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THE UNDERGROUND STORE FOR THERMAL ENERGY

STRESZCZENIE

Ciepło można gromadzić w wodach podziemnych wypełniających stare zroby kopalniane oraz w wodach stagnujących w skałach zbiornikowych. Jednak najbardziej efektywne może być gromadzenie ciepła w wodzie w sztucznych zbiornikach konstruowanych w kopalniach podziemnych, lub w dużych wyrobiskach odkrywkowych. Ciepło może być dostarczane lub odbierane za pomocą odwracalnych, lub wprost przez iniekcję albo wypompowywanie ciepłej wody.

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ABSTRACT

Heat can be stored in ground waters, which fill up old mining workspaces, and in aquifers of slow migrating waters. The most effective, however, would be use of especially constructed tank reservoirs inside existing mining openings either underground or in open pits. The delivery of heat to the store can be done with use of heat exchangers or by direct injection of hot water. Recovery of stored heat will be possible through heat exchangers operating in a reverse-circulation mode or, by direct pumping out of hot water from the store space.

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INTRODUCTION

Depending on certain location, underground reservoirs may have a form of vertical elongated, narrow dimension cylinders, while located inside boreholes of a large diameter, or in vertical shafts. Large dimension cylinders should be located in abandoned open-pits, coated on later with the confining dump material in follows of the pit re-cultivation process.

Effectiveness of heat storage - i.e. the heat-recovered to heat-stored ratio, will be limited due to hydraulic confines of reservoir and its thermal insulation. If, however, the heat to be stored is normally considered as a waste, and a damaging threat to the environment, then effectiveness of its storage is of less importance. Reducing of delivery of waste heat to open waters, and availability of heat energy when needed are the advantages important in a balance of gains and loses of the heat storing. The most intensive recovery of stored heat in yearly cycles would be mainly in winter, when local deficit arises in a heat energy supply. In shorter periods, intensive recovery will be related to needs of washing or laundering, in work-shifts e.g. for bathing. Irregular cycles of storing will apply for the specific industrial production - e.g. food processing.

Main sources of heat to be stored would be wastewaters from the desalination plants, cooling waters from industrial powerhouses, and solar heat either from special roof-panels or collected from street snowmelt installation working in summer in a reversed cycle. Special source of high temperature heat energy are oxidizing coalmine spoil heaps (Dybciak et al. 2000).

Pipelines delivering hot waters to and from heat store may resemble the existing common district heating pipeline system, but their length should be limited due to lower temperatures of transferred water.

At the Meeting on Mining and Geothermics held in the Center for Innovation in Gladbeck, Germany (2001), several presentations regarded the heat-storing concepts in coalmines. These were: Ulrich Northmeier's "Solarspeichen der Grubenbauten", Karl-Heitz Tetzlaff's "The better way to energy economy without emissions", Stanislaw Ostaficzuk's "Nutzung der Grubenwarme im oberschlesien Steinkohlebergbau" and Dietmar

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Sauer's "Geothermische Elektrizitaetsgewinnung". Obviously, storing hot water in coalmines has enormous prospects due to practical environmental and technical reasons.

POSSIBLE SOURCES OF HEAT TO BE DELIVERED INTO UNDERGROUND STORES

Any heat that water can carry on may be stored in a confined reservoir. Short cycles of storing and using heat appear more economic, than the long ones, because even efficient insulators do not prevent dissipation of heat energy. Therefore, stores designed for long cycles of collecting and using heat should be fed with cheap heat energy. The best solution is based on waste heat - extracted from cooling systems, from sun collectors or from burning out of unwanted disposals. Specific source of heat energy are oxidizing coalmine spoil heaps.

Waste heat from desalination plants: Coalmine waters are usually mineralized, so due to ecological reason must be re-injected back to their source, blended with fresh water prior to delivery to open water reservoirs or river, or, desalinated in industrial plants. Desalination plants (Heliasz & Ostaficzuk 2000) separate salts and water, which is almost distilled and well over 20 °C hot. That is, too hot for being let into lakes or rivers. In winter, can be utilized in domestic or space heating system; in summer, formally is considered a waste. Because of desalinating plants of coalmine-water, and coalmines are located close one to each other excess waste waters are suitable for underground storing in coalmines.

Cooling water from industrial power stations and electric power plants: Waste technological waters usually have temperature higher than 20 °C. These waters may provide heat energy for heat pumps, or can be dedicated to direct use in winter, when demand for heat energy arises e.g. in fish-farms or snow-melt systems. Underground stores for water of 15 to 25 °C would be especially effective, due to sustaining effect of geothermal heat flow. On the other hand, the stored heat capacity to reservoir capacity ratio would be rather small. For that reason, heat store for low temperature waters should be located within existing groundwater reservoir rocks or inside filled up coalmine spaces. Specially constructed tanks would be less uneconomic in storing waters of low temperature.

Heat from oxidizing coalmine heaps: Normally, new energy sources bear relatively high initial cost of investment. Lowering that cost could be possible throughout extensive adaptation of existing valor of coalmine. Then, the proposed innovation lies in a multi-stage use of coalmine heaps in a complex process of thermal utilization of coalmine facilities without costly investments. (The CO^2 intensive emission from oxidizing mining waste heaps can be chemically neutralized by changing it into gypsum or loam inside abandoned underground mining workings, or for feeding plants inside greenhouses and tents).

Insulating ability of coal-mine spoil material, especially after oxidation is very high due to highly porous structure of a heap, and a low conductivity of skeleton material composed of ashes, burned clay nodules, and slake. It has been practically confirmed: temperature inside a 65-year old heap was within a range of 95 °C. Heaps, in most cases, are covered with snow blanked in winter, while the inside-temperature of oxidizing heap exceeds 250 °C at the depth of 5 m (see Dybciak et al. 2000). Therefore, the temperature gradient is at least 50 °C/m, what demonstrates very poor thermal conductivity of coalmine wastes. Thus, heat flow escape from a heat store to be insulated by burned-out coalmine spoil, or installed inside a heap will be considerably small. Because of its good insulating properties coalmine spoil heap can be used for >100 °C heat stores. Pressurized water tanks may keep water up to 130 °C hot, therefore may take delivery of heat from efficient solar panels, and direct heat from oxidizing spoil heap with the necessary reduction of temperature. These heaps, which have burned out long time ago may bear cold liquid store as well.

Solar heat: Sun delivers 300 to 500 W/m^2 of recoverable thermal energy, but solar heat collectors are rather expensive. Thus, solar heat can be worth storing only from already existing installations. These could be:

- Heat collectors working in a reversed cycle as de-icing installations under pavements, street crossings, open-air car-parks;
- Solar panels collecting heat for short time use (e.g. for industrial bathrooms or technological processes).

Ice floe and return water from low-temperature heating installations for storing cold: Shallow underground stores can be successfully utilized also for storing cold. Demand for cold water arises in spring - for freezing of ice-skating stadiums and in summer - for air-conditioning. Ice floe or ice blocks cut off from frozen rivers can be saved till the next season if kept dry in underground stores.

HEAT STORE DESIGN

There are various possible designs of store with, generally, utilizing of natural confinement and insulating properties of rocks, or artificially constructed and coated, or kept underground in rocks confinement with artificial insulation:

1. A vertical cylinder in mineshaft containing water, or water and highly porous filler.
2. Adapted mining chambers with highly porous fill saturated with water.
3. Set of cylinder reservoirs sited in coalmine openings, or sunk-down into cold spoil heap, or topped-up with coalmine spoil.
4. Concrete or metal tank covered with and founded upon a layer of ashes and cinder inside an abandoned quarry or sandpit.

Table 1. Parameters of cylinder tanks
Tabela 1. Wymiary zbiorników cylindrycznych

Item *Nr*	Volume *Pojemność*	Diametre *Średnica*	Height/length *Wysokość//długość*	Confining surface *Powierzchnia ścian*	Elongation *Wydłużenie*	Ratio *Współczynnik*
No.	**V (m^3)**	**F (m)**	**L (m)**	**S (m^2)**	**L/F**	**S/V**
1*	1000	0,5	5102	8 000	10 204	8
2*	1000	1	1274	4 000	1 274	4
3*	1000	2	318	2000	159	2
4	1000	3	142	1340	47	1.34
5	1000	5	51	921	10	0.92
6	1000	6	35	724	5,9	0.74
7	1000	10	13	556	1.3	0.56
11*	10 000	3	1425	13 430	475	1.34
12	10 000	5	510	8020	102	0.8
13	10 000	6	354	6710	59	0.67
14	10 000	10	127	4145	12.7	0.41
15	10 000	15	56	2992	3.7	0.3
16	10 000	30	14	2732	0.47	0.27

*) Horizontal pipes

5. For storing cold water, confined, shallow lying reservoir rocks may be used. Stores for ice blocks may be sited inside shallow, dry underground openings coupled with cold-water store; melt-water from ice store should be continually transferred to the cold-water reservoir.

Facilities as listed in items 1, 2, and 3, are available within the vicinity of coalmines, normally subjected to re-cultivation.

Heat capacity of water-filled heat store depends on the volume and temperature interval of water, which is used as heat absorbent. One cubic meter of water contains 4.18 MJ of heat energy per 1 °C. Considering 50 °C as a working interval, one may store 209 MJ of heat energy inside each cubic meter of water in a heat store. This equals to a portion 10-hour outflow of heat from 30 m^2 of 200 W/m^2 solar panel surface.

In a small store, consisting a set of four cylinder-reservoirs, 25 m^3 each, as much as 20.9 GJ of heat may be kept, ready for immediate use.

The time-efficiency of storing heat will depend on reservoir insulation properties, outside temperature - i.e. temperature of confining massif walls, and the surface to volume ratio of reservoir (see Tabs. 1 & 2).

VERTICAL COALMINE SHAFT

Turning out the vertical mine shaft of cylinder shape into heat reservoir has considerable advantages. The most important is that it already exists. Due to its shape, and orientation, it is not subjected to breakouts or total collapse. With water reservoir inside, the confining stress will be practically counterbalanced. Unexpected leakage of warm water will make insignificant harm either to environment, or to abandoned coalmine. The 6 m in diameter, i.e. of 28 m^2 cross-section, the cylinder shaft may be utilized as a vertical store 360 m tall, of total capacity 10 000 m^3. The heat content at 50 °C temperature interval will be >2090 GJ.

By pumping out hot water at a rate of 100 m^3/h, the store may provide output power equal to 2 MWt throughout 100 hours; the total output of energy will be, however, diminished due to technological and efficiency factors. It is important property of vertical cylinder store that despite of drop of average temperature due to pumping out of hot water, the temperature of top part of water column remains close to its maximum. The old style bathroom boilers used to function that way.

MINING CHAMBERS

Deep mining chambers in abandoned coalmine are, with the passage of time, subjected to collapsing and flooding, For that reason, and in order to preventing terrain surface against damages, subsurface openings are artificially filled up with rock-debris, sand, mud-pulp or some wastes. There are practically three possible ways of storing and recovering heat from abandoned mining chambers.

1. Through pipe loops left inside fill material (usually, a kind of mud, composed of sands, coalmine spoil, occasionally - industrial waste), interconnected with the pipes on the surface.
2. Through open pipes either submerged in water, which fills up non-collapsed and unfilled section of mine, or cut throughout the confining wall, which cuts off abandoned mining section.
3. Through wells drilled from the surface down into abandoned coal mine.

SET OF PARALLEL CYLINDERS

For short time interval between storing and using of hot water, smaller tanks will be more economic. Old, used

Table 2. Heat conductivity and heat capacity media at 20 °C; insulating property ranking
Tabela 2. Przewodność i pojemność cieplna w t. 20 °C oraz ranking własności izolacyjnych

Medium *Materiał*	**Heat conductivity [W/m°C]** ***Przewodność cieplna***		**Heat capacity [kJ/kg°C]** ***Pojemność cieplna***		**Medium** *Materiał*
	Minimum	**Maximum**	**Minimum**	**Maximum**	**Ranking**
Ash	0.300	0.370	0.750	0.795	**Mineral fiber**
Asphalt	0.170	1.000	0.921		**Cinder**
Brick	0.116	1.233	0.795	1.047	**Peat**
Cinder	0.047	0.814	0.750	0.837	Timber
Clay	0.750	1.256	0.840	0.879	Brick
Concrete	0.128	1.512	0.779	0.837	Concrete
Granite	2.908	4.091	0.754	0.920	Asphalt
Gravel	0.800	0.930	0.840	1.842	Ash
Limestone	0.920	1.400	0.795	0.920	Sand
Mineral fiber	0.034	0.058	0.750		Clay
Peat	0.047	0.093	1.884		Gravel
Sand	0.326	1.884	0.712	0.840	Sandstone
Sandstone	0.814	2.400	0.712	0.920	Limestone
Shale	1.396	1.977	0.754		Shale
Timber	0.052	0.372	1.383	2.721	Granite

Table 3. Initial heat loss of cylinder tanks (average for the first 1°C drop)
Tabela 3.Początkowa ucieczka ciepła ze zbiorników cylindrycznych (średnia dla spadku temp. 1°C)

Item *L.p.*	Volume *Pojemność*	Height *Wysokość*	Diam. *Średnica*	Confining surface *Powierzchnia ścian*	S/V ratio *Wspólcz. S/V*	Heat *ciepło*	Heat-loss flow *Ucieczka ciepła*	Time to 1°C temp. drop *Czas spadku temp. o 1°C*	2% heat loss-time *czas 2% ubytku ciepła*
No.	V (m^3)	L (m)	F (m)	S (m^2)b		GJ	kJ/s	h	
1	1000	5102	0,5	8 000	8	209	400	3	
2	1000	1274	1	4 000	4	209	200	6	
3	1000	318	2	2000	2	209	100	12	
4	1000	142	3	1340	1.34	209	67	18	
5	1000	51	5	921	0.92	209	46.5	26	
6	1000	35	6	724	0.72	209	36.2	33.5	
7	1000	13	10	556	0.56	209	27.8	43.5	
11	10 000	1425	3	13 430	1.34	2090	671.5	18	
12	10 000	510	5	8020	0.8	2090	401	30	
13	10 000	354	6	6710	0.67	2090	335.5	36	
14	10 000	127	10	4145	0.41	2090	272.5	44	
15	10 000	56	15	2992	0.3	2090	196	62	
16	10 000	14	30	2732	0.27	2090	136.6	88	

tanks (e.g. from petrol station), or technological water tanks of several dozen cubic meters capacity each, parallel interconnected, may well suit the purpose. Also, for economic reason tanks may be additionally insulated with abundant coalmine spoil material, especially from burned-out heap. It has been found that in result of burning, the most of spoil turns out into a kind of cinder of highly insulating properties.

RESERVOIR TANK CONSTRUCTED INSIDE OPEN-CAST MINE PIT

Such could be the case of brown coal mining, where electric power station is located close to the pit. Waste hot water is usually in abundance there, and pit is obligatorily to be re-cultivated i.e. filled up with temporarily removed topping layers of the deposit. Locating reservoirs at the bottom to refilling of pit may have two advantages:

1. The reservoir will be operating for the long time, because of its safe location inside a refilled pit, and due to its close proximity to the source of hot water.
2. The missing volume of recovered resource will be compensated by reservoir tank, thus enabling complete filling of pit, and making the terrain surface flat.

Table 4. Heat flow drop through surrounding rocks 0.3 m out of the reservoir - in days (control calculations by Z. Malolepszy)
Tabela 4. Spadek strumienia cieplnego w skałach otaczających zbiornik cylindryczny - w odległości 0,3 m - dni (obliczenia kontrolne wykonał Z. Malolepszy)

Days/heatflow drop *Dzień/zanik strumienia ciepła*	**Initial**	**1.25**	**8.6**	**18.25**	**36.0**	**75.0**	**91**
$V_{10\,000\,m^3}$/6m; 37.0 °C: 80 °C const.	1	0.75	0.5	0.375	0.24	0.13	0.12

Table 5. Temperature drop with the passage of time due to heat dissipation through coating fill - in days (control calculations by Z. Malolepszy)
Tabela 5. Spadek temperatury pod wpływem wnikania ciepła w materiał otaczający zbiornik cylindryczny w kopalni odkrywkowej - dni (obliczenia kontrolne wykonał Z. Malolepszy)

Days/temperature drop °C *Dzień/spadek temperatury °C*	0	35	70	105	140	175
$V_{10\,000\,m^3}$/30m; 8.5 °C: 80 °C =>	0	0.93 °C	1.80 °C	2.59 °C	3.28 °C	3.95°C
$V_{10\,000\,m^3}$/30m; 8.5 °C: 50 °C =>	0	0.55 °C	1.02 °C	1.48 °C	1.93 °C	2.38 °C

INSULATING COAT

The dilemma regarding heat-loss from reservoir can be resolved on an economic basis. If the hot water is cheap, and available as a waste, then problem of insulation will be of less importance. If, on the other hand, stored water must retain its high temperature for a long period, then, the insulation of reservoir will be important. In the former case, insulation can be provided by confining rocks or, by mineral fill. In the latter - artificial insulation should be used by a combination with natural materials (see Tab. 2).

THERMAL EFFICIENCY OF A HEAT STORE

Calculations are made for initial heat flow in the Upper Silesia geological condition and for heat store inside pit within the Polish Lowlands, according to formula:

$$Q = k*P*dT$$

where:
- Q = initial heat flow [W] into confining walls of reservoir [P*m$^{2]}$;
- k = heat transfer coefficient [W/m^2 °C];
- P = total surface of confining walls [m^2];
- dT = initial temperature difference in- and outside of wall [°C];

The heat-loss through conductivity into confining rock walls in Silesia, coated with 5 cm of insulating substance (e.g. uretane) will initially reach 1W/m^2 °C. Thus, the temperature-drop will be controlled by water volume in reservoir, the confining wall surface (i.e. height to diameter ratio), and the temperature difference between stored water, and the confining walls.

With initial temperature difference 50 °C between water in a tank and surrounding rock, the initial heat loss, or temperature drop will be as presented in Tab. 3.

The escaping heat flow from the reservoir will be accumulated in surrounding rocks, and the temperature difference between hot water and the reservoir casing will be diminished accordingly (Tab. 4).

Escape of heat will result in temperature drop inside reservoir (Tab. 5). The slower heat escape the longer will be water kept warm inside reservoir tank. In practice, the maximum time allowed for storing heat will be a half to two-third of a year.

CONCLUSION

Natural geological conditions are favorable for subsurface location of heat reservoir tanks, and mining openings fit for that purpose. Moreover, using already existing mining shafts or giant pits has double advantage by elimination of excavating works, and reducing the necessary extent of recultivation of mining damages after mining activity cease.

According to thermal properties of surrounding rocks, each next cycle of storing and using heat will meet higher outside temperature. Thus, a unit heat flow through reservoir walls i.e. heat loss from reservoir will be further diminished. Underground stores will keep heat long enough for annual exploitation cycle, mostly for space heating; the short-term-use reservoirs may serve production needs in food and chemical industry.

With the passage of time, temperature of surrounding rocks will get closer to the temperature inside, thus the heatflow stream will be reduced (Tab. 4). Moreover, at lower temperatures of stored water, the drop of temperature inside reservoir will be compensated due to reversed heatflow from the rocks.

According to Tables 1 to 3, the most efficient are cylinder reservoirs 6 m in diameter located inside mineshafts. These will have better storing performance with more expensive maintenance and exploitation while deeper located. Smaller reservoirs are less efficient than bigger ones because of poor surface to volume ratio, what directly controls heat escape.

The most promising for storing heat in water of higher temperature would be stumpy cylinder reservoirs of large diameter located inside abandoned open-pit mines and insulated with cinder, coalmine spoil, and ashes (Tab. 5).

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