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Geothermal energy and heat storage in aquifers

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AUTHORS

W.P.G. Ewalts	TNO Institute of Applied Geoscience, Delft
M.C. Geluk	The Netherlands Geological Survey, Haarlem
J.P. Heederik	TNO Institute of Applied Geoscience, Delft
A.J.M. Huurdeman	TNO Institute of Applied Geoscience, Delft
G.J. van Mourik	Energy Research Project Management Office, Utrecht
A.D. Postma	Energy Unlimited Foundation, Rotterdam
A.L. Snijders	Heidemij Adviesbureau, Arnhem
F. Walter	TNO Institute of Applied Geoscience, Delft
A. Willemsen	Heidemij Adviesbureau, Arnhem

INTRODUCTION

F. Walter

After the first energy crisis in 1973 various research programmes to do with energy conservation and diversification of energy resources were set up in the Netherlands. A number of these were directed to the rest of the subsoil for the following purposes:

- the extraction of geothermal energy from great depths (1800-3000 m below surface);
- the extraction of geothermal energy from shallow depths, using the heat pumps;
- seasonal storage of heat and cold at shallow and intermediate depths;
- the storage of energy from power plants in caverns or porous bodies, e.g. compressed air in aquifers during daily periods of low consumption.

These programmes were funded by the Netherlands Ministry of Economic Affairs and by the Commission of the European Community.

During this technical meeting the results of investigations on geothermal energy extraction and heat storage in the subsoil will be presented. The subjects discussed will include the geohydrological boundary conditions, geological, geochemical and environmental aspects, the test facility that is being established on TNO premises in Delft and the results of a geothermal test well in Asten.

Although the energy situation has changed considerably during the last years and instead of a shortage there now appears to be an energy surplus, it is most likely that the subjects discussed during this meeting remain topical. The main driving force may become the urgency to reduce carbon dioxide emission because of its environmental consequences.

NATIONAL RESEARCH PROGRAMME ON GEOTHERMAL ENERGY AND ENERGY STORAGE IN AQUIFERS (NOAA)

G.J. van Mourik

1 INTRODUCTION

In 1985 the Ministry of Economic Affairs commissioned the Energy Research Project Management Office (PEO) in Utrecht, which supervises many research programmes, to undertake the National Research Programme on Geothermal Energy and Energy Storage in Aquifers (NOAA). This programme has three main themes:

- geothermal energy research, aimed at possible exploitation of this source of energy to a maximum depth of 1500 m below the surface;
- energy storage in aquifers, with studies on the storage of both heat and cold in aquifers;
- adiabatic compressed air storage to buffer electricity, in which storage and recovery of the compression heat leads to improved efficiency compared with "conventional" compressed air storage.

2 GEOTHERMAL ENERGY PRODUCTION

The purpose of the research on the application of geothermal energy is to provide answers to the following two questions:

- Are there any aquifers in the Netherlands within the specified depth range that are capable of producing adequate thermal energy?
- For which applications can geothermal energy be used efficiently and under what conditions?

The second question has already been answered. The basic power capacity for some consumer categories studied is too low for independent efficient use of geothermal energy at the required temperature level. Geothermal energy for heating can in due course play an important part for several other categories. Large-scale use of geothermal energy will eventually be possible for heating large-scale housing projects, greenhouse market gardening complexes and industrial buildings and processes.

At current gas prices, geothermal energy can already be used efficiently in the large-scale housing projects now being built. Every year 20 MW geothermal energy could be connected. At a gas price of 50 cents or more per m^3 incorporation even becomes attractive in existing large-scale construction. The total savings in natural gas would be 500 million m^3 per annum. This assumes a capacity of 1500 MW to which 600,000 homes are connected. The use of geothermal energy in greenhouse market gardening becomes attractive at gas prices of 40 to 50 cents per m^3. Potential savings in this sector amount to 1,400 million m^3 of natural gas per annum. This requires 3,000 MW of geothermal energy. Industrial projects are cost-effective only at gas prices of 50 to 60 cents per m^3. Savings totalling 400 million m^3 of natural gas per annum are potentially feasible in this sector at a connected load of 2,200 MW.

It will thus be possible to save a total of 2.3 billion m^3 of natural gas per annum in the above categories at maximum use.

To be able to answer the first question on the availability of suitable aquifers test wells are necessary. The first test well was drilled in 1987 in the Asten district (North Brabant), to study a number of potentially suitable aquifers. Assessment of the data obtained from the test well showed that two aquifers can be considered for geothermal energy production - the Breda Formation at a depth of roughly 950 m and the Berg Sand a a depth of some 1500 m. If geothermal energy is produced from the Breda Formation at a temperature level of roughly 35°C, the specifications of the customers - in this case market gardeners specializing in greenhouse tomatoes and cucumbers - necessitate inclusion of a heat pump. Calculations showed that direct use of geothermal energy from the Berg Sand at a temperature level of roughly 60°C, including a thermo-electric power unit for the necessary pump power, is more favourable in terms of energy and economics than the production of low temperature geothermal energy and the use of a heat pump.

It was shown that production of geothermal energy is technically possible, though the geological risks are great. There are also applications for this energy, even if cost-effective use is out of the question at current energy prices. So there is definitely justification for concluding that the geothermal energy is not an interesting option at present but could eventually be an alternative to the present sources of energy. This conclusion and the fact that there are no technical blocks preventing the production of geothermal energy mean there is no need to continue the study over the next few years. But it is of interest to gain practical experience now for use in the future. This will be possible if thermal production from the Asten test well turns out to be satisfactory for supplying heat to the nearby greenhouse market gardening area. For the time being, connecting the wells to the greenhouse would be a good and useful conclusion to the present study.

3 ENERGY STORAGE

Underground storage of heat had already been studied before 1985 during the National Geothermal Energy Research Programme (NOA-I) and the National Solar Energy Research Programme (NOZ). The outcome was two practical experiments. In the city of Groningen 96 houses are heated partly by solar energy; in summer the solar heat is stored underground. This saves 50% of heating costs. Solar is also being used to heat an office block in Bunnik. Here too, the solar heat together with the refrigeration heat is temporarily stored underground during the summer.

The current study on energy storage is concentrated mainly on the storage system used in the office building in Bunnik. Here, use is made of sand formations below the groundwater level, the so-called aquifers. Energy in the form of hot water can easily be pumped into or out of aquifers. Aquifers suitable for storing energy in the form of heat or cold are found at relatively shallow depths under a large part of the surface of the Netherlands - usually at a depth of less than 100 metres. But if aquifers at greater depths could also be used, the area of application could be considerably expanded. The permeability of the aquifer determines the rate at which water can be pumped in or out. This means that several wells are needed to meet the required pump capacity.

Energy storage in aquifers can be incorporated in various energy systems without too many problems. The matrix table I gives several examples of systems in which energy storage can be used effectively. Here, energy storage not only means storage of heat but possibly also storage of cold. Thus, for example, the extracted formation water can be cooled in winter by ambient air to, say, 4°C and be used in summer for cooling buildings or cooling in the process industry (see bottom horizontal line of the table). At the Perscombinatie in Amsterdam, for example, this system is used for partial cooling of the press hall.

The pay-out times in the matrix table I are given at a specific gas price, to give an idea of the cost-effectiveness of energy storage. The table also indicates the combinations so far studied and/or field tested under the NOAA.

The research on energy storage will be continued over the coming years and the "National Test Facility for Storage of Heat and Cold in Aquifers" research programme in Delft will play an important role here. The energy storage research will make a clear distinction between storage of cold and storage of heat. Storage of cold presents few technical problems and has a short pay-out time in new construction projects. The investment costs for the entire system are already usually lower than conventional investments for refrigeration

Table I Feasible pay-out times for the various possible uses(gas price: 40 cents per m^3 for large-scale consumers and 50 cents per m^3 for small-scale consumers)

heat source \ heat consumer		large scale			small scale	
		residential area	glasshouse complex	industry	utility building	glasshouse farm
40 - 90°C	industrial waste heat	<5	<5	▨ <5	☒	☒
	co-generation	▨ <5	░ <5	<5	▨ 5-10	☒
	solar heat	▒ >15	☒	?	▒ 10-15	░ 10-15
4 - 40°C	condensor heat	☒	☒	☒	▒ 5-10	10-15
	ambient heat	?	?	☒	?	?
	ambient cold	☒	☒	▒ 5-10	░ <5	░ <5

░	**feasibility studies completed**	?	**insufficient data / not studied**
▨	**design studies completed**	☒	**not applicable**
▒	**field experiments completed**	5	**pay out time in years**

apparatus. Future research will be restricted to system development and cost cutting and will lead quickly to field testing and demonstration (within a period of 5 years from now).

Things are different with heat storage. A major problem here is the desruption of chemical equilibria in the groundwater due to heating or excessive bacterial activity, which may result in precipation and well blocking. Cheap and ecologically compatible water treatment techniques to prevent this blocking are being searched for on an international level. The results will probably not be available for a while yet, so research in the coming years will be of a slightly more fundamental nature than in the case of cold storage.

4 ADIABATIC COMPRESSED AIR STORAGE

Adiabatic Compressed Air Storage (ACAS) is an alternative to PAC (Lievense concept) and OPAC. PAC and OPAC stand for Pumped Accumulator Power Station and Underground Pumped Accumulator Power Station, respectively. These are storage systems for electric power (temporarily converted to mechanical energy). It is not yet clear whether there is a need for these large storage systems in the Dutch grid. A study carried out by NEOM in Sittard will lead in the future to a recommendation on the need for electric power storage and (if this need is acknowledged) on the most suitable storage system. Apart from these possibilities, Shell has also developed a system (SPAC) which may stand an excellent chance in any eventual selection.

The NOAA programme first took stock of the technical bottlenecks in the ACAS (Adiabatic Compressed Air Storage) system, such as the stability of rock, displacement processes between air and water and geochemical reactions. Solutions for complete or partial elimination of the technical bottlenecks were also presented. The design of the aboveground system and the costs of an ACAS were also studied for the NEOM research. No further steps are being taken until the NEOM recommendation is issued. For the time being it is assumed in NOAA that large-scale storage systems will not be incorporated in the power grid in the near future. So further research is not anticipated in the short term.

AQUIFER ENERGY STORAGE AND GEOTHERMAL ENERGY:
POSSIBLE APPLICATIONS AND GEOHYDROLOGICAL PRECONDITIONS

A.L. Snijders
and J.P. Heederik

ABSTRACT

In the Netherlands, research on the possibilities of energy storage in aquifers and exploitation of geothermal energy was started about 10 years ago. Both concepts offer good opportunities for saving energy, but in spite of this neither energy storage nor geothermal energy have found wide application.

This paper deals with the principles, the identified applications and the profitability of the two concepts. On the basis of the applications one can formulate the requirements with regard to project size, flow rate and temperature level. For heat and cool storage as well as for geohydrological energy exploitation these requirements can be translated into geothermal conditions such as the thickness and permeability of the aquifer and the confining formations, the dispersivity, the groundwater velocity, the water composition and the well spacing. Furthermore, we will discuss the similarities and differences between the two concepts.

1 INTRODUCTION

In the early seventies, two consecutive oil crises and a growing environmental awareness caused the interest in renewable and environmentally sound energy sources to increase strongly. This interest and political pressure resulted in 1979 in the start of the National Research Programme on Solar Energy and the National Research Programme on Geothermal Energy and Heat Storage. In the framework of these programmes, between 1979 and 1984 a large number of studies were carried out on energy storage and geothermal energy:

- research on temperatures at great and shallow depth;
- a survey of the geothermal potential of different geological formations;
- a study on the reservoir characteristics of potential aquifers; and
- a number of feasibility studies on heat storage, for projects in Almere, Bunnik, Leiden and Groningen, and on geothermal energy, for projects in Spijkenisse and Delfland.

Two of these projects, those in Groningen and in Bunnik, were actually implemented.

On the basis of the results and conclusions of these studies, in 1985 the National Research Programme on Geothermal Energy and Aquifer Energy Storage (1985-1989) was formulated. Major components of this research programme are a study of the interactions between operational and geohydrological requirements, a more detailed survey of aquifers suitable for energy storage and geothermal energy exploitation, and investigation of the geothermal reserves of identified potential formations. In the framework of this research programme a cold energy storage project has also been implemented (Amsterdam).

In this paper we will first briefly discuss the principles of energy storage (heat and cool storage) in aquifers and geothermal energy exploitation, followed by an outline of the possible applications. These applications determine the characteristic dimensions such as (storage) capacity, maximum flow rate and desirable temperature level. Finally we will discuss to what extent the geohydrological conditions at a projected site are favourable or unfavourable for the desired dimensioning.

2 PRINCIPLES

2.1 Principle of heat and cool storage

Figure 1 schematically shows the principle of heat storage in an aquifer. The energy saving/energy supply system of which the store is a part always includes a heat source and a heat consumer. In a period of heat surplus, groundwater is pumped up, heated and subsequently injected again into the aquifer. In this way a reservoir of hot water is created around the 'hot well'. Whenever there is a heat deficit, the hot water is pumped up from the hot well and the heat is delivered to the consumer. The cooled water is injected into the 'cold well'. Usually a heat exchanger is employed to separate the groundwater circuit from the water circuit that connects the heat source with the consumer.

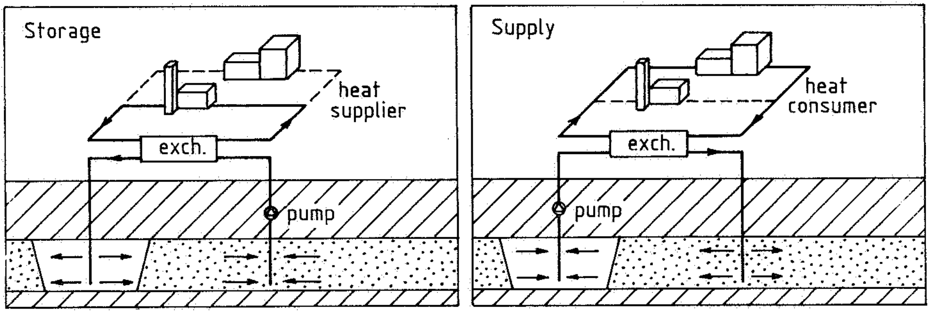


Figure 1 Principle of aquifer heat storage

Obviously, the heat storage system consists of at least two wells, a hot well (with a temperature of, for instance 90 °C) and a cold well (with a temperature of, for instance, 40 °C). The two wells are usually located in the same aquifer to avoid problems owing to differences in water composition.

The principle of cool storage is analogous to that of heat storage. Cold water at a temperature suitable for cooling is stored in the cold well during wintertime and is extracted from this well in summer to be used for air conditioning or process cooling. The temperature level of the cold well in this case may be 6 °C and that of the hot well, for instance, 14 °C.

2.2 Principle and characteristics of geothermal energy exploitation

Everywhere on earth, the temperature rises with increasing depth as a result of the decay of radioactive isotopes in the earth's crust and the thermal resistance of the soil layers. In volcanic areas, the phenomenon of geothermal energy is often observable at the surface as hot water wells and geysers.

Depending on the temperature level and the application, a distinction is made between high- and low-enthalpy geothermal energy. In high-enthalpy (also called high-caloric or high-temperature) geothermal energy applications the temperature is over 150 °C and the energy can be employed for generating electricity. In low-enthalpy systems the temperature is between 30 °C and 150 °C.

The geothermal gradient in the Netherlands is on average 3 to 3.5 °C per 100 m. At a depth of several metres below ground level the temperature is constant at about 10-12 °C irrespective of the season. As a result, the temperature at 100 m depth is about 15 °C and at 3000 m it is about 100 °C.

Exploitation of geothermal energy consists of pumping up warm or hot formation water from a production well. At the surface, the heat is transferred to the heat transport circuit in a water-water heat exchanger. The cooled formation water cannot be discharged into the surface water because of its usually high salt content. This is one of the reasons that geothermal energy is exploited using a 'doublet', a pair of wells consisting of a production well and an injection well (Figure 2). The cooled formation water is re-injected into the original formation. A secondary consideration for re-injection is to maintain the original pressure in the reservoir.

In order to prevent short-circuiting between the 'hot' production well and the 'cold' injection well, the wells must be far enough apart. This spacing is decisive for the lifetime of a doublet. To enable both wells to be drilled from one location, they are often drilled at an angle.

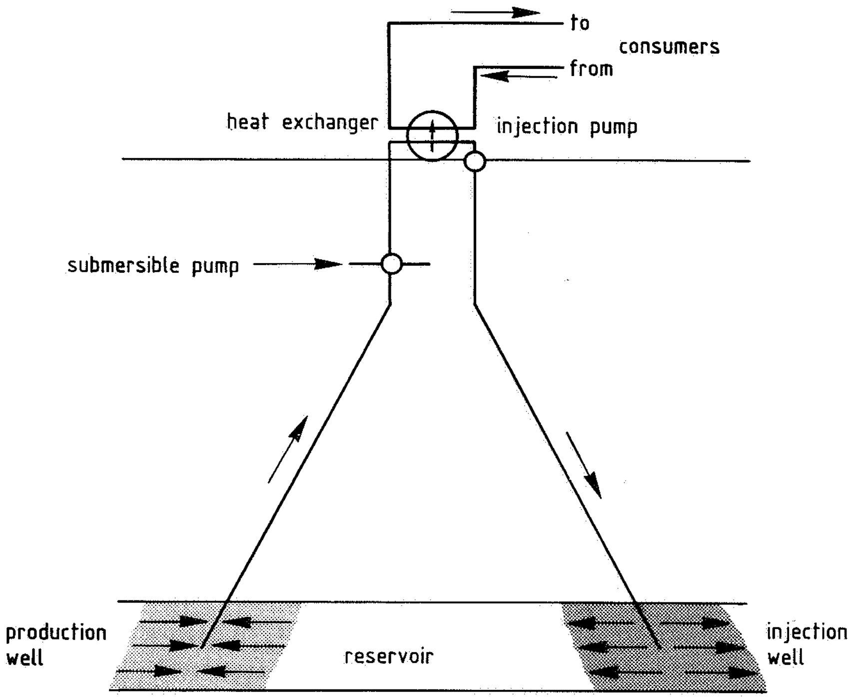


Figure 2   Principle of geothermal energy exploitation (Duns, 1982)

Low-enthalpy geothermal energy exploitation is characterised by:

- a temperature of the formation water produced of between 30 °C and 150 °C (in the Netherlands an upper limit of 90 °C is currently used);
- limited possibilities for regulation of the flow rate. For this reason geothermal energy is to be considered primarily for the supply of the base-load;
- dependence on a suitable location, because of the need for an adequate reservoir formation in the soil;
- high investments. The costs of a doublet and the investments in the surface system are substantial;

- favourable environmental qualities of this renewable energy source. The saving of fossil fuels limits the emission of harmful combustion products.

3 APPLICATIONS

3.1 Applications for heat and cool storage

The possible applications of heat and cool storage can be presented in a matrix with the heat consumers along the horizontal axis and the heat sources along the vertical axis (see Figure 3). The heat demand of the heat consumers determines the size or the capacity of the store.

Large-scale storage projects can be implemented in combination with a residential area (district heating), a glasshouse horticulture complex or an industrial plant. Storage projects at a small company, a utility building or an individual glasshouse horticultural company are likely to be small-scale. The terms large-scale and small-scale will be quantified later on.

The temperature level at which the heat is stored is mainly determined by the heat source. Industrial waste heat, heat and power co-generation and solar collectors are usually high-temperature heat sources. The condensor heat of refrigeration machines and the heat which can be extracted during summer from the ambient air or the surface water (ambient heat) result in low-temperature storage. The fact that during the wintertime heat can be transferred to the ambient air or the surface water (ambient cold) makes it possible to store cold energy.

Some combinations of heat source and heat consumer are unlikely or impossible and therefore cannot be considered an application for heat or cool storage. For instance, it is unlikely that industrial waste heat or the heat from a co-generation plant will be applied for small-scale projects. The application of solar heat for a glasshouse horticulture complex is unlikely because of the large space occupied by solar collectors. The amount of heat produced by condensors of refrigeration machines is generally too small and at too low a temperature to be used in large-scale projects. The temperature level of ambient heat is also too low for such projects, but for a residential district or a glasshouse complex the use of a heat pump may be considered. Ambient cold is not suitable for residential districts or glasshouse complexes because there is no demand for cooling.

The feasibility studies carried out so far indicate that the profitable applications of heat and cool storage are to be found in the upper left and lower right corners of the matrix. Large-scale storage at high temperature of industrial waste heat or heat from co-generation for district heating or glasshouse complexes is profitable in some cases (Bredero, 1986; Pater, 1987). The same holds for cool energy storage for utility buildings and industrial processes (Techniplan, 1986; MAB, 1988). Since realisation of storage projects is most likely for profitable applications, we will discuss the dimensioning of the store in these cases on the basis of two examples.

The first example is the combination of a co-generation plant with a residential area. A co-generation plant produces electricity for the public grid and heat for a district heating system covering 22 000 dwellings (Heidemij, 1985; Pater, 1987). The heat produced in summer in combination with electricity can be stored and used for the district heating network during wintertime. The required storage capacity in this case amounts to about 1 million m^3 groundwater at a flow rate of the store of about 400 m^3 per hour. One hot well and one cold well are not sufficient now; several doublets are necessary because of the high flow rate. The hot wells are at 90 °C and the cold wells at 40 °C. Storage of heat in an aquifer saves 3.7 million m^3 of natural gas annually.

The second example is cool storage for cooling of a printing office (Techniplan, 1986). The cold store is charged in winter by cooling groundwater with cold ambient air. During summer, the cold is used to cool the rooms in which the printing presses are located. In this case the capacity of the store is about 200 000 m^3 of groundwater and the maximum flow rate 120 m^3 per hour. Owing to the small temperature difference between cold and hot well (here 6 °C and 10 °C), cool storage employs a relatively large flow rate. Cool storage replaces cooling by electrical chillers, so that electrical energy is saved. In the present case the saving of electricity is about 250 MWh per year.

Generally the dimensions of the store are determined by the energy supply or energy saving system of which the store is a part. The most characteristic parameters are the number of cubic metres involved in the storage process (storage capacity), the maximum flow rate, the temperature difference between hot and cold well, the energy saving that is achieved, and the investments in the storage system.

ENERGY STORAGE

heat consumer heat source		large scale			small scale	
		residential area	glasshouse complex	industry	utility building	glasshouse farm
40 - 90°C	industrial waste heat				☒	☒
	co-generation					☒
	solar heat		☒			
4 - 40°C	condensor heat	☒	☒	☒		
	ambient heat			☒		
	ambient cold	☒	☒			

GEOTHERMAL ENERGY

40-90°	geothermal heat				☒	☒
30-40°	geothermal heat			☒	☒	☒

Figure 3 Applications of energy storage and geothermal energy

In Table 1 we have indicated the practical limits for these parameters. The table should be read as follows: a small-capacity storage project has a capacity in the order of 25 000 m^3 groundwater, and a large-capacity project has a capacity in the order of one million m^3 groundwater. A small-capacity storage system does not necessarily have a small flow rate, a small temperature difference, etc.; a small store may indeed have a large temperature difference between hot and cold well. The investments should be understood as the investments in the whole storage system, that is, the investments in wells, pumps, pipes, separation heat exchanger, water treatment and control systems.

Table 1 Characteristic dimensions for energy storage and geothermal energy

	Energy storage		Geothermal energy	
Temperature in formation (°C)	-	-	60	90
Parameter value	Small	Large	Large	Large
Capacity (m^3)	25,000	1,000,000	-	-
Depth (m)	50	200	1,500	2,500
Temperature difference (°C)	6	50	30	60
Flow rate (m^3/h)	25	500	100	200
Power (MW_{th})	0.5	10	3	10
Energy saving (m^3 natural gas eq.)	25,000	2,500,000	2,000,000	4,000,000
Investments (Dfl 1000)	500	5,000	8,000	20,000

In Chapter 4 we will discuss the interaction between the characteristic dimensions as indicated in Table 1 and the geohydrological conditions. The energy saving and the investments will not be considered separately, but as part of the profitability of the storage system.

3.2 Applications of geothermal energy

Low-enthalpy geothermal energy was first applied in the seventies in social housing projects near Paris. Recent research in the Netherlands has also proved that the incorporation of geothermal energy in district heating projects has good prospects. In addition to district heating, also glasshouse horticulture and industrial plants are among the potential users.

Whether exploitation of geothermal energy at a certain location is technically and economically feasible will depend to a large extent on the operational requirements set by the consumer. Important operational requirements are:

- the temperature levels of the water supplied and returned;
- the thermal power of the doublet. The power of a geothermal doublet is determined by the flow rate and the usable temperature range;
- the annual load-duration curve. The installed base load power and the number of operating hours determine the gross energy saving.

The profitability or economic feasibility is determined by the investments and by the value of the net energy saving that can be achieved with the geothermal doublet, less the operational costs of the doublet. In comparison with energy storage, the investments per megawatt installed power for geothermal energy are very high, at least Dfl 1 to 1.5 million/MW. At the present price of natural gas of about Dfl 0.25/m^3 and a payback period of about 10 years, a geothermal doublet must save at least 500 000 m^3/MW of natural gas per year. Since one doublet supplies a production power of several MW_{th} to several tens of MW_{th}, the application of geothermal energy will only be suitable for large-scale projects. To enable a comparison with energy storage, the possible applications and the main parameters of geothermal energy exploitation are also shown in Figure 3 and Table 1.

The net energy saving is equal to the gross energy saving less the pumping energy required to operate the doublet. This pumping energy is mainly determined by the flow rate and the pressure difference needed for extraction and injection, and is therefore dependent on the geohydrological conditions. To limit the electricity costs for the pumping, in some circumstances application of a co-generation unit may be economically attractive.

The opportunities for applying geothermal energy depend strongly on the government's energy policy. Whereas in the seventies and early eighties strategic considerations led to energy saving being given a higher priority than cost saving, today the application of alternative energy sources is determined to a large extent by its cost. In the future, however, it is very well conceivable that environmental considerations will dominate the energy policy, in which case geothermal energy will be a viable option.

4 GEOHYDROLOGICAL PRECONDITIONS

4.1 Geohydrological preconditions for heat and cool storage

The thickness of the aquifer(s) is one of the parameters characterising the geohydrological situation at a site where a store is projected. A great thickness of the aquifer makes a large storage capacity possible and allows a high flow rate per well. Whether this is favourable or not depends on other considerations. For instance, application of a thick aquifer for a store with a relatively small capacity leads to an unfavourable volume-area ratio and thereby to relatively high heat losses. This means that the temperature difference between hot and cold well is partly nullified and the energetic efficiency of the store decreases. Figure 4 illustrates that for a store with a given capacity it is possible to indicate an aquifer thickness at which the storage efficiency is maximal. The curves in this figure are the result of calculations which do not take the natural groundwater flow and the dispersivity into account (Heidemij, 1987) The influence of the natural groundwater flow will increase as the diameter of the store becomes smaller, or in other words as the H/R ratio becomes larger. We will elaborate on this further on.

Thus a thick aquifer is favourable for the profitability of the store if a large capacity and high flow rate are desirable. If this is not the case, the profitability can be affected negatively by the energy losses from the store (see Table 2). Under these circumstances it is possible to use only the upper part of the aquifer for storage (Techniplan, 1986). The capacities stated in Table 1 correspond with aquifer thicknesses of 10 to 100 metres.

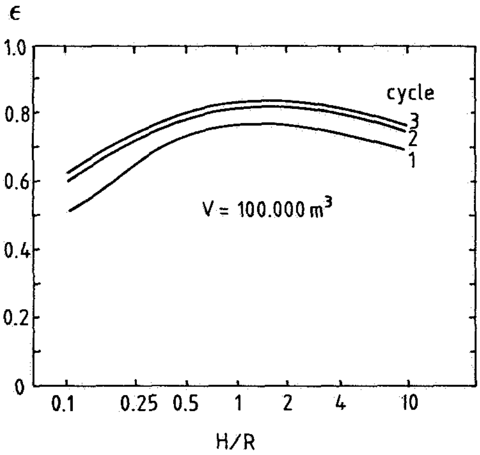


Figure 4

Recovery factor as a function of aspect ratio H/R (H=height, R=radius)

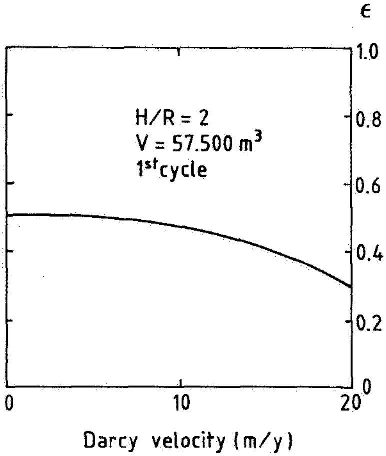


Figure 5

Recovery factor as a function of Darcy velocity

There is no relationship between the thickness of the confining layers and the storage capacity. When the store is located in the upper aquifer, a greater thickness of the upper confining layer results in a higher permissible injection pressure, and thereby in a higher flow rate per well. Furthermore, the better thermal insulation of thicker confining layers is favourable for the energetic efficiency of the store. A thickness of 10 to 20 m of the layers is sufficient for this purpose. A very thick upper confining layer adversely affects the profitability, because of the higher investments for the wells.

A high permeability of the aquifer is favourable for a store where high flow rates are to be used for extraction and injection. On the other hand, a high permeability is a negative factor if high temperature differences are to be maintained with respect to the natural groundwater temperature, as the energy losses due to natural convection increase. For storage at high temperature, horizontal permeabilities of 1 to 30 m/day are favourable, be it that the higher values require that also a substantial anisotropy should be present if the energy losses due to natural convection are to remain within acceptable limits. At still higher values of the horizontal permeability the energetic efficiency and thus the profitability of the store decrease rapidly. In the case of storage at low temperatures or cool storage, the influence of natural convection is much less so that higher permeabilities are permissible.

In an aquifer with a high dispersivity, the temperature difference between the injected water and the groundwater surrounding the store is diminished. This implies that a high dispersivity is unfavourable for the efficiency and thus for the profitability of the store.

The natural groundwater flow causes the injected water to move, resulting in a decrease in the energetic efficiency of the store. For a given natural groundwater flow velocity, a store with a small diameter is more sensitive to the influence of the groundwater flow than a large-diameter store. Figure 5 illustrates the influence of the natural groundwater flow on the storage efficiency for a store with an aspect ratio of two. This figure is based on calculations for an aquifer with a horizontal permeability of 20 m/day and an anisotropy of 1:5 (Heidemij, 1987). The influences of the natural convection and the dispersivity of the aquifer (dispersion length 10 m) have been incorporated in the results. The energetic efficiency (just like the recovery factor in Figure 4) is based on equal volumes of water being extracted and injected, with the natural groundwater temperature as reference temperature.

The figure clearly shows that for a store with a given capacity and a given aspect ratio, it is possible to determine a threshold value for the natural groundwater flow below which the influence on the storage efficiency is negligible. If the natural groundwater flow negatively affects the storage efficiency, then the influence on the profitability is also negative.

Finally, some attention should be paid to the water composition as a geohydrological condition at a given location. As is the case with the dispersivity of the aquifer and the natural groundwater flow velocity, there is no relationship between the water composition and the capacity and flow rate of the store.

Temperature differences lead to a shift of the thermodynamic equilibriums between the minerals in solution and the minerals in the solid phase. This implies that an unfavourable water composition (e.g. hard water) may cause precipitation of minerals (calcium) if the water temperature is raised or lowered. This precipitation can be prevented by limiting the temperature difference between the hot and the cold well, or by treating the groundwater. Limiting the temperature difference can be considered unfavourable for the store because the desired temperature difference cannot be achieved, and groundwater treatment is unfavourable for the profitability because of the investment and operating costs involved.

It is also possible that a rapid growth of micro-organisms takes place in the immediate vicinity of the hot or cold well if the water contains much assimilatable organic carbon. This growth can be limited by avoiding temperatures which are conducive to the development of micro-organisms or by applying groundwater treatment.

Table 2 Relationship between geohydrological conditions and characteristic dimensions in energy storage

Geohydrological conditions	Capacity	Flow rate	Temperature difference	Profitability
Aquifer thickness	+	+	-	+/-
Thickness confining layers	o	+	+	+/-
Permeability	o	+	-	+/-
Dispersivity	o	o	-	-
Groundwater flow velocity	o	o	-	-
Groundwater composition	o	o	-	-

+ positive	- negative
o no influence	+/- sometimes positive, sometimes negative

In Table 2 we have summarized the relationship between the characteristic dimensions of the store on the one hand and the local geohydrological conditions on the other. The table shows that there is a relationship between the temperatures of the hot and the cold well and all geohydrological conditions. It is also evident that the relationship between the geohydrological conditions and the profitability is not univocal. Owing to the large spread in storage capacities, flow rates and desired temperature differences, a set of geohydrological conditions which leads to a profitable project in one case may be unfavourable for the project's profitability in another situation.

4.2 Geohydrological preconditions for geothermal energy exploitation

The availability of geothermal energy and its exploitability are dependent on the geohydrological conditions. The production rate, i.e. the pump discharge, the usable temperature difference and the geothermal lifetime of a doublet are decisive for the profitability of

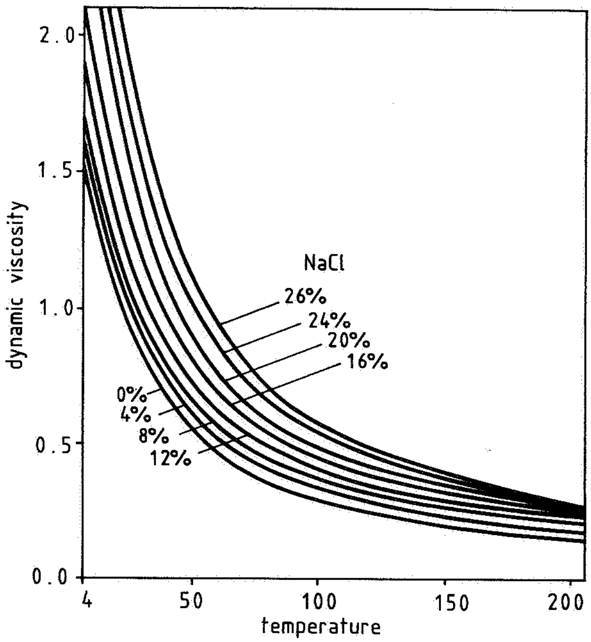
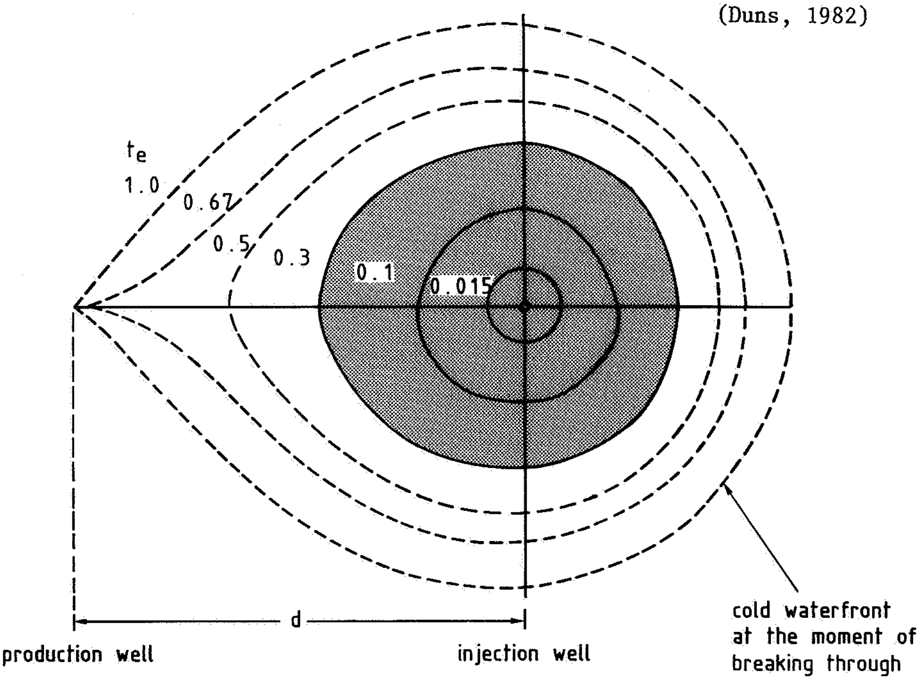


Figure 6
(above)
Relationship
between dynamic
viscosity,
temperature
and salt
content
(Jerry, 1983)

Figure 7
(below)
Expansion of
cold-water
from between
injection and
production
well
(Duns, 1982)



geothermal energy exploitation. In the same way as in Table 2, the influence of the main geohydrological parameters on the flow rate, the usable temperature difference, the geothermal lifetime and the profitability of a doublet for geothermal energy exploitation are indicated in Table 3.

Table 3 Relationship between geohydrological conditions and characteristic dimensions in geothermal energy exploitation

Geohydrological conditions	Production	Usable temperature difference	Break-through time	Profita-bility
Depth	-	+	o	+/-
Aquifer thickness	+	o	+	+
Lateral extent	o	o	+	+
Effective porosity	o	o	+[1]	+[1]
Permeability	+	o	o	+
Groundwater flow velocity	o	o	+/-[1]	+/-[1]
Groundwater composition	-	-	o	-
Well distance	-[1]	o	+	+/-

+ positive - negative [1] very small influence

o no influence +/- sometimes positive, sometimes negative

The main geohydrological conditions for geothermal energy exploitation are: depth, thickness, permeability and well distance. The depth and the geothermal gradient determine the temperature of the formation water produced; the greater the depth, the higher the temperature. On the other hand, a greater depth requires higher investments and higher operating costs due to the extra pumping energy to overcome the higher friction losses in the production and injection well.

The product of thickness and permeability, i.e. the transmissivity, determines the recharge capacity of a reservoir according to the well-known Darcy formula. Apart from the well losses, this recharge capacity is determinative for the production rate. The usable temperature difference and the production rate determine the geothermal power of a doublet. On the other hand, a high production rate adversely affects the geothermal lifetime of the doublet. The production rate of a doublet depends, apart from the transmissivity, on the dynamic viscosity, the well dimensions, the distance between the production and injection well, and the pressure difference created between the two wells. The dynamic viscosity depends on the temperature (depth) and to a lesser extent on the salt content (water composition). It is especially during re-injection that the viscosity plays an important role. As a result of the decreasing temperature, the viscosity increases sharply in the temperature range that is important for low-enthalpy geothermal energy (between 100 and 30 °C). See Figure 6.

The geothermal lifetime of a doublet is determined by the breakthrough time of the cold injection water to the production well. The breakthrough time depends mainly on the well distance, the thickness and the lateral extent of the reservoir, the production rate of the doublet, and to a lesser extent the effective porosity.

Figure 7 represents the expansion of the cold-water front. If the breakthrough time is 25 years, the shaded area represents the expansion of the cold-water front 2.5 years after commencement of re-injection.

An optimum geothermal reservoir would have to meet a number of the geohydrological requirements described above. A more important issue, however, is whether the combination of geohydrological conditions at a specific location can result in a technically and economically feasible exploitation of geothermal energy.

5 CONCLUDING REMARKS

Energy storage can be applied on a large scale as well as on a small scale. The temperature of the store is determined by the combination of heat source and heat consumer. High-temperature storage is generally profitable for large-scale applications, low-temperature storage primarily for small-scale applications. Geothermal energy is only suitable for large-scale applications.

The temperature range for energy storage is between 90 °C and 4 °C, while for geothermal energy a lower limit of 30 °C is adopted, a temperature which corresponds in the Netherlands with a depth of at least 900 m. For energy storage up to 90 °C the depth at which a suitable aquifer can be found is within about 200 m.

The production rate of an energy storage doublet will be between 25 and 150 m^3/h. The production rate of a geothermal doublet will have to be at least 100 m^3/h in view of the high drilling costs.

The lifetime of an energy storage system is determined by the technical lifetime of the components. In geothermal energy applications the geothermal lifetime is determined by the geohydrological conditions and the technical lifetime of the doublet is determined by the lifetime of the components.

There is no univocal relationship between the profitability of an energy storage system and the geohydrological conditions at a given location. Owing to the large spread in storage capacities, flow rates and desired temperature difference between hot and cold well, geohydrological conditions which lead to a profitable project in one case may be unfavourable for the project's profitability in another situation. For geothermal energy exploitation the relationship between profitability and geohydrological conditions is more straightforward, on the one hand because of the (economic) necessity of applying large-scale projects and on the other hand because heat losses in the reservoir are irrelevant.

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GEOCHEMISTRY AND ENVIRONMENTAL EFFECTS OF HEAT STORAGE IN AQUIFERS

A. Willemsen

ABSTRACT

When groundwater is heated and subsequently injected into an aquifer, chemical reactions occur as a result of the change in temperature.

On the one hand this means that the water will often require treatment to prevent calcite precipitation, on the other hand the water treatment and the reactions in the aquifer may influence the quality of the groundwater in the aquifer. When fresh groundwater is used, account should be taken of the consequences for the quality of the water of the method of treatment chosen.

In addition to calcium-related reactions there are also reactions involving silicates and cation exchange, and redox reactions occur in the aquifer.

From information currently available, it can be seen that, with storage at temperatures up to 100 °C, redox reactions can be particularly important in addition to the reactions with calcite. The rate of reaction of silicates is generally so slow that no scaling as a result of silicate precipitation during cooling is expected. Reactions with silicates and cation exchange will generally only bring about a minor change in the composition of the water in the aquifer.

Redox reactions can cause problems (these include scaling and corrosion as a result of sulphide formation) if the aquifer has a high organic matter content.

Research is presently being carried out at IEA (International Energy Agency) level into the environmental effects and chemical aspects of heat storage in aquifers.

In this framework an attempt is also being made to develop (new) environmentally sound treatment techniques.

Therefore this article only provides a description of an interim state of affairs.

1 INTRODUCTION

When groundwater is heated and injected into an aquifer at a temperature different from the original, reactions will occur between sediment and water.

As a result of the heating, water is placed in a situation in which there is no equilibrium between the composition of the water and the environment. The solubility product of calcite, for example, is strongly dependent on temperature.

When the temperature increases the water will tend to lose calcium to the solid state (i.e. calcite precipitation) if the water at the original temperature is in equilibrium with the calcite.

This reaction can seriously impede the operation of the storage system by scaling of the heat exchanger, ducts, wells and aquifer. The treatment of water to prevent precipitation, carried out before the water is heated, will thus frequently be necessary (see e.g. Willemsen, 1984; Willemsen and Appelo, 1985).

When the heated (treated) water is injected into the aquifer, other reactions will also occur. Silicates such as felspars, quartz, etc. dissolve when the temperature is raised.

Cation exchange will buffer a change in the composition of the cations, but the exchange constants are also temperature dependent.

It is possible that an increase in temperature will accelerate the mineralization of organic material, which could give rise to various redox reactions.

When the store is unloaded a portion of the injected water will be recovered. The recovered water is cooled and reinjected into other wells. This infers that those processes which occurred during heating will (partially) be reversed.

In this way, for example, it is possible that a precipitation of silicates and a re-dissolution of calcite will occur on cooling. Recently, the water chemistry at the pilot project at St Paul (USA) has been described by Holm et al (1987) and by Perlinger et al (1987). These publications showed that during storage in aquifers the water is constantly subject to changes in composition. These continuous changes can, on the one hand, influence the operation of the storage process (clogging), and on the other hand they may influence the quality of the groundwater in and around the storage system (environmental effects).

This paper will discuss both aspects.

2 GEOCHEMISTRY

2.1 Introduction

The reactions due to heating and cooling processes are the result of a shift in chemical equilibria which are dependent upon temperature. This shift in equilibrium is the driving force behind the reactions. The time required for the reaction to attain equilibrium is however dependent upon the rate of the reaction, which is different for every specific reaction of dissolution and precipitation. Relatively speaking, the precipitation and dissolution of calcite, and cation exchange have a high rate of reaction in relation to, for example, the reactions involving the most common silicates, and in relation to the mineralization of organic material.

This infers that calcite will precipitate earlier on heating, than silicates on cooling. This is why it is important to consider both the shifts in equilibrium and the rate of reaction.

2.2 Reactions in the aquifer

The most important reactions which occur when heat is stored in an aquifer are associated with calcite, ion exchange, silicates and redox reactions.

Calcite

As indicated above, calcite will precipitate when the aquifer is heated. When hot water is injected into an aquifer, the water will lose heat to the sediment. The warm front will hence run behind the water front. When the water, which already lost calcite behind the warm front, passes the warm front, then calcite will dissolve from the aquifer. When the stored heat is discharged the water will pass the warm front in the opposite direction, and calcite will therefore precipitate once again. A similar argument holds for water which, after cooling, is injected into the "cold" wells, and which, in the following cycle, is reheated and injected into the "hot" wells. This infers that there is a net transport of calcite from relatively cold regions to the hottest zone. Therefore it is important to determine the extent to which this will cause clogging in the aquifer around the hot wells. A coupled chemical-transport model has been developed for this. (Willemsen and Nienhuis, 1988; a previous version of this model was described by Appelo and Willemsen, 1987).

Ion exchange

Every aquifer has a certain potential to exchange ions. Cations particularly bind to clay, oxides, carbonates and organic material.

The capacity to exchange is expressed as CEC (Cation Exchange Capacity) in meq/100 g dry sediment. This CEC can range from approximately

0.5 meq/100 g (coarse sand) to more than 10 meq/100 g (material with a high clay content). Expressed as per litre groundwater this corresponds to 30 to 600 meq/l. For fresh water in particular this means a large buffer capacity in relation to the dissolved amount of meq/l (see e.g. Heidemij and Free University, 1988).

One of the consequences of this exchange capacity is that when calcite precipitates for example, Ca ions will be subsequently supplied by the exchange complex. Much more calcite can precipitate in this way than would be expected if a simple equation without exchange had been used. This is why ion exchange is incorporated into the coupled chemical-transport model mentioned above, along with the temperature dependence of cation exchange.

Silicates

Many aquifers consist largely of quartz and silicates. All silicates will tend to dissolve as temperature increases. This means that there is a potential risk of precipitation of silicates when heated groundwater cools.

Reactions with calcium and ion exchange can frequently be considered as equilibrium processes within the period of reaction involved in seasonal heat storage. It takes from a few hours to a few days for them to attain an equilibrium in the aquifer. However, reactions involving silicates cannot usually be considered as equilibrium processes within the periods of reaction involved in heat storage (see e.g. Perlinger et al., 1987). This means that the risks of scaling caused by the precipitation of silicates when the water cools are markedly smaller, compared to the risks of scaling by calcite precipitation when the water is heated.

Dissolution of silicates will bring about a (small) increase in the concentrations of Na, K and SiO_2.

With heat storage at temperatures above 100 °C (e.g. at 150 °C), the precipitation of silicates can cause a more serious problem when the water cools. Problems such as these are very familiar from geothermal studies (see e.g. Phillips et al., 1980). For the time being it is assumed in the Netherlands that heat will be stored at temperatures below 100 °C. It is partly for this reason that kinetic processes have not been incorporated into the coupled chemical-transport model.

Redox reactions

When heating the aquifer the organic material present might be broken down more rapidly. This can give rise to a more strongly reducing environment. This could, for example, lead to sulphate reduction followed by the precipitation of FeS and the formation of methane. This was observed in the heat storage project in Groningen (the Netherlands)(see Heidemij and LUW, 1987).

A prerequisite for these processes is the presence in the water of sufficient assimilable organic carbon (AOC). However, the AOC-content of groundwater is often very low. Therefore, problems will only be expected in those cases where the sediment contains much organic material.

It is possible that problems (clogging, change in water quality) are more likely to occur around the wells, where, cumulatively, much AOC is introduced, be it in low concentrations (see e.g. Hijnen and Van Der Kooij, 1984; Van Beek and Kooper, 1980; Van Beek and Van Der Kooij, 1982; Heidemij and LUW, 1988).

Problems associated with reactions with iron and manganese can be avoided by maintaining the system anaerobic when using anaerobic groundwater (see e.g. Olsthoorn, 1982; Brandes et al., 1985).

2.3 Reactions above ground

When the storage is being filled, water is pumped to the surface, heated in a heat exchanger, and reinjected into the aquifer via other wells.

Water is thus heated in the heat exchanger above ground, and the first reactions will take place there, or in the ducts and wells after the heat exchanger. The dissolution of silicates will obviously not occur above ground on heating, the precipitation of calcite, however, will be common. The silicates will be able to precipitate out at the cooling stage.

Kinetic processes play an critical role in these precipitation reactions. Problems associated with the precipitation of silicates in the heat exchanger on cooling will not generally occur because of the slow rate of reaction. The reaction surface in the ducts is many times smaller than the reaction surface in the aquifer. Moreover, the time the water remains in the pipe system is much shorter than the period the water remains in the aquifer.

The rate of reaction of calcite is however much faster than that of most silicates.

The precipitation of calcite in the system above ground therefore frequently poses a problem. The difference in temperature across the heat exchanger plays an important role here. With a small ΔT (< 20 K) the rate of reaction will generally be so slow that no calcite precipitation occurs. (This has been observed, for example, in practice at the heat storage project in Bunnik, the Netherlands; see Heidemij and Bredero, 1988.) Precipitation will generally occur when ΔT is large (> 40 K).

3 WATER TREATMENT

The treatment of water to prevent calcite precipitation will often be necessary. There are many techniques available which treat the water in order to avoid calcite precipitation, such as softening via chemical precipitation of calcite or via ion exchangers, acidification, decarbonation (with the aid of acidification and degassing), and complexation (e.g. polyphosphates in detergents)(see e.g. Admiraal, 1971 and KIWA, 1971).

A number of factors play a role in heat storage which are quite anomalous in comparison to the application of water treatment for industrial cooling processes or the softening of drinking water for example. Treated water is injected into an aquifer. By dispersion (mixing), free convection, and regional groundwater flow, part of the water injected is lost from the store. This means that, when an aquifer containing fresh water is used, account should be taken of the consequences of the treatment for the groundwater quality.

A portion of the treated water is recovered and used again in the subsequent cycles. It is not impossible that the treatment intensity will increase because of re-dissolution of the calcite on cooling.

When calcite is present in the aquifer (usually the case), the use of acid dosing as a method of treatment, results in an increase in the required treatment for water being reused that had been treated in previous cycles. Complexation will also intensify the treatment (unless the complex is broken down in the aquifer). Techniques which remove CO_2, Ca, or both, exhibit a decreasing treatment intensity.

Table 1 contains the existing chemical techniques, grouped according to principle of operation, and according to the ion to be treated (for $CaCO_3$ this may be the Ca^{++} ion, the CO_3^{--} ion, or both).

Methods of treatment which only operate on the water phase will increase in intensity. The treatment will become part of the water injected.

Methods of treatment which make use of adsorption/desorption are non-specific (as are complexation and acidification), since other cations (e.g. Mg and K) are also removed. In this way too much is treated in effect. When H^+ exchange is used, the added H^+ ion causes acidification. Without the degassing of CO_2 the treatment will hence be intensified.

Treatment using chemical precipitation is specific to the calcite equilibrium. Only Ca^{++} and CO_3^{--} are removed. Precipitation reactors can be executed in the form of a fluid bed or as a sludge reactor (see Graveland et al, 1983).

In addition to chemical techniques, mechanical techniques are also applied, such as the scrubbing of the heat exchanger (e.g. via a fluid bed exchanger, see e.g. Klaren, 1987). The risk of the wells becoming blocked makes filtration (removal of the precipitate) necessary. If the amount of precipitate to be removed is small, it would seem that such methods are quite feasible.

In addition to the re-dissolution of calcite, other reactions will occur in the aquifer which influence the treatment, or result from the treatment. Both the redox reactions (e.g. CO_2 production), the dissolution and precipitation of silicates (e.g. pH buffering), and cation exchange will, in conjunction with the water treatment, determine the eventual composition of the water. In order to gain more insight into the eventual consequences of these processes, research is presently being carried out at IEA level into the chemical and environmental aspects of heat storage.

In this framework an attempt is also being made to develop (new) environmentally sound methods to treat water.

In this way work is being carried out in the Netherlands to develop a combined fluid bed heat exchanger/precipitation reactor in which chemical dosing can be omitted completely.

Table 1 Chemical treatment techniques against calcite scaling

reaction principle ion	solution	ion-exchange (solid solution interface)	solids / gases
Ca^{++}	complexation $Ca^{++} + 2L^- \rightarrow CaL_2$	$Ca^{++} + 2NaX \rightarrow 2Na^+ + CaX_2$	(e.g. : precipitation of calcium phosphate; seldom used)
both	$2HL + Ca^{++} + CO_3^{--} \rightarrow$ $\rightarrow CaL_2 + H_2CO_3$	$Ca^{++} + CO_3^{--} + 2HX \rightarrow$ $\rightarrow H_2CO_3 + CaX_2$	$NaOH + Ca^{++} + HCO_3^- \rightarrow$ $\rightarrow CaCO_3\downarrow + Na^+ + H_2O$ $Ca(OH)_2 + Ca^{++} + 2HCO_3^- \rightarrow$ $\rightarrow 2CaCO_3\downarrow + 2H_2O$
CO_3^{--}	acid addition $2H^+ + CO_3^{--} \rightarrow H_2CO_3$	(anion - exchange ; seldom used)	1.) $H_2CO_3 \rightarrow CO_2\uparrow + H_2O$ 2.)
comments effects when used for heat storage	L : Ligand - reaction is not specific for Ca^{++} or CO_3^{--} - treatment increases (becomes part of injected water)	X : exchanger - reaction is not specific for Ca^{++} or CO_3^{--} - H^+ -exchange : see acid addition - Na^+ -exchange : treatment decreases	- precipitation reaction is specific for $CaCO_3$ - degasing is not specific 1.) degasing after H^+-exchange 2.) degasing after acid addition - treatment decreases.

4 ENVIRONMENTAL EFFECTS

4.1 Introduction

The environmental effects of heat storage can be grouped under the following parameters:

- thermal effects;
- water quality (not including temperature);
- hydrological consequences (groundwater potential);
- fluctuations in ground level.

In addition to these potentially negative effects, heat storage also has a positive effect: the saving of fossil fuels and hence a decrease in the emission of combustion products. Here a discussion will be given of the potentially negative effects. The actual cases should be considered in the light of the positive effects.

Olsthoorn (1985) previously discussed the possible environmental effects of heat storage. Heidemij Adviesbureau (1986, 1987) also conducted studies of the environmental effects of heat storage (see also Willemsen and Groeneveld, 1987).

All these studies concluded that the potential effects of heat storage on the quality of the groundwater require the most attention. Thus, in the following a discussion will only be presented of the potential effects of heat storage on groundwater quality. The reader is referred to the above-mentioned studies for a discussion of the other aspects.

4.2 Water quality, reactions in the aquifer

The reactions which occur in the aquifer as a result of the heating process result in a (relatively small) change in the composition of the water. (See previous section on reactions in the aquifer.) If much organic material is present in the aquifer, it is possible that particularly the formation of sulphides and the generation of methane will cause local deterioration of the water quality. This will generally have very few consequences for the quality of the water at some distance from the store. Outside the store the oxides present (such as iron oxides) will actually re-oxidize the reduced compounds, which means that sulphides and methane will be transported across short distances only. If no oxides are present the natural conditions in the aquifer are strongly reducing.

4.3 Water quality, consequences of the treatment

The environmental effects as a result of the water treatment are determined by:

- the original quality of the water;
- the method of treatment chosen;
- the subsequent reactions in the aquifer;
- the percentage of the treated water which is reused.

Original quality

The relative changes as a result of the water treatment are strongly dependent upon the original quality. If the original groundwater is brackish the environmental effects of the water treatment are minimal. However, if the original water is fresh, a great deal of attention should then be paid to the effects of the treatment on the quality of the water.

Method of water treatment, subsequent reactions and reuse

The various chemical methods have been previously discussed and are presented in Table 1. With the aid of the classification in this table they can be grouped according to environmental effects. Here the assumption is made that a net addition of certain ions is less desirable than the mere removal of ions. On the basis of this assumption a grouping according to increased environmental effects is presented in Table 2.

Table 2 Classification of existing methods of chemical treatment to prevent precipitation of calcite according to increased environmental effect for use in heat storage

No.	Method	Most important effect
1	Precipitation with $Ca(OH)_2$ Degassing of CO_2 after H^+ exchange	Removal of $CaCO_3$ (Partial) removal of cations and CO_2
2	Precipitation with NaOH	1 Na^+ for 1 Ca^{++} and 1 HCO_3^-
3	Degassing of CO_2 after acidification	Anion (Cl^-) for HCO_3^-
4	Na^+ exchange	Na^+ for all cations (partial)
5	Acid dosing and complexation	Addition of ions only increase the intensity of treatment by reuse

This classification corresponds (in reverse order) well to a classification according to investment costs. Acid dosing is very cheap, whilst precipitation reactors and degassing following H^+ exchange are quite expensive. Existing mechanical methods of treatment (also mere removal of $CaCO_3$) can in some cases (of little precipitation) be a good solution. The costs should be balanced against the effects in all cases.

The above classification cannot immediately be applied to every situation. The choice can be strictly determined by the original composition. If the natural Cl^- content is high, the degassing of CO_2 following acidification with HCl can cause an infringement of the prescribed level of Cl for drinking water. If this were not the case for Na^+ with Na^+ exchange then the latter treatment would be preferable to the degassing of CO_2 using HCl.

5 DISCUSSION AND CONCLUSIONS

When heat is stored in aquifers, chemical reactions occur which can be detrimental to the management and which can affect the quality of the water. It would seem that the reactions give rise to relatively small changes in the water composition (at temperatures below 100 °C). The environmental effects of these reactions are therefore considered to be of minor importance. This expectation is at present under verification with the aid of experiments both in the field and in the laboratory.

The treatment of water to prevent calcite precipitation will frequently be necessary. The consequences of water treatment for the quality of the groundwater should be included in the choice of treatment methods. Existing techniques are available which have relatively minor consequences. However, at the same time these are quite expensive. Work is being conducted on the development of affordable methods of treatment which are also environmentally sound.

The circumstances in which geochemical and environmental problems are found, are, for the sake of simplicity, presented in Table 3.

Table 3 Main groups of problem areas of geochemistry and the environmental effects of heat storage, related to the composition of water and sediment (schematic)

Sediment	Water in aquifer	
	Brackish	Fresh
"Clean"	Ca	Ca, Env.
Much organic material	Ca, Redox	Ca, Redox, Env.

Ca: Calcite precipitation
Redox: Sulphate reduction (and methane production)
Env.: Consequences of the treatment and reactions for the quality of the water

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NATIONAL FACILITY FOR TESTING THE STORAGE OF HEAT AND CHILL ENERGY IN AN AQUIFER

W.P.G. Ewalts

ABSTRACT

Energy requirements for heating and cooling can be reduced by applying aquifer thermal energy storage (ATES). Excess thermal energy (heat or chill) is stored in aquifers by injecting hot or cold water through wells. Hot water stored in summer can be used during the winter to heat buildings, whereas cold water stored in winter is used during summer to cool machinery or buildings.

From the moment that it was decided to study the feasibility of ATES in The Netherlands it was clear that many aspects of thermal energy storage would be encountered and therefore it was decided to construct a national test (pilot) plant as soon as possible. This plant, which will reveal the technical and economic problems that could occur when applying aquifer thermal energy storage is currently being constructed at the TNO Zuidpolder site in Delft. From preliminary surveys it was concluded that the hydrogeological conditions at this site are favourable for ATES and are representative of the greater part of the western Netherlands.

With the help of the test facility, operational parameters can be varied to investigate the physical, chemical and bacteriological processes at field scale under operational conditions. Furthermore, the results of the experiments will reveal the economics of a thermal energy storage system, under the conditions prevailing in The Nether-

lands. After extensive research and testing the plant will be used as a demonstration plant for ATES application.
Research and testing will be exectued by research institutes, universities and private companies.

1 INTRODUCTION

In the last ten years various authors (Van Dalfsen, Speelman, Tsang, and Van Mourik) have recommended investigating the potential for utilizing aquifers for seasonal storage of heat and chill energy in The Netherlands. In the United States, France and Denmark aquifer thermal energy system (ATES) projects have already been established and promising experiments are being carried out. In The Netherlands only one ATES system is currently operational (Bredero office building at Bunnik). The technical and economic feasibility of ATES has never been thoroughly tested. Futhermore, there may be a disparity between calculated and field data. Many of these problems result from the lack of knowledge about various physical and/or chemical processes and technical bottlenecks within such an ATES system. In 1986 a study was carried out to investigate the feasibility of establishing an ATES plant for testing most problems at field scale. As a result, a pilot plant is now being constructed on the premises of The Netherlands Organization for Applied Scientific Research, TNO, at Delft. The Stichting Projectbeheerbureau Energie-Onderzoek (PEO), Directorate-General for Energy of the European Economic Community and TNO are funding the design, the construction and all experiments carried out at this test facility plant.

2 OBJECTIVES

The objectives of the project are:

- to construct a pilot plant for storage of heat and chill in an aquifer and to carry out applied scientific research to evaluate

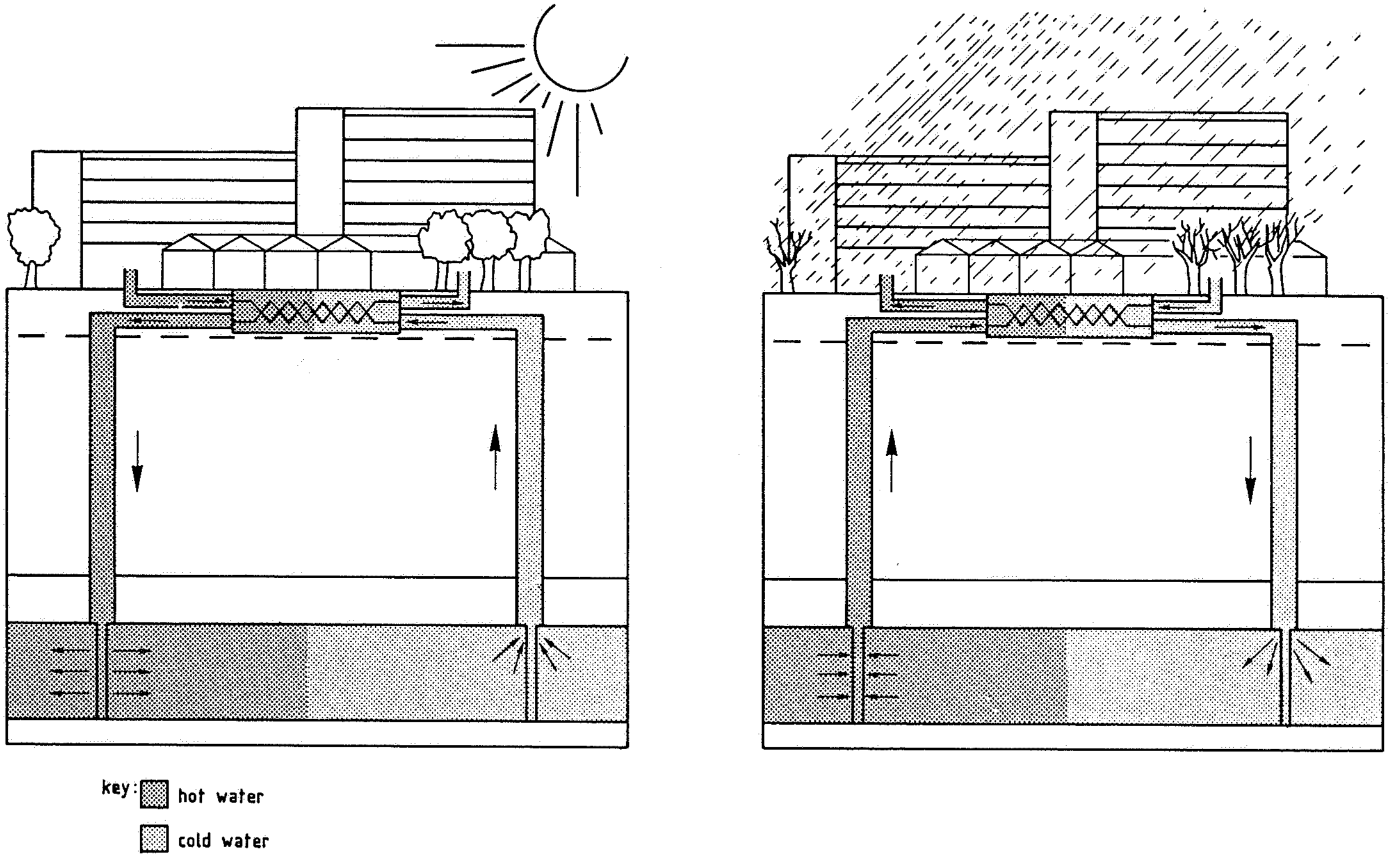

Figure 1 Principle of ATES

relevant aspects of this form of energy storage.

- to evaluate the technical and economic aspects of an aquifer thermal energy storage plant coupled to a heat and power cogeneration system.

3 ORGANIZATION AND FUNDING

The project is being managed and coordinated by TNO Institute of Applied Geoscience. The expertise for several research programmes is also being provided by other TNO institutes, such as the TNO Institute of Applied Physics/Technical University Delft, and by the Free University of Amsterdam, Heidemij Adviesbureau BV Arnhem, Groundmechanics Delft and others.

The estimated sum of 3.6 million guilders needed for construction, testing and demonstration will be provided by:

- Stichting Projectbeheerbureau Energie-Onderzoek
- European Economic Community
- TNO Central Organization

4 PRINCIPLE OF THE ATES SYSTEM

The principle of the ATES system is illustrated in figure 1. ATES stands for Thermal Energy Storage which implies that such a system can be used to store heated as well as cooled water.

The aquifer is used the same way for heating and cooling. The only difference is in whether cold or hot water is stored. There are three modes of aquifer operation: charging, storage and discharging. During charging, water is extracted from one or more extraction wells on the cold side of the plant and is warmed up by the heat exchanger. The heated water is then injected at the warm side, through one or more injection wells, for storage. This process continues for a period, typically in summer. After injection the heated water is stored until the energy demand increases. During discharging, water from the warm

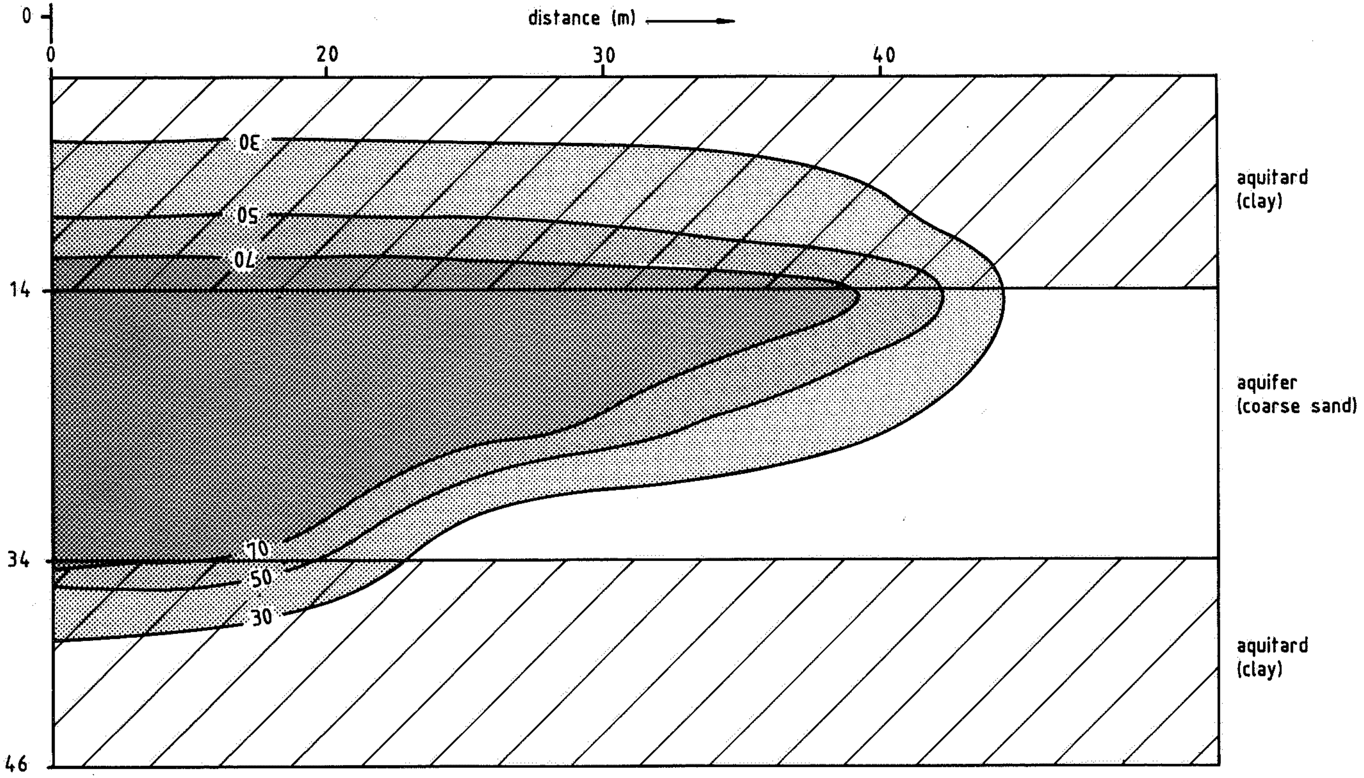

Figure 2 Calculated temperature (^{o}C) field after two injection cycles

side is extracted through one or more extraction wells to heat buildings. After use the cooled water is reinjected at the cold side through one or more injection wells in winter.

Note:

At the TNO site the cold and warm wells are 250 m apart. A shorter distance would be preferable, but this is not possible at the TNO site because of the siting of the office buildings.

5 THE AQUIFER

An aquifer suitable for energy storage is composed of a layer of permeable sediments (sand) approximately 20-30 m thick, confined by upper and lower layers of much less permeable material (aquitards). The natural groundwater flow should be low or controllable. At the TNO site the aquifer is 20 m thick and consists of very coarse sand, confined by a 14 m overburden of clay and by a bottom layer of clay that is 12 m thick: see fig. 2.

The groundwater flow at the location is estimated to be 18 m/year.

6 NUMERICAL SIMULATION OF THE TEMPERATURE FIELD

Figure 2 also illustrates the simulated temperature field after 478 days of injection. The aim of this numerical simulation was to predict the behaviour of the injected hot water and its movement through the aquifer. From figure 2 it is clear that due to buoyancy the higher temperatures are to be expected in the upper part of the aquifer. From this it can be concluded that heated water can be extracted from the upper part of the aquifer. As a result of this study locations of the wells and of other geotechnical and geothermal equipment within the pilot plant could be properly chosen.

7 EXPERIMENTS

The primary aim of the experiments is to study the physical, chemical and bacteriological processes within the aquifer storage system at field scale under operational conditions. Secondly, the experiments will investigate the economics of a thermal energy storage system, under the conditions prevailing in The Netherlands.
The bottlenecks encountered in applying such a storage system are the movement of sand and formation fines, clogging, scaling, changes in the chemical and bacteriological composition of water, water treatment and uncontrollable flows of heat and water in the aquifer.
The experiments and tests with respect to cold and hot water storage can be grouped into four categories:

1 Experiments to investigate operational problems, such as screen and well plugging, doublet performance, well deliverability, well injectivity, etc.

2 Experiments to evaluate the movement of heated or cooled water in the reservoir, by studying the formation characteristics, carrying out tracer tests, monitoring temperature distribution and doing numerical simulations.

3 Experiments to study the geomechanical and geotechnical impacts of storage of heated water, such as deformation of the substrata, pore pressures, soil subsidence.

4 Experiments to evaluate the geochemical and bacteriological impacts of heated or cooled water on the composition of the aquifer material and of the formation water.

The above-mentioned experiments are related to each other and the results will be evaluated with respect to the overall functioning and economics of the plant. All the experiments should result in adequate solutions for the problems encountered in aquifer thermal energy storage. The experiments are outlined below.

1 Evaluation of matrix stabilization techniques. This is important to prevent the transport of material like sand and silt in the aquifer. In the laboratory, cores of matrix material are stabi-

lized at different temperatures. In the aquifer, the matrix is stabilized by adding chemicals to the aquifer water.

- Long-duration tests involving cycling injected water at subsequent temperature levels give the well and system performance.
- Well impairment and regeneration tests.
- One of the bottlenecks in the storage of heat is clogging carried by chemical precipitation or by the transport of sand and silt particles.

2 Geohydrological, thermo-geochemical and geobacteriological parameters and the distribution of these parameter values in the subsoil influence the movement of heat in the subsurface. With the help of so-called 'Spitsmuis and Begemann' methods cores of sand are taken from the aquifer and from the bottom and overburden clay layers. From these cores the following parameters are determined: heat transfer coefficient, heat capacity, porosity, permeability, grain size and matrix structure.

- Geophysical well logging of spontaneous potential, resistivity short and long normal, natural gamma radiation, gamma gamma and density, pump and flow tests have already been executed to obtain additional information on the lateral distribution of heterogeneities in the storage reservoir.
- The distribution of heat or chill in the storage reservoir determines the temperature of extracted water and therefore also the recovery factor. It is important to investigate the lateral movements of water and heat or chill in the aquifer. This is done by executing tracer tests, to detect preferential flow paths. The latter are used to calibrate the results of numerical simulations of temperature distribution.

3 Soil subsidence and deformation can occur as a result of temperature rise in the formations. To understand this phenomenon several instruments have been installed to monitor the relationship between temperature distribution and soil deformation and/or subsidence.

4 The composition of formation water will change as a result of temperature-dependent physico-chemical processes. Wells can be

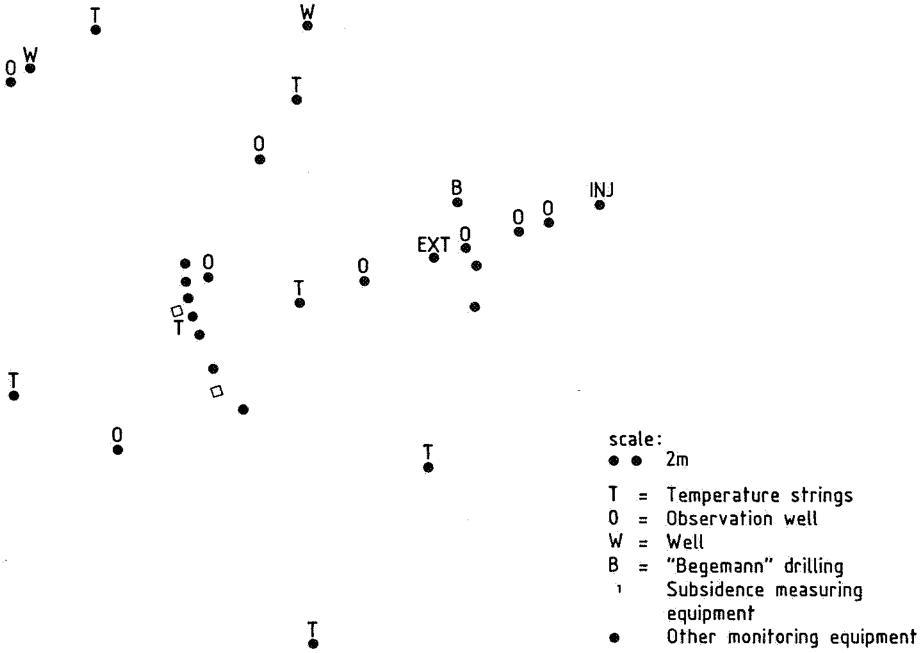

Figure 3 Location of wells and monitoring equipment

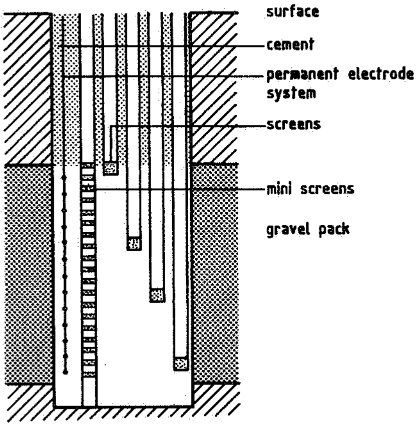

Figure 4 Observation well

blocked by precipitation of calcareous material, etc. To understand these processes it is necessary to evaluate the composition of formation water and aquifer material and their changes under operational conditions.

8 EQUIPMENT INSTALLED

Due to the rather high groundwater flow a double doublet of wells has been drilled. The layout of the storage side is given in figure 3. Each doublet consists of one fully penetrating injection well (screen at 15 to 33 m below surface) and one partially penetrating extraction well (screen at 15 to 21 m below surface). Two additional fully penetrating wells (screens at 15 to 33 m below surface) have been drilled, for evaluating well regeneration techniques.

Furthermore, seventy monitoring wells for observation and specific research have been completed. Two of these observation wells are equipped with a permanent electrode system and 20 mini screens as well as 5 observation screens (see figure 4). The permanent electrode system consists of a 26 conductor cable on which 13 pairs of electrodes are fixed at intervals of 1.5 m. The purpose of the permanent electrode cable is to measure changes in the resistivity of the subsoil. Changes in resistivity can be caused by changes in the chemical composition of water, or by temperature changes.

A mini screen has a filter length of 15 cm and a diameter of 2.5 cm. The mini screens are used for tracer tests and geochemical monitoring. In the remaining observation wells 1 to 5 screens have been installed. These screens are 1 m long and are intended to monitor water levels and temperature changes and to collect water samples. At the test site 32 temperature strings have been installed. A string is a cable with 6 temperature sensors spaced 2.5 m apart. The temperature strings and sensors are distributed over the test site according to a certain pattern derived from the numerical simulation. The temperature strings and sensors are used to continuously monitor waterplume movements in the aquifer. Furthermore, piezo resistivity pressure gauges and assessment hoses have been installed to monitor the subsidence of soil at the plant location.

9 MONITORING EQUIPMENT

To monitor most of the processes a computer controlled-monitor system will be installed for the subsurface system as well as for the aboveground installation.

All sensors installed in the monitor wells will be operated by this monitor control unit and processed in a mainframe computer to yield user-defined system performance.

10 RESULTS

The first results after drilling pump wells and observation wells, show that the porosity of the aquifer is 30 to 36 per cent and the transmissivity 40 to 70 Darcy.

From flow tests, core samples and geophysical well logging it is clear that the lithology of the entire aquifer is uniform, and only a small part of the aquifer is less permeable.

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GEOLOGICAL ASPECTS OF GEOTHERMAL ENERGY

M.C. Geluk

ABSTRACT

Within the framework of the Dutch National Energy Research Programme, the Geological Survey of The Netherlands co-operated with other institutes to ascertain the geothermal potential of geologic formations in the Dutch subsurface. Requirements, that must be met by a reservoir-rock to be suitable for geothermal exploration or seasonal storage of warm and cold water, are sufficient thickness, lateral continuity, porosity and permeability.

The result of inventory studies were, that extraction of geothermal energy appears to be possible in the western and northern parts of The Netherlands.

Seasonal storage in shallow aquifers however appears to be possible in major parts of The Netherlands, excluding some eastern and south-eastern areas.

1 INTRODUCTION

Within the framework of the Dutch National Geothermal Energy Research Programme, the Geological Survey of The Netherlands (RGD) has co-operated with other institutes in studies to determine the geothermal potential of the Dutch subsurface.

The most useful existing material drawn on for these studies was borehole and seismic data collected by the oil/gas industry and information from numerous shallow borings made for drinking- water purposes.
The Mining Law of The Netherlands, which dates from 1810 and was written in French, does not provide for the release of onshore data; there are other regulations for offshore data. After consultations, the industry gave the RGD permission to use non-released data from wells and seismic data for a broad-scale inventory of Paleozoic and Mesozoic deposits and a detailed inventory of Tertiary and Quaternary (Cenozoic) deposits.
This led to two separate studies differing as to methods and purpose:

a) Investigation of deep aquifers (Paleozoic and Mesozoic deposits), situated at depths ranging from 2 to 4 km, in relation to the explotation of low enthalpy geothermal energy.

b) Investigation of shallow aquifers (Cenozoic deposits) with depths less than 2000 meters, in relation to the temporary storage of warm/cold water and the exploitation of low enthalpy geothermal energy.

1.1 General geological information

The subsurface of The Netherlands, i.e., the uppermost 4 km, is composed predominantly of clay and shale, with an interbedded occurrence of limestones, evaporites, coalbeds, and sandstones. In this subsurface only the sandstones are considered suitable aquifers for geothermal purposes. Aquifers which might be present in limestones of

Upper-Cretaceous/Lower-Tertiary and Dinantien age will not be dealt with here because of the highly variable reservoir quality: karstified parts of these formations only have good reservoir properties locally (figure 1).

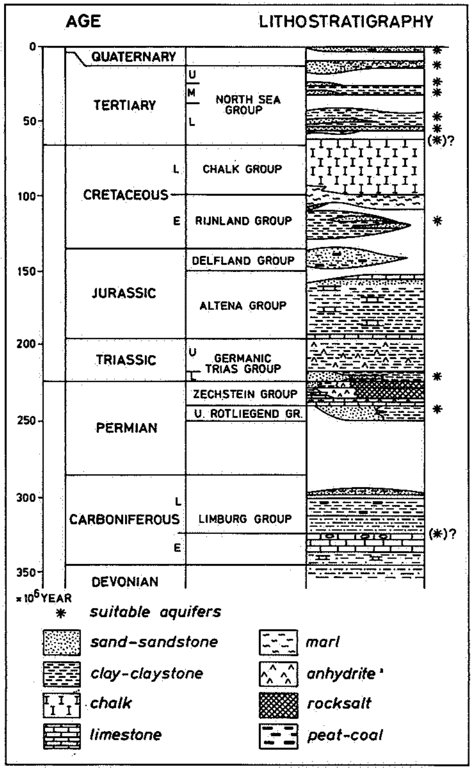

Figure 1 Aquifers suitable for geothermal purposes in The Netherlands (after RGD, 1984)

The general rule is that clastic sediments are more compacted and cemented the deeper they are now, or were once buried. Compaction and cementation are processes with a negative influence on porosity and permeability, their effect varying according to the original composition of the sand (e.g. the stability of minerals present within

the sediment), the sorting of the sand, and the formation of cement in the pore fluids.
The effect of these processes on reservoir characteristics is seen clearly in the distribution of aquifers in the subsurface: good aquifers occur mainly within the uppermost 1000 m; below that they are rare.

The Dutch subsurface has a geothermal gradient of 3-4°C/100 m, which is slightly higher than that in the surrounding countries. This range is normal for a sedimentary basin with no volcanic activity. Thus, the approximate temperature at 2000 m varies between 70 and 90°C.

The total geothermal potential in the uppermost 7000 m of the Dutch onshore territory and above 40°C is estimated at 5.10^{22} Joules. This value is known as the resourçe base. Only a small proportion of this huge amount of heat is present in reservoirs, but even if only a small part of that energy could be extracted it would still represent a very large potential.
The following requirements must be satisfied for a reservoir-rock to be suitable for the extraction of geothermal energy: sufficient thickness of the reservoir, sufficient porosity and permeability, and sufficient lateral continuity.
Because the criteria concerning the amount of geothermal energy (and thus the necessary reservoir characteristics) vary strongly, generalization is not justifiable.

2 DEEP AQUIFERS

2.1 General introduction

In the deep subsurface three possible aquifers are considered suitable for the extraction of geothermal energy. These are, in order of age, the Slochteren Sandstone Formation (Lower Permian), the Bunter Group (Lower-Germanic Trias), and sands of the Vlieland Formation (Lower-Cretaceous).

The depositional setting and the spatial distribution of the various sediments will be treated in broad terms. The reservoir characteristics will be discussed in more detail.

2.2 Slochteren Sandstone Formation (Lower-Permian; 280-250 Ma B.P.)

During the Permian and Triassic, the region which is now The Netherlands was situated on the southern border of a large sedimentary basin which occupied a large part of northwestern Europe. During the Lower-Permian, river systems deposited their loads in areas with a pronounced subsidence. These areas had a north-south orientation. They lay in the eastern part of The Netherlands and in the offshore area to the West. In the structurally more stable areas between these lows, wind-blown (eolian) sands formed large dunes. The sediments further towards the basin centre consist of clay, anhydrite, and rock-salt, the bulk occurring in the northern part of the country. The Slochteren Sandstone Formation has promising reservoir characteristics in the province of Noord-Holland, north of Amsterdam, and in the provinces of Groningen and Friesland in the northeastern part of the country (figure 2).

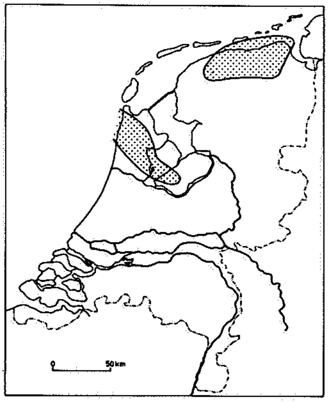

Figure 2 Prospective areas for the Slochteren Sandstone Formation (after RGD, 1983a)

In Noord-Holland the thickness of the formation lies in the range of 200-250 m. The formation consists mainly of well sorted and rounded eolian sands with good reservoir properties. Average values for porosity and permeability are 16% and 30-600 mD. The depth of the top of the formation ranges between 2000 and 2800 m, with corresponding temperatures of 80-110°C. Structurally, this area is very complex.

In Friesland and Groningen the formation shows distinct particle-size characteristics determined by its position within the basin. The Slochteren Sandstone Formation is frequently divided into an upper and a lower unit by a shale intercalation. Net sand thickness ranges from 100 to 150 m. The sands were deposited in alternating fluvial and eolian environments, as is clearly reflected by the sorting. The wind-laid sands are well sorted, whereas the water-laid sands are poorly sorted. The latter also contain more clay, which occurs in thin layers or beds.

The reservoir characteristics are less favourable than those in Noord-Holland, these sands having an average porosity of 20% and a permeability ranging from 25 to 290 mD.

The top of the sandstone lies at depths between 2250 and 2500 meters, with corresponding temperatures ranging from 85 to 100°C.

2.3 Bunter Group (Lower-Triassic; 230-225 Ma BP)

During the Triassic, the border of the basin shifted southward and the coarsest sands were correspondingly deposited farther south by fluvial systems. Massive sand deposits dominate in the Lower-Triassic sediments in the southern parts of The Netherlands, whereas towards the north they grade laterally into shales with some intercalations of sandstone beds, the Lower and Main Buntsandstein Formations. Since the sandstone layers in these units are seldom thicker than 25 m, they will not be discussed in this overview.

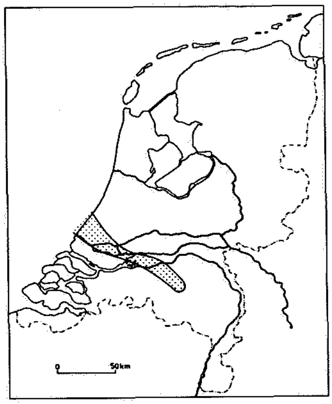

Figure 3 Prospective area for the Bunter Group (after RGD, 1982)

The Bunter Group developed as a massive sandstone area in the region between The Hague and Breda (figure 3), the thickness varying between 160 and 220 m. The reservoir characteristics are in general not very good, due to the intercalation of claystone beds and strong cementation of the sands. However, some wells have shown that parts of the formation have excellent reservoir properties. Exact values have not been published but are expected to be approximately 15% for porosity and 50 mD for permeability. The southern part appears more promising, because the clay content decreases and the grainsize seems to increase in that direction.
The depth of the top of the formation varies between 3000 and 4000 m, and the temperatures range from 85 to 120°C.

2.4 Vlieland Formation (Lower Cretaceous; 140-120 Ma BP)

During the Lower Cretaceous a large part of The Netherlands was sea. Sedimentation occurred in localized basins in the western, northern, and eastern parts of the country. At the margins of these basins sands were deposited in a continental to shallow marine environment.

The deposition and distribution of the sands were directly related to sea-level fluctuations. Sands with good reservoir properties have been recognized in the area around The Hague and Rotterdam in the West-Netherlands Basin (figure 4). These sands form sand-tongues in a shale sequence. The most promising units are the Rijswijk, Berkel, and IJsselmonde sandstones.

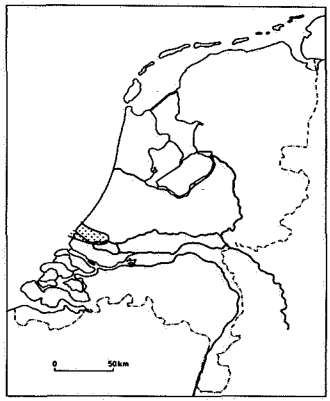

Figure 4 Prospective area for the Rijnland Group (after RGD, 1983b)

The Rijswijk Sandstone is considered to be a transgressive coversand. Generally it is a massive, moderately consolidated body of sand, usually intercalated with a few thin layers of clay. The average thickness is 25-30 m with large variations within short distances (up to 100 m). In the southern part the unit is usually a massive sand, toward the north it passes into a sequence of alternating shales and sands sequence.

The average porosity varies between 20 and 28% and the average permeability is 500 mD, with maximum values of 1000 to 5000 mD over vertical intervals of 1-2 meters.

The Berkel Sandstone is generally a massive body of sand which was deposited during a regressive phase. Little is known about distribution and thickness. The sandstone is coarse-grained, the sorting varying from moderate to good. A single core determination indicated an average porosity of 16-17% and an average permeability of 10 to 1000 mD.

The IJsselmonde Sandstone is a complex of sand-bodies, varying in thickness from 70 to 300 m, with intercalated claystones up to 10 m thick. The sandstone forms an excellent reservoir. A strong lateral variation in grain size, sorting, and rounding is present. Average porosities range from 20 to 30%, permeability is about 500 mD but locally can be as high as 10,000 mD.

The depth at which the top of these deposits occurs falls within the range of 1500-2500 m, with temperatures from 65 to 85°C.

The Rijswijk and Berkel sandstones are present in the area between Rotterdam, The Hague, and Hoek van Holland, the Rijswijk Sandstone occurring almost everywhere in this area. The Berkel Sandstone is found in an E-W-orientated zone just north of Rotterdam, the IJsselmonde Sandstone running parallel to it just south of Rotterdam. In the area between Rotterdam and The Hague two aquifers seem to be present: as already mentioned in section 2.3, the Bunter Group is considered to be a potential aquifer suitable for extraction of geothermal energy in this area.

3 SHALLOW AQUIFERS

3.1 General introduction

As already pointed out, the shallow aquifers are considered more appropriate for seasonal storage and recovery applications than for exploration of geothermal energy. In descending order of age, the suitable aquifers are the Basal Dongen Sand, the Brussels Sand, the Berg Sand within the Breda Formation, and various Plio-Pleistocene sand units.

During the last 65 Ma, i.e., the Tertiary and Quaternary, there has been a slow regression in a northwestward direction in NW Europe. From the Miocene (22-5 Ma BP) on, the sea retreated to the present shoreline, and The Netherlands slowly took on its present shape in this period. Before the Miocene, throughout The Netherlands, abundant clays with minor sands were deposited in a mainly full-marine environment. Sediments were transported westward and northwestward. In general, grainsize and such reservoir characteristics as thickness, porosity, and permeability, become therefore more favourable in the opposite direction. Subsequent deposition took place in continental (fluvial) to shallow marine environments.

3.1 Basal Dongen Sand

This sand has the best characteristics in certain parts of the south-eastern region of The Netherlands (figure 5). The grain size shows a coarsening upward trend, and small amounts of clay occur.
The thickness of the sand in this area is 40-100 m, the average porosity around 30%, and permeability is about 500 mD, the top of the formation lies at a depth of 300-400 m. The sand is overlain in this area by the Berg Sand (see section 3.4).

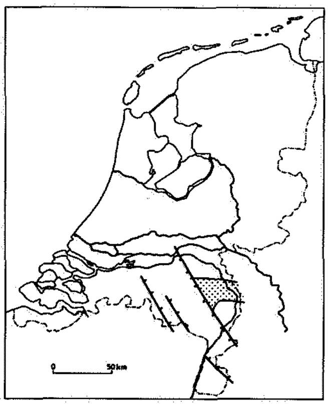

Figure 5 Prospective area for the Basal Dongen Sand (after RGD & DGV/TNO, 1985)

3.3 Brussels Sand

The Brussels Sand is present in the subsurface in the southwestern and northern parts of The Netherlands (figure 6), and could well be a suitable source of geothermal energy for use throughout the country. The thickness ranges from 50 to 125 m in the southern part of the area and from 30 to 100 m in the northern part. The Brussels Sand in the north shows strong lateral variations in thickness due to syn- and post-sedimentary salt tectonics.

The sand is very fine and the degree of sorting moderate. The average permeability is 50 mD, but for cleaner sands 200-600 mD. Porosity values lie around 30%.

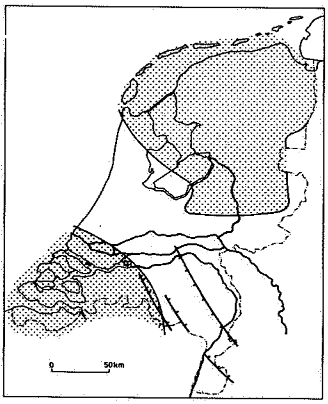

Figure 6 Prospective areas for the Brussels Sand (after RGD & DGV/TNO, 1985)

In the southern area occurence, the top of the unit is found between 100 and 700 m.

In the northern area, depth ranges from 300 to 1150 m. Generally the Brussels Sand is overlain by a clayey sequence, the Asse Clay, which makes it suitable for storage purposes. In the province of Groningen water is now being produced from this unit for the thermal bath at Nieuweschans.

3.4 Berg Sand

Promising areas for the Berg Sand are the southwestern, southeastern, and eastern parts of The Netherlands (figure 7). The sand is very fine, except in the southern part of the country, where it is fine. Sorting is poor to moderate. More clayey sands in the eastern part of the country show average porosities of 30-35% and an average permeability of 100 mD, whereas in the southern region permeabilities up to 1000 mD occur. The Berg Sand is overlain by the Boom Clay.

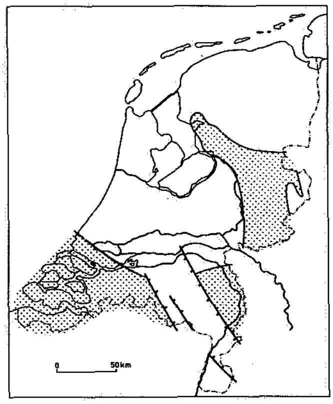

Figure 7 Prospective areas for the Berg Sand (after RGD & DGV/TNO, 1985)

The inventory studies did not raise expectations about this unit in the Central Graben. However the Asten-2 boring showed that the Berg Sand may well be one of the most promising aquifers. This case shows how important it is not to base local prognoses on the results of general inventory studies of this kind.

3.5 Sands of the Breda Formation

Within the Breda Formation, six sand members can be distinguished. All of them seem to have possibilities for the storage of thermal energy. These sands are present in the southern and central-northern parts of The Netherlands (figure 8). Some of the sands have a limited distribution. Other sands are stacked in the onshore Central Graben and these sands vary in thickness from tens of meters up to 200 m. In the southern part of the country the sands are coarse, whereas in the northern part they are fine to very fine. Sorting varies from poor to very good. Average porosities lie around 35%; permeability varies strongly, from 100 to 40,000 mD, but generally lies between 200 and 1000 mD.

In some places clay is present on top of the sands.

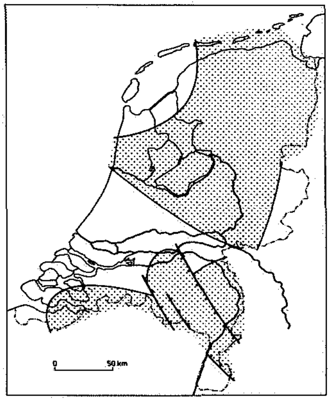

Figure 8   Prospective areas for sands of the Breda Formation (after RGD & DGV/TNO, 1985)

3.6 Younger sands

In the uppermost few hundred meters in The Netherlands there are very interesting aquifers, some of them having considerable lateral extension (figure 9). Major aquifers are present in the Oosterhout, Maassluis, and Scheemda/Kiezeloöliet formations, and minor sands in many others. The thickness of the individual sands ranges from 10 to 150 m; depth varies from 0 in the southern region to 600 m in the northwestern part of the country.

Porosity values are close to 35%, and average permeability varies from 1 to 6 Darcy. These younger sands are commonly overlain by clay deposits, which makes them ideal reservoirs for seasonal storage.

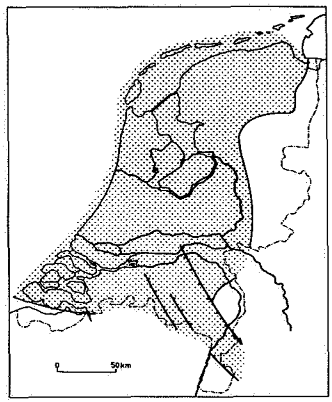

Figure 9 Prospective areas for the younger sands (after RGD & DGV/TNO, 1985)

4 CONCLUSIONS

Some parts of The Netherlands offer good conditions for the exploration of geothermal energy. These areas are located mainly in the western and northern parts of the country.
Storage and recovery of warm/cold water appears to be possible in the greater part of The Netherlands, the exceptions being the southern part of Limburg and the eastern part of Twente.

5 ACKNOWLEDGEMENTS

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GEOTHERMAL STUDY OF THE CENTRAL GRABEN (NORTH BRABANT); EVALUATION OF THE RESULTS OF AN EXPLORATORY GEOTHERMAL WELL IN ASTEN

J.P. Heederik
and A.J.M. Huurdeman

ABSTRACT

The first exploratory geothermal well in the Netherlands was completed in 1987. It was drilled by TNO Institute of Applied Geoscience on behalf of the Energy Research Project Management Office (PEO), as part of the National Research Programme on Geothermal Energy and Energy Storage in Aquifers (NOAA). The preparation, implementation and evaluation were carried out in collaboration with the State Geological Survey (RGD), the State University of Utrecht (RUU) and Comprimo Engineering BV. The research was partly funded by the Directorate General for Research and Development (DG XII) of the Commission of European Communities. The test well has yielded much useful data. The results and conclusions of the geothermal study of the Central Graben were recently set out in a draft final report, whose principal findings are summarized in this article.

1 INTRODUCTION

A succession of oil crises and the increasing environmental pollution caused by the emission of harmful combustion products from fossil fuels have contributed to the greater interest shown since the early 1970s in durable and environmentally compatible sources of energy. Geothermal energy - like solar energy, wind energy and tidal energy - is reckoned among the durable forms of energy.

Programmatic geothermal research in the Netherlands began in 1979. As part of the National Research Programme on Geothermal Energy and Heat Storage (NOA-I), an inventory study was carried out between 1979 and 1984 on the geothermal potential of various aquifers at depths between roughly 1000 and 3000 m, based on data available from earlier exploratory oil, natural gas and coal borings. This inventory study indicated possible sites for geothermal energy projects in the Netherlands. In 1985, on the basis of the NOA-I conclusions, a new research programme was formulated and started - the National Research Programme on Geothermal Energy and Energy Storage in Aquifers (1985-1989). This programme, henceforth referred to as the NOAA, was to continue to build on the results of the research carried out during NOA-I.

Temperature increases with depth in the earth's crust. This phenomenon is called the geothermal gradient. In the Netherlands, the geothermal gradient is 3 to 3.5°C per 100 m. As there is a constant temperature of 10 to 12°C near the surface at a depth of some 5 m, the temperature at 100 m is about 15°C, at 500 m about 30°C, at 1000 m about 45°C, at 1500 m about 60°C, at 2000 m about 75°C, and so on.

If geothermal energy is to be extracted in the form of hot water, the subsoil or the rock has to to be able to act as a reservoir, i.e. must satisfy certain conditions. For instance, the water-bearing bed or aquifer in which the hot water occurs must be sufficiently thick and porous to allow large amounts of water to be stored in it. If the production or pumping of the available water is to be economically feasible, the aquifer must be sufficiently permeable. Permeability is a measure of the ease with which water can pass (or be pumped) through an aquifer. The aquifer must also extend over a sufficiently large horizontal area and be sufficiently continuous horizontally. In principle, the geological and geohydrological conditions in the Netherlands appear to be favourable for the extraction of low-temperature geothermal power. This conclusion is based mainly on data that were not collected specifically for the geothermal energy study. The lack of such data was another reason for advocating drilling exploratory geothermal wells in the post-1984 phase of the research. It was argued that results from these exploratory wells could be used to verify earlier conclusions and would enable more reliable estimates to be made of the geothermal potential of the different geological formations. The results from test wells are also essential to research on the technical and economic feasibility of specific projects.

Under the NOAA programme the first exploratory geothermal well in the Netherlands was commissioned in 1986 by the Energy Research Project Management Office. This geothermal test well in Asten/Heusden was drilled under the aegis of the TNO Institute of Applied Geoscience, in collaboration with the State Geological Survey, the State University of Utrecht and Comprimo Engineering BV. The well was funded by the Energy Research Project Management Office and the European Community. The purpose of the test well was, firstly, to investigate the geothermal potential of three geological formations at various depths - the Breda Formation, the Voort Sand and the Basal Dongen Sand - and, secondly, to provide information for assessing the technical and economic feasibility of an actual geothermal power project in which that geothermal power could be used in the greenhouses of the local market gardening industry.

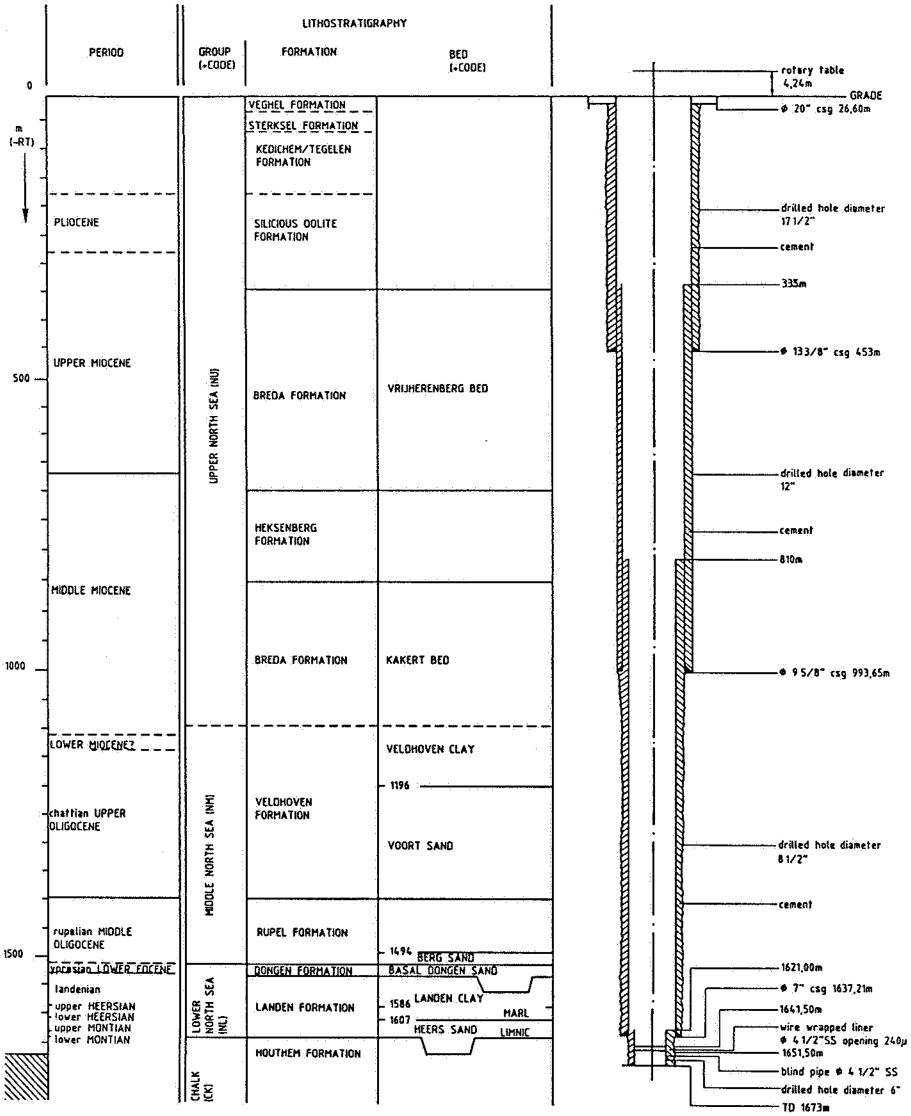


Figure 1 Stratigraphic diagram and Asten (2) test well completion (Source: State Geological Service, TNO Institute of Applied Geosience)

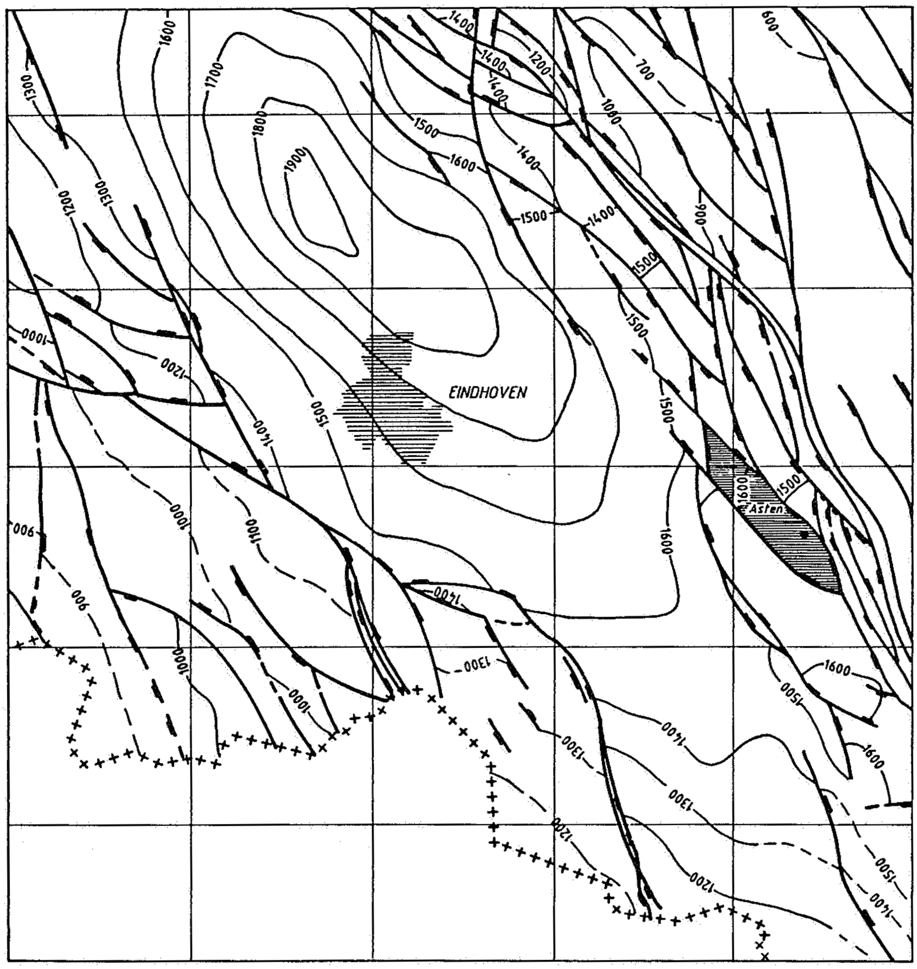
2 THE TEST WELL

The following factors were important when designing the test well:

- The local structural geology (inferred from drilling data from exploratory oil wells drilled in the region in the 1950s - i.e. wells in Asten (1) and Nederweert).
- The need for optimal data acquisition on the geology and reservoir characteristics, to be achieved by very frequent sampling from the vibrating screen, coring identified potential reservoir formations and a very extensive geophysical well-logging programme.
- The need for a production and injection test in the deepest formation (the permeabilities of the higher formations were to be determined by Repeat Formation Tests (RFT)).
- The ability to use the hole as a production or injection well after the geothermal potential of the drilled formations had been demonstrated. Allowance had to be made here for the possibility of installing a submersible pump at the required depth.

As the first purpose of the test well was acquiring reliable geological data and reservoir characteristics on the entire profile of the hole, it was decided to drill a vertical hole. For a geothermal test doublet, however, a deviated hole would have been preferable - though much more expensive - because of the geothermal life of such a doublet.

The final depth was originally planned to be 1550 m below mean sea level. But detailed study of the Asten (1) well-logging data revealed adequate reasons for continuing the hole to a final depth of roughly 1650 m. This presented a chance to test yet a fourth formation - the Upper Cretaceous Formation (the *Houthem Formation*), which had been shown to have good geothermal potential in Belgium. Figure 1 shows the well as actually drilled.



FAULTS AND TERTIARY BASE DEPTH CONTOURS

scale 1 : 350,000

Figure 2 Tectonic situation of the region and position of the "Asten 2 Block" on the edge of the Central Graben
(Source: State Geological Service)

3 GEOLOGY

Previous tectonic activity, especially during the Tertiary and Quaternary, brought about an extensive fault system in the Asten region. The faults trend NW-SE or WNW-ESE, so that various blocks have developed (Fig. 2). Downthrow of the Central Graben area along the NW-SE fault system has resulted in differences of more than 1000 m in Tertiary base depths. West of the Central Graben the Tertiary base is at a depth of some 850 m and to the east it is at about 600 m deep. The maximum Tertiary base depth in the Graben is almost 2000 m (Fig. 2).

The fault system of the Central Graben consists of several faults that can be traced over long distances (the peripheral Peel fault is the most important), interspersed with a large number of smaller faults at varying slips. In many cases the crust part between the faults has fragmented into smaller blocks. The test well is in one such block. The bordering NW-SE faults are 2.5 kilometres apart and the distance between the N-S faults is roughly 2 kilometres (Fig. 2).

In the course of the Cenozoic (Tertiary and Quaternary) the sedimentation environment in the Netherlands developed from a mainly marine sedimentation environment (Lower Palaeocene) to continental conditions (Pleistocene). Various formations, especially those under the Tertiary sediments, have good reservoir characteristics locally in other parts of the Netherlands as well. Initially, four formations in the Central Graben area seemed to be worth investigating for their suitability for geothermal exploitation. From top to bottom:

- Breda Formation, depth approx. 940 - 1000 m below m.s.l.
- Voort Sand (Veldhoven Formation), depth approx. 1200 - 1400 m below m.s.l.
- Basal Dongen Sand (Dongen Formation), depth approx. 1500 - 1530 m below m.s.l.
- Houthem Formation, depth approx. 1650 - 1670 m below m.s.l.

Later, the Berg Sand (Rupel Formation) was added on the strenght of the test well results, particularly the core tests. The test well provided accurate lithostratigraphical and lithological descriptions of the various reservoir formations relevant to geothermal energy. The lithostratigraphical position of these beds is given in Fig. 1. The information obtained from this test well - certainly in geological terms - is of regional importance and by no means confined to the Central Graben and/or geothermal energy.

4 GEOCHEMISTRY

It is usually difficult to obtain good well data on the composition of formation water at various depths. Water is produced only occasionally and even then not until the final depth is reached. The Vening Meinesz Laboratory of the State University of Utrecht (RUU) has developed a method to fill the gap in geochemical information by testing the pore water in sediment samples. The sample material suitable for this test is, in order of decreasing suitability core material, "roller bit" lumps, stabilizer and lumps carried up and "small lumps" sampled on the vibrating screen. The samples were checked to ensure they were not contaminated with drilling mud. The method involves extracting pore water from the samples, after which the pore volume can be determined by drying and weighing. In this way it is possible to determine within reasonably reliable limits the original chloride content of samples from different depths. The calculated chloride content of the pore water at various depths is given in Fig. 3. As chloride is the major component of formation water below the "fresh-salt" interface, the chloride gradient is also representative of the total content of dissolved matter. The minimum values in the curve give an impression of the salt content during an earlier sweetening phase, while the maximum values are an indication of the present increasing salinity of the arenaceous layers. The chloride content of the water causing the present salinity increase (25,000 - 60,000 mg/l) is considerably higher than the chloride content of seawater (19,300 mg/l). The "fresh-salt" contact (chloride content approx. 150 mg/l) in Asten is

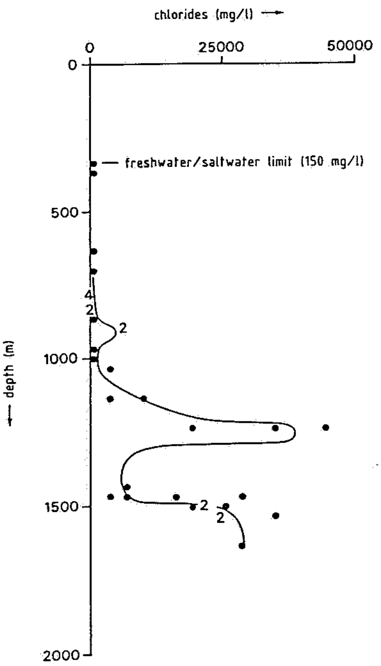


Figure 3 Chloride contents of the formation water in Asten
(Source: Vening Meinesz Laboratory, State University Utrecht)

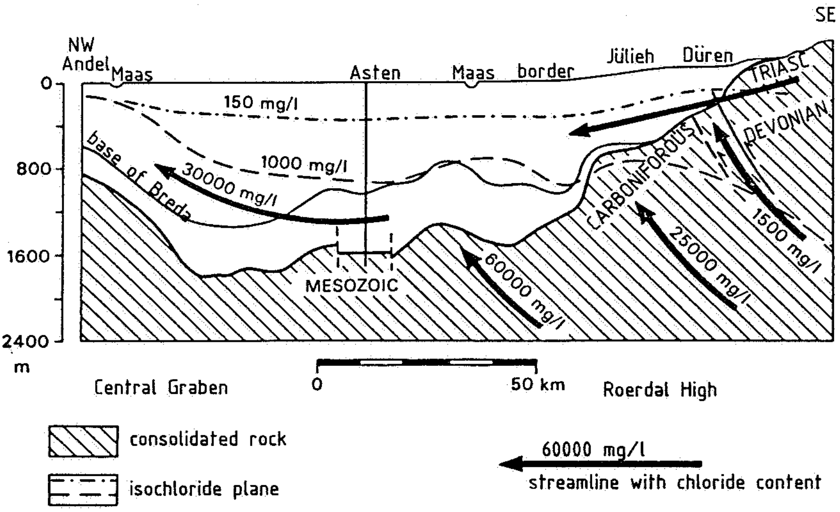


Figure 4 Hydrogeological profile oriented according to the most probable direction of flow of the deep groundwater
(Source: Vening Meinesz Laboratory, State University Utrecht)

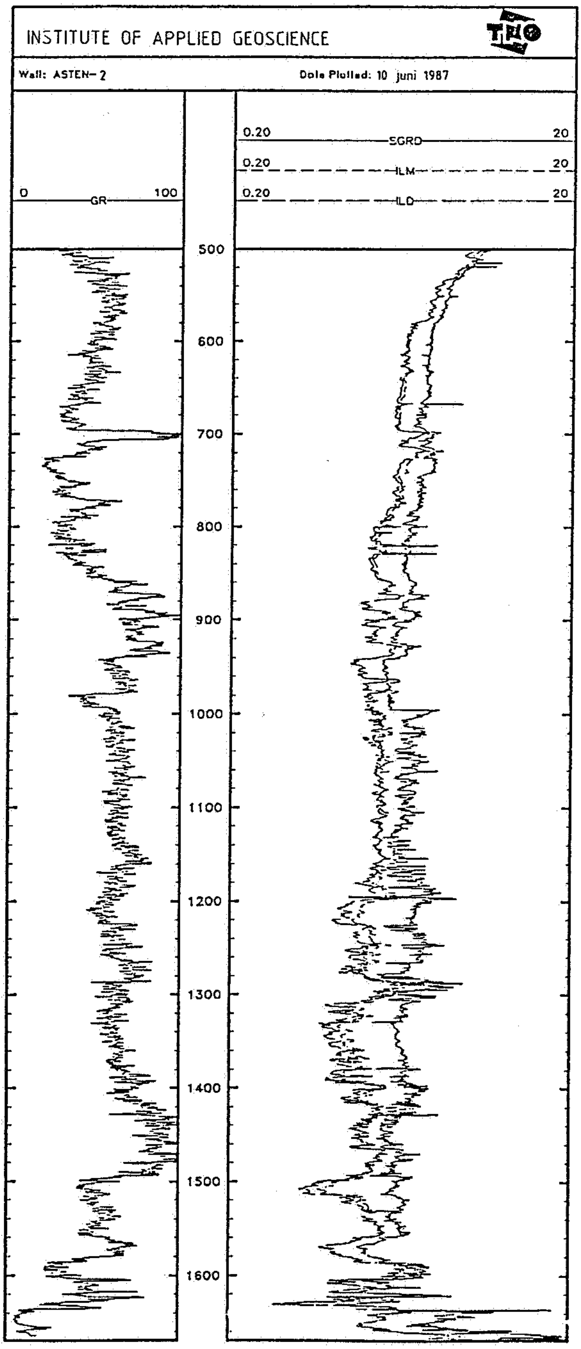


Figure 5 Gamma ray and resistivity logs of the exploration well Asten 2

at roughly 320 metres.

Figure 4 shows a hydrogeological profile orientated according to the most probable direction of flow of the deep groundwater. It is assumed the deep groundwater is supplied from the southeast. The deep groundwater in the Central Graben is a "mixed water" of fresh infiltration water from the Ardennes and the Eifel and saline to very saline thermal formation water percolating upward through crevices and zones with karst development and discharging into the Tertiary cap of the Central Graben. The salinity increases north-westwards. During the course of geological development, salinity increase (percolation) alternated with sweetening (infiltration). In the Central Graben, the fresh-salt contact (150 mg/l chloride) and the 1000 mg/l isochloride contact are hundreds of metres apart. At Asten, this distance is just under 700 m.

5 FORMATION EVALUATION

Porosity, pore content, permeability and temperature are the principal characteristics of geological formations which together determine the geothermal potential and, to an important extent, the reservoir behaviour. Petrophysical interpretation methods are important in the process of formation evaluation, which also uses data from geophysical well-logging (Fig. 5) and core tests to evaluate these characteristics. The porosity and permeability of the cored sections are measured in the core samples. By correlating core porosity and permeability across the cored sections with the calculated and/or derived (from various geophysical well-logging data) porosity and permeability, reliable porosity and permeability values can be determined for the uncored sections.

The average or representative porosity and permeability of the various reservoirs considered for geothermal exploitation were calculated, and so was the total transmissibility of the reservoirs that consisted of several beds. The steady-state flow equation, was used to calculate the productivity index (which is a value indicating the production rate of the relevant reservoir per unit of pressure drop). The results of the formation evaluation can be summarized as follows:

Table 1 Reservoir characteristics of the formations studied

Formation	Depth (m)	Thickness (m)	Porosity %	Transmissivity mD.m	Productivity $(m^3/h)/bar$	temperature °C
Breda	939- 998	59	40	88100	24.3	35.5
Voort	196-1415	219	32	4161	1.4	49.2
Berg	1494-1513	19	35	16150	6.6	59.5
Dongen	1513-1530	17	24	136	0.06	60.
Heers	1628-1636	8	38	4480	1.8	62.3
Houthem	1647-1665	18	23	n/a	0.6	62.9

The findings showed that two of the formations investigated have potential for geothermal exploitation, i.e.:

- Breda Formation (Kakert Bed) with a productivity index of P_i = 24.3 $(m^3/h)/bar$ and an average temperature of 35.5°C.
- Berg Sand with a productivity index of P_i = 6.6 $(m^3/h/bar)$ and an average temperature of 59.5°C.

6 GEOTHERMAL RESERVES

The geothermal reserve of an area depends on the temperature and on the reservoir characteristics. In the Netherlands the temperature gradient varies from place to place between 3°C/100 m and 4°C/100 m. The average temperature gradient in the Asten block is approximately 3.2°C/100 m.

The thermal reserve of a specific reservoir is determined by the reservoir volume, the amount of formation water available and its average temperature, the density of the water and of the matrix, and also by the heat capacity of the water and the matrix. Figure 6 shows the temperature distribution across the Asten block for the reservoirs considered for geothermal energy production. Two cases are distinguished in determining the usable heat ΔT-Geothermal energy production with and without the installation of a heat pump. The minimum injection temperature without a heat pump will be approximately 30°C, but with a heat pump the injection temperature can drop to 17°C. Not all the heat available can be tapped. In France it is customary to use a production factor of 0.33. As there are no supporting studies on the situation in the Netherlands, a conservative production factor of 0.25 was assumed in this research.

Using the above criteria to calculate the geothermal reserves in the Asten fault block leads to the results shown in table 2.

The geothermal reserves in the Central Graben can be roughly estimated by extrapolating the test well results for the Asten fault block. For this extrapolation it is assumed that the reservoir characteristics of both formations are continuous in the Central Graben. To allow for the uncertainty in this assumption, the reserves were multiplied by a risk factor of 0.25. The results are shown in table 3.

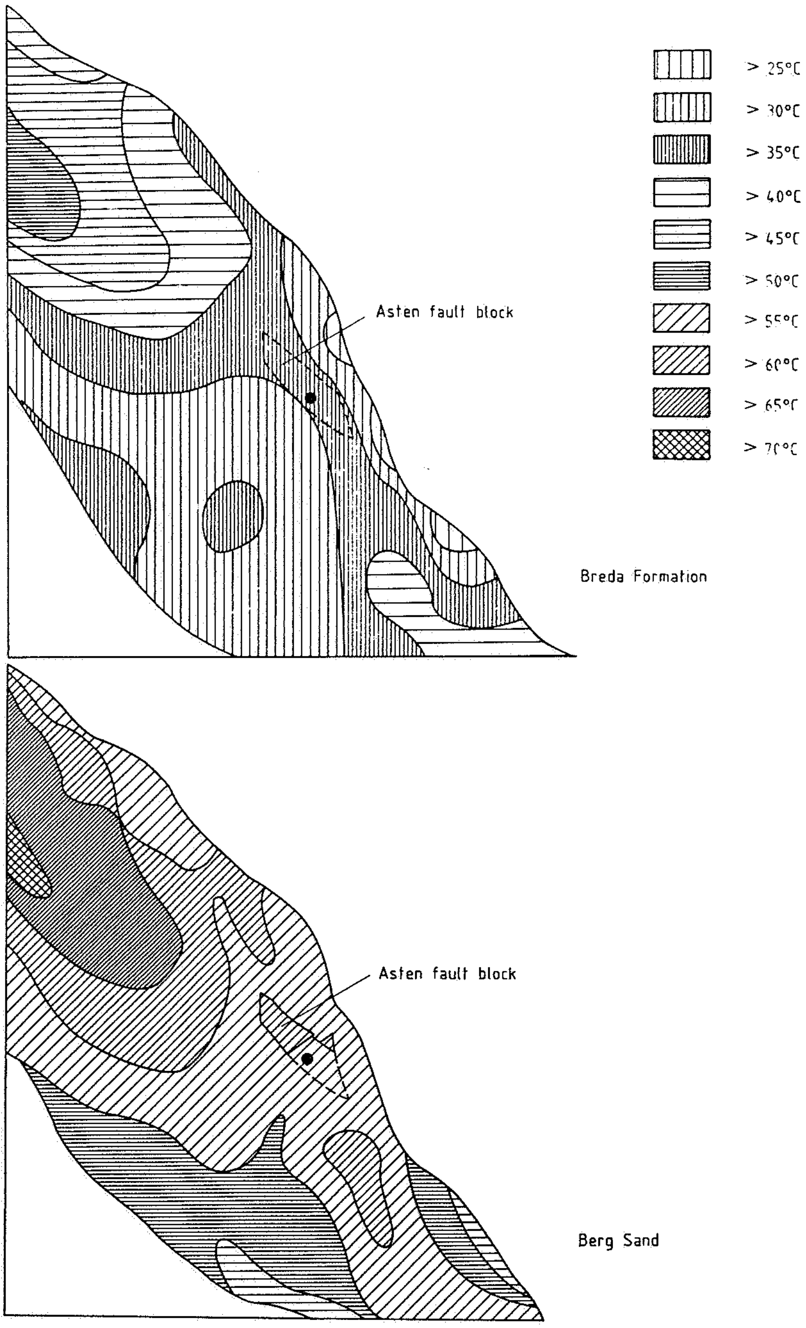


Figure 6 Temperature distribution in the Central Graben for two potential geothermal reservoirs

Table 2 Geothermal reserves in the Asten fault block

Formation	Geothermal reserves without heat pump	 with heat pump
Breda Formation	27.5×10^{15}J	43.4×10^{15}J
Berg Sand	7.6×10^{15}J	12.0×10^{15}J
Total of Asten fault block	35.1×10^{15}J	55.4×10^{15}J
Expressed in tonnes oil equivalent	838×10^{3} TOE	1323×10^{3} TOE
Expressed in natural gas equivalent	998×10^{6} m³ (STP)	1575×10^{6} m³ (STP)

Table 3 Reserves in the Central Graben

Formation	Geothermal reserves without heat pump	 with heat pump
Breda Formation	310×10^{15}J	490×10^{15}J
Berg Sand	90×10^{15}J	140×10^{15}J
Total of Central Graben	400×10^{15}J	630×10^{15}J
Expressed in tonnes oil equivalent	9.5×10^{6} TOE	15×10^{6} TOE
Expressed in natural gas equivalent	11.4×10^{9} m³ (STP)	17.9×10^{9} m³ (STP)

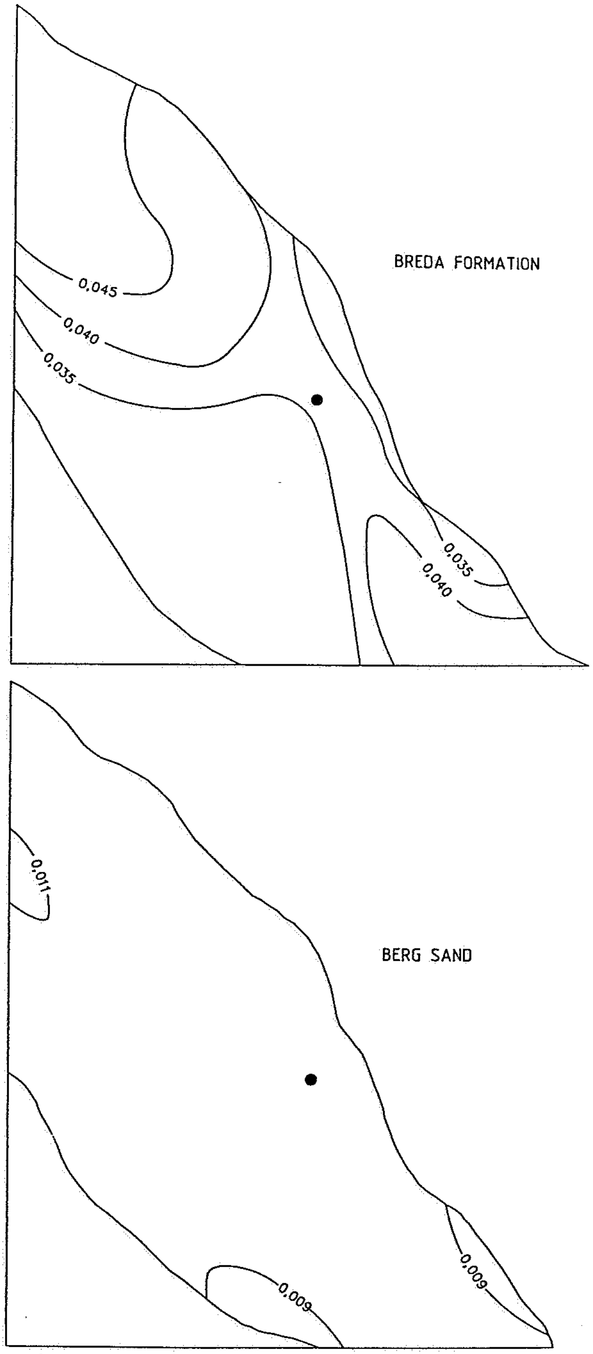


Figure 7 Heat capacity map of two potential geothermal reservoirs in the Central Graben

The disadvantage of this method of quantifying geothermal reserves is that a limited allowance is made for economic recoverability of these reserves. To counter this objection, the geothermal reserve can be expressed in the so-called heat capacity of the formation at a specific location. The heat capacity is expressed in the energy supplied per unit temperature and pressure drop and is a function of the reservoir characteristics of the formation, the temperature-dependent liquid properties and the well radius and radius of influence of the well system.

The radius of influence of the well system was estimated to be approximately 1000 m. If it is also assumed that the well will be completed with a 6" liner, the heat capacity can be calculated at any required location in the Central Graben, using the adapted equation for steady-state flow. It is also possible to compile a heat capacity map of the area for any relevant formation. The thermal capacity of the production well in a geothermal doublet can be determined at any required location by using the heat capacity map (Fig. 7) in conjunction with the information on the productivity of the formation and the temperature map. The heat capacities of the two potential formations in Asten are :

	Heat capacity
Breda Formation	28 kW/bar°C
Berg Sand	8 kW/bar°C

If the required pressure drop Δp and the difference between production and injection temperature ΔT are known, the power of a geothermal doublet can be calculated easily:

	Breda Formation with heat pump	Berg Sand without heat pump
Δp	10 bar	20 bar
Δt	18.5°C	29.5°C
Thermal power	5.2 MW	4.7 MW

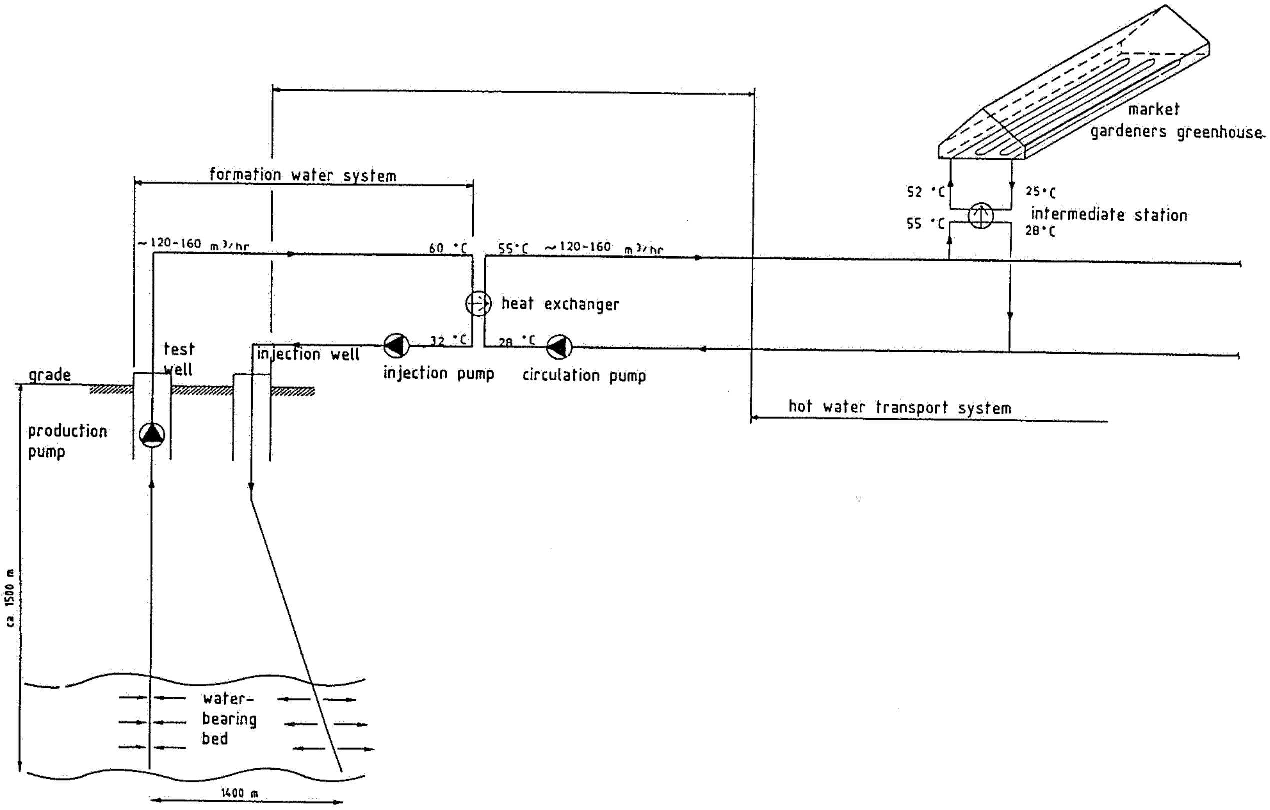


Figure 8 The principle of geothermal power production
(Source: COMPRIMO)

7 GEOTHERMAL TEST DOUBLET AT ASTEN

The research at Asten has shown that there are substantial geothermal reserves in the Central Graben area. But the possibilities of geothermal energy recovery depend on more than the geological and reservoir conditions. Not only must a geothermal energy project be technically and economically feasible: potential customers must also be prepared to purchase this unconventional heat instead of natural gas. Moreover, a positive attitude on the part of the local and provincial authorities as well as the power supply companies is essential. These non-technical boundary conditions were considered in depth when the drilling site for the first geothermal test well in the Netherlands was selected.

Low enthalpy geothermal heat is produced by a so-called geothermal doublet. A doublet consists of two wells: an injection well and a production well. The hot formation water is pumped up in the production well by a submersible pump, passed through a heat exchanger in which the heat is transferred to a heat transport line, after which the formation water, having cooled off meantime, is re-injected through the injection well into the original formation (Fig. 8). In Asten, the salinity of the formation water and the need to maintain the pressure in the reservoir are the two main reasons for using the doublet principle. Apart from the technical provisions, the life of a doublet is dictated by the period it is able to continue producing the required heat. The flow rate, the spacing of the production and injection wells, the porosity and the reservoir thickness affect the longevity of the doublet. If flow rate, porosity and reservoir thickness are known, the necessary subterranean distance between the two wells of a geothermal doublet of a certain required life can be calculated.

Though the results of the research show that geothermal energy production in Asten is technically possible, there are still many uncertain factors which must be resolved through research. That is why completion of a geothermal test doublet is the most suitable follow-up to the geothermal test well. If the existing test well is used, a test doublet can be achieved in the following steps:

- Phase I : completion of the geothermal test well to production well and testing of the reservoir (Berg Sand)
- Phase II : drilling the deviated second well for the test doublet
- Phase III : completion and testing of the geothermal test doublet.

8 POTENTIAL FOR GEOTHERMAL ENERGY PRODUCTION

Calculations by Comprimo BV show that geothermal energy production from the Berg Sand without using a heat pump is more economically attractive than production of geothermal energy at a lower calorific value from the Breda Formation with the use of a heat pump. In this case, the specifications of the customers are important. The greenhouse market gardeners who will be served by the Asten geothermal project grow tomatoes and cucumbers and must be supplied with heating water at a temperature of 30°C. Therefore, when producing from the Breda Formation it will be necessary to use a heat pump. While a heat pump has no positive effect on the economics of any proposed project in Asten, the power requirements of the various pumps - head about 250 metres and a capacity of 120 m^3/h - are so high that thermoelectric power combination is definitely economically attractive. The layout of the proposed geothermal energy project is given in Fig. 8. The design criteria can be summarized as follows:

Criteria:

- Formation water production rate	120 m^3/h
- Formation water supply temperature	60°C
- Formation water injection temperature	32°C
- Temperature difference ΔT=	28°C
- Area of greenhouses supplied	7.65 ha

Power and Operating Hours:

- Thermal capacity of geothermal energy source	3.8 MW_{th}
- Electric output of thermoelectric power plant	300 kW_{el}
- Thermal output of thermoelectric power plant	500 kW_{th}
- Equivalent full load hours	6000 hours/annum

If the results from the test doublet are positive and a start were made on implementation of a complete field test project, such a project could save 2.3×10^6 sm^3 natural gas per annum. That is roughly 54% of the total natural gas currently consumed per annum by the market gardeners who would receive the geothermal energy. Depending on the spread of the assumed subterranean boundary conditions and on the natural gas price range, the pay-out time of the portion of the investments to be funded by "third parties" will be between 5 and 7 years.

9 CONCLUSIONS

The test well has demonstrated that geological inventory studies should be used with great care when estimating geothermal reserves. Before the well was started, four possible potential geothermal reservoirs were identified. One of these reservoirs (Breda Formation) turned out to be suitable. However, without the data from the test well the reservoir with the best long-term prospects - the Berg Sand - could not have been identified. The results from the test well enable any estimates of the geothermal potential of specific geological formations on the basis of the NOA-I results to be evaluated and/or adjusted. Test wells such as the one in Asten are indispensable for reliable determination of the geothermal reserves elsewhere in the Netherlands or in other geological formations.

The technical feasibility of geothermal energy recovery can be studied in the field by completion of a geothermal test doublet. The test well and related research have confirmed that such a test doublet can be realized in Asten.

LEGISLATIVE AND ADMINISTRATIVE ASPECTS OF GEOTHERMAL ENERGY AND THERMAL ENERGY STORAGE

A.D. Postma

ABSTRACT

The Dutch research programme on geothermal energy and thermal energy storage in aquifers, the NOAA (Nationaal Onderzoekprogramma Aardwarmte en Energieopslag in Aquifers), was mainly concentrated on technical and economical aspects. Recently some studies have been undertaken with respect to the legislative an administrative aspects involved. Legislatory constraints exist because legislation does not provide for storage of energy in aquifers and extraction of heat from the subsurface. The frameworks of legislation involved here are mining, environmental and physical planning legislation. As extraction and injection of water play a major role in geothermal energy and energy storage projects especially the Groundwater Act and the Act on Soilprotection are in force with respect to the granting of licences and the raising of levies.

Administrative issues of importance are those concerning the way in which a project will be financed and controlled, choices which are mainly dependent on the complexity of a project. Apart from that, the covering of risks relating to these kind of projects, such as disappointing exploration drillings, unexpected short lifespan of a geothermal doublet and damage to the environment due to accidents, are important issues which have to be solved on short term.

1 INTRODUCTION

The implementation of geothermal and energy storage projects on a large scale is hindered by a number of constraints. These constraints can consist of technical, economical, legislatory and administrative problems.

The technical and economical aspects have been the subject of extensive research in the recent past, as a part of the NOAA-research programme. Also a few studies have been undertaken with respect to the legislatory and administrative aspects involved. Now that the technical problems seem to be solvable and the systems developed are potentially profitable, studies into its legislative and administrative aspects have become urgent. These aspects need to be evaluated and constraints need to be resolved before they jeopardize the realisation of geothermal energy or energy storage projects in aquifers.

In the paper presented here some of the most important legislative aspects will be discussed in Chapter 2. Chapter 3 will deal with the administrative aspects and the risks involved in the development of geothermal energy and energy storage projects. Finally, Chapter 4 will give some major conlusions.

2 LEGISLATORY ASPECTS OF GEOTHERMAL ENERGY AND ENERGY STORAGE

Three frameworks of legislation play a role where geothermal energy and energy storage projects are concerned: mining , environmental and physical planning legislation.

2.1 Mining Legislation

Mining legislation regulates the exploration and mining of minerals. For example: in case of exploration drilling a license from the Ministry of Economic Affairs is needed, for the mining of minerals one needs a concession for the area in which the mining takes place.

The Mining Acts only pertain to those minerals which are named in the acts. Since neither water nor heat is named in the mining acts, legislation in its present form seems not to provide for geothermal energy and storage of energy in aquifers.

As a consequence no permission is needed for exploration drilling nor is a concession needed for mining. Nor do the technical and security regulations, laid down in the Mining Acts, apply. Moreover geothermal- and energy storage projects do not fall under the Government Inspection of Mines.

An amendment to the mining legislation in order to incorporate thermal energy mining and storage is not to be expected on short term.

2.2 Environmental Legislation

A number of activities undertaken in geothermal energy exploitation and thermal energy storage in aquifers may have an impact on the environment. Environmental consequences can be expected as a result of the use of groundwater, the treatment of water to prevent choking of filters and heat-exchangers and the heating of soils.

As a result of these consequences, projects which are undertaken come under environmental legislation of which the Groundwater Act and the Act on Soilprotection are the most important.
The Groundwater Act regulates the quantitative control on groundwater. According to this act it is forbidden to extract water from or inject water into the ground unless authorized by the Provincial Council. Not only is authorization by the province needed, a levy of up to 2 cents/m^3 has to be paid. Also repeated reporting on the amount of water extracted is obligatory.

The intervention between projects, and extraction of heat stored in an aquifer by a third party, can be prohibited by means of the Groundwater Act. This can be realised by not granting a request for permission to withdraw groundwater in the near surroundings of an existing project.

In 1987 the Soil Protection Act came into force. Its purpose is to protect soil and groundwater against undesired influences. This protection is guaranteed in two different ways. First, a general protection level has to be reached by the realization of specific regulations under the Act. Regulations under the Soil Protection Act which may have their impact upon the realization of geothermal or thermal energy storage are expected in 1989. Second, on a provincial level special protection areas can be designated on the basis of their vulnerability either as soil-protection- or as groundwaterprotection areas. On a provincial level, too, a special levy can be raised.

The Public Nuisance Act (Hinderwet) and the Act on Pollution of Surface Waters (Wet verontreiniging oppervlaktewater) are important in this context as well. Purpose of the Public Nuisance Act is to prohibit or diminish danger, damage and nuisance for the surroundings, caused by human activities. In general a license will be necessary for all projects. The Act on Pollution of Surface Waters was enacted to keep surface waters as clean as possible. A licence will be necessary when salt or polluted water is to be discharged into surface water on a regular basis.

Environmental legislation is divided into a large number of different laws. A separate law, the WABM (Wet algemene bepalingen Milieuhygiëne), has come into force in which the procedures are described for granting licences. These are especially important when a number of different laws apply to one project.

2.3 Physical Planning Legislation

The contruction of buildings and the use of land should not conflict with the Physical Planning Act. In all cases a building licence has to be taken out. A building licence will only be issued if it is not in conflict with existing zoning plans (bestemmingsplannen) and local building regulations. This means that in a number of cases geothermal and energy storage projects cannot be realized unless (minor) changes in the zoning plans are made. A permission can also be granted when a change in the plans is intended in the near future.

3 ADMINISTRATIVE ASPECTS OF GEOTHERMAL ENERGY AND STORAGE PROJECTS

A number of administrative aspects are important with respect to the realisation of projects. The most important administrative aspects are the choice of a form of administration and the possibilities for financing the project. Risk analysis is also a point of concern.

3.1 Forms of Administration and Financing

Both the type of administration and the way of financing a project are largely dependent on the type and the scale of this project. Especially the scale of a project can vary enormously. For example: a geothermal project can consist of one shallow doublet from which a company extracts heat by means of a heat pump. But it can also consist of a large number of deep wells from which heat is extracted to heat a whole town district. Evidently the two projects will not be financed and managed in the same way.

In the case of a small-scale project, in which one participant is involved, this participant will finance and manage the project. This is e.g. the case at Bredero in Bunnik (The Netherlands), where a small thermal-energy-storage-system is operational. Financing such a project may be supported by companies specialized in "energy services", companies which are paid out of savings made on primary energy.

In more complex projects, in which a number of participants are involved, management and financing will preferably be executed by an intermediate. This could either be a private company or a (public) utility company. In most cases a private company will not be interested in participation because of the marginal profits. The pay-off time runs to 5 years or even longer, which is far too long to interest industrial parties in participating. A public utility company uses less strict economic criteria and will therefore be more willing to invest in geothermal energy and thermal energy storage. This is the most important reason why a public utility company is the most suitable party for financing and administrating these kinds of projects. The utility company will play the same role as some now do in town heating projects.

In the case of very complex projects, projects where large amounts of heat are involved, a third way of financing and managing is possible. In such cases the construction of a joint venture between the public utility company and private companies is preferable, especially when conflicts of interest are expected to arise between the public utility company and the private companies involved. This will occur when such amounts of heat are involved that the public utility company fears a substantial decrease in income. In a joint venture construction all parties involved come to a long term agreement on mutual delivery of heat and/or services. A more profitable situation is also reached for the private companies involved because the larger part of the investments will be raised through a loan by the joint venture. Only a small amount of capital will have to be invested directly by the private companies, while the pay-off period of this capital will be within reasonable limits. Moreover the loan will not influence the company's possibilities for further company loans.

In all thermal energy storage projects where the heat supplier and consumer are not the same party, agreements on delivery and purchase of heat, in both the amount and the temperature, must be laid down for at least the pay-off time of the project.
Especially in case of waste heat, laying down such long term contracts can cause trouble, mainly because future changes in the processes involved might reduce the amount of waste heat.

3.2 Covering Risks and Uncertainties

A final aspect which can block the realization of both geothermal energy and storage of thermal energy is the amount of risk and uncertainty involved in these new technologies. The most important risks and uncertainties are:

- Geological and hydrological uncertainties with respect to the local subsurface, only to be resolved by "expensive" exploration drilling.
- The reliability of the operation is uncertain. The uncertainty is created by possible choking of the system.
- The lifespan of a geothermal doublet, increasing with increasing distance between bore-holes, is influenced by uncertain geological factors.
- Unpredictable damage to the environment, due to accidents, may take place.

Uncertainties and risks as described above cannot be predicted in a statistically satisfactory way, mainly due to the lack of data. This lack of statistical data will force insurance companies not to insure projects unless a high premium is paid.

The existance of risks as described above can inhibit realization of projects on the scale desired, and need therefore be eliminated as soon as possible. As a large part of these constraints are related to uncertainties with respect to technologies involved, part of the solution lies in the setting up of a number of pilot projects. The primary goal of these projects must be the increase of knowledge with respect to its technology. The Dutch government should participate in these projects.

Other constraints are largely set by local parameters, as for example the geological quality of the subsurface. High investments are needed for test drilling without the certainty of success. Such local constraints will lead to a decrease in the amount of projects realized on a national scale. One way to overcome this is the spreading of locally induced risks over a large number of projects, i.e. on a national scale. This could either be done by participation of the government in all projects, or by the formation of some sort of funds.

4 CONCLUSIONS

- Mining legislation, in its present form, does not provide for geothermal energy and energy storage projects. As a concequence no licence and/or concession is needed, nor do the safety regulations apply.
- A licence is needed for the extraction of groundwater, according to the Groundwater Act. Moreover a levy can be raised. The actual amount of groundwater drawn must be registered.
- The Act on Soilprotection is enacted to protect soil and ground water against unwanted influences. Regulations under the Act which are important for geothermal energy and energy storage in aquifers are expected in 1989.
- When realizing a project a building licence is obligatory. A building licence request is not granted when the project is in conflict with local zoning plans.
- The way of financing and managing a project is largely dependent on the type and the scale of a project. Small projects can be financed and managed by the end user, larger projects are best financed and managed by a public utility company. Complex projects can best be set up in a joint venture construction.
- Long term contracts with respect to delivery and purchase of heat should be laid down when more than one party is involved.
- A number of pilot projects should be set up in order to be able to solve some important technical constraints.
- The formation of funds should be realized to spread the risks of locally induced constraints.

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