The long term storage of solar heat in the ground

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29. THE LONG TERM STORAGE OF SOLAR HEAT IN THE GROUND

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1. INTRODUCTION

The storage of solar heat from the summer for the winter obviously is a worthy objective. In the North West European climate, like in most climates, such seasonal storage would almost double the net heat gain from a solar collector, when used for heating purposes. Moreover seasonal storage would eventually eliminate the need for auxilliary heating and thus induce a substantial simplification and cost reduction in a solar heating installation.

A necessary condition for a succesfull seasonal storage is that the associated investments should be low. A rough limit for the acceptable investment can easily be established. For the calculation we have to consider the future prices of energy, because seasonal storage is an option for the future too.

For residential and commercial heating an energy carrier that might eventually replace the presently widely used natural gas is SNG. Cost estimates for SNG show that the price of SNG will amount to some two or three times the present price of natural gas. The rapid depletion of the natural gas fields may therefore be expected to lead to an increase of the gas price from the present Dfl 0.30/m^3 to about Dfl 0.75/m^3 of natural gas equivalent. This corresponds to a heat price of Dfl 0.10/kWh (0.04 US $) after correcting for the efficiency of a good central heating boiler ($\approx$ 80 %).

For a seasonal storage in the ground, as described below, the lifetime is similar to that of public gas or water mains, which is about 40 years. The maintenance of such a grid is only a low percentage of the investment. Also in the future economical situation, which will be a rather stable one with restricted growth, the interest rate will be low. Taken together these considerations lead to the conclusion that the annual costs of the storage will almost certainly not exceed 10 % of the investment, if the running costs (s.a. the power supplied to the pumps) are kept low by appropriate engineering.

Consequently a first, rough estimate of the acceptable investment is Dfl 1, – (0,4 US$) per kWh of the heat reclaimed by means of the seasonal storage as such.

Of course this value is only a first approximation. However, it enables one to make a first pre-selection between the systems for seasonal storage that may become economically viable in the long run, and those that will not.

2. PRE-SELECTION OF VIABLE SYSTEM(S)

Although seasonal storage in eutectic salts and by means of physical absorption on active substances have been proposed, the only systems in actual operation nowadays are three systems using large amounts of water. In the Philips Experimental House in Aachen a 40 m^3 steel container is applied for the purpose, in the Zero Energy House at Copenhagen a 30 m^3 steel container and in Frank Hooper's House in Canada a 240 m^3 concrete tank. Holland and Orgill [1] have investigated the investment in such containers. They conclude that a large concrete tank offers the cheapest solution for containing the water. For a well constructed and really large container the investment may be as low as Dfl 125,– (50 US$) per m^3. A simple calculation shows that the heat stored in water amounts to some 60 kWh/m^3 between the temperature limits of 80 °C and 25 °C. For several reasons these limits should be considered as the practicable ones. In seasonal storage the heat capacity of the storage medium is used only one time per year. So in this case the investment amounts to some Dfl. 2,–/kWh reclaimed. The costs exceed the criterion deduced by such an extent that there seems to be little hope for the economic viability of the scheme. From cost data taken from several Dutch solar heating experiments it appears that the investments for steel water containers lie in the range of Dfl 300,– to 500,– per m^3. The size of the container does not influence the costs in a systematic way. These costs rule out the steel containers immediately as a general solution for seasonal storage. For phase change materials and physical absorption systems the costs per unit of stored heat are equal to or higher than the costs for steel water containers. Exploratory calculations made in discussions between some Dutch experts have shown that invariably the cost reduction because of the reduction in volume tends to be surpassed by the increase of costs resulting from the high price of the storage medium.

Yet, by turning away the attention from technologically more advanced systems to technologically less advanced systems, the discussions have been very fruitfull.

3. SEASONAL STORAGE IN THE GROUND

For a well trained physicist it is an easy, though time-consuming task to write down the equations governing the unsteady heat transfer in a homogeneous, or even an inhomogeneous medium, to develop a computer code based on these equations, and to apply that code to the case of solar heat supplied to and extracted from a given amount of soil in a more less stochastic way. By repeating the calculations for some well selected different situations a reliable judgement can be given on the feasibility of the seasonal storage of solar heat in the ground. The results may also serve to establish a suitable lay-out of the storage and its efficiency. However, this physical approach itself is rather ill-suited for the selection of the situations that are worthy of the more elaborate calculations with a computer. The engineering approach, in which the influence of varying the main parameters is approximated in a simplified model, is more efficient for this purpose. As the engineering approach is the more instructive one for the objective of this paper, at least in first instance, this approach will be used to present the case of seasonal storage in the ground. Which means that first the results of some engineering calculations for a particular case will be presented. Thereafter some more general conclusions will be drawn from the results by application of the physical laws governing the heat transfer. The particular case concerns the seasonal storage of 750.000 kWh of heat in soft saturated soil, the storage serving the autonomous solar heating of the Town Office of Lelystad (The Netherlands) as designed by architect J. Kristinsson.

From both cost and physical considerations a suitable general layout for the storage proves to be the layout depicted in *fig 1.* The features of the layout are :

— the heat is stored in an appropriate volume of soil, having a more or less hemispherical shape,

— the heat is supplied to and extracted from the storage by means of pipes which may run vertical or inclined, whatever is to be preferred,

— in order to prevent excessive heat losses to the atmosphere a thick insulating cover is mounted on top of the storage.

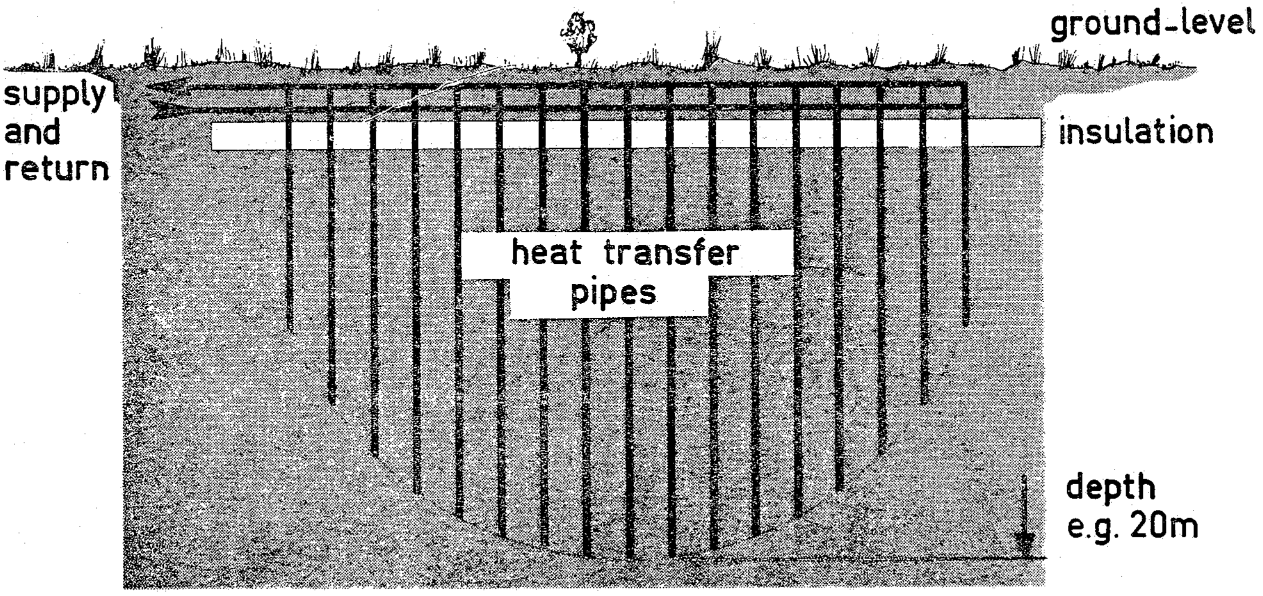

Fig. 1. — **General layout of the seasonal storage for the town office of Lelystad.**

Further data on the soil are (approximately, homogeneous)

thermal conductivity	1,5 W m^{-1} °C^{-1}
thermal capacity	1200 J kg^{-1}
density	1600 kg m^{-3}

The thermal resistance of the insulating sheet equals 10 m^2 °C W^{-1}.

Perhaps at this point it already should be remarked that the insertion of pipes in soft soil is fairly easily. By using a lance with a high velocity water jet at its tip a straight hole can be « drilled » into the ground to a depth of 20 m and more within about half an hour. This explains the preference for the application of the more or less vertical heat transfer pipes.

In *fig. 2* the simplified model of the storage is depicted which has been used to explore the performance of the storage and the influence of any deviations from the hemispherical shape. The storage is assumed to be a body of revolution and consists of a cylindrical central part, and a quarter of a torus surrounding the central part. The temperatures refer to the fully loaded condition. The temperature in the hot core (inside the dotted line c) is assumed to be uniformly 70 °C. In the shell the temperature gradient is assumed to be uniform and equal too (70 — 20) : 8 = 6,25 °C m^{-1}. The heat flow through the shell is approximated by forcing this temperature gradient on the area of the surface halfway between the inner and outer boundary of the shell.

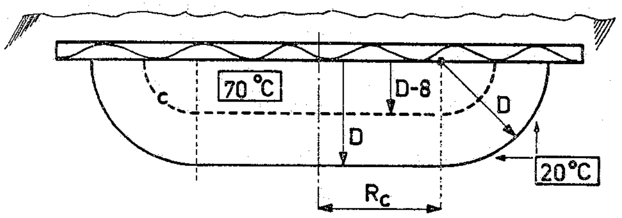

Fig. 2. — Simplified model of the seasonal storage.

The data and assumptions given above permit the calculation of dimensions of the storage (i.e. the combinations of Rc and D) that satisfy the condition that the heat content of the storage should be 750.000 kWh when the storage is fully loaded, and the heat flow through the shell in this situation. The average heat content of the storage is only about half the maximal heat content, and the same applies to the temperature gradient in the shell. So in order to calculate the heat losses for the full year half the maximum heat flow through the shell should be substituted. The calculations of the heat loss through the insulating sheet is straightforward. In *table 1* the results of some calculations are presented.

The last two colums of table 1 give the total length of the heat transfer pipes, and their number. These data were again obtained by an engineering type calculation of the temperature differences between the pipes and the soil. The criterion being that this temperature should not exceed 10 °C on the average, both when loading and emptying the storage. A larger temperature difference was considered to be undesirable because of the associated high outlet temperatures of the solar collectors. To take into account the effect of the fluctuations in both the supply and the extraction of the heat the « real » time available for the heat transfer was supposed to be equal to 1500 hrs per year, both for supply and extraction.

4. DISCUSSION OF THE RESULTS, ECONOMICS

From the results in *table 1* two points are immediately clear.

— A restricted deviation from the ideal, hemispherical shape of the storage does not introduce a significant decrease in its thermal performance ; this goes to a breadth/depth ratio of about 3.

— The thermal efficiency of a seasonal storage of the stated capacity is fairly high, being in the order of magnitude of 75 %.

The main physical limitation to the validity of this conclusion is that the influence of any groundwater flow has not been accounted for.

On the site where the storage will eventually be built, this neglect is justified. The soil contains much clay and is almost impermeable. Moreover the horizontal pressure gradient is virtually zero, because the site is situated in an Ijsselmeer polder, surrounded by canals on all sides. Obviously sloping land and permeable soil, like sand and peat offer completely different situations. Blocking the ground water flow by, e.g., injecting clay might be considered in such cases.

Another limitation, which is not obvious from the foregoing is that the pipes should be positioned almost completely below the ground water level. In soil which is not saturated the repeated heating and cooling of a pipe easily creates an air gap between the pipe and the soil. Also a dry region around a warm pipe may develop. Both effects result in a considerable increase in the heat transfer resistance. Longitudinal fins on the outside of the pipes can lighten these problems to a certain extent.

Cost estimates have shown that the economic prospects of the described ground storage are fair. The investments are assessed to about Dfl 1. million

TABLE 1. — Characteristics of the seasonal storage for various shapes.

DEPTH D	RAD. CYL. Rc	HEAT LOSS	EFFIC.	LENGTH PIPES	NUMBER O. PIPES
27	0	175.000	76,5	23,500	1315
25	2.7	177.700	76,3	23,800	1380
20	9.8	188.600	74,8	24,000	1590
15	18.4	218.000	70,9	24,900	2000
10	31.7	315.000	58,0	28,200	3120
m	m	kWh/yr	%	m	—

(400.000 US $) for a first prototype. Further optimization of design is expected to permit a substantial reduction of these costs. Mainly by reducing the labour cost for the fitting at the top ends of the pipes. A double connection has to be made here, because the pipes contain an inner return pipe (originating at the bottom end of the pipes). Preliminary estimates show that the criterion deduced before will probably be met.

The storage may be positioned either underneath or alongside the building it has to serve. The environmental impact of the storage is small and has a transitory character.

5. SOME GENERAL ASPECTS

Inspection of the data of *table 1* shows that the schematic temperature distribution is close to the temperature distribution that would establish itself in a natural way when the heating of the storage is concentrated in the core, with some additional heating in the shell. This way of heating is obtained automatically when inside the pipes the downward velocity of the hot water (from the collectors) is kept at a very low value. A simple calculation proves that this requirement can be easily brought into agreement with the volume flow required for the collector area ($\approx$ 2500 m^2) which is required for the heat demand of the Town Office.

From this harmony between collector area, storage capacity, way of heating and temperature distribution in the storage it follows that the main effects of changing the capacity of the storage can be deduced from a linear transformation of all its dimensions, at least in first approximation (the main restriction being that there may be practical upper limits to the depth of the storage). This approach leads to the following proportionalities:

Volume ÷ Capacity
All lengths') ÷ (Capacity)$^{1/3}$
Number of pipes ÷ Capacity
Total length of pipes ÷ (Capacity)$^{2/3}$
Temperature gradients ÷ (Capacity)$^{-1/3}$
All areas") ÷ (Capacity)$^{2/3}$
Heat losses ÷ (Capacity)$^{1/3}$

Putting the lowest acceptable efficiency, somewhat arbitrarily, at 60 % the corresponding lower limit of the capacity is found to be about 200.000 kWh. Such a storage could be serve 20 properly insulated, average dwellings in The Netherlands. Capacities beyond the 750.000 kWh for which the calculations were made will have efficiencies higher than the 75 % calculated.

It goes without saying that in the N.W. European climate the critical period for a seasonal storage is the end of the winter, say the last weeks of February. In this period sunshine may be insufficient for the required space heating during cold spells. In order to have some reserves of high temperature heat for such a period it seems advisable to use the occasional clear days in winter for supplying high temperature heat to the very core of the storage.

LITERATURE

[1] K.G.T. HOLLAND and J.F. ORGILL, Potential for Solar Heating in Canada, Report 77-01, February 1977, University of Waterloo, Canada, Office of Research Administration.

') Except mutual distance between pipes which should be kept constant.

") Except cross section of pipes, which should be kept constant.