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# Corrosion in Low-Temperature Geothermal Applications

**E.C. Knipe**
*ASHRAE Associate Member*

**K.D. Rafferty**
*ASHRAE Associate Member*

## ABSTRACT

From 1948 to 1954 there were a number of documented histories of low temperature geothermal applications in the ASHRAE Transactions. These early systems experienced failures due to corrosion and scaling within five to fifteen years after installation (corrosion that was not documented). This paper addresses the authors' experiences in the area of low-temperature geothermal corrosion.

Two solutions to low-temperature corrosion have been employed: Chemical treatment and isolation. The cost of treating an open flow system results in operating costs far in excess of the first cost associated with isolation. The degradation of the heat exchange from an isolation process is a small penalty to pay for reduced corrosion potential. Government restrictions preclude use of chemicals in fluids that are reinjected into the ground. The design/material selection procedure for an isolation heat exchanger should consider both dissolved gasses and microorganisms in addition to chemical species normally considered for potable analysis. Potability should not be confused with lack of corrosion and scaling tendencies. When are Ryznar and Langelier indices valid as indicators of corrosion? It has been shown that the best performance in isolation heat exchangers for geothermal applications has been with the plate type design. The plate heat exchangers have superior heat transfer capabilities, are compact and expandable, are manufactured from corrosion resistant materials, are of relatively low cost, offer simple disassembly for maintenance, and multiplex capability. A slight increase in energy use will be noted due to a temperature drop across the heat exchanger. However, the small approach capability of plate type units minimizes the effect. Plate heat exchangers have virtually no effect on a heat pump centered system since source resource fluid is used only to temper the heating/cooling loop. As the temperature of approach is decreased across the heat exchanger, costs rise. The plate type heat exchangers can be readily fit into any type system, including central heat pump (two-pipe), central heat pump (four-pipe), terminal heat pump (two-pipe), and direct use (no heat pump). The addition of a plate heat exchanger to isolate the low-temperature geothermal fluid does not necessarily mean adding complexity to existing systems.

## INTRODUCTION

During the past six years, the authors have had the occasion to be involved in the review, renovation, and redesign of a number of low temperature geothermal applications.[1,2] These systems involved intermediate temperature (200 to 120 °F [95 to 50 °C]) and low temperature (120 to 50 °F [50 to 10 °C]) geothermal fluids for both direct application in heating and indirect application via heat pumps.

Our experiences have lead us to conclude that the information provided in Chapter 56 of the ASHRAE Handbook (Applications) may require some clarification to aid designers in the use of

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Edward C. Knipe, PE, Principal Engineer, Brown and Caldwell,Eugene, Oregon and Kevin Rafferty, GEO-HEAT Center, Oregon Institute of Technology, Klamath Falls, Oregon.

low-temperature fluids.[3] Chapter 56 provides excellent information on direct use systems, direct application systems, and on the material selection problems associated with them.

## INFORMATION PRESENTLY PROVIDED

Presently the definition of geothermal energy in the minds of most designers does not include low-temperature resources of less than 194 °F (90 °C). As a result, designers considering low-temperature groundwater-based systems are inclined[4] to refer to the "Applied Heat Pump" Chapter in the *ASHRAE Handbook--1984 Systems*, Chapter 10.

The information provided in Chapter 10 of *Systems* leads the system designer to conclude that corrosion in low-temperature water systems and those with heat pumps is not a significant problem. The references provided in *Systems* dating from the period 1945 through 1955 cover systems in which low-temperature geothermal fluids were circulated either directly through the building heating/cooling loops or through compression/refrigeration machinery.

Chapter 56 outlines very clearly the potential problems related to isolation of the geothermal fluid and material selection requirements necessary to avoid premature failure due to corrosion. This paper discusses systems we have reviewed utilizing geothermal (or well water) resources in the low-temperature range and their associated corrosion problems.

## CORROSION AVOIDANCE

Generally, engineers have used one of two solutions in addressing the potential for corrosion from low-temperature well water resources. These are chemical treatment of the fluid or isolation of the fluid by appropriate material selection to avoid corrosion and scaling.

### Equitable Building

The Equitable Building located in Portland, Oregon, serves as an excellent example. The original design, as documented in the *ASHVE Transactions*, involved the direct use of a 59 °F (15 °C) or 64 °F (17.7 °C) fluid (depending upon the season) in the heating and cooling water loops for the building.[5,6] Figure 1. shows the system schematic in the original paper of 1948. The equipment installed when the building was constructed in 1948 consisted of black steel piping, heating and cooling coils equipped with cast iron headers (accessible for cleaning), copper tubes, and aluminum fins. The centrifugal heat pumps installed at that time had standard copper shell-and-tube heat exchange surfaces. Well water circulated throughout the building and through all coils and heat exchangers prior to re-injection.

A review of the original project correspondence files for the building showed that within six months of the building start-up it became apparent that there was a significant corrosion problem. This corrosion was exhibited in the form of pitting of the copper tubes in the finned heat transfer surfaces and in the heat pump heat exchange surfaces. Attempts were made to mitigate this corrosion initially with chemical treatment of the well water fluid prior to its use in the building system. Upon the recommendation of a water treatment company, sodium hydroxide was added to the fluid at a settling tank before circulation through the system. This practice continued during the period 1948 through 1958. This sodium hydroxide treatment cost more than $3,000 per year in 1949 and continued to rise for the next ten years.

By 1958 (even with this treatment), corrosion had reached a point where a number of the finned coil tubes in the airstreams had failed. At that time a conversion was made from a direct utilization system to an indirect system. This conversion consisted of the installation of three shell-and-tube heat exchangers, replacement of certain heating and cooling coils that had failed, and the installation of a sand filter in the well water piping system. Figure 2. reflects the modifications made to the original system in 1958 to isolate the chiller evaporators, condensers, and various heating and cooling coils from the effects of the groundwater-induced corrosion.[7]

Installations of similar design have continued to provide excellent service to their owners through the use of the shell-and-tube heat exchangers. Currently, the Equitable Building (since renamed the "Commonwealth Building") operates with virtually no significant problems using the geothermal wells originally completed in 1948. The Commonwealth Building's present energy use of 63,000 Btu/sf-yr (715 Mj/m - yr) confirms the groundwater heat pump's viability in today's building designs.

Other designers in the Northwest have adopted the low-temperature concept and applied it to a number of buildings constructed during the past five years. These new buildings have installed systems almost identical to those initially designed for the Equitable Building. The authors believe this is so because the information provided them (in Reference 4) does not adequately sensitize the designers to the potential for corrosion and scaling with low temperature fluids. The unwanted results of these recent designs have been some rather difficult problems associated with corrosion caused by direct circulation of groundwater in the mechanical systems.

## LOW TEMPERATURE CORROSION SPECIES

As indicated in Chapter 56 of the Applications Volume, there are specific chemical species the designer should consider in making the material selections for an isolation heat exchanger and/or for other system piping. The designer should consider the effects of dissolved solids, gases, and microorganisms in addition to the chemical species normally considered for potable water analysis. When making these selections. The following key chemical species must be quantified in order to accurately evaluate corrosion and scaling tendencies: oxygen, hydrogen ion (ph), chloride ion, hydrogen sulphide, carbon dioxide, ammonia, sulphate ion, transition metal ions, silica, calcium carbonate, and calcium sulphate.

In reviewing a number of projects in the Pacific Northwest Area of the United States (where corrosion difficulties have occurred), it was discovered that designers had tested only for those species associated with normal potability analyses. Once potability had been confirmed, designs were executed in a manner nearly identical to that used in the Equitable Building. Well water fluids were circulated directly through the HVAC heat transfer elements such as finned coils, water-to-air evaporators and condensers. In fact, potability by itself does not have any direct relationship as to whether the low temperature fluid will exhibit corrosive or scaling tendencies.

### Bacteria

Various geothermal fluids at lower temperatures can also support bacterial microorganisms. The organisms observed in the Northwest that cause the most significant problems are the "iron bacteria" of which crenothrix is the most common. These bacteria oxidize ferrous iron to the ferric state and, in the process surround themselves with a thick, gelatinous mass. Flow restriction due to this mass is the largest problem associated with the bacteria, although its presence can also promote certain types of pitting corrosion. These bacteria attack any iron bearing alloy and will cause eventual failure in systems with iron piping as well as significant fouling.[8,9] Maintenance costs are increased substantially to remove bacteria and their detritus.

### Testing Required

Designers can request their water testing laboratories to provide them with indices of corrosion in addition to providing the concentrations of the above noted chemical species. Two indices in common use as indicators of corrosion and scaling are the Ryznar and Langelier indices. These indices can be readily calculated from basic water analysis data or requested as part of the lab analysis.

Values for the Langelier Index are calculated as follows:

Langelier Index = pH - pH

pH = pH from test of well water

pH = calculated pH of saturation of calcium carbonate

Values for pH are easily arrived at employing tables developed by Nordell or plot by Powell.[10,11]

Values for the Ryznar Stability Index are calculated as follows:

Stability Index = $2pH_s - pH$

$pH_s$ = calculated pH of saturation of calcium carbonate

pH = pH from test of well water

Table 1 indicates the values of these indices with respect to scaling and corrosion. In general, Ryznar stability indices between six and seven are desirable along with Langelier indices of 0.0 plus or minus 0.25. As can be seen, both indices give a subjective tendency for the corrosion or scaling performance of the water.

It is critical to be aware, however, that these indices are based primarily upon the solubility of calcium carbonate. As a result, the values do not consider other sources of scaling, corrosion, and fouling, such as dissolved gases, microorganisms, or other chemical species so common in geothermal fluids. Therefore, the Ryznar and Langelier indices should be considered accurate predictors only for fluids of low total dissolved solids and devoid of dissolved gases and microorganisms.

## Choices

Where noxious chemical species, bacteria, and/or high corrosion or scaling potentials exist, the designer has several choices. Presently, most state and federal agencies preclude the use of treatment chemicals in low temperature geothermal fluids that are to be reinjected. Equally, most jurisdictions are urging the reinjection of spent fluids into the ground to avoid depleting the natural groundwater resource. With these restrictions, chemical treatment (even if it were cost effective) is unlikely to be permitted. This leaves the designer with a choice of specifying either isolation of the geothermal fluid with a heat exchanger and conventional materials for piping, coils, and valves, or special materials throughout the mechanical system if the geothermal fluid is to be circulated throughout the system.

## Plate-type Heat Exchangers

In most cases where isolation is deemed advisable, the plate type heat exchanger has proved to be the most successful. Plate heat exchangers provide superior heat transfer capability, compact space requirements, and relatively low cost for the isolation of low-temperature geothermal fluids in heat pumped installations. Where severe corrosion potential exists, specific attention should be paid to the utilization of special alloys in the heat exchanger. Equally important when scaling or corrosion potentials exist is the need to address the piping system on the geothermal fluid side.

## Materials

Certain materials have shown superior performance in meeting these duties. The materials that have performed best are the interior epoxy-coated piping and valves, galvanized steel (in certain cases), plastics, and glass fiber epoxy resin piping materials. Where significant scaling tendency is indicated, the designer should take particular note to provide a significantly greater number of plates within the heat exchanger to provide for design rated performance. In addition, maintaining fluid pressure in the well water side of the system above saturation pressure for the particular scaling species has also proved to be a successful strategy to reduce or avoid scaling.

Several chemical species in low-temperature fluids have presented particular problems and deserve extra mention. Designers should pay very close attention to any presence of either hydrogen sulphide or ammonia or ammonium ions. These species, even in concentrations of less than one part per million, attack all copper or copper-bearing alloys and cause extremely rapid failure.

Chlorides are also a potential problem where stainless steel alloys are being considered. Especially in plate heat exchangers where stainless steel is used, the forming operations can leave very high residual stresses at the surface of the plates if the plates are not annealed. If chlorides are present, then stress corrosion cracking is a definite possibility. The design should verify with the heat exchanger manufacturer that Chlorides in the fluid are acceptable.

Upon the manufacturer's recommendation coupon tests may be necessary.

Table 2, adapted for this paper from "Materials Selection Guidelines for Geothermal Energy Utilization Systems," gives the effects of various water constituents on various materials of construction.[12] Designers can minimize their potential corrosion problems by using such a chart and relating those materials and water constituents to find those materials having the best resistance to corrosion.

The plate heat exchangers have virtually no effect on the energy utilization of the heat pump based, low-temperature geothermal heating systems. This is due primarily to the low approach temperatures, which result from the superior heat transfer performance of plate heat exchangers in low temperature geothermal systems. Some slight loss of performance may be seen in non-heat-pumped systems since the secondary-side fluid temperature will always be below that of the primary fluid.

### Dissolved Oxygen

Another mechanism that has caused corrosion problems in recent designs has been the fact that designers frequently employed settling tanks or other air/fluid interfaces to accommodate variable well water flow rates. The reduction in pressure, from the hydrostatic pressure at the base of the well to the surface pressure (or atmospheric pressure), causes a number of chemical constituents to come out of solution and effervesce. Carbon dioxide is especially troublesome in this regard. These gases, once they are no longer dissolved, can by themselves cause significant corrosion. When enhanced with an oxygen interface (such as seen in a "settling type" tank) the corrosion rate is significantly accelerated. The designer can devise a system employing a hydropneumatic tank and level sensor to avoid the use of settling tanks. With a hydropneumatic tank downstream of the heat transfer surfaces, the geothermal side of the loop can be kept under pressure at all times (and without an oxygen interface). This configuration, shown in Figure 3, provides a system where, regardless of initial corrosion potential, actual corrosion is minimized. Another system applicable to larger installations is the use of variable speed pumps, a tank, and level controls.

## SUMMARY

In summary, it would be desirable for Chapter 10 of ASHRAE Systems to either include data on low-temperature corrosion within the chapter or explicitly refer the user to Chapter 56 of Applications with a notation that the narrative in Chapter 56 is equally applicable to low-temperature fluids used in heat pump systems. It is as important to include the isolation of the fluid in a heat exchanger in low-temperature well-water-based geothermal heat pump systems as it is in direct use systems. The corrosivity of low-temperature fluids is not generally assumed to be significant. However, based upon a number of installations reviewed in the Pacific Northwest, there is significant potential for corrosion and scaling within low-temperature resources. This potential cannot be determined directly from conventional potability analyses. Designers are strongly advised to take advantage of a complete water analysis identifying key corrosive species before proceeding with design or materials selection.

The Ryznar and Langelier indices should only be considered as acceptable substitutes in very low total dissolved fluids containing no dissolved gases or microorganisms. With this information designers can specify corrosion-resistant materials, where there is a serious corrosion potential, or can specify additional surface area where scaling is a likely problem.

The use of isolation heat exchangers in low-temperature heat-pumped geothermal installations has little or no significant effect on the energy utilization of the systems while significantly reducing (in most cases) the maintenance cost associated where a direct utilization strategy applied.

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## TABLE 1

## VALUES OF LANGELIER AND RYZNAR INDICES

| LANGELIER SATURATION INDEX | TENDENCY OF WATER |
|---|---|
| + 2.0 | scale-forming, and for practical purposes noncorrosive |
| + 0.5 | slightly corrosive and scale-forming |
| 0.0 | balanced, but pitting corrosion possible |
| - 0.5 | slightly corrosive and nonscale-forming |
| - 2.0 | serious corrosion |

| RYZNAR STABILITY INDEX | TENDENCY OF WATER |
|---|---|
| 4.0 - 5.0 | heavy scale |
| 5.0 - 6.0 | light scale |
| 6.0 - 7.0 | little scale or corrosion |
| 7.0 - 7.5 | corrosion significant |
| 7.5 - 9.0 | heavy corrosion |
| 9.0 and higher | corrosion intolerable |

TABLE 2.

Main Environmental Factors And Effects on Materials

| MAIN ENVIRONMENTAL FACTORS | MATERIAL | EFFECT |
|---|---|---|
| Oxygen | Mild and low alloy steels | Uniform corrosion |
| | | Pitting and crevice corrosion |
| | | Fatigue endurance limits |
| | Stainless steels | Stress corrosion cracking |
| | Titanium alloys | Pitting and crevice corrosion |
| Hydrogen Ion (pH) | Mild and low alloy steels | Uniform and localized corrosion |
| | | Uniform corrosion |
| | | Stress corrosion cracking |
| | | Sulphide stress cracking |
| | Stainless steels | Pitting and crevice corrosion |
| | | Stress corrosion cracking |
| | Titanium alloys | Pitting and crevice corrosion |
| | Copper alloys | Stress corrosion cracking |
| Chloride Ion | Mild and low alloy steels | Uniform pitting and crevice corrosion |
| | | Stress corrosion cracking |
| | | Sulphide stress cracking |
| | | Uniform and localized corrosion in geothermal steam |

TABLE 2. (Continued)

| MAIN ENVIRONMENTAL FACTORS | MATERIAL | EFFECT |
|---|---|---|
| Chloride ion (cont'd) | Stainless steels | Pitting and crevice corrosion<br>Stress corrosion cracking |
| | Titanium alloys | Pitting and crevice corrosion<br>Stress corrosion cracking |
| Hydrogen | Mild and low alloy steels | Uniform pitting and crevice corrosion<br>Stress corrosion cracking<br>Hydrogen blistering<br>Corrosion fatigue<br>Erosion-corrosion in steam lines |
| Hydrogen | Stainless steels | Pitting and crevice corrosion<br>Sulphide stress cracking |
| | Nickel alloys | Sulphide stress cracking and hydrogen embrittlement |
| Hydrogen (cont.) | Copper alloys | Uniform corrosion |
| | Cobalt alloys | Sulphide stress cracking resistance |
| Carbon Dioxide | Mild and low alloy steels | CO vapor pressure and flow rate effect on design<br>Uniform pitting and crevice corrosion<br>Corrosion fatigue |
| | Stainless steel | Pitting and crevice corrosion |

TABLE 2. (Continued)

| MAIN ENVIRONMENTAL FACTORS | MATERIAL | EFFECT |
|---|---|---|
| Ammonia | Mild and low alloy steels | Uniform corrosion |
| | Stainless steels | Uniform pitting and crevice corrosion |
| | Copper alloys | Stress corrosion cracking, "season cracking" |
| Sulfate ion | Mild and low alloy steels | uniform pitting and crevice corrosion |
| | Stainless steels | Pitting |
| Transition metal ions | Aluminum alloys | Pitting and crevice corrosion |
| Temperature | Mild and low alloy steels | Uniform pitting and crevice corrosion<br>Sulphide stress cracking |
| | Stainless steels | Pitting and crevice corrosion<br>Stress corrosion cracking |
| | Titanium alloys | Pitting and crevice corrosion |
| Flow velocity | Mild and low alloy steels | General effects |
| | Stainless steels | General effects |
| | Nickel alloys | Applicability in high flow rates |

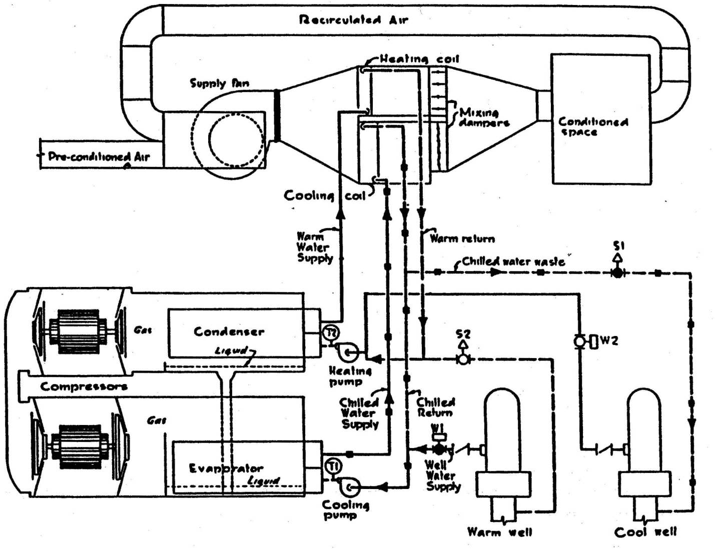

Figure 1. Basic heat pump scheme, heating cycle

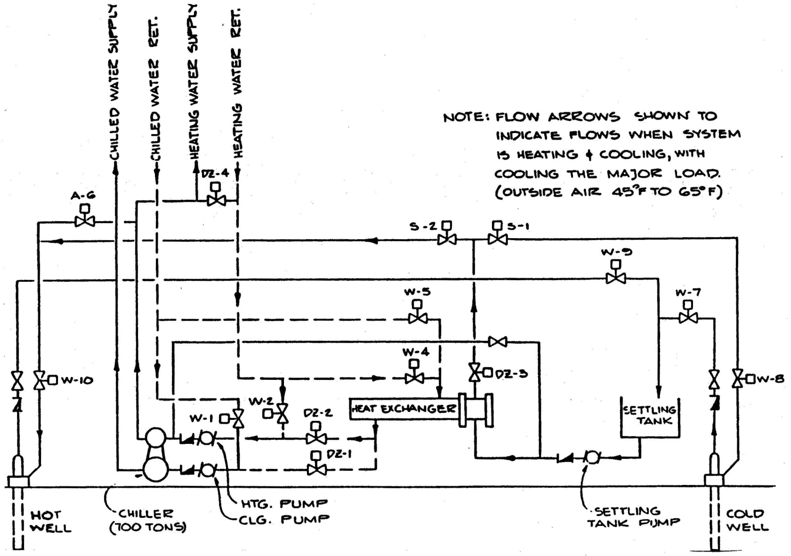

Figure 2. Simplified heat pump flow diagram Commonwealth building in Portland, Oregon

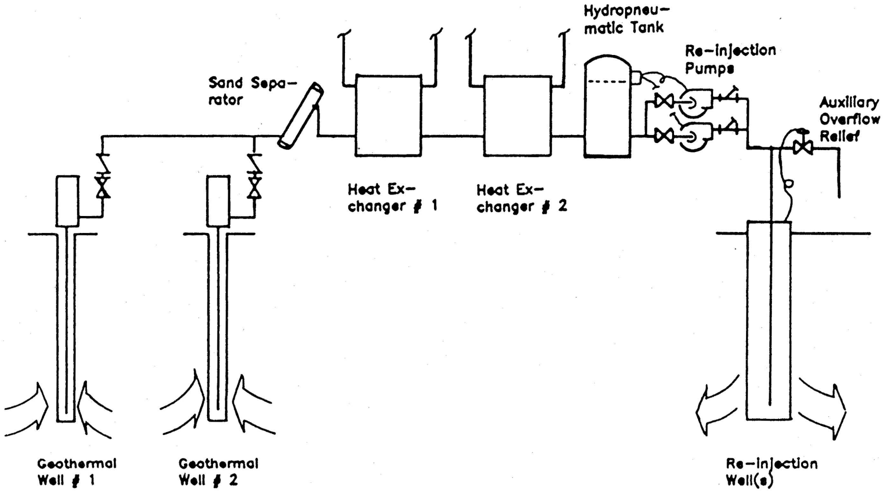

Figure 3. Closed, variable speed pumping system (small components omitted for clarity)