The geothermal potential of Swiss alpine tunnels
Forecast and valorization

Jules Wilhelm[1] and Ladislaus Rybach[2,3]

[1]*Consulting Engineer, Chemin du Fau-blanc 26, 1009 CH-Pully, Switzerland ;*
e-mail : jules.wilhelm@bluewin.ch
[2]*Institute of Geophysics ETH Zurich, Switzerland ;* [3]*Geowatt AG, Dohlenweg 28, CH-8050 Zurich, Switzerland ; e-mail : rybach@geowatt.ch*

ABSTRACT
A survey conducted by the Swiss Federal Office of Energy in the middle of the 90's proved that a significant number of existing tunnels, with an estimated total heat potential of 30 MWth, is suitable to further development. Currently five sites in the Alps utilise available tunnel water for space heating and production of sanitary warm water and five more are going to do so in the next future.
An additional 30 MWth of geothermal energy is estimated to be available at the portals of the two important alpine tunnels under construction, with lengths of 35 km (Lotschberg) and 57 km (Gotthard). Approximately additional 35 MWth are expected from planned tunnels during the next ten years. Thus, nearly 80 MWth will be disponible in 2012-2014.
The available geothermal potential of future tunnels can be evaluated in reducing the theoretical potential by the cooling effects and the expected limitations of the water inflow rate during and after construction.
Advanced computational methods and practical tools for potential assessment have been developed to give realistic values for the early planning of portal-near heating systems.
Careful planning and steady cooperation between tunnel management and heat consumers contribute to optimize the valorization of this interesting form of geothermal energy.

INTRODUCTION
Groundwater drained by deep tunnels, where the rock temperature can be as high as 30-40°C or even more, is suitable to be used for heating of nearby buldings or agricultural developments (Fig. 1).

For more than 150 years, around 1200 tunnels with a total length in excess of 1600 km have been built in Switzerland and currently a further 170 km are under construction. Temperature and inflow of tunnel water reaching the portals of some of them gave incentives many years ago to utilize this geothermal potential locally for heating purposes. Examples of thermal utilisation of tunnel water exist for more than twenty years [8].

Figure 1 Water inflow in a tunnel (courtesy Matrans)

GEOTHERMAL POTENTIAL OF SWISS TUNNELS
In the framework of the programm "Energy 2000", the Federal office of energy initiated in 1995 a study in order to determine the overall geothermal potential of the Swiss tunnels and galleries, including some adits [2]. As a result, 13 tunnels were selected out of more than 600 for further investigations and possible realisation. The tunnels with geothermal potential

are listed in Table 1, along with their main characteristics. The calculated heat potential amounts to a total of about 30 MWth. Two of the tunnels were already in service before 1995, three more were realised since than.

Table 1. The geothermal potential of some Swiss Alpine tunnels

Name	Canton	Type of tunnel	Water discharge [l/min]	Temperature of water [°C]	Heating capacity [kWth] (1)
Ascona	TI	Road	360	12	150
Furka (2)	VS	Railway	5400	16	3'758
Frutigen	BE	Investigation tunnel	800	17	612
Gotthard (2)	TI	Road (N2)	7200	15	4'510
Grenchenberg (South portal)	SO	Railway	18000	10	11'693
Hauenstein (Base tunnel)	SO	Railway	2500	19	2'262
Isla Bella	GR	Road	800	15	501
Lotschberg	VS	Railway	731	12	305
Mappo-Morettina (2)	TI	Road	983	16	684
Mauvoisin	VS	Investigation tunnel	600	20	584
Polmengo	TI	Investigation adit	600	20	584
Rawyl	VS	Investigation adit	1200	24	1'503
Ricken (2)	SG	Railway	1200	12	501
Simplon (Portal Brigue)	VS	Railway	1380	13	672
Vereina	GR	Railway	2100	17	1'608
				Total	**29'927**

(1) Potential at the portal of the tunnel, without heat pump, cooling to 6°C
(2) Operating

Presently six installations utilizing the geothermal potential of tunnels are in operation. Five of them, working with the thermal potential of the tunnel water, are listed in Table 1. In the sixth one, the Grand St. Bernard road tunnel, the heat is extracted from the air circulating inside the tunnel. Three of these installations will be described below, the case of the Furka Railway tunnel with more details.

The St. Gotthard highway tunnel

Since 1979, the buildings of the highway maintenance centre located at the south portal of the St. Gotthard highway tunnel, in the nearby of the locality of Airolo, are heated and cooled by geothermal energy, provided by the tunnel water discharged at a rate of 6700 l/min. The temperature of the water is 17°C, and is almost constant over the year. In cooling the water by 2.3°C, the heat pump delivers a thermal power of 1860 kW.

This installation is subject to extension up to an additional 4000 kW, by increased cooling of the tunnel water. Additional consumers are located at Airolo, where the water should be transported by a 400 to 500 m. long pipeline. Studies are underway to check the economic feasibility of this extension.

The Ricken railway tunnel

The south portal of this tunnel is located near the village of Kaltbrunn. Tunnel water flows out at the portal at a rate of 690 l/sec and a temperature of 12°C. This potential allows a multipurpose hall, a sport centre, a civil defence centre and a kindergarten, to be heated by the means of a heat pump, since 1998. Installed thermal capacity is 156 kW, and 28 tons of heating oil is saved annually.

The case of the Furka railway tunnel

This tunnel of a length of 16 km is located under the pass of the same name, between the localities of Reap, at the east, and Oberwald, at the west, in the canton of Wallis. Since the end of its construction, in 1982, underground water flows out at the west portal at 5400 l/min and a temperature of 16°C (Fig. 2). This represents a thermal power of 3'600 kWth, when cooled to 6°C.

Topographic conditions permit to conduct the tunnel water by gravity to the centre of the locality, by a 1'200 m. length pipeline disposed in a common trench with other utility pipes at the time of their construction, in 1990. These two factors represent a significant reduction of the investment cost of the project [6].
By 2002, a sport centre and 15 family and apartment houses were heated by the geothermal energy of the tunnel water (Table 2). Individual installed capacity varies between 8.80 and 200 kWth, totalizing 942.20 kWth.

Figure 2 Appartment houses in the village of Oberwald heated by the water of the Furka tunnel. The total heating potential of the tunnel water amounts to 3 MWth (90 l/sec at 16°C) (photo J. Wilhelm)

Table 2. Heating with tunnel water at Oberwald (status by the end of 2001)

Building	Number of apartments	Year of construction	Heating capacity kWth	Heating system
1	1	1965	10.50	ext. radiator
2	14	1992	42.00	floor
3	12	1992	32.00	floor
4	32	1993	155.00	floor + warm water
5	8	1993	32.20	floor
6	20	1994	108.00	floor
7	12	1994	43.00	floor
8	Sport centre	1995	200.00	heating + ventilation
9	19	1995	108.00	floor
10	11	1995	51.00	floor
11	2	1996	33.00	ext. radiator
12	5	1996	22.50	floor
13	2	1996	13.20	floor
14	22	1999	76.00	floor
15	11	2000	50.00	floor
16	1	2000	8.80	floor
		Total :	**942.20**	

Comparative studies showed that the optimal layout consists in a decentralised distribution system delivering the tunnel water directly to the consumer's heating installation equipped by individual heat pumps ("cold district heating"). According to recent measurements, the mean seasonal performance factor of the installations is about 4.0.
Investment cost of the distribution system was SFr. 750'000.00. Each consumer pays a unique connection fee of SFr. 1'200.00 per kW of installed compression power. Price of water consumption is SFr. 0.15 per m^3. The point of return of the investment will be reached at an installed heating capacity of 1200 kWth.
Measurements were conducted between 1993 and 1996 to determine the effective heating performance and the costs of the energy of one of the individual heating unit (Kristall house). Table 3 shows the characteristics of this installation.

Table 3. Kristall house - Main data

Year of construction		1992
Heating capacity	kWth	42.00
Compressor capacity	kWth	12.0
Water consumption (theoretical)	l/min	46.00
Connection fee	SFr.	14'400.00

The cost of the energy for heating resulting during the three years of observation is listed in the Table 4.

Table 4. Cost of the energy for the consumer at Kristall House

Heating Period	Energy for heating [kWh]	Expenses for operation [SFr.] Tunnel water	Electricity	Maintenance	Total	Specific cost of the energy [SFr/kWth]
1993-94	52'690	1'181.40	2'622.70	0.00	3'804.10	0.0722
1994-95	56'724	844.40	2'874.50	226.35	3'945.25	0.0696
1995-96	50'435	631.20	2'329.20	452.65	3'413.05	0.0677

The above prices don't include the investment for the heat pump. However, as stated by the owner of the Kristall House, the related expenses are in balance with those of an oil tank and chimney as well as the room they need.

The consumer's price of the kWh of heat is below SFr. 0.07, which is a little bit higher than by heating with oil. This will be the case for all alternative energies as long as the price of oil remains under SFr. 40.00-45.00/100 kg. Presently this price varies between SFr. 35.00 and 40.00. It is commonly admitted that the preservation of the environment, above all of tourist regions in the Alps like Oberwald, justifies this difference. Furthermore one can expect that forthcoming improvement of the system will lead to a direct economic balance between tunnel water and oil heating.

PLANNING OF FUTURE PROJECTS

The useful geothermal potential of existing tunnels, as shown above, is well known when planning the consumer's network. In the case of future tunnels, projected or under construction, this potential has to be estimated, taking into account several geological and construction parameters. Such estimate is necessary for the planning of the distribution network, and to prepare the consumers to be connected to the network as soon as possible after the potential is available. As the construction of a large tunnel lasts up to ten years and even more, time is there to set up simultaneously the technical and administrative measures, such as regulations, organization, contracting, planning, including preliminary and preparatory works, the duration of which varies between 3 and 5 years [9]. Moreover, coordination between the tunnelling organisation and the authority in charge of the valorisation of the geothermal potential permit to optimize the works, generally with benefits to the two parties. For example, the owner of the tunnel to be constructed could take advantage of the cooling of the tunnel water, when limitation of its temperature before rejecting into an external water system, is required. Also the drainage system can be arranged to improve the heat transfer conditions along and outside the tunnel. By coordinated planning, these measures can be realized at reasonable cost and for mutual benefit [4].

The way to estimate the useful geothermal potential of future tunnels, e.g. the theoretical potential reduced due to the decrease of the water discharge and temperature, is described below.

The initial geothermal potential

The temperature of the rock mass and the outflow rate of the tunnel water depend of the geological, hydrological, geothermal and topographical conditions of the site. They can be prognosticated by advanced modelling, like the three dimensional numerical model developed for the Gotthard Base tunnel by the Research Group of Radiometry and Geothermics of the Swiss Federal Institute of Technology [ETH] in Zurich. The diagram of figure 3 shows the forecasted rock temperature in the axis of the tunnel [3]. In-situ temperature measurements performed in some excavated sections of the tunnel adits and shafts, marked by dots on the diagram, prove the accuracy of the forecast.

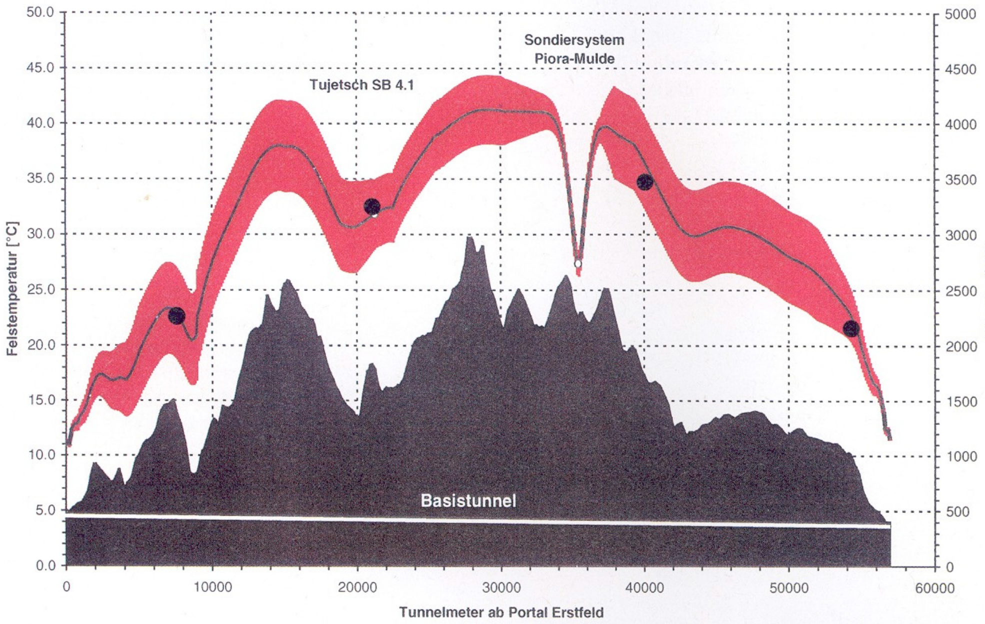

Figure 3 Comparison of calculated to measured temperatures in the Gotthard Base Tunnel [3]. Forecast : black line. Field of uncertainty : red. Black dots : rock temperatures measured in the axis of the tunnel.

To determine the location and the excepted discharge rate of the underground water in the tunnel, a numerical method based on the same program that for the temperature forecast has been prepared. This three dimensional model is conceptually based on a hydro geological model, the lithological units of the underground being characterized by their hydraulic conductivity, determined through in situ investigations. As for the temperature, measurements on existing tunnels, like the Koralm Tunnel in Austria, proved the good correlation between calculated and in situ values [5].
For energetic valorisation, the heating power of the tunnel water is calculated as follows :

$$P\,[\mathrm{MWth}] = C \cdot Q \cdot \Delta T$$

were C is the specific heat capacity of the water ($4{,}18 \cdot 10^3$ J/l · °K), Q is the water discharge (l/sec), and ΔT is the useful temperature (T – To). T is the temperature of the tunnel water, To is the temperature of reference, i.e. the temperature of the water after heat extraction.
In general, the temperature of the tunnel water is the same as that of the rock. The water discharge can either be calculated, as indicated before, or estimated from hydrogeologic data. The heating power of the tunnel water at the portal is the sum of the partial powers of n sections of equal lengths. Shorter sections will be selected when the discharge is high.

The useful potential
To obtain the effective geothermal potential at the portal of a future tunnel the initial geothermal potential has to be corrected by some physical and/or time dependent effects, reducing either the discharge or the temperature of the water.
The water *discharge* could be subject to the following limitations :
- limitation due to environmental constraints
- reduction for the execution, by technical measures during tunnelling
- natural decrease of the water discharge

The *temperature* of the water will be affected by the natural cooling of the rock mass around the tunnel and by the way the water will be evacuated inside and along the tunnel, e.g. the arrangement of the drainage system.

Limitations of the water discharge

Reductions of the water discharge for environmental purposes are often necessary to preserve the natural underground reservoir or to limit the heat rejected into a nearby river, in order to avoid the temperature to exceed a critical value influencing the biological equilibrium of the river fauna and flora. These limitations are generally decided before the beginning of the tunnel construction, and the corresponding measures form part of the method of execution of the tunnel. Thus, one can estimate the corresponding reduction of the water inflow.

Additional reductions of the water inflow could occur to ensure the technical feasibility and the security of the construction. When crossing geologically uncertain sections, advanced boreholes permit to detect the presence of underground water, and subsequently create a watertight cylinder around the tunnel profile by grouting. Such measures are currently decided during the tunnelling work, so their effect on the water discharge can not be determined before crossing the corresponding sections. On the other hand, their efficiency is very difficult to control. For example in the two main karstified zones of the Lotschberg base tunnel, such measures led to a drastically reduction of the forecasted underground water inflow from 100-200 l/sec to a few l/sec. Despite of these uncertainties, the remaining water discharge after drainage and sealing work must be properly estimated, in cooperation with the tunnelling organisation, as early as possible, because it represents the more important factor of reduction of the thermal power, which could even influence it by an order of magnitude.

The natural decrease of the water discharge can be correctly predicted using modern simulation tools and on the basis of the longterm observations in old tunnels.

Limitations of the temperature of the water

Like for the water discharge, simulation models and observations are suitable as well to estimate the natural cooling of the rock mass around the tunnel, which affects the temperature of the underground water. For example, long term observation in the Simplon tunnel shows that in that given conditions, the temperature dropped drastically during the first three years after construction, and during the following century the mean cooling rate was as low as 0,04-0,05°C per year [7].

The second factor influencing its temperature is the way the underground water is collected and conducted up to the portal of the tunnel. The general layout and the material of the drainage system, including thermal isolation, the rate of discharge of the water, the temperature inside the tunnel are factors influencing the temperature of the drained tunnel water.

The cooling of water flowing in a buried pipe can be calculated by the following formula :

$$T(L) = To + (To + Te) \exp[-(K/QC) \cdot L]$$

where	L	:	length of the pipe
	To	:	temperature of the water at the beginning of the pipe
	T(L)	:	temperature of the water at the end of the pipe
	Te	:	temperature in the tunnel
	Q	:	water discharge (l/sec)
	K	:	heat transfer coefficient (W/mK)
	C	:	specific thermal capacity of the water = $4{,}18 \cdot 10^3$ (J/l · °K)

As an example, water of 35°C at a discharge of 50 l/sec, flowing in a 70 cm diameter cement pipe, buried at 50 cm on the top, will be cooled by 5°C over a distance of 20 km, when the

temperature in the tunnel is 25°C. The same is limited to 1°C with a Flumrock isolation of 5 cm.
This is another demonstration of the importance of a close and early collaboration between the tunnel builder and the team in charge of the tunnel water heating system.
In conclusion, it can be stated that the most important parameter influencing the forecast of the useful thermal potential of future tunnels and also the most uncertain one, is the reduction of the tunnel water discharge during tunnelling, which depends of the method of execution of the tunnel. It can roughly be estimated before the tunnelling work begins, and must be precised by a step by step approach, following the development of the construction of the tunnel.

THE BASE TUNNELS OF THE ALPTRANSIT PROJECT

Introduction

The base tunnels of St. Gotthard and Lötschberg form part of the Swiss AlpTransit project, dedicated to provide high-speed railway link at low altitude between the north of Europe and Italy. The underground conditions of both tunnels are expected to be suitable for the valorisation of their geothermal potential for heating purposes at the immediate vicinity of the four main portals, Frutigen and Steg at the Lotschberg, and Erstfeld and Biasca at the Gotthard Base Tunnel [11].

The Lötschberg Base Tunnel

The 34,6 km long Lotschberg Base Tunnel leads southward from Frutigen, in the Kandertal Valley, to Raron, in the Rhone Valley. When completed, it will constitute two single-track tubes, but in the first phase, scheduled to be in service in 2006, only one of the tubes will be operational on one third of the total length. In the northern 13 km, the tunnel passes through a succession of various, heavily folded sedimentary layers of the Wildhorn and the Doldenhorn nappes, as well as Flysch and a Taveyannaz series. Toward the south the Aar massif, mainly granitic rock formation, and the autochthonous sedimentary shell had to be crossed [11].
Peak temperature of the rock of about 40°C was expected. The actual temperature will be probably 5 to 10% lower. Groundwater outflows of many hundreds of l/sec were anticipated at many places, particularly in the Doldenhorn section. Here, more than one hundred years ago, during the construction of the first Lotschberg tunnel, unexpected groundwater outflow carrying soil and rock debris buried several hundreds meters of tunnel and 23 miners died. To prevent such accident, extensive investigations were carried out for the present tunnel, and reconnaissance boreholes are drilled sequentially during construction before crossing karstified water bearing sections. All identified zones have been successfully sealed by cement grouting before crossing them. The decision to seal the tunnels was also taken for environmental reasons, as mentioned before, in order to preserve the natural underground reservoir of the Kander Valley, and to protect the biotop of the Kander River in limiting its heating by the warm underground water drained by the tunnel [10].
As a consequence, the discharge rate of the tunnel water at Frutigen will be limited to about 80 l/sec, and to 60 l/sec at the south portal. With expected water temperature of 19-20°C at Frutigen, and 20-22°C at Raron, the heat potentials will be between 3,5 and 4,0 MW at each portal. A feasibility study currently in progress will determine the potential of consumption after 2006. This potential will be utilised for heating of apartment houses and industrial buildings, and for a significant tropical and fish farming project at Frutigen.
In 1995, the natural geothermal potential, without limitation of the water outflow by grouting, was estimated respectively at 12 and 8 MW [8].

The Gotthard Base Tunnel

The 57 km long Gotthard Base Tunnel is located between the locality of Erstfeld, in the canton of Uri, and Bodio, in the canton of Tessin. It will cross the Aar and Gotthard massifs, which form the backbone of the Swiss Alps. They consist mainly of gneiss and granites. Between these massifs, sediments are compressed and at places considerably fragmented. As a result, the Gotthard tunnel must pass through a vast range of layers, from very hard Gotthard granite, through the high-stress permine gneiss of the Levantina, to the butter-soft rock of the Tavetsch intermediate massif [8].

The expected hydrogeological and geothermal conditions are variable as well, with underground water inflow ranging from a few l/sec to several hundreds of l/sec per kilometre of tunnel, and rock temperature reaching 45°C.

Excavation work at the Gotthard tunnel main tubes only began in 2002. At present, initial geothermal potential in the range of 15-25 MWth is expected both at Erstfeld and Bodio. Like at the Lotschberg, these figures are subject to reduction depending of the result of the sealing works during construction. At present the useful potential is estimated to be approximately 10 MWth at each portal.

In the region of Altdorf-Erstfeld, heat consumers, mainly apartment houses and industry zones, are located in the nearby of the portal. In Tessin, the main consumers are those of the city of Biasca, 8 km away from the portal. The estimated potential of heat consumption is between 10 and 15 MW. During 2003 and 2004, coordinated studies will be prepared to determine the feasibility of the use of the tunnel water for heating and also for recreational purposes, taking into account a possible modification of the project at the north portal.

The realisation of the heating projects of the Gotthard will probably start by the end of the present decade.

AKNOWLEDGMENT

The authors thank the concerned authorities, the Swiss Federal Office of Transport and the Swiss Federal Office of Energy, as well as the Directions of the two AlpTransit Projects, for their support of the investigations described in this paper.

BIBLIOGRAPHY

1. Aerni, K., and al. (2002) : Gotthard-Basistunnel : Spezielle Aspekte und Stand der Arbeiten. TUNNEL 4/2002.
2. Geissmann, M. (2002) : Das Projekt Tunnelassernutzung AlpTransit und das Programme EnergieSchweiz. Proc. 13. SVG-SSG Symposium, Mitholz, 2002.
3. Keller, F. (2002) : Gotthard Basistunnel : Geologie zwischen Prognose und Befund. sia tec21
4. Gorhan, M. (2002) : Tunnelwassernutzung Basistunnels AlpTransit. Bedeutung eines koordiniertes Vorgehen. Proc. 13. SVG-SSG Symposium, Mitholz, 2002.
5. Graf, F., Kohl, T., Megel, T., Rybach, L., Fuchs, R., (2001) : Hydraulic-geothermal modelling of Koralm tunnel. Felsbau 19, 54-59.
6. Nanzer, K. (1999) : Warmwassernutzung aus dem Furkatunnel. Proc. 3. European Geothermal Conference, EGC 99, Basle, 1999.
7. Pahud, D., Vuataz, F.-D., Bianchetti, G. (1993) : Refroidissement de la roche dans le tunnel du Simplon. Modélisation par calcul analytique. IAS No 25, 1993.
8. Rybach, L., Wilhelm, J., (1995) : Poential and use of warm waters from deep Alpine tunnels. Proc. World Geothermal Congress 1995, Florence, Vol.3.
9. Rybach, L., Wilhelm, J. (2002) : Geothermische prognosen bei tiefliegenden Tunneln. Proc. 13. SVG-SSG Symposium, Mitholz, 2002.
10. Teuscher, P. (2002) : Lotschberg-Basistunnel. Stand der Arbeiten. Proc. 13. SVG-SSG Symposium, Mitholz, 2002.
11. Wilhelm, J. (2002) : Potentiel géothermique des tunnels de base d'Alptransit. OFEN, Berne, 2002.