Department of Chemistry, Experimental Station, Corvallis, Oregon, to Mr. White of Klamath Falls stated, "...from the examination of the sample of mineral water sent to us, we have no reason to believe that the solids contained therein are in a more healthful combination than in ordinary waters." Based on analysis today, as was found in 1911, the total dissolved solids vary from 800 to 1,000 parts per million (mg/l), the majority of which are sulfates, and sodium.

White Pelican Hotel

During that same year, 1911, a new and "grand" structure was completed in Klamath Falls about a quarter of a mile southwest of the Big Springs. This was the four-story brick White Pelican Hotel at the corner of Main and Esplanade. Mr. Harry Drew, a recent curator of the Klamath County Museum, reported in an April 17, 1977, newspaper article, "The White Pelican was to be one of the most pretentious enterprises in this part of the country and one of the finest hostelries on the Pacific Coast. The opening ceremonies came in the grandest fashion, with much "to-do", and the hotel was formerly christened on December 2, 1911." He also stated, "With the opening of the White Pelican, the hotel soon became the center of the city's entertainment. Private parties were given in the spacious dining room and extravagant dinner dances were also held there during the winter."

Big Springs contributed an important function to the hotel, in that it provided the heat for the building, and water for a tile-lined swimming pool in the basement. Natural hot spring water from the north end of the present Modoc Field was piped into a storage tank and then through an underground concrete tile and wood pipe placed in a rock-lined trench to the hotel, a distance of about 2,000 ft (300 m). The storage tank was located under the presently covered bleachers at the field. Little is know of the actual heating system of the hotel; probably cast iron radiators, but evidently the geothermal water was adequate for heating.

During the early morning hours of October 16, 1926, a fire started in the hotel, and by evening all that was left was a pile of rubble and one standing wall.

Balsiger Motor Company

In 1927, the property was sold for new construction and by 1930, Balsiger Motor Company was in operation. It has changed hands several times in the last few years, and is presently occupied by Cell-Tech. During this time, over 66,000 ft^2 (6,100 m^2) of building was heated by the same geothermal waters, running through the same pipeline that was constructed for the White Pelican Hotel. The water is still used directly in heat exchangers and for domestic tap water. Remains of

Bathhouse Near Big Springs (Courtesy of Klamath County Museum)

White Pelican Hotel (Courtesy of Klamath County Museum)

Balsiger Motor Company (today)-- Site of the White Pelican Hotel

the original tile-lined pool can be seen in the basement. The original artesian spring flow had to be replaced with a drilled well about 1944, due to a drop in the water level. In 1973, the well was deepened to 260 ft (80 m), producing 160°F (71°C) water. It is estimated that the temperature drops 4°F (2°C) in the pipeline and that 30 gallons per minute (2 l/s) are used to heat the building. The pump, located at a depth of 40 - 50 ft, is shut down in the summer months.

The geothermal water was also used to wash cars and for some cleaning of automotive parts. An estimated savings of $1,200 to $1,500 per month is realized in space heating by using geothermal energy. Due to the high ceilings in the show room and maintenance shop, the temperature will drop to 68°F (20°C) in extremely cold weather. The original heating system at Balsiger's had a crude oil-fired boiler to boost the water temperature; however, this system has not been used for many years. Maintenance has been very little for the entire system. None of the radiators have been replaced since 1930; however, part of the pipeline in the alley was replaced about 25 years ago. The impeller of the constant rate pump at the well site was replaced about 20 years ago, and several of the circulation pumps in the building have been replaced. Presently, the owners of the building own 75% of the water rights to Big Springs.

Klamath Union High School

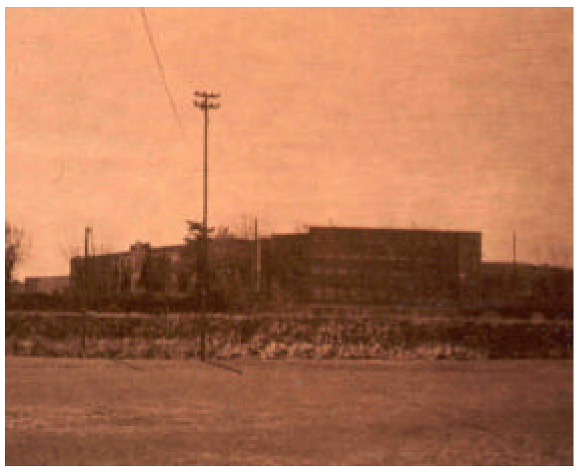
At the same time Balsiger was being constructed, around 1928-29, construction was also started on Klamath Union High School. The site was located on the ruins of one of Klamath County's three controversial courthouses, to the west of Big Springs, and across Modoc Field from Butler's Natatorium. The original field house for the high school was located near the presently covered bleachers, with the tap water heated by water from the springs. In the early 1930s, Pelican Court, the present basketball court, was constructed and a well was drilled north of the Natatorium to heat the building. A 6-inch (150-m) cast iron line, bolted together every 8 ft (2.5 m), was run about 1,000 ft (300 m) from the artesian well to the building. The system was initially tied into Balsiger's well so that flow from one system could be reversed to the other. A weir near the center of the field provided an overflow to the storm sewer.

In the early 1940s, the well, and evidently the building enclosing Butler's Natatorium, was purchased by the school district. The Butler well, the first well drilled on the field, was used until the later 1940s when it was abandoned due to sanding problems.

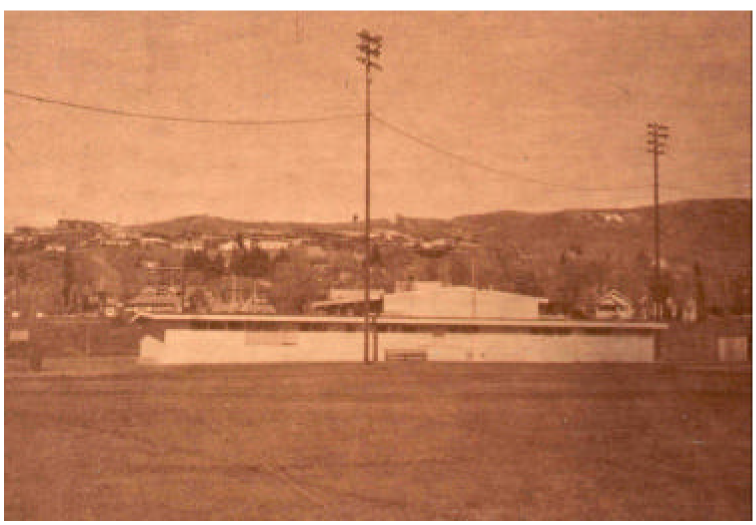
A new locker room and building were constructed to replace the Natatorium. This building, still in use by the high school, encloses the original Butler well and swimming pool.

In 1964, a third well was drilled between the Butler well and the original high school well to the north. This well, 257 ft (78 m) deep, is used as a injection well for water from the original high school well. At the present time, 350 to 400 gallons per minute (22 to 25 l/s) are pumped from the first well at about 165°F (74°C), transported the 1,000 ft (300 m) in a 6-inch (150 mm) pipeline to the heat exchanger room at the high school, where it flows through ten shell-and-tube heat exchangers, and then flows back to the injection well. Downhole heat exchangers in the injection well are used to heat the swimming pool water, the floors, and the walks of the bathhouse with 140°F (60°C) water. A 15°F (8°C) temperature drop occurs across the shell-and-tube heat exchangers at

Mike Balsiger sitting on one of the original cast iron radiators.



Klamath Union High School



**Present high school swimming pool--site of Butler's Natatorium
Hot Springs addition in background.**

the high school producing about 2.8 million Btu/hr (2.9×10^6 kJ/hr) during peak heating, or about 6.5×10^6 Btu/yr (6.8×10^6 kJ/yr). Both space heating and domestic hot water heating are provided; the space heating being supplied by central forced air and radiators. The average annual maintenance and operational costs are about $200 per year per well. Carbonate deposits will build up in the heat exchanger; however, this has not been a serious problem. Only one major repair has been necessary in approximately 50 years of operation, the replacement of 300 ft (90 m) of heat exchanger pipe in the injection well in 1972. As a preventative maintenance measure, 3 to 5 pounds (2 to 3 kg) of paraffin are placed in the well each year to prevent corrosion at the air-water interface.

The water level in the supply well has dropped to 10 ft (3 m) below the casing top over the years. Some feel that the pumping the area has reduced the artesian pressure; however, the injection well should compensate for the high school production well--the two are located approximately 500 ft (150 m) apart. In the 1939 newspaper article, it was reported, "Some have ventured the opinion that the digging of wells for heating purposes has reduced the pressure so that it is now insufficient to force water to the surface. Those who lived in the city before that development took place, however, maintain that the springs started to dry up long before boring wells were even though of." It should be noted that three wells, two production and one injection are located in Modoc Field, and at least six more are located adjacent to the field, principally to the south. The injection well for the city district heating system is located about one block south of the field.

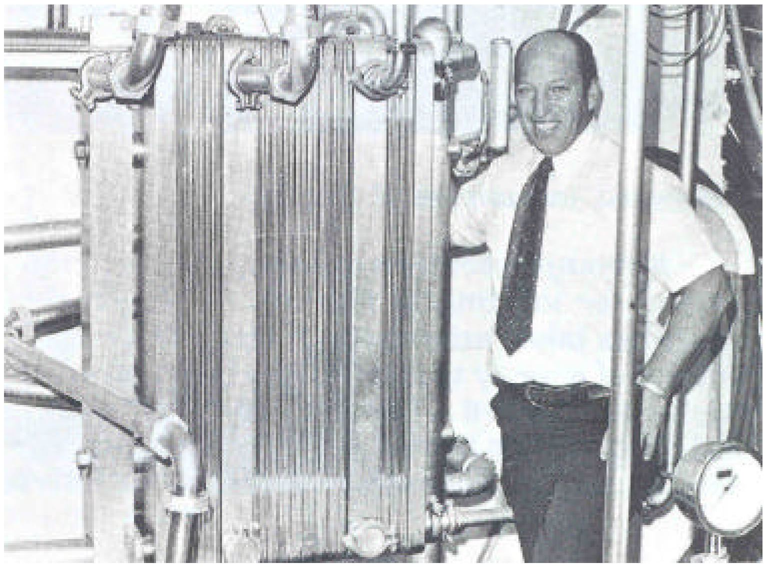
Medo-Bel Creamery

Another well, adjacent to the Big Springs, was used by Medo-Bel Creamery (formerly the Lost River Dairy) to pasteurize milk (Lund, 1976c). This was the only known use of geothermal water for a creamery in the world. The water also supplied heat to the 30,000 ft^2 (2,800 m^2) building, providing a substantial savings during the winter months.

A 765-ft (233-m) deep well was drilled in 1945 and cased to 358 ft (109 m) with 8-inch (200-mm) diameter casing, and to 489 ft (149 m) with 6-inch (150 mm) diameter casing. The original well had an artesian flow of around 30 gal/min (1.9 l/s) at the surface of 180ºF (82ºC) water. Based on a profile in 1974, the well water varied from 177ºF (80ºC) at the surface to 208ºF (98ºC) at a depth of 450 ft (137 m), with the artesian surface at 4 ft (1.2 m) below the ground surface. The geothermal hot water was pumped directly from the well to the building approximately 50 ft (15 m) away through an overhead line. The overhead line allowed easy maintenance and prevented freezing during cold weather since it was self draining.

Rather than using downhole heat exchangers as is common in Klamath Falls, the water was used directly in air handling units in each room and in the plate-type pasteurizing heat exchanger. The used hot water was then emptied into the storm sewer where it was later used by industry in the south end of town.

The pasteurization process involved pumping up to 50 gal/min (3.2 l/s) into the building and through a short time pasteurizer (Cherry Burrell plate heat exchanger of stainless steel construction). The geothermal water was pumped from the well at 189ºF (87ºC) and passed through the heat exchanger where the milk was heated to a minimum temperature of 171ºF (77ºC) for 15 seconds and then quickly chilled to 38ºF (3ºC) to retain its flavor. If the milk was not heated to 171ºF (77ºC) or for 15 seconds, it was recirculated until the required exposure was obtained. As an added bonus, the outgoing heated milk was cooled somewhat by passing it by the incoming cold milk and the cold milk in turn heated slightly by the outgoing milk. Milk was processed at a rate of 600 gal/hr (0.63 l/s), and a total of 500,000 pounds (230,000 kg) were processed each month.



Owner, Elmer Belcastro, standing next to the plate heat exchanger (pasteurizer).

Medo-Bel Creamery with well house and supply line in the left background.

Some steam was necessary in the process to operate equipment; thus, geothermal water was heated by natural gas to obtain the required temperature. Geothermal hot water was also used for other types of cleaning.

In addition to the milk pasteurizing, some batch pasteurizing of ice cream mix was carried out by geothermal heat. A 250-gallon (0.95-m) storage tank was used to mix geothermal hot water and process steam to a temperature of about 250°F (121°C). This heat was then used to pasteurize the ice cream mix at 145°F (63°C) for 30 minutes.

The annual operation cost of the system was negligible; however, the savings amounted to approximately $1,000 per month as compared to conventional energy costs. The creamery went out of business in the early 1980s.

<u>Highway Pavement De-Icing</u>

A major truck route, leading from the Klamath Falls urban area, has a steep grade approaching a traffic light heated by geothermal hot water (Lund, 1976a). This route, the urban portion of U.S. 97 on Esplanade Street, was reconstructed in 1948, in order to widen the bridge across the U.S. Bureau of Reclamation's "A" canal. Since the approach and stop at the intersection with Alameda Avenue caused difficulty with traffic stopped on the eight percent adverse grade, geothermal de-icing was incorporated in the design as an experiment. It was estimated that the pavement would be sufficiently clear of snow and ice to provide free travel at a temperature of -10°F (-23°C), and under conditions of a 3 inch (75 mm) per hour snow fall.

A 419-ft (128-m) deep well was drilled at the bottom of the hill, near the original natural artesian hot water "Big Springs." The well was drilled 14 inches (355 mm) in diameter and cased to a depth of 307 ft (94 m) with 12-inch (305-mm) ID casing. Several years later, the static water surface dropped to 18 in. (0.5 m) below the ground level (personal communication with Charles Leib).

A downhole heat exchanger was placed in the well consisting of two 2-inch (50-mm) diameter wrought iron pipes in parallel for the input line connected to a single 2-inch (50-mm) diameter pipe for the output line. A 1-hp centrifugal pump is used to circulate the heat exchanger fluid. The heat exchanger extends to a depth of 315 ft (96 m) with the upper portion of the outflow leg is insulated by a 3-inch (75-mm) diameter, closed pipe to prevent cooling near the surface. A 3/4-inch (20-mm) line was also placed in the well to allow the well water to be pumped. A separate pump (added several years later discharges approximately 10 gallons/minute (0.6 l/s) to the storm sewer for increased heat flow. When drilled the maximum well temperature was 190°F (88°C) at the bottom decreasing to 150°F (66°C) at 250 ft (76 m) depth. The surface temperature has dropped from 143°F (62°C) to 98°F (37°C) over the years as the well appears to be cooling for unexplained reasons.

The heat exchanger in the well is connected to a distribution line (header) placed parallel to the roadway on the north side, decreasing from 2-1/2 to 2 to 1-1/4 inch (64 to 50 to 32 mm) in diameter. At 30 ft (9 m) intervals a grid system is connected to the header at valve boxes supplying the heat

Esplanade pavement melting system after a heavy snowfall. The well is located in the white building to the left of the photograph.

Sidewalk in front of Roosevelt Grade School. Two wells are used to heat the building and melt snow at the bus loading area.

Residential driveways using geothermal water for snow melting. Note that the location of the coils can be determined from the melting pattern.

to the Portland Cement concrete pavement. Each grid system consists of ten loops of 3/4-inch (20-mm) diameter wrought iron pipe placed 3 inches (75 mm) below the pavement surface on 18 inch (0.5 mm) center-to-center spacing (Figure 12).

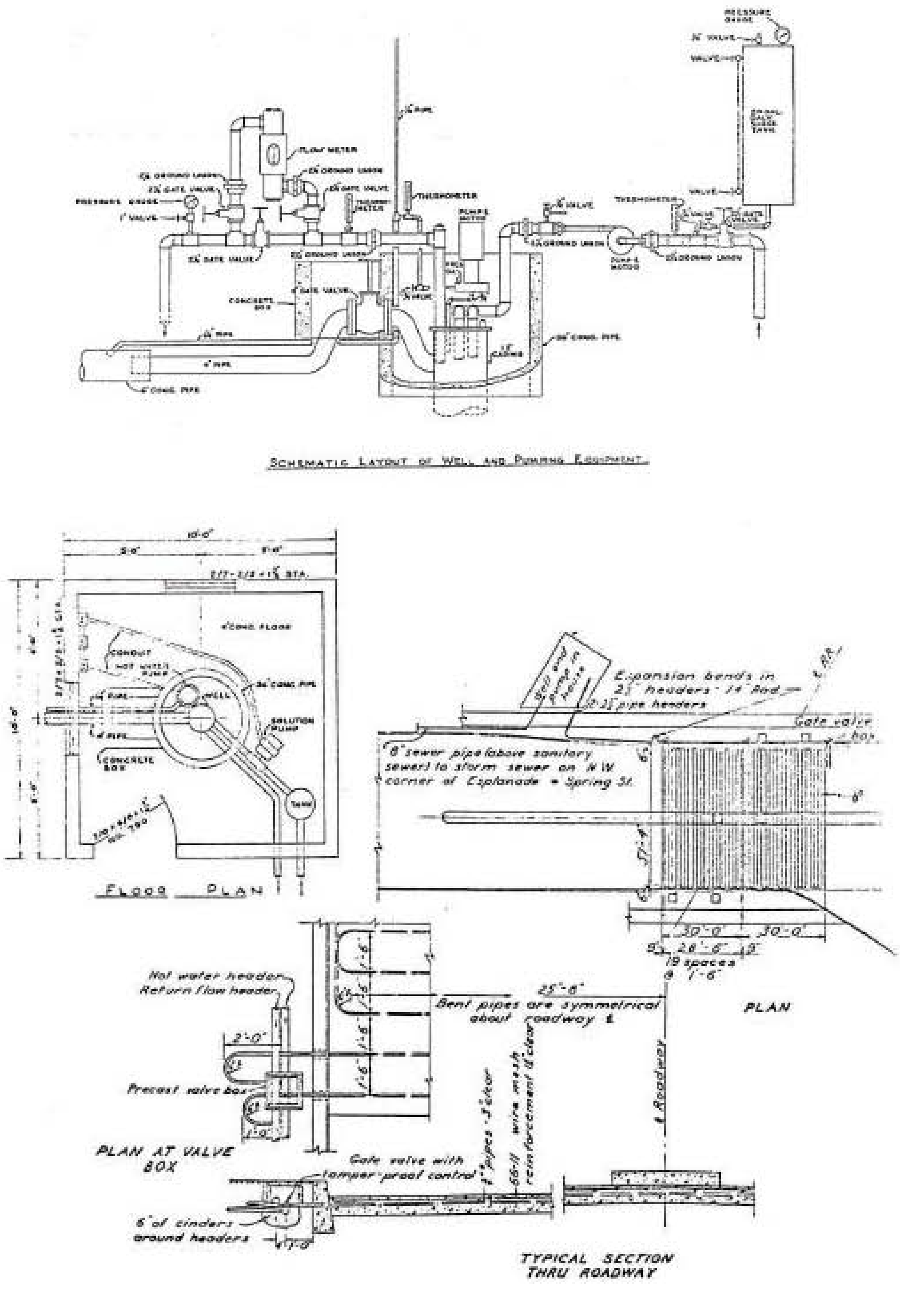


Figure 12. Highway snow melting system (Alameda Avenue).

Unlike the typical closed-loop heating system in Klamath Falls, the system uses a 50-50 mixture of antifreeze and water as the circulating fluid. This mixture is "good" to -50°F (-45°C) and thus, will not freeze and break the pipes if the pump motor stops. Leakage is replaced by antifreeze/water from a 20-gallon (75-l) surge tank kept 2/3 full in the pump/well house. Once or twice a year, the entire system is checked and replacement antifreeze/water added through an air vent in the upper end of the system on the bridge deck. Approximately 50 gallons (190 l) per year are needed for replacement. The temperature drop in the grids is approximately 30 to 35°F (17 to 19°C), with the range varying between 100 to 130°F (38 to 54°C) and 70 to 105°F (21 to 40°C). This is estimated to supply 0.35 x 10^6 Btu/hr (0.37 kJ/hr) to the grid. Based on this calculation, the heat flow can melt up to 1/2 inch (12 mm) per hour snowfall, with heavier snow falls taking four to six hours to melt entirely. This has been substantiated by observations.

The heated pavement section is only 51 ft (15 m) wide by 420 ft (128 m) long; however, almost three miles (5 km) of 3/4-inch (20-mm) grid pipe are under the pavement. Similar snow melting systems are in place under sidewalks in front of Roosevelt Grade School and several residences in the community (Lund, 1976b). The original cost of these systems was around \$1.00/ft^2 (\$10.00/m^2) which would be 50 to 100% higher at today's prices.

Klamath Ice and Storage Company

This company has seven cold storage warehouses kept at below freezing temperature (Lund, et al., 1978). To prevent the soil under the floor slabs from freezing and frost heaving, a closed-loop system of heating coils is placed approximately 3 ft (1 m) below the floor slab under cork insulation and some soil. The system consists of 2-inch (50-mm) diameter pipes placed 4 ft (1.2 m) apart and filled with oil. The oil is heated through a 125-ft (38-m) downhole heat exchanger in a 6-inch (150-mm) diameter cased hot water well approximately 1,100 ft (335 m) deep under artesian conditions. Over 1.19 x 10^6 Btu/hr (1.25 x 10^6 kJ/hr) is utilized in this unique system. Prior to the installation of this system, the soil under the floors was freezing, heaving, and causing the wall to bow outward. This heating system has solved the problem. Geothermal hot water is also used to remove block ice from containers by heating the outside to break the adhesion of the ice. The buildings are located about 2,000 ft (600 m) south of "Big Springs."

RESERVOIR TESTING

Introduction

Except for information obtained by local well drillers and plumbers, who considered it proprietary, there was very little known about the Klamath Falls geothermal resource prior to 1974. In about 1960, Oregon Water Resources Department set up a net of about 15 wells in which static water level was sporadically recorded. This was discontinued in 1963 due to lack of funds. Also in 1963, Culver and Garrison started taking static levels and temperature profiles on a monthly basis on 14 wells. This effort was instituted because the new geothermally heated campus was planned and there was some fear in the community that pumping for the campus would adversely affect other wells. This was continued through 1963 as background data, and through 1964 and 1965 the first two years of campus operation. Although small seasonal variations were noted, campus operation did not appear to affect other wells and the work was discontinued. No attempt was made to understand or delineate the resource. The variations noted probably were due to DHE use which was difficult to determine.

During the summer of 1974, Lund, Svanevik and Culver under took the first scientific study of the Klamath Falls KGRA under contract with the Atomic Energy Commission. This work included delineation of the then known resource area, estimated geothermal heat use, temperature profiles and water analysis of 45 wells, description of the heating systems utilized and the economics of utilization. Based on temperature profiles, water levels and well depths, a series of contour maps were developed depicting well bottoms, water levels and temperatures a various elevations above sea level.

It was estimated that approximately 400 wells were in use heating about 500 structures. About 350 wells had downhole heat exchangers installed--the rest are pumped. Well depths for residences varied from 90 to 900 ft (27 to 274 m) with most between 200 and 300 ft (61 to 91 m). Commercial establishments and schools, requiring more heat, increased well depths to over 1,800 ft (549 m) with 1,000 to 1,300 ft (305 to 396 m) common. Water levels varied from artesian to 350 ft (107 m) with 50 to 100 ft (15 to 30 m) most common.

Due to limitations of both time and funding, it was impossible to study in detail several areas of interest noted during the course of the work. Specifically such things as: a better understanding of the geology and hydrology of the area, reported water level fluctuations depending on season and use, apparent large variations in permeability as indicated by the location of good wells within 100 ft (30 m) or so of inadequate wells, and the apparent convecting cell in wells with open annulus and perforations as indicated by temperatures of shallow levels being higher than reported at that depth during drilling. Some of these questions have been answered, others only partially.

Historical Aquifer Testing

Also in 1974, the USGS and OIT performed the first known geothermal aquifer test. OIT Well #5 was pumped at approximately 500 gpm (2 m^3/min) and OIT #6, 500 ft (152 m) away and the Presbyterian Hospital well, 800 ft (244 m) away were monitored. Response to pumping was almost immediate; although, drawdowns were small, 3 ft (0.9 m) in OIT #6 and 1 ft (0.3 m) in the hospital well. Sammel calculated a transmissivity of 22,000 ft^2/day at the prevailing temperature of 192ºF (89ºC)(Sammel, 1980).

In August 1976, the Geo-Heat Center conducted a 28-hour test of the museum well. The well is drilled to 1,234 ft and penetrates layers of shale, clay, tuff and basalt. The driller's log indicates that many of the basalt layers are fractured. The well is cased to 450 ft (137 m) with 10-3/4-inch (27.3-cm) casing. Well completion and temperature are shown in Figure 13. At completion, the well had a shut-in pressure of 2 psig and produced 188 gal/min (11.9 l/s) of 188ºF (86.7ºC) water.

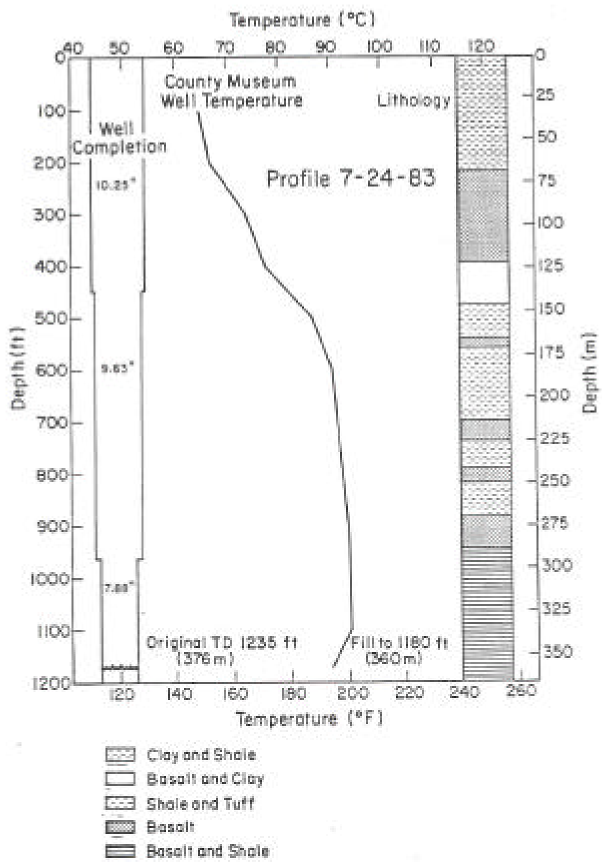


Figure 13. Well completion, temperature profile, and lithology for the County Museum well.

Twelve nearby wells were monitored during the test. Those wells for which data could be analyzed were less than 500 ft (152 m) deep and had temperatures ranging from 133 to 185ºF (56 to 85ºC). Sammel calculated transmissivity of 20,000 ft^2/day at prevailing temperature. The test results indicated hydraulic continuity between all the wells and greater hydraulic conductivity parallel to the regional structure. Figure 14 shows drawdown contours due to pumping at 970 gpm (61.2 l/s). A spinner survey conducted during injection into the well in 1983 indicated approximately 50% of the water injected entered formations at 470 to 520 ft (143 to 158 m) and the remainder at 1,020 to 1,100 ft (311 to 335 m). The well probably produces from the same formations.

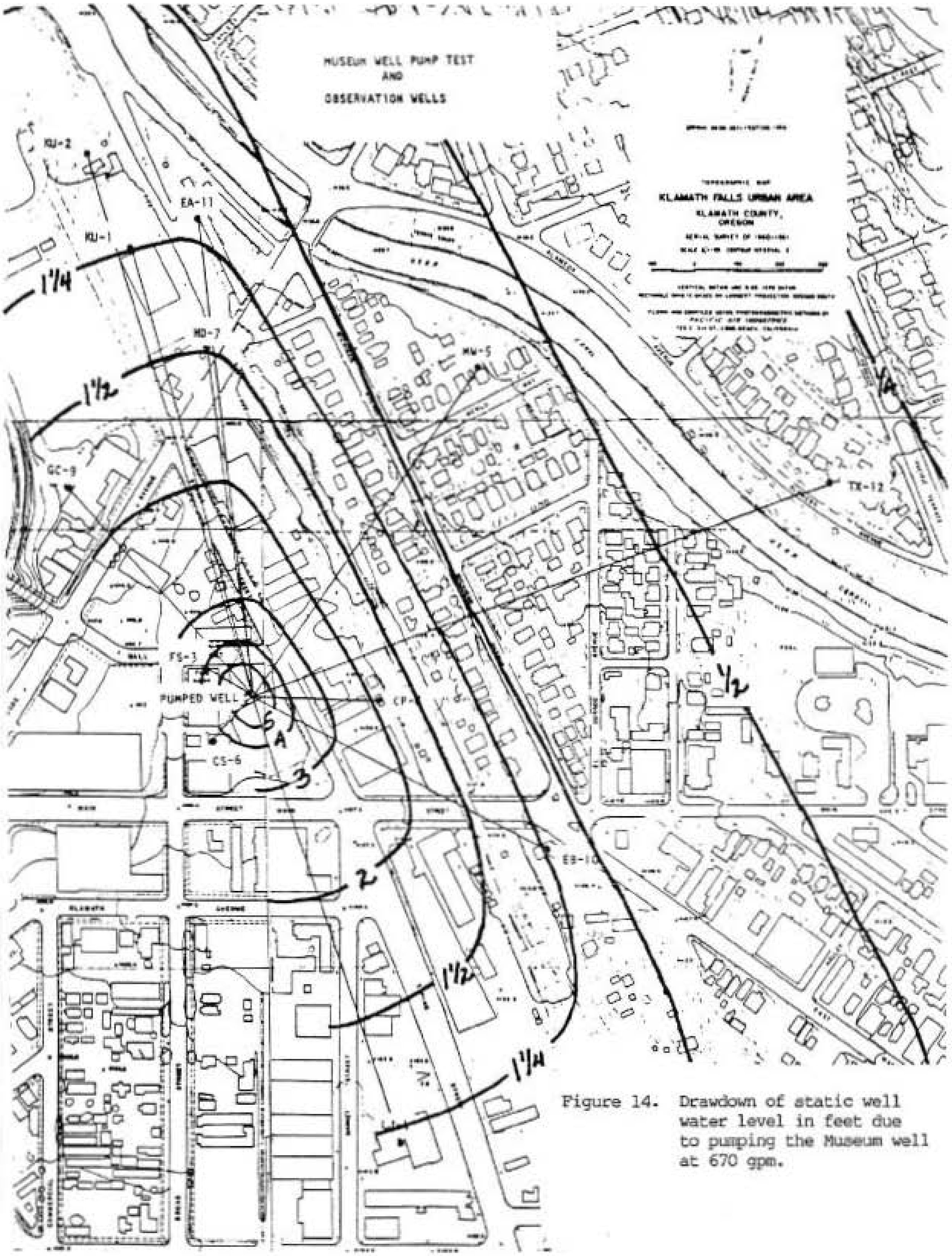


Figure 14. Drawdown of static well water level in feet due to pumping the Museum well at 670 gpm.

Test of the City Heating System Wells

The City system wells have been tested on several occasions by Lawrence Berkeley Laboratory (LBL) personnel. LBL uses conventional units designed for single-phase, liquid dominated geothermal aquifers. Transmissivity is defined in units of millidary x feet/centipoise [md (ft/cp)] and storativity in units of ft/psi. Using these units, aquifer properties are independent of viscosity.

Note: At some point in time, city production well numbers have been interchanged. This is apparently because of production use. The second well drilled is now designated CW-1 since it is the primary producer.

City Well #2 was completed in November 1979, to a depth of 367 ft (112 m). Construction and lithology are shown in Figure 15. CW-2 was pump tested in August 1979 for 15 1/2 hours. During the test, a maximum pumping rate of 680 gpm (42.9 l/s) was held constant for 7 1/2 hours. Maximum drawdown was 77 ft (23.5 m) and temperature varied from 217 - 219°F (102 - 204°C).

CONSTRUCTION*:

Depth: 367 feet
Drilling Method: Rotary
Casing: 12-inch; 0 to 300 feet
Perforations: None

Annular Seal: 0 to 300 feet
Driller: Carl Enloe
Completion: November 6, 1979
Static Water Level at Completion: -76 feet

* From driller's log

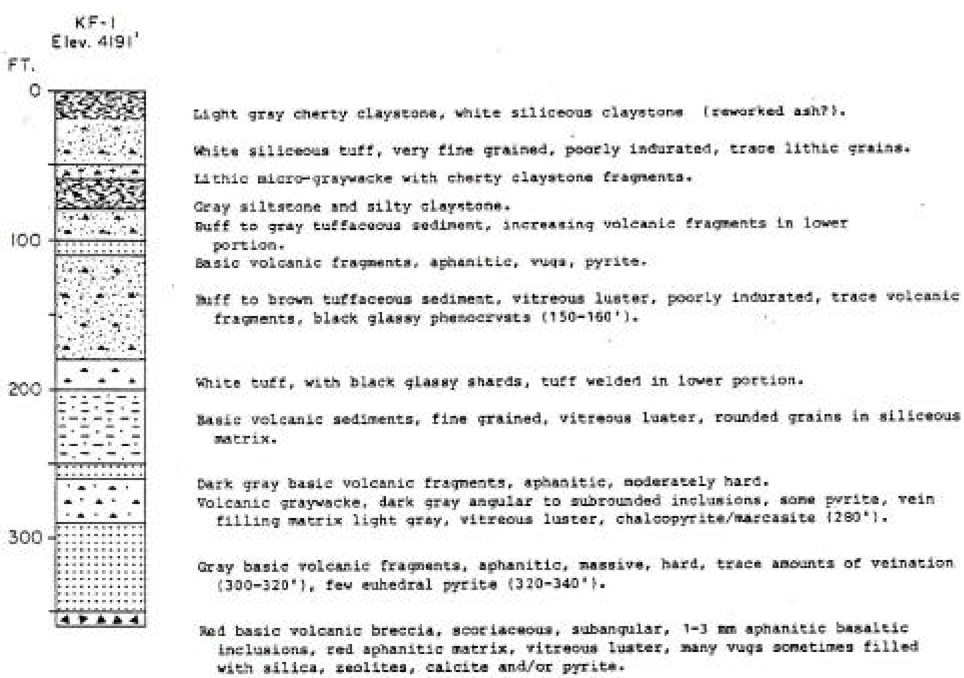


Figure 15. Construction and lithology--City of Klamath Falls Well #1 (O'Brien and Benson, 1980).

Interference was monitored in three nearby wells. Rapid water level declines were noted in all the monitor wells. The nearest, 150 ft (45.7 m) away, responded in less than 10 seconds and after 7 1/2 hours of pumping at 680 gpm had a drawdown of 1.2 ft (0.37 m). Transmissivity ranged from 1.4 x 10^7 to 1.5 x 10^7 md (ft/cp), storativity ranged from 2.4 x 10^{-3} to 7.8 x 10^{-3} ft/psi and a permeability of 100 darcies was noted. Late drawdown data suggested a hydraulic boundary was encountered. LBL concluded the test offered promising potential for reservoir sustainability; but, a longer term test was needed to predict long-term effects (Benson, et al., 1979).

City Well #1 was completed to a total depth of 900 ft (247 m) in January of 1980. Lithology and temperature are shown in Figure 16. At the time, the temperature profile was obtained, the well was solidly cased to 360 ft (110 m). Notice that the maximum temperature occurs at a depth of approximately 240 ft (73.1 m). Below this depth, the temperature decreases. From a depth of 250 ft (76.1 m) to the bottom of the well, the temperature remained constant (O'Brien and Benson, 1981). The reversal of temperature gradient below 240 ft (73.1 m) is indicative of lateral hot-water flow in the aquifer (Bodvarsson, et al., 1982; Benson, et al., 1982; Blackwell, et al., 1982).

This author believes that if the temperature profile is accurate, drilling another 25 to 30 ft (7.6 to 9.1 m) probably would have encountered another flow of water at approximately the same temperature. That flow, if present, may be somewhat poorly connected to the shallower flow and would have lesser effect on nearby wells.

CW-1 was first pump tested in January 1980. The well produced 190ºF (88ºC) water at a maximum rate of 60 gpm (3.8 l/s) with a drawdown of 170 ft (51.8 m). The low temperature of the water and the very low productivity made the well unsuitable for its intended use. Consequently, the well was perforated from 195 to 240 ft (59.4 to 73.1 m). Shortly thereafter, the well was again pump tested. A maximum rate of 900 gpm (56.8 l/s) of 214ºF (101ºC) water was obtained with a reported drawdown of 50 ft (15 m). The significant increase in the well productivity indicates nearly all the water enters in the perforated zone.

Two additional pump tests have been conducted on CW-1. During a 2-hr test, it was pumped at 780 gpm (49.2 l.s) with a drawdown of 8 ft (2.4 m) and wellhead temperature of 209ºF (98.3ºC). During a 4-1/2-day test, it was pumped at 540 gpm (34.1 l/s) with drawdown of 4.5 ft (1.4 m) and wellhead temperature of 208ºF (97.8ºC).

1981 Test - Production From
CW-1 & CW-2 with Injection to Museum Well

On September 29, 1981, LBL conducted a 16-hr pump test of City Wells #1 and #2, and the Museum well. The test was designed to check the district heating system for flaws and to determine reservoir response to withdrawal and injection. Nine monitor wells were used: four in the production area and five in the injection area.

During this test, the production wells were pumped at several different rates for varying amounts of time. Each of the monitor wells in the production area behaved differently both before and after the test period. Analysis of a short segment of data from the Parks Steamer Well (while CW-1 was

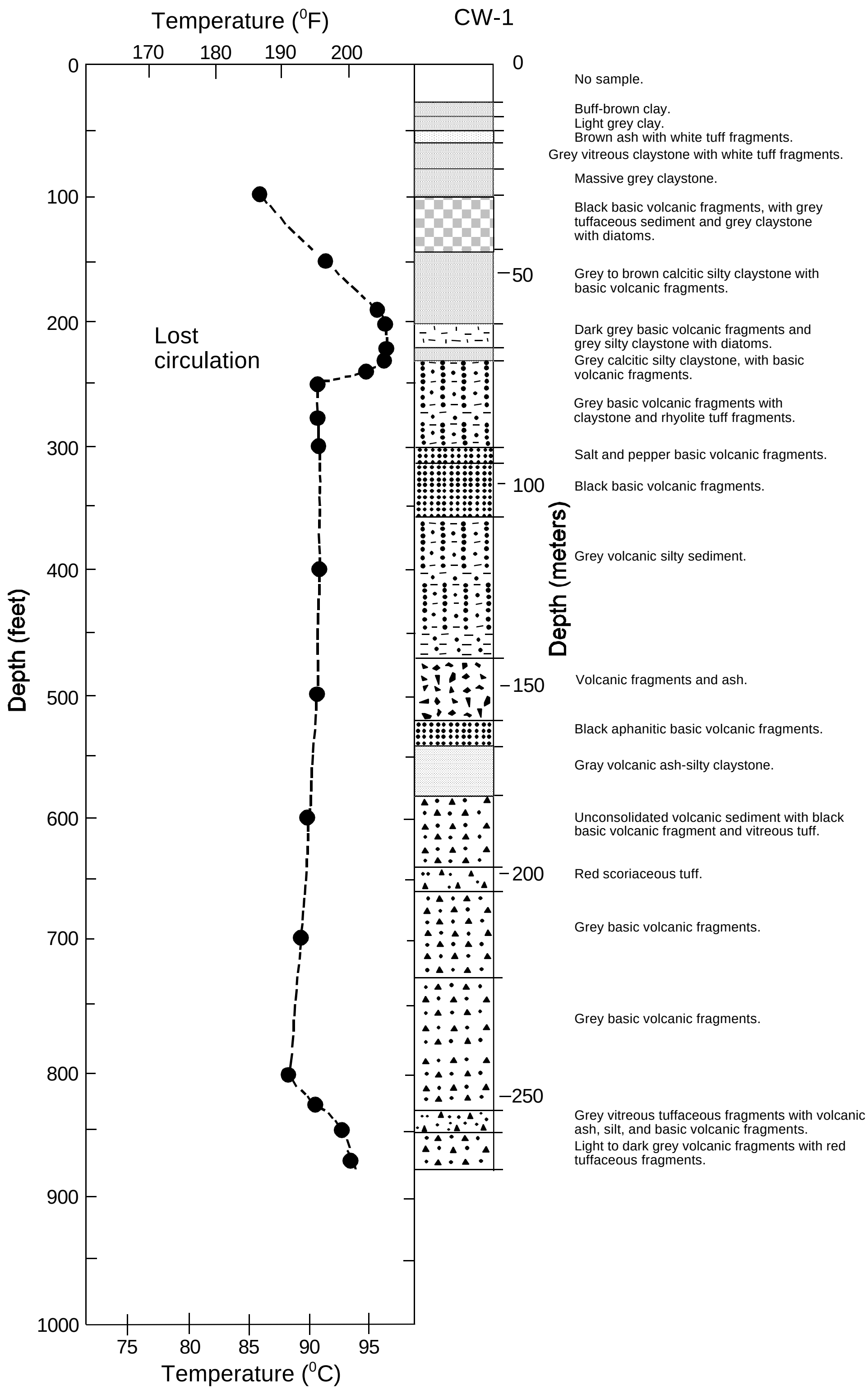


Figure 16. Temperature profile and lithology of Klamath Falls City Well #2 (Benson, 1980).

pumped) suggested a transmissivity of 3.4×10^7 md (ft/cp). Due to fluctuations in pumping rate, it was difficult to determine reservoir properties with accuracy.

A total of 5.4×10^5 gal (2.44 m^3) of 205°F (96°C) were injected into the Museum well. Data analysis in the injecting area indicated transmissivity in the range between 1×10^6 and 10×10^6 md (ft/cp). These results were in reasonable agreement with the 1976 drawdown test of the Museum well. Most wells in the injection area produce water cooler than that injected, but thermal breakthrough was not detected. Two of the five monitor wells showed an increase in head due to injection. At the time it was unknown which strata in the injection well were accepting fluid.

Because the test was short, neither the degree of hydraulic communication between the production and injection areas, nor the effects of withdrawal and injection on nearby wells were accurately assessed (Benson, 1981).

Tracer Testing

Two tracer tests were conducted as part of the 1983 testing. There were several objectives of these tests. First, of course, was to learn more about the Klamath Falls aquifer. However, since tracer testing was, and still is, in early stages of development and understanding, other objectives were to test tracers and tracer theory. The Stanford personnel, involved in the test, were soon to be involved in another tracer test and this was to be a test run of some of the equipment and tracers.

Tracers selected were rhodamine WT, fluorescein, and potassium iodide. The fluorescent dyes can be detected down to about 1 part per billion--the iodide to about 1 part per million.

The first test was on the Klamath Union High School doublet system. There are four doublet systems in Klamath Falls. The KUHS system was chosen because more was known about the flow rates and operational history, and because it was located closer to the proposed City system production/injection test area.

The KUHS system was started in the early 1960s. The production well is 257 ft (78.3 m) deep and perforated for 25 ft (7.6 m) near the bottom. The production well is 240 ft (73.1 m) deep and cased to 120 ft (36.6 m). The wells are spaced 250 ft (76.1 m) apart. The system is turned on in the fall and pumps a constant 320 gpm (20.2 l/s) until it is shut off in the spring. About 15 gpm (0.95 l/s) is diverted to heat a machine shed and residence, the rest goes to the school 600 ft (183 m) away, through heat exchangers and back to the injection well.

At the start of the heating season, the temperature of the produced water is 164°F (74°C); but, it cools by 5°F (2.8°C) in 3 to 10 days depending on the heat load. Once this initial cooling has occurred, the water temperature remains constant until spring. The following fall, the temperature is back up to 165°F (74°C) at start up. During the heating season geothermal water enters the heat exchangers at about 160°F (71°C) and leaves typically at about 152°F (67°C).

The KUHS doublet tracer test was carried out in May and June of 1983. The tracers were injected at the wellhead of the injection well. The wellhead piping is such that the tracers were mixed immediately with the down-flowing water. One pound (450 g) each of rhodamine WT and fluorescein were mixed in 100 gallons (0.4 m^3) of geothermal water. The rhodamine WT was in the form of liquid 20 percent active, so the 1-pound solution contained 90 g of the red-pink dye. Fluorescein comes in dry powder form and is greenish when dissolved in water. All of the fluorescein was considered active. Five hundred pounds (227 kg) of potassium iodide was mixed in 150 gallons (0.6 m^3) of geothermal water; it is easily soluble and colorless. The dyes were injected first, requiring about 15 minutes for the injection. The potassium iodide was injected about an hour later, the injection taking about 20 minutes.

An automatic sampling apparatus was set up at the KUHS production well and programmed to fill one bottle every half hour. Five other wells were sampled by hand during the tracer test: Balsiger, 260 (79.2 m) deep; Medo-Bel, 765 ft (233 m) deep; Eccles, 787 ft (240 m) deep; Friesen, 563 ft (172 m) deep; and Garrison, 240 ft (73.1 m) deep (Figure 17). Samples were collected from these wells every hour at first and then less frequently. The flow rate and temperature of the Medo-Bel well were measured at 75 gal/min (4.73 l/s) and 180ºF (82ºC). The flow rate of the other wells had to be guessed: Balsiger, 30 gal/min (1.9 l/s); Eccles and Friesen, 20 gal/min (1.26 l/s) each; and Garrison, 10 gal/min (0.63 l/s). Other wells in the area were not pumped at the time of the testing.

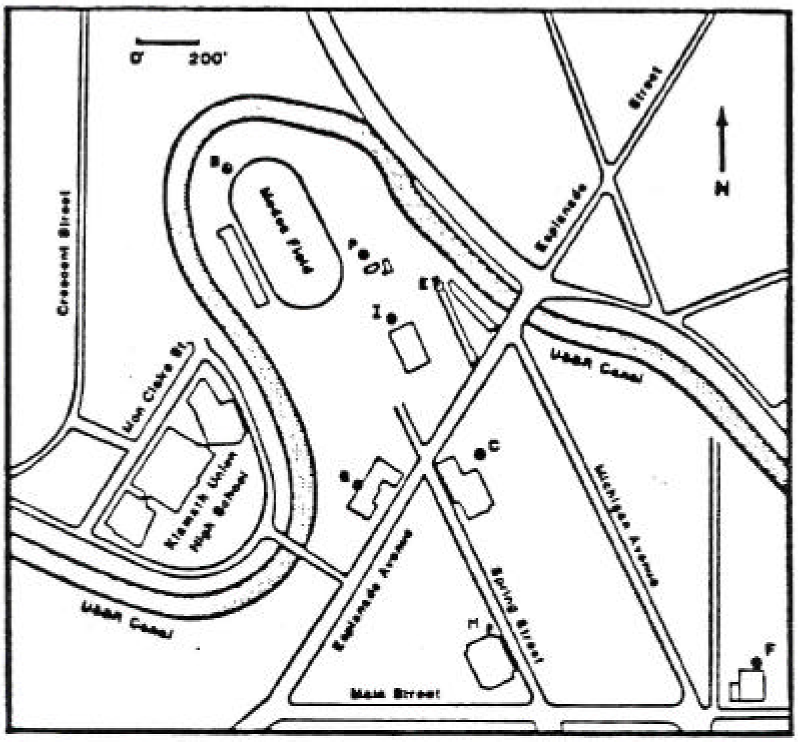


Figure 17. Location of wells for the Klamath Union High School tracer test. P, production well; I, injection well; B, Balsiger well; C, Medo-Bel well; E, Eccles well; G, Garrison well; F, Friesen well; M, County Museum well.

The concentration of the dyes was measured in a fluorometer. It was discovered during the test that injecting the dyes at the same time was a mistake. Although recommended lamps and filters were used in the fluorometer, there was considerable interference between the two dyes. A reading on the fluorometer could not be assigned to one dye only, so the values obtained were semi-quantitative. Also, a mixture of the two dyes showed less color and fluorescence than expected. The data analysis will be based on the more accurate iodide measurement.

Breakthrough Curves

Tracer breakthrough was observed in the KUHS doublet production well 2 to 3 hours after the 20-minute tracer slug injection. The concentration of potassium iodide with time in the production well is shown in Figure 18. The maximum tracer concentration was reached in 5 to 6 hours after the end of the tracer injection.

After that, the concentration fell rapidly at first and then more slowly. The dye tracers showed the same breakthrough behavior as the potassium iodide.

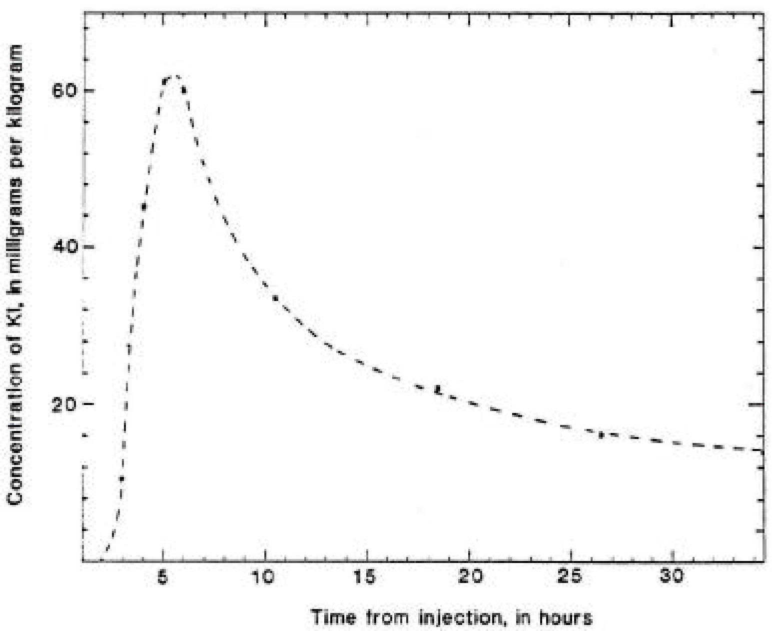


Figure 18. Breakthrough curve in production well, KUHS doublet test.

The 227 kg of potassium iodide were injected in 20 minutes. For a doublet flow rate of 305 gal/min (19.2 l/s), this corresponds to the tracer slug having a concentration of about 9,820 mg/kg. The maximum tracer concentration measured in the production well was about 60 mg/kg, or two orders of magnitude lower.

Fluid re-circulation must be considered in the doublet tracer test. The high school is about 600 ft (183 m) away from the doublet system. The hot water is pumped to the school in a 6-inch (152 mm) pipeline and then passed through 13 shell-and-tube heat exchangers which are connected in a mixed series/parallel arrangement. The geothermal water is cooled in the heat exchangers and returned to the injection well. The travel time of the geothermal water from the production well to the injection well depends on the flow rate, and the volume of the piping and heat exchangers. It takes about 3 minutes for water pumped at 305 gal/min (19.2 l/s) to travel 600 ft (183 m) in a pipeline 6 inches (152 mm) in diameter. Assuming that each of the 13 heat exchangers has the same volume as the 600 ft (183 m) of pipe, it will take 45 minutes for the geothermal water to travel between the wellheads at the surface.

For a tracer breakthrough time of 2 hours and 30 minutes, and assuming a surface travel time of 45 minutes, a second breakthrough would be expected at about 5 hours and 45 minutes, passing through a maximum between 10 and 13 hours. However, since the initial tracer pulse was diluted by two orders of magnitude, the second tracer pulse is unlikely to show much effect on the shape of the tracer concentration curve.

The flow pattern in the KUHS doublet system is affected by the other pumped wells in the area. The largest of these is the Medo-Bel well, flowing 75 gal/min (4.7 l/s). It is about 450 ft (137 m) away from the injection well, in the opposite direction to the production well. The total flow rate of the other 4 wells in the area added up to about 80 gal/min (5.1 l/s). The nearby pumping is, therefore, about one-half that of the KUHS production well. The hydraulic gradient of the hot well is superimposed on the pumping gradient associated with the wells sampled in the tracer study. The gradient is about 0.5 percent and perpendicular to a line between the injection and production wells. The KUHS doublet system is not an isolated system in the aquifer.

The tracer breakthrough curve for potassium iodide in the Med-Bel well is shown in Figure 19. The breakthrough occurred 26 to 27 hours after injection was completed in the doublet injection well. The tracer concentration reached a maximum value less than 1.5 mg/kg, which is an order of magnitude less than the maximum value in the doublet system. This occurred after 180 to 200 hours. After that, the tracer concentration decreased slowly, but steadily. Tracer returns were not detected in the other wells monitored in the area.

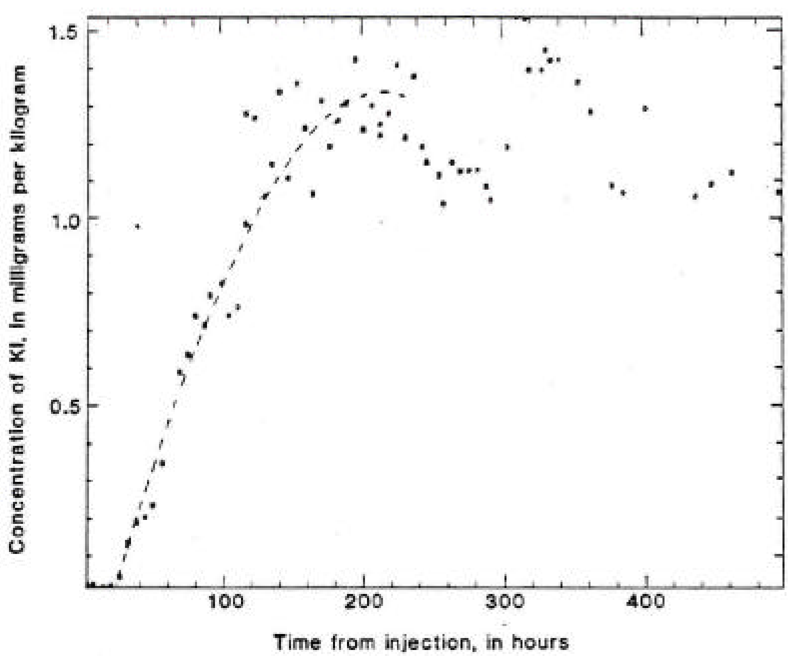


Figure 19. Breakthrough curve in Medo-Bel well, KUHS doublet test.

Interpretation

The peak tracer concentration in inter-well tracer testing moves through the reservoir at the average fluid velocity. Using 5 to 6 hours as the time of peak concentration in the KUHS production well, the calculated average flow velocity between the doublet wells is 43 to 49 ft/hr (13 to 15 m/hr). The same kind of calculation for the Medo-Bel well gives a tracer velocity of 2.3 to 2.6 ft/h (0.7 to 0.8 m/hr). These values are within the range of tracer velocities measured in geothermal fields worldwide (Horne, 1984).

The arrival time of the peak concentration can also be used to estimate the porosity-thickness value. Taking t_r and t_x as the peak arrival times for radial and doublet systems, respectively, the porosity-thickness becomes:

$$(p\ \phi h)_r = 2 \text{ cm},$$

$$(p\ \phi h)_x = 6 \text{ cm}.$$

If fracture flow is assumed, the above values represent the fracture width.

The amount of tracer recovered in production wells indicates the connectivity to injection wells. Production wells that receive more tracer than others are more likely to suffer thermal drawdown when cold fluids are being injected. The amount of tracer recovered can be determined by measuring the area under the breakthrough curve. For the KUHS production well, the amount recovered after 4 to 5, 8 to 9, and 100 to 110 hours was 15, 25, and 122 kg, respectively. These correspond to 7, 11, and 54 percent of the total amount of potassium iodide injected. Because of recirculation, the tracer recovery after the first 10 to 13 hours becomes difficult to interpret. Nevertheless, the breakthrough curve does show that 10 to 20% of the total tracer material injected was recovered in the first day of the test. This suggest that the doublet is not an isolated system in the geothermal aquifer.

Because tracer material is lost from the doublet recirculation system, the tracer concentration does not reach equilibrium concentration with time. The swept reservoir volume, therefore, cannot be determined.

The shape of the tracer breakthrough curve can give information about the nature of the flow between the injection and production wells. The interpretation method is based on having a reservoir flow model. Such models are now being developed for geothermal reservoirs (Fossum and Horne, 1982; Jensen and Horne, 1983).

Injection Tracer Testing

Test Description

The doublet tracer test was carried out a few months ahead of the main aquifer pumping-injection test. Among the reasons for carrying out the doublet test was the need to develop tracer testing techniques appropriate to geothermal resources, particularly those of low-to-moderate temperature. This goal was reached with respect to tracer selection and measurement techniques. Rhodamine WT was found to be environmentally acceptable, easily measured, and low in cost. Therefore, this dye was selected for use in the injection tracer test. Potassium iodide was also found to be environmentally acceptable; but, the higher concentrations required and greater cost rule it out in situations where fluorescent dyes can be used.

In the main aquifer pumping-injection test, the production well (CW-1) was pumped for 3 weeks without injection. The pumped water was then injected into the County Museum well for about a month. This well is about 3,000 ft (.91 km) away from the production well and down the hydraulic gradient. The natural hydraulic gradient between the two wells is about 0.5 percent and the total head difference is about 15 ft. During the aquifer pumping-injection test, the gradient was expected to be reversed so that flow would occur from the site of the injection well in the direction of the production well.

In a doublet system, there are no wells between the production and injection wells. This is not the case for the production and injection wells used in the aquifer pumping-injection test. The area between CW-1 and the County Museum well is heavily exploited. In this situation, the flow path can be traced by sampling the wells between the production and injection well. Most of the wells have downhole heat exchangers; but, there are a few that are pumped at low flow rates or have artesian flow. The flowing wells identified for water sampling for tracer analysis were: Friesen (Main Street, laundry), Olympic (E. Main Street, apartments), Butler (Esplanade Street, residence), Division and Oak Streets (residence), and Medical Clinic (Main Street).

The aquifer pumping test was started on July 5, 1983. The production well was pumped at 720 gal/min (45.4 l/s) and the 212°F (100°C) water discharged into the USBR irrigation canal that runs across the geothermal field. After 3 weeks of pumping, the injection part of the test was started. On July 26 at 10:11 a.m., the geothermal water flow was diverted into the County Museum injection well. The aquifer production-injection test was terminated 4 weeks later on August 24 at 5:35 p.m. The injection flow rate was 40 to 42 kg/s during the 4-week period.

The rhodamine WT tracer was injected into the County Museum well on July 27 from 10:14 a.m. to 10:19 a.m. The method of injection was the same as used in the doublet-tracer test. Two 25-pound drums of rhodamine WT solution was dissolved in 33 gallons (0.12 m^3) of water. The dye solution was 20 percent active so that each pound contained 90 g of rhodamine WT. Therefore, the total mass of rhodamine WT was 4.55 kg and its concentration in the 5-minute injection slug was about 360 mg/kg.

An automatic sampling apparatus was installed at the production well. The five flowing wells listed above were sampled by hand. Samples were collected every 1 to 2 hours and analyzed for rhodamine WT the same or following day.

After a few days of injection, the Med-Bel well began to flow. This happened sometime between July 29 and August 1, when it was first sampled for tracer analysis. With time, other wells were

added for water sampling: Fire Station, August 1; Spires and Mest (garage), September 9; and Jones (garage), September 23. One or two samples were taken from a few other wells.

Breakthrough Curves

The rhodamine WT tracer was detected in several wells during the injection tracer test. Of the wells that were sampled from the start of the injection test, only the Friesen well showed tracer breakthrough. This occurred after about 16 days of injection. The Friesen breakthrough curve is shown in Figure 20 in terms of μg/kg of rhodamine WT tracer. The Friesen well is located about 1,000 ft (305 m) northeast of the injection well. It is pumped at about 20 gal/min (1.3 l/s) with a water temperature of 172ºF (78ºC).

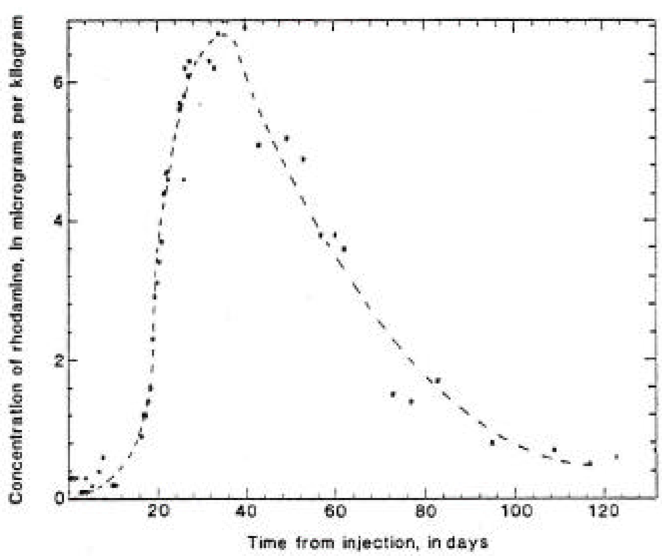


Figure 20. Breakthrough curve in Friesen well, County Museum well injection test.

Tracer breakthrough was evident from the start of flowing of the Medo-Bel well. The tracer concentration with time is shown in Figure 21. At the same time that sampling was started from the Medo-Bel well, samples were also collected from the Fire Station well which is 130 ft (40 m) from the County Museum injection well. Tracer breakthrough in the Fire Station well was also evident from the start of sampling. The tracer concentrations measured were about double those shown for the Medo-Bel well and decreased similarly with time. The curve did not show a maximum value.

Rhodamine WT was detected in at least two additional wells: Spires and Mest, and Jones. The Spires and Mest well is near the Friesen well about 1,000 ft (305 m) northeast from the injection well.

Tracer breakthrough occurred before September 9th; but, it was not possible to determine when maximum tracer concentration occurred. The highest tracer concentration was about 40 µg/kg, indicating a stronger response than in the Friesen and Medo-Bel wells. The well flowed irregularly during the injection tracer test. The Jones well is 1,120 ft (341 m) to the southeast of the County Museum well, in the opposite direction to that of the Medo-Bel well. The first sample (September 23) showed no tracer; but, the second sample (October 9th) showed about 12 µg/kg. After October 9th, the tracer concentration decreased with time.

No tracer was detected in the remainder of the wells sampled: Production, Medical, Olympic, Butler, and Division. These wells are located at greater distances from the injection well than the wells where the dye tracer was detected.

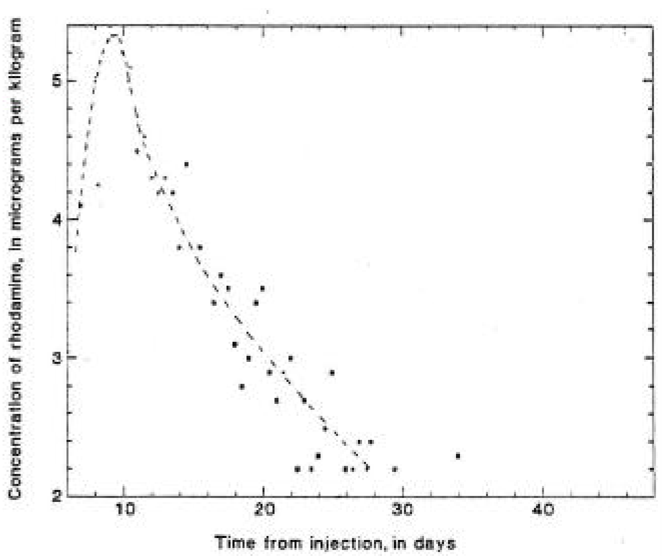


Figure 21. Breakthrough curve in Medo-Bel well, County Museum well injection test.

<u>Interpretation</u>

To determine the amount of tracer recovered in each well, it is necessary to know the flow rate. This was known only (approximately) for the Friesen well. The well was pumped at about 20 gal/min (1.3 l/s), which represents 2.8 percent of the total flow rate injected at the County Museum well. Integrating the area under the breakthrough curve in Figure 21, the mass recovered was estimated to be 25 to 35 g. This represents 0.6 to 0.8 percent of the total mass of rhodamine WT tracer injected. The flow rate for the other wells was not known.

The average fluid velocity in the aquifer can be estimated for three of the wells where tracer breakthrough occurred. The fluid velocity from the injection well to the Medo-Bel well was about 70 ft/d (21 m/d), the Friesen well about 30 ft/d (9.1 m/d) and the Jones well 15 to 20 ft/d (4.6 to 6.1 m/d). The corresponding values estimated in the doublet tracer test were 1,000 to 1,200 ft/d (305 to 366 m/d) between the injection and production wells, and 55 to 65 ft/d (16.8 to 19.8 m/d) between the injection well and the Medo-Bel well. The tracer testing data shows a correlation between average tracer velocity and well spacing, the tracer velocity being inversely proportional to well spacing. A correlation of this type would be expected for radial flow away from an injection well. The exception to this observation is the high tracer velocity between the injection and the production wells in the KUHS doublet test.

If radial flow is assumed from the County Museum injection well to the Friesen well,

$$t_r = \frac{\pi r^2 \varphi h}{Q}$$

can be used to determine the porosity-thickness product, h. The maximum tracer concentration was measured about 36 days after the injection started. Taking the distance between the wells as 1,000 ft (305 m), the porosity-thickness is calculated to be 0.6 ft (0.18 m). If the aquifer porosity is assumed to be 0.1, the effective aquifer thickness is 6 ft (1.8 m). The ratio of thermal velocity to tracer velocity is typically 1:5.6 in geothermal aquifers. Taking the tracer breakthrough time as 36 days, thermal break-through in the Friesen well would be expected in about 200 days or 6 to 7 months. The magnitude of the thermal effect would depend partly on the temperature difference between the injected fluid temperature and the aquifer temperature between the County Museum and the Friesen wells, and partly on the nature of the fracture system in the aquifer rocks.

Concluding Remarks

The problem of geothermal fluid injection concerns how best to dispose of spent fluids and maintain reservoir pressure in geothermal developments without rapid and excessive cool-down of the fluids produced. Tracer testing holds promise as a means of providing some answers to this problem. The method traces fluid flow in the reservoir, which is related to subsequent cooling of the fluids produced. Tracer testing methods and interpretive techniques for geothermal reservoirs are still in the development stage. The interwell tracer tests in Klamath Falls were carried out to provide field data that would be useful in developing interpretive methods for fractured geothermal reservoirs as well as to compliment the aquifer production-injection testing of the Klamath Falls resource.

Traditional pressure-transient tests show the time behavior of aquifers and reservoirs when subjected to a change in production. They are used to determine the flow properties of aquifers and their ability to store fluids. However, they cannot show the movement of fluids in fractured reservoirs. Because geothermal reservoirs tend to be highly fractured, tracer testing has become an important tool in the evaluation of geothermal aquifers and reservoirs.

The main result of the interwell tracer tests in Klamath Falls is the quantification of fluid velocities in the reservoir. The highest velocity was that measured in the doublet tracer test, 43 to 49 ft/h (13 to 15 m/h). Other fluid velocities were much lower, 2.3 to 2.6 ft/h (0.7 to 0.8 m/h) from the doublet injection well to the Medo-Bel well. In the aquifer production-injection test, the fluid velocities were in the range 0.7 to 3 ft/h (0.2 to 0.9 m/h). The fact that tracers were recovered in the tests demonstrates that injected fluids migrate with time to production wells. For fluid velocities below about 1 m/h, there appears to be an inverse relationship to well spacing, as would be expected for radial flow away from injection wells.

The relationship between tracer and thermal velocities is important in the evaluation and design of injection schemes in geothermal reservoirs. However, the results obtained in the KUHS doublet test indicate that additional methods of analysis are needed. According to theory, because of the rapid returns, the production well should have cooled down long ago to temperatures not useful for space heating. This not being the case, the results may indicate that tracer breakthrough curves alone are not sufficient to predict subsequent thermal drawdown. The doublet test shows that the assumption of a direct relationship between rapid tracer breakthrough and subsequent thermal breakthrough may not be correct when considering small volumes in large reservoirs.

Aquifer Pump/Injection Stress Test (Sammel, 1984)

(Edited by G. Culver, Geo-Heat Center)

During the summer of 1983, investigators from several institutions collaborated in an intensive study of the geothermal resource at Klamath Falls. Funded largely by grants from the U.S. Department of Energy (DOE), scientists from Lawrence Berkeley Laboratory (LBL), Stanford University, and the Oregon Institute of Technology (OIT) were co-investigators under the terms of a proposal submitted to DOE by the U.S. Geological Survey (USGS). Participation by USGS personnel was funded by the USGS Geothermal Research Program.

The work included tracer studies by Stanford University, a pumping and injection test by LBL, temperature studies and collection of aquifer-discharge and use data by OIT, and sampling for chemical analysis by USGS.

The principal objectives of the investigation, as stated in the proposal to DOE, was to acquire "from the shallow geothermal reservoir at Klamath Falls... chemical and hydraulic data on which to base predictions of reservoir performance, and an evaluation of potential for development." The major purpose "is to provide interested parties in Klamath Falls with scientific data to be used to evaluate alterative for the future of the geothermal resource; a second purpose is to assess potential impacts of possible alternatives." It is also expected that "knowledge gained in the investigation can be used to aid in the evaluation of other fault-controlled geothermal systems." Clearly, it is not the purpose of this study to recommend specific courses of action regarding the development of the geothermal resource at Klamath Falls; but rather, to provide the scientific data that will be required for decision-making by agencies and citizens in Klamath Falls.

Data Reports and Files

Data, collected during the summer of 1983 specifically for the aquifer test, are presented in graphical and tabular form in the USGS Open-File Report 84-146 (Benson, et al., 1984). The report can be consulted in the public library at Klamath Falls and may be obtained from the USGS Open-File Services Section, Western Distribution Branch, Box 25425, Federal Center, Denver, CO 80225.

All data collected during the investigation resides in a central data file in Klamath Falls. It is the intent of local agencies and citizens that the file be kept current as new data becomes available on current responses in the aquifer and the history of the geothermal development. Both kinds of data will be required in order to refine estimates of the potential of the resource made in this report.

In January 1983, a new effort to gather data on the geothermal resources was initiated by the Klamath County Chamber of Commerce. By March 1983, a program of data gathering and aquifer monitoring was underway, carried on largely by volunteer efforts but with financial support from the Chamber of Commerce, the Klamath County Economic Development Association, and the city of Klamath Falls. Much of the volunteer work was organized by a well-owners group, Citizens for Responsible Geothermal Development (CRGD).

The initial objective of the program was simply to collect and organize existing knowledge of the resource and to monitor water levels and temperatures in the geothermal aquifer; but, this program led directly to and largely made possible the aquifer-testing study that is the subject of this report.

The objectives of the 1983 aquifer test were:

1. To assess the degree of hydrologic interconnection among the various lithologic units that comprise the Klamath Falls geothermal aquifer.

2. To evaluate the hydrologic properties of the aquifer (permeability-thickness and storage coefficient) that govern the water-level drawdown and buildup in response to pumping and reinjection.

3. To assess the spatial variations or directional properties of these properties that will influence the local response to pumping and reinjection.

4. To locate the hydrologic boundaries of the aquifer.

Based on the results of this test, it is possible to predict the impact of pumping and reinjection on the fluid levels in the nearby wells.

Emphasis is placed on the overall interpretation of the aquifer test, rather than on the details of individual well performance. In that sense, this report can be considered only as a preliminary report on the data analysis. To fully analyze the details of each performance requires a tremendous amount of time. Based on the preliminary analysis presented here, it appears that rigorous evaluation of the data will also require detailed numerical simulation and/or the development of new analytic solutions applicable to hydrothermal systems such as the one at Klamath Falls. The above does not, however, lessen the utility of the preliminary interpretation presented here. As will be shown, the hydrologic system responds in a remarkably uniform manner, given the complexity of the system. The average values of the aquifer properties (permeability-thickness, and storativity) determined from this analysis are more than adequate to provide reliable estimates of the short-term effects of pumping and reinjection.

Description

Hydrologic testing in the Klamath Falls geothermal aquifer is complicated by numerous factors, including: (1) an extremely heterogeneous geologic regime, (2) spatial and vertical temperature variations, (3) a large regional flow of geothermal water, (4) partial penetration of the aquifer by both the production/injection wells and the observation wells, (5) seasonal fluctuations in the water levels due to pumping and the effect of downhole heat exchangers, (6) the necessity for a method of well completion compatible with the utilization of downhole heat exchangers, (7) the relatively high permeability of the system, requiring high resolution instrumentation, and (8) the high temperature (100°C) of many of the wells, requiring the use of non-conventional instrumentation. In order to obtain useful test data in such a system, the test must be long enough for a large reservoir volume to be perturbed. In addition, extensive measurements of pressure and temperature changes must be made to evaluate the spatial variation of the reservoir properties. To this end, a six-week interference test involving 52 observation wells was planned for the mid-summer months. Water-level monitoring in previous years had shown this period to be relatively free of seasonal water-level fluctuations.

The interference test actually covered a seven-week period in July-August 1983, and consisted of monitoring water-level changes in 52 wells while pumping and reinjection operations were ongoing in two other wells. An area of approximately 1.7 square miles of the geothermal aquifer was monitored during the test. For the first three weeks, the observation wells were monitored while City Well-1 (CW-1) was pumped. For the final four weeks, hot water was pumped from CW-1 and concurrently reinjected into the County Museum well. Locations of production, injection and monitored wells are shown in Figure 22.

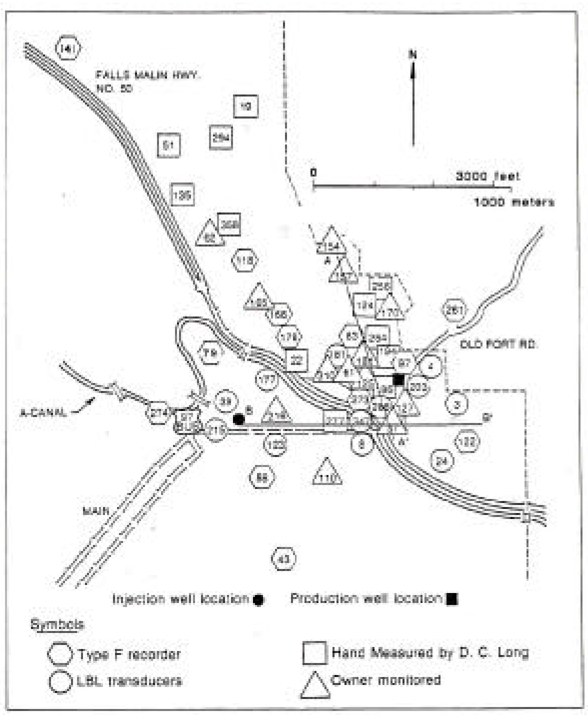


Figure 22. Observation-well location map.

Schedule

The test consisted of four segments: background monitoring pumping, pumping and reinjection, and recovery monitoring. Background data was collected for one week prior to the test (June 29 - July 5). Additional background data was also available from on-going seasonal monitoring of water levels. On July 5th, the pump in well CW-1 was turned on. All the pumped fluid was discharged to the A-Canal until July 26 (with the exception of a 1/2-hour period on July 25). From July 25 to August 24, all water pumped from well CW-1 was reinjected into the County Museum well. On August 24, the two wells were simultaneously shut-in and pressure recovery was monitored for one week (August 24 - September 1).

In order to determine the nature of seismic activity at Klamath Falls, seismic monitoring was included in the data-gathering activities of our study. A seismography, installed by LBL in a well near Hillview Street, continuously recorded seismic events prior to and during the aquifer test. Several barely detectable seismic events occurred during this period; but, there was no increase during the pumping or injection phases of the test. The passage of freight trains through Klamath Falls was easily detected by the instrument, and the seismic noise generated by the trains was an order of magnitude greater than the natural events.

The July 21 earthquake at Coalinga, California (Richter magnitude 5.9), was clearly recorded by the Stevens recorder in 4 monitor wells (Svanevik, Eck, Parks, and Jones). These wells presumably responded at the proper resonant frequency for the detection of the relatively long-period waves of the earthquake. The quake was not detected on the seismometer instrument which was designed to monitor higher frequency local events.

Pumping Rate

Well CW-1 was pumped with a 50-hp shaft-driven pump. The pumping rates during the test are shown in Figure 23. For the first three weeks of the test, the rate remained constant at 720 gal/min (45 l/s). Once reinjection began, the back pressure at the reinjection well resulted in a slightly lower and somewhat variable flowrate of 695 to 660 gal/min (44 to 42 l/s).

Injection Rate

The County Museum well was used for injection for the last four weeks of the test. During this period, the injection rate was identical to the pumping rate and is shown in Figure 24.

Production Well

Instrumentation

Throughout the aquifer test, measurements were recorded daily for flowrate, wellhead temperature, and water level. The flowrate was measured with a Doppler flowmeter, which requires the presence of at least 30 ppm of suspended solids or gas bubbles in the fluid. Because the suspended solid content in this water is very low, nitrogen gas was injected into the flow stream. Flowrates measured with this instrument compared reasonably well with measurements made with an in-line turbine meter. Doppler flowmeter measurements, which are those reported, are believed to be correct to within ±10 percent.

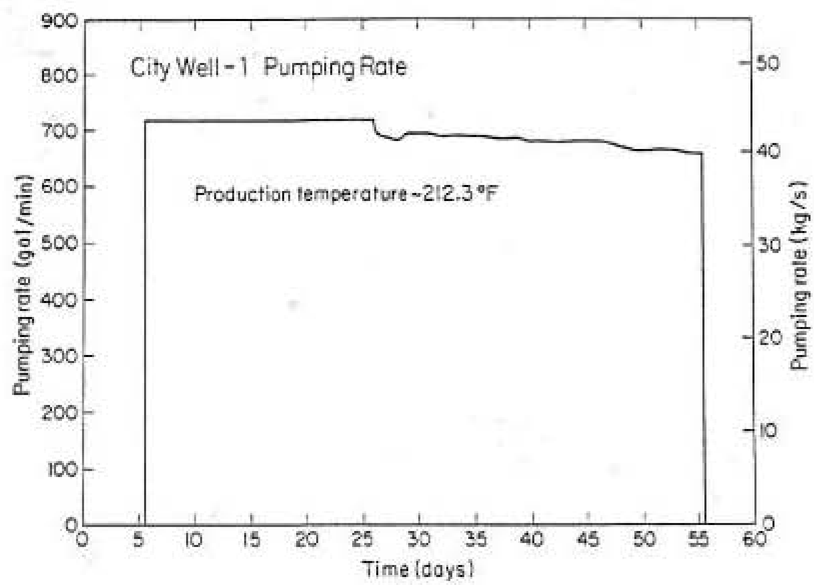


Figure 23. Pumping rate from well CW-1, July 1 to August 29, 1983.

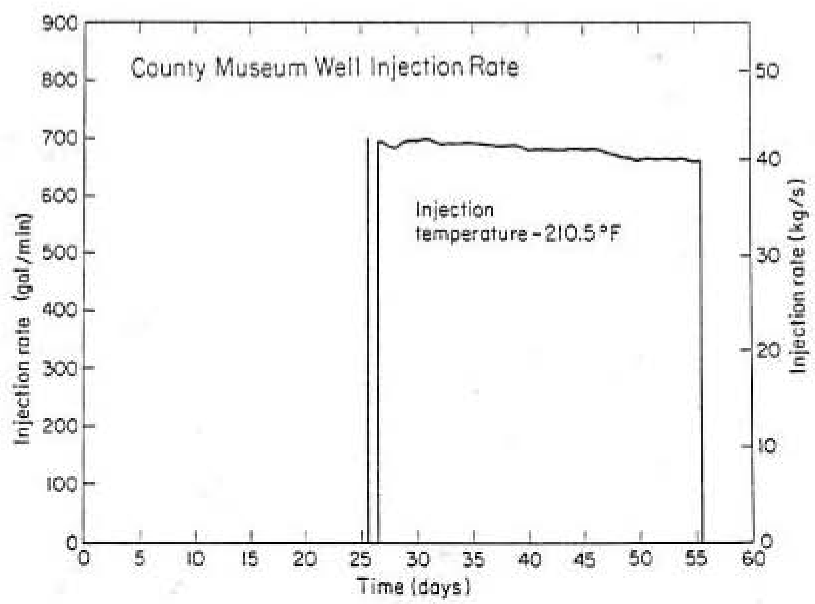


Figure 24. Injection rate into the County Museum well, July 1 to August 29, 1983.

Wellhead temperatures were measured with a bimetallic thermometer. Calibration of the thermometer after the test indicated that measured temperatures were 3.25ºF (1.8ºC) lower than their correct values. The values given in this report are corrected to account for this discrepancy.

Water-level measurements in the pumped well were obtained with a bubble tube assembly. This consisted of a small-diameter tube which is lowered to a suitable depth below the water level (150 ft or 46 m below the casing top in this well). At the surface, a bourdon-type pressure transducer was attached to the tube. Measurements were obtained by purging the tube with nitrogen and recording the pressure on the bourdon-tube gauge. The pressure on the gauge is a reflection of the pressure exerted by the column of fluid above the bottom of the tube. Measured values could be resolved to ±0.5 pounds per square inch (psi)(1.15 ft of water). Well completion, lithology and previous test were discussed above.

Injection Well

Previous Tests

In September 1981, a sixteen-hour injecting test was conducted on the Museum well in which approximately 210ºF (99ºC) water as injected into the Museum well at a maximum rate of 960 gal/min (61 l/s). An injectivity index of 8.5 (gal/min)/ft was recorded (Benson, 1982a). After the injection test, it was determined that the well bottom had filled with debris from the original depth of 1,235 ft (376 m) to a depth of 1,195 ft (364 m)(C. Leib, personal communication, 1983).

A second injection test was conducted in February 1982. For five days, approximately 540 gal/min (34 l/2) of 169 to 205ºF (76 to 96ºC) water was injected into the well. An injectivity index of 29 (gal/min)/ft was recorded (Benson, 1982b). Well completion and lithology were shown above in Figure 13.

Instrumentation

Throughout the injection phase of the 1983 test, the wellhead pressure and flowrate were measured. A bourdon-tube pressure gauge was used to monitor the wellhead pressure. Data was recorded once daily. The gauge resolution was approximately 0.5 psi. Flowrates were measured with the same system used to measure the pumping rate. The injection rate was identical to the pumping rate during the injection phase of the test (see Figure 24).

Other measurements made during the test included a flowing temperature profile, a spinner survey and the downhole pressure-falloff test. The temperature survey was made with a downhole temperature tool that is accurate to within 1.8ºF (1ºC). The spinner survey was made with a high-temperature downhole flowmeter designed at Lawrence Berkeley Laboratory (Solbau, et al., 1983). The pressure falloff data was obtained with a downhole pressure tool designed at Lawrence Berkeley Laboratory and incorporating a quartz-crystal pressure transducer (Solbau, et al., 1981). Resolution is better than 0.01 psi (0.023 ft of water). During the early part of the falloff, data was recorded at one second intervals. Once the rate of pressure falloff decreased, the recording interval was increased to 1 minute and then to 10 minutes.

Observation Wells

Well Lithology

Well depths, casing top elevation, and temperatures are highly variable in the 52 observation wells. By and large, the observation wells are relatively shallow (<400 ft or 122 m). There is no single identifiable rock unit comprising the geothermal aquifer. Presumably both the fractured basalts and contact zones between different rock layers provide the bulk of the system's permeability. Also, the principal fault zone that transects the area probably creates highly permeable near-vertical fluid conduits. The bulk of the geothermal water is stored in the pore spaces of the shale, tuff and unconsolidated sedimentary units. Conceptually, the geothermal aquifer is defined as the entire thickness of the sections penetrated by the geothermal wells. Within the aquifer, the permeability and porosity are variable. Mathematically such aquifers can be treated as a double porosity system (Warren and Root, 1963).

Instrumentation

Water-level changes in the observation wells were measured with one of three types of instrumentation: downhole pressure probes, continuously recording float defectors, and hand-operated conductivity-type detectors. Measurement of fluid levels is difficult in most of the wells in Klamath Falls because the well-bore is filled with pipes used in the downhole heat exchanger system. Also, many of the wells have several feet of oil or paraffin above the water in order to protect the well casing and pipes. This and the presence of steam at the water surface creates difficulties in using conventional conductivity probes for water-level measurements. Alternative methods for measuring water level were used whenever possible.

In wells with sufficient clearance to install a 2-inch (51 mm) probe, water-level measurements were made with the downhole pressure transducer. The transducer was lowered to approximately 50 ft (15 m) below the water surface. Changes in the height of the water column above the transducer are reflected as pressure changes. Data from the wells instrumented with downhole pressure transducers were digitally recorded at 10-minute intervals through-out the test. However, when the flow rates were changed, data was recorded at 1-minute intervals (or less) for several hours.

In some of the wells with limited access, water levels were monitored continuously with Leupold-Stevens Type F water-level recorders. The Leupold-Stevens recorder uses a float and pulley system to monitor water-level changes, and the data is recorded by a clock-driven strip chart. Measurement of the water-level depth was accurate to within 0.1 ft (0.03 m). Time resolution of approximately 15 minutes was possible. However, float hang-ups and mechanical difficulties decreased the practical resolution of both the depth to water and time.

Additional Measurements

Throughout the test, records of several other characteristics and activities that potentially affect aquifer pressures were monitored. These included daily average ambient temperature, atmospheric pressure, micro-seismic activity, and flow in the A-Canal. Chemical samples were also taken in the pumped well at regular intervals throughout the test. Samples were also taken in order to monitor the migration of the injected tracers through the reservoir.

Production Well

Well Productivity

Daily records of flow rate, wellhead temperature, and water level are given in Table 4. Because changes in fluid level were measured only to within ±1.15 ft (0.35 m), productivity estimates are highly variable and range from 72 to 188 (gal/min)/ft (15 to 39 l/s/m). Also influencing these data are several other factors, such as the seasonal water-level buildup during the test and interference effects from the injection well. Previous estimates of well productivity range from 18 to 120 (gal/min)/ft (3.7 to 25 l/s/m). The lack of a well defined trend in the values, suggests that variations in the productivity index result from measurement errors. Based on all of the well productivity measurements, the best estimate of the PI for CW-1 is 100 (gal/min)/ft (20.7 l/s/m).

Temperature

As indicated in Table 4, no measurable temperature change occurred during the test. A comparison between these and previous data indicate that the wellhead temperature increases with flow rate. The change due to changing flow rate (±13.5ºF or ±7.5ºC) is larger than anticipated from conductive heat losses along the wellbore. This is an indication that mixing of the reservoir fluids is occurring and that hotter fluids are drawn to the well at higher flow rates.

Summary

The water-level drawdown and wellhead temperatures obtained from these and previous tests are plotted as function of flow rate in Figure 25. (Note that the data indicating a PI of 18 [gal/min]/ft [3.7 l/s/m] is not shown in the figure. Only data obtained with the currently installed bubble tube system is plotted.) The scatter in the drawdown data is probably due to errors in measurement. The scatter in the temperature data may be the result of measurement error or seasonal variations in the aquifer temperature. For the purpose of estimating the wellhead temperatures and well drawdown as a function of flow rate, the curves (straight lines) shown in Figure 25 can be used.

A review of the current and past data indicates the following:

1. The produced fluid enters the wellbore between 195 and 240 ft (59 and 73 m).
2. The production temperature is rate dependent; the higher the flow rate, the higher the temperature of the produced water.
3. The well draws water from a large volume of hot water; hence, temperature decline in the near-term is anticipated to be minimal.
4. The productivity index of the well is approximately 100 gal/ min per foot of drawdown (20.7 l/s/m).

Table 4. Summary of Pumped and Injection Well Data from the 1983 Aquifer Test

Date	Flowrate (gal/min)	Pump well Temperature (°F)1/	Pump well Water level (ft)2/	Injection well well-head pressure (psi)
7-05-83 3/	0,720	212.3	64,72	0
7-06-83	720	212.3	74	0
7-07-83	720	212.3	74	0
7-08-83	720	212.3	74	0
7-09-83	720	212.3	74	0
7-10-83	720	212.3	74	0
7-11-83	720	212.3	74	0
7-12-83	720	212.3	74	0
7-13-83	720	212.3	74	0
7-14-83	720	212.3	74	0
7-15-83	720	212.3	74	0
7-16-83	720	212.3	74	0
7-17-83	720	212.3	74	0
7-18-83	720	212.3	74	0
7-19-83	720	212.3	74	0
7-20-83	720	212.3	74	0
7-21-83	720	212.3	74	0
7-22-83	720	212.3	74	0
7-23-83	720	212.3	72	0
7-24-83	720	212.3	72	0
7-25-83	720	212.3	72	0
7-26-83 4/	720,695	212.3	72	0,37
7-27-83	690	212.3	71	39
7-28-83	685	212.3	69.5	36
7-29-83	695	212.3	69.5	37
7-30-83	695	212.3	69.5	37
7-31-83	695	212.3	69.5	38
8-01-83	690	212.3	69.5	38
8-02-83	690	212.3	68.5	38
8-03-83	690	212.3	68.5	38
8-04-83	690	212.3	67.5	38
8-05-83	690	212.3	67.5	39
8-06-83	685	212.3	67.5	39
8-07-83	685	212.3	67.5	39
8-08-83	685	212.3	67.5	40
8-09-83	680	212.3	67.5	40
8-10-83	680	212.3	67.5	40
8-11-83	680	212.3	67.5	40
8-12-83	680	212.3	67.5	40
8-13-83	680	212.3	67.5	40
8-14-83	680	212.3	67.5	40
8-15-83	680	212.3	67.5	40
8-16-83	675	212.3	67.5	—
8-17-83	670	212.3	67.5	—
8-18-83	665	212.3	67.5	--
8-19-83	665	212.3	67.5	42
8-20-83	665	212.3	67.5	43
8-21-83	665	212.3	67.5	42
8-22-83	665	212.3	66.5	43
8-23-83	660	212.3	66.5	43
8-24-83 5/	660	212.3	66.5, 63	43

1/ Reported temperatures are corrected to post-test calibration. Calibration indicated that the gauge was reading 3.25°F low throughout the test.

2/ Water level, in feet below measuring point, calculated from pressure-gauge readings. Gauge resolution of 0.5 psi equivalent column of water (= 1.15 feet).

3/ Pumping starts at 15:10 (3:10 p.m.)

4/ Injection starts at 10:11.

5/ Shut in at 17:35:41 (= 5:35 p.m.).

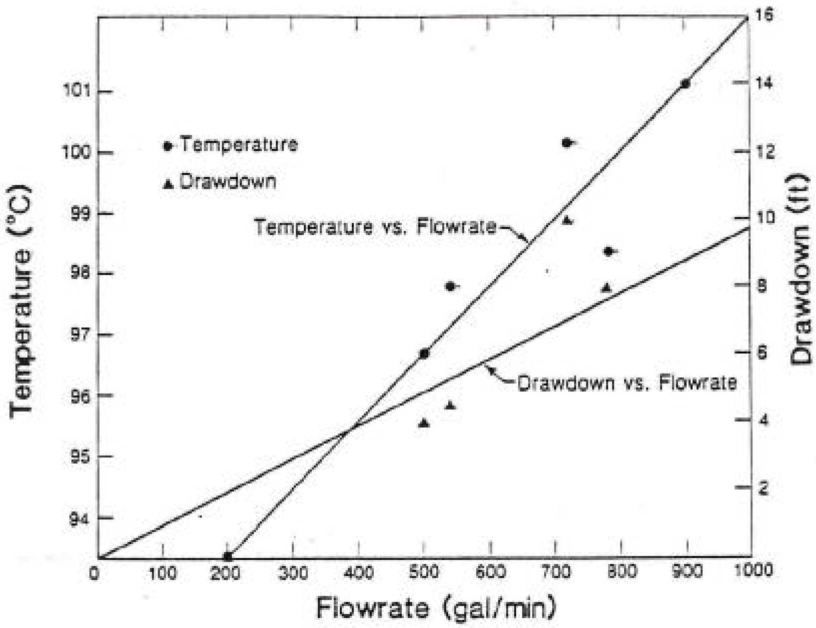


Figure 25. Drawdown and wellhead temperature vs. flow rate for well CW-1.

Injection Well

Temperature

Two temperature profiles of the County Museum well were obtained during the 1983 tests. The first, measured while the well was not in use shows a maximum well temperature of 199ºF (92.9ºC) at a depth of 1,000 ft (305 m)(Figure 13). From approximately 600 to 1,100 ft (183 to 335 m) depth, the well is nearly isothermal, indicating either a convective thermal regime in the reservoir or inter-zone flow in the wellbore. Without additional information, it is not possible to determine which of these possibilities is correct. A second temperature profile, shown in Figure 26, was obtained during injection. This type of survey is used to identify the deepest injection zone intersecting the well. The isothermal profile indicates that water entered the formation to a depth approaching 1,150 ft (351 m). Cooler temperatures below this depth show that the injected water does not reach the bottom of the well.

Spinner Survey

On August 15, 1983, a downhole flowmeter (spinner) survey was conducted in order to identify the interval(s) accepting the injected water. The spinner survey is shown in Figure 26. In the cased portion of the well (0 to 450.5 ft)(0 to 137.3 m), the fluid velocity (indicated by revolutions per minute [RPM]), is nearly constant, as expected. Below the casing, the vertical fluid velocity is highly variable, reflecting substantial variations in the bore diameter. Comparison of the average spinner velocity in the casing to the average velocity below 520 ft (159 m) indicates that nearly 50 percent of the injected fluid enters the rock formations between 470 and 520 ft (143 to 159 m). As can be seen from the lithologic log in Figure 26, this interval occurs in a shale (or tuff) separating two basalt units. Any one (or all) of these units and their contacts could be accepting fluid. The decrease in spinner velocity below 1,020 ft (311 m) indicates that the remainder of the fluid is injected into a relatively thick basalt and shale (tuff) unit between 1,020 and 1,100 ft (311 and 335 m).

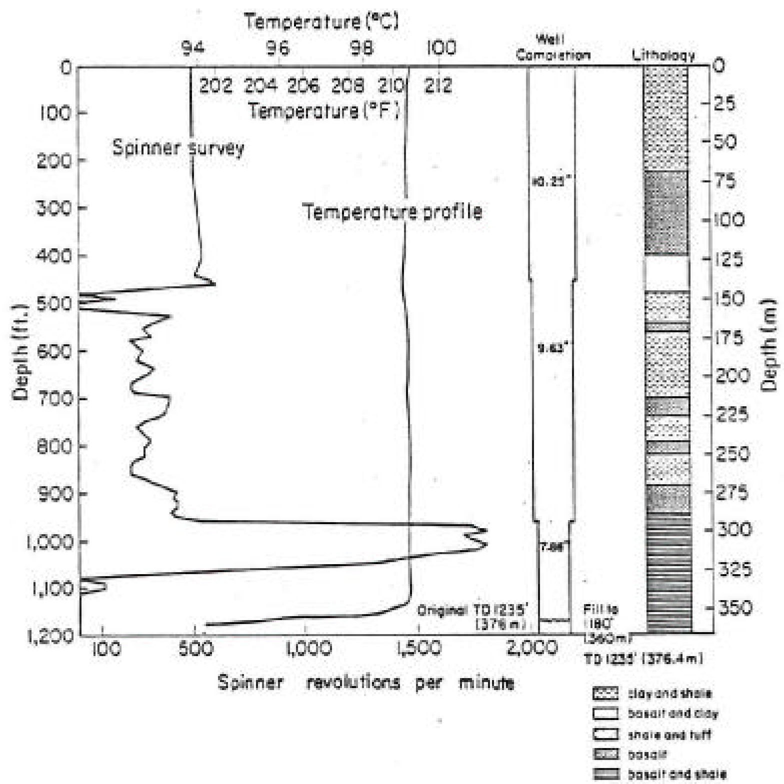


Figure 26. Temperature profile and spinner survey obtained during injection into the County Museum well.

<u>Well Injectivity</u>

Injection rates and wellhead injection pressures were measured throughout the 29-day injection period. The data are tabulated in Table 4. The wellhead pressures increased from approximately 39 tp 43 psi (269 to 296 kPa) over the test period. The temperature of the injected fluid remained constant at 210ºF (99ºC) throughout the test. Note that the injection temperature is 9 to 18ºF (5 to 10ºC) higher than the maximum temperature previously measured in the County Museum well (Figures 13 and 26). The average well injectivity during this test was 7.1 (gal/min)/ft (1.5 l/s/m). The apparent decrease of well injectivity (and productivity) during this test in comparison to the measurements taken in 1976 and 1982 could be attributed to plugging of the formation with material sloughing from the wellbore face, perhaps between 470 and 520 ft (143 and 159 m). The higher injectivity reported from the February 1982 test (29 [gal/min]/ft, Benson, 1982b) could have resulted partly from the higher density of the cooler injection fluid.

Pressure-Falloff Data

On the last day of the injection test, a pressure transducer was lowered into the injection well. The injection pressure was measured at a depth of 900 ft (274 m) for several hours prior to shut-in. The pressure falloff was then observed for eight days. The data was analyzed using a conventional Miller-Dyes-Hutinson (MDH) semi-log plot of the data (Earlougher, 1977). This approach was used instead of the Horner method (which is more common for falloffs) because it was recognized that relatively soon after shut-in, the well would be influenced by interference effects from the production well, thus, complicating the late-time data analysis. The MDH method is valid for pressure-falloff analysis if the time period is short with respect to the test duration. From the slope of the semi-log straight line, a permeability-thickness of 1.35×10^6 millidarcy-feet (md-ft) is calculated. The well has a large positive skin effect, indicating that the permeabilities of the rocks immediately adjacent to the wellbore are lower than those of the reservoir rocks.

Interference Data Analysis

Observation Well Data

Water-level measurements were obtained from 52 wells during the aquifer test. Water levels clearly changed in all of the wells, except one (No. 141), in response to both pumping and reinjection. All of the raw data obtained during the 1983 aquifer tests have been published by Benson, et al., 1984. The interference data from two of these wells, typical of most of the data, are shown in Figures 27 and 28. Both wells followed the same basic pattern. Pressures (water levels) decreased while only the pumping well was active. When injection began, the water levels in both wells rose rapidly. Water levels in many of the wells rose above their pretest levels, even those relatively close to the pumped well. Prior to shut-in, the water level was nearly 1 ft (0.3 m) higher than its pretest level. This behavior is the reflection of three trends: (1) the water-level rise that normally occurs in the early summer months, (2) atmospheric pressure changes and, (3) the decreased heat loads on the downhole heat exchangers. Measurements made during this test clearly showed that water levels varied significantly in response to downhole heat exchangers use. Throughout the test, the water level fluctuated in response to heat-exchanger use. In general, fluctuations of less than 1 ft (0.3 m) were observed. However, during the middle of the test, the water level rose by nearly 2 ft (0.6 m). This rise was a significant fraction of the entire change caused by pumping (50 percent). The maximum water-level decline (4.7 ft or 1.4 m) in response to pumping was measured in the Steamer well (No. 203), which is only 122 ft (37 m) from CW-1. In general, water-level changes in response to pumping and reinjection decreased with distance from the active well(s). However, there is a pronounced elongation of the cone of depression around the pumped well which indicates that the reservoir permeability is anisotropic. This is discussed in greater detail in the section entitled "Steady State Analysis."

Methodology

The fractured and heterogeneous nature of the system and the interpretation of previous short-term tests suggests that a double-porosity model best describes the pressure-transient behavior in the observation wells (Benson, et al., 1980; Deruyck, et al., 1982; and Benson, 1984). Double-porosity behavior is characteristic of naturally fractured reservoirs in which the fractures provide most of the permeability for fluid flow and rock matrix sorts the bulk of the reservoir fluid.

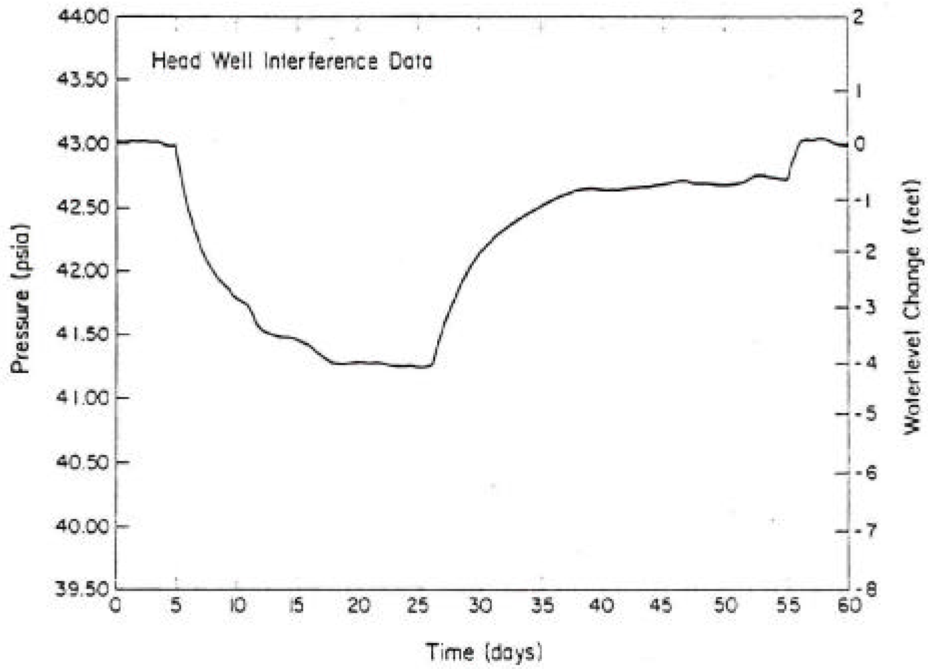


Figure 27. Interference data from the Head well (No. 101), July 1 to August 29, 1983.

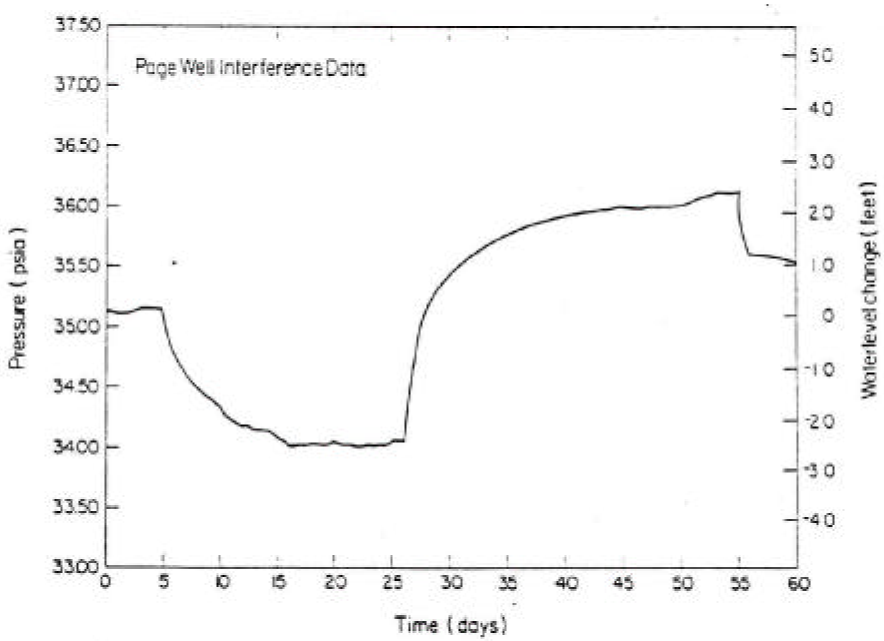


Figure 28. Interference data from the Page well (No. 177), July 1 to August 29, 1983.

Interference data in double-porosity systems can be analyzed with several procedures, some of which are described by Kazemi, et al., 1969; Deruyck, et. al., 1982; and Lai, et al., 1983. For the purpose of analyzing these data, two methods are used; a log-log type curve matching technique (Deruyck, et al., 1982) and a semi-log curve matching technique (Lai, et al., 1983). From both of these analysis procedures, the following reservoir properties are obtained: the permeability-thickness of the formation (kh), the bulk storativity $(\varphi ch)_t$, and the double-porosity parameters ω and λ. The parameters ω and λ are those defined by Warren and Root (1963) as:

$$(1) \qquad \omega = \frac{(\varphi c_t)_f}{(\varphi c_t)_f + (\varphi c_t)_m}$$

and

$$(2) \qquad \lambda = \alpha r_w^2 \frac{k_m}{k_f}.$$

In the expressions given above in equation 1 and 2, and the preceding paragraph,

k	= permeability (daries),
h	= thickness (ft),
φ	= porosity (dimensionless),
c_t	= total compressibility of rock and water (1/psi),
α	= a geometric factor (1/ft^2),
r_w	= well radius (ft),

and the subscripts f and m refer to fractures and rock matrix, respectively.

In order to perform a detailed analysis of the drawdown and buildup data, the data must be relatively free of perturbations created by sources other than pumping or injection. This constraint has several implications for the data analysis: (1) wells affected by heat-exchanger use are not suitable for detailed analysis, and (2) because the late-time data obtained from all of the wells are influenced by the seasonal water-level buildup, only the relatively early-time data are considered reliable. For these reasons, detailed analyses are performed only on unused wells and only the first 300 to 400 hours of data from both the pumping and reinjection phase of the test are used for analysis.

Pressure-buildup data from the injection phase of this test are analyzed by assuming that the pressure transients occurring in the initial pumping period have reached steady state and therefore, can be ignored in the subsequent calculations. In relation to the background noise (attributed to other well users and seasonal water-level changes), errors due to other this assumption are small. During the injection test, the flow rates were slightly variable (42 to 40 kg/s). This variation is also neglected in the analysis because water-level changes due to sources (barometric pressure fluctuations and other well users) are of the same order of magnitude as those resulting from the flowrate variations and do not affect the overall data interpretation.

Type-Curve Analysis

Each of the data sets suitable for detailed interpretation was plotted on log-log paper. The data was then matched to the double-porosity type curves prepared by Deruyck, et al., 1982. If the observation well is distant from the active well and the test duration is sufficiently long, the double porosity behavior does not greatly influence the determination of transmissivity and the Theis Curve is used for the analysis (Theis, 1935).

Type-curve matches for drawdown data measured in two of the wells are shown in Figures 29 and 30, which are typical of all wells analyzed. In each case, the match between the theoretical and measured data is excellent. Table 5 summarizes the values of kh, $(\varphi ch)_t$, ω, and λ obtained from the analysis of each data set. Note that values for the parameter kh are all in good agreement with one another. The average of these values is 1.5×10^6 md-ft. The extremely heterogeneous nature of the geothermal aquifer creates uncertainty as to the appropriate value of the reservoir thickness. Therefore, it is not possible to evaluate independently the value of the permeability. However, if the thickness is estimated to be 1,000 ft (305 m), the reservoir permeability is approximately 1.5 darcies. This is significantly higher than the permeability of most geothermal systems (Bodvarsson and Benson, 1983). The values of $(\varphi ch)_t$ range from 0.792 to 3.03×10^{-3} ft/psi. The anomalously high values $>10^{-2}$ occur in a region of high permeability and porosity that surrounds the pumped well and is intersected by several of the observation wells (Benson and Lai, 1984). This is discussed in greater detail in the section entitled "Steady State Analysis." Variations in the value of $(\varphi\ ch)_t$ also reflect the anisotropic permeability of the system (Earlougher, 1977). The values of ? range from 0.01 to 0.3. The value for ω of 0.3 is calculated from a well that is 2,200 ft (671 m) from CW-1. For a well this far from the active well, the pressure transients are not very sensitive to the double-porosity parameters (Benson, 1984). Neglecting this value, the average value for ω is 0.014. Values for the parameter λ range from 1.51×10^{-5} to 1.86×10^{-7}. This variation may result from local permeability heterogeneity and/or lack of sensitivity to the parameter (Benson, 1984). On the basis of the present analysis, the best estimate of λ for the hillside area lies between 10^{-6} and 10^{-7}.

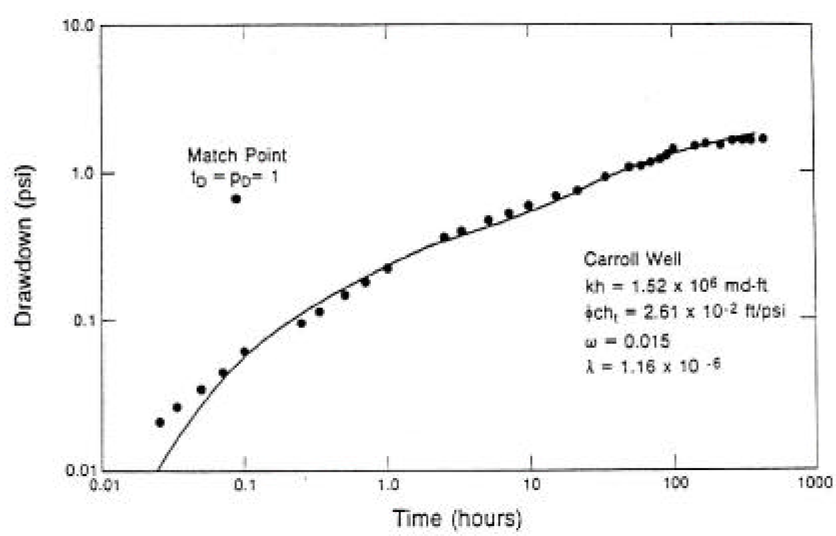


Figure 29. Double-porosity type-curve match for the Carroll well (No. 3) drawdown data.

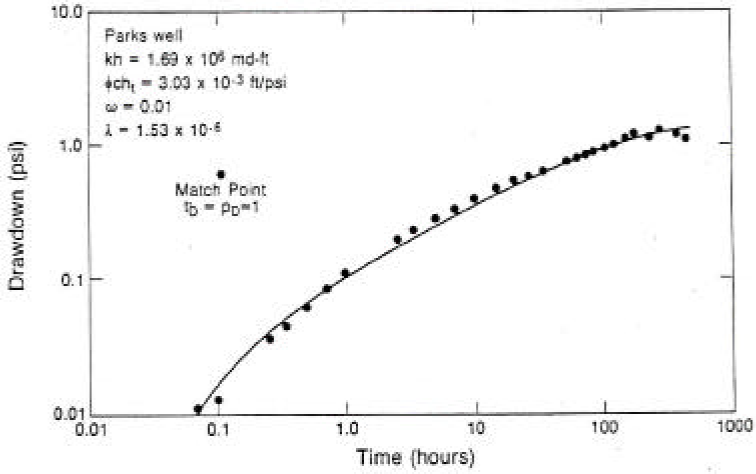


Figure 30. Double-porosity type-curve match for the Parks wells (No. 4) drawdown data.

Table 5. Summary of the values of the kh, $(\varphi ch)_t$, and the parameters ω and λ calculated from semi-log and type-curve (log-log) analyses.

Well	No.	kh (md-ft)		$(\varphi ch)_t$ (ft/psi)		ω		λ		Active well
		Semi-log	Log-log	Semi-log	Log-log	Semi-log	Log-log	Semi-log	Log-log	
Assembly of God	24	1.55×10^6	1.74×10^6	6.9×10^{-3}	5.1×10^{-3}	0.02	0.01	1.0×10^{-7}	2.7×10^{-7}	PRO
Parks	4	1.92×10^6	1.96×10^6	2.2×10^{-2}	3.0×10^{-3}	0.04	0.01	1.3×10^{-6}	1.7×10^{-6}	PRO
Carroll	3	1.47×10^6	1.52×10^6	2.7×10^{-2}	2.6×10^{-2}	0.01	0.015	7.5×10^{-7}	1.1×10^{-6}	PRO
Head	101	1.35×10^6	1.39×10^6	1.1×10^{-2}	9.5×10^{-3}	0.02	0.01	2.2×10^{-7}	4.1×10^{-7}	PRO
Parks Steamer	203	1.04×10^6	1.34×10^6	1.1	0.79	0.001	0.01	1.5×10^{-5}	1.5×10^{-5}	PRO
Page	177	1.74×10^6	1.74×10^6	4.8×10^{-3}	5.7×10^{-3}	0.1	0.3	6.0×10^{-7}	1.9×10^{-7}	PRO
Head	101	1.35×10^6	1.17×10^6	4.6×10^{-3}	6.1×10^{-3}	0.3	0.3	5.0×10^{-6}	5.1×10^{-7}	INJ
Carroll	3	1.23×10^6	1.27×10^6	2.2×10^{-3}	2.3×10^{-3}	0.1	0.3	1.5×10^{-6}	2.2×10^{-7}	INJ
Parks Steamer	203	1.41×10^6	1.35×10^6	2.6×10^{-3}	3.2×10^{-3}	1	1	------	------	INJ
Assembly of God	24	9.60×10^5	9.54×10^5	3.5×10^{-3}	4.1×10^{-3}	1	1	------	------	INJ
Page	177	1.32×10^6	1.43×10^6	7.8×10^{-3}	7.3×10^{-3}	0.02	0.06	3.0×10^{-7}	2.4×10^{-7}	INJ
Medo Bell	39	1.13×10^6	1.14×10^6	2.8×10^{-3}	1.1×10^{-3}	0.04	0.15	9.0×10^{-8}	2.7×10^{-8}	INJ
Spires and Meet	123	1.05×10^6	1.28×10^6	7.9×10^{-3}	6.0×10^{-3}	0.003	0.006	3.0×10^{-7}	1.8×10^{-7}	INJ

Similar analyses were performed on the pressure buildup in response to injection.

From the results of the type-curve analysis of both the drawdown and buildup data, the following estimates of the reservoir parameters are obtained:

kh $= 1.4 \times 10^6$ millidarcy-ft (md-ft)
$(\varphi ch)_t = 5 \times 10^{-3}$ ft/psi
$\lambda = 10^{-7}$
$\omega = 10^{-2}$

The reservoir properties calculated for individual wells have a remarkably small spread around the average values, especially in light of the highly heterogeneous nature of the system.

Semi-Log Analysis

In addition to type-curve matching, the data were analyzed with the semi-logarithmic method discussed previously. Whereas, type-curve matching tends to weight the data interpretation towards the early-time data, semi-logarithmic analyses are strongly weighted towards the late-time pressure response. Nevertheless, in both instances, it is the late-time data that establishes the value of kh. In the semi-log method, the pressure data are plotted versus log (time). The permeability-thickness of the system is calculated from the slope of the semi-log straight line that is drawn through the late-time data points. The storativity, $(\varphi ch)_t$, is calculated from the time at which the straight line intersects the x-axis (i.e., $\Delta p=0$). In order to evaluate the double-porosity parameters, ω and λ, the data are history-matched using the analytic solution developed for double-porosity systems by Lai, et al., 1983. The values of λ and ω are chosen from the best history matches.

As an example, the Page well drawdown analysis is illustrated in Figure 31. The straight line shown in the graph is used to calculate the permeability thickness of the reservoir. The intercept, at 7 hours, is used to calculate $(\varphi ch)_t$. The data matches for different pairs of λ and ω are also shown. The best match is obtained for $\lambda = 6 \times 10^{-7}$ and $\omega = 0.1$. Data from each of the wells analyzed with type curves were analyzed using this technique. The results of the analyses are given in Table 5, together with the results of the type-curve match. With few exceptions, the results from the two methods of analysis are in excellent agreement with one another. The shape of the log-log plots suggests, however, that a double-porosity model appropriately describes the pressure transients in the Klamath Falls geothermal aquifer, and this suggest also that the log-log plots, which take early data into account, may provide the more reliable estimates of storativity.

Data from some of the wells in which water-level measurements were made with float recorders or conductivity meters were also analyzed using the semi-log technique. In each case, it is clear that the late-time data does not lie on a single straight line, as is expected from the results of the previously discussed analyses. The average value of kh, 1.6×10^6 md-ft, is in good agreement with that calculated from the other analyses, 1.5×10^6 md-ft. The pressure response at the Zion Church well (No. 274), does not follow the same trend as the other wells. The drawdown and the rate of drawdown are far less than for the other wells. However, the well clearly responded to pumping. This behavior is attributed to the lack of high permeability fractures of strata in the vicinity of this well. As a result of this, both the rate and magnitude of drawdown are less than observed in the other wells.

The results of the semi-logarithmic analyses are in good agreement with those obtained by type-curve matching. Taken together, the two methods show that the aquifer behaves hydrologically like an infinitely large double-porosity system. The lack of evidence for hydrologic discontinuities in the system indicates that there is a large volume of hot water available in the near-surface aquifer, as well as the deep geothermal circulation system.

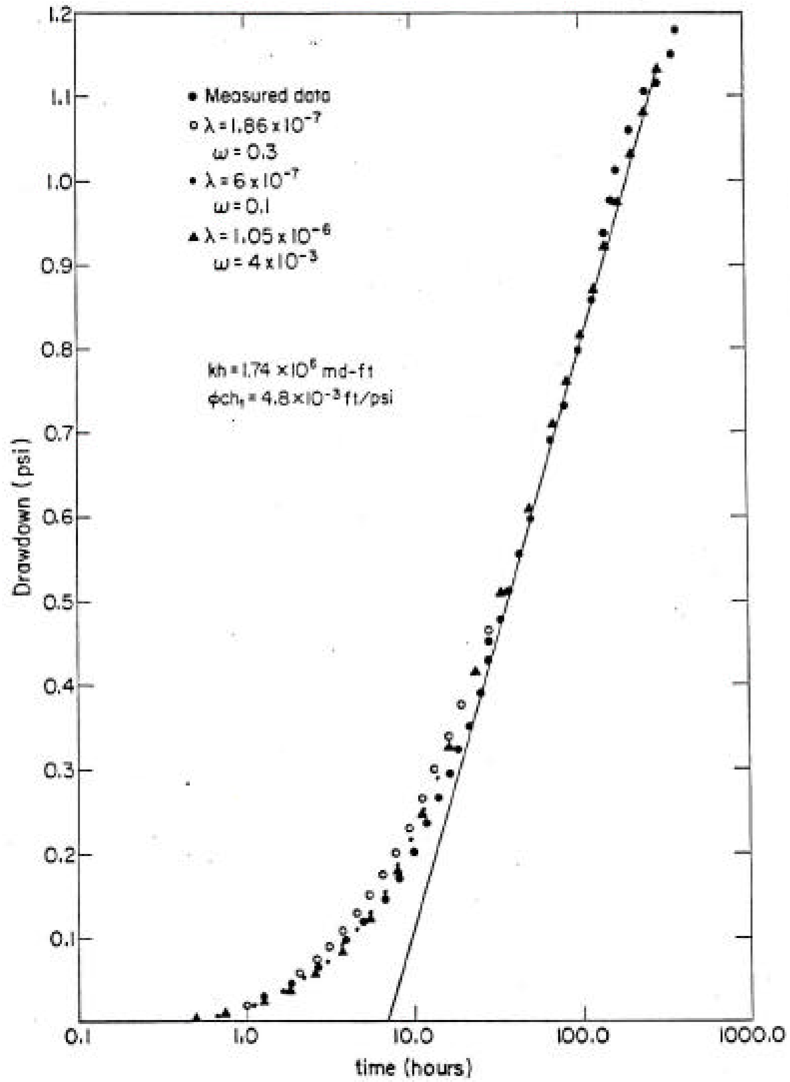


Figure 31. Semi-logarithmic analysis of the Page well (No. 177) drawdown.

Steady State Analysis

An alternative approach to analyzing the well test data is to look at the distribution of the pressure drawdown in the reservoir at a specified time. This approach tends to emphasize the difference between individual well performance and the anisotrophy of the hydrologic properties. For example, the drawdowns in 22 of the observation wells, after 336 hours of pumping at a rate of 720 gal/min (45 l/s). (Data from wells strongly affected by heat-exchanger use or measurement error were not considered in this analysis.) In general, as shown in the figure, drawdowns were greatest in the immediate vicinity of the production well. However, there is not a monotonic relationship between the radial distance to the observation well and the magnitude of the drawdown. Instead, the drawdowns are somewhat greater than expected along a NW trend that is parallel to the regional structure. The elongation of the drawdowns in this manner is indicative of anisotropic aquifer permeability. Although there are no reliable data from wells at distances greater than about 1,500 ft (457 m) transverse to the trend, the indications of anisotrophy are consistent with the interpretation of previous test data from the Museum well (Lund, et al., 1978). The trend of the major axis of permeability is nearly the same as the strike of the major-normal fault that transects the area. Possibly, this fault, or fault zone, provides addition high-permeability fractures along which fluid flows easily. Comparison between the observed drawdowns and preliminary theoretical calculations (not discussed here) indicates that the ratio of the major to minor axis permeability is between 5 and 10.

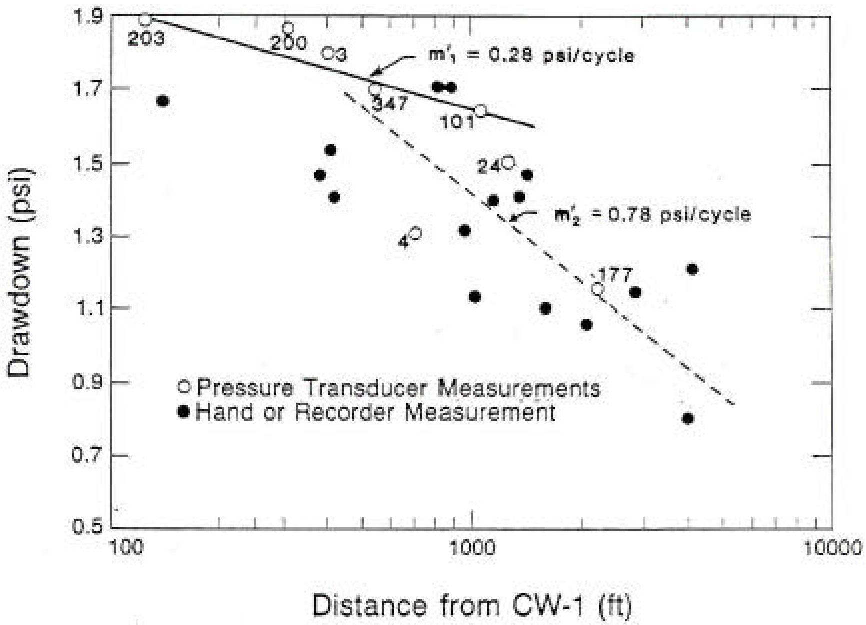


Figure 32. Pressure drawdown vs. distance for 24 observation wells after 336 hours of pumping at a rate of 720 gal/min.

Permeability anisotropy can not fully explain the observed pressure drawdowns. For example, there are several wells in which the drawdowns are greater or less than predicted by anisotropy. In particular, wells that are close to the A-Canal experience smaller drawdowns than those elsewhere (see Figure 22 for A-Canal location). Drawdowns in several of the wells were slightly greater than anticipated from simple anisotropy. The discrepancies were not large and interpretation must be postponed until individual analyses of each of the 52 observation wells are completed.

When a steady-state flow condition (or approximately steady-state flow) is reached, it is possible to calculate the reservoir permeability from distance vs. drawdown graphs (Thiem, 1906). For a homogeneous, isotropic system, the data points should all fall on a single straight line (when the drawdown is plotted as a function of logarithm of the radial distance to the well). Clearly, the system is neither homogeneous nor isotropic. However, such a graph can provide insight into the behavior of the system. The drawdown versus distance for the 24 observation wells that have continuous records (after 336 hours of pumping at 720 gal/min) is shown in Figure 32. There is a large scatter of the data points, indicative of anisotropy and aquifer heterogeneity. However, one possible interpretation is that there are two regions in the aquifer, a high-permeability region in the vicinity of the pumped well (indicated by slope m_1') and a lower permeability region surround it (indicated by slope m_2'). Slope m_1' is determined by 4 of the 5 transducer wells located along Old Fort Road near the pumped well. The fifth (Well 4) is anomalous, and Well 101 (Head), may fall along this trend fortuitously. Slope m_2' is an estimated fit to the remaining data points which results in a calculated permeability of about 3 x 10^6 md-ft, a value greater than any derived from analyses of individual well responses. Although this interpretation is not very convincing, because of the scatter in the data points, it does explain several observations in the data that are unexplained by other interpretations. The presence of a high permeability inner region explains the small drawdowns (in comparison to those predicted by the average values of kh and $[\varphi ch]_t$) in the immediate vicinity of the pumped well and the anomalously high values of the storage coefficient (Benson and Lai, 1984). In the absence of detailed analysis of the extent and shape of this inner region and the anomalies represented by wells beyond this region, it is not possible at the present time to provide further interpretation.

A similar analysis can be applied to the pressure buildup caused by reinjection. The pressure buildup, after 300 hours of pumping at a rate of approximately 700 gal/min (44 l/s), for 7 of the observation wells measured by transducer. The best straight line fit to these data is shown in the graph. A kh of 1.35 x 10^6 md-ft is calculated from the slope of this line. This is in excellent agreement with the average calculated value of 1.4 x 10^6 md-ft.

Conversion of the data from the remaining observation wells to a common basis is not yet complete, however, and this conclusion is a preliminary one.

Although the steady state analysis is not entirely consistent with the interpretation of the pressure-transient data, two additional factors are suggested by this approach: a pronounced permeability anisotropy and the presence of a high permeability region around the pumped well. The analysis of these two factors can not be considered to be complete. Furthermore, other interpretations may explain the observed pressure response as well as those presented here. Until additional analyses are performed, a more definitive answer can not be obtained.

Temperature Data

Downhole temperatures were measured in all the wells monitored with downhole pressure transducers (Figure 21). The objective of these measurements was to determine if pumping large amounts of geothermal water would quickly change the aquifer temperature. Data from 6 of these wells are shown in Figure 33. During the measurements, the Rogers well was being used for space heating with downhole heat exchangers. Therefore, most of the temperature changes in the well probably was due to heat-exchanger use rather than temperature changes in the aquifer. Throughout the test, the temperature declined in the Spires and Mest well. This occurred because pumping of hot water from the well had ceased, and the bore-fluid temperatures was equilibrating with the surrounding rock. Data from the remaining wells were unaffected by use and, therefore, are indicative of aquifer-temperature changes induced by pumping.

Temperatures in the Page well, Head well, and Harley Davidson well remained nearly constant throughout the test. The temperatures at the Parks and Carroll wells increased by approximately 1.8 and 0.9ºF (1 and 0.5ºC) respectively. The temperature in the Parks Steamer well decreased 1.8ºF

(1ºC) during pumping and increased 1.8ºF (1ºC) when injection began. The temperature decline in the Parks Steamer well appears to be caused by fluid-level changes in the wellbore rather than aquifer-temperature changes (as evidenced by the temperature recovery during injection). All of these changes were small and no systematic trend is apparent. Also, these changes are less than those that occur in a yearly cycle (Lund, et al., 1978). The lack of significant temperature change during the test precludes the possibility of establishing a relationship between pumping and temperature changes in the aquifer. Meaningful measurements can only be made over a much longer time period (years). However, the absence of definitive temperature response indicates that a large volume of hot water, at a relatively constant temperature, is stored in the geothermal aquifer and fault system.

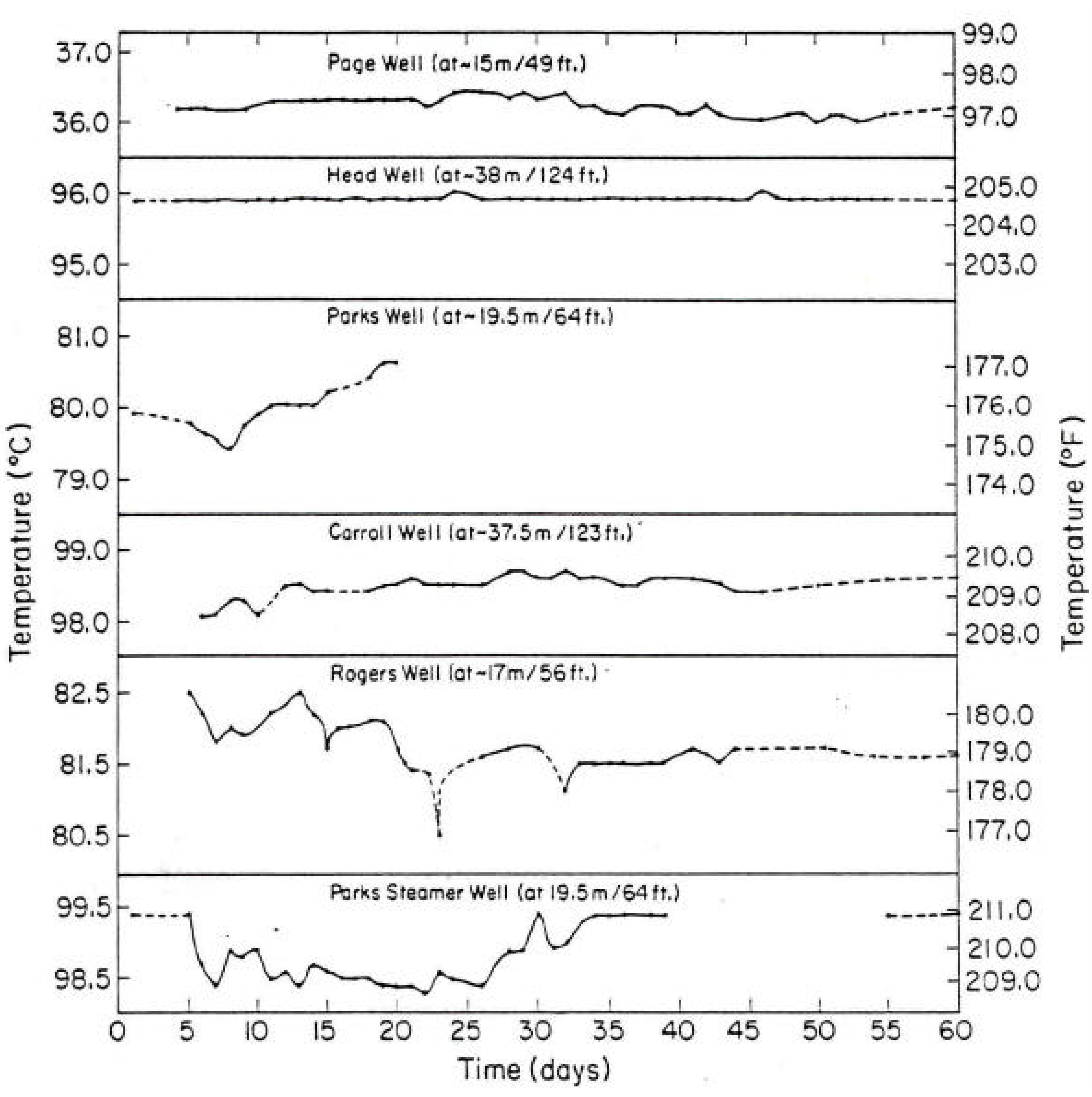


Figure 33. Downhole temperature data from Page, Head, Parks, Carroll, Rogers, and Parks Steamer wells (No.'s 177, 101, 4, 3, 200 and 203). Time in days from July 1, 1983.

Summary

An enormous quantity of hydrologic data has been obtained from the Klamath Falls geothermal aquifer. It is an unprecedented achievement both for the extraordinary high quality data obtained and for the cooperation of the many individuals who provided data, interest, and participation in the aquifer test. Under well controlled conditions, the response of the aquifer and the individual wells to both pumping and reinjection were measured. The test was of sufficient duration and the data of adequate quality so that conventional and non-conventional analysis techniques could be applied with a great deal of confidence. Although this large data set could not be thoroughly analyzed in the time thus far dedicated to the task, many of the questions previously unanswered are now answerable. However, as is the case in any scientific investigation, new questions have also arisen. The status of the investigation can be summarized as follows.

The geothermal aquifer underlying the city of Klamath Falls is primarily a fault- and fracture-controlled system. The fault(s) and fractures provide highly permeable paths along which water moves easily. The sediments and tuffaceous rocks provide the bulk of the storage capacity of the aquifer as indicated by the double-porosity type pressure transients. Pressure-transient and steady-state analyses of the drawdown and buildup data from many wells were similar; although, there are numerous unresolved discrepancies. Average values for the hydrologic properties of the system are as follows:

$$kh = 1.4 \times 10^{6} \text{ md-ft}$$
$$(\varphi ch)_t = 5 \times 10^{-3} \text{ ft/psi}$$
$$\lambda = 10^{-7}$$
$$\omega = 10^{-2}$$

No hydrologic boundaries were detected during the test. On the basis of the above results, the radius of investigation (at 336 hours) is estimated to be 3.5 miles (5.6 km). The lack of boundaries to the system within this radius has several important consequences. First, it sheds an interesting light on the hydrologic properties of the fault zone that is the primary conduit for hydrothermal circulation. Unlike the response predicted by classical models for constant-potential or constant-flow faults, this fault was invisible to hydrologic testing. Several hypotheses can explain this observation. First, the hot water may upwell over a broad region rather than along a single fault zone that could be detected hydrologically. Second, the fault permeability may be of the same order of magnitude as the permeability of the near surface aquifers and hence, indistinguishable. Third, a single fault may provide the conduit for upwelling from great depth; but as the fault approaches the surface, the width of the fractured zone increases and creates a diffuse permeable region in the near surface. Additional research in this area could provide further insight into the nature of the supply conduits. A second implication of the lack of hydrologic boundaries to this system is that the hydrothermal system is an integral part of the regional hydrologic system. As such, fluid recharge should be in abundant supply.

However, if the hydrologic gradient is altered so that the natural groundwater flow system is disturbed significantly, cold water may enter the geothermal aquifers. The lack of temperature change in the aquifer during these test indicates, however, that such an occurrence would not happen rapidly and perhaps, not at all. This too, is an area in which additional research would be fruitful.

Details of individual response of each of the 52 observation wells have not been analyzed. Data from many of these wells were strongly affected by downhole heat-exchanger use. As such, they were not amenable to the analysis procedures used here. However, additional investigation of these data will provide insight into local variations of the hydrologic properties. Of particular interest is the region of very high permeability surrounding CW-1. This, too, will be pursued in future investigations.

The overall hydrologic characteristics of the geothermal aquifer have been determined. Most of the data are remarkably consistent and local variations in hydrologic properties have only a second order effect on the pressure response. This agreement allows the prediction of the aquifer response to pumping and injection with a relatively simple mathematical model.

Summary and Conclusions of 1983 Reservoir Test

The central focus of the research described is the response of the shallow geothermal aquifer to stresses imposed by pumping and injection of the thermal water. In order properly to interpret the data derived from the pumping and injection tests, a number of additional tests and studies were made. These included chemical analyses, tracer tests, temperature measurements, and the collection of lithologic, climatic, seismic, discharge, and utilization data. As a result of these activities, some existing concepts of the geothermal aquifer were confirmed and several crucial new concepts were developed.

Occurrence and Characteristics of the Thermal Water

Lithologic and hydrologic data obtained from approximately 175 drillers' logs showed that the thermal water is derived from a stratified and a really heterogeneous aquifer. Within the total thickness of rocks that contain the aquifer, water moves preferentially in permeable strata that include lacustrine and volcanic sediment, and basaltic to andesitic flow rocks, breccia and pyroclastics. The known thickness of rocks that comprise the water-bearing zones is nearly 2,000 ft (610 m). The total thickness and a real extent, and hence the volume, of the reservoir are not known.

The areal distribution of hydraulic heads and temperatures in the aquifer suggest that the thermal water rises along a fault zone near the northeast edge of the hot-well area and flows southwestward. The temperature of the water, which initially is higher than 248ºF (120ºC), decreased in the direction of flow, and at distances greater than 3,000 ft (914 m) from the fault, is generally less than 176ºF (80ºC).

Thermal water discharges at the land surface from wells in an area of about 3/4 square mile (2 km^2) centered about 3,000 ft (914 m) from the fault zone. This area formerly contained 5 groups of thermal springs that reportedly produced boiling water. Some of the artesian wells still produce water at or near the boiling point (96ºC); but, hydraulic heads reportedly have declined about 15 ft (4.6 m) over the past 40 or 50 years. The occurrence of artesian pressures indicates that the aquifer is locally confined by rocks of low permeability at its upper surface.

The decline of artesian head and the final disappearance of the springs occurred in conjunction with an increase in withdrawals of thermal water and heat. An exclusive cause-and-effect relation between these occurrences is obscured, however, by the possibility that spring flows had begun to decline prior to any pumping, possibly in response to climatic changes. An analysis of climatic records might indicate whether or not a decrease in precipitation has reduced recharge to the geothermal system; but, the apparent great age of the thermal water may make this determination difficult or impossible. An understanding of the full causes of head decline is essential to an assessment of the long-term potential of the reservoir; but, a complete understanding was not achieved during this study.

Seasonal fluctuations in water levels occur in the aquifer as fluid withdrawals and the use of DHEs increase or decrease. These fluctuations correlate closely with changes in mean-daily air temperature. They show that water levels respond quickly to changes in the demand for heat, and the uniformity of the responses indicates that the aquifer properties and the thermal water supply are reasonably uniform throughout the hot-well area.

The annual winter decrease in water level is about 4 to 6 ft over much of the area; but, fluctuations are as large as 11 ft near the center of the area. On the northwest and southwest margins, fluctuations are 1 ft or less. The resulting inverted "cone of depression" is typical of producing well fields in homogeneous aquifers; but, the magnitude of fluctuations in wells near the center of the cone could be due partly to a smaller transmissivity (permeability times thickness) in this area. No evidence of a significant decrease in transmissivity was observed in this area during the aquifer test, however.

In wells containing DHE, a predictable qualitative relationship was observed between increased heat demand and a decrease in water level. However, the effects of DHEs on temperatures and water levels in the aquifer as a whole were not determined by our study. Some of our data indicate that aquifer temperatures are nearly constant during the heating season, and this suggests that the effects of DHEs on water levels probably are small and local compared to the widespread effects of pumping.

Our interpretation of the annual cycle of drawdown and recovery in the aquifer is based on measurements made during only the past 4 to 5 years in several wells. These records suggest that drawdowns due to current levels of withdrawal and DHE are probably reach an equilibrium condition during the period of maximum use (February - March) each year. If equilibrium is attained, it implies that the maximum withdrawals thus far made from the aquifer are balanced by recharge.

We have found no clear indication that a general temperature decrease has occurred in the aquifer as the result of increasing withdrawals. Individual DHE wells show temperature decreases if the natural convective flow in the well is interrupted for any reason, and temperature decreases occur in heating systems if the efficiency of the DHE is impaired by corrosion or a decrease in the heat-exchange surface area. Temperatures quickly increase again if these adverse conditions are remedied, and neither of these effects indicates a change in aquifer conditions. The temperature data are inadequate for a determination of long-term changes, however, and no final conclusion concerning such changes has been reached during this study.

Current Use of Thermal Water

Thermal water is discharged to storm drains, sewers, and the A-Canal by about 70 wells in the hot-well area. In four pairs of doublet wells, water is pumped from the aquifer and injected again through the second well. Excluding the doublet-well discharge, the average discharge of thermal water from wells in the hot-well area is approximately 540 gal/min (34 l/s) or 775,000 gal/day. The amount of heat removed from the aquifer by pumped and artesian wells is nearly 40 x 10^6 Btu/h (12 MWt). This is about the same quantity of heat discharged by the more than 380 wells that use DHEs.

The low efficiency of the pumped discharged is mitigated somewhat by the fact that a significant amount of the discharge is collected and reused for heating prior to its final disposal into Lake Ewauna. Despite this cascading of uses of discharge, the abstraction of heat by DHEs appears to be a more efficient use of the resource than the present pumped discharge.

The results of the injection and tracer tests indicate that pumping could be made a more efficient use of the resource if accomplished by reinjection. Using the estimated figures obtained in this study, a comparison can be made of the thermal efficiency of pumping and discharging water at the surface versus pumping and reinjecting the water into the aquifer. Assuming that the average temperature of the water now withdrawn by pumped wells is 176ºF (80ºC)(a conservative figure), and using as a base temperature the average temperature of shallow groundwater in the area (54ºF or 12ºC)(Sammel, 1980), a calculation shows that the pumped wells discharge about 1,016 Btu per gallon of water pumped. For comparison with the reinjection case at a comparable scale of use, estimates of the heat and pumping requirements for a representative district heating plan can be used. Assuming that the water is reinjected, only part of the heat is discharged, the remainder being returned to the aquifer. On the basis of estimates made by OIT for a district heating plan of moderate size, the net withdrawal of heat is estimated to be about 330 Btu per gallon of water withdrawn. Thus, from the standpoint of heat losses from the aquifer, the consolidated use of heat from one or two wells with reinjection is clearly several times more efficient than a distributed use of heat from many wells without reinjection. Additional benefits obtained by the return of water to the aquifer are, of course, the maintenance of pressures and water levels in the reservoir.

A comparison of a large-scale heat-exchanger use, such as a district heating plan, with current individual use of DHEs cannot be made on the same basis as the previous example. However, data on which to base such a study are now available, and a meaningful comparison could probably be made by engineers in this field.

Geochemistry of the Reservoir Fluids

The chemical and isotopic compositions of the thermal and non-thermal waters of Klamath Falls show that the water in the shallow thermal aquifer is a mixture of a cold, dilute groundwater with a hot, more saline component originally at a temperature between 300 and 374ºF (150 and 190ºC). The mixing produces waters at 203 to 266ºF (95 to 130ºC) with a corresponding small range of salinity. The mixed thermal waters contain (in order of decreasing concentration) SO_4, Na, SiO_2, Cl, HCO_3, Ca, and K, and have a total salinity of about 1,000 mg/kg. This chemical composition is typical of waters that have equilibrated at high temperatures in a geothermal reservoir.

The non-thermal waters contain HCO_3, SiO_2, Na, Ca, Mg, Cl, K, and SO_4; salinity is less than 250 mg/kg. Although the cold water involved in the mixing could not be sampled, extrapolation of the data for the mixed waters shows that the cold component contains more Cl than the analyzed cold waters (10 vs 4 mg/kg) and more tritium (about 2 TU). The isotopic and chemical compositions of the mixed thermal waters show that both hot and cold components could have originated from local or regional groundwater and that none of the water is of magmatic origin.

Sources of recharge have not been identified during this study. Deuterium concentrations suggest that recharge may occur at higher altitudes than those in the immediate vicinity of Klamath Falls, and the low tritium concentrations show that the cold recharge water has had a long (>30 years) residence time in the ground. These indications imply that the water has traveled a significant distance from the points of recharge and that the flow may occur in a deep regional aquifer.

The sulfate-water isotope geothermometer gives a probable temperature of 372°F (189°C) for the deep thermal water. This temperature is in agreement with the silica (quartz) geothermometer when applied in a mixing model, and these models also produce a reasonable thermal end member on the basis of isotopic (18°) mixing. The consistency of these results probably warrants a considerable amount of confidence in these geothermometers.

The Na-K-Ca geothermometer suggests that cation re-equilibration has occurred in the mixed water, and indicated temperatures are close to those observed in the waters sampled. The results are similar in part to those obtained in other fault-controlled geothermal systems in volcanic terrains, such as Warner Valley in south-central Oregon (Sammel, 1981) or Newberry Volcano in west- central Oregon (Sammel, 1983), where cation geothermometers indicate temperatures significantly lower than original reservoir temperatures. The cation geothermometer and other chemical data at Klamath Falls suggest that the re-equilibration zone could represent an extensive and possibly deep low-temperature reservoir.

<u>The Tracer Tests</u>

Information obtained from the tracer tests provides a preliminary basis for important decisions regarding the use and development of the resource. These decisions relate mainly to the possible consequences of reinjection if this method is to be employed as a part of the development strategy. The analysis of the pumping and injection tests leaves little doubt that reinjection of the thermal water at almost any point in the aquifer could raise water levels over a large area. However, this analysis must take into account the tracer-test results which relate to the thermal effects of reinjection.

The tracer tests tend to confirm the nature of the aquifer indicated by the pumping test. They show the small volumes of fluid move rapidly through large fractures and permeable porous media. The transfer of large volumes of water is much slower, however, because most of the rock volume has low permeability. Most of the heat in the aquifer is stored in the massive rock material, and this storage has the effect of slowing the temperature decrease that occurs when cooler water is introduced into a hot aquifer.

The production of the thermal and hydraulic consequences of injection has large uncertainties at the present time. For example, the preliminary tracer analysis indicates that thermal breakthrough between closely spaced production and injection wells may occur in a matter of a few weeks or months; whereas, experience with doublet wells at Klamath Falls shows that significant temperature changes do not occur in 3 of the 4 existing doublet pairs during the 9-month heating season. The fact that temperature has decreased in one doublet pair (S. M. Benson, oral communication, 1983) suggests, however, that injection brings with it a significant risk and, therefore, must be used with caution.

Results of both the tracer tests and the pumping test suggest that injection wells should be carefully designed and located. In planning the locations, the indications of anisotrophy observed in the pumping test may be useful for guiding the placement of points of injection. For example, the probability of increased pressure support along the axis of anisotrophy should be weighed against the increased likelihood of thermal breakthrough along this axis. The depth of injection also will be an important consideration in relation to the depths of water entry in existing wells. Lithologic logs and drillers' reports can be consulted in making these determinations. Monitoring and tests of all injection activity will be essential for increasing understanding of the aquifer behavior and for reducing uncertainties in predictive models.

<u>The Hydrologic Tests and Their Interpretation</u>

The aquifer test conducted for this study differed from previous tests at Klamath Falls in the duration (50 days), its three distinct phases (pumping, pumping and injection, recovery), and the areal extent and intensity of monitoring (52 observation wells). Data collected during the test provide an unparalleled opportunity to study the hydraulic characteristics of an extensive, heterogeneous aquifer system in volcanic rocks. The data contain complexities, not resolved for this report, that will provide opportunities for analysis and research for some time to come.

<u>Aquifer Behavior Under Stress</u>

The plots of drawdown versus time obtained during the test fit theoretical curves that represent double-porosity conditions in the aquifer. The worlds "double porosity" are used here to describe an aquifer in which the initial flow in response to pumping occurs largely in more permeable strata or in fractures; whereas, flow at later times is sustained partly by contributions from less permeable masses of rock (the matrix). Examination of drillers' logs and well cuttings indicates that the Klamath Falls aquifer contains both fractured rock and granular strata of high permeability as well as unfractured, massive rock and sedimentary strata of low permeability. For practical purposes of use and development, these two types of aquifers behave similarly and may have identical potentials for development.

Pressure changes were transmitted rapidly at the start of the pumping test. This finding is in accord with results of the doublet-well tracer tests, which show that the thermal water moves rapidly in permeable strata or fractures. The rapid and uniform response of observation wells also indicates that the permeable strata and fracture zones are confined by rocks of low permeability so that they behave more like a network of pipes than an unconfined reservoir. This concept is supported by the isotopic data (tritium), which show that little recent meteoric water mixes with the thermal water in the shallow aquifer.

Drawdowns caused by the aquifer test generally were not as large as those caused by current winter withdrawals. Consequently, the aquifer was not stressed sufficiently to cause new patterns of behavior to occur at its boundaries. The aquifer test did not reveal any hydrologic boundaries within 6,000 ft (1,830 m) of the production well in a NW direction and within 4,500 ft (1,370 m) in a SW direction. One implication of this fact is that the presumed supply vents in the fault zone did not act as restrictions on the flow. Thus, the fault conduits must be at least as transmissive as the aquifer rocks.

The absence of significant temperature changes in the produced water and in monitor wells during the aquifer test implies that no detectable cold-water flow as induced by the drawdowns. Cold-water recharge might have occurred at the boundaries of the hot-well area; but, such effects would have been very small, and thus, not likely to have been detectable in the late stages of the test.

During the third week of the pumping test, water levels had begun to fluctuate and, in some wells, to rise, presumably in response to a decrease in heat demand in supply wells and DHE wells. The effect was to obscure that true drawdown curve and, possibly, to mask the interception of recharge or low-permeability boundaries in the final stages of drawdown must be tempered by the possibility that small effects could have been missed.

Effects of Injection

The start of injection produced a rise in water levels that was detected almost immediately in all monitor wells. Aquifer characteristics observed during the injection phase of the test satisfactorily match those observed during the pumping-only phase.

The effectiveness of injection wells in supporting water levels and hydraulic pressures has been qualitatively known for many years at Klamath Falls as the result of experience with the 4 pairs of doublet wells. The analyses of the drawdown and injection data presented, show clearly that injection of thermal water is capable of offsetting the immediate and widespread drawdowns that occur during pumping. This conclusion could have been arrived at solely on the basis of the drawdown data; but, the results of the injection test are doubly reassuring on this point.

The price to be paid for the benefits of reinjection resides in the possibility of thermal breakthrough. This potential threat is subject to analysis and prediction; but, the complexities of these analyses have not been completely resolved for this report. Thermal breakthrough is reversible; but, longer time may be required for reversal than was required for the occurrence.

Potential for Development

In considering additional development of the geothermal resource at Klamath Falls, the issue, expressed in its simplest terms, is whether or not a specific development can occur without harm to the resource or to existing users. The issue, thus stated, is an oversimplification, however. The following discussion attempts to address some of the many considerations that have a bearing on what constitutes the resource and what constitutes "harm."

Present development at Klamath Falls utilizes a part of the total resource that exists in a shallow aquifer and a supply conduit (fault zone) of unknown depth and volume. Within and beneath the shallow aquifer, deeply circulating meteoric water mixes with high-temperature water from a deeper source. The depth and volume of the mixing zone are unknown; but, the zone could extend beyond the boundaries of the hot-well area. Thus, the resource may include a reservoir of hot water that is not currently tapped by wells and that may have a potential for development.

Basic groundwater theory shows that water levels decline in predictable ways in a pumped aquifer supplied by a line source (the fault). Because the fault was not seen as a restrictive boundary during the aquifer test, we conclude that additional pumping could occur in the shallow aquifer before the storage capacity and flow capacity would be fully utilized. The consequences of additional pumping would be to increase drawdowns in the aquifer as gradients of flow increases to meet the new demand. Were this to occur, there would be little possibility of "harm" to the aquifer or reservoir because underlying recharge patterns are not likely to be affected by activities at shallow depths. However, if water levels were drawn down sufficiently to induce recharge of shallow meteoric water in the fault or the aquifer, temperatures ultimately would decrease. This decrease would be reversible, but only by decreasing pumping or altering its timing. Present knowledge does not permit us to predict whether or not cold-water recharge could be induced in the shallow aquifer.

In the shallow aquifer, increasing drawdowns could produce adverse consequences for some well owners. A small decline in water level would not directly result in a sufficient increase in pumping costs in most wells; but, a decrease in artesian head in some wells could prolong the time each year during which pumping is required, thereby increasing the cost. A decline in water level in the DHE wells will decrease the available heat-exchange area and, in some wells, will uncover the upper perforations that help to maintain temperatures in the well.

Reinjection can offset water-level declines due to pumping; but in the immediate vicinity of a production well, water levels will always be lower than elsewhere. The aquifer-test analyses provides preliminary basis for predicting the consequences of both pumping and reinjection, thereby permitting potentially harmful effects to be foreseen and possibly avoided.

A possible approach to new development is the drilling of deep wells into the underlying mixing zone. The hoped-for benefits would be the availability of hotter water than that obtained in most of the shallow wells. The chemical nature of the mixed water and probably high regional thermal gradient imply that the thickness of this zone could be as small as few thousand fee and probably is not greater than about 6,000 ft (1,830 m). It is, therefore, within economic drilling limits. The mixing zone is not necessarily extensive, however, and it could be restricted to the fault conduits. Whether or not the mixing zone is deep or areally extensive, development of this zone might result in interference with wells in the shallow aquifer. Thorough testing would be required in order to determine or predict the consequences of development.

This brief discussion indicates that additional development is not ruled out by our present understanding of the aquifer conditions; but, that development will be accompanied by risks and costs, some of them not well understood. Predictions made possible by these analyses make extrapolation over periods of years highly uncertain, and our current ignorance of recharge conditions and climatic effects leaves a large gap in our understanding of critical factors in the aquifer behavior.

The magnitude of possible additional development of the shallow aquifer cannot be estimated on the basis of available information. Specifically, we lack information on the volume and extent of the aquifer, its boundary conditions, the magnitude and sources of recharge, and the impact of DHE wells. Pending such admittedly costly and time-consuming investigations, continued monitoring of temperatures, water levels, withdrawals, and DHE use can provide invaluable data on which to base decisions regarding additional development. The knowledge gained in our investigations represents a considerable advance; but clearly, it is only a first step toward a full understanding of the nature of the Klamath Falls geothermal system. If further development were to occur in small, carefully planned stages, and if the effects of such development were carefully monitored, much more could be learned about the limits and potential of this promising energy resource.

Finally, we point out that recent advances in geothermal development make feasible many alternative approaches to the use of the resource. Binary-fluid heat pumps, advanced heat exchangers, distributed reinjection, cascading of thermal uses to lower temperatures, and simple conservation measures are alternatives, most of which would permit additional use of the resource with few or no adverse consequences. A mix of these alternatives, developed with the same spirit of community cooperation and initiative that proved so helpful in the testing program, could extend the life of the resource and provide benefits in ways that probably are limited only by the resourcefulness and imagination of the Klamath Falls community.

In late 1984, the city retained William E. Nork, Inc. of Reno, Nevada, to provide a hydrologic assessment of the reservoir. This was the first heating season for the district heating system. Nork, of course, had the data from the 1983 test, but also had continuously recorded water levels from 15 wells, weekly hand-measured levels from 9 wells, plus measured and/or estimated pumping rates from a number of wells taken at different outdoor temperatures.

He reached the same conclusion as Sammel--that indeed pumping rates go up and water levels go down in response to lower outdoor temperatures. However, he had longer term data, from mid-October through early June, and was better able to quantify pumping rates based on weather data.

Nork used an "inverted VARFLOW" reservoir simulation model. Instead, of estimating water level declines in response to pumping, he utilized the recorded water levels, estimated pumping rates based on weather data, and known pumping rates of the district system to estimate recharge to the system.

Using the model, Nork estimated summer recharge at about 300 gpm and winter recharge at about 600 gpm. He attributed the recharge to snow pack at 2 different elevations (Nork, 1985).

DEVELOPMENT AND UTILIZATION

Introduction

The shallow geothermal reservoir in Klamath Falls extends for at least 6.8 mi (11 km) in a northwest-southeast direction with a width of about 1.9 mi (3 km). More than 500 wells ranging in depth from about 100 ft (30 m) up to 2,000 ft (600 m), and obtaining or contacting water from 70 to 230ºF (21 to 110ºC), have been drilled into the reservoir.

Today, most of the eastern portion of the city of Klamath Falls is heated by geothermal fluids. The principal heat extraction system is the closed-loop downhole heat exchanger (DHE) utilizing city water in the heat exchangers. Typically, one well serves only one house by the use of the DHE. In a few cases, DHEs will serve several homes, an apartment building or a school.

Present uses include over 500 residences, seven city schools, Oregon Institute of Technology (OIT), Merle West Medical Center, Klamath County Jail, YMCA, Maywood Industries, melting of snow from a state highway pavement, direct use in a laundry, and for heating swimming pools. Several locations make use of waste hot water discharged into storm drain lines. The total estimated capacity of Klamath Falls geothermal systems is 118.8 x 10^6 Btu/h (34.8 MWt) and the annual energy use is 267.1 x 10^9 Btu/y (78.3 x 10^6 kWh/y). Table 6 provides a summary of the Klamath Falls utilization.

Table 6. Information Summary of Klamath Falls Systems

System	Resource Temp.	Max. Flow (gpm)	Capacity (10^6 Btu/h)	Annual Energy (10^6 Btu/y)
Residential (550 homes)	120-210	NA	43.6	95.4
Oregon Institute of Technology	192	620	16.8	38.2
City District Heating	210	650	13.0	28.4
Merle West Medical Center	191	325	10.5	23.9
Klamath County Jail	150	700	10.5	23.0
Klamath Schools (7)	147-180	NA	8.7	19.8
Apartment Buildings (13)	140-190	NA	6.5	14.2
Maywood Industries	118	450	3.0	6.8
Swimming Pools (5)	140-190	NA	1.1	4.3
Churches (5)	140-200	NA	1.7	3.9
Klamath County Shops	118	113	1.6	3.6
YMCA	147	120	1.4	3.1
Highway De-icing	190	NA	0.4	2.5
			118.8	267.1

Well Construction

Two types of geothermal wells have been developed in Klamath Falls. The most common type utilize a downhole heat exchanger primarily for residential heating. Larger commercial and district heating systems utilize production wells with lineshaft turbine pumps to deliver geothermal fluid to buildings.

Most of the wells in Klamath Falls are drilled with cable-tool (percussion) drilling equipment. Early wells, which utilized downhole heat exchangers, were relatively shallow mainly because of their location in the better geothermal areas. The casings of these early wells were only deep enough to case off cold surface water and to prevent caving near the surface. The typical casing length was 30 ft (9 m) and, in many cases, had only 1/8 in. (3 mm) wall thickness. As a result, caving would often occur below the casing, filling in the lower portion of the well and causing the temperature of the water to decrease. Electrolysis would develop between the downhole heat exchanger and the wellbore below the casing requiring replacement of the heat exchanger in less than 10 years.

Measurements of electrical potential between heat exchanger pipe and well casing indicated values up to one volt AC and DC with 100 and 300 millivolts being common, and up to 100 milliamps with 5 to 30 milliamps being common. This electrolytic corrosion has been suspected of being a major source of corrosion. Sacrificial anodes and isolation junctions have been used to minimize electrolytic corrosion, which is probably due to power lines in the vicinity and to the practice of grounding residential electrical circuits to cold water pipes (Lund, 1976).

The usual construction of newer wells, involves a wellbore 10 to 12 in. (254 to 305 mm) in diameter, and a casing 8 in. (203 mm). Well depth is determined by a sufficient strata of free-flowing water, a temperature >160ºF (71ºC), and the length of coil required to supply heat for the structure. Contractors consider 2 ft (0.6 m) of cross-flow geothermal fluid near 190ºF (88ºC) as the minimum to provide sufficient heat for a typical 1,600 to 1,800 ft^2 (150 to 170 m^2) home, with longer sections more desirable (Culver, 1974).

Drillers prefer to continue drilling 10 to 25 ft (3 to 8 m), after encountering a free-flow strata, to provide space for a mud leg and a volume for holding debris that may slough into the well and cover the lower flow.

Once the wellbore is complete, casing is started down the hole. Perforations are cut in the casing as it is lowered, so that free-flowing water can enter the casing. The casing extends to the bottom of the bore and, by Oregon law, must be set in a solid formation. If required, a packer may be installed to block off cold-water flows. Packers are generally made by securing burlap to the casing in the desired position as the casing is lowered. After the casing is set, grout is placed above the burlap to provide a permanent seal. Present casing thickness is 1/4 to 5/16 in. (6 to 8 mm), and the expected life is well over 50 years.

Two sets of perforations are cut into the casing (consisting of ten to twenty, 12 in. long by 1/4 in. wide slots), one set at the live hot water flow and the other just below the static water surface (or below the packer when cold-water flows are encountered). Since the bore is larger than the casing (2 to 4 in. clearance is desirable), the perforations allow a vertical circulation cell to develop in the well, circulating inside and outside the casing. This results in the hotter, bottom hole fluid temperature being brought to the surface, allowing higher temperature to come in contact with the entire length of the downhole heat exchanger.

Typical drilling and 8 in. casing costs run \$25 to \$40 per foot (\$82 to \$131 per meter), depending upon the amount of hard rock encountered. Figure 34 illustrates the typical well completion practice and downhole heat exchanger.

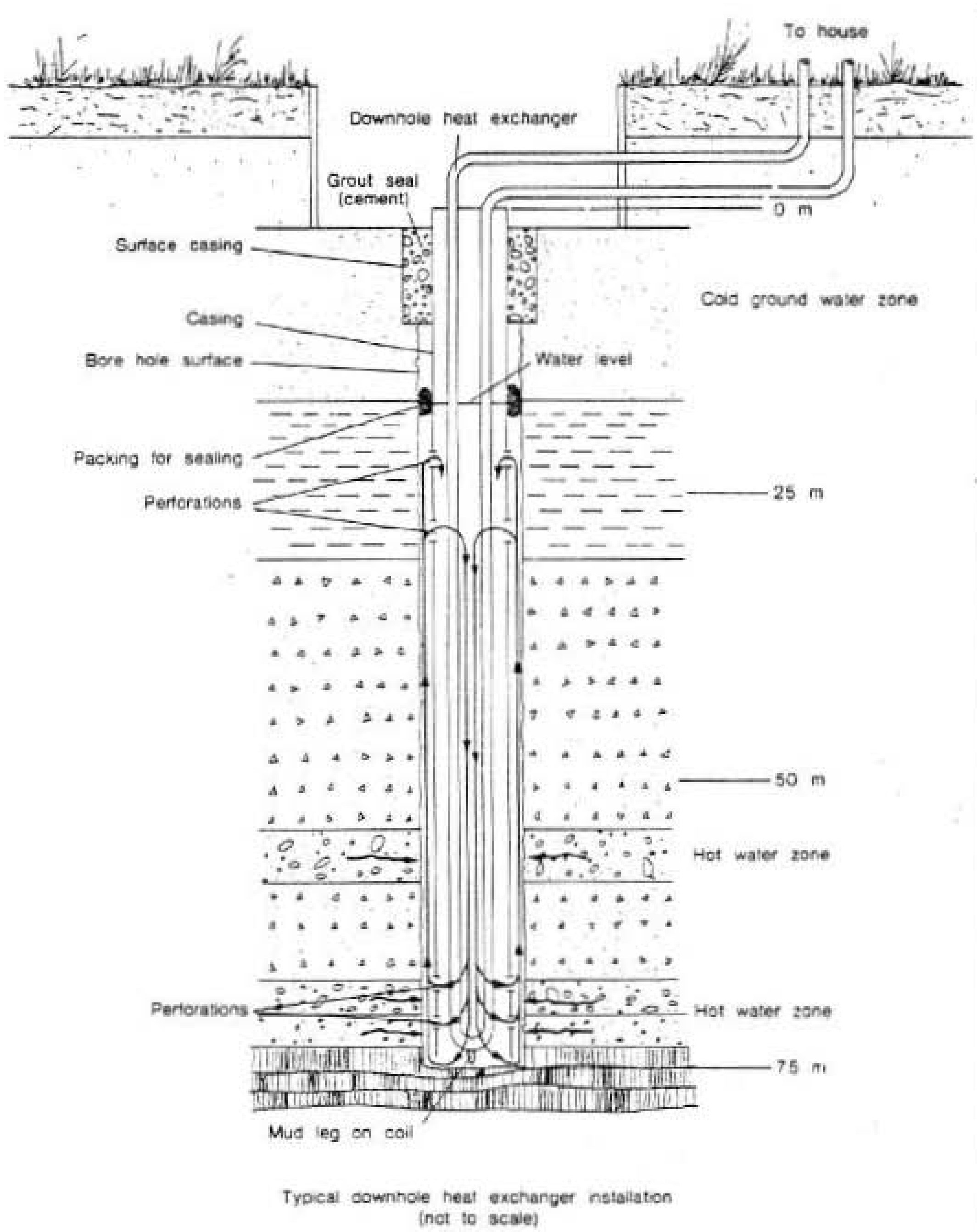


Figure 34. Typical Klamath Falls well with downhole heat exchanger (Justus, et al., 1980).

Large space and district heating projects in Klamath Falls, such as the city district heating system, OIT, Merle West Medical Center, Maywood Industries, several schools, etc., utilize production wells with lineshaft vertical turbine pumps installed.

Direct-use production wells consist of three main parts: surface casing (pump housing), the inlet portion, and the production casing between them. Surface casing diameter is usually two nominal pipe sizes larger than the pump bowls. For example, a production rate of 350 to 700 gpm (22 to 44 l/s) requires an 8-in. (203-mm) diameter pump and a nominal surface casing diameter of 12 in. (305 mm).

The production well pumps are vertical lineshaft turbines with fluid coupling type variable-speed drive units as shown in Figures 35 and 36. The variable-speed drive provides for continuous operation of the pump to provide constant pressure at the wellhead and in the supply line under varying flow requirements. Pump discharge pressure is monitored by the fluid coupling control, which changes turbine shaft speed to maintain constant discharge pressure from no-flow to full-flow conditions and eliminates the need for storage tanks required with intermittent pump operation. The actual design of the pumps evolved over the initial 16 years of operating the OIT geothermal heating system.

In 1964, at OIT, direct drive lineshaft vertical turbine pumps were originally installed with electric motors in 5 ft (1.5 m) pits; this resulted in overheating of the motors. Open lineshaft water lubricated bearings, spaced at 10 ft (3 m) intervals, developed problems due to hot water vaporizing in the bearing housing causing them to burn out.

In 1970, the pump system design was modified by adding variable-speed fluid coupling drives, extending the motor to the surface for ventilation and using an oil lubricated enclosed lineshaft. The 13-stage pump was set at 450 ft (137 m) in the 1,716 ft (523 m) OIT Well No. 5, where the static water level was 358 ft (109 m) below the surface. The pump was custom designed for a 5 in. (127 mm) differential expansion (lateral between the lineshaft and the column. The start-up procedure is to lower the shaft to the bottom then raise it 5 in. (127 mm) to allow for expansion during the time to reach thermal equilibrium.

The following materials, which have performed satisfactorily, are used for pump construction:

Column	Bowls	Bowl Bearings and Impellers	Pump Shaft	Impeller Lock Collets
ASTM A53 Grade A	ASTM A48 Class 35 Gray iron	ASTM 584 Alloy UNS Leaded red bronze	Type 416 SS	Type 316 SS

Turbine oil No. 68 is used for lineshaft lubrication.

Since 1970, the only serious problem has been with the main thrust bearing in the driver. This bearing has had to be replaced four times at a cost of about $1,200 per replacement. The column in No. 5 was replaced after 25 years of operation due to corrosion. Oxygen is prevented from contacting the inside of the column by maintaining a back-pressure with the variable-speed drive.

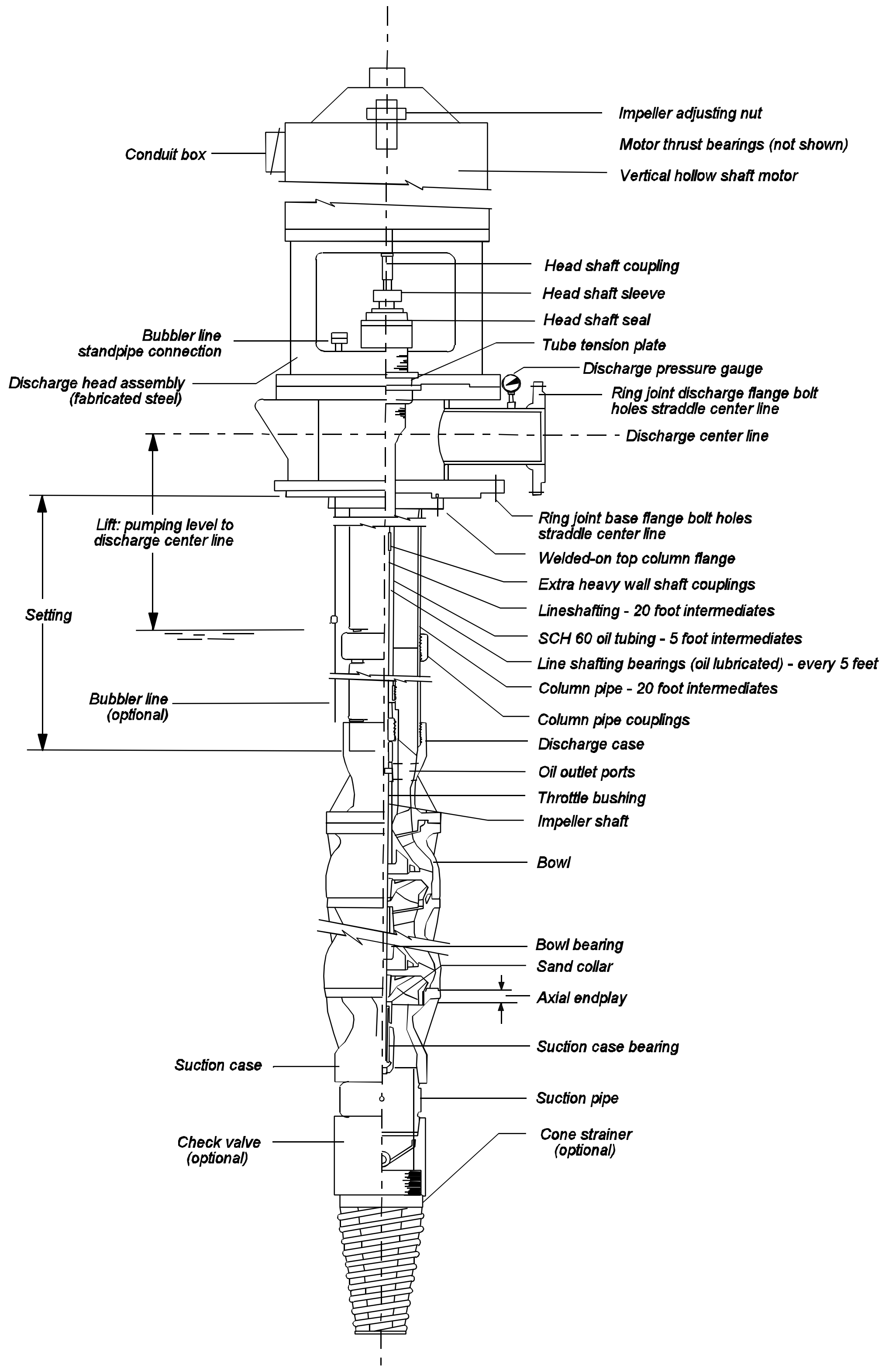


Figure 35. Typical lineshaft turbine pump with an enclosed oil-lubricated shaft (Culver and Rafferty, 1989).

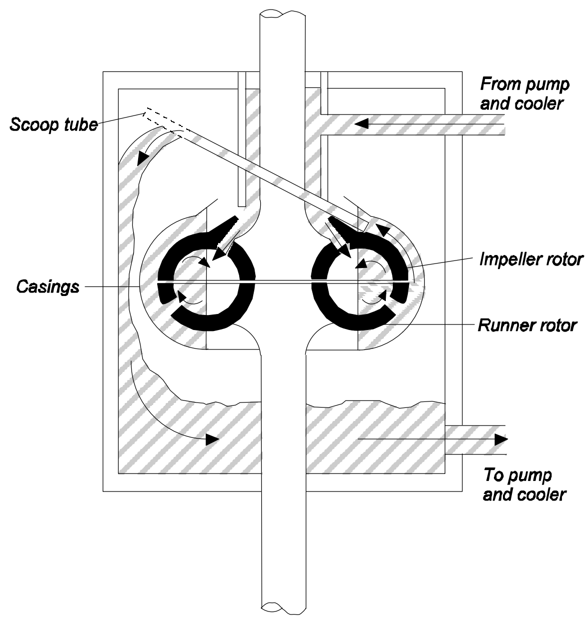


Figure 36. Fluid coupling (Culver and Rafferty, 1989).

Start-stop modes of operation causes serious corrosion problems, with the introduction of oxygen, such as that experienced by the neighboring hospital well.

The life of the OIT vertical turbine pumps has been over 20 years and the design developed has been the basis for other installations such as that at Merle West Medical Center, YMCA, Maywood Industries, city district heating, county jail, and others in the community.

Heat Exchange Systems

Three types of heat exchange systems are utilized. The downhole heat exchanger--typically serving one house, plate heat exchangers for district heating systems, and tube-and-shell heat exchangers for Klamath Union and Mazama High Schools. Merle West Medical Center employed tube-and-shell heat exchangers for about four years; fouling problems resulted in the conversion to plate heat exchangers.

Downhole Heat Exchanger

Since the turn of the century, geothermal well water has been piped through space heating systems in Klamath Falls. Even though the water in the area is usually pure for geothermal (800 to 1,200 mg/L), it corroded and scaled plumbing systems of the area so that, in a relatively short time, the systems had to be repaired or replaced. In about 1930, the first downhole heat exchanger (DHE), locally known as a coil, was installed in a geothermal well. The heat exchanger coil consists of two strings of pipe connected at the bottom by a reverse bend. The temperature of the well water and the predicted heat load determine the length of the pipe required. Based on experience, local heating system contractors estimate approximately "1 ft of coil per 1,500 Btu per hour" required (1.44 kWt/m). The coil pipes are connected to the supply and return of the distributing piping and the entire system filled with city water. Figure 37 illustrates a typical system. The heating coil is typically 2 in. (51 mm) in diameter and the domestic water coil is 3/4 in. (9 mm) in diameter. The "thermo-syphon" process (or gravity feed in standard hot water systems) circulates the water, picking up heat in the well and releasing the heat in the radiators. Circulation pumps are required in cooler wells or in larger systems to increase the flow rate. Thermo-syphon circulation will provide 2.9 to 5.1 psi (20 to 35 k Pa) pressure difference in the supply and return lines to circulate 16 to 24 gpm (3.6 to 5.5 m^3/h) with a 10 to 20°F (6 to 11°C) temperature change (Culver, 1978).

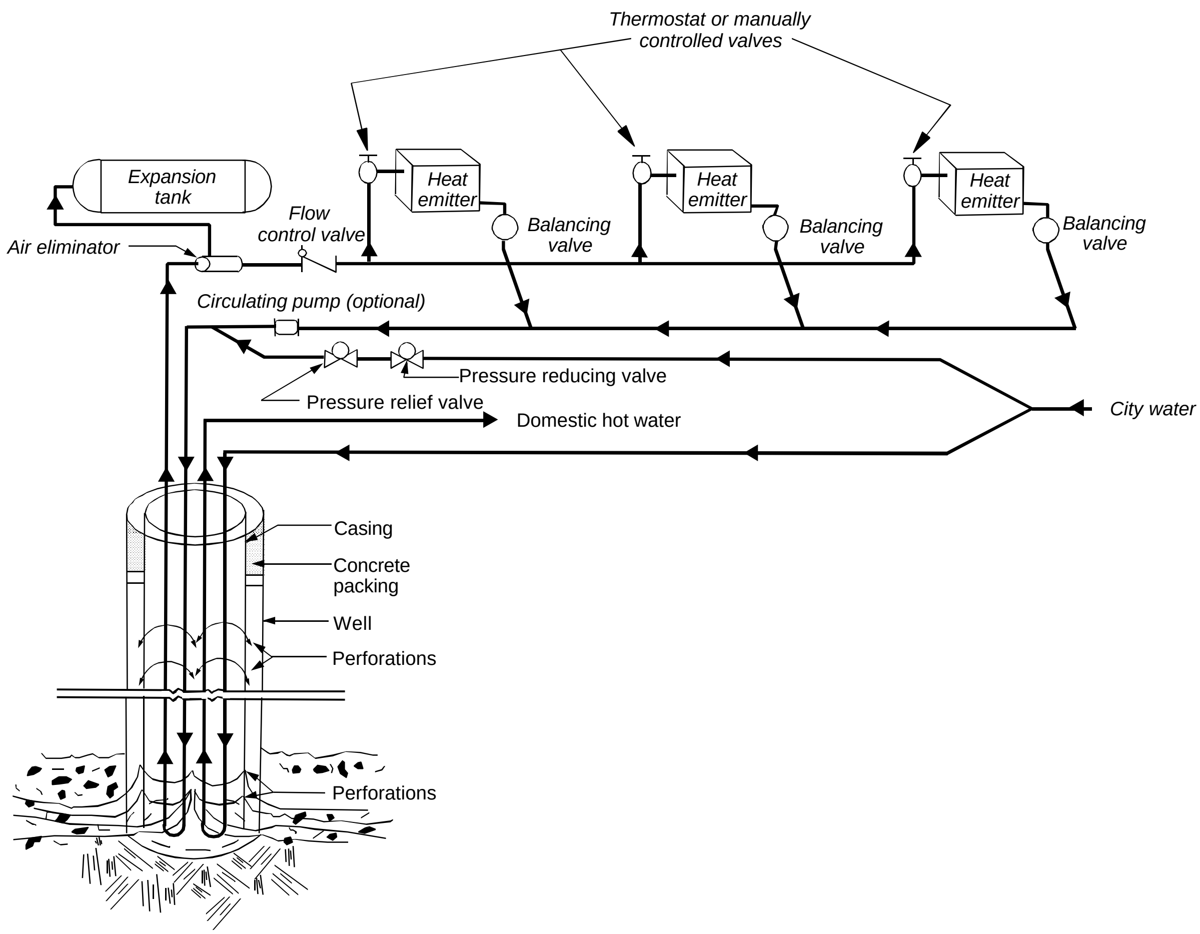


Figure 37. Typical hot-water distribution system using a downhole heat exchanger (Culver, 1978).

The largest output of a DHE is at Ponderosa School, where a 460 ft (140 m), 198°F (92°C), well contains two 2-in. (50-mm) and one 3-in. (76-mm) downhole heat exchangers. Two circulating pumps (7.5 hp each) with an estimated maximum flow of 525 gpm (33 l/s) produce a capacity of 4.2 x 10^6 Btu/h (1.2 Mwt) from the DHEs (Lienau, 1976).

Most heat exchanger pipes are standard black iron pipe; although, a few are double strength near the top in deep wells to reduce stresses, or at the water line to provide longer corrosion resistance. Other materials have been tried for use at the water line including fiberglass and brass, and based on limited information, these appeared to extend the life of the system. The most common, economical, and apparently effective method of reducing corrosion is to pour used motor oil or paraffin in the well.

These materials either reduce evolved gases and water vapor, or provide a protective coating on the coil surface, or both. Several types of corrosion-resistant paints have been tried with questionable results.

There are several older or cooler wells that are pumped directly into the storm sewers or canal. In most cases, the well is pumped in order to increase the flow of geothermal waters and to raise the temperature of the well to a level locally considered satisfactory for use in space heating, about 140ºF (60ºC). In a few instances, mostly in the artesian area, well water is pumped directly through the heating system.

The downhole heat exchanger system is economical, minimizes corrosion problems, conserves the resources, and eliminates the problem of waste-water discharge.

Plate Heat Exchangers

Based on the experience at OIT, after a few years of operation, it was apparent that use of the fluid directly would not be acceptable over the long term. Serious corrosion problems occurred, particularly in copper and copper alloys. Copper tubing, due to attack by hydrogen sulfide (H_2S), failed in as little as 5 years. In addition, various solder used for joining the copper piping were completely removed from fittings in as little as 2 years (Rafferty, 1989).

In response to this situation, plate heat exchangers have been installed in many buildings to isolate the building heating system from exposure to geothermal fluid. By 1990, these heat exchangers will be installed in all campus buildings. Figure 38 shows a typical installation. Most of the heat exchangers are constructed of type 316 stainless steel and nitrile (Buna-N) rubber gaskets.

The plate heat exchangers have subsequently been installed in the YMCA, city district heating system, Merle West Medical Center, County Jail, etc. The plate heat exchanger is generally considered superior to the tube-and-shell type in applications for geothermal liquid-to-liquid heat transfer where close approach temperatures are desirable and plate materials other than mild steel are required for corrosion resistance. They require little floor space, are easily cleaned, and are much more efficient. Of particular importance is the ease of changing exchanger surface area to accommodate changes in flow and temperature conditions by adding or removing plates.

Distribution Systems

Distribution systems for Klamath district heating systems fall into two general designs: open and closed. The closed type includes central heat exchangers, such as the city district heating; while, the open system delivers geothermal fluid directly to the buildings. OIT operates an open-type system.

This is an important distinction since the open-type design exposes the entire distribution system to the geothermal fluid.

A variety of piping materials have been applied to Klamath geothermal systems. Residential heating systems are generally connected to DHEs with 1.5 in. (40 mm) black iron pipe. District heating systems have used Schedule 40 steel and fiberglass epoxy resin pipe which employs two types of installation methods: direct buried and concrete tunnel.

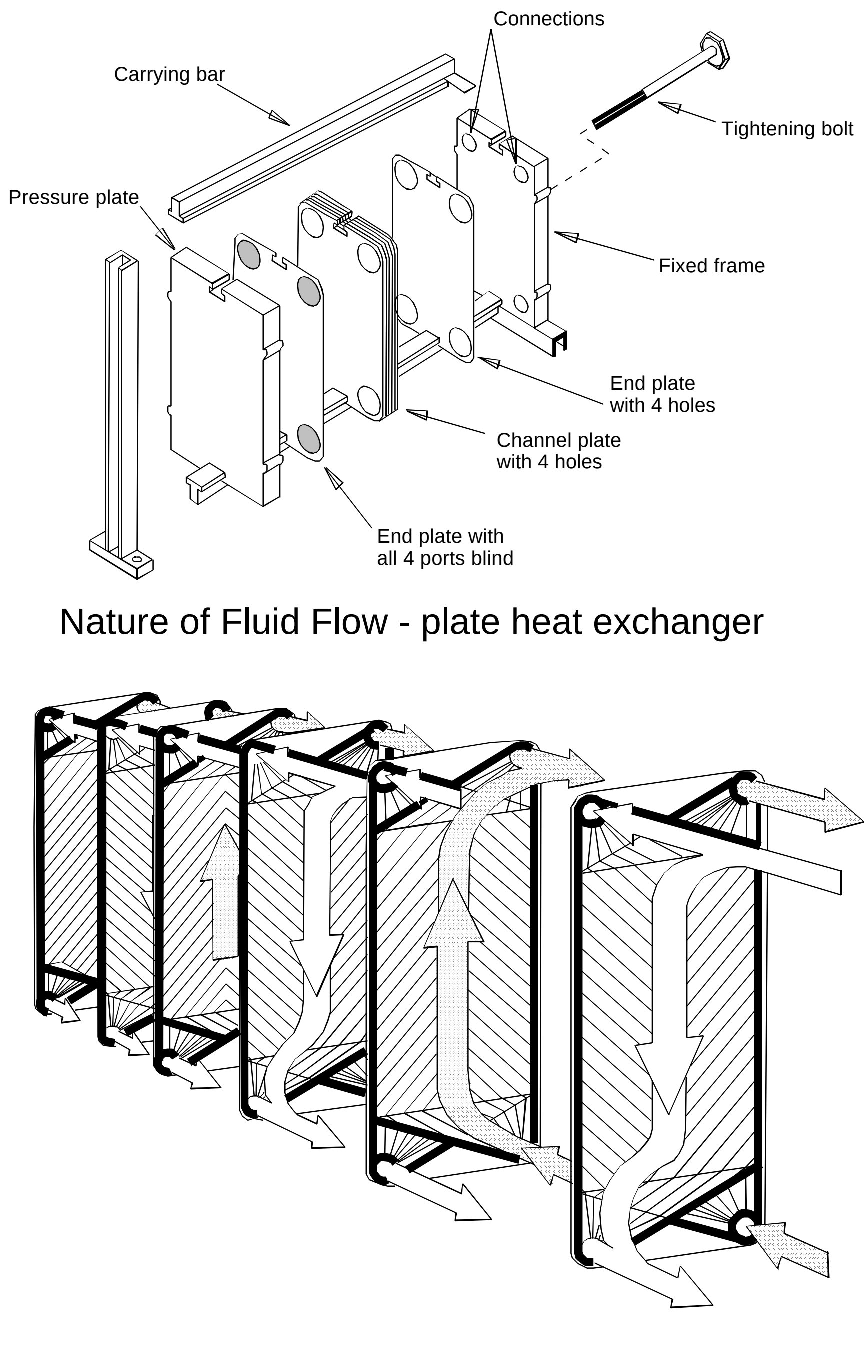


Figure 38. The plate heat exchanger (Culver and Rafferty, 1989).

The following from Rafferty and Lienau, 1988, provides a description of the Oregon Institute of Technology distribution system:

"The original OIT campus distribution system consisted of direct-buried steel piping. This piping, which delivered the geothermal fluid to each building, was field insulated and covered with a bituminous mastic coating.

In the early- to mid-1970s, it was discovered that the coating material was no longer intact in many locations. As a result, groundwater from the soil was able to penetrate the insulation and cause serious corrosion of the steel piping. This occurrence was most pronounced at elbows in the piping system. Evidently, repeated expansion and contraction of the lines caused numerous cracks in the coating in those areas.

Beginning in the mid- to late-1970s, a program of distribution system replacement and modification was begun. The new hot water supply piping consisted of factory pre-insulated fiberglass piping. This piping, as shown in Figures 39 and 40, was installed in underground concrete tunnels which were located largely under the campus side-walks. As such, the tunnels also provide an effective snow melting system for the walkways.

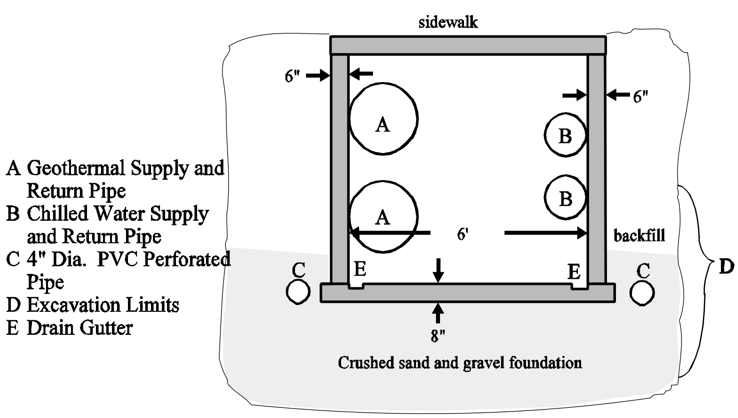


Figure 39. Tunnel construction detail (Lund and Lienau, 1980).

The tunnel installation is expensive; however, it offers the opportunity to accommodate other utilities and affords much better piping access than direct burial. Plans are in place to complete the tunnel system to all buildings in 1989. Current cost for the 6' x 6' tunnel is approximately $300 per linear foot without piping.

In most cases, the piping is hung from the walls of tunnels. Epoxy adhesive joining is used on all fiber-glass piping on the campus. This has been quite successful with no leaks reported.

In addition to changes in the hot water supply lines, the disposal side of the system has been completely redesigned. As originally constructed, each building discharged the "waste" geothermal fluid to the storm sewer. The storm sewer system then delivered this water along with roof and surface drainage to a ditch at the west side of the campus.

As a result of a Klamath Falls City ordinance, all geothermal systems must employ injection for disposal of effluent by 1990. In response to this ordinance, the campus has been installing, over the past few years, a dedicated geothermal fluid collection network. This piping of 3 in. through 8 in. (76 to 203 mm), pre-insulated, fiberglass material is being installed in the campus tunnels along side the supply piping.

Figure 40. Tunnel system interior view (Lund and Lienau, 1980).

Completion of a portion of the collection system resulted in an innovative design for a new classroom building constructed in 1988. The building heating system was designed to use the "waste" water (125ºF or 52ºC) from the collection system rather than the primary geothermal supply water. This design eliminates the need to increase total geothermal pumpage for the campus."

A layout of the Klamath Falls distribution system appears in Figure 41. The system consists of two major portions: transmission line and distribution loop.

A description of the system, from Rafferty, 1989, follows:

"The transmission line employs two types of installation methods: direct buried and concrete tunnel. The entire 4,400 ft (1,231 m) length is composed of 8 in. (203 mm), pre-insulated, Schedule 40 steel piping with a fiberglass jacket. From the production wells to Point A (Figure 41), this line is direct buried. Expansion joints are of the controlled flexing type with 304 SS carrier. After the passing under a state highway and across a canal bridge, the line enters the concrete tunnel. The tunnel is located for the, most part, under a sidewalk and was designed to accommodate a second 8 in. transmission line to provide for system growth.

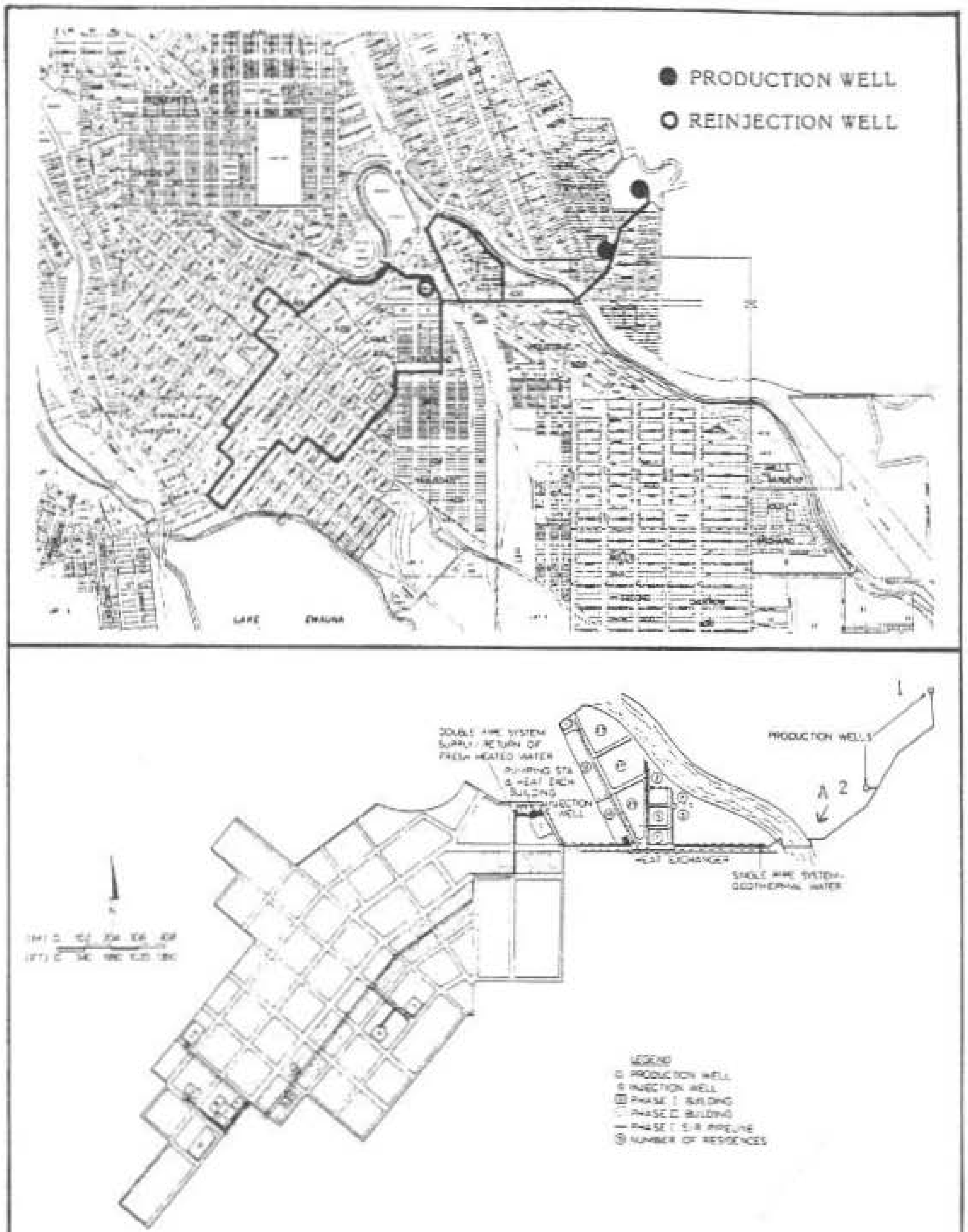


Figure 41 Proposed area to be heated by Phase I (Lienau, 1981)

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Figure 41. Proposed area to be heated by Phase I (Lienau, 1981).

All of the secondary loop is direct-buried piping. Approximately 4,400 ft (1,341 m) of the total is 10 in. (250 mm), pre-insulated, Schedule 40 steel similar to the transmission line. Sizes less than 10 in. (8,280 ft or 2,524 m) are pre-insulated FRP piping of the key-lock type mechanical joining.

A problem encountered with the city system was a failure of the joining system used on the fiberglass piping in the secondary loop. A detail of a typical joint is shown in Figure 42.

The failure of the system was the result of the lock ring portion of the joint becoming detached from the piping. The lock rings were attached, by the manufacturers, with an epoxy adhesive. This adhesive was evidently improperly manufactured or applied. In any case, failure of the epoxy permitted axial movement in the joint. Eventually resulting in leaks at these locations. The existing fiberglass material will be replaced entirely with ductile iron when the city secures funding for the construction (Rafferty, 1989)."

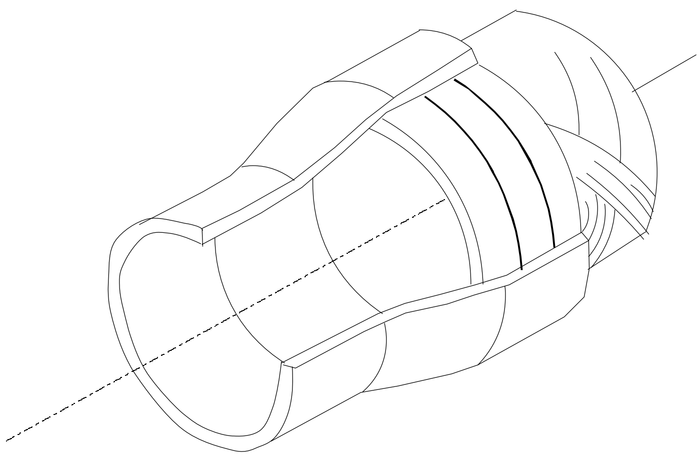

Figure 42. "Kwikey" connection system detail (Rafferty, 1989).

Heating Systems and Operation Characteristics

Residential Systems

A typical home heating system employs a downhole heat exchanger as shown in Figure 37.

It should be noted that the use of downhole heat exchangers requires special well completion techniques that were described in the "Well Construction" section of this paper. In addition, it may be necessary to provide electrical isolation junctions at the surface to reduce downhole electrolysis problems. Figure 43 indicate some of the combinations of downhole heat exchangers and domestic hot water connections utilized.

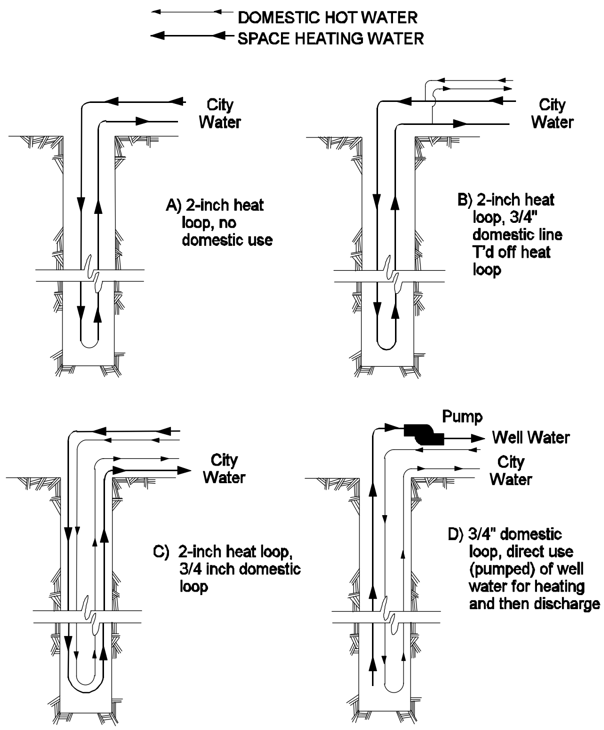

Figure 43. Combinations of downhole heat exchangers and domestic hot water connections.

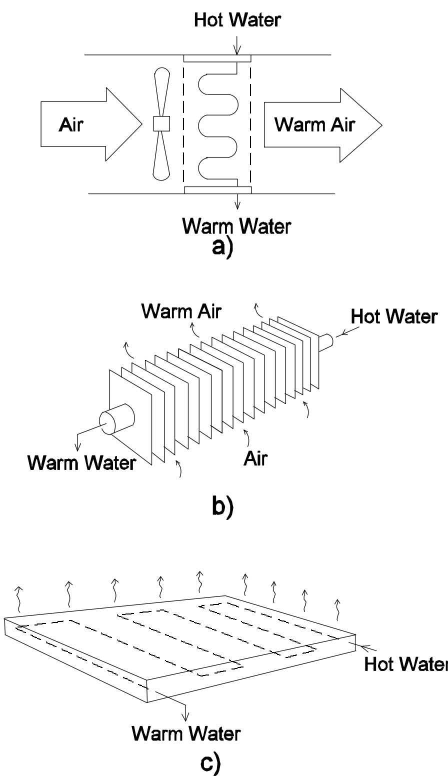

Figure 44. Convectors: (a) forced air, (b) baseboard finned tubed, and (c) radiant panel.

Natural thermal convection is often adequate to provide water circulation in heating systems employing a DHE. A circulation pump may be required in the heating system to increase the flow of the fluid through the heat convector (to increase the heat transfer rate).

Three major types of heat convectors (emitters) are used for residential space heating: forced air, baseboard convection, and radiant panels illustrated in Figure 44.

All can be adapted directly to geothermal or converted by retrofitting existing systems. Retrofitting existing systems may require larger fan coil units or additional baseboard convectors if the fossil fuel system required a high design temperature (above 200°F or 93.3°C) or the geothermal fluid has a low temperature (generally below 150°F or 65.6°C)(Lund, 1978). The details of each type of system are as follows:

> Forced air. This system heats the incoming cold air by finned tube hot water coils and then distributes the heated air to the residence by ductwork to vents, usually located on outside walls. These units can economically use fluids of 120°F (48.9°C) and higher with temperatures above 160°F (71.1°C) being most efficient. One major advantage of forced air systems is the ability to incorporate air conditioning at a small additional cost. Retrofit would normally only require the placement of the finned tube hot water coil in the plenum of an electric or gas-forced air furnace. The distribution system (ductwork) would not have to be modified.

> Baseboard convection. This system uses hot water as the heat transfer medium where the hot water is distributed to convector units located at the base of outside walls. Fins attached to the piping transfer the heat to the room by means of natural convection. These units are economical above 140°F (60°C) with above 160°F (71.1°C) being the best range. The efficiency of the unit can be increased to use lower temperature water by placing a fan behind the unit to help circulate the air. Depending upon the temperature, retrofitting the system would require additional units or lengthening existing units.

> Radiant panels. This system is located in floors, walls or ceilings, and radiate heat to the room. Hot water is circulated in coils of pipe (usually plastic or copper) imbedded in concrete or plaster. Their main advantage is the uniform heat provided without a draft and the lower temperature fluid that can be used. Use of fluid temperatures as low as 100°F is possible. The main disadvantage of this system is that it is difficult and expensive to repair if problems develop (especially leaks). This method is popular in garage and basement floors, and for melting snow on driveways and sidewalks.

> Circulation pumps. Natural thermal convection is often adequate to provide water circulation in heating systems, especially those with downhole heat exchangers. A circulation pump may be required in the heating system to increase the flow of the fluid through the heat convector (to increase the heat transfer rate). This may be necessary for low-temperature geothermal fluids or in extremely cold weather. It will be mandatory when two or more residences share the same well to balance the heat load. Generally, a pump from 1/6 to 1/2 horsepower (0.12 to 0.37 kW) will be adequate.

Controls. Thermostatically controlled valves are desirable to control the heat within a residence. This is especially important with zoned heating systems, where each zone will have a thermostat.

Oregon Institute of Technology

The Oregon Institute of Technology campus has been heated by the direct use of geothermal hot water since 1964. Three hot water wells drilled during the original campus construction vary from 1,300 to 1,800 ft (396 to 549 m). These wells supply all of the heating needs of the 11 buildings 600,000 ft^2 (55,742 m^2) campus. The combined capacity of the well pumps is 980 gpm (223 m^3/h) of 192ºF (89ºC) water. All are equipped with variable-speed drives to modulate flow to campus needs. The actual flow rate for heating is dependent upon outside temperature. Swimming pool and domestic hot water heating impose a small but relatively constant year-round flow requirement.

In addition to heating, a portion of the campus is also cooled using the geothermal resource. This is accomplished through the use of an absorption chiller. The chiller, which operates on the same principle as a gas refrigerator, requires a flow of 600 gpm of geothermal fluid and produces 154 tons (1,848,000 Btu/hr) of cooling capacity.

A layout of the campus heating system appears in Figure 45.

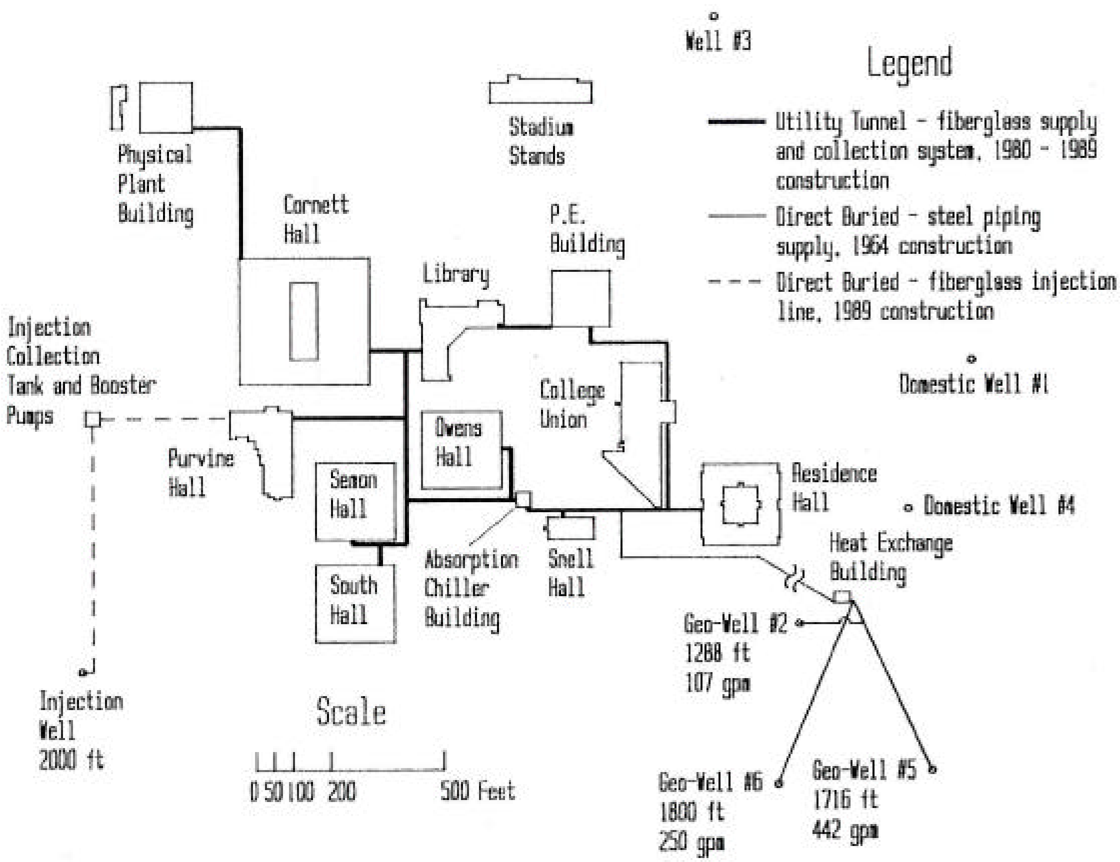

Figure 45. OIT geothermal heating system layout.

The annual operating cost of the system is about $35,000 including maintenance salary, equipment replacement and the cost of pumping. This amounts to about 6 cents per square foot per year.

Three hot wells produce the fluid for the campus geothermal system. These wells, #2, #5 and #6 (Figure 45), are capable of producing 130 gpm, 500 gpm and 350 gpm (8.2, 32 and 22 l/s) respectively.

The three wells deliver geothermal fluid through short underground pipelines to a tank located in the "heat exchanger" building above the campus. A diagram of the control scheme for the production facility appears in Figure 46.

The two control valves respond to a signal from the tank level control modulating toward the closed position as the tank level rises (decreases in campus heating demand). As the valves close, the pressure in the lines from the production wells rises. This rise in pressure signals the variable-speed drive units to begin slowing the production pumps, thus reducing their output. The opposite sequence would result in the event of a decrease in the tank water level.

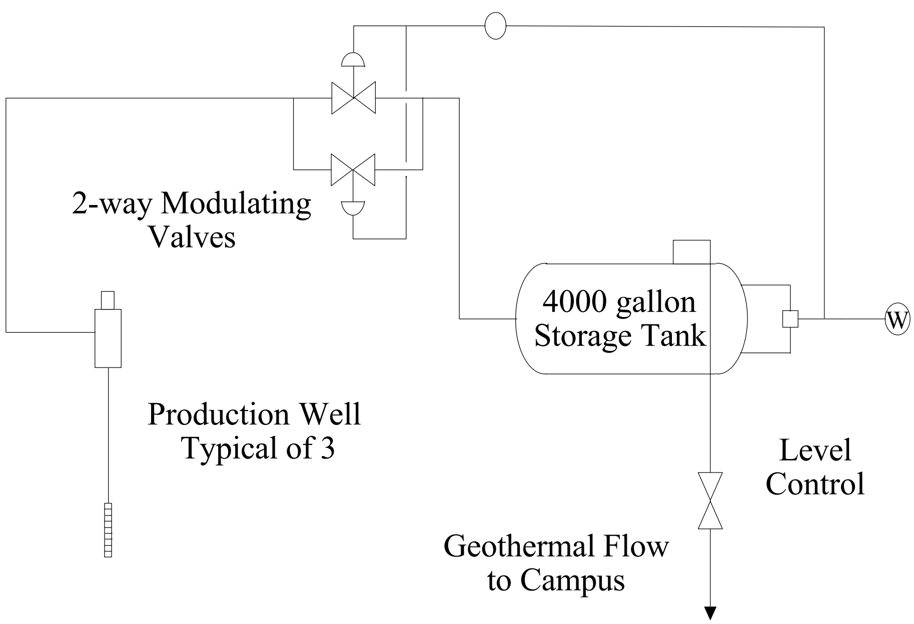

Figure 46. Diagram of the control scheme for the OIT production facility.

Each of the pumps is equipped with a fluid coupling type variable-speed drive unit. This device, similar to the torque convertor in an automobile, is placed between the electric motor and the pump driveshaft. It permits the pump speed, and hence its output, to be varied according to system demand. In addition, the variable-speed drive allows the pump to be "soft started" or brought up to full speed slowly, thus reducing the shock in the system.

In addition to providing for the heating needs of the campus, the geothermal resource, in conjunction with an absorption chiller, supplies a portion of the cooling needs as well.

The chiller, which works on the same principle as a gas-fired refrigerator supplies the base load cooling needs of approximately 280,000 ft^2 (26,000 m^2) of building area. To accomplish this task, it requires 600 gpm (136 m^3/h) of 190ºF (88ºC) geothermal water. In comparison to a standard application, this machine produces only about 50% of its cooling capacity. This is due to the fact that absorption chillers are designed to operate on a 240ºF (116ºC) heat input. The OIT resource only produces 190ºF (88ºC) fluid and as a result, the machine capacity is reduced. Despite this, it produces the required cooling capability at a fraction of the operating cost of an equivalent electric chiller.

Figure 47 presents a flow scheme for a typical lithium-bromide/water absorption cycle. The OIT installation appears in Figure 48.

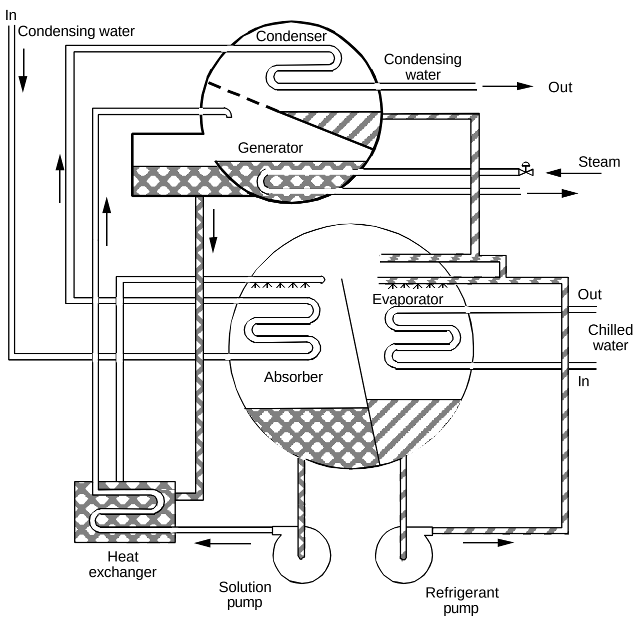

Figure 47. Typical absorption chiller components.

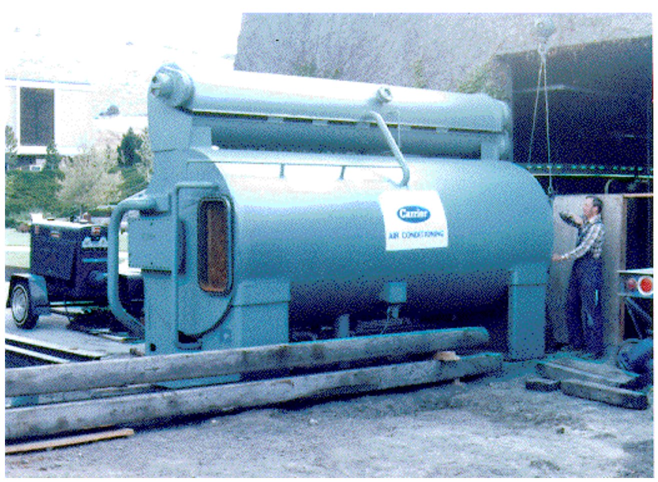

Figure 48. OIT absorption chiller.

Since its original construction, the OIT system has employed surface disposal. Geothermal waste water has historically been collected, either through the storm sewer or more recently via a dedicated collection network, and delivered to a drainage ditch on the west side of the campus.

In the future, however, all geothermal effluent will be reinjected. A new collection tank will be installed just west of Purvine Hall (Figure 45). All waste flow will be delivered from the collection system to the tank. From hear booster pumps will deliver the flow through a 1,500 ft pipeline to the new injection well located at the southwest corner of the campus.

The injection well, which was completed to a depth of approximately 2,000 ft (610 m) in late 1988, cost approximately \$300,000. Testing is currently in progress and it is hoped that the well will be capable of accepting a flow of approximately 750 gpm (170 m^3/h).

Maywood Industries (Lienau, 1976)

Maywood Industries, a decorative molding and door manufacturing plant, consists of a 110,000 ft^2 (10,000 m^2) building. To maintain plant temperature at 65°F (18°C), a 1,500 ft (457 m) deep well was drilled, producing warm water at 118°F (48°C). This water is used directly in forced-air heating units, the lowest temperature use of this type in Klamath Falls. The water is exhausted at 55°F (13°C) after passing through the larger heat exchangers four times. The net savings during an average winter day is \$320 and the annual savings as compared to fossil fuel heating is \$35,000. The payback period was less than four years.

City District Heating System (Lienau, 1981)

In 1977, a federal (DOE/DGE) field experiment contract was awarded to the city of Klamath Falls to design, construct and initiate operation of a geothermal space heating district in the central business district of the city. This project was for a city-owned and operated system, initially to serve 14 city, county, state and federal office buildings, and 120 residences (Phase I) with subsequent expansion to an 11 block area adjacent to the initial secondary supply line (Phase II), and final expansion to commercial buildings on 54 city blocks (Phase III). The project included two production wells, an injection well, transmission lines, controls and retrofitting equipment for the government buildings.

A summary of the heat loads are as follows:

Phase I (14 government buildings)

Peak heat load	21.2 x 10^6 Btu/h (6.2 MWt)
Geo-fluid flow	1,060 gpm (69 l/s)

Phase II (11 commercial blocks)

Peak heat load	34.8 x 10^6 Btu/h (10.2 MWt)
Geo-fluid flow	1,740 gpm (110 l/s)

Phase III (54 commercial blocks)

Peak heat load	143 x 10^6 Btu/h (41.9 MWt)
Geo-fluid flow	7,150 gpm (451 l/s)

Total cost of the project was \$2.58 million, consisting of 65% federal funds, and the remainder from city, county and state funds which are summarized below:

Item Description	Amount
Production wells (2)	\$ 63,965
Primary pipeline	1,269,711
Secondary pipeline	790,966
Retrofit	249,890
Engineering & Administration	205,468
	\$2,580,000

Since Phase I is a demonstration project funded primarily by the federal government (DOE), the economic analysis is based on Phase II. The pipe diameters in Phase I are sized to handle Phase II. Pipe tees were installed at the principal businesses along the 11 block commercial area; thus, future hookup costs will be minimal.

For economic evaluation, the lowest cost existing energy source available to the downtown area (natural gas) was used for comparison. Cost of natural gas (1982) for commercial buildings is \$5.67/10^6 Btu (\$5.37/GJ). The first year geothermal unit energy cost is \$5.84/10^6 Btu (\$5.53/GJ) where the cost of capital is 8%, and operation and maintenance (O & M) costs will inflate at the economic inflation rate of 7%. District heating costs are, therefore, made up largely of capital charges (94%) which, after the system is built, do not escalate. A 20-year-life-cycle comparison and geothermal is shown in Figure 49, indicating a "break even" cost at under 5 years and a payback of under 8 years.

Customer geothermal energy price was two-thirds of the price of natural gas when the system operated from 1984 to 1985. In February 1985, the system was shutdown and subsequently, it was decided that all the fiberglass piping would be replaced as discussed in the distribution section.

Since completion of the downtown loop and transmission line, two other small district systems have been tied into the main transmission line.

The Michigan Street system serves a residential area to the north of the transmission line. To deliver heat to this system, a fraction of the flow in the main line is shunted through a heat exchanger and then back into the line. Since there are only eight houses currently connected to the system, the impact on the temperature delivered to the main loop heat exchanger is small. As in the case of the main loop, this system employs a central heat exchanger and secondary loop to deliver heat to the customer (Rafferty, 1989).

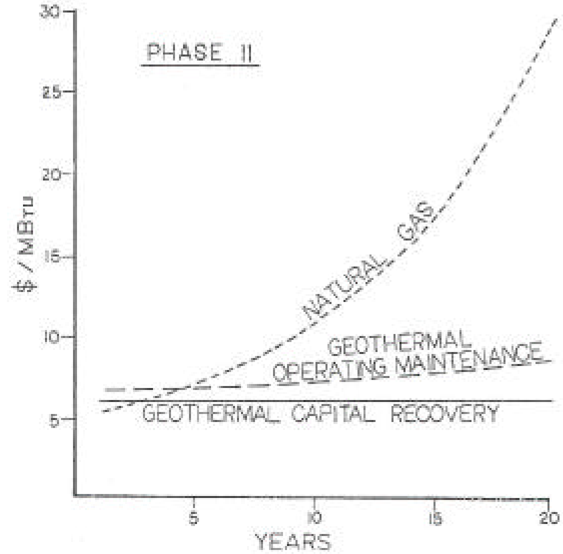

Figure 49. Phase II unit energy cost comparison (Lienau, 1981).

The Mills Addition system is connected to the main transmission line only for emergency backup purposes. This system uses, as its primary source of heat, water which was previously wasted to the storm sewer. A number of existing geothermal systems in this area of the city were previously operated on a "pump and dump" basis. The Mills Addition system was implemented in an effort to collect this fluid, extract any useful heat and then deliver it to an injection well. Toward this end, the fluid is collected in a gathering system, passed through a heat exchanger and then delivered in a separate line to the injection well used by the main system. A secondary loop delivers heat to the customers. Emergency backup for this system is provided by a second heat exchanger connected to the main transmission line. This system is not currently operated due to legal difficulties with a nearby facility which was collecting heat from the storm sewer system. Since this heat is no longer available, an agreement must be reached with this facility before the system can be operated (Rafferty, 1989).

Institutional Factors

The development of the city district heating system, completed in 1981, resulted in institutional and legal problems that led to the establishment of a city ordinance controlling the use of the resource and a Geothermal Advisory Committee to oversee utilization and development (Lienau, 1984).

An organized citizens group, Citizens for Responsible Geothermal Development (CRGD), objected to the city pumping its production wells located in an area of many private wells. The private wells are used for heating homes and small declines in water levels would effect the performance of the downhole heat exchangers.

Citizen reaction to the building of the district heating system caused serious delays in the start up of the project, from the fall of 1981 to the spring of 1984. The city ordinance, established by an initiative referendum of the citizens group, required that any water pumped from a geothermal well be returned to that same well.

The state of Oregon, in 1981, filed a law suit against the city, claiming that state regulation preempted city action. This issue was resolved in the Oregon Court of Appeals, in 1985, ruling in favor of the city. The ruling stated that local governments have the right to manage geothermal resources within their local jurisdictions.

In 1983, the Klamath Aquifer Test consisted of a seven-week pressure interference test and doublet tracer testing involving the cooperation of many citizens, local organizations, USGS, Lawrence Berkeley Laboratories, Stanford University, and the OIT Geo-Heat Center. This aquifer test, together with concurrent data gathered from over 50 wells, was perhaps the most extensive and, in some ways, the most complete aquifer test ever conducted (Sammel, 1984).

The findings are as follows:

1. An extensive aquifer was identified,
2. The reservoir had a rapid response,
3. No change in temperature was observed,
4. Injection makes a significant difference in water levels for the entire systems,
5. Theory shows good agreement with actual test results,
6. There is a double porosity reservoir,
7. No hydraulic boundaries were detected,
8. Air temperature is an accurate prediction of geothermal fluid use,
9. District heating is four times as efficient as individual use, and
10. A prediction model was presented for pressure changes in the reservoir for short-term pumping and injection.

In 1985, a Geothermal Advisory Committee (GAC) was organized that consist of a cross-section of representatives from all interested groups. The GAC's role is to recommend specific action with regard to development and management of geothermal resources in the county. Specifically, it recommended a Geothermal Resource Management Plan, which was adopted by the City Council, and based on the 1983 Aquifer Test. This plan's primary objective is to eliminate surface disposal from approximately 100 pumped geothermal wells by July of 1990. The main problem with the reservoir is the annual water level decline of about 1.0 ft per year (0.3 m/y) which could be controlled by the development of injection wells.

Beginning in 1988, annual public meetings have been held, where options are presented in dealing with compliance and the penalties that will be enforced if they are not met.

A Geothermal Data Center has been established by the city, which compiles well data and issues permits for well development and/or modifications. They also maintain a monitoring network of strategically located wells throughout the reservoir.

Based on the Klamath Falls experience and problems encountered establishing a geothermal district heating system, the following recommendations are offered:

1. Public Awareness Programs. Early in the planning process, a community survey should be conducted of citizen use and attitude towards further development of the resource. Obtain as much support as possible from citizens, community service organizations and government entities that have overlapping authority on the area involved.

2. Geothermal Advisory Committee. Organize a committee representing a cross-section of all citizens to recommend specific action with regard to development and management of the resource. Encourage citizens to become involved in monitoring and other programs, provide factual information and establish communication channels.

3. Test Programs. Identify and perform reservoir test programs early in order that a solid baseline of data may be obtained in the event a legal question arises concerning the heating district influence on environmental items. A continuing monitoring program throughout the life of the project is essential.

4. Statutory Authority. Identify existing statutory authority and incentives for development. The entity involved should become active within the lawmaking process to provide and develop necessary strategy and incentives for future users of the system.

5. Market Survey. An in-depth market survey of the surrounding area should be developed. A market survey of potential users of the system should be a continuous process which is a function of the reservoir potential and its performance with regard to existing, as well as future users.

Conclusions

The actual geothermal energy utilization in the Klamath Falls urban area is estimated near 120×10^6 Btu/h (35 MWt) for over 500 wells. Based on research on downhole heat exchangers (Culver, 1978), the urban area has a potential of around 680×10^6 Btu/h (200 MWt) using the present wells. Based on USGS Circular 790 (Muffler, 1978), the reservoir has a potential of 2.8×10^{16} Btu (30×10^{18} J), a wellhead potential of 7.0×10^{15} Btu (7.4×10^{18} J) at a 24% efficiency.

The use of one well to heat one home is somewhat expensive in initial investment, from $5,000 to $10,000 appears to be typical. The actual operating cost, including maintenance, is quite low, amounting to less than $100 per year. This initial investment cost can be reduced by having several homeowners share the same well.

The potential of the reservoir in the urban area is obviously much greater than is presently being used. The initiation of the district heating project for the downtown area will hopefully make better use of the resource and provide geothermal to a greater number of customers.

The Klamath Falls development and use of geothermal heat, especially the downhole heat exchanger, can provide an example for applications in other parts of the world. Rural areas, with only a low-temperature resource, can provide space conditioning with geothermal fluids at a cheaper cost than conventional fluids.

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