GEOTHERMAL USE OF DEEP FLOODED MINES

BAZARGAN SABET Behrooz[1], DEMOLLIN Elianne[2], Van BERGERMEER Jan-Jaap [2]

[1]BRGM, 1, avenue du Parc de Brabois 54500 Vandoeuvre - France; b.bazargan-sabet@brgm.fr

[2]Municipality of Heerlen, Geleenstraat 25, postbus 1 6400 Heerlen – The Netherlands; e.demollin@heerlen.nl, J.van.Bergermeer@heerlen.nl

ABSTRACT: *Many mining regions in European countries contain extensive areas of flooded underground mines. The water within these mines represents a significant and widespread opportunity for extracting low enthalpy, geothermal energy. This green and renewable energy is particularly suitable for residential and commercial heating requirements using an existing or planed district heating network. Based on current energy prices, mine water used as geothermal resources could significantly reduce the annual costs of a district heating plant compared to conventional heating methods that burn fossil fuels. The paper presents some preliminary results obtained in the frame of the Minewater project, funded by the Interreg IIIB North West Europe, which aims at investigating all issues related to a successful use of this new renewable energy resource.*

KEYWORDS: *Minewater, geothermal energy, flooded mines, district heating*

RÉSUMÉ: *Plusieurs régions minières en Europe possèdent des mines ennoyées qui ont le potentiel de fournir de l'énergie géothermique basse enthalpie. Cette énergie renouvelable est particulièrement appropriée pour une utilisation en chauffage collectif par réseau de chaleur. Compte tenu du prix actuel de l'énergie fossile, l'utilisation de l'eau des mines comme source de chaleur peut réduire de manière significative le coût annuel de la production de chaleur des collectivités. L'article présente quelques résultats obtenus dans le cadre du projet "Minewater" financé par le programme Interreg IIIB Europe du Nord Ouest dont l'objectif est d'étudier tous les aspects relatifs à l'utilisation de l'eau des mines comme ressources énergétiques.*

MOTS-CLEFS: *l'eau des mines, énergie géothermique, mines ennoyées, chauffage collectif.*

1. Introduction

Despite of some resurgence of the mining activities in the last years, economic distress caused by the mine closure and absence of new investments in the mine-scarred lands strike many former mining communities impeding them transition from an extraction industry to new enterprises. But nevertheless after closure, mined areas left remarkable potentials and resources that could be favourably exploited using existing local skills. Extracting low-enthalpy, geothermal energy from mine water is one of these possibilities. Indeed, after flooding, the mined area leaves behind an extensive reservoir of warm groundwater that could be used by the heat supply sector, promoting at the same time the strategy for generating long-term local employment and incomes. Besides, unlike the commodity working, the use of these new resources is environmental friendly and consistent with the sustainable development.
The economic relevance of using mine water is justified by the costs for conventional district heating and cooling that are rising globally in the past 50 years. For the past four years, fossil fuel prices have been increasing and are predicted to remain high for the foreseeable future. At the same time, the application of the United Nations Framework Convention on Climate encourages the

greater use of renewable energy. In this frame, the competitive use of geothermal mine water energy has been considered as one of the most promising options in the former mining areas.
Trust in this opportunity brings a consortium of European regions to launch a project called “Minewater” funded by the EC Interreg IIIB programme. Minewater aims to revive old and declining mining areas by producing energy from water trapped in flooded mines. The main objective of this 20 M€ project is to reduce the ex-mining communities’ ecological footprint by demonstrating that it is both economically viable and environmentally sound to extract geothermal energy from water in closed coal mines. It seeks also to disseminate experiences on this renewable resource throughout European countries, which faces the challenge of managing the decline of traditional coal industries. Subsidiary objectives include developing new housing areas within old communities that will benefit from this energy. The project is piloted on a trans-national basis by the council of Heerlen (Netherlands).
The Minewater project comprises feasibility investigations in Germany and France and the construction of a pilot site in “Oranje Nassau” (O.N) coal mine concession in Heerlen. The project leans on a large spectrum of geological, mechanical, hydraulic, thermal and chemical studies. We present hereafter some considerations that must be tackled in order to identify the capacity of this particular reservoir and to optimize the use of the resource.

2. General considerations

The water filled mine has a large geothermal potential. The mine is a ready-made reservoir and requires minimal infrastructure construction. Drilled wells into the deep galleries or simply existing shafts can be used for the water extraction using submersible pumps lowered to the bottom. Even if some free convection can be occurred deforming the linear geothermal temperature distribution along the depth of the shaft, the thermal equilibrium with the surrounding rock can be likely assumed so as at great deep the water temperature is nearly the same than the rock temperature.
At the utilities level the warm extracted water must be maintained under pressure in order to conserve the dissolved gas (e.g. CH_4, CO_2) usually present in the coal mines. Furthermore the water may contain a quantity of diverse toxic, corrosive or scale-forming elements and can not be used directly in the heat production facilities. Thus, warm mine water must pass through a heat exchanger where heat is transferred to a secondary circuit. The cooled water is then re-injected into the mine by a second borehole at a sufficient distance to the production borehole (doublet operation).
In the same way, cold water can be extracted from shallow parts of the mine and be used for the cooling purposes during the summertime. The warmed water returned to the mine can be stored in an adequate buffer zone (i.e. deep part) and then reused during the winter for enhancing the heating efficiency.
In general, the temperature of the water extracted is not enough to be used in a district heating network and must be heightened before distribution. According the amount of the extra-heat needed to rise the water temperature, different technique and process can be used. Heat pumps however, seem to be the most efficient way. Indeed the COP (i.e. the ratio between the amount of heat generated and the amount of energy needed to operate) of a standard heat pump ranges between 3 and 6, while this value is about 1.2 for the natural gas. Figure 1 represents the whole process of district heat producing using mine water geothermal energy.

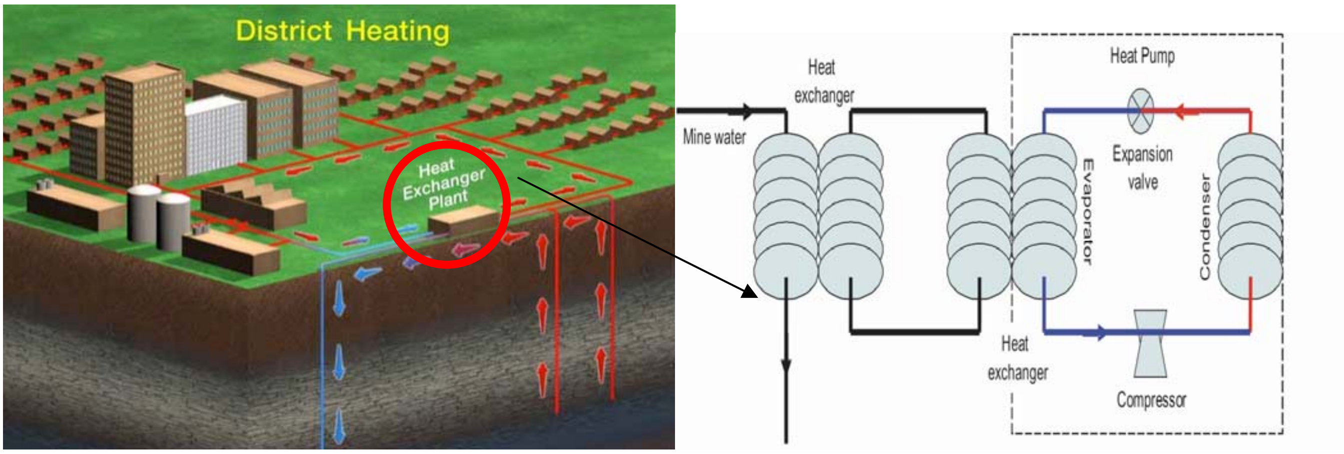

Figure 1. District heating using mine water geothermal energy.

To illustrate the economical benefit of this system, we suppose that a thermal installation has to produce 40 GWh of heat by year in a continuous way. The utility can be supplied by mine water at 40 ^{0}C with a flow rate of 30 l/s and the installations have the capacity to extract 20 ^{0}C from this resource. The quantity of heat extracted is given by:

$$Q = q\,\rho C_{pw}\,\Delta T \qquad (1)$$

where: q - flow rate, ρ is the density and C_{pw} - specific heat capacity of the water.

Using values above the energy extracted is about 22 GWh by year representing 55 % of the total energy needed. If the other 18 GWh is produced using heat pumps, the operating electrical energy needed, assuming a COP of 3, is 6 GWh, which cost 420000 € assuming 70 €/MWh (average European price). For the same case, if the extra-energy is provided by natural gas, the cost will be 872000 € assuming a COP of 1.2 and a market price of 58 €/MWh.

3. Reservoir characterization

The reservoir in a mine is the total volume of voids that remain after extraction of the ore and waste rock from coal seams. In the case of deep underground mining, total shut down of the mine-water drainage pumps induces progressive flooding of this reservoir. In order to assess the geothermal capacity of a mine, the first step is the evaluation of the water volume available into the reservoir. This must be carried out by tacking into account the "exploitation history". Indeed, during the exploitation phase, the volume of voids is equal to the volume of ore extracted. However, at the end of the exploitation the volume of voids would be significantly lower either because the overlying rock that is no longer supported by the ore that has been removed is allowed to fall behind the operation (caving in) or because the created void is backfilled. In addition high pressures at deep levels may cause the convergence of the roof reducing the volume of the cavity.

The residual volume (V_{res}) that can be filled with the water is deduced from the total extracted volume (V_{ext}) by relation (1):

$$V_{res} = V_{ext} - cV_{bak} - V_{sub}, \qquad (2)$$

where: V_{sub} - subsidence volume, V_{bak} - backfilled volume after compaction and c- bulking rate.

The total extracted volume encompasses the volume of galleries and shafts in addition to the volume of ore extracted. V_{sub} can be evaluated by numerical modelling or by using empirical

formula (e.g. Proust 1964). V_{bak} depends on the method used for the excavation. In the case of caving in the bulking rate is usually near to 0.7 while for a working backfilled with compacted sand c = (1-Φ) ≈ 0.85 where Φ is the porosity of the backfill.
At the end of the exploitation period and after decommissioning groundwater in the mine is allowed to rise to its natural level. Due to the geological structure of the working however, the water level is not uniform in the reservoir and the filling process is not homogeneous in time. Indeed, the available voids are made of a very complex multi-level network of galleries shafts and fractures separated by an assembling of different porous media (i.e. overburden layers, different extracted panels, faults and fissures) having various permeability. Thus, the mined area generally doesn't form a unique reservoir but a juxtaposition of different reservoirs-system having more or less good inter-connectivity.
In the case of the pilot experience in Heerlen for instance, the geological study (P. C. H. van Tongeren & B. Laenen 2005) has shown that the O.N. concession area is structurally separated into 4 reservoir parts. Although there are open links between each of these semi-individual O.N. mine parts (stone-drifts, galleries), in general, each (semi-)separated reservoir part nevertheless will largely react in its own specific way, if mine water extraction and / or injection actions are not carried out directly in, or very close to these connective pathways.

4. Temperature recovery

Once the reservoir is filled with water (end of the flooding), its temperature is different from the natural temperature that can be drawn from the geothermal gradient. This is caused by the fact that during the flooding period water flows in mush quicker than the natural flow through the porous media in different layers of the rock bead. Indeed, the greatest part of the water entering into the reservoir passes through the network of the interconnected shafts and galleries.
Thereby, a time period is needed before obtaining temperature equilibrium between the reservoir and the surrounding media. It is obvious that evaluating this time is an important issue for the geothermal use of the reservoir since water extracted can not have high thermal performance within this period.
A simple way to obtain a rough estimation of time needed for the temperature recovery is to consider a water filled horizontal parallelepiped gallery (h × b × l) white no flow inside it. We suppose that both water and surrounding rock have constant temperature. This hypothesis is valid in the case of a gallery with small height (h). The analytical solution of this problem can be written as:

$$T(x,y,z,t) = T(x,l,t)\,T(y,b,t)\,T(z,h,t) \tag{3}$$

$T(x,l,t)$ is the solution of the equation (4):

$$\kappa \frac{\partial^2 T}{\partial x^2} - \frac{\partial T}{\partial t} = 0 \tag{4}$$

Where κ is the thermal diffusivity of the water.

If ΔT_i is the initial difference of temperature between the water and the rock, the transient flow of heat will lead to reducing the temperature gap. Using Carslaw & Jaeger (1959) formulation, the solution of equation (4) can be written as:

$$\Delta T(x,l,t) = \frac{4\Delta T_i}{\pi} \sum_{n=0} \frac{(-1)^n}{2n+1} e^{-\kappa(2n+1)^2 \pi^2 t / 4l^2} \cos \frac{(2n+1)\pi x}{2l} \tag{5}$$

Thus, using (3) the temperature recovery for the horizontal parallelepiped gallery is obtained by:

$$\Delta T(x,y,z,t)=\frac{64\,\Delta T_i}{\pi^3}\sum_{n=0}\frac{(-1)^n}{2n+1}e^{-\kappa(2n+1)^2\pi^2t/4l^2}\cos\frac{(2n+1)\pi x}{2l}\sum_{n=0}\frac{(-1)^n}{2n+1}e^{-\kappa(2n+1)^2\pi^2t/4b^2}\cos\frac{(2n+1)\pi y}{2l}\sum_{n=0}\frac{(-1)^n}{2n+1}e^{-\kappa(2n+1)^2\pi^2t/4h^2}\cos\frac{(2n+1)\pi z}{2l} \tag{6}$$

To illustrate this case, we suppose $\Delta T_i = 40\ ^0C$. The water thermal diffusivity κ is about 1.510^{-7} m^2/sec and the dimensions of the gallery are: l = 1000 m, h = b = 5 m. Figure 2 shows the result of (6). Here the origin of the coordinates' system (x, y, z) is placed at the centre of the gallery.

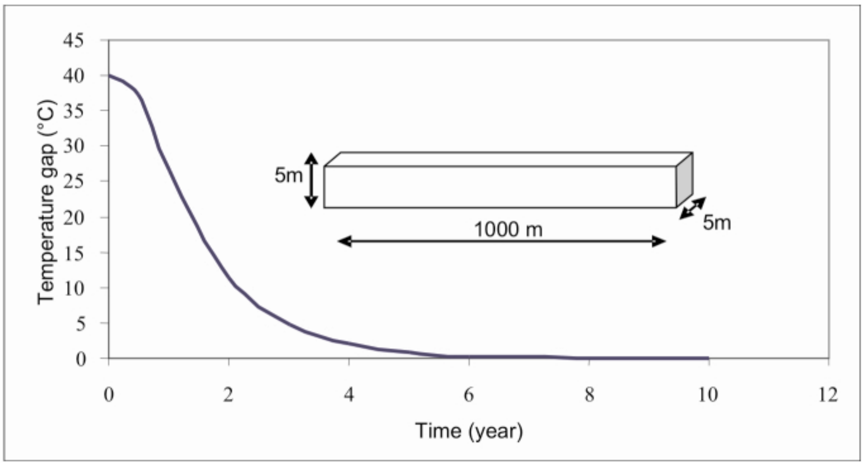

Figure 2. Diminution of the temperature gap between the rock and the water as a function of time.

According to the Figure 2, the water will reach the temperature equilibrium within 6 years. The time for temperature recovery could be even faster if convective thermal flow is considered inside the gallery.

5. Waste water

Re-injection of the waste water (cooled water) into the reservoir is the most usual process in the low enthalpy geothermal energy production. In the case of mine water the main objective of the re-injection is to dispose of the waste water, since it usually contains dissolved toxic minerals that prohibit pouring it into the natural streams. Re-injection of the waste water is also used to maintain the reservoir pressure and to enhance the energy recovery (Pruess and Bodvarsson, 1985).
Regardless of the objective however, the low temperature of the waste water is a serious constraint upon the re-injection (Home, 1982). Indeed re-injected water may move through the interconnected network of galleries to the production zones in a very short time. This rapid migration is undesirable, because it can produce thermal drawdown at the production wells. Thereby, it is important to identify these fast flow channels and choose the re-injection location in order to avoid rapid propagation of the cool front. Since the problem is basically site-dependant, tracer tests and numerical modelling taking into account the real geometry of the working must be carried out at the feasibility phase. Analytical approach can however gives primary information about the behaviour of the system.
Let us consider a one dimensional flow channel between the production and re-injection wells. The temperature change along the flow channel can be deduced from solution proposed by Bodvarsson, Pruess and Lippmann (1985), relations (7).

$$\begin{cases} T(t) = T_0 - \dfrac{q_i}{q_p}(T_0 - T_i)\left[1 - erf\left(\dfrac{\lambda\, x\, h}{C_{pw} q_i \sqrt{\kappa(t - \dfrac{x}{\beta})}}\right)\right] & if \quad t > \dfrac{x}{\beta} \\ T(t) = T_0 & if \quad t \le \dfrac{x}{\beta} \end{cases} \tag{7}$$

where: q_i and q_p - injection and the production flow rate (in case of total re-injection $q_i = q_p$), T_i - injection temperature, T_0 - reservoir initial temperature, λ - bulk thermal conductivity (Brailsford & Major 1964), h - height of the considered zone, and x - position along the channel axis.

(β) depends on the volumetric heat capacity (σ) of the material in the flow channel and is given by relation (8):

$$\beta = \frac{q\, C_{pw}}{\sigma\, h\, b}, \text{ where: } \sigma = \rho_w C_{pw}\, \Phi + \rho_s C_s (1 - \Phi) \tag{8}$$

The value of the porosity determines whether the channel is a gallery ($\Phi = 1$) or a working area ($0 < \Phi < 1$).

To illustrate the sensibility of the thermal drawdown to the flow path, let us consider a network of galleries of 20 km long with a section of 25 m^2 (5*5). The cool water is injected with a flow rate of $100 m^3/h$ at one end of the network at 20 ^0C and produced at the other end at the initial temperature of 50 ^0C. Figure 3 shows that the temperature at the production end will fall after only 100 days of production.

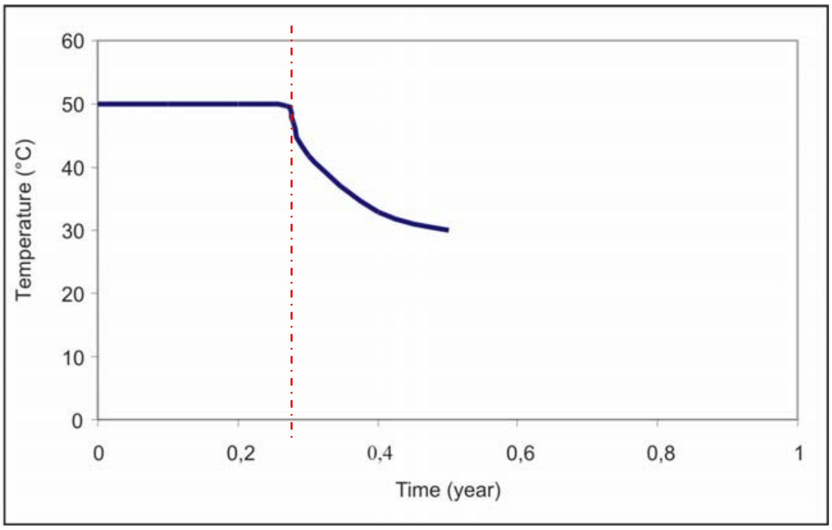

Figure 3. Temperature drawdown, the cold water flows only through the galleries' network

These simple calculations show the great importance of the injection zone that must be crucially chosen in an area without direct connection with the production well. Such zones could be an isolated gallery or a backfilled working area enough fare from the production well.

6. Heerlen pilot site

In the frame of the European INTERREG IIIB NWE Program a pilot site in Heerlen (The Netherlands) aims to demonstrate how an abandoned and flooded coal mine can be used as a safe and ecological way to heat and cool buildings. The concept is to use the flooded workings and void volumes of the coal mine as a thermal reservoir for large-scale, subsurface cold/heat storage. Depending on seasonal demand, heat will be withdrawn from or transferred to the mine water by means of a heat pump, which will thereafter be re-injected.

The municipality of Heerlen is located directly above the Oranje Nassau coal mines, which were decommissioned in 1974 and flooded thereafter. Interconnected by a huge network of shafts and stone drifts, the four different mines form water reservoirs of approximately 11 million m^3 in total. The cold and warm water reservoirs have temperatures of approximately 14-18 ^{0}C and 25-30 ^{0}C, respectively. At the beginning of the project water production has been modelled using TOUGH 2 (P. C. H. Van Tongeren & B.Laenen (2005)) according to three different scenarios:

- In the first scenario, water was produced from one mined-out panel area. The necessary flow-rate has been fixed at 40 m^3/h. This reflects 1/5 of the initially requested warm water and represents the amount that a well should minimally produce. At filter-height, the minimum pressure has been kept at 70% of the initial hydrostatic pressure in order to avoid any risk of the rock-matrix collapse.

Calculation results have shown that the mined panel cannot produce the requested water-flow. The pressure quickly diminishes till the minimally acceptable value and the produced water-flow quickly dwindles down to zero.

- In the second scenario both production and injection of a similar amount of water has been considered. The mined-out panel areas are surrounded by an 'open' conduit system. The modelling started with a production of cold water during 100 days at 250 m depth, and the injection of warm water (35° C) with a flow of 40 m^3/h at 550 m depth (summertime situation). The situation was reversed in a second phase where warm water was produced from the lower parts and cooled water at 10° C was re-injected within the upper zones. During both phases production was controlled by the reservoir pressures. The modelling shows the largest part of the re-injected water to stay put within the -550 m level (fig. 4).

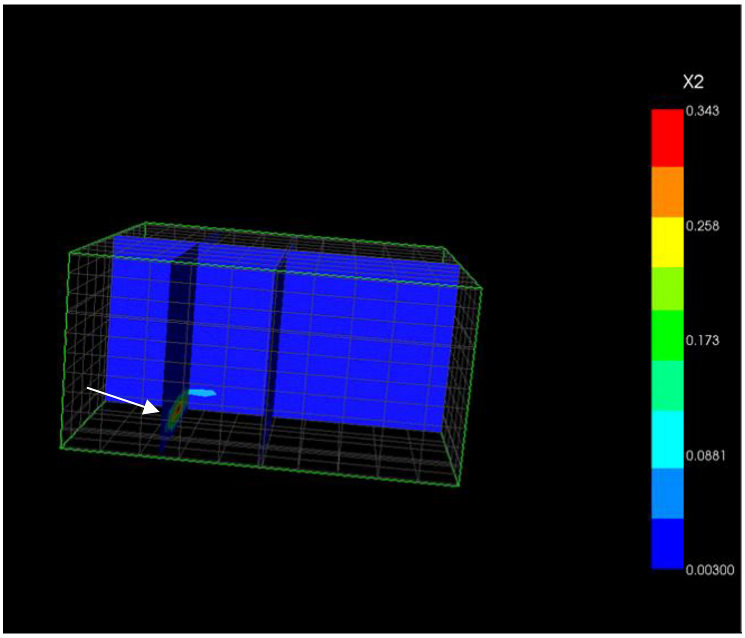

Figure 4. Spreading of the tracer (= X2) in the mine after about 30 days of injection into a work-out panel area at -550 m. Note that the largest tracer-part is still within the panel-area (see arrow).

The initial pressure within the injection-panel strongly rises while the pressure within the production-panel drops fast. This coincides with a decrease in the water production flow. Once a flow-contact is established with the adjoining gallery, a part of the re-injected water is quickly drained. From this time, both pressures increase. The pressure-course in both cells feeds the suspicion that both productivity and injectivity of the panels is too low to guarantee water-flows of 40 m^3/h. Water-flows of 15 m^3/h or less do not result in very strong pressure-courses and whenever 'pressure-communication' within the mine is established, these amounts of water-flow can be maintained sufficiently long as well. However, these water-flows are too low to be able to satisfy the requested demands of cold and warm water.

- In the third model the reservoir behaviour has been investigated for simultaneous water production from, and injection into open stone-drifts. The 'first phase' of this model started with a period of 100 days, during which cold water was pumped from a stone-drift at 250 m depth and warm water (35° C) was injected (40 m^3/h) into a stone-drift at 550 m depth. In the 'second phase' this situation has been reversed: production of warm water from the lower stone-drift, and re-injection of the cooled-down water into the upper one.

This third simulation showed an almost instant 'pressure-communication' between the injection- and the production cells. The injected water quickly fills-in the volume of the stone-drift into which it is injected (fig. 5). only a small part of the injected water penetrates into the mined panel areas surrounding these stone-drifts. Likewise, the water flow from these panel areas towards the stone-drifts remains limited too.

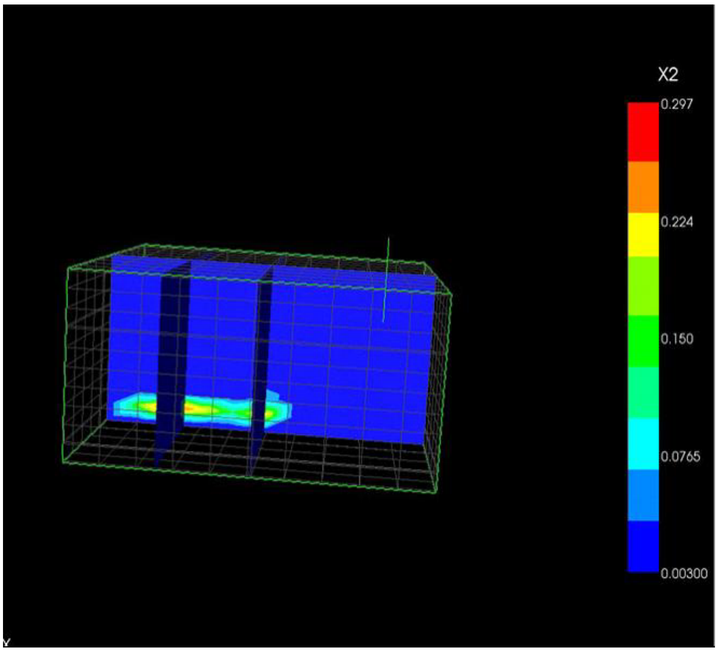

Figure5. Spreading of the tracer (= X2; injected warm water) into the mine after a period of 5 days.

In this model the shortest distance between the two wells is 1200 m. In this case, the temperature breakthrough occurs after 19 days. Figure 6 shows the evolution of the temperature at the production cell during the first phase (cold water production). This means that in an average stone-drift diameter of 14 m2, and with a requested water flow of about 250 m^3/h, the distance between the two wells should be in the order of 25 km if no quick temperature contamination is targeted. This would be far beyond the concession limits.

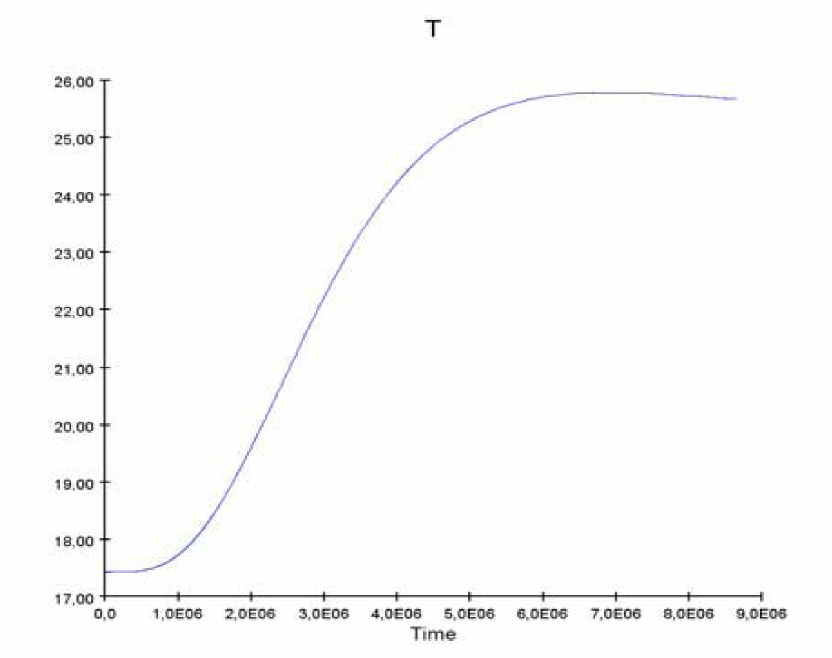

Figure 6. Evolution of the temperature at the production cell (cooling phase)

In the same way, sufficient production of warm water cannot be maintained longer than a couple of weeks within the required / anticipated temperature range.
In order to prevent the temperature degradation of the water, a ‘buffering zone of warm water’ has been considered. This consists in the production of cool mine-water in a shallow open stone-drift and the simultaneous injection of reheated cooling waters in a stone-drift near the bottom of a shaft.

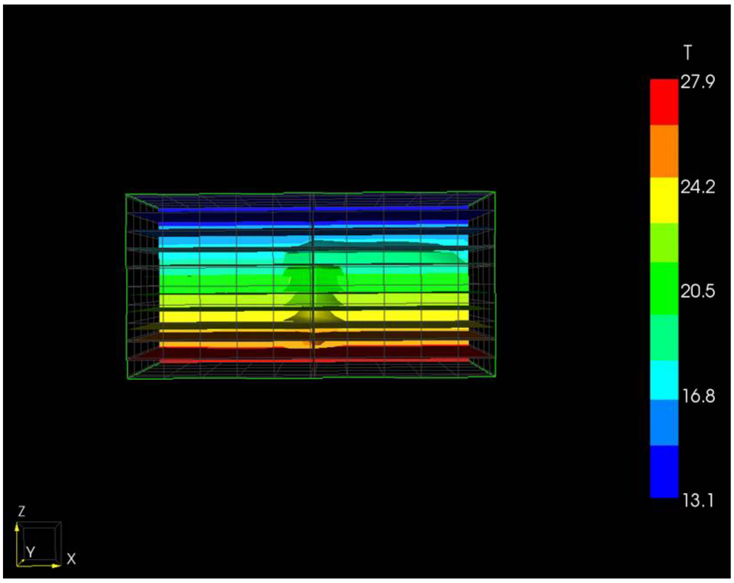

Figure 7. Build-up of temperature (T) around the shaft column after 100 days of warm water injection at - 550 m depth into a stone-drift simultaneously with the cold water production from a stone-drift at - 250 m.

The modelling has shown that the injected warm water will preferentially penetrate and occupy the areas next to the shaft and doing so, steadily will rise to shallower levels. Due to the different hydraulic behaviour between mined-out panel areas and open stone-drifts the injected water will slowly invade the mined-out panel areas. In the end, a kind of “Christmas-tree” configuration of warm water will be created in, and around the shaft column (fig. 7), that can act indeed as a ‘buffering zone’ at the production of sufficient amounts of warm water. In this scheme, the time to create such a ‘buffering zone’ will largely depend on the amount of cooling that takes place during the summertime. Whereas this amount has been anticipated to be energetically equal to the amount of warmth that is needed at the production of warm water, the additional geothermal warmth co-produced -however small - will swing the overall energy-balance in favour of the warm water production.

7. Energy concept in Heerlen

The redevelopment of a former mining area, including a large scale new building plan, is being realized with a low energy infrastructure for heating and cooling of buildings, using minewater of different temperature levels as sustainable source. The combination of low temperature emission systems with advanced ventilation technologies and integrated design of buildings and building services provide an excellent thermal comfort for 365 days a year, including sustainable heating and cooling and improved indoor air quality. This sustainable energy concept gives a reduction of primary energy and CO_2 of 50 % in comparison with a traditional concept (level 2005).
The minewater energy concept in Heerlen is in principle as follows: Minewater is extracted from four different wells with different temperature levels. In the concession of the former ON III mine, mining took place to a level of 800 m. In this concession the warm wells (~ 30 ^{0}C) can be found. In the former ON I mine, mining took place to a level of 400 m and here the cold wells are situated. The extracted minewater is transported by a primary energy grid to local energy stations. In these energy stations heat exchange takes place between the primary grid (wells to energy station) and the secondary grid (energy station to buildings). The secondary energy grid provides low temperature heating (35^{0}C – 45^{0}C) and high temperature cooling (16 -18 ^{0}C) supply and once combined return (20.-25^{0}C) to an intermediate well.

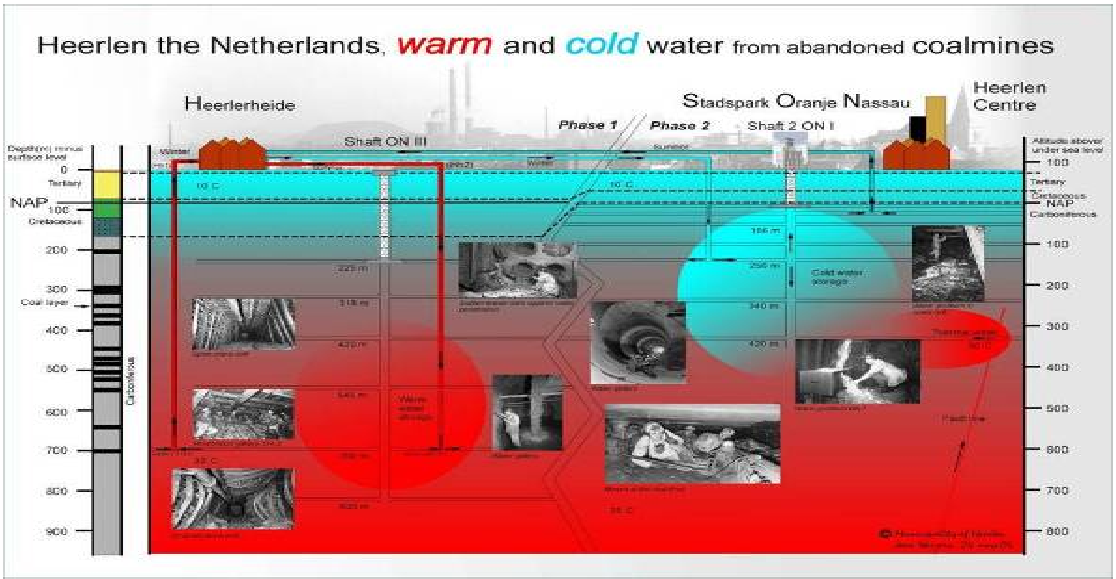

Figure 8. Schematic cross section of the underground conditions of the ON I and ON III mines

The five well locations and energy stations will be connected by three pipelines of 7 km each. Warm water is transported from the warm wells at the north and cold water is transported from the shallow wells at the southern region to the energy stations. Return water of 20-25 ^{0}C is transported to an intermediate well (450m). The temperature levels of the heating and cooling supply are “guarded” in the local energy stations by a poly-generation concept of electric heat pumps in combination with gas fired high-efficiency boilers. The surplus of heat in buildings (for example, in summer, cooling, process heat) which can not be used directly in the local energy stations can be lead back to the minewater volumes for storage. Domestic hot water (DHW) is prepared in local sub-energy stations in the buildings by heat pumps, small scale compression heat pump (CHP) or condensing gas boiler, depending on type of building and specific energy profile.

8. Conclusion

Flooded underground mines are enhanced low-enthalpy geothermal energy extraction potential since a deep underground mine has the essential elements to form an effective geothermal reservoir. These elements are water, heat and high porosity due to excavations. The network of shafts and galleries can be used to recover mine water at elevated pumping rates and heat exchangers can be associated to heat pumps to extract the energy needed for many industrial processes as for instance the district heating. Mine water is therefore a source of renewable energy that can contribute to the reduction of green-house gases emissions. The optimal use of this significant resource however, must be preceded by appropriate studies since the structure of the reservoir is highly complex and very site-dependant. In particular, finding suitable location for geothermal water extraction and waste water re-injection has crucial importance and must seriously be investigated regarding the sensitivity of the system to the thermal drawdown.
If appropriate cares are taken during the design phase, the use of the mine water geothermal energy can bring substantial economic and environmental outcomes. In this frame the development of the live pilot site in Heerlen and its success testify that the mine water can provide a focus for sustainable regeneration of former mining areas, improving self-image, health and economy for local communities.

9. Acknowledgements

The authors gratefully acknowledge the financial support of the European Commission to the Minewater project.

10. References

Bodvarsson, G.S., Pruess, K. and Lippmann, M. (1985). *Injection and Energy Recovery in Fractured Geothermal Reservoirs*, Soc. Pet. Eng. J., 25 (2), 303-312. LBL-15344.

Brailsford, A.D, Major, K.G. (1964). *The thermal conductivity of aggregates of several phases, including porous material*. Br J Appl Phys 15:313–319.

Carslaw, H.& Jaeger, J.C.(1959). *Conduction of Heat in Solids*, Oxford University Press, 2nd Ed.

Home, R,N. (1982). *Gothermal reinjection experience in Japan,* J. Pet. Tech (march 1982).

Proust, A. (1964). *Etude sur les Affaissements Miniers dans le Bassin du Nord et du Pas-de Calais*, Douai, juin

Pruess, K., and Bodvarsson, G.S. (1985). *Thermal effects of reinjection in geothermal reservoirs with major vertical fractures*, J. Pet. Tech., 36 (10), 1567-1578. LBL-16269.

Van Tongeren P. C. H , Laenen B. (2005) *Selected well-site locations in the first phase of the minewater-project of the city Heerlen, the Netherlands*, limited distribution**.**