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WELL, HYDROLOGY, AND GEOCHEMISTRY PROBLEMS ENCOUNTERED IN ATEs SYSTEMS AND THEIR SOLUTIONS

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**Well, Hydrology, and Geochemistry Problems
Encountered in ATEs Systems and Their Solutions⁽¹⁾**

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Abstract

In aquifer thermal energy storage (ATES) systems, wells provide the interface between the energy storage and use. Efficient operational wells are, therefore, essential for the system to run at maximum (design) efficiency. Adequate test drilling to accurately predict aquifer properties is essential in the design phase; proper construction and development are crucial; and proper monitoring of performance is necessary to identify the early stages of clogging and to evaluate the adequacy of well rehabilitation. Problems related to hydrology, well, and aquifer properties include 1) loss of permeability resulting from gas exsolution, chemical precipitation, and dispersion and movement of fine-grained particles; 2) loss of recoverable heat caused by excessive regional ground-water gradient, hydrodynamic mixing of injected and native ground water, buoyancy flow (because of temperature-induced differences in water density), and heat conduction through the cap and base of the storage zone; 3) leakage up along the well casing; and 4) "fracturing" of a shallow upper aquiclude as a result of an injection pressure greater than the hydrostatic pressure on the aquiclude.

The predominant geochemical problems encountered are precipitation of carbonates in some areas and iron plus manganese oxides in others. These precipitation problems can be anticipated, and thus avoided, via geochemical calculations. The likelihood of iron carbonate (FeCO_3) precipitation is less certain because of the lack of adequate research. Corrosion is a frequent problem.

Most of the hydrochemically related clogging and corrosion problems that have been encountered in ATES systems can be predicted and avoided by appropriate design, construction, and operation of new ATES systems, assuming that a comprehensive and careful site investigation that includes appropriate hydrologic and geochemical modeling is carried out in advance. Because of local variations in hydrology and water chemistry, each project must be carefully examined and the installation planned based on a knowledge of the kind of problems that could be encountered and site conditions. It is prudent to carefully consider the need for water treatment and to anticipate that there will be some increase in injection pressure and decrease of specific capacity over time. Therefore, the design should include 1) the capability to monitor the specific capacity, 2) an injection pressure control, 3) a permanent backflush system, and 4) a safety valve.

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INTRODUCTION

Aquifer thermal energy storage (ATES) systems make it possible to achieve large storage volumes, hence a large potential energy transfer, and obtain economy of scale, particularly if local ground-water gradients are small. A driving force for alternative energy forms is Europe's quest for energy self sufficiency (Rybach et al. 1988, Louwrier et al. 1988).

During the early studies of Iris (1979) and colleagues at the Ecole des Mines de Paris, the concept of seasonally recharging a solar/geothermal doublet was developed and commercialized for an urban area containing 200 housing units near Paris, France (Hadorn et al. 1990). Since then the majority of ATES systems involve the doublet concept. However, because of the loss in recoverable heat caused by buoyancy flow experienced at Colombier, near Neuchatel, the second Swiss ATES site (known as SPEOS) utilized a novel radial drain design in separate but adjacent aquifers.

China clearly leads in utilization of chill storage having had "several years of experimentation" by 1965 (Yan and Woo 1981), with as many as 500 wells in Shanghai province alone (Lundin 1990). There are various other heat and/or chill storage sites not included in this review because they were not reported in our primary sources.

Many ATES systems have storage temperatures in the range of 12 to 40°C, but there have been only six with temperatures of >85°C (Horsholm, Mobile, Plaisir, SPEOS, St. Paul, and Utrecht; Lundin 1990, Molz et al. 1983, Willemsen 1992).

The objective of this paper is to review the technical design and implementation problems encountered to date in ATES systems worldwide, examine the extent to which these problems are unique to ATES as opposed to generic problems known to the applicable disciplines, and identify the solutions exploited to resolve these problems so that they can be avoided in future ATES systems.

The scope of this review includes those ATES systems that have been recorded in the Seasonal Thermal Energy Storage (STES) newsletter, the JIGASTICK'88 and THERMASTOCK'91 conference proceedings, or are included within International Energy Agency (IEA) Annexes III, VI, and VII and for which enough information was found to make a meaningful entry into the Appendix table. Thus, the review is not all-inclusive but does include the majority of all experimental and commercial ATES sites. Economic and environmental aspects of ATES systems are not considered in this paper. The information collected on problems and solutions has been summarized in the Appendix along with selected key information pertinent to the problem encountered. In the following text, ATES sites are referred to by their identification in the table (acronym, company, or city).

WELL DESIGN AND CONSTRUCTION

In ATES systems, wells provide the interface between the energy store and the remainder of the system; therefore, they are critical for the successful operation of the total system. Therefore, wells need to be carefully designed, drilled, and completed to prevent operational problems.

DESIGN CONSIDERATIONS - In a storage system, individual wells are generally used both for production and injection. Thus, they are operated under both hydraulic drawdown and pressure buildup conditions. For the latter case, this normally means a tight well-head construction to avoid gas escape and a pressure relief device to avoid excessive pressure. On the other hand, if the water level is low, a negative pressure can occur. In this case, airtight construction is necessary to avoid oxidation of Fe^{II} by atmospheric oxygen; either a set of injection tubes of different diameters and/or a down-hole throttle may be necessary during the injection phase to prevent exsolution of dissolved gas and clogging of the aquifer with gas bubbles.

Because water almost always contains some particulates, most injection wells will clog with use. However, it has been shown that well performance after clogging from silt and sand-sized particulates can easily be restored by backflushing (Andersson 1988). However, specific capacity may be only partially restored if the clogging is due to clay-sized material or amorphous precipitates that may result from water clarification. If it is expected that frequent backflushing will be needed, it is advisable to design wells with a permanent backflushing system.

CONSTRUCTION ASPECTS - Even drilling a well in an unconsolidated formation involves a risk of clogging, especially if a non-biodegradable mud is used as a drilling fluid. In this case, clogging is caused by fine-grained sediment entering the more permeable parts of the formation and lodging there (Glenn and Slusser 1970).

A loss of gravel pack permeability can occur while the screen and the gravel pack are being emplaced. If these components are not carefully installed, formation sediment may be admixed with the gravel pack, resulting in a permanent loss of permeability. Particle migration and bridging of pores during well operation, especially at high flow rates, may also result in clogging (Andersson 1988).

Short-circuit flow along the casing was a problem at the Mobile and Bunnik sites, allowing the mixing of the thermally altered water with native ground water (Molz et al. 1978). This occurs as a result of an inadequate seal above the gravel pack and upwards along the casing.

It is obvious that inadequate well design, improper drilling, or inadequate well construction can cause severe damage to the total ATEs system. Therefore, adequate test drilling to accurately predict aquifer properties is essential in the design phase of the project. It is then up to the engineer and the well driller to carry out their work skillfully. To reduce potential drilling and well construction errors, some simple but important "guidelines" can be stated (Andersson 1990): 1) use biodegradable polymers instead of clay minerals (e.g., bentonite) in the drilling fluid, 2) before setting screen and gravel pack, circulate water until the hole is clean, 3) design screen slot size and gravel pack carefully to avoid sand production or clogged gravel pack, 4) spot weld down-hole pipe connections so that they cannot loosen and allow air entry, and 5) develop the well (e.g., by airlift) until the water is free of particulates and no sand is circulating.

HYDROGEOLOGY

FREE CONVECTION OR BUOYANCY FLOW - Buoyancy flow is the flow in the aquifer that is driven by the difference in density between hot and cold water (or between saline and fresh water). Buoyancy flow occurred at all sites where storage occurred at relatively high temperatures in aquifers with a high permeability, i.e., Bunnik, Colombiar, Horsholm, SPEOS, Campuget, and Mobile. Buoyancy flow can not be prevented for given hydrogeologic and storage conditions, such as thickness and permeability of the aquifer on the one hand, and temperatures and amounts of water on the other hand. However, the amount and effect of buoyancy flow within a cycle can be reduced and the effect of buoyancy flow on the storage efficiency can be greatly minimized by implementing one or more of the following design measures:

- Inject warm water over the full height of the aquifer and production of water only over some upper part of the aquifer as was done at Mobile, Horsholm, and Delft. The results from tests at Mobile and theoretical calculations on the subject by Buschek et al. (1983) show that this can significantly increase the thermal efficiency of the store.
- Drill horizontal instead of vertical wells as was done at SPEOS. When there are two levels of wells and the "warm" wells are above the "cold" wells, there will be a layered store, as with short-term storage in tanks. In such a situation, the density difference will cause a stable situation when the lighter water is above the heavier, colder water. At SPEOS, it was subsequently found that there was a low-permeability layer between the hot and the cold wells and that heat loss to the surface could be lowered significantly by switching the cold wells and warm wells.
- Prevent vertical flow through the (vertical) wells when pumping is stopped. At Bunnik, it was found that vertical flow through wells occurred and contributed significantly to the buoyancy flow. Vertical flow was subsequently prevented by placing a packer in the warm well, which was manually closed when the store was not used. In practice it was found, however, that the packer leaked a lot of the nitrogen gas used to close the packer. This gas caused high pressures in the top layer of aquifer adjacent to the warm well.

BREACHING OF CONFINING LAYER (AQUICLUDE) - When the injection pressure becomes higher than the minimum pressure required to lift the confining layer, the confining layer will breach and the water will flow to the surface. This phenomena is known from artificial recharge (Olsthoorn 1982) and from injection carried out to minimize subsidence caused by a lowering of the ground-water table (Rijkswaterstaat

1986). In general, the rule can be used that the injection pressure in meters of water head above the surface level should not be larger than 0.2 times the depth of the top of the screen below land surface. For the final design of an injection well, an accurate calculation of the allowed injection pressure should be made, taking into account the weight of the total column of rock and water above the top of the screen or above the top of the aquifer (whatever is the most critical point) and the angle under which the matrix is likely to start to move. Breaching of the confining layer occurred at Horsholm and may have occurred at Mobile. At Horsholm, a pressure transducer that should have shut down the system before too high an injection pressure was reached did not function properly. This is not an isolated occurrence, as pressure transducers at St. Paul also failed.¹ At Mobile, it was speculated that the failure may have been caused by piping along a improperly sealed well casing rather than breaching the aquiclude (Molz et al. 1978).

In general, breaching of the confining layer can be prevented by an adequate design of the storage system. Account should be taken of the necessary injection pressure during maximum flow and of possible clogging. Also, safety measures should be taken such that the system shuts off above a certain injection pressure. One should therefore not rely on a single pressure transducer.

THERMAL BREAKTHROUGH - The injection and production wells should be at an optimum distance from each other that should allow for the maximum required amount of energy to be stored. Whether any influence of one side on the temperatures at the other side is desired depends on the injection temperatures with respect to the natural ground-water temperatures. If the injection temperatures at the "warm" and "cold" sides of the store are such that the natural ground-water temperature is between those temperatures, then thermal breakthrough is undesirable. Undesirable thermal breakthrough occurred, for example, at Kristianstad. If, on the other hand, "warm" and "cold" sides have injection temperatures that are both below or above the natural ground-water temperature, then some thermal breakthrough is wanted. Kowalczyk and Havinga (1991) performed calculations on the thermal efficiency of a store as a function of well distance. They showed that the optimum well distance depends on the type (heat, cold, or combined) and the temperatures of the store. In case the injection temperatures are on both sides of the natural ground-water temperature, the radius of influence of cold and warm well should not reach each other (well distance larger than 3 times R_{th}). In the other case the wells should be in each other's range of influence (well distance approximately 1 to 2 R_{th}). The potential for thermal breakthrough depends of course also on the regional flow, the direction of this flow with respect to the locations of the wells and on the existence of preferential flow paths.

PREFERENTIAL FLOW PATHS - Aquifers normally exhibit higher permeability in some layers than in others, resulting in a greater volume of water being injected into the higher permeability layer(s). The effect of variable permeability layers is to increase the surface area of the store and, therefore, the thermal losses. The flow of thermally altered water to a greater distance in some layers than other, cannot be prevented, but the following countermeasures can be taken to prevent excessive losses caused by preferential flow paths.

- If feasible, use (screen) only the part of the aquifer exhibiting similar permeability values.
- Contrary to the standard practice with water production wells of using the maximum slot size and gravel pack grain size that is allowed by the grain size in the aquifer, for ATEs wells an (small) increase in resistance to flow across the screen and gravel pack may be beneficial by causing the injected water to be distributed more uniformly over the various aquifer layers. This approach will, of course, reduce the specific capacity.

REGIONAL FLOW - Where regional gradients in pressure head in the aquifer are relatively large and the permeability of the aquifer is high, there will be a significant regional flow that will cause part of the stored energy to be lost. Significant losses from regional flow occurred at Bunnik, SPEOS, and Tuscaloosa (Schaetzle and Brett 1989). The losses caused by regional flow can be minimized by altering the upstream head or effective permeability by developing

- An active gradient control or "bypass" for the regional flow wherein the upstream head is reduced by pumping from one or more wells upstream of the store to one or more downstream wells (transfer to

¹ M. Hoyer, Oral Communication.

surface water as is now done at Tuscaloosa). Willemsen and Groeneveld (1989) showed with computer calculations that such a bypass can effectively reduce the effect of the regional flow on the thermal efficiency of the store to zero.

- Passive gradient control wherein the impact of regional flow is minimized by judicious control of pumping schedules can be effective if the regional flow is not too great (Schaetzle and Brett 1989).
- Low-permeability screen around the store, as proposed by Hadorn et al. (1990) whose calculations have shown that such a screen can significantly reduce the effect of the regional flow on the thermal efficiency.

Both of these methods to decrease the extent of the regional flow through the aquifer store require significant investments, and care must be taken to ensure that they are cost effective. A low-permeability screen is only feasible in shallow aquifers. Other methods that may be used to reduce the loss in the efficiency of the store without actually reducing the regional flow itself are to

- Inject into the store upgradient of the recovery well. This requires that the quality of the energy in the upstream part is higher, the wells are in line with the regional flow, and that the warm and cold sides are both higher or lower than the natural ground-water temperature. Otherwise, steps must be taken to minimize thermal breakthrough, which means that the wells have to be placed orthogonal with respect to the regional flow.
- Inject more water in the upstream than downstream well and/or produce more from the downstream than in the upstream well. This implies that the wells on each side have to be placed in the direction of flow.

However, application of these methods may also involve significant cost.

GEOCHEMICAL SCALING AND CLOGGING

As is evident from the Appendix table, scaling of heat exchangers and clogging of wells, gravel pack, adjacent aquifer caused by chemical precipitates has been frequently encountered in existing ATEs systems, especially the precipitation of carbonates in the systems operating above 85°C and Fe and Mn oxides in low temperature (<40°C) systems.

CARBONATES - Scaling (i.e., precipitation within the above-ground portion of an ATEs system) and precipitate-induced aquifer clogging (i.e., reduced aquifer permeability caused by precipitation within the aquifer) results from carbonate and Fe plus Mn oxide precipitation. Problems with carbonates has occurred at St. Paul, SPEOS, Horsholm, and Plaisir (Appendix). Extensive clogging occurred at St. Paul because the engineers and geologists involved were unaware of the inverse solubility of carbonate minerals with temperature. Subsequently, the quantity of carbonate available for precipitation was underestimated; hence, precipitation cylinders clogged within a day or so because of the extensive precipitation that occurred. A Na-ion exchange system was subsequently installed that has been essentially trouble-free. At SPEOS, carbonate precipitation was prevented by adding acid for some years; but, the acid addition was terminated because of increasing Cl concentration and hardness levels of the water. Since then, there has been continuing experimentation with a variety of physical approaches ("non-sticking heat exchanger coatings," recirculation of plastic balls), alkali addition to raise the pH, and fluidized bed heat exchangers. However, as these treatments resulted in fine-grained carbonate precipitates that have frequently clogged the well/aquifer interface. At Horsholm, as at SPEOS, acid addition was used to prevent carbonate scaling. Aquifer clogging at Plaisir occurred when the treatment control system failed. In the later stage of this project, a cation exchanger was installed and no further carbonate clogging was encountered.

Thus, Na-exchange resins provide a trouble-free method of avoiding carbonate scaling and clogging, as long as care is taken to ensure that clay swelling and/or dispersion does not occur and the disposal of the acid or salt used to recharge the resin is not a problem. The likelihood of clay swelling/dispersion can be estimated from the sodium adsorption ratio and used in conjunction with the salinity of the water. An environmental consequence of the cation exchange method is that sizable amounts of either salt or acid, used in recharging the exchange resin, must be discharged to surface or ground water.

Although not yet implemented in other than an experimental mode, a fluidized bed heat exchanger with an in-line activated carbon column to remove dissolved organic carbon has recently been successfully tested.²

IRON AND MANGANESE HYDROXIDE PRECIPITATION - The precipitation of Fe and Mn oxides is caused by a change in water chemistry. Precipitation of Fe^{III} oxides can be induced by increasing either the redox potential (Eh) or the pH. As illustrated in the Fe stability field diagram shown in Figure 1, if either the Eh or pH of a slightly reduced water (point A in the diagram) is increased, precipitation of Fe oxides is likely. Not shown on this figure is the effect of Fe concentration; as Fe concentration increases, its oxide will precipitate at progressively lower Eh and pH values. In practice, there are at least three processes involved to create the Eh and pH changes. Those are (Andersson 1990) 1) oxygen is added from some source and the Eh value is increased (displacement from A to B in Figure 1); 2) waters differing in their Eh status are mixed upon entering the well causing either an increase or decrease in Eh and possibly pH (A to B or B to A); or 3) carbon dioxide escapes from the water, increasing the pH-value (A to C). The latter process is also believed to be one of the main factors causing the precipitation of carbonates in a well with little or no scaling in the heat exchanger. Where there are significant Fe concentrations, Fe carbonate rather than Ca carbonate may precipitate. Although definitive information is not yet available, the precipitation of Fe carbonate is suspected at several locations in Sweden (e.g., Lomma). The Fe carbonate precipitate in these cases is not readily solubilized by acid treatment of the well.

Shallow, unconfined aquifers generally have levels of Fe and Mn that are likely to yield oxyhydroxide precipitates if air is allowed to enter the ATES system. Some Fe oxide, along with pyrite, was found on the heat exchanger at Horsholm, presumably the result of partial oxidation of dissolved sulfides caused by air leaking into the system. An air leak in the ATES system at Bunnik caused Fe and Mn scaling of the well screen. Iron oxide precipitation was presumed to be the cause of clogging at Klippan.

However, none of the processes causing Fe oxide precipitation need occur during injection if the system is airtight, and the aquifer is selected or the hydrology is controlled to eliminate the mixing of dissimilar waters near the well. For these reasons, the likelihood of Fe oxide clogging during injection is low in a properly designed system. If for any reason an airtight system is not feasible, any one of a number of iron removal methods may be used (Vail et al. 1992). The principal processes leading to a greater likelihood of clogging in production and injection wells with water containing elevated levels of Fe are illustrated in Figure 2.

CLOGGING BY MICROBIAL GROWTH - Clogging by biofilm or microbial slime is a well-known phenomena in the water-well industry (Driscoll 1986). The most frequent biologically caused well clogging is that associated with iron bacteria, especially the ones belonging to the Gallionella family. However, in a highly reduced environment, clogging can also be associated with sulphur bacteria. In ATES applications, clogging by iron bacteria slime will be a potential risk mainly in low-temperature systems (less than 25°C) and in waters with an iron content of at least 1 mg/L. Other conditions that favor major bacterial growth are Eh values between 200 and 400 mV and pH values between 5.5-7.5.

GAS CLOGGING - Gas clogging may occur as a result of the exsolution of gases present in excess of the amount that would be present at equilibrium with air at atmospheric pressure. This occurred at Delft because of the methane overpressure in the source/storage aquifer, and presumably at Scarborough (see Appendix), but did not occur at Utrecht, because a total pressure sufficient to maintain the dissolved gas in solution was maintained at the latter site.

CLAY DISPERSION - Swelling and dispersion of clays contained within the aquifer sediment occurs when the Na saturation exceeds an amount determined by the ionic strength (i.e., conductivity) of the water (Willemsen 1992). Clay swelling and dispersion are unlikely to pose a problem in consolidated or silica-cemented aquifers even when the water is passed through a Na ion exchanger repetitively, as at St. Paul. However, it is the suspected cause of the last clogging problem encountered at Plaisir.³ Clay swelling

² A. Willemsen, Unpublished Data.

³ A. Vinsot, Personal Communication.

and/or dispersion has been avoided at Utrecht, by treating the minimum fraction of the water necessary to prevent carbonate scaling; no scaling is observed at a calcite saturation indices of 0.6 to 0.7 (Willemsen 1992). A large amount of sediment was recovered at Mobile (Molz et al. 1983). The amount of suspended sediment may have been increased by the use of a foreign water (i.e., local surface water) into the aquifer and/or the inadequacy of the gravel pack.

CORROSION

Both chemical and electrochemical corrosion occur in ATES systems. Chemical corrosion is induced by constituents such as CO_2 , O_2 , H_2S , dissolved sulfide, chloride, and sulphate. Sites that have used HCl to remove or prevent carbonate precipitation, e.g., SPEOS and Horsholm, have experienced significant corrosion. Corrosion was also experienced when a pipe connection was not sufficiently tight and allowed a small amount of air to diffuse through the threaded joint and react with reduced ground water (Andersson 1992). Electrochemical corrosion appears to be more frequent than chemical corrosion. Electrochemical corrosion is caused mainly by joining metals with different electrochemical potentials but electrochemical corrosion also occurs on monometallic components that have been stressed, e.g., welded joints, cut surfaces or damaged coatings. Further, it seems that electrochemical corrosion causes loss of material only on parts of well screens and casings. Usually it occurs in water that is slightly acidic and with total dissolved solids greater than about 1000 mg/L (Driscoll 1986).

Protection against corrosion is in most cases dependent upon the choice of materials for each specific system. For instance, different steel alloys may cope with expected corrosion, as well as plastic materials, ceramics, or corrosion-resistant coatings. A world-wide method for galvanic corrosion protection of wells is to use a cathodic protection system, normally accomplished by connecting a sacrificial anode to the well casing (Driscoll 1986).

CONCLUDING DISCUSSION

Most of the hydrochemically related clogging and corrosion problems that have been encountered in ATES systems can be predicted and avoided by appropriate design, construction, and operation of by performing a comprehensive and careful pre-investigation. Because of local variations in hydrology and water chemistry, each project must be carefully examined and the installation planned on the basis of a knowledge of the kind of discussed in this paper that could be encountered and specific site conditions.

Virtually all common hydrologic and geochemical problems have been encountered at one or another of the ATES sites (e.g., buoyancy flow, breaching of confining layer, gravel pack failure, particle clogging, air clogging, methane clogging, precipitation Fe and Mn oxides), in addition to carbonate precipitation which is somewhat unique to ATES and geothermal systems. It is prudent to anticipate some build-up in injection pressure and decrease of specific capacity over time and therefore, to include in the design 1) the capability to monitor the specific capacity, 2) an injection pressure control with more than one transducer, 3) a permanent backflush system, and 4) a safety valve.

Clogging is the most frequent problem encountered in ATES systems. Rapid filtration (e.g., sand, fiber filters) and frequent backflushing is effective against particle clogging. Backflushing may need to be done as frequently as twice daily, as in the chill storage wells in Shanghai province during charging (Lundin 1990). Bacterial biofilms or slime are rarely a problem unless the water being stored is a surface water or has been enriched in nutrients and/or energy substrates. It is presumably for this reason that the water used to cool the cotton mills in Chanzhou is not only filtered three times but is chlorinated twice (Shen 1988, Yong-Fu et al. 1991). Where Fe precipitation is a potential problem, confined aquifers are preferred and care should be taken that CO_2 is not allowed to form a separate gas phase nor to escape. It is also desirable to limit the drawdown to the minimum extent possible.

Iron oxide and Ca carbonate solubility, as well as clay swelling and dispersion calculations have been found reliable in predicting when these problems will not occur. However, not enough experience has yet been gained to allow the prediction of Fe carbonate precipitation. Research on this problems, as well as on the effects of kinetic inhibitors (e.g., DOC, PO_4 , Mg) on Ca carbonate precipitation and complexation with

dissolved organic carbon on the apparent oversaturation of Fe oxides is underway within Annex VI of the IEA.

Steps to detect and avoid corrosion include 1) not allowing contact between metals or alloys with different electrochemical potentials, 2) not allowing oxygen to enter the system at any point, and 3) avoiding the use of acid to prevent scaling and clogging, and 4) installing a corrosion detector.

CONCLUSIONS

- There is an acute need for greater use of multi-discipline experience in the design and implementation of ATEs because most technical problems encountered to date could have been avoided if they had been anticipated in the design, construction, and implementation stage and the appropriate steps taken to prevent their occurrence.
- From a hydrogeological point of view, confined aquifers are strongly preferred over unconfined aquifers, because the potential for mixing of reduced and oxidized waters is much reduced.
- Minimize buoyancy flow losses by injecting thermally altered water over the full height of the aquifer but produce only from the upper part of the aquifer, or drilling horizontal instead of vertical wells, and install a means of preventing flow from hot to cold sides of the store during periods when pumps are not operating.
- Use best available hydrologic modeling to optimize distance between warm and cold wells.
- Losses from excessive regional flow can be minimized by lowering the upstream head by pumping or by injection an appropriate distance up gradient of the recovery well.
- Multiple pressure transducers should be included in the design to shut down the system before excessive pressures can cause a breaching of the confining layer.
- Closed systems are generally essential to avoid loss of carbon dioxide and entrance of air.
- Where the aquifer is over-pressured with carbon dioxide and/or methane, a sufficient overpressure must be maintained to avoid the exsolution of these gasses to form discrete gas phase which can clog the aquifer.
- The drawdown of an aquifer containing significant Fe concentrations during production should be limited to the extent possible, to avoid local degassing and a possible pH rise, by using highly permeable aquifers or additional wells.

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Figure 1. A portion of the Eh (or pE) versus pH stability field for iron illustrating the likely precipitation of ferric hydroxide and/or ferrous carbonate (siderite) as result of a change in Eh or pH ($a_{Fe} = 10^{-4}M$, temperature = 25°C; after Jenne 1968).

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Figure 2. Illustration of hydrologic and geochemical processes that facilitate the precipitation or dissolution of carbonates and/or Fe and Mn oxides in or close to (a) production well in an unconfined aquifer (carbonate and Fe/Mn oxide precipitation) as contrasted to (b) a well where oxygen-containing water that is undersaturated with respect of Fe oxides (e.g., surface water or treated ground water) and carbonate is injected into a confined aquifer that contains elevated levels of dissolved Fe resulting in potential carbonate dissolution as well as Fe.Mn oxide precipitation remote from the well itself, and (c) injection of Fe-rich water where air is allowed to enter the system resulting in Fe oxide precipitation on the well screen, gravel pack, and adjacent aquifer.

APPENDIX

Key Aspects of Experimental and Commercial Aquifer Thermal Energy Systems from Selected Literature Sources (as of May 1992; C = Commercial, E = Experimental; Alphanumeric reference designations are given at left margin of Reference section.)

Site, Country	Years Operated/ C or E	Recovery Temperature Range		Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/Cl --mg/L--	Treatment	Principal Problems (and Solutions)	Ref.
		Warm ----- °C	Cold -----					
Carlton, Canada	1/C	14/11	7/8	Sandstone/Confined	Not given	None	None	Da91
Scarborough, Canada	5/C	50/20	3/10	Glaci-fluvial sand/ Confined	7.8/1.0/90/3	None	Degassing of methane clogged aquifer and building explosion danger caused pump shut down (mechanical and acid treatment planned)	Mi92
Winnipeg, Canada	6/C	15/4	7/9	Limestone/Confined	Not given	None	None	Ma91 ¹
Hørsholm, Denmark	6/E	100/65	50/70	Glaci-fluvial sand/ Confined by boulder clay	7.2/4.0/80/30	Acid + degassing	Clogging of central well due to delayed carbonate precipitation (acid treatment); Leakage through confining clay aquilide due to excessive pressure (used alternate well); Severe corrosion caused by acid treatment (reduce acid usage); Heat exchanger scaling and clogging of injection well caused by Fe oxidation (restored by mechanical cleaning and acid treatment)	IQ91
1st National Cotton Mill, Chanzhou, China	3/C		16/12	Fluvial fine to coarse sands/ Confined	--/0.08/--/--	Filtered (3 times), chlor- inated (3 times)	Clogging near well caused presumably to Fe and Mn dissolution and reprecipitation (minimize O ₂ in stored water, back flush frequently)	Sh88 SZ88
Shanghai, China	Several/C	40/20	/1	Quaternary sand & gravel/Confined	"semi-salty"	Use tap water	Corrosion (fill store with tap water, pressure- filter before reinjection)	YQ91
Aulnoy sous bois, France	5/C	13	7	Sand/Confined	--/--/0.6/ --	None	Some clogging of injection well due to aeration and Fe precipitation (closed system with respect to air and acid treated well)	IV88 IV85

Site. Country	Years Operated/ C or F	Recovery Temperature		Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/Cl --mg/L--	Treatment	Principal Problems (and Solutions)	Ref.
		Warm	Cold					
Bonnaud, France	1/E	33		Sand/Confined		None		SG82
Campuget, France	1/E	33/16		Sand + gravel/Unconfined		None	Buoyancy flow and/or preferential flow lowered thermal efficiency; Aquifer polluted with bacteria from above ground greenhouses (plan to close system and/or use disinfectants)	1-80
Montruell sous bols, France	2/C	26/20		Sand/Confined	None		Clogging of injection well, possibly due to migration of fines (Lowered maximum flow by changing the on/off regulation to frequency regulation of the pump)	1V85
Plaisir (Thiervall- Grignon), France	3/E	120/80		Sand with clay layers/Confined	"Soft"	1. Precipitation with lime, Al, and FeCl ₃ 2. Na exchange	Clogging of wells and corrosion due to aeration in the lime treatment (changed treatment to Na exchange); Clogging of aquifer possibly due to clay dispersion resulting from Na treatment	P091
Trappes, France	3/C	50/25		Sand/Confined	--/160/--/70	NaCl-addition	Clogging of well (add acid)	VC91
Amsterdam, Netherlands	5/C	10/12	5/8	Sand + gravel/Confined	7.1/450/7/5000	None	None	KL91
Bunnik, Netherlands	5/C	26/18	10	Sand + gravel/Confined	7.2/140/10/50	Injection of soft Fe-free tap water	Recovery efficiency decreased by regional and buoyancy flow enhanced by buoyancy flow between wells during shut down (Install packer in store well); Minor clogging of injection well by Fe due to leakage of air into the system (made system air tight)	BS85
Delft, Netherlands	2/E	12	7/12	Sand + gravel/Confined	6.7/290/30/1200	None	Clogging of wells due to exsolution of CH ₄ gas due to pressure drop (degas before injection or keep pressure on system)	HM91
Utrecht, Netherlands	1/C	90/50	45/30	Marine silty sand/ Confined	8.0/50/1/400	Na exchange	None	LP91

Site. Country	Years Operated/ C or E	Recovery Temperature Range		Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/C1 --mg/L--	Treatment	Principal Problems (and Solutions)	Ref
		Warm	Cold					
Falun, Sweden	6/C	14/8	2/4	Esker/ Unconfined	6.8/3.5/30/20	None	Scaling of heat exchanger by iron (frequent acid flushing)	GR89
Klippan, Sweden	8/C	17/9	5/11	Glacial outwash/ Unconfined	8/4/50/40	None	Clogging of warm wells by iron (abandoned and replaced with infiltration ponds)	EH83 Le92
Kristianstad, Sweden	8/C	25/22	10/16	Sandstone/ Semitconfined	8.0/0.2/80/20	None	Thermal breakthrough to cold well (less warm water injected)	Kr91
Lomma, Sweden	4/C	20/12	3/5	Glaciifluvial sand/ Confined	7.3/6.5/85/130	None	Clogging of wells during production (acid treatment with limited success; experimental treatment planned)	An92a
SAS Office, Sweden	5/C	15/8	2/12	Esker/Unconfined	7.0/<0.1/170/140	None	Iron clogging of one well (acid treated); Leak in suction pipe to well pump (repaired)	AJ91
Sparren, Sweden	1	15/13	2/5	Limestone/ confined by boulder clay	6.9/0.5/220/2000	None	Corrosion on well pumps caused by air entrance (made system air tight); Leakage caused by excessive pressure (removed constricting backflow valve)	An92b
The Triangle, Sweden	2/C	15/13	2/5	Limestone/ Confined by boulder clay	7.7/0.5/170/250	None	Unreliable control valve (replaced); Heat exchanger clogged by gravel (changed pump)	La92
Columbier- Robinson, Switzerland	1/E						Low recovery efficiency caused by buoyancy flow (abandoned)	HC90

Site, Country	Years Operated/ C or E	Recovery Temperature Range		Geology/ Type of Aquifers	Water Chemistry pH/Fe/Ca/Cl --mg/L--	Treatment	Principal Problems (and Solutions)	Ref.
		Warm ----- °C	Cold ----- °C					
SPDOS, Dorigny (Lausanne), Switzerland	10/C	80/35		Glaciifluvial sandy; clay layer between 2 aquifers	7.4/--/80/30	Acid	Carbonate scaling and clogging. (1982-85: wash exchanger and store with HCl. 1986-89: lower pH with HCl); Increasing HCl concentration and corrosion (1990: fluidized bed heat exchanger); aquifer clogging (1991: acid wash)	SG91
Mohile, Alabama, U.S.	5/E	56/36 54/29 52/39		Confined	7/ < 0.1/4/20		Bouyancy flow (changed screened depth); Clogging from >5 µm suspended solids in surface water (use aquifer water); Clogging from suspended solids (sand filtration, periodic back pumping with surging) and gas (vent gases); Leakage through upper aquiclude (avoid excessive injection pressure)	MM83
Melville (Long Island), New York, U.S.	2			Glacial Outwash/ Unconfined	--/20/15/27		Air and iron clogging (drill new wells in area where aquifer contains less Fe); gravel pack failure (repacking will be required); Low chill recovery efficiency due to high regional flow rate	3.4
St. Paul, Minnesota, U.S.	11	97/39		Cemented sandstones/ Confined	8/2/50/2	Na exchange	Carbonate scaling of heat exchanger and aquifer clogging (water treatment)	Wa84 HE91
Stony Brook, New York, U.S.	1/E	50/45		Glacial outwash/Uncon- fined but "Leaky"	7/1/2/6	None	Clogging from suspended sediment (filter water); Iron clogging (add Na sulphite and back flush)	SS82
Tuscaloosa, Alabama, U.S.	10/C		7			None (sand filter)	Chill recovery efficiency low as a result of high regional groundwater flow (modify well operations pump ground water to surface water to counteract regional flow)	SB89

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2 Lemmeke, L. 1992. Oral communication.

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