GEOTHERMAL APPLICATIONS OF THE MADISON (PAPASAPA) AQUIFER SYSTEM IN SOUTH DAKOTA

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INTRODUCTION

Basis for the present study. The Madison is the deepest artesian aquifer currently utilized in western South Dakota. Records of deep municipal, military, and industrial water wells, and several hundred oil tests furnish information on the quality, quantity, depth, temperature, and pressure head of Madison water. Temperatures as high as 180°F have been recorded. Over much of the area, the temperature reflects the normal gradient of about 2°F per hundred feet of depth. One large area in westcentral South Dakota , and a smaller one in the southwestern corner of the state have appreciably higher gradients which are as yet une xplained.

Various uses for the warm waters have been suggested, notably for wool washing, for hot water baths, for space heating, and for grain drying and other agricultural uses. To date, the only applications have been for space heating using existing municipal wells as the source of the heat.

The success of heating installations at Midland and Philip, coupled with the corrosion and s caling problems which have characterized all uses of Madison water, prompted a proposal to the Division of Geothermal Energy, Energy Research and Development Administration. This paper summarizes the final report under Contract No. EY-76-S-07-1625

Objectives. Objectives of the study fall into three broad groups:

1) Study the geology, hydrology, temperatures, and chemistry of the Madison Formation and its contained fluids.
2) Design a central space-heating installation suitable for small towns, and corollary study of materials, water treatment, costs as compared to existing and projected energy sources, and practical uses for the water from which the heat has been partly extracted.
3) Investigate legal aspects of geothermal development in South Dakota, including exixting state and federal laws, and the possible role of REA cooperatives in financing and/or operating small central geothermal installations.

Organization and management. The Department of Geology and Geological Engineering compiled and interpreted data on the Madison reservoir. Porosity studies based on electric logs were made by Sherwin Artus, Denver consulting reservoir engineer.

Water quality was determined by Dr. Dan Carda of the Mining Experiment Station at the School of Mines. Water treatment was considered by Sheppard T. Powell, Baltimore consultant to R, W. Beck. Corrosive effects of waters from individual wells were determined by Dr. Stanley Howard of the Metallurgy Department, assisted by Dr. Carda.

R. W. Beck and Associates designed geothermal heating installations for the town of Midland, and for two settlements on the Cheyenne River Indian Reservation. The study included design, materials, costs, and uses for the spent water.

GEOLOGY OF THE MADISON FORMATION

Distribution and thickness. The Madison carbonates were deposited in a broad seaway which covered much of the area now occupied by the Rocky Mountains in lower Mississippian time. South Dakota lies on the eastern edge of that former seaway.

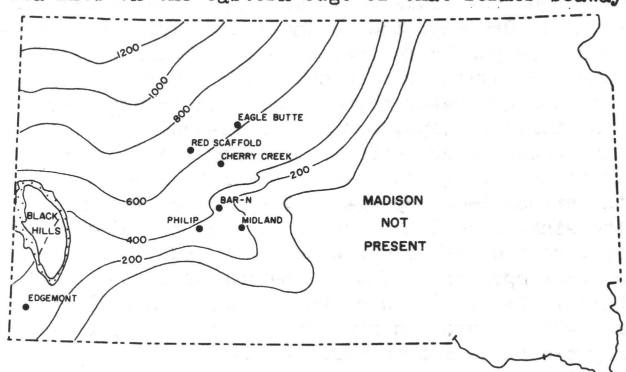

Fig. 1. Areal extent and isopach of the Madison Formation in South Dakota. Contour interval = 200 feet. Scale- one inch = 133 mi.

The formation thickens from zero along the eastern edge t o 1,300 feet in the northwestern corner of the state, and to 2,700 feet in the center of the Williston Basin of North Dakota.

In the deeper parts of the Williston Basin, and extending into northern South Dakota, the upper most Madison contains evaporite units which greatly reduce the quality of the formation water.

Structure. As a result of later structural movements, the Madison has been downwarped into the Williston Basin to the north, and uplifted and eroded over the Black Hills. Its greatest depth in northwestern South Dakota about 7,000 feet.

Porosity and permeability. Three types of porosity occur, 1) normal intergranular porosity particularly in the dolomites, 2) joint and fracture porosity, and 3) solution openings ranging from slightly enlar ged joints to caverns in which the drill may drop several feet. Permeability is also affected by the types of openings. It is not surprising that well yields vary widely.

In an effort to locate favorable areas for obtaining high yields, Sherwin Artus made electric log analyses of the Madison section in 150 wells in South Dakota. No consistent areal or vertical trends in porosity could be recognized, but a few better-than-average areas were delineated.

HYDROLOGY

Geolog ical background. The Madison is noted throughout its areal extent for large artesian flows, and for the attendant drilling problems of well control and lost circulation.

Following retreat of the early Mississippian sea, the newly deposited carbonate terrain remained slightly above sealevel for a long period of time. A widespread karst topography was developed. Sufficient limestone was removed by solution and erosion to pr oduce a surface relief of several tens of feet, and the insoluble clays and chert remained behind as a surficial blanket of red residual soil. Subsequent deposition buried the topography beneath several thousand feet of strata.

When the Black Hills were uplifted during the Laramide Orogeny, the sediments overlying the Madison were partly removed by erosion, and surface water was again able to enter the cavern system. Much surface water now filters down through bare limestone outcrops, but more spectacular infiltration occurs where streams crossing the Madison outcrops lose large volumes of water to sinkholes in the stream bed. Because all water now entering the sinks cannot be accepted by the hydrologic system, some of it breaks back to the surface as resurgent springs around the perimeter of the Black Hills. The position of these springs has shifted somewhat as erosion prog ressed, but the present-day sinkholes and springs are descendants of an earlier system.

The relationship between water losses to sinkholes and discharge from resurgent springs has been verified by ten years of stream gauging across the sinkhole zones and at the springs. The volume of water returned to the surface is greater than that lost to the sinkholes, indicating that the more important part of the recharge to the Madison aquifer is derived from rain and snowmelt which infiltrate the outcrop area.

Two other facts indicate that the outcrops around the Black Hills constitute the recharge area for the Madison aquifer in South Dakota and the eastern Powder River Basin in Wyoming . The potentiometric surface is highest adjacent to the outcrops, and the total dissolved solids increase down dip in all directions from the Black Hills uplift.

Little is known about the movement of water once it enters the artesian system. The potentiometric surface slopes away from the Hills, steeply at first, then becoming nearly flat under the central part of the state, so no definite directions of water movement can be inferred. Limited age-dating of the Madison water gives contradictory estimates of the rate of movement.

Potentiometric surface. Whereever possible the potentiometric surface surface map has been based on producing water wells, with either a direct measurement of static level or one calculated from the shut-in pressure. A few isolated drill-stem-tests have been used for control in the northwestern corner of the state. Except for a small anomalous area in Mellette County, a flowing Madison well can be anticipated whereever the formation is present and where the surface elevation is less than 2,400 feet.

Hydrologic characteristics. Little information is available on transmissivities, storage coefficients, or specific capacities of Madison wells in South Dakota. The following wide ranges of values have been compiled from wells in western South Dakota and northeastern Wyoming:

Specific capacity-0.1 to 10.6 gpm/foot of drawdown
Transmissivity - 400 to 89,000 gpd/foot
Storage coefficient - 5×10^{-5} to 1×10^{-4}

Yields. Recorded yields in the Black Hills area range from 80 gpm on the pump to over 1,000 gpm free flow. A discharge of 500 gpm, either by natural flow or pumping can be considered an average for a properly completed Madison well. Some wells would require acid fracturing to reach this figure.

Interference. It seems advisable to maintain a distance of half a mile between Madison wells in a well field; a mile would be better if engineering considerations permit.

Temperature.The Madison temperature map (Fig. 2) is based upon temperatures obtained directly from flowing or pumping wells, or from bottom-hole recorders on resistivity logs run in oil tests. In the case of flowing or pumping wells, water reaching the surface may be slightly lower than formation temperature when the upward movement of the water is slow, and wells in long service frequwntly yield water a few degrees warmer than the figures obtained on initial production tests.

Most deep oil tests in western South Dakota bottom in the Ordovician or the top of the Precambrian basement. Hence most bottom hole temperatures have been recorded deeper than the Madison. They have been corrected back to the top of that formation assuming a uniform temperature gradient.

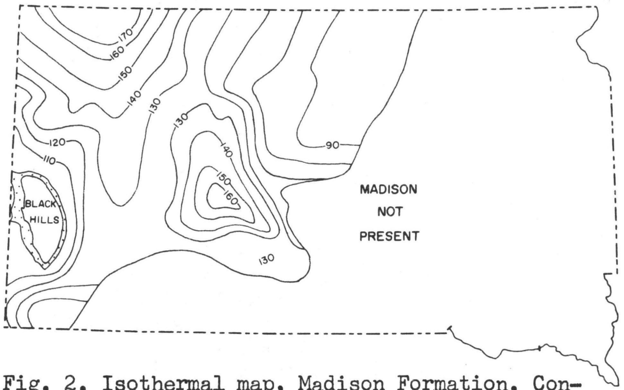

Fig. 2. Isothermal map, Madison Formation. Contour interval 10°F. Scale-one inch = 133 miles.

WATER QUALITY

General. Water quality varies widely within the Madison aquifer; it is highest close to the outcrop and degrades radially outward. The northwestern corner of the state has the poorest quality, the greatest depth, and the highest temperatures. The water in most cases exceeds recommended EPA levels for human consumption on several parameters; however, people at Edgemont, Philip, Midland, and Dupree drink it with no known ill effect. The water is often superior to that from the shallower Cretaceous sandstone aquifers.

Madison water, when permitted to cool and evaporate in the atmosphere, produces a heavy white deposit composed primarily of gypsum and amorphous s ilica. This deposit does not form in pipes where temperature and pressure are maintained. The entrained gas is composed largely of nitrogen, carbon dioxide, and traces of oxygen. Hydrogen sulfide is apparently the chief cause of corrosion.

The concentration of toxic elements does not reach dangerous levels in any of the waters tested; the secondary utilization of cooled Madison water should present no major problems.

CORROSION AND SCALING STUDIES

General. These were divided into three phases 1) documentation of heat exchanger experience with Madison waters, 2) theoretical prediction of corrosion and scaling properties, and 3) on-site corrosion and scaling investigations.

History of geothermal applications. Madison wells at Philip and Midland are used for space heating as well as for municipal supplies.

Midland. School District 114 at Midland heats its two largest buildings with Madison water. Each is heated with recirculating water which has been heated by geothermal water in a primary heat exchanger. Both primary exchangers are conventional shell and tube units with Madison water flowing through the tubes. The steel shell in the older building has been replaced once in thirteen years, while two sets of copper tubes have been installed during that time. The newer building's heat exchanger has not failed since its installation five years ago. Failure of older units resulted from corrosion rather than by scaling. X-ray analysis of the interior of the tubes showed the presence of a layer of copper (I) sulfide corrosion product.

Philip. The Philip water plant is heated by two forced-air heat exchangers and one natural convection baseboard exchanger. The tubing is copper

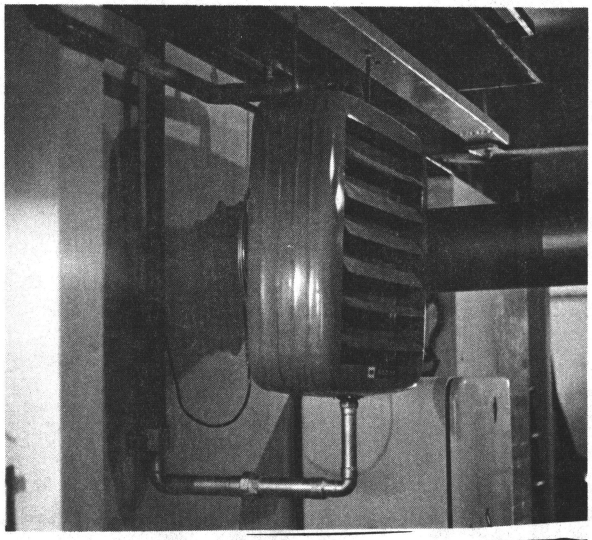

Fig. 3. Heat exchanger at Philip water plant.

and all joints are soft soldered. The cores of the exchanger fail due to corrosion of the small vertical tubes which have service lives ranging from two to five years. The copper baseboard exchanger failed as a result of corrosion after 11 years of service. Sectioning of the tubing through the point of failure showed fairly uniform attack of the tubing walls, with no evidence of pitting. A black, loosely adhering crust of copper (I) sulfide was observed throughout the inside of the cores.

Corrosion and scaling experiments. Due to the complexity of Madison waters and difficulties encountered in using Langelier and Riznar indices to predict corrosion and scaling tendencies, an experimental program was undertaken to provide reliable information on 1) the corrosion behavior of commonly used heat exchanger metals and alloys, and 2) the probability of scaling. Test racks con- two 2-inch diameter samples of each of 12 metals plus glass, were inserted inside a 4-inch diameter PVC tube through which Madison water flows (Fig. 4). Periodic observation of the disks permits preliminary evaluation of the corrosion and scaling properties of the water. The glass disks were used as a sensitive means of visually assessing the occurrence of scaling. The first test rack was installed at Philip; later similar racks were installed in flow lines at the Bar-N Ranch Haakon County, and at Edgemont, Fall River County.

These three locations provide waters of widely different temperatures and chloride and sulfate concentrations.

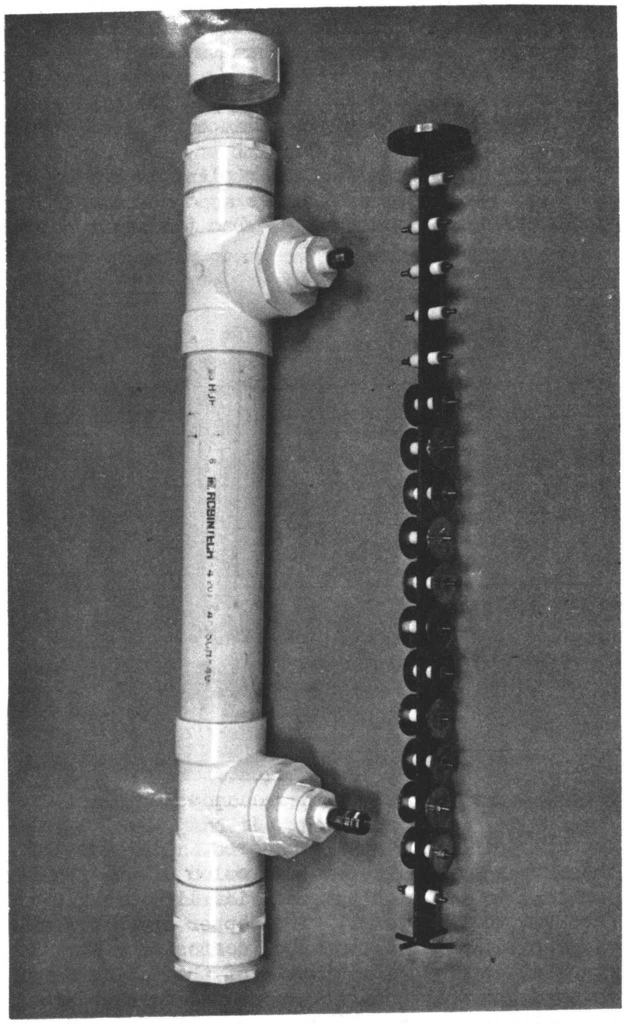

Fig. 4. Corrosion test unit.

Preliminary results at Philip. The test rack was installed at the water plant on April 5, 1977. Flow rate through the test chamber was 7.5 gpm, and the discharge temperature was 157°F. Several weeks after installation, the rack was found to be coated with the same powdery black copper (I) sulfide observed in copper heat exchangers in the water plant. On September 1, 1977, one disk of each metal was removed and examined for corrosion. No scale was found on the glass. Two different copper alloy 613 specimens, copper, Admiralty brass copper alloy 715, and the stainless steels showed very minor uniform attack. Two copper 958 specimens and Monel showed general etching. Carbon steel and aluminum were heavily attacked. Dealloying was not observed in any specimen or in the brass nuts used to secure the disks (which were mounted on Teflon collars and washers to preclude galvanic corrosion. Corrosion was determined by cleaning the corrosion products from the samples and weighing to determine total weight loss.

Results show that 304 and 316 stainless steel would serve well in waters similar to those at Philip. Most of the copper alloys, copper, and Admiralty brass would provide approximately 50-year service with wall thicknesses of 0.025 in. Since most of the heat exchanger cores would normally have walls of this thickness for structural purposes, factors other than corrosion rates may determine the selection of heat exchanger materials.

Recommendations and conclusions. The following recommendations are made to minimize scaling and corrosion:

1) For primary heat exchangers, use 304 or 316 stainless steel. In Philip-type water, with chlorides less than 100 ppm, the service life of stainless steel is expected to be indefinite.
2) In systems without a primary heat exchanger, stainless steel is recommended over copper and copper base alloys on the basis of corrosion resistance. However the high cost of stainless steel for individual users may make thick-walled (0.05 in.) copper or copper base alloy more economical.
3) In waters with chloride concentrations greater than 100 ppm, copper and copper-base alloys might serve as well or better than stainless steels.
4) Since corrosion rates in copper exchangers appear to be substantially higher in stagnant than in flowing water, a corrosion control program should be established for summer shut down.
5) Prediction of scaling tendency by the Langelier and Ryznar indices using currently available water quality data has been unsatisfactory.

GEOTHERMAL APPLICATIONS

General. The following facts formed the basis for design of potential heating applications in western South Dakota:

1) Western South Dakota is dotted with small farming and ranching communities, but overall population density is low.
2) Major businesses and industries are related to agriculture. Cattle and winter wheat are the primary sources of cash income.
3) There is no natural gas line in the area; home heating systems in small communities must use fuel oil or propane. Some all-electric heating systems are in use.
4) No major rail service passes through the area; thus no commercial centers of any size.
5) Water for both domestic and agricultural use is scarce. Potable water is as important as the potential geothermal heat value of the Madison water. Attention must be paid to both aspects of the water in utilization studies.

Space heating. The most fruitful application appears to lie in the use of geothermal heat for small space heating systems. The cost advantages of a geothermal system must be evaluated against the cost of home and business heating with fuel oil or propane. The chemical characteristics of the Madison water will determine the materials required for a reliable system.

A central system appears to be the most logical concept. It would consist of a heat exchanger or converter located at the geothermal source to transfer heating energy to a secondary closed-loop hot water distribution system for end use in the community buildings. This concept confines to one area any potential fouling due to scaling or corrosion. The secondary loop would be closed also, and the water treated for corrosion and scale control. With such a system, standard piping and end-use heating exchangers can be used.

Central heat exchangers. A minimum of two full-size heat exchangers (three half-size units are also a possibility) should comprise the heat transfer system. Each exchanger must be capable of transferring approximately 100 percent of the design heating requirements from the Madison water to the heating system. It is tentatively suggested that plate-type heat exchangers using plates of 316 stainless steel be considered for geothermal applications in this area. The plate type heat exchangers consist of a series of plates through which fluids flow in alternating directions. A plate type exchanger with countercurrent design has a better heat transfer rate per square foot of surface area than the shell and tube type. It is more compact, has better expansion capability if added capacity is required, and is easier to maintain than the conventional shell and tube design.

The design of distribution systems for Midland and two settlements on the Cheyenne River Indian Reservation is included in the final project report, together with detailed economic analysis. Projections at Midland indicate that the cost of conventional fuels will equal the cost of geothermal energy between 1979 and 1980, and thereafter geothermal energy will be less expensive.

End use applications for Madison water. Midland utilizes Madison water without treatment as its municipal supply even though the water quality does not meet EPA standards. In Philip, the water is treated and used as the city supply. Madison water underlying the Cheyenne River Indian Reservation cannot be used as a drinking water without extensive treatment.

The volumes of water required to heat a small community is greater than that which can be absorbed normally for domestic and light industrial use. The following are possible applications for the excess:

1) limited irrigation where soils are suitable
2) distribution through rural systems to supply livestock and domestic water.
3) heating of livestock buildings, greenhouses, or grain dryers with residual heat.
4) recreation, as swimming pools or hot baths.

Specific findings. Several guidelines have evolved from this study:

1) For application to central heating systems, the geothermal source should have an energy level at or above 140°F.
2) The economic justification for utilization is predicated upon the cost savings effected by replacing the existing energy source. Geothermal heating will be more attractive if it can replace propane, fuel oil, or electricity, rather than natural gas.
3) End uses for water should utilize remanent heat as well as the water. Uses are limited by the relatively low energy level and the poor quality of the water.
4) The cost of a well, or of two wells if re-injection is required, is a major economic factor.

From the economic analysis of the proposed Midland system, the breakdown of investment cost (without meters) is as follows:

Distribution system	50%
Central facility	11
End use	7.5
Design, engineering, and construction management	8.4
Well	23.1

LEGAL ASPECTS

South Dakota has no existing statutes relating to geothermal resources. Under existing South Dakota water law, hot water for heating homes would fall under domestic use, which carries the highest priority, subject only to the stipulation that the water may not be wasted or that its withdrawal must not interfere with existing rights.

South Dakota municipalities have the authority to construct, operate, and maintain a system to provide heat from geothermal sources, and to finance the same with revenue bonds. South Dakota Rural Electric Cooperatives do not at present have authority to operate a system to provide heat from a hot water source, nor does the Rural Electrification Administration have authority to make loans for heating systems using only geothermal water.

It is recommended that South Dakota prepare and enact legislation governing the development of geothermal energy.