IEA RESTRICTED

INTERNATIONAL ENERGY AGENCY

ENERGY CONSERVATION THROUGH ENERGY STORAGE

ANNEX 1

LARGE SCALE THERMAL STORAGE SYSTEMS

FINAL REPORT

A REPORT OF THE EXECUTIVE COMMITTEE FOR A PROGRAMME OF RESEARCH AND DEVELOPMENT ON ENERGY STORAGE ESTABLISHED UNDER THE AUSPICES OF THE INTERNATIONAL ENERGY AGENCY

OCTOBER 1981

E. L. Morofsky

Prepared by

FOR TECHNICAL EVALUATION

The Center of Hydrogeology of the University of Neuchâtel acting on behalf of the Swiss Federal Office of Energy and as Operating Agent for Large Scale Thermal Storage Systems Projects.

FOR ECONOMICAL EVALUATION

Studsvik Energiteknik AB, Sweden, acting under contract of the National Swedish Board for Energy Source Development.

This report is classified

IEA RESTRICTED

i.e. distribution is restricted to officials of IEA Members Governments. Further distribution is up to IEA Member Governments.

Edited by

The Centre of Hydrogeology of the University of Neuchâtel / CH - 2000 Neuchâtel 7

under contract of the Swiss Federal Office of Energy

CONTENTS

ANNEX 1

LARGE SCALE THERMAL
STORAGE SYSTEMS

Belgium, Commission of the European Communities, Denmark,
Germany, Sweden, Switzerland, United States

A. GENERAL

1. INTRODUCTION

The Implementing Agreement for a Programme of Research and Development on Energy Conservations through Energy Storage was signed in Paris on 22 th September 1978. At present, the following Countries and organizations have signed the Implementing Agreement :

- Belgium : Prime Minister's Office Science Policy
- Commission of the European Communities
- Denmark : The Ministry of Energy
- Germany : Kernforschungsanlage Jülich GmbH
- Netherlands : Stichting Energieonderzoek Centrum Nederland
- Sweden : The National Swedish Board for Energy Source Development
- Switzerland : Swiss Federal Office of Energy
- United States of America : Department of Energy

The Implementing Agreement includes actually 2 Annexes concerning :

Annex 1	Large scale thermal storage systems
Annex 2	Lake storage demonstration facilities in Mannheim

All the above mentionned countries participate in Annex 1 with the exception of the Netherlands.

Denmark, Germany, Netherlands, Sweden and United States participate in Annex 2.

This is the final report concerning the research in the framework of Annex 1 of the Executive Committee of the different countries who signed the Agreement. It was approved by all the countries concerned at the meeting of the Executive Committee held in Paris, on 13th and 14th April 1981.

It includes the following points :

- The Executive Committee's activities in Annex 1
- A technical and economical evaluation of the projects presented in the framework of Annex 1 as well as the conclusions.
- Various information concerning the follow up of the Executive Committee's work in the framework of large scale storage systems.

2. EXECUTIVE COMMITTEE EXPERTS MEETINGS

During 1980, two meetings of the Executive Committee took place, the first in Mons, Belgium, on April 29th and 30th, the second in Paris on October 9th. A list of the members of the Executive Committee is annexed (page 4 and 5).

In the meeting of Mons, each participating country reported on their project status. Dr Bernd Kramer of the IEA mentioned that energy conservation must play an important role in the future. For this reason energy storage is expected to have an important place in conservation efforts.

It was also mentioned that potential overlaps may occur between the work of the Committee on Energy conservation through Energy Storage and the work of the Solar Heating and Cooling Group and the proposed annex on vertical subsoil heat exchangers under the Implementing Agreement on Advanced Heat Pump Systems.

During the meeting of Mons, the technical evaluation methodology for Annex 1 presented by Switzerland was also discussed. Representants of Sweden presented an economical evaluation methodology.

The Committee also discussed new areas for common interest with the aim to sign annexes : flywheels, electrochemical storage, small thermal storage systems.

In the Paris meeting, representants of Switzerland and Sweden presented a draft of the technical and economical evaluation report under Annex 1, which is included in the present report. The Executive Committee decided that :

- Annex 1 is officially terminated, the annex results and methodology should be published.
- Annex 2 is officially terminated. Wherever possible funds assigned to this project should be used for a new jointly-funded hardware demonstration project on large scale energy storage
- Italy will prepare a draft annex on flywheel energy storage systems.
- Netherlands will prepare and circulate a draft annex on small-scale energy storage systems.

The Executive Committee also unanimously decided to

- pursue the possibilities for international cooperation in the field of thermal storage initiated by Annex I. The objectives of this cooperation should now be to enlarge the number of large scale thermal storage field experiments. Therefore, in addition to the Hørsholm and University of Minnesota projects which will be carried out on a national basis, it would be worthwhile to permit the realization or the acceleration of additional projects through an IEA jointly-funded programme. On a short term, the Dorigny project seems to be the best candidate to serve as the basis for an IEA demonstration project. Switzerland is preparing such a proposal for the Dorigny project and will present it at the next Executive Committee meeting.

A working meeting on large scale thermal storage systems was held in Paris on October 8th 1980, to finalize and discuss the results of the technical and economic evaluation of the project under Annex 1 and to identify the next possible steps in the area of large scale energy storage systems to be presented to the Executive Committee.

3. PROJECT MANAGEMENT

At the Inaugural meeting of the Executive Committee in Lausanne 9/10th November 1978, Dr G. F. Pezdirtz of the United States was unanimously elected chairman and Dr A. Fehr of Switzerland was elected vice-chairman for Annex 1.

The Centre of Hydrogeology of the University of Neuchâtel, Switzerland (Prof. A. Burger) is acting as Operating Agent (O.A.) for Annex 1.

TABLE 1

IEA - ENERGY STORAGE EXECUTIVE COMMITTEE

List of members

Country	Name	Organization	Address	Telephone	Telex
BELGIUM	P. Marchal	SPPS	8, rue de la Science 1040 Bruxelles	(02) 230 4100	
	J. Brych	Fac. polytechnique de Mons	9, rue Houdain 7000 Mons	065 33 81 91	
CEC	Jan Knobbout	European Community	200 B, rue de Loi Bruxelles	(02) 735 0040	21 877 Comeu B
	Peter Zegers	European Community	200 B, rue de Loi Bruxelles	(02) 735 0040	21 877 Comeu B
DENMARK	Björn Qvale	Technical University of Denmark	Lab. for Energetics Building 403 DTH 2800 Lingby	(02) 88 46 22	37 529 DTHDIA
FEDERAL REPUBLIC OF GERMANY	Franz Friedrich	PLE/KFA - Jülich	P.O.B. 1913 D - 517 Jülich	02461-614744	88 3556 KFA-D
	Reinhard Jank	Mitec GmbH Munich	Daimlerstr. 15 D - 8012 Ottobrünn	089/6095081	
	V. Lottner	PLE/KFA Jülich	D - 517 Jülich	02461-614879	
NETHERLANDS	K. Joon	Netherlands Energy Research foundation	P.O.B. 1 1755 Z G Petten	02246-6262	57 211

TABLE 1 (continuation) IEA - ENERGY STORAGE EXECUTIVE COMMITTEE

List of members

Country	Name	Organization	Address	Telephone	Telex
SWEDEN	Ingvar O Andersson	Board of Energy (NE)	Box 1103 S - 16312 Spanga	08-75 20360	12992
	Peter Margen	Studsvik Energiteknik	S - 61182 Nyköping	0155-80000	64013
	Rune Hakansson	Studsvik Energiteknik	S - 61182 Nyköping	0155-80000	64013
SWITZERLAND	Arthur Fehr	Federal Energy Office	Kapellenstrasse 14 CH - 3003 Berne	031 61 56 10	33065
	André Burger	University of Neuchâtel	Centre of Hydrogeology CH - 2000 Neuchâtel 7	038 25 64 34	33065
	Bernard Mathey	University of Neuchâtel	Centre of Hydrogeology CH - 2000 Neuchâtel 7	038 31 46 78	
U.S.A.	G. F. Pezdirtz	DOE Advanced Conservation Technology	Room 416 600 E St - Washington DC 20545	202-3769897	7108220176
	Michel Siat	RPA	28 av. de Messine F - 75008 Paris	561 95 33	641809F
I.E.A.	Bernd Kramer	IEA	2, rue André Pascal F - 75775 Paris Cedex 16	524 99 75	630190F

B. LARGE SCALE STORAGE SYSTEMS

1. INTRODUCTION

Storage of heat as a technical component within a heat-supply system has in the past been conceived only as a means of decoupling heat and electricity production in cogeneration plants. At present, with high energy prices (and with still higher price increases expected), the question of the possible benefits of TES (Thermal Energy Storage) as a means of saving energy has now started to grasp the interest of energy suppliers.

In contrast to conventional district heating, TES is as a solar heat supply system, not only a component among others, but the presupposition, if one wants to cover more than a marginal part of the annual heat demand by solar energy.

Today, no technology of storing very large amounts of heat by any kind of latent or chemical storage, which is economically viable, is known (or only in sight). Therefore, this task can actually be solved only by storage of sensible heat. The natural medium of storage is therefore, of course, water, having a comparably high specific heat capacity and many other favourable properties. This poses immediately a temperature limit of heat storage at less than 100°C, (in free aquifers or containers) which results in possible restrictions for application in conventional district heating systems (employing frequently temperatures of 130°C and even higher). In new district heating systems or systems using solar heat, this limit generally causes no problems.

During the past few years, a number of different concepts have been developed, representing a wide variety of characteristics. It is common to all concepts that they strive for the lowest specific costs possible. This is caused by the results of numerous systems analyses, showing that the economic boundary for long time storage (seasonal) is in the magnitude order of 30 $/m3 water-equivalent or even less. It is the main goal of this evaluation work to describe the TES concepts which seem at present to be of greatest interest from the technical and from the economic point of view. Our task was confined to these concepts which have been presented by the participating countries of the IEA-energy storage implementing agreement, thereby not considering the one or the other additional concept.

It is the aim of this task to give a technical and economic assessment of some of the most interesting large-scale TES projects in the participating countries. To evaluate a general impression of the frame, in which TES has to be seen, in the following chapter a few examples of application are illustrated. In Chapter 3, the different concepts in question are briefly described and assessed. In Chapter 4, the economic situation of the projects presented is discussed. In the final Chapter 5, conclusions will be given.

2. THERMAL ENERGY STORAGE (TES) APPLICATIONS

2.1. Seasonal storage and specific cost

The low limit of specific costs stems from the fact, that a store intended for seasonal storage is used only little more than once per year. This cost limit can be avoided to some extent by operating the store in a way which allows a more frequent annual utilization.

2.2. Utilization of large-scale TES with combined heat and power production (CHP)

2.2.1. Description of the system

CHP is a thermodynamic process generally superior to the heat pump process. Used in a district heating (DH) grid as a heat source, it loses some of its advantages because of four main reasons :

- Usually only a thermal load of 50-60 % of the maximum load is covered by CHP. The remaining load has to be covered by oil or gas burning peak boilers with a comparable bad energy utilization. Therefore, about 15-20 % of the annual thermal energy is produced by the peak load boilers.

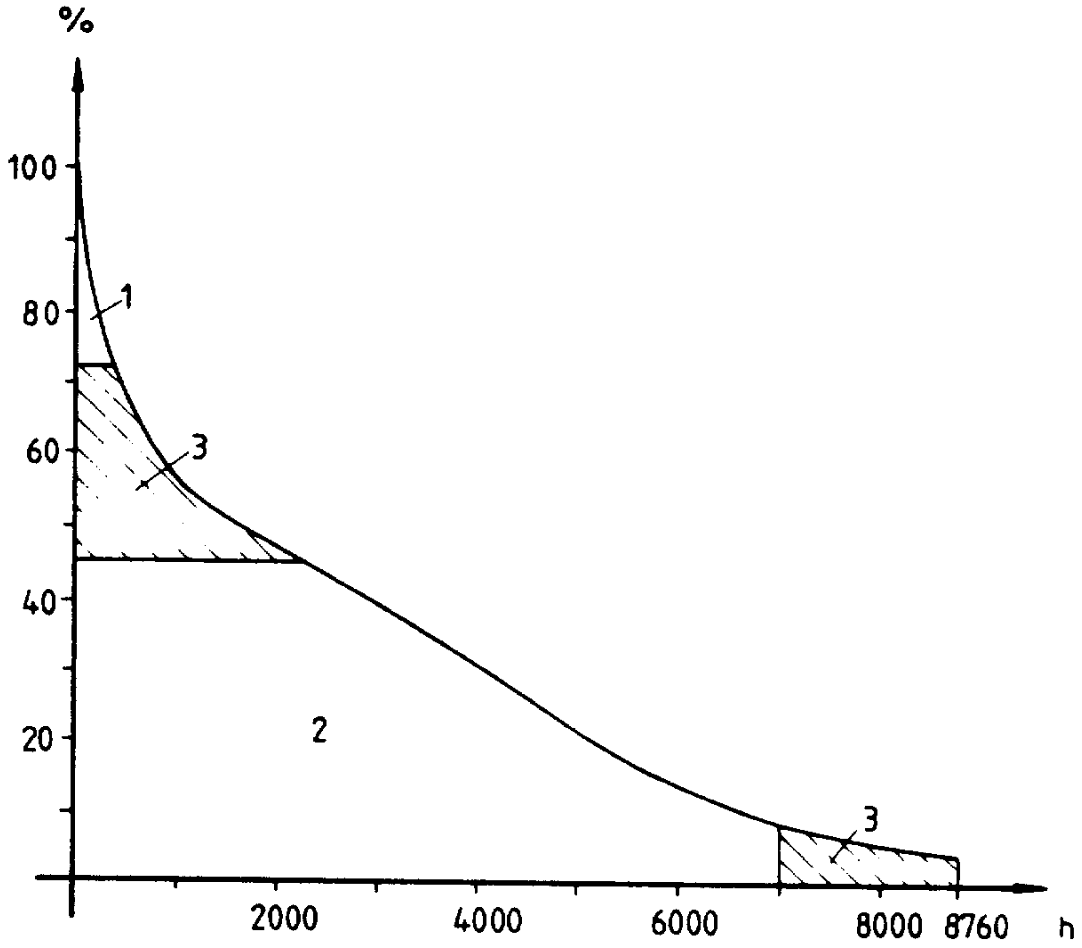
- In low-load periods (ambient temperatures > 12°C) CHP usually is shut down for technical reasons. Here, about 10 % of the annual thermal energy demand has to be covered by the boiler.

- During times of medium load the energy utilization of the CHP-process is less efficient than during optimum load.

- Usually DH grids are designed for quite high transport temperatures, e.g. 135 °C - 70°C, causing unnecessary heat losses during transport.

Utilization of large TES would allow for an extensive reduction of these drawbacks. But unlike solar energy seasonal storage systems, it is not necessary to design the store for 30 % or even more of the annual energy demand, but only for a small fraction of that. It is then possible to cover practically the whole annual demand by the CHP-process and to increase the duration of full operation of the heating turbines up to 5'000 h/year and more. This result can be achieved in the following way :

FIGURE 1. Annual duration of load in the case of combined heat and power production



Annual duration of load (in hours)

1. Peak load (boiler, 27 % of the maximum load)
2. Base load (CHP, 45 % of the maximum load)
3. Load covered by TES (28 % of the maximum load)

A store with a capacity of only 2 % of the annual heat demand can be loaded by CHP at all times when the heat demand is less than 45 % of the maximum load. The charging/discharging system must be designed to be able to cover high charging/discharging loads. By this operation, the store is able to cover 10 % of the heat demand in winter and 5 % in summer. Only about 2-3 % of the annual heat demand have still to be covered by the peak load boiler. (Figure 2).

2.2.2. Concrete example

See the case in a concrete example where the annual heat demand will be 500 GWhth (or 50'000 users), requiring a maximum load of 190 MWth :

85 MWth : CHP

53 MWth : TES

52 MWth : Peak load boiler

The peak-load boiler has an annual operation time of less than 250 h. During other times with ambient temperatures of not much lower than 0°C the back-up load of the TES is only needed for 2-3 h. Therefore, a heat capacity of about 10 GWh is necessary. Assuming a usable difference of temperature of T = 40°K, a storage volume of 250'000 m3 is required.

2.2.3. Economical comparison

The store supplies 15 % of the annual heat demand, thereby replacing 88 GWh of oil (efficiency of the boiler 85 %). With costs of heat by oil of 35 $/MWhth, the annual saving of energy costs is $3,08 \cdot 10^6$ $. An additional saving occurs, compared to a conventional DH-system, by saving peak-load capacity. In a conventional DH-system (without store), the peak-load capacity would be 60 % or 114 MWth, from which 29 MWth can be saved. With specific costs of $0,58 \cdot 10^5$ $/MWth, $1,68 \cdot 10^6$ $ can be saved. Taking an annuity of 13 % this results an annual savings of $0,23 \cdot 10^6$ $. On the other hand, additional 75 GWh have to be produced by CHP (15 % of 500 GWh). With present specific costs of 10 $/MWh, this results in heat costs of $0,77 \cdot 10^6$ $/a. The store causes operational costs of 44'000 $/year, which also have to be subtracted from the saving indicated above.
The total annual savings are therefore 3,3 Mio $. Using an annuity of 13 % again, we arrive at 25,4 Mio $ as limiting

costs of the storage system, or 102 $/m3. By this use of a store, every year, 7'300 tons of oil are substituted by 2'100 tons of coal.

Today it is possible to reduce the temperature of the back-coming water to 40-35° by use of automatic regulation valves in the customers rooms which are to be heated. This would allow for a higher temperature difference available for the store, say ΔT = 50°K. Consequently, the storage volume necessary can be reduced by a factor of 1,25, leading to a volume of 200'000 m3 in the example described above and therefore to specific limiting costs of 127 $/m3.

2.3. Incineration plant for waste

Thermal and electrical energy production in a wastage incineration plant usually undergoes few changes during the year and a certain number of installations are not working during the weekend.

The role of a thermal energy storage can be doubled : seasonal storage for the supply of energy during the winter and daily storage to avoid the turning on of peak-load boilers at the end of the week. This is the case of the Hørsholm plant (Denmark) which is taken into consideration later. It also happens that the incineration plant can be stopped for technical reasons (repairing the ovens, difficulty burning certain wastage). These interruptions can last as long as 6 to 7 days in succession. This is the case of the Ebenhausen Central in Germany.

2.4. Utilization of TES as a weekend store

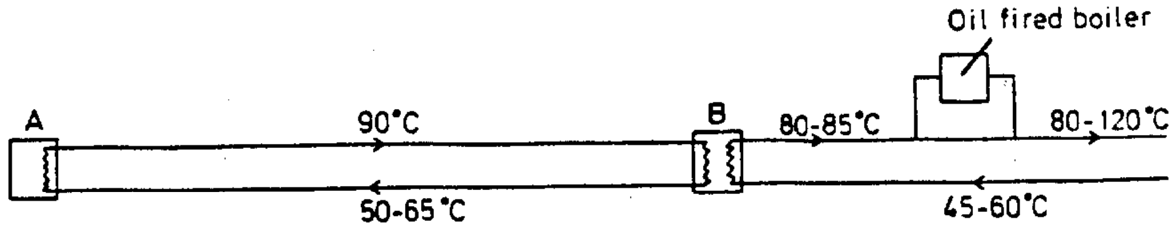
Quite often in district-heating systems, because of the low electrical load during the weekend, the cogeneration is stopped and the heat load is covered by oil reserve boilers. In a heat-supply system of 15 MWth (max. load) the weekend heat during the whole year accumulates to 15 GWh (German climatic conditions). With 80 % efficiency, 18'750 MWhth of oil have to be fired instead of using combined heat and power production, leading to annual fuel costs of 0,656 Mio $. Since the present price level of heat from cogeneration is 10 MWh, an annual saving of 468'500 $ would (a = 13 %) allow for an investment of 3,6 Mio $. If one wants to cover the heat demand of the coldest winter-weekend, a capacity of 11'700 m3 water equivalent is necessary. Therefore, the limit of specific costs is (most economic) 308 $/m3. The store has an annual utilization factor of n = 25.

2.5. Seasonal storage of industrial waste-heat

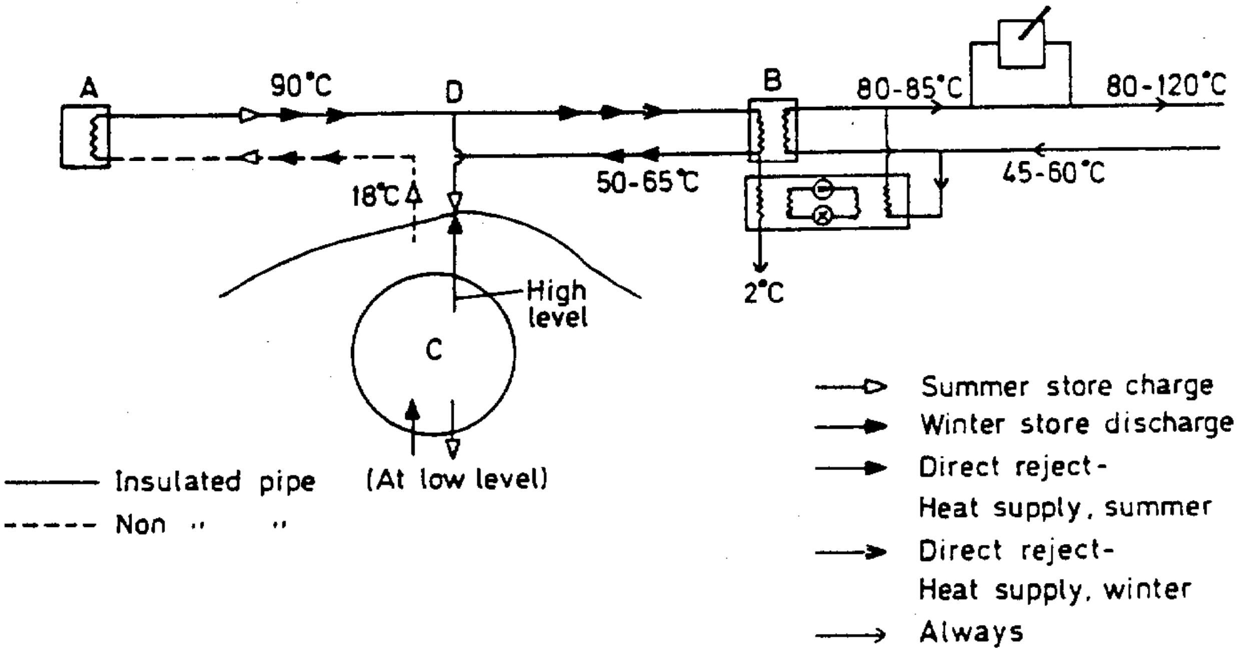
If one wants to make use of industrial waste-heat produced during summer (and otherwise rejected), an amount of about 25 % of the annual heat energy demand has to be stored for 100-150 days in a hot-water magazine. Considering the same size of district-heating system as above (500 GWh/a), where the base-load of heat is delivered by industrial waste-heat instead of CHP, a storage capacity of 125 GWh or 2,4 Mio m3 of water (ΔT = 45°K)has to be at hand. Assuming, that by additional chargings/dischargings the storage volume can be used 1,5 times a year, the store delivers 188 GWh/a (with 15 % thermal losses), having a value of 6,58 Mio $. Using an annuity of 13 % again, the costs of the store can be 51 Mio $ or 21,3 $/m3 (operational costs and future price increases not considered). Using cogeneration as a heat-source instead of (costless) industrial reject heat, this figure has to be about 25-30 % lower.

Seasonal storage of solar heat (being the subject of another IEA-Implementing Agreement) would require an even lower cost-limit.

Scheme without heat store; two-way pipe



Scheme with heat store, two-way pipe, heat pump



Scheme with heat store, one-way pipe, heat pump

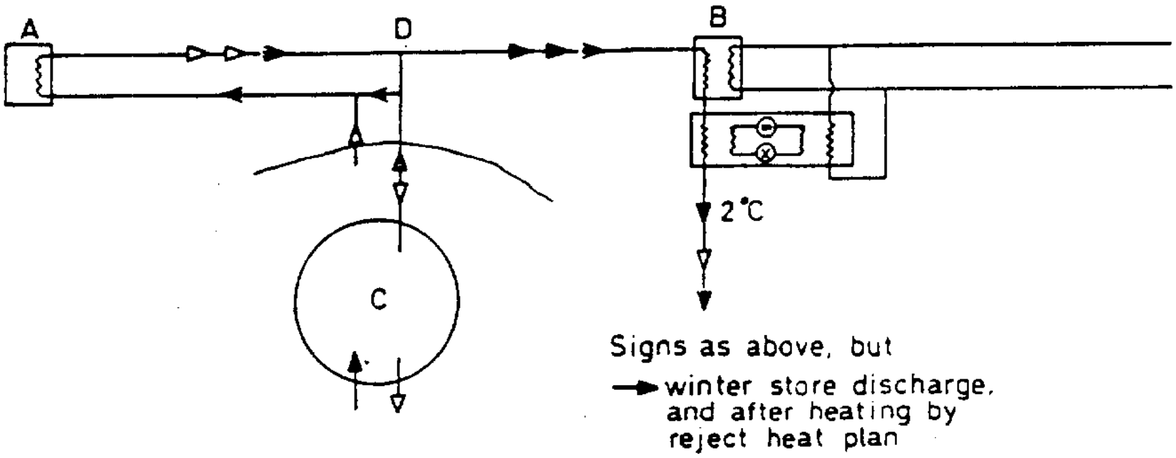


FIGURE 2. DIFFERENT POSSIBILITIES OF CONNECTING A LARGE SCALE STORAGE SYSTEM TO A DISTRICT HEATING (SWEDEN)

Charging of store during summer

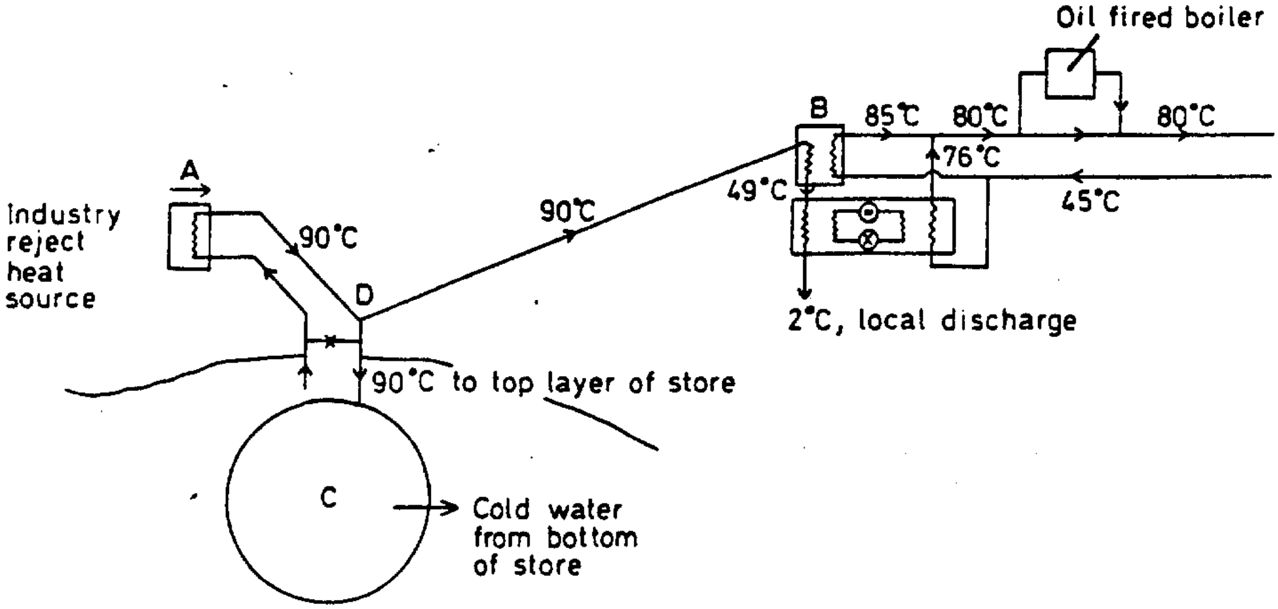
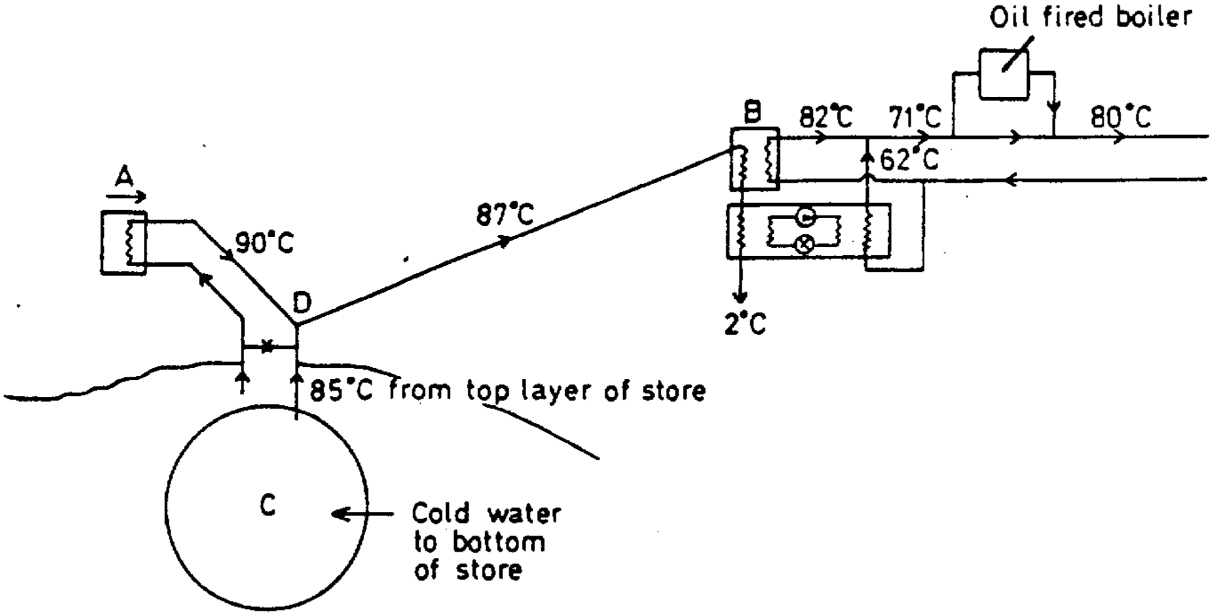


FIGURE 2. CONTINUATION.

Early discharge of store



Late discharge of store

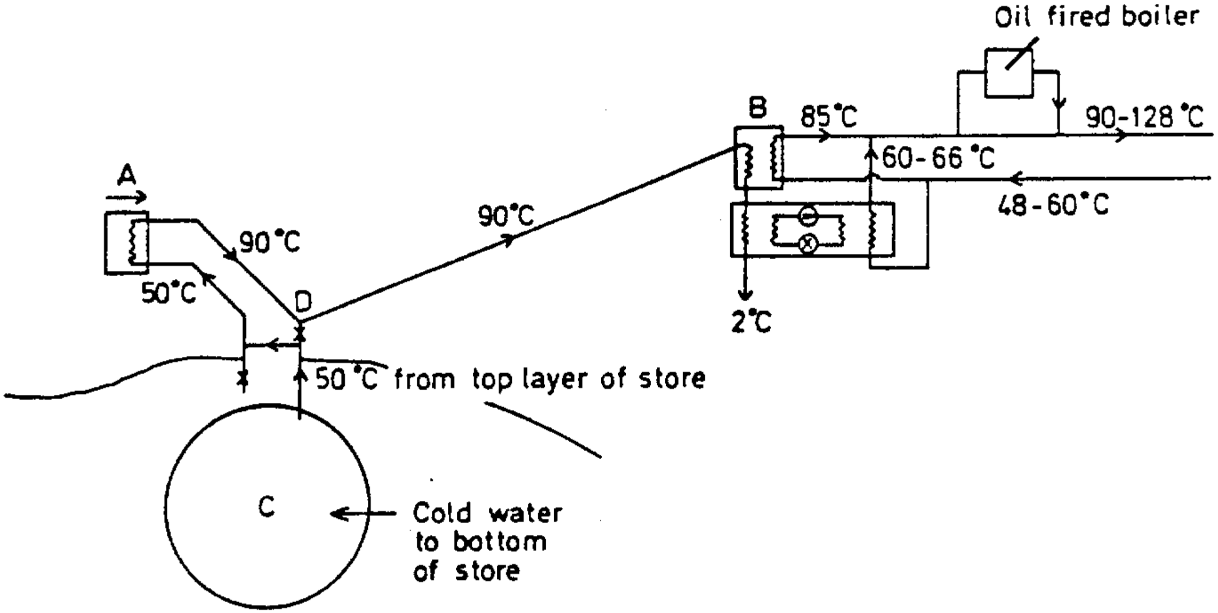


FIGURE 2. CONTINUATION

2.6. Thermal energy storage and solar energy

The interest which is found in large scale thermal storage systems can be put into close relationship with the increasing development of research in the field of solar energy.

It is certain that development of solar energy on a large scale for heating in buildings is closely attached to economical development of seasonal storage. The problems caused by the integration of seasonal storage in the framework of solar plants are studied by the IEA Solar Heating and Cooling Group in the framework of the Annex VII : Central solar heating plants with seasonal water storage.

Excellent contacts are maintened between the members of Solar and Large Scale Thermal Storage Groups.

The technical solutions held at the present time for the storage of seasonal solar energy are mainly applicable to the underground storage and extraction of heat in layers of tubes at shallow depth, pipes driven vertically into the rock, accumulator consisting of layers of pipes superimposes, etc. These solutions usually demand the use of a heat pump for the extraction of heat out of the accumulator.

An interesting construction is at present in service at Ingelstadt (Sweden). The accumulator consists of an isolated concrete tank of 5'000 m3 supplied by cylindro-parabolic solar collectors with surface of 1'320 m2. Water from the accumulator is heated to 95°C at the end of the summer. The heat is used for a small district heating system.

In the case of application of a large scale storage system concept for solar energy, one must consider that the utilization factor is less than 1,5 per year. This implies an investment which must be less than 20 \$/m3 to assure the economical efficiency of the accumulator.

2.7. Summary

The results given in the examples above can be refined greatly by considering actual boundary conditions, local costs of heat from different heat-sources, financing conditions (a matter of great importance), climatic conditions (influencing the utilization number), studies of investments, etc.

The order of magnitude of the specific cost-limits will, however, be retained. This gives a clear frame for the investments costs of thermal storage systems allowed for different application cases. According to these results (table 1) for these applications different techniques of storage will have to be developed, satisfying the actual application requirements. Many of these different techniques are discussed in this paper.

Table 1 : Specific costs of storage for different application cases.

Application	Utilization factor	Capacity & of annual demand (Qa)	Size (m3)	Energy saving potential (% of Qa)	Economic limit of specific costs ($/m3)
Seasonal storage of industrial waste-heat	1,5	25	$2,4 \cdot 10^6$	42	22
Waste incineration (Ebenhausen)	4	6	$2,7 \cdot 10^4$	23	51
Mediumterm storage for cogeneration	8,8	2	$2 \cdot 10^5$	14	127
Weekend store (replacement of oil-firing)	25	0,75	$6 \cdot 10^3$	26	308

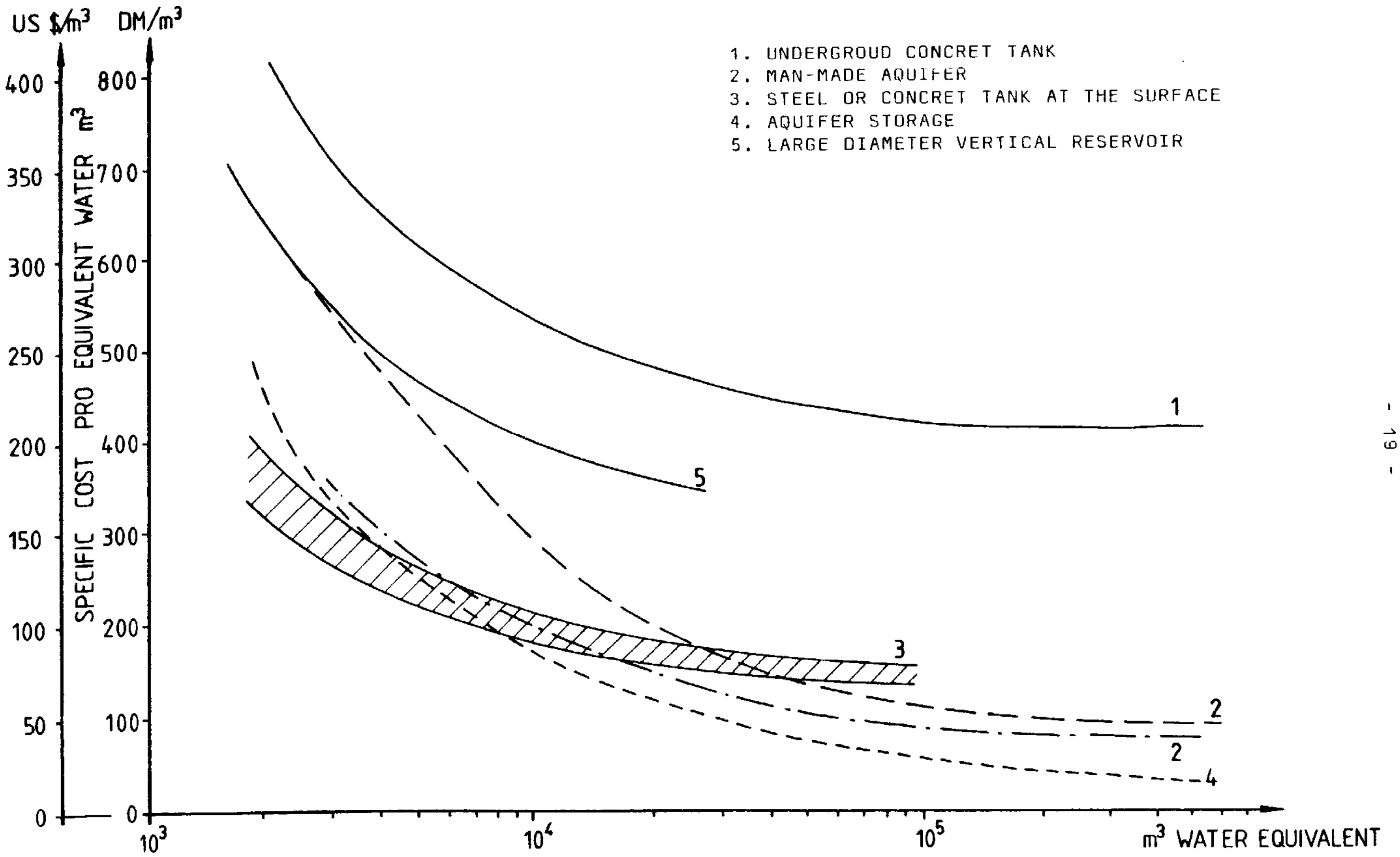


FIGURE 3. CONSTRUCTIONS COSTS FOR DIFFERENT HEAT STORAGE SYSTEMS IN FUNCTION OF EQUIVALENT WATER CONTENT.

3. DESCRIPTION OF THE THERMAL ENERGY STORAGE CONCEPTS

3.1. Thermal Energy Storage in Free Aquifers

3.1.1. Historical and Technical Description

The first studies on the use of aquifers as thermal storage system seem to have been carried out by RIBBINOV, UMAROV and SADHIKOV (1971). The first suggestion published and technically evaluated is that of Meyer and Todd (1973). This study envisaged a system of storage in deep aquifers, connected to an electric power station.

Figure 5 illustrates the difference between confined and unconfined (free) aquifer.

One of the first known field experiments was carried out in 1974 by the Centre of Hydrogeology of Neuchâtel in Switzerland, in a phreatic aquifer (injection of 500 m3 of water during 15 days at 50°C). Other experiments have been carried out in Germany (Experimental Area, Hülser Bruch) in France (Campuget, Bonod) in the United States (Auburn) and in Japan. In general these results were used to test mathematical models used for the simulation of larger storage facilities.

It shoud be mentioned that in the Republic of China many towns and industrial concerns have developed a cold water storage concept which is operational on a large scale since 1965, notably in Shanghai.

The water is chilled at surface during the winter and used in summer for industrial purposes and for air-conditioning. An experiment of the same type has been successfully carried out at the Texas A & M University.

Figures 6 and 7 give a summary of the different concepts possible in the use of an aquifer (free or confined) for heat storage. The choice of a system depends on numerous parameters, among which can be mentioned :

- the temperature level in the accumulator
- horizontal and vertical permeability values
- ground water level

FIGURE 4.

AQUIFER THERMAL ENERGY STORAGE POTENTIAL CONSUMER AND PRODUCER OF HEAT

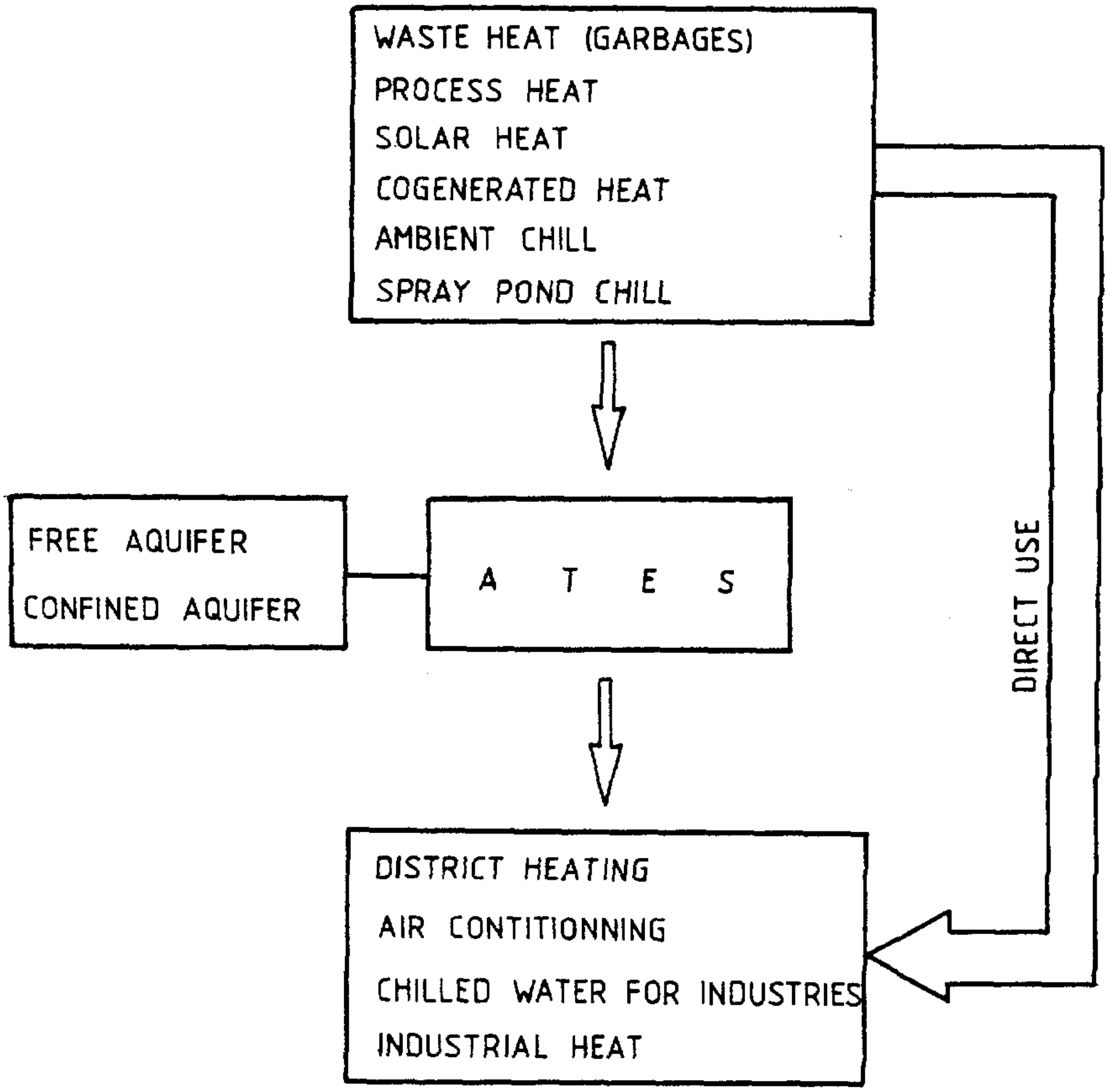
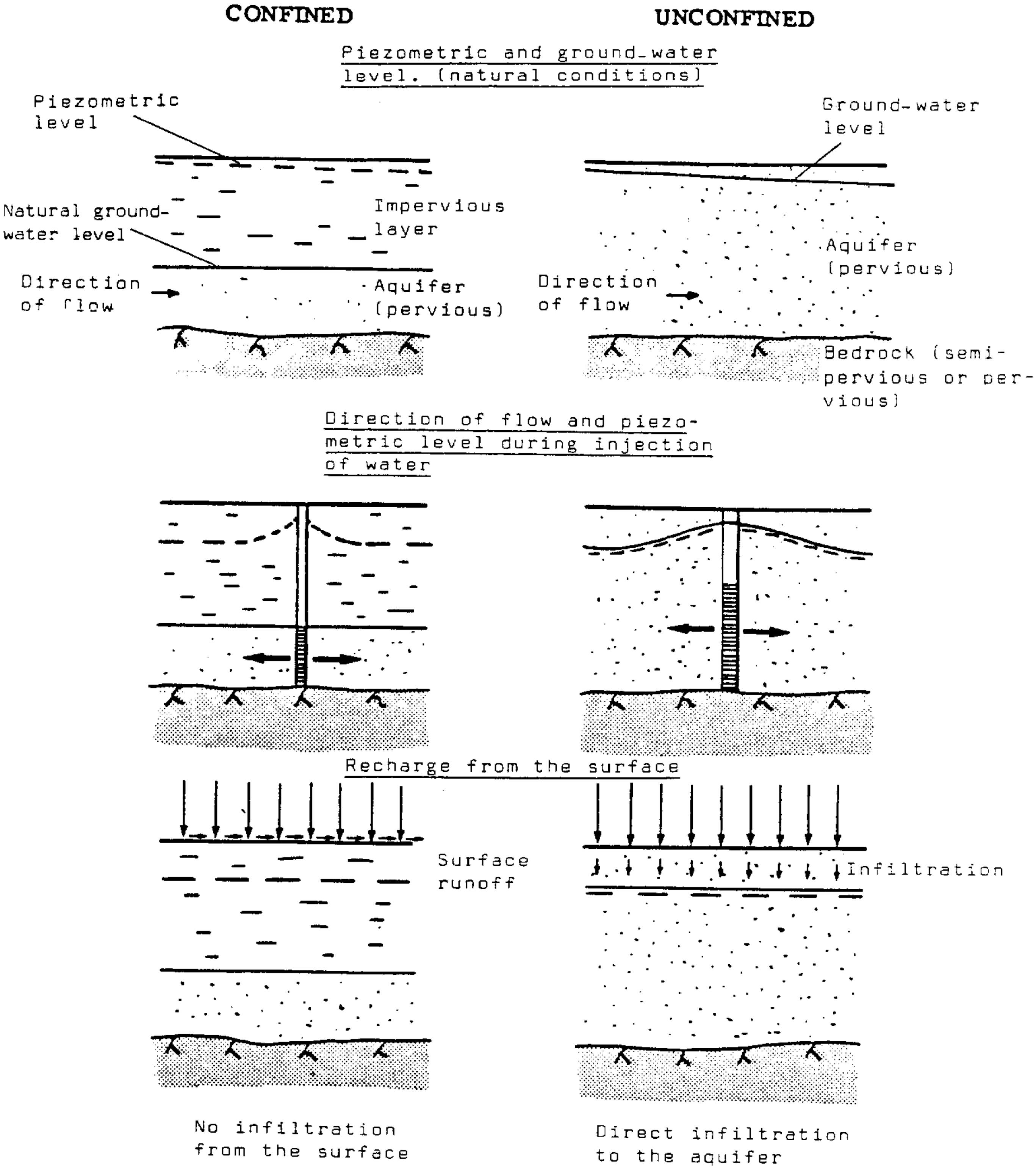


FIGURE 5. DIFFERENCES BETWEEN CONFINED AND UNCONFINED AQUIFERS.



- ground water outflow rate
- environmental constraints
- injection and extraction flow
- aquifer dimensions

At present aquifer thermal energy storage is only envisaged in porous media. For the moment, it is difficult to envisage the control of a thermal disturbance in media having a heterogenous permeability (fissured media : limestone, granite, metamorphous rocks).

3.1.2. Applicability

The concept of free aquifer storage is predominantly applicable in long term storage schemes (especially seasonal). The combination of seasonal and weekly cycles increases the possibility of making the system economically feasible (Case of the Hørsholm site). The integration of an underground accumulator in a producer-consumer system is of prime importance in the choice of the type of storage. Possible cold or heat sources and potential consumers are given in figure 4.

Cogeneration, waste and solar heat are at present the most interesting sources in areas where heating demand exceeds 1'000 day degrees. In region where air-conditioning is necessary, the combination of a hot and a cold store has aroused much interest, but has not so far been experimented. (Case of the Solaterre project).

The main problem at consumer side lies in the temperature of the heat extracted from ground water.

Below 50°C : it is clear that it is necessary to use a heat pump for the functionning of the heating system. Between 60°C and 80°C a low temperature district heating system can be connected to the store. Above 90°C practically all demands can be met, but the accumulator should be deep and confined. It can be admitted that the temperature in a free aquifer should not exceed 85°C.

Cold water production is generally obtained by the use of spray nozzles, operating during the cold season. Among possible application of the water stored one can mention air-conditioning and industrial use of cooling-water.

3.1.3. Energy saving potential

The energy saving potential of an underground store is largely dependent to the system into which it is integrated.

In a case where the energy producing unit operates continuously all the year (Cogeneration) the storing of summer excess production and its use in winter for space and district heating allows a saving of up to 25 % of the total annual energy demand. In a case where production varies in time (solar for example) the potential saving can reach 40 to 60 % according to climate and type of installation.

It is clear that the size of the accumulator, the storage temperature which a heat pump can necessitate, the climate, the nature of the source of heat or cold, the needs, are parameters which should be well defined in the calculation of the energy saving potential of an underground accumulator.

3.1.4. Cost/benefit ratio

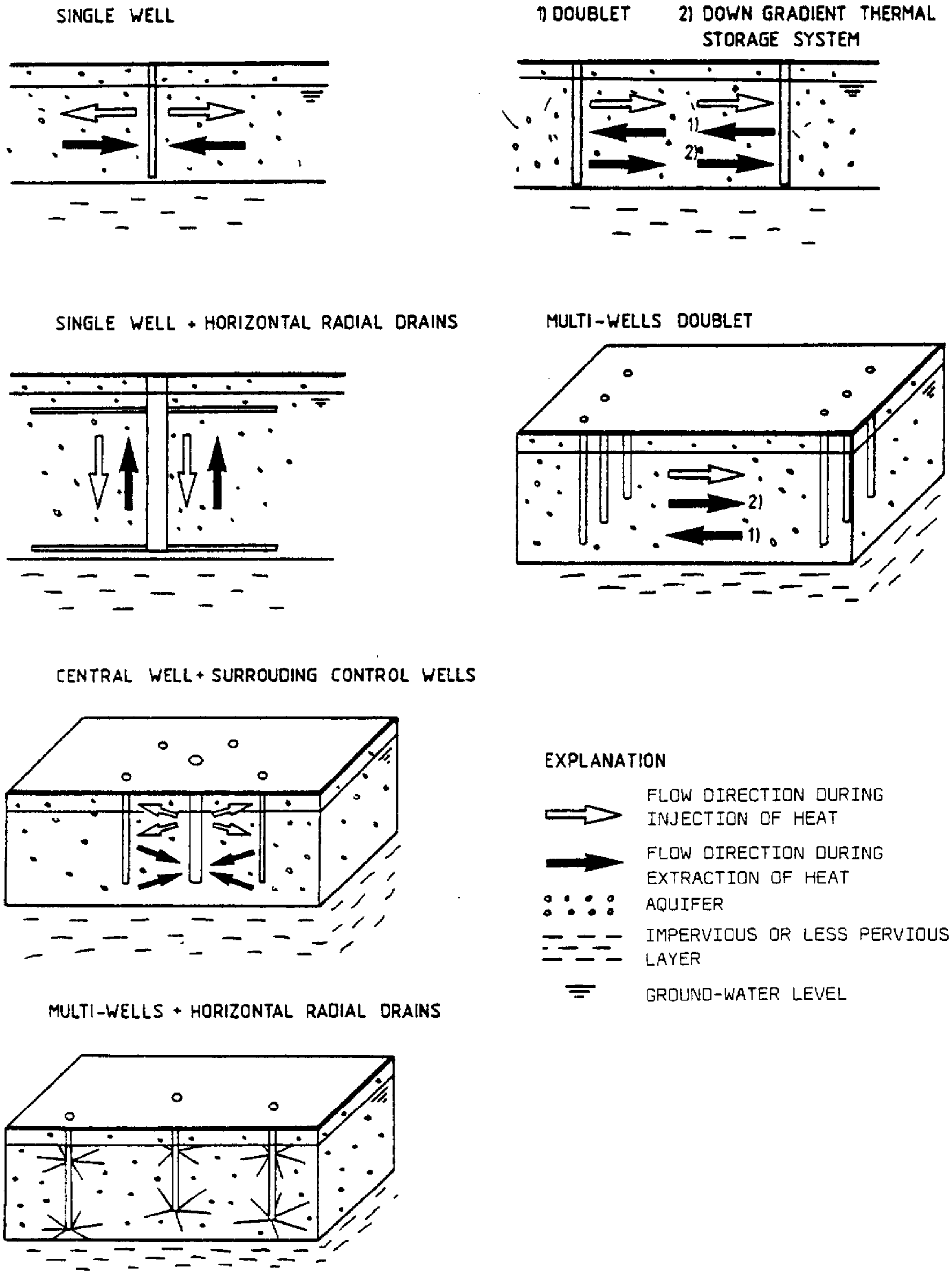
Among the factors which influence the cost/benefit ratio of aquifer heat storage the following parameters can be mentioned :

- the producer-consumer system to which the store is linked
- the size of the accumulator, on which depends the recovery ratio
- external equipment heat (exchangers, pumps, etc.)
- water injection and water extraction temperature

It will be seen that, in the economic analysis presented in this report, the unit cost of the accumulators presented by participants as hardware funded projects decreases strongly as the volume increases (see 3.2.).

FIGURE 6. THERMAL ENERGY STORAGE IN FREE AQUIFERS

PROPOSED GEOMETRIES FOR INJECTION AND PUMPING WELLS



SINGLE WELL

1) DOUBLET 2) DOWN GRADIENT THERMAL STORAGE SYSTEM

SINGLE WELL + HORIZONTAL RADIAL DRAINS

MULTI-WELLS DOUBLET

CENTRAL WELL + SURROUDING CONTROL WELLS

MULTI-WELLS + HORIZONTAL RADIAL DRAINS

It could therefore be concluded on a first approximation that the cost/benefit ratio of aquifer storage tends to improve with volume and that this technology, except in cases where heat pumps are used, should be reserved for systems where thermal energy needs are high and correspond to heating demands attaining at least several hundred or even thousand inhabitants. This point is important in so far as the choice of an experimental project by the IEA shall supply information for large scale accumulators.

3.1.5. Technical risk

For free-aquifer storage numerous technical risks subsist by reason of insufficient knowledge of the behaviour of thermal disturbances and interaction between the medium and the hot water injected (chemical reaction, environmental effects, clogging, bad control of the disturbance, lack of knowledge on permeability).

Tests carried out at Colombier (Switzerland) in 1974 seem to show that there is natural convection over and above a critical temperature gradient which depends on permeability structure. In the Swiss and Danish projects, special attention has been given to the study of prevention of this phenomenon.

It has now been shown practically and theoretically that aquifer heat storage is possible. It should however be borne in mind that the final objective of Annex I of the Implementing Agreement "Large scale storage systems" consists of bringing to light all the difficulties yet to be overcome on large scale practical construction.

These difficulties are known, but their relative importance can only really be assessed when several full-scale accumulators, linked to a system comprising a heat-producer and heat-consumer have been brought into operation.

In the case of cold water storage, the numerous Chinese experiments, the success of the test conducted by Texas A & M University, show that the technical risks are minimal, and that this technology can be put into practice on a large-scale.

3.2. Thermal Energy Storage in Confined Aquifers

3.2.1. Technical description

The first experiments in aquifer storage were carried out in free aquifers : Bonod, Colombier, Hülser Bruch, Campuget. However, it is generally admitted that deep, confined aquifers constitute an extremely interesting thermal storage potential. The advantages and disadvantages of storage in free of confined aquifer are given in Table 2. Among the greater advantages of confined aquifers can be mentioned :

- the possibility of injecting water at a temperature above 95°C
- generally slow ground water flow
- lower thermal losses

The confined aquifer concept differs little from that for free aquifer (figure 5). It should be noted that in the case of very deep aquifers, the revalorization of geothermal exhausted fields can be a very interesting possibility.

Finally, it should be mentioned that in the case of heat storage in ground water, the concept (single well, doublet, deep doublet) depends on local geological conditions, which will nearly always be determinant in the choice of a system.

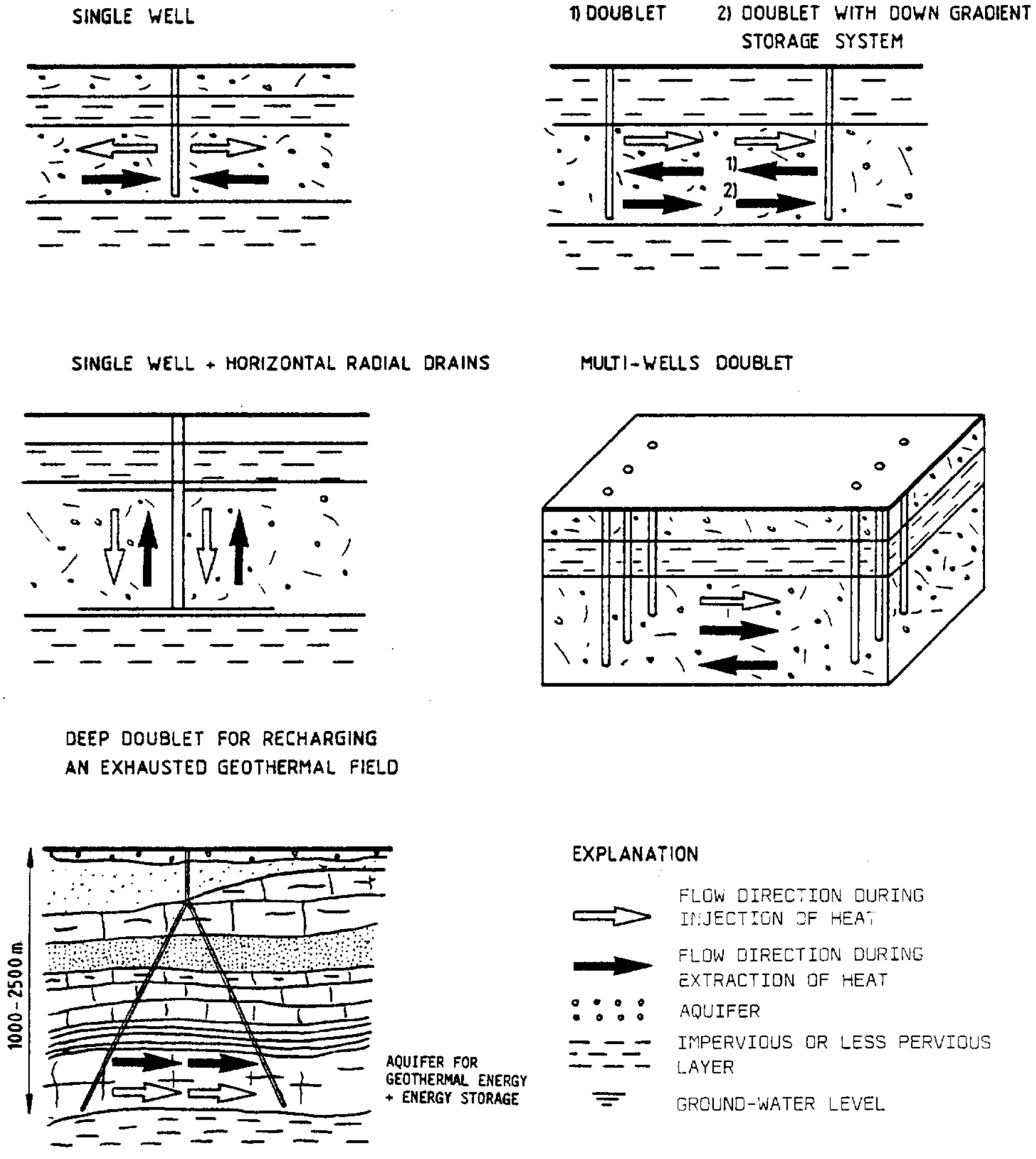
The possibility of deep heat storage in porous media remains badly known. In very fissured media, where the fissures are spaced only several meters apart, disturbance control is certainly possible. In cases where hich permeable fissures are spaced more than 10 meters apart, a very high energetical loss should be expected.

3.2.2. Applicability

The fields to which confined aquifer storage can be applied are very similar to those for free-aquifer storage. One important advantage : it is possible to store heat above 95°C, avoiding the use of heat pumps, and allowing the store to be branched to a high temperature heating network. It should be noted that deep aquifer storage is less favourable for cold water storage.

FIGURE 7. THERMAL ENERGY STORAGE IN CONFINED AQUIFERS

PROPOSED GEOMETRIES FOR INJECTION AND PUMPING WELLS



3.2.3. Energy saving potential

The same remarks as for free-aquifer storage apply. Climate, nature of the source of heat or cold, demands, are parameters which will be essential in defining the energy saving potential.

On the other hand, for an equal volume, the energy saving potential of the accumulator is greater in a confined than in a free aquifer, due to the lower thermal losses.

3.2.4. Cost/benefit ratio

For an equal volume, confined-aquifer storage is more costly because it is deeper, but it is a more attractive proposition because higher temperatures can be attained. For the moment, however, we do not possess sufficient technical informations to prove that one concept is economically more competitive than the other.

The problem of the storage cost according to the volume stored and the temperature is examined in this report.

3.2.5. Technical risk

As in the case of free-aquifer storage, numerous technical risks subsist. Tests carried out by the Auburn team have shown that heat storage up to 60°C is possible without major risk.

Tests at present being carried out by the same team should bring to light problems which can occur during water injection up to 120°C. It should be mentioned that in a confined aquifer, generally deeper, the ecological risks are less than in a free aquifer.

TABLE 2.

UNDERGROUND HEAT STORAGE

Comparison of advantages and disadvantages of free and confined aquifer concepts

FREE AQUIFER		CONFINED AQUIFER	
+	−	+	−
- low drilling cost	- natural water flow generally high	- temperature above 95°C	- high drilling costs
		- slow natural ground-water flow	- rocky media more frequent deeper down
- well adapted for chilled water storage	- frequent natural convection	- valorization of a geo-thermal field	- difficulty of control of heat mass if media fissured
- easy and economical utilization for low temperature storage	- temperature lower than 95°C	- low ecological risks	
- possible ecological risks	- losses to the surface		

3.3. The man-made aquifer concept

3.3.1. Technical description

The principles of the concept are given in fig. 8. The bulk material of this aquifer is treated in a way which allows for a defined permeability. The aquifer is confined by two concentric circular "slit-walls". This technique is well known from the technique of fresh-water reservoirs. The slit-walls are filled with bentonite materials, this establishing a good barrier for the hot water from the interior. The ring-space between the two concentric slit-walls is filled with natural gravel.Since it has a thickness of more than 10 m, it gives a sufficient thermal insulation. The transition between the aquifer and the surface is the only artificial insulating material. The thickness of this insulation has to be economically optimized. Similar to the lake-concepts, the surface has also to be sealed against rainwater. But unlike these lake-concepts, this problem is less serious here since in case of leakage repairing measures are much easier.

The man-made aquifer has the same specific heat as natural aquifer (or slightly better), which means ca. 30 % less than pure water. It is much more independent from geological conditions than natural aquifers, but also fairly untouched by constraints coming from accessibility for surface buildings in areas of high population - or industrial - density, getting more and more important at present. Due to the higher permeability, a stable temperature stratification is to be expected under all circumstances, this allowing for sufficient high discharging rates to be operated for short-time storage. This advantage may overcompensate the higher specific costs of this aquifer compared to the natural aquifer.

3.3.2. Applicability

The man-made aquifer can be operated in all possible ways. Since it is expected to allow for temperatures up to 95°C, it can also serve for conventional (high temperature) district heating networks. With regard to geological or surface restraints, this type of store is less sensible than natural aquifers and lake-type stores. Also, there is no size-limit coming from eventual construction constraints.

3.3.3. Energy saving

This potential depends from the mode of operation. In actual cases, it can be higher than 30 % of the annual heat demand of the customers served.

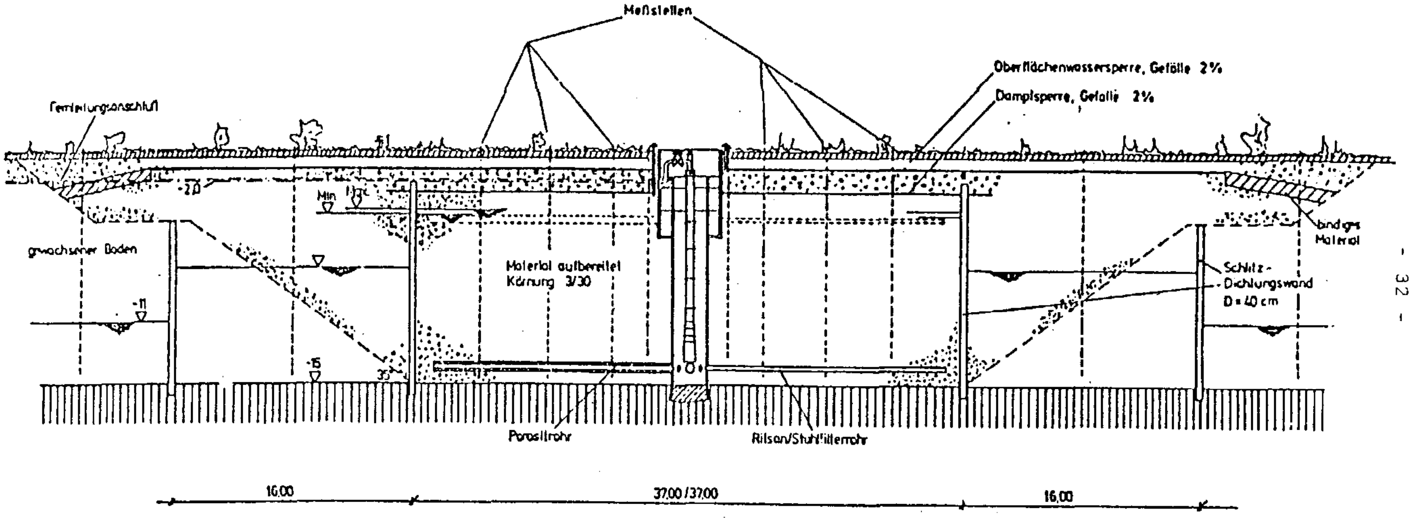


FIGURE 8. Aquifer storage Grosshadern-Munich. Heat storage concept (COMMISSION OF THE EUROPEAN COMMUNITIES)

3.3.4. Cost/benefit ratio

The man-made aquifer will have higher specific costs than the natural aquifer, but it is expected to have lower specific costs than lake-type hot water magazines. Since in its operation characteristics it is very similar to these latter stores, the man-made aquifer may prove to have the best chance of economic operation in actual application cases.

3.3.5. Technical risk

The biology and chemistry of mass transport in the volume of the aquifer has been studied in small scale experiments. As a result, the man-made aquifer is said to be able for operation with water of 95°C temperature.

This result has still to be verified in a field experiment. Only then this type has superior properties compared to the natural aquifer.

Since the hot volume is confined by two ring walls with large volume of gravel inbetween, no serious risks of safety are expected. However, the influence of possible small leaks to the surrounding has still to be considered comprehensively. The heat-exchangers (and all pipings) may be affected by the water quality, being rather strange to conventional district heating systems. Therefore, a special water treatment and the use of special materials for the piping (e.g. asbestos-cement-concret) have to be foreseen. Also this question cannot be regarded at present as being settled completely satisfactory.

3.4. Underground heat storage in vertical pipes

3.4.1. Technical description

The interest shown in solar energy storage has led many technicians and companies to try to find a simple method for underground storing energy.

The example of earth collectors placed at a depth of 1 to 2 meters is now well known. A network of polyethylene pipes, 500 to 1'000 meters long for a family house, allows the injection and extraction of solar energy at low temperature. This technology is the object of numerous research and development projects in IEA countries. It is not included in Annex 1, we mention it for information. A detailed description of these systems can be found in the papers of the "Nordic Symposium on Earth Heat Pumps Systems" which was held at Göteborg on 15th and 16th October 1979.

When the quantities of energy to be stored exceed the heating needs of a few family houses, it becomes necessary to store the heat in voluminous accumulators. A first solution consists in making an excavation in which a heat exchanger formed by polyethylene pipes is placed in layers. In light soils with a good contact coefficient (saturated silt and clay) a great future can be foreseen for this technique.

Thermal insulation of the accumulator would allow its temperature to be raised and thus avoid having to use a heat pump, during part of the year at least. It is however still necessary to undertake research in the field of watertight thermal insulating material. The use of heat pumps could also be avoided by the construction of accumulators of 50'000 to 100'000 cubic meter, which give a very favorable increase in the volume/surface ratio. In coarse ground with low humidity, (gravel, sand) it is necessary to place a watertight sheet around the accumulator. There again, studies have to be carried out to find the best and the cheapest material.

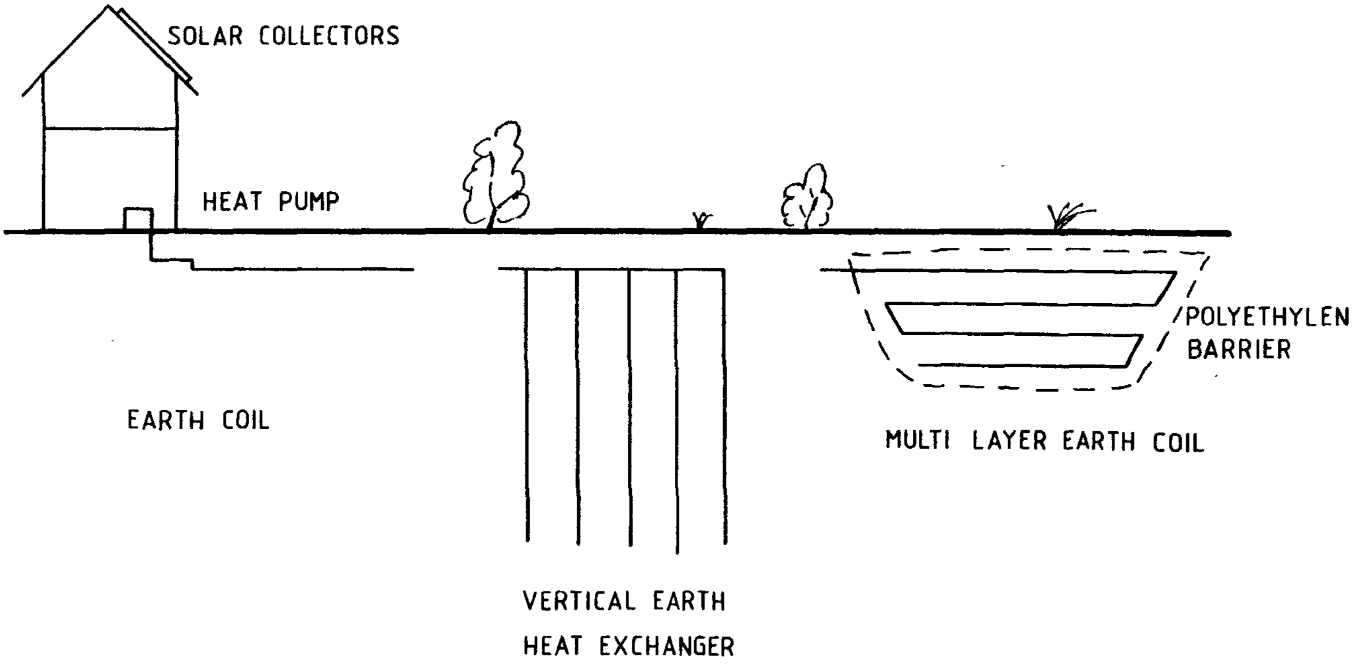
In rocky ground, where excavation by machine are difficult, an extremely interesting storage solution consists in implanting vertical boreholes at a depth of up to 100 meters.

This proposal is the object of development for example in Sweden (Sunrock project).

In 1965, G. Brun proposed the storage of the energy of a solar power plant in dry limestones or granites, heated to 500°C. The solar plant produced vapour at 230 atü and at 500°C. This vapour was chanelled into boreholes containing

FIGURE 9.

SUB-SURFACE THERMAL ENERGY STORAGE CONCEPTS



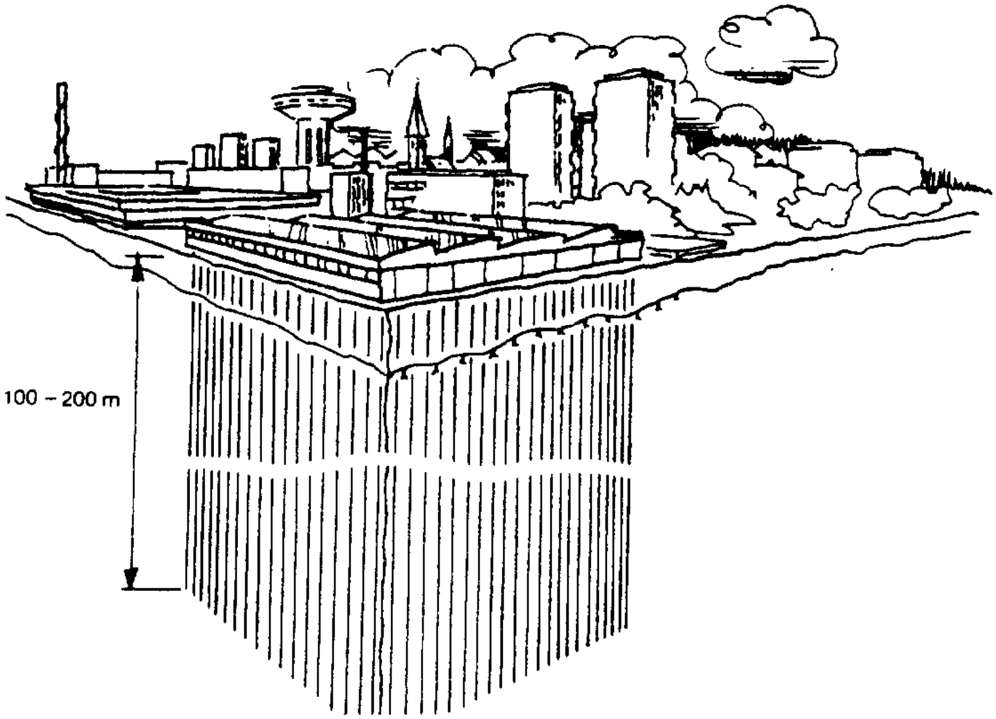


FIGURE 10. ILLUSTRATION OF POSSIBLE VERTICAL PIPES STORAGE IN ROCK. (SWEDEN)

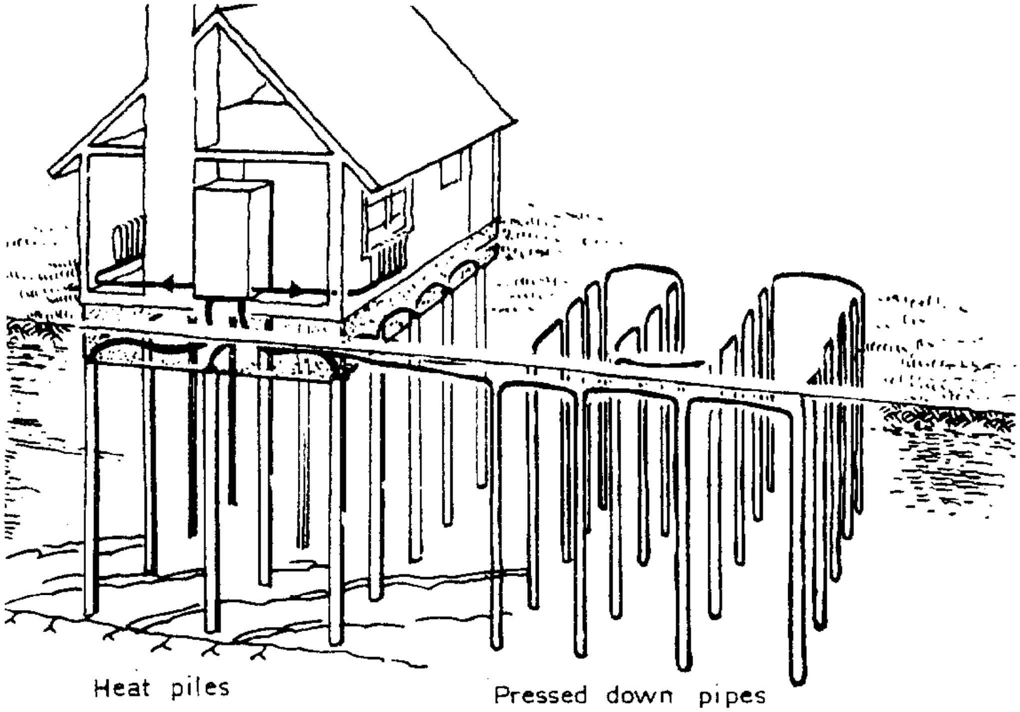


FIGURE 11. ILLUSTRATION OF A VERTICAL PIPES STORAGE SYSTEM IN CLAY OR LOAM FOR A FAMILY HOUSE (SWEDEN)

2 concentric steel pipes which allow the system to operate in a closed circuit. For a solar plant, he envisaged the heating of a volume 200 meters high and 300 meters in diameter, containing 9'000 boreholes spaced 3 meters apart. The cost of running the system was to be under 0.03 dollars per kWh, and thermal losses insignificant.

G. Brun's proposition pushes the vertical pipes technology to the extreme point of its development. It is clear that systems with smaller accumulators and lower temperatures should first be studied and built.

Finally it should be noted that in very soft ground (loam, clay, fine sand) the vertical pipes can be driven in and not bored, thus reducing the cost.

3.4.2. Applicability

The vertical pipes concept can be applied in practically all cases where heat storage is necessary.

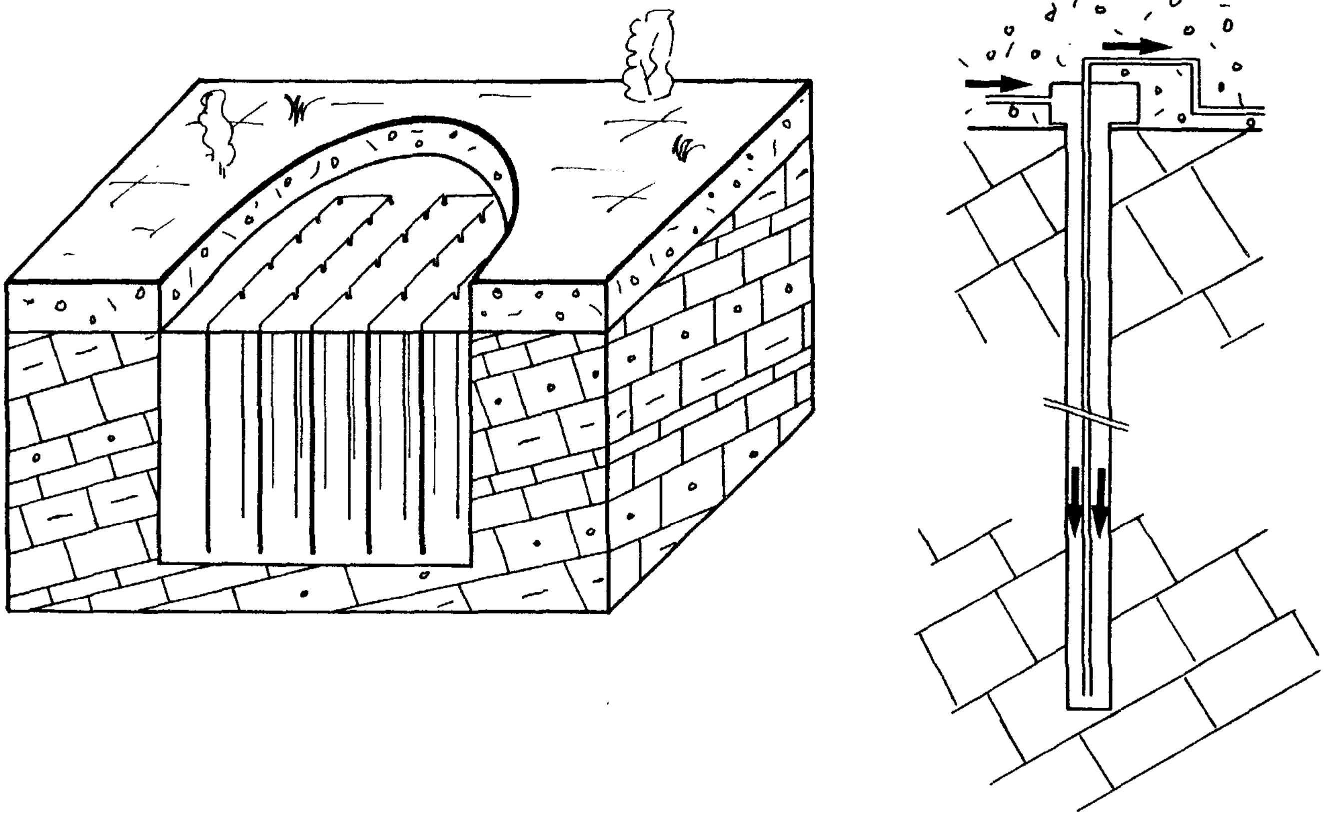
The geological constraints are less important than in aquifer storage, and this solution can be considered as being very widely applicable. The main constraint lies in the heat exchanger which is formed in the ground. Only simple perforation techniques, different from the classical borehole methods, will allow a reduction of the cost per meter to a competitive level.

The vertical pipes technology is well adapted for seasonal storage of solar energy, since the size of the accumulator can be varied to meet the needs of the energy consumer. This is the application for which it is at present being developed. For a large scale thermal storage system (heating for several thousand inhabitants) if geological conditions are favourable, aquifer storage will definitely be more economical.

At medium term (4 to 5 years) it can be estimated that the application of the vertical pipes storage will be limited to installation whose dimensions will not exceed those necessary to heat a few hundred inhabitants. At long term, solution such as that proposed by G. Brun could be studied and made operational.

FIGURE 12.

VERTICAL PIPES THERMAL ENERGY STORAGE CONCEPT



3.4.3. Energy saving potential

As in the case of aquifer storage, the energy saving potential depends on the system to which the heat accumulator is linked. The valorization of solar energy product by a thermal way, largely depends on an efficient seasonal storage. Thermal storage by vertical pipes being well adapted for solar energy, its energy saving potential is considerable. We can quote the case of an experimental construction which is going to be put into operation at Cortaillod (Switzerland) for the heating of 12 family houses. Without storage, the solar installation would offer an energy saving of 30 %. With an accumulator of 5'000 m3, consisting of 400 vertical pipes from 6 to 8 meters long, and a gas heat pump, it can offer a saving of 60 % of the total primary energy consumption.

If the accumulator temperature was sufficiently high to avoid using a heat pump, the energy saving potential of the accumulator would exceed 50 % and avoid the use of another energy than solar.

3.4.4. Cost/benefit ratio

It is difficult to give a precise estimate of the economic interest of a system which up to now has not gone past the experimental stage. In the case of storage by vertical pipes, it can be admitted that the cost is mainly dependent on the length of the boreholes. Consequently, the unit-cost, above a limit rapidly reached, will vary little according to the size of the accumulator. Aquifer storage certainly offers a bigger reduction in construction costs proportionately to volume.

A meter of vertical pipe will produce, according to conditions prevailing, 30 to 100 kWh per year. To be an economically interesting proposition, the cost of a meter of boring should be situated between 5 and 8 dollars per meter, costs which appear possible at the moment.

Finally, it should be noted that investment costs are above all dependent on the maximum thermal power extracted, since it is the power which determines the length of the pipes.

Therefore, in an actual application an economic optimization of the size of the back-up system has to be evaluated.

3.4.5. Technical risk

Heat storage by vertical pipes is adaptable to many types of ground. It presents a lower geological risk than aquifer storage. A further advantage is that the heat exchanges are made by conduction, which avoids furring of the exchangers. The presence of ground water with rapid outflow could prevent all storage. A peripheral hydraulic control is necessary in this case.

One of the weak points of the system, which requires serious checking when operational, is the branching of a great number of pipes at surface.

If the vertical pipes are in steel, cathodic protection of the whole of the pipes is necessary to avoid a rapid corrosion.

3.5. Large diameter vertical reservoirs

3.5.1. Concept description

This concept has been developed and studied by Professor Brych and his team at the Mons Institute of Technology, (Belgium).

The principal is as follows : a large diameter (1,5 to 9 m) vertical drill hole is made of a depth going from a few tens of meters down to a few hundred meters. The drill hole is cemented and if necessary sheated with steel.

The reservoir thus constructed is adapted for short term heat storage (daily or weekend storage). The fact that the reservoir is very long in comparison with its diameter ensures a very good stratification which limits to the maximum the mixture between hot and cold water going in and out.

3.5.2. Applicability

Taking into consideration the heavy investment made necessary by this type of accumulator (200-600 dollars/m3) this method must be reserved for daily of weekend storage.

The technical advantages of this system are the following :

- insulation facility thanks to thermal conductivity and specific heat of the surrounding terrain
- perfect tightness if necessary
- practically no pollution
- invisible store
- maintenance and operating facilities
- possibility of applying the system in many places under various geological conditions.

Much more effective than the conventional method although little known is the method proposed for the drilling of vertical reservoirs (large diameter turbodrilling) the diameter of which may range from 1 to 6 m. For diameters ranging from 1 to 3,6 m the design and engineering are already known. The modules with diameters ranging from 3,6 to 6 m and more are still to be studied, and practically without limitation in respect of ground conditions.

The excavation for vertical reservoirs is possible close to the heat sources and this method seems to be particularly effective for daily storage and even seasonal storage for solar houses. In which case, thermal insulation around the tube must be envisaged.

3.5.3. Energy saving potential

Energy saving potential of large diameter reservoirs is that of daily or weekend storage i.e. 10-20 % of total energy consumption of the system to which the store is connected. By increasing the number of vertical reservoirs at proximity to one another the importance of the ground accumulator would become larger and the losses would be reduced.

3.5.4. Cost/benefit ratio

Economic information is not yet complete for this system. At the present time only a prototype has been carried out and the drill hole technique has not been tested on an industrial scale. In the case of individual drill holes and for diameter of 2 to 3 m one must count a price of 350 to 450 dollars per cubic meter.

With steel tubing price the cubic meter would reach 600 dollars. In multiplying the number of drill holes on the same site it would be possible to reach 170 $/m3 of accumulator.

3.5.5. Technical risk

With this method the technical risks are relatively low in comparison with techniques such as lake or aquifer storage. Among the possible risks are :

- Insufficient thermal insulation created by an important ground water flow around the store
- Corrosion of tube (when steel)
- Mechanical resistance of the tubing
- Difficulties in cementation

Complementary research will be made in years to come on this system, in order to assure a better knowledge of these phenomena, particularly in the case of very large diameter boreholes.

3.6. Basin - type stores

3.6.1. Technical description

One of the first concept - developed in 1971 by Prof. Schöll from Stuttgart/W.-Germany - was an earth-basin concept, leaning itself closely to the technology of water reservoirs. One of the main features of the concept was to use the extracted soil as material for the dams around the reservoir.

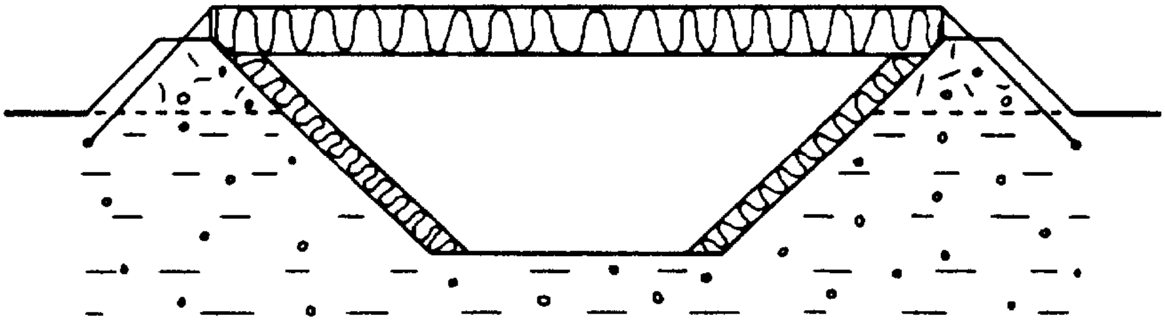


FIGURE 13. BASIN TYPE STORE: SCHOLL CONCEPT (GERMANY)

The basin was thought to be covered by a PUR-insulation, sealed by plastic foils against steam from below and against rainwater on the upper side. Prof. Schöll proposed to drop the bottom heat insulation (assuming the existence of a larger layer there, bearing no ground water), because he expected that there was a quasi-stable equilibrium of thermal flux after a few years of operation.

As consequence to this very simple concept, the costs for constructing this basin were estimated to be remarkably low. In a first study of this concept, carried out by KFA Jülich, for a large basin-type stores (100'000 m3) specific costs of about 22,2 $/m3 were estimated. This result was not completely discouraging in the light of the economical cost-limit given above. Therefore, in the Mannheim storage project, an experimental warm-water reservoir of 30'000 m3 volume should be erected, where some of the problems shown up in the Jülich study should be investigated in practice. It turned out during the first phase of this project, that the problem of thermal stratification is not a crucial one.

In contrast, the problem of choosing materials for thermal insulation and sealing came out to be a very serious one. No final choice on these different materials could be given, but it was stated that there would be at least three different layers of materials necessary to overtake the different tasks of insulating, sealing and protection against buoyancy from the groundwater surrounding. Further details on this are given at the end of this chapter.

The main results of the Mannheim project were the following :

1) The stratification of water layers with different temperatures could be described mathematically with sufficient precision. The calculations could be confirmed experimentally in models of laboratory size as well as of technical size (3'000 m3). As a consequence, a precise computation of the thermal insulation is possible. The time dependence of this stratification, being quite important for the long-time storage, can be described with high confidence.

2) A detailed proposal for the charging/discharging system has been developed, being able to charge/discharge the store with minimal disturbance of the stratification (and therefore with minimal internal mixing losses).

3) A swimming insulation of the basin surface turned out to be - mainly for safety reasons - not cheaper than a rigid construction. In cases of leakage of the basin, repairing works can be done in the latter in case without danger of destroying the "lid".

4) Again due to safety reasons, an additional ditch has to be foreseen around the basin, which is able to retain more than 60 per cent of the volume of the reservoir in emergency cases.

5) Even reinforced asphalts were unsuited as a sealing and insulating material, because of the creep emerging under temperatures up to 90°C and insufficient sealing properties.

6) In the special case of Mannheim, the relatively high ground water level leads to very high additional costs for ground water removal during the erection period.

As a consequence, the simple concept of Prof. Schöll has to be substituted by a more complicated solution. The most serious objection comes from the still unresolved question of insulating and sealing materials between water and soil. Here, at least three layers of different materials have to be used, overtaking independently the tasks of buoyancy safeguard, sealing and thermal insulating. Experimantal investigations of sealing and insulating materials have been undertaken in Studsvik and in cooperation with German manufacturers (see later). As a tentative result, one must say that at present only foam glass seems to be a suitable heat insulating material, whereas to date, no sealing material has been found having the required properties with sufficient confidence. As usual with lifetime investigations, these experiments take a long time; therefore, no final judgement on this question can be given today. The investigations are continued.

3.6.2. Applicability

The concept of large unpressurezed hot water basins can be applied virtually to all existing district heating networks, because its possible level of temperature is almost 100°C. For the geologic restraints, the concept is complementary to aquifers : it should be applied only, when no ground-water layers are present. Since it allows also for very high heat loads, operation as short or medium time store is possible, thereby improving the economy to some extent.

3.6.3. Energy saving potential

As it is the case with all storage concepts, this potential depends mainly on the operation mode. Therefore, if operated as seasonal store, the saving potential is in the range of 30-40 % of the annual heat demand. Operated as a short-time store, the saving potential is about 10-20 % of the annual heat demand. Weekend stores have a saving potential of about 25 % of the annual heat demand (if applicable).

3.6.4. Cost/benefit ratio

For seasonal storage operation, the energy saving potential of the basin type magazine is somewhat higher than for natural aquifers (and perhaps in the same range than man-made aquifers, operated with high temperatures). According to present knowledge, the costs seem to be appreciably higher, leading to the conclusion that the domain of application is only medium of short time storage, allowing for 10 or more annual utilizations. In this application, the cost/benefit ratio should be sufficient good to rise the interest of potential heat energy suppliers. But here, this concept competes with the concept of cylindrical steel container, insulated outside (and therefore without risk of vapour diffusion).

3.6.5. Technical risk

The problem of choosing a well suited material for heat insulation and sealing has not been finally solved today. There are proposals which may fulfil the requirements (e.g. foam glass and special plastic or rubber foils), but this has still to be proven in time-consuming materials research.

As a consequence, an application of this type of TES can only be recommended as an experimental project of smaller size.

3.7. Lake heat store

3.7.1. Technical description

Since materials which occur freely in nature are the cheapest, a promising way to achieve a cheap heat store is to separate a cheap part of a lake or bay of the sea by vertical insulation curtains from the surrounding colder water, and to separate the top by floating blocks of insulation from the atmosphere. The bottom, in contrast, can be open to create an inverted cup. This inverted cup can be filled with hot water which due to its lower density is contained within the cup.

The outward horizontal forces due to the difference in density between the hot water within the cup and colder water outside must be taken up by anchoring cables or ring cables, but are about a factor 20 lower than horizontal forces acting on steel tanks of similar height erected above ground, where the static pressure of the hot water is not at all balanced by a pressure outside the vassel walls.

The top of the magazine is covered by an insulated floating lid.

This concept of lake magazine was proposed for study and was examined in a first feasibility study by the National Swedish Board for Energy Source Development in 1977.

3.7.2. Applicability

To assess the overall economics of a lake storage scheme, it must be considered in conjunction with specific applications. The concept is applicable essentially in long term storage (especially seasonal). Combination of seasonal and week-end storage can be envisaged.

Cogeneration and industrial waste heat are actually the most interesting sources. Solar energy would also benefit in the future of this type of store.

A suitable lake or coastal bay must exist at reasonable distance from consumer and producers of heat.

In the case envisaged by Studsvik, the lake heat store is connected to a district heating with a peak demand of 200 MW supplied by oil fired boilers. The figure 16 illustrates the seasonal variation of heat demand and thermal balance of store. During the summer the store is charged with excess reject heat. During autumn and winter the store is discharged. Through the whole period the industry also continues to deliver reject heat to the network to the same extent as without the store.

The use of a heat pump greatly increase the amount of heat which can be stored per m3 of store and allows also the heat in the surface water of the lake to be used for storage.

3.7.3. Energy saving potential

Energy saving potential of a lake heat store is largely dependant to the system into which it is integrated.

The same remarks as for free or confined aquifer storage apply. In the case of cogeneration the storing of summer excess production and its use in winter for space heating allows a saving of up to 25 %.

3.7.4. Cost/benefit ratio

An economic analysis made by Studsvik Energiteknik AB (Sweden) suggests that by the time such stores could be builts commercialy. They should be an economic proposition on systems where excess summer reject heat is available free of charge. An assumption is that fuel prices will continue to escalate over the life of the store and that the financial benefit from this escalation is taken into consideration. This assumption naturally concerns all energy storage concepts. Other vital remark is that the technical performances and cost of the insulation and tightening materials are confirmed.

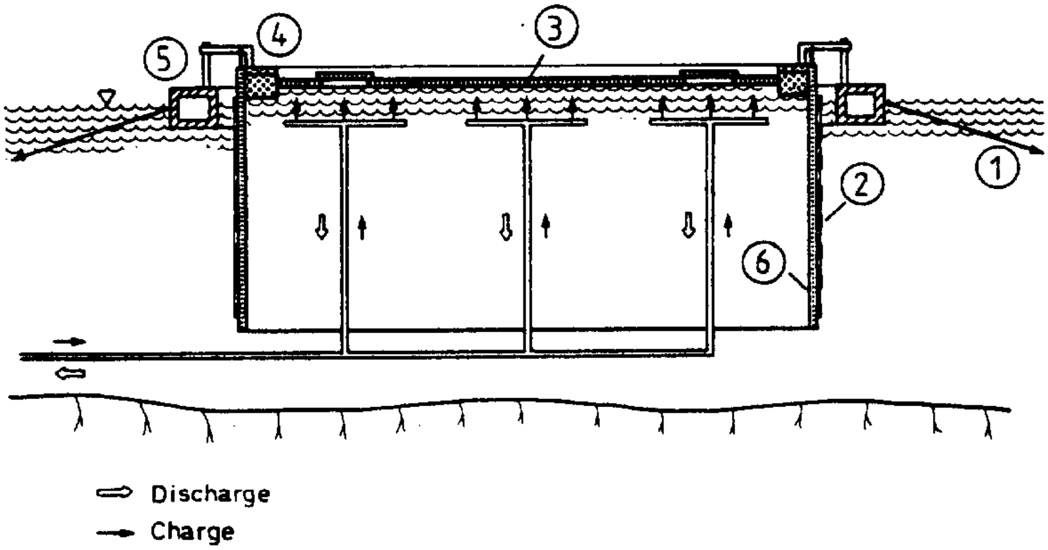
While these considerations suggest that the lake store will save considerable quantities of oil and be economically justified for long term storage where conditions are suitable, the initial application of smaller versions of the lake store may be for shorter term storage where it can achieve major cost reductions compared to the present for more expensive types of store in use.

3.7.5. Technical risk

The lake magazine presents a number of problems due to its special environment. The insulation and seeling sheets of the "curtains" must be capable of withstanding the action of hot water, ring cables or anchoring cables must resist corrosive action of hot or cold lake or sea water containing oxygen and in some case salt. Extra forces are imposed by currents, waves, wind and ice.

The aesthetic point of view (lake or bay recovered with thermal insulation) has not to be neglected.

FIGURE 14. DESIGN FOR A LAKE HEAT STORE FOR SEASONAL STORAGE OF HOT WATER (SWEDEN)



① Anchoring cable

② Watertight layer with titanium net

③ Surface insulation

④ Inner pontoon

⑤ Outer pontoon

⑥ Insulation blocks

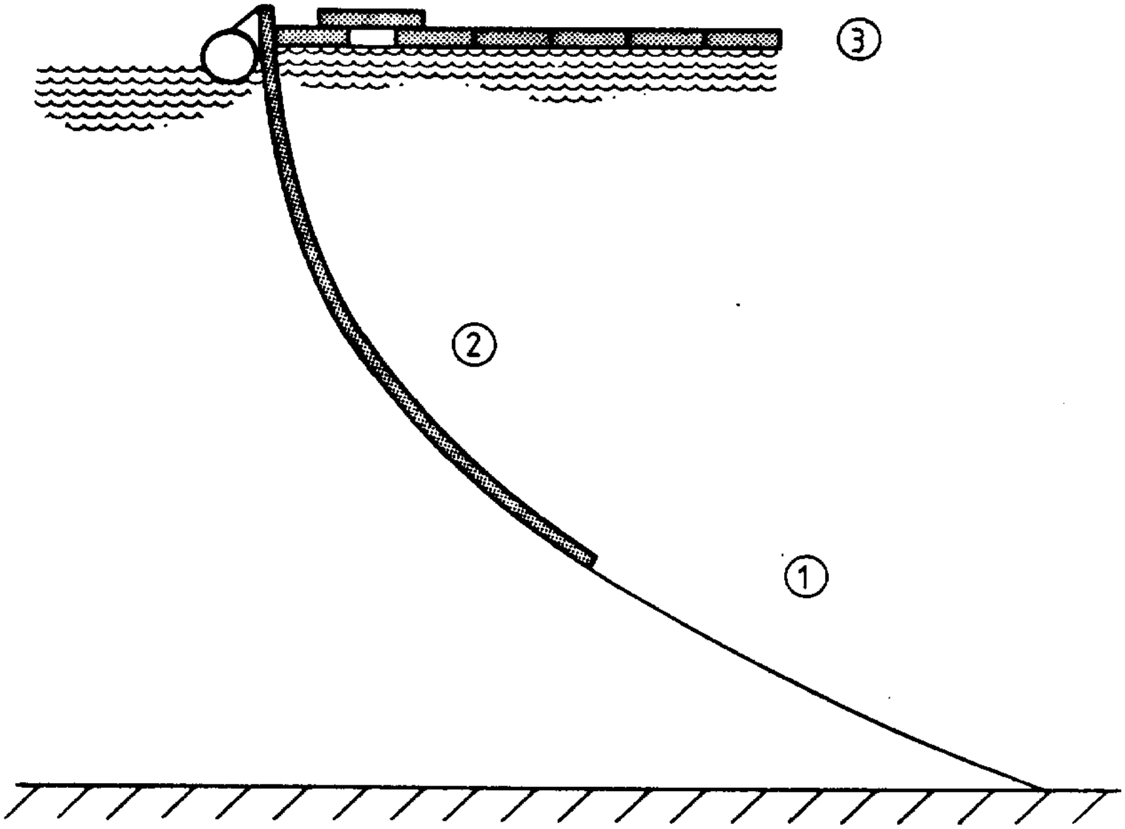


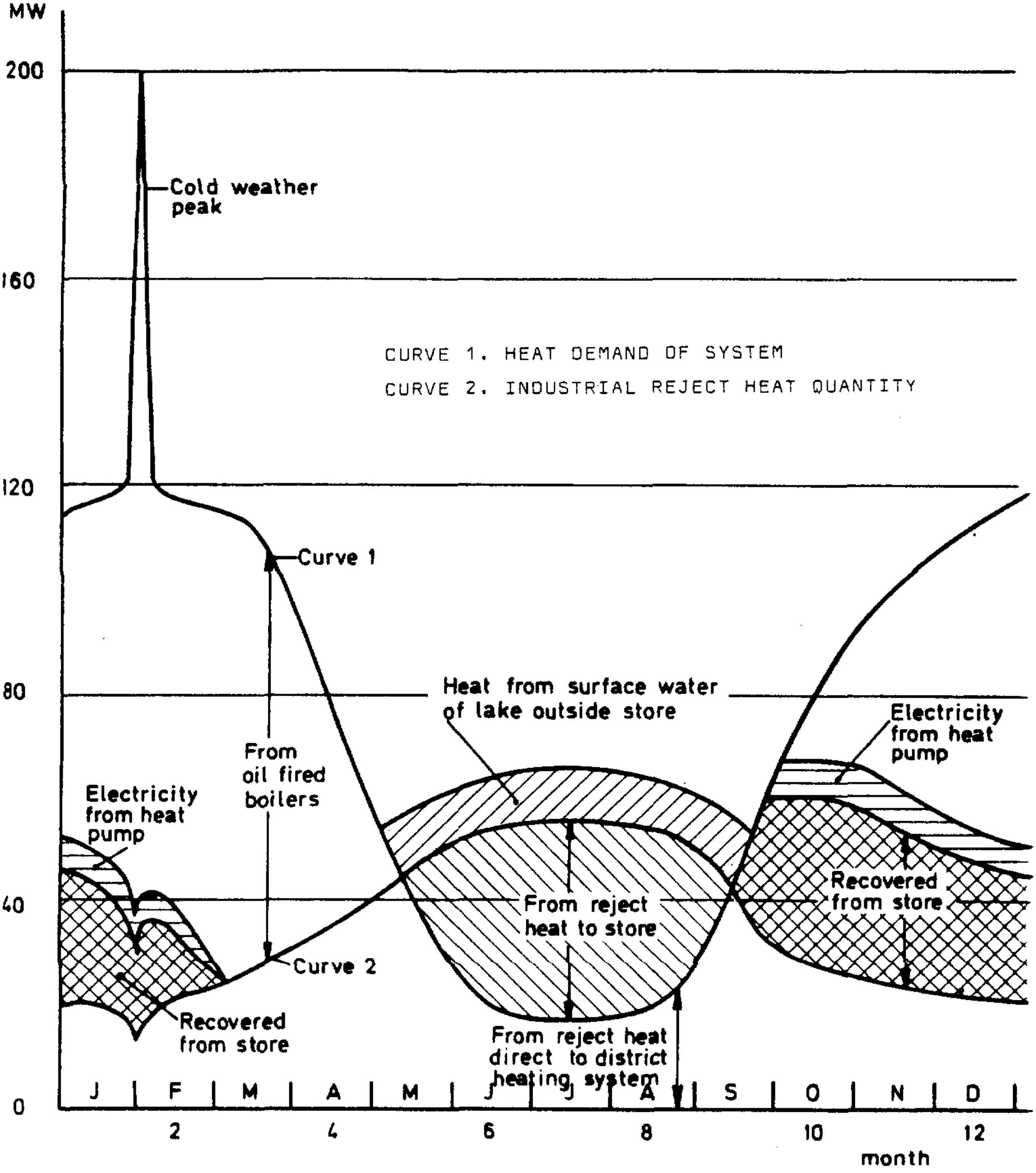
FIGURE 15. LAKE HEAT STORE : ANOTHER CONCEPT FOR SURFACE INSULATION AND SIDE WALL (SWEDEN)

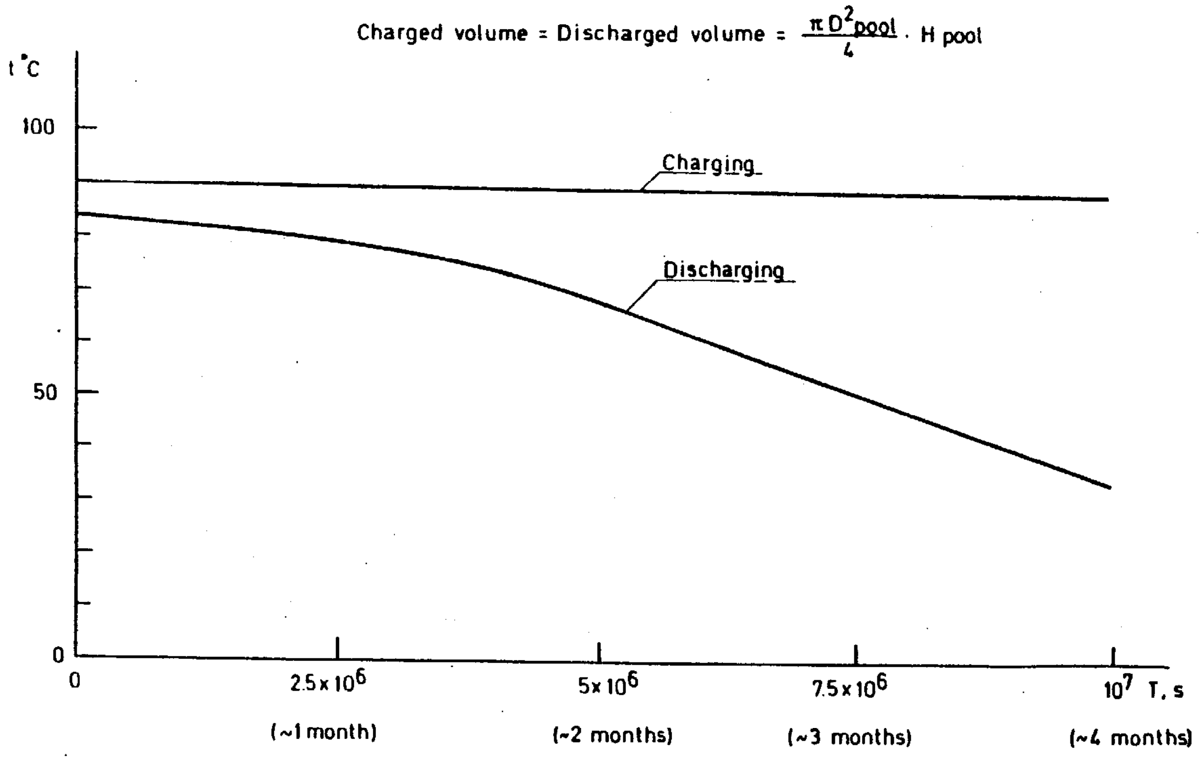
① Anchoring cable

② Side wall insulation

③ Surface insulation

FIGURE 16. LAKE HEAT STORE: SCHEMATIC PRESENTATION OF HEAT STORAGE CYCLE (SWEDEN)





*) Charging 4 months. Storage 1 month. Discharging 4 months.

FIGURE 17. CHARGING AND DISCHARGING TEMPERATURES IN A LAKE HEAT STORE (Sweden)

4. PRESENTATION OF IEA PROJECTS

4.1. Bellingham project (U.S.A.)

4.1.1. Technical description

The project is investigating the development of a district heating system in the city of Bellingham (Washington, U.S.A.). Energy will be recovered from a warm gas stream, the prime pollution control system, from Intalco Aluminium Company in Ferndale Washington. Energy will be transported to the city via hot (100°C) water. Storage couples the constant energy source to the variable demand of space heating and hot domestic water production. Title of the project is : Application of Thermal Energy Storage to Process Heat and Waste Heat Recovery.

Heat will be accumulated by means of 2 cylindrical steel tanks 3'400 m3 each. The accumulator is a daily type. The storage is intended to supply thermal energy to the network during the peak load with a maximum power of 200 MWh per day. The maximum temperature of the accumulator is 99°C, the minimum is 93°C. The store will be loaded for 95 % of the time and in service for 5 %.

4.1.2. Economic data

The total investment foreseen for the storage concept is the following :

- 2 bare tanks	.250	Mio	$	1980
- Foundations	.038	"	"	"
- Surface preparation	.029	"	"	"
- Insulation	.108	"	"	"
Total investment	.425	"	"	"
Specific investment	62	$/m3		

4.1.3. Project status

At the present time, the project is in the second of four phases. Construction of the store could start in 1984, and be in operation in 1985.

4.2. SPEOS PROJECT - DORIGNY / LAUSANNE (Switzerland)

4.2.1. Project description

The project is entitled SPEOS ("Stockage Pilote d'Energie par un Ouvrage Souterrain", "Pilot Underground Heat Storage"). It is to be built in the Lausanne periphery, at Dorigny.

The project concerns seasonal warm water storage in a saturated porous medium. The system is based on the concept of a vertical central well with two levels of horizontal radial drains. The main direction of injected and pumped water is vertical, to limit the influence of natural convection within the aquifer. Moreover, this geometry allows a good hydraulic control of the injected water and limits the water velocity near the drains.

In the SPEOS concept, heat can be provided by waste heat (industry, garbage) or by solar collectors. The water produced can be used to supply space heating for buildings. The concept is thus a seasonal storage for 300 to 1'000 inhabitants (storage capacity 1'000 - 5'000 MWh) designed to meet heating and top water demand, linked to solar collectors fields or waste heat producers.

SPEOS should be considered as a pilot plant for the first years (oil burners will be used) and as an operating plant with solar collectors for the following years.

If the accumulator operates between 70 and 25°C a heat pump should be used. The annual efficiency is then 75 %. If the accumulator operates between 70 and 40°C the use of a heat pump can be avoided, but the annual efficiency is then 40 %.

Size of the store : Diameter 44 m Height 19 m

Temperature in store : 70°C at injection
25 to 30°C at the end of winter

The heat produced will supply part of the load for a gymnastics hall which at present burns 60 metric tons of oil.

Finally it should be noted that in view of the low permeability of the ground in which the accumulator is placed, the installation of vertical sand drains is envisaged. The greater permeability of these drains ensures a better heat and water transfer.

4.2.2. Economic data

- Total investment for the store including pumps, heat exchanger, mesuring equipment	654'000	$ 1980
- Total investment pro cubic meter water equivalent	33	$
- Total investment in U.S. dollars pro kWh annually pumped out of the store	0,87	$/kWh
- Annual cost for operating and maintenance	14'000	$
- Maintenance cost pro kWh pumped out of the store	0,0018	$/kWh

4.2.3. Project status

The project for the development of an underground heat storage technology is directed by l'Institut de production d'énergie de l'Ecole polytechnique fédérale in Lausanne, and le Centre d'Hydrogéologie de l'Université de Neuchâtel.

The Dorigny site was given priority selection among 9 other sites investigated in Switzerland. The site was chosen for technical and administrative reasons.

Exhaustive geophysical and geological studies have been made concerning the Dorigny site, in order to get the best possible knowledge of the ground structure. Sixteen investigation boreholes have been made. A large diameter borehole (1 meter) made it possible to do 2 pumping tests, each of 20 days, and to measure the ground permeability. At the same time, laboratory tests were carried out to determine the chemical modifications which take place in the aquifer during heat storage.

A great number of simulations with finite elements models have been made, to get an appraisal of the disturbance behaviours and the storage production.

The technical study is at present entirely completed. The construction phase could begin in the weeks following the conclusion of financing agreements.

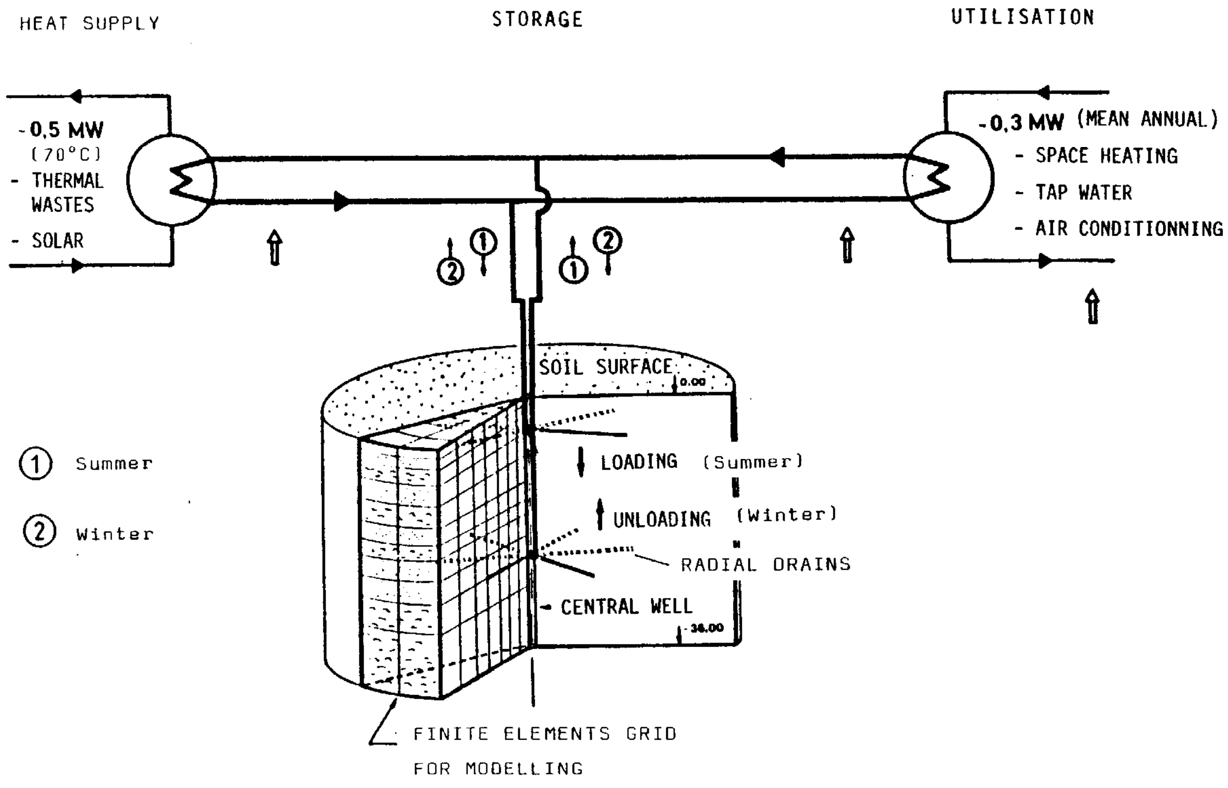
4.2.4. Financing status

In the short term, the Dorigny project seems to be the best candidate to serve as the basis for an IEA jointly-funded hardware demonstration project.

The financing of the design and preliminary field investigations has been assured by national funds.

The costs for construction and testing of the Dorigny installation for 3 years have been estimated to be 2.2 millions Swiss francs. Of this amount Switzerland will take the bill of 1.57 millions Swiss francs, the remainder being attributed by other the participating countries. The Operating Agent will propose a draft annex 3 describing the international cooperation for realization of this demonstration project.

FIGURE 18. STORAGE CONCEPT OF THE SPEOS-DORIGNY PROJECT



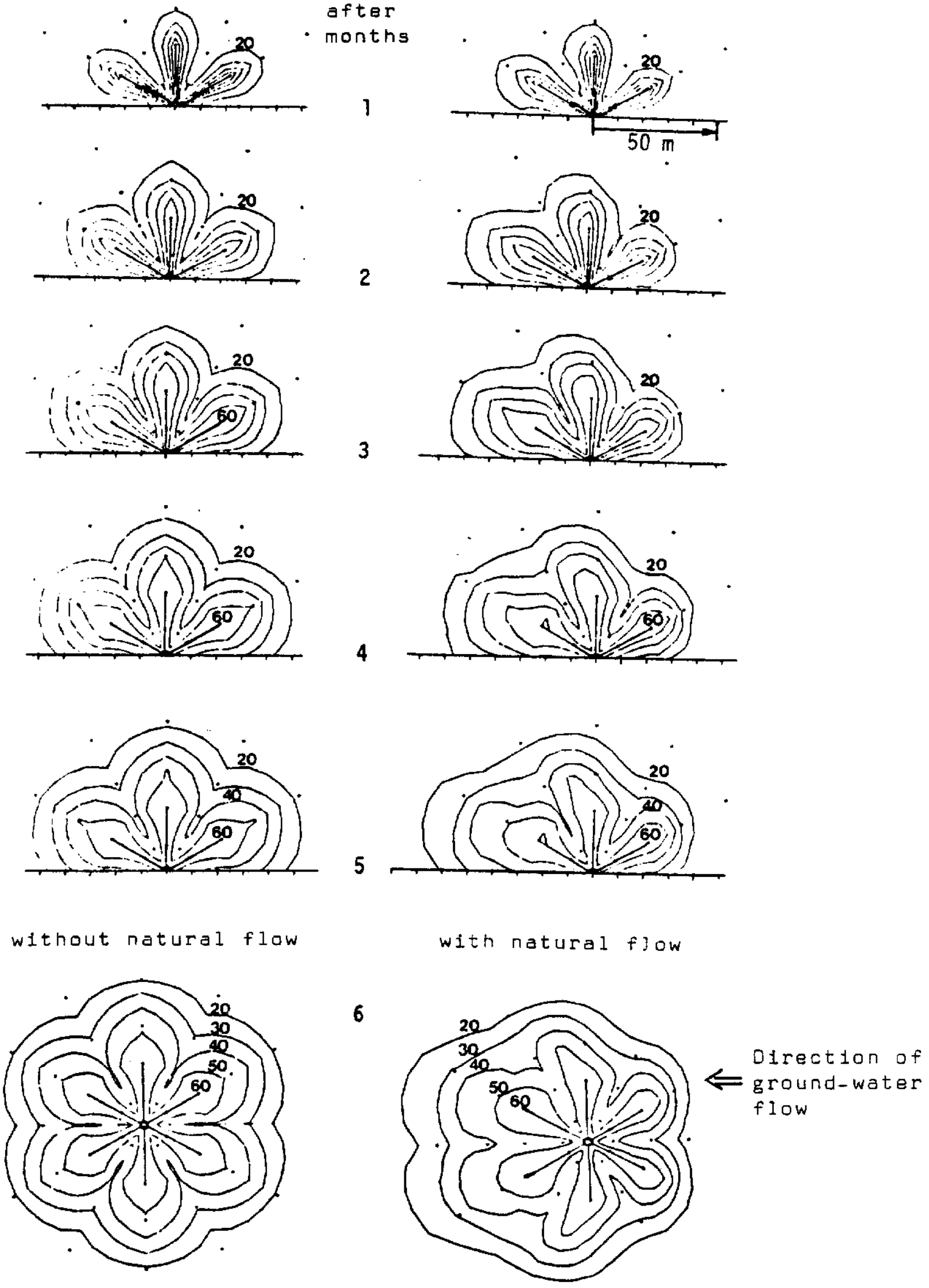


FIGURE 19. DEVELOPMENT OF THE TEMPERATURE FIELD IN THE UPPER DRAINS HORIZONTAL PLANE DURING INJECTION PERIOD (2.24 l/s) WITH AND WITHOUT NATURAL FLOW THROUGH THE ACCUMULATOR (SWITZERLAND)

4.3. HØRSHOLM Project (Denmark)

4.3.1. Project description

The Hørsholm site lies 25 km to the north of Copenhagen. The aim of the project is the seasonal and weekly storage of heat produced by a garbage burning plant. The plant actually exists, but part of the energy is lost because the production structure is not well adapted to consumer demand. The plant at present supplies a district heating network.

The function of thermal energy storage will be partly to store heat from work days to weeks-end during the summer and partly to store heat from summer until winter (August to November). The energy saving resulting from the introduction of weekly storage are about 6'000 MWh/year. The energy saving resulting from the introduction of bi-monthly storage are about 2'500 MWh/year. At present the average and usual forward temperature is as high as 105°C while the return temperature during winter is 65°C and during summer 75°C.

The thermal energy store (aquifer) considered is situated on a branch of the system where the heat consumption is due to a small number of institutions. It is possible to isolate this branch of the system, and by lowering the temperature in this part of the system, it should be possible to improve the effective heat recovery from the thermal energy store. The aquifer is partially confined and partially free.

4.3.2. Economic data

- Total investment for the store including equipment	537'000	$ 1980
- Total investment pro cubic meter water equivalent	15	$/m3
- Total investment pro kWh annually pumped out of the store	0,20	$/kWh
- Annual cost for operating and maintenance	19'000	$/year
- Maintenance cost pro kWh pumped out of the store	0,007	$/kWh

4.3.3. Status of the project

The final goal of the Danish aquifer storage project is to establish a pilot warm water storage plant. The project is a cooperative effort between three institutions.

- The Technical University of Denmark
- Risø National Laboratory
- Geological survey of Denmark

The project was started in the summer of 1978 and is expected to run until the end of 1982.

The Hørsholm site was selected following several investigations on Danish territory. Hørsholm was chosen firstly for geological reasons and also because it is situated near a district heating system and a garbage burning plant.

Geoelectrical surveys and 5 test wells have been made. Preliminary pumping tests and a pumping test with constant capacity have been designed for determination of the hydraulic properties and boundary conditions of the aquifer and the leakage factor of the confining bed. Samples of ground water, aquifer material and the confining clay have been taken for chemical and mineralogical analysis.

A two-dimensional aquifer flow model has been used to study buoyancy effects. It has been shown that high values of the aquifer permeability ($k > 50$ Darcy) combined with aquifer height H larger than 20 m gives rise to highly undesirable convective currents at injection temperatures in the interval 80 - 100°C. Stable flow conditions were found at lower values of the aquifer permeability ($k < 15$ Darcy and $H = 20$ m).

Technical study for the store is now nearly finished.

4.3.4. Financing status

The Government of Denmark will assume the total investment and maintenance cost for the Hørsholm demonstration plant.

FIGURE 20. HØRSHOLM: THE PRINCIPLE OF AQUIFER THERMAL ENERGY STORAGE. (DENMARK)

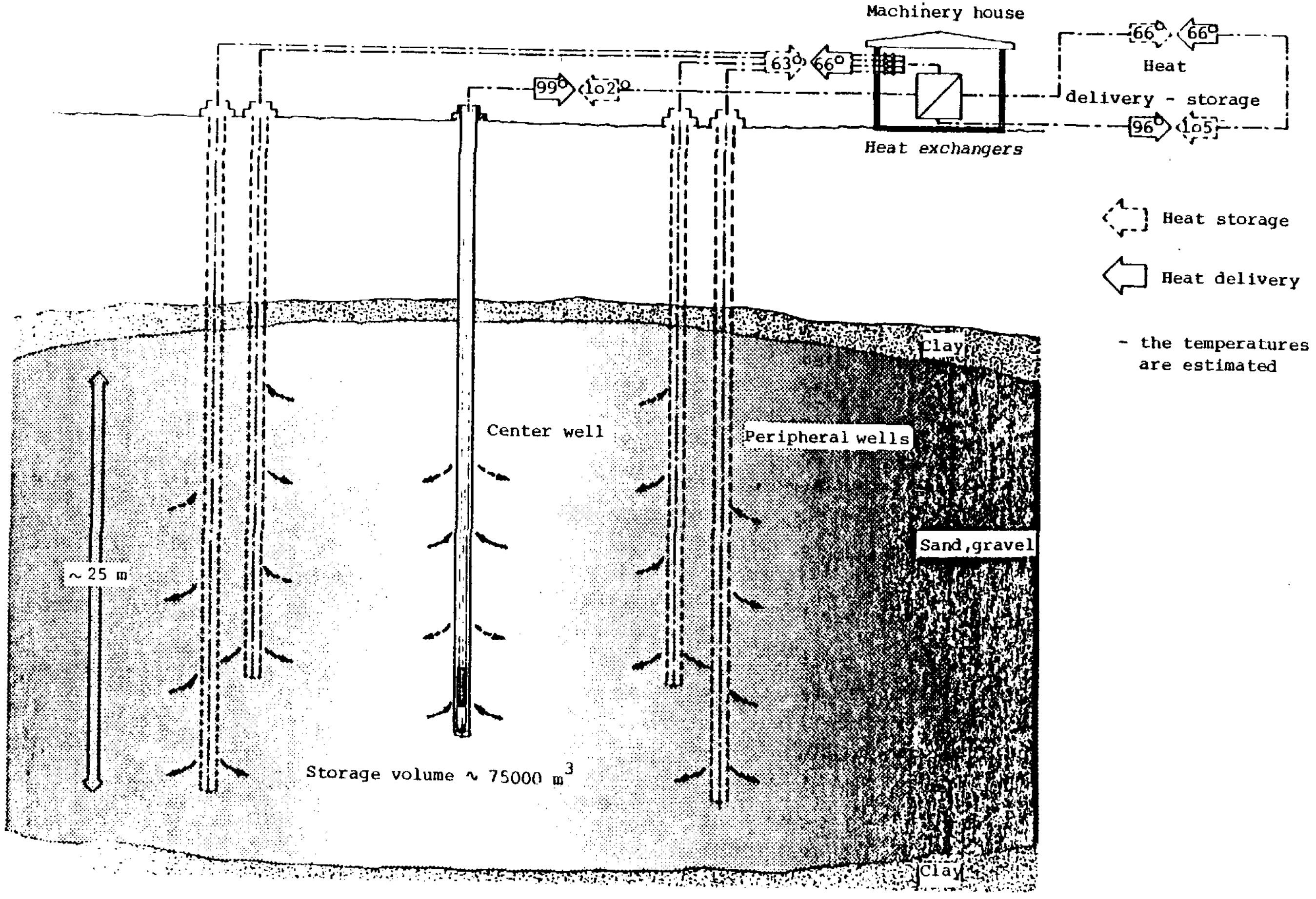


FIGURE 21. SITE OF HØRSHOLM. TYPES OF WELLS.

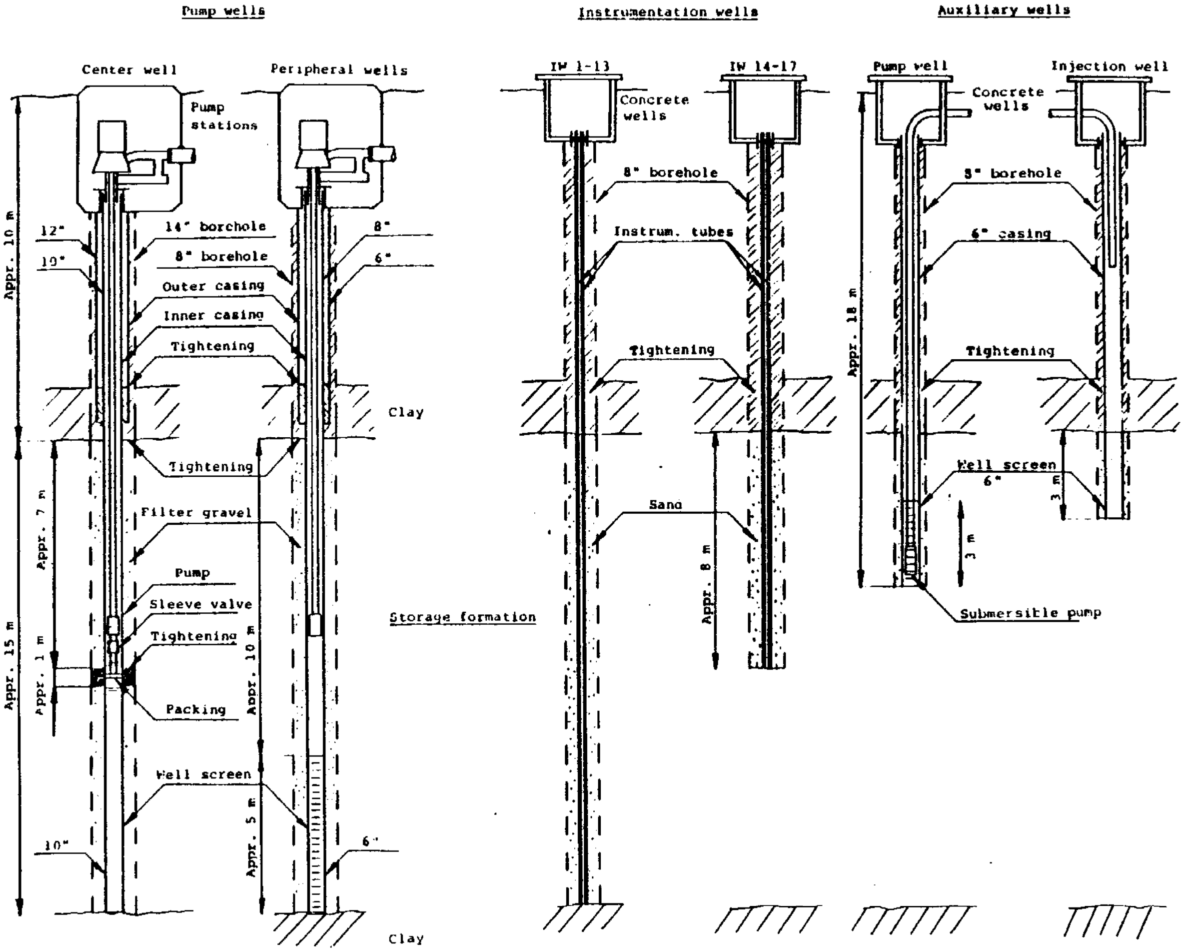
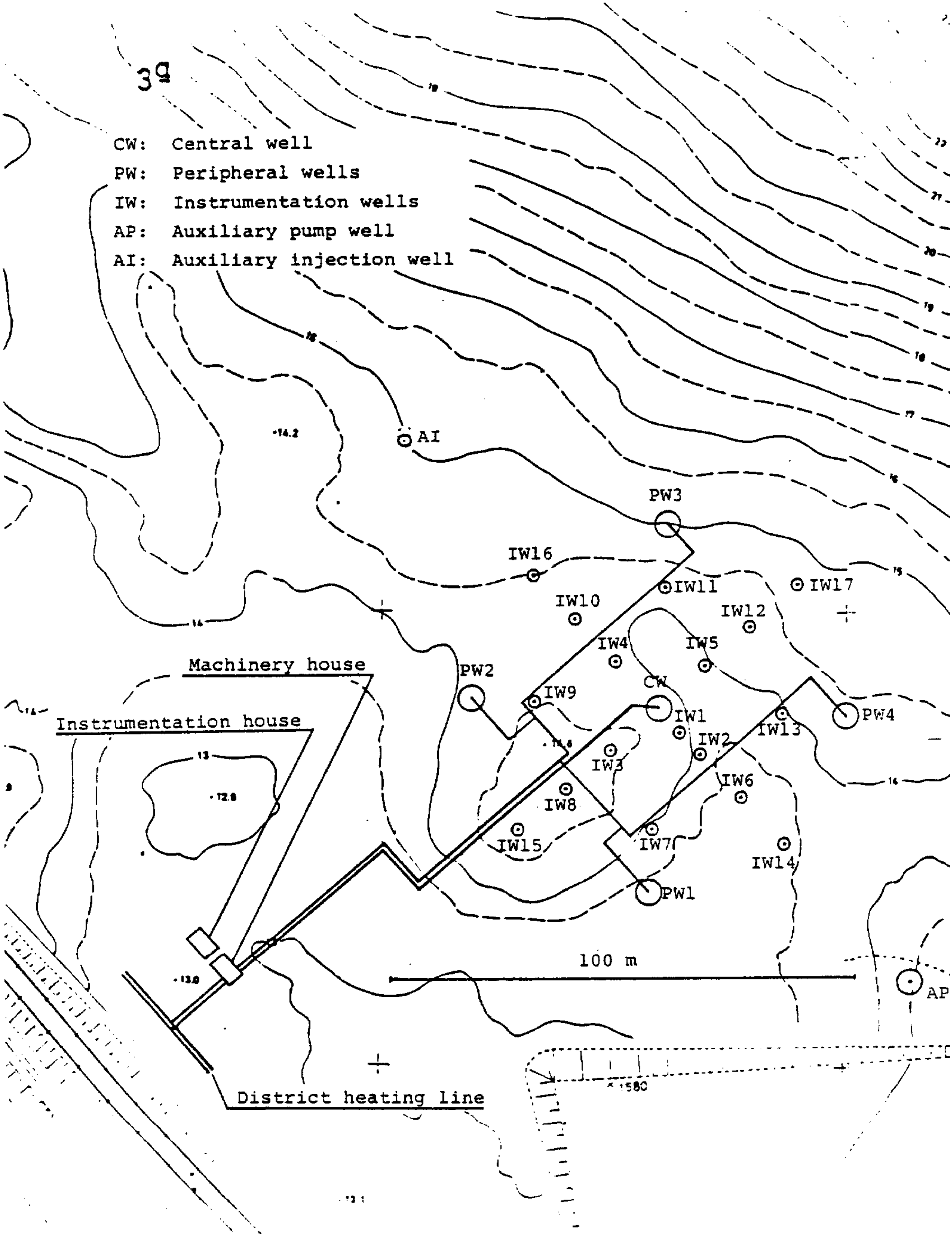


FIGURE 22. MAP OF THE STORAGE AREA IN HØRSHOLM



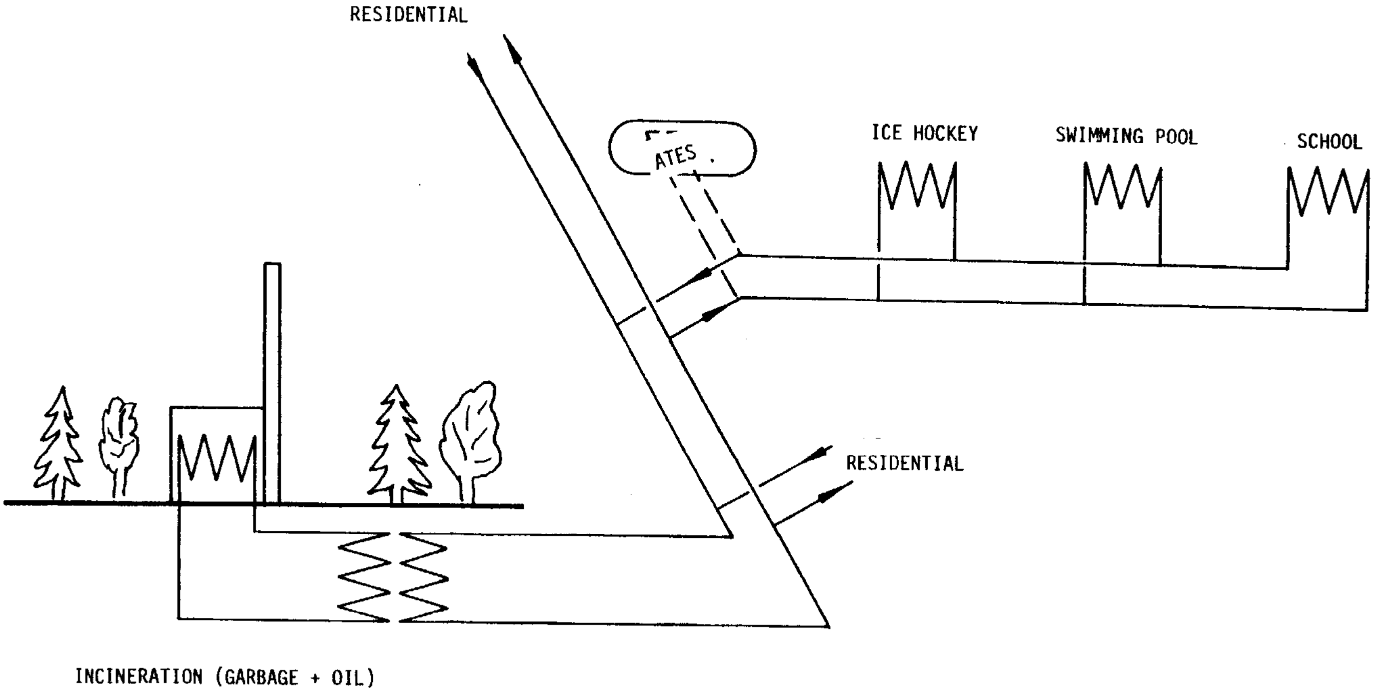
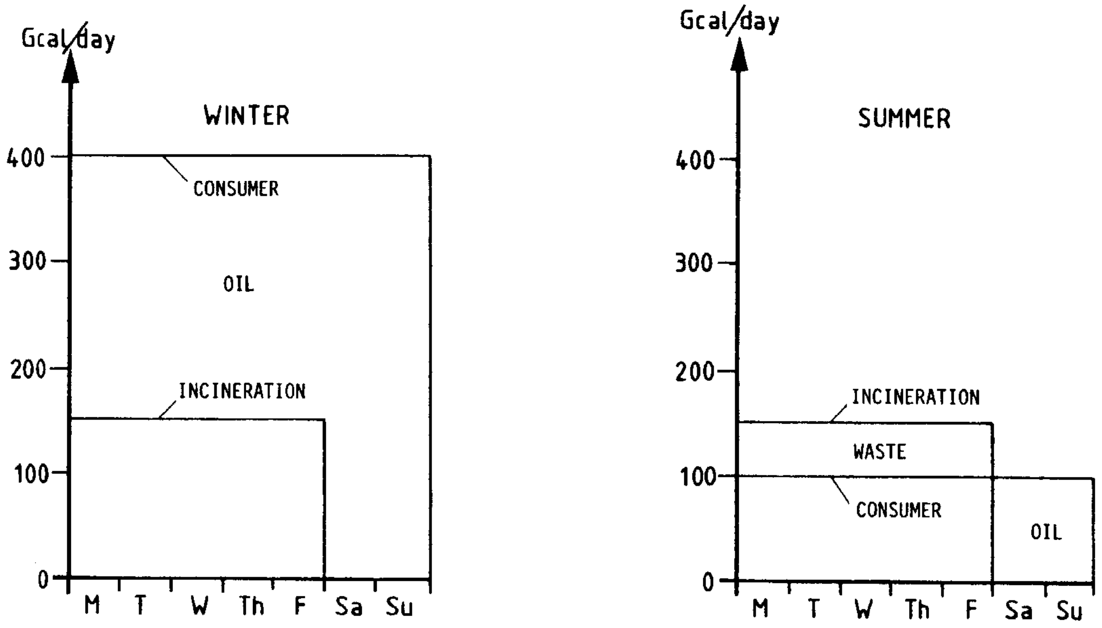


FIGURE 23. Site of Hørsholm. Schematic diagram showing distribution of heat from the store.

FIGURE 24.



SCHEMATIC PRESENTATION OF DEMAND AND SUPPLY OF HEAT IN HØRSHOLM

4.4. KLIPPAN - STIDSVIG Project

4.4.1. Project description

The project presented is intended to test the possibility of storing heat in Quaternary geological formations frequently found in Scania : the Eskers. A free aquifer is generally to be found near the surface in these formations.

The energy supply is based on the waste heat of an industry. The energy is consumed in a district heating network in the town of Stidsvig. The injection and pumping temperatures are low, and it is necessary to use a heat pump.

The economic study showed that the storage temperature should be higher. Otherwise, the storage was not an economic proposition. An oil furnace covers the peak load of the district heating system.

4.4.2. Economic data

- Total investment for the store including equipment	1'400'000	$
- Total investment pro cubic meter water equivalent	4,3	$/m3
- Total investment pro kWh annually pumped out of the store	0,36	$/kWh
- Annual cost for operating and maintenance	114'000	$
- Maintenance cost pro kWh pumped out of the store	0,03	$/kWh

4.4.3. Project status

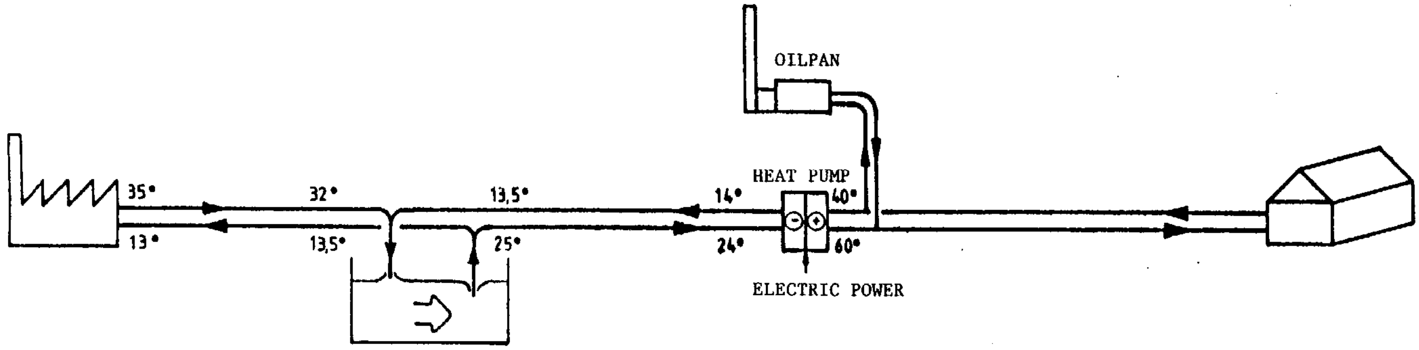
The study concerning the Klippan storage is being carried out by the Royal Institute of Technology in collaboration with the VBB Engineering office.

The basic evaluation of the storage aquifer system, including technical and economical studies, is now finished.

A two-dimensional finite elements model has been made to test the effect of a thermal doublet on the regional outflow of the aquifer. Several tests have been carried out to find the optimal geometry for the storage constructions.

The second phase of the study includes the storage system design. It is at present being carried out and comprises :

- storage tests (heated water infiltration)
- aquifer analysis (re-evaluation of thermohydraulic parameter)
- storage system design (geometry and operation)



EXTRACO LTD	TRANSMISSION LINE	HEAT STORAGE	TRANSMISSION LINE	HEATING PLANT	HEATING NETWORK	200 HOUSES
	$E = 2{,}86 \cdot 22/10 =$ $= 6{,}29$ Gwh/år	WATER FLOW $121 \cdot 85 \cdot 24 \approx 250000 \, m^3/$år	$E = 3{,}96 - 1{,}10 =$ $= 2{,}86$ Gwh/år	$E = 3{,}96/3{,}6 =$ $= 1{,}10$ Gwh/år	$E = 3{,}60 \cdot 1{,}10 =$ $= 3{,}96$ Gwh/år	$E = 18000 \cdot 10^{-6} \cdot 200 =$ $= 3{,}60$ Gwh/år
	$H = 6{,}29 \cdot 10^{3}/(85 \cdot 24) =$ $= 3{,}08$ Mw	STORAGE VOLUME $125000/0{,}25 = 500000 \, m^3$	$H = 1{,}60 - 0{,}45 =$ $= 1{,}15$ Mw	$H = 1{,}60/3{,}6 =$ $= 0{,}45$ Mw	$H = 1{,}60 \cdot 1.10 =$ $= 1{,}76$ Mw	$H = 8 \cdot 10^{-3} \cdot 200 =$ $= 1{,}60$ Mw
	$Q = 121 \, m^3/h = 33{,}6 \, l/s$		$Q = 99 \, m^3/h = 27{,}5 \, l/s$		$Q = 76 \, m^3/h = 21{,}1 \, l/s$	

FIGURE 25. SITE OF KLIPPAN - STIDSVIG: HEATING SYSTEM

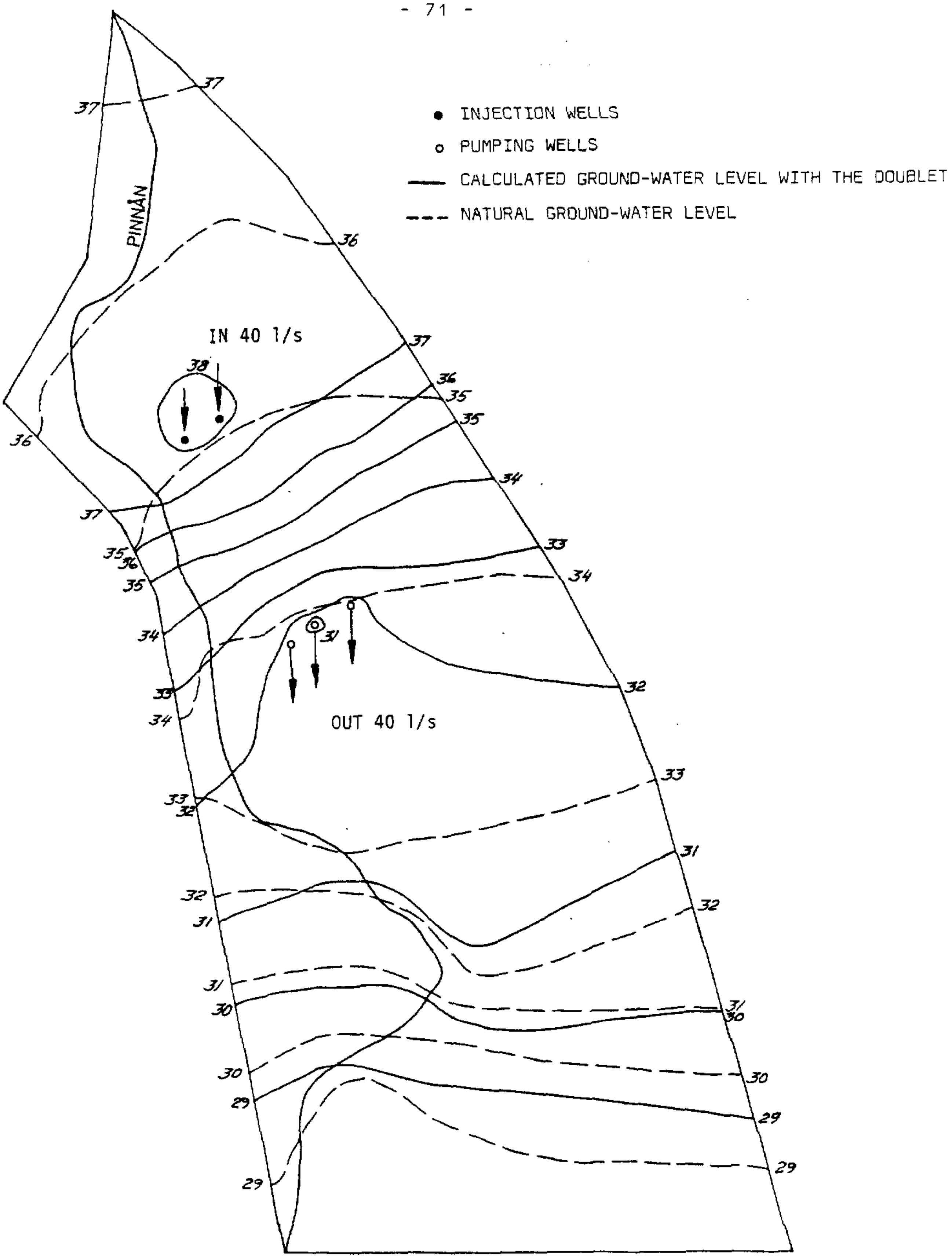


FIGURE 26. SITE OF STIDSVIG. NATURAL GROUND-WATER LEVEL (----) AND CALCULATED GROUND-WATER LEVEL (——) WITH AN 40 l/s INJECTION - PUMPING DOUBLET.

4.5. University of Minnesota Ates Project

4.5.1. Project description

The aims of the project are the construction of a high temperature heat accumulator (150°C) which can be linked to a district heating system operating at high temperature. The project's originality resides in the high temperature of the store, its volume ($4 \cdot 10^6$ m3) and the depth of the aquifer (210 - 280 m). The heat stored will be supplied by a cogeneration plant during summer months and will be used in winter to cover peak heating demands.

The information given is however incomplete and does not allow a precise description of the storage system used to be given (single well, doublet ?).

4.5.2. Economic data

Construction costs are undetermined at this time. It is estimated that the total cost will be in the range of $4 to $8 million, spread over a period of three years.

4.5.3. Project status

The project is directed by the University of Minnesota. Other major participants are :

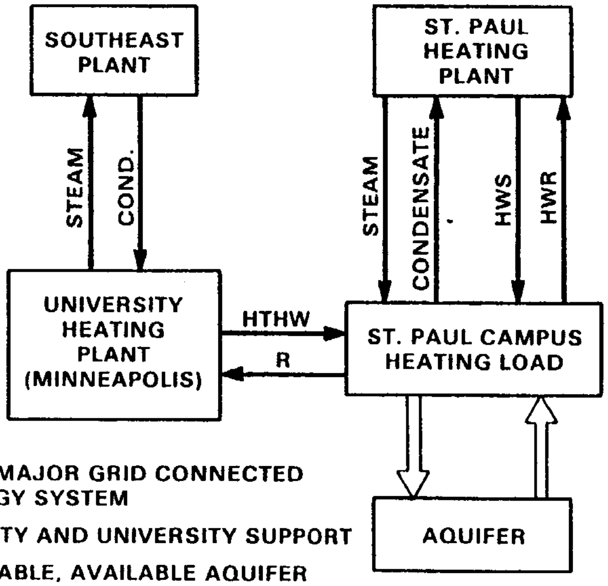
- Honeywell Technology Centre
- GE Tempo
- US Geological Survey
- Minnesota Geological Survey
- Minnesota Energy Agency

The first operational storage should take place in 1983. Project is in design stage. Until aquifer characterization is complete, temperature and energy recovery data can only be approximated. The conceptual design of the project should be completed in 1982.

4.5.4. Financing status

Design, construction and investment outlay will be financed by the United States Government and the University.

UNIVERSITY OF MINNESOTA
HTH
ST. PAUL, MINNESOTA



OTHER MAJOR PARTICIPANTS

HONEYWELL TECHNOLOGY CENTER
GE - TEMPO
USGS
MINN. G.S.
MINN. ENERGY AGENCY

ENERGY SOURCE

COGEN STEAM

USER APPLICATION

DISTRICT HEATING

AQUIFER

F.I.G.-
CONFINED
200'-300' THICK
CHARACTERISTICS
IDEAL FOR STORAGE

- — INTEGRATED INTO MAJOR GRID CONNECTED COMMUNITY ENERGY SYSTEM
- — STRONG COMMUNITY AND UNIVERSITY SUPPORT
- — WELL KNOWN, RELIABLE, AVAILABLE AQUIFER
- — ENERGY SOURCE AND USER APPLICATIONS IN PLACE AND RELIABLE
- — LAND RIGHTS HELD BY PROJECT ORGANIZATION

FIGURE 27. ST. PAUL - MINNESOTA PROJECT'S MANAGMENT

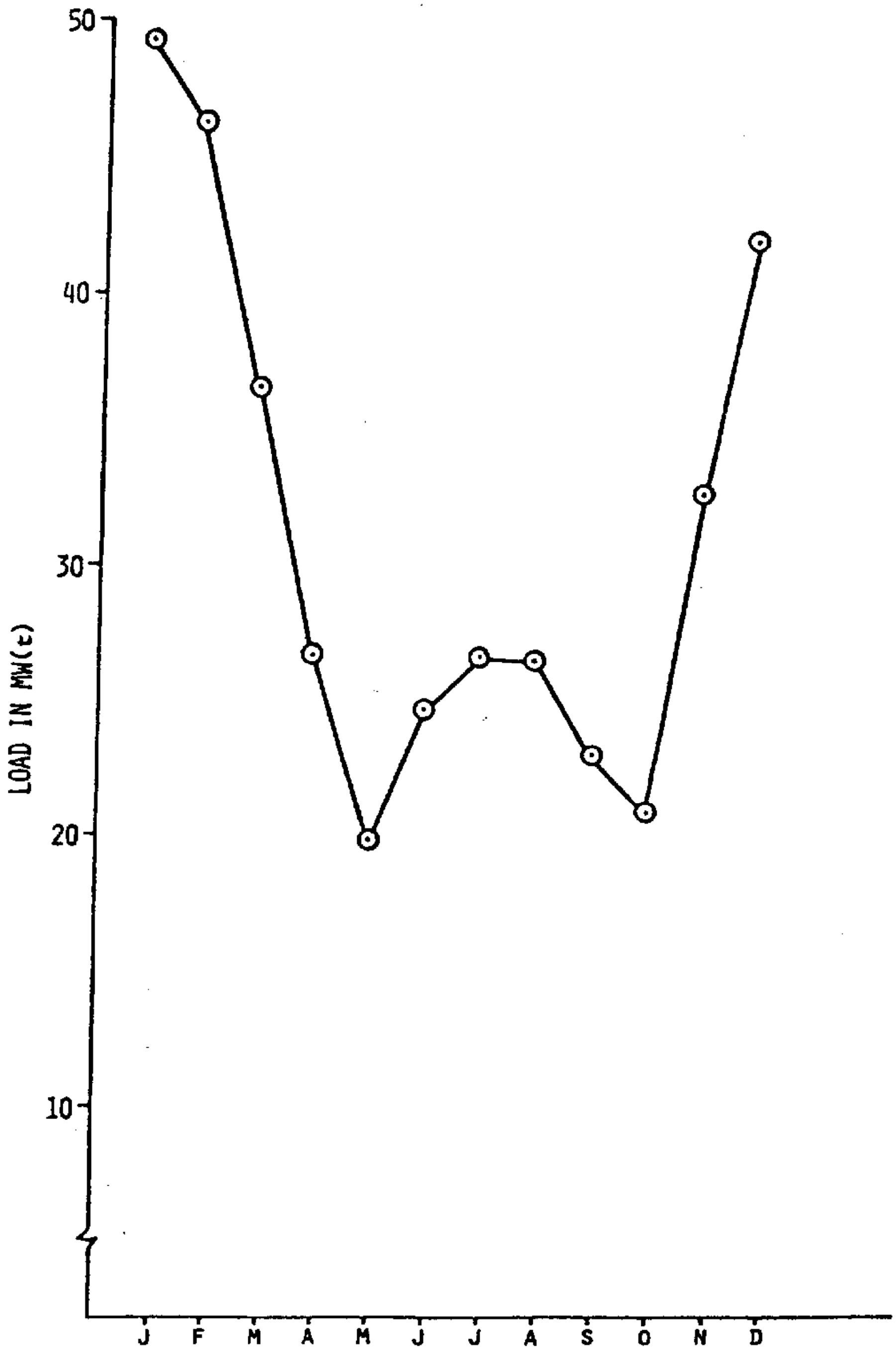


FIGURE 28. PROJECTED 1980 -1981 AVERAGE MONTHLY DEMAND FOR ST. PAUL CAMPUS

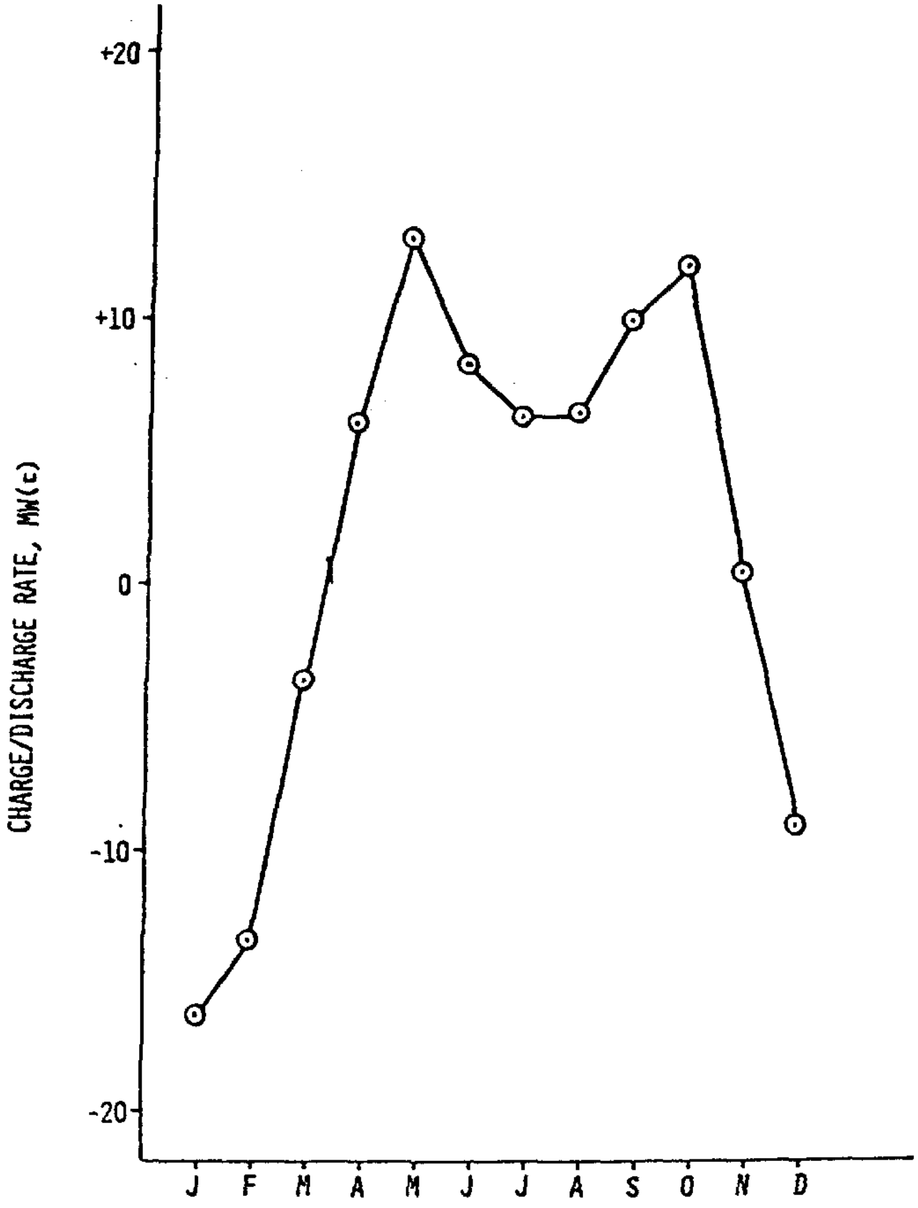


FIGURE 29. ST. PAUL - MINNESOTA: AQUIFER CHARGE/DISCHARGE HISTOGRAM

4.6. Munich-Grosshadern (CEC -GERMANY)

4.6.1. Objectives

- Demonstration of the feasibility of a heat storage system in near surface ground water, and of the possibility of branching the storage system to a heating network. Proof of the economical character of the installations.
- Acquisition of technical data (yield, operational), and of their limits.
- Definition of specifications for aquifer storage generally.
- A search for the operating conditions which will make underground heat storage an economical technique.

Research supported by the CEC is to be effected in 4 phases, i.e. :

Phase I	Preliminary experiments on the chemical composition of water, and definition of the project for an experimental accumulator.
Phase II	Construction of the accumulator and tests.
Phase III	Prolonged experimentation on the storage system (2 to 3 years).
Phase IV	Branching of installations and operating over a prolonged period.

4.6.2. Technical description of demonstration project

Choice of a site

The site chosen for the execution of the project lies in the grounds of the München-Grosshadern clinic. The ground consists of a gravelly aquifer 15 meters thick. The natural aquifer level is at -11 meters, impermeable layer at -15 meters. The heat store is hydraulically isolated from the aquifer by a bentonite wall prepared on the site. The upper layer consists of 1.5 meter of coarse gravel sandwiched between two layers of bitumen. The lower layer functions as a vapour barrier, the upper layer as a barrier against infiltration.

Heat injection and withdrawal are effected by horizontal drains connected on a central well. The accumulator consists of the original ground material which has been rehandled, gauged and washed. A system for measuring the temperature and quality of the water is provided for.

Branching of the installation and thermal studies

The accumulator will not be permanently branched to the clinic's air-conditioning installations until it has been in service for 3 years. Preliminary trials are provided for (Phase III) in the following temperature ranges :

- 95° / 60°C	Remote control heating
- 60° / 45°C	Heat pumps
- 40° / 30°C	Heat pumps
- 6° / 20°C	Waste heat coming for example from the air-conditioning system.

In the final period, (Phase IV) it is planned to use the München-Grosshadern store for storage of waste heat coming from the clinic's air-conditioning system. Storage will be on a daily, and partly on a weekly basis.

4.6.3. Economic data

The combining of cold-storage and waste heat, linked to an air-conditioning and heating installation is a very attractive proposition from an economic point of view.

Up to 1973, on account of extremely low energy costs, heat storage over and above a period of one day was not economical. With the lowering of storage costs, regulation of thermal demand over a period of 15 days becomes an economically attractive solution, even with storage systems of the more conventional type.

4.6.4. Financing status

The Study of the Commission of the European Communities concerns the theoretical and experimental feasibility study for an aquifer heat storage system. This study is executed in the framework of the EC Energy Conservation R & D Programme by Messerschmidt-Bolkow-Blöhm. Financial support is assured at 50 % by the Commission of the European Communities and at 50 % by the Federal Republic of Germany, (BMFT).

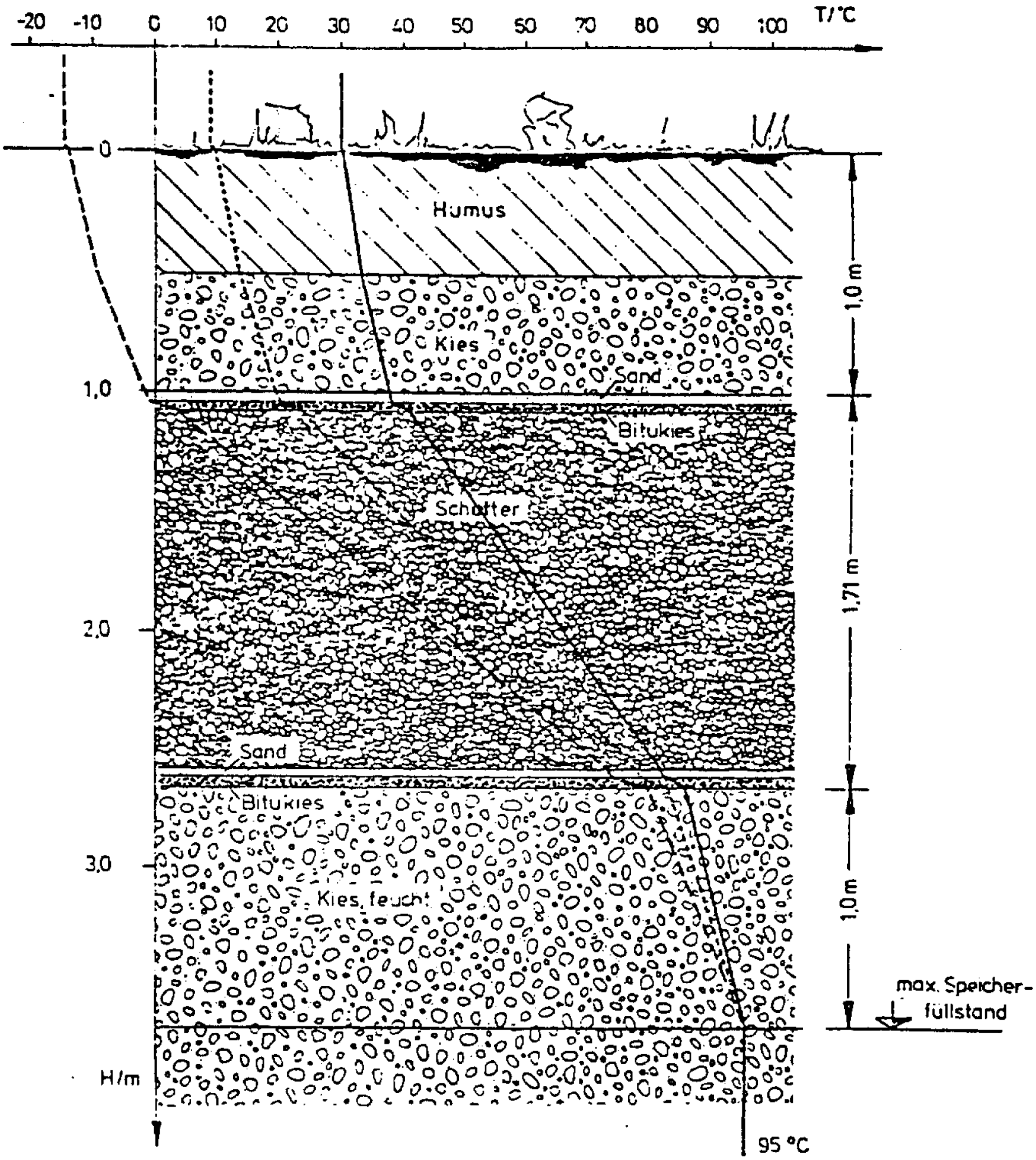


FIGURE 30. STEADY STATE TEMPERATURE GRADIENT FROM SOIL SURFACE TO THE TOP OF THE ACCUMULATOR IN GROSSHADERN-MUNICH.

4.7. Mons demonstration project (Belgium)

4.7.1. Technical description

The Belgium project which started in September 1978 is a part of a national research and development programme on energy established under the auspices of the Belgian Government. Management of the project is carried out by the Faculté polytechnique de Mons.

Large diameter turbodrilling

Devised in USSR and developed in Czechoslovakia between 1962 and 1968, this method has not been used in Western countries up to now. It consists in a drilling head with conventional rockbits arranged in a satelliste configuration. Drilling head is driven by turbodrills feeded with mud from the drill string. The drilling head turns freely round the axis of the hole under the action of resulting reactive tarque. Advantages of such a system are the following :

- High rate of penetration
- No special equipment except for mud distribution
- Low cost of drilling

However, pumping capacity and consequently energy consumption are important.

Experimental studies in vertical storage tanks

The experimental field is located near the Deep Drilling, Exploration Engineering and Rock Mechanics Laboratory of the Faculté polytechnique de Mons. The components of the circuit are a vertical cylindrical tank, consisting of a 25 m deep drilled hole with 9-5/8" A.P.I. casings, a cold water reservoir and a 93 KW heating unit.

The experiment was started by heating the water in the storage tank to about 90°C,using the heater unit. When the water has reached 90°C, the heater is turned off and the tank is connected to the cold water reservoir. Cold water is then injected into the storage tank at a flow rate of 50 to 250 liters pro minute. The thickness of the mixing layer is determined by analyzing the response from a serie of thermal probes placed at different depths in the experimental tank. It was measured that the thickness of the mixing layer was quite significant. As an example, considering a storage tank with a diameter of 2 m, height of 220 m, and a daily storage cycle, the thickness of the mixing layer is 24 m.

Pilot project

Dimensions selected for the storage tank are compatible with the current technological requirements : 3,5 m for the diameter of the drilled hole; 3,2 meters for the diameter of the storage tank; 0,2 m for the thickness of the cement ring and 480 m for the depth of the storage tank. No informations are given at this time about connection of the store to a producer or a consumer of heat.

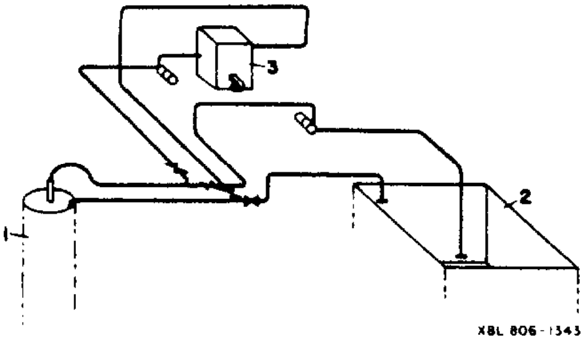


FIGURE 31. EXPERIMENTAL CIRCUIT AT FACULTE POLYTECHNIQUE DE MONS.

1. HEAT STORAGE TANK (25 m DEEP)
2. COLD WATER RESERVOIR
3. BOILER

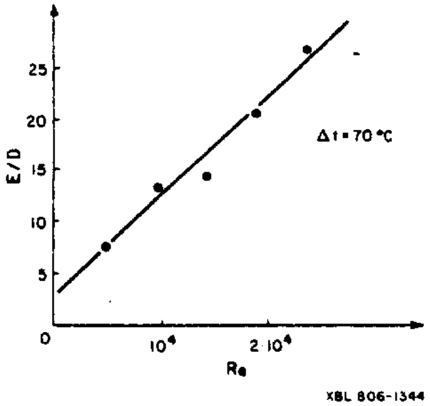


FIGURE 32. EXPERIMENTAL STUDY OF THE MIXING OF HOT AND COLD FLUIDS.

E = THICKNESS OF THE MIXING LAYER
D = DIAMETER OF THE STORAGE TANK
Re = REYNOLDS NUMBER

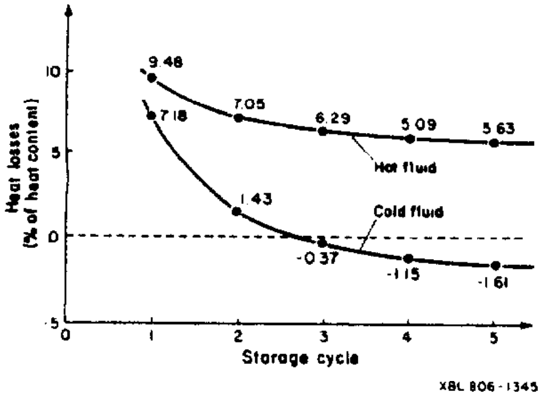


FIGURE 33. LARGE-DIAMETER DRILLED STORAGE TANK LOSSES IN THE GROUND DURING DAILY STORAGE CYCLE. EVOLUTION OF GLOBAL HEAT LOSSES FOR HOT AND COLD FLUIDS.

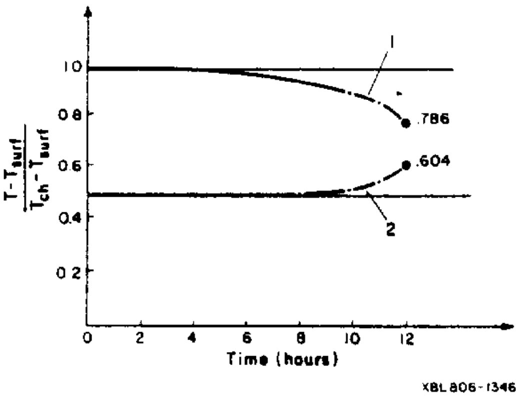


FIGURE 34. LARGE-DIAMETER DRILLED STORAGE TANK LOSSES IN THE GROUND DURING DAILY STORAGE CYCLE.

1- TEMPERATURE PROFILE DURING UNLOADING PERIOD (DIURNAL)
2- TEMPERATURE PROFILE DURING LOADING PERIOD (NOCTURAL).

FIGURE 31 - 34.

VERTICAL CYLINDRICAL STORAGE TANK. PILOT PROJECT MONS. TECHNICAL DATA.

4.8. Ebenhausen project

4.8.1. Project description

The Ebenhausen plant is designed for incineration of special wastes from a wide area of Bavaria, Germany. It uses the heat produced for the generation of electricity, working continously throughout the whole year. Every year is one regular shut-down of the plant for overhauling purposes. It turned out during the first five years of operation, that 4-6 unplanned shut-downs occur in addition to that, due to the difficult properties of the special wastes burned. These shutdowns lead to interruptions of up to 7 days.

From the steam turbine, a heat load of 11 MWth (in Winter) to 13 MWth (in Summer) can be discharged at a temperature level of 110°C. Within a range of 2 km around the plant there are several heat users :

- 5 smaller industrial customers
- public customers (school, administration building, etc)
- residential customers (1'500 inhabitants)
- small conditioning plant for agricultural products.

The overall maximum heat demand in winter is 8,8 MWth. The average heat demand and heat supply are given in Fig. 35.

To meet the heat demand during unplanned shut-down times, a reserve boiler has to be installed, being able of covering the winter peak demand of heat. To dimension the heat load of the reserve boiler, the following assumptions are taken :

- Regular overhauling in July : 331 MWhth
- For shut-down periods of 7 days each

  January : 1'396 MWhth

  March : 1'078 MWhth

  April : 833 MWhth

  October : 791 MWhth

Covering these shut-down times by the reserve boiler gives an overall heat-demand of 4'430 MWhth. Given an efficiency of 80 %, 5'540 MWhth have to be produced by burning oil and could be saved by the reserve boiler. Given an oil price of 0.65 DM/l this leads to annual costs of 336'000.- DM. Three options with different boiler-sizes have been studied :

7'150 m3 - 27'500 m3 - 39'900 m3

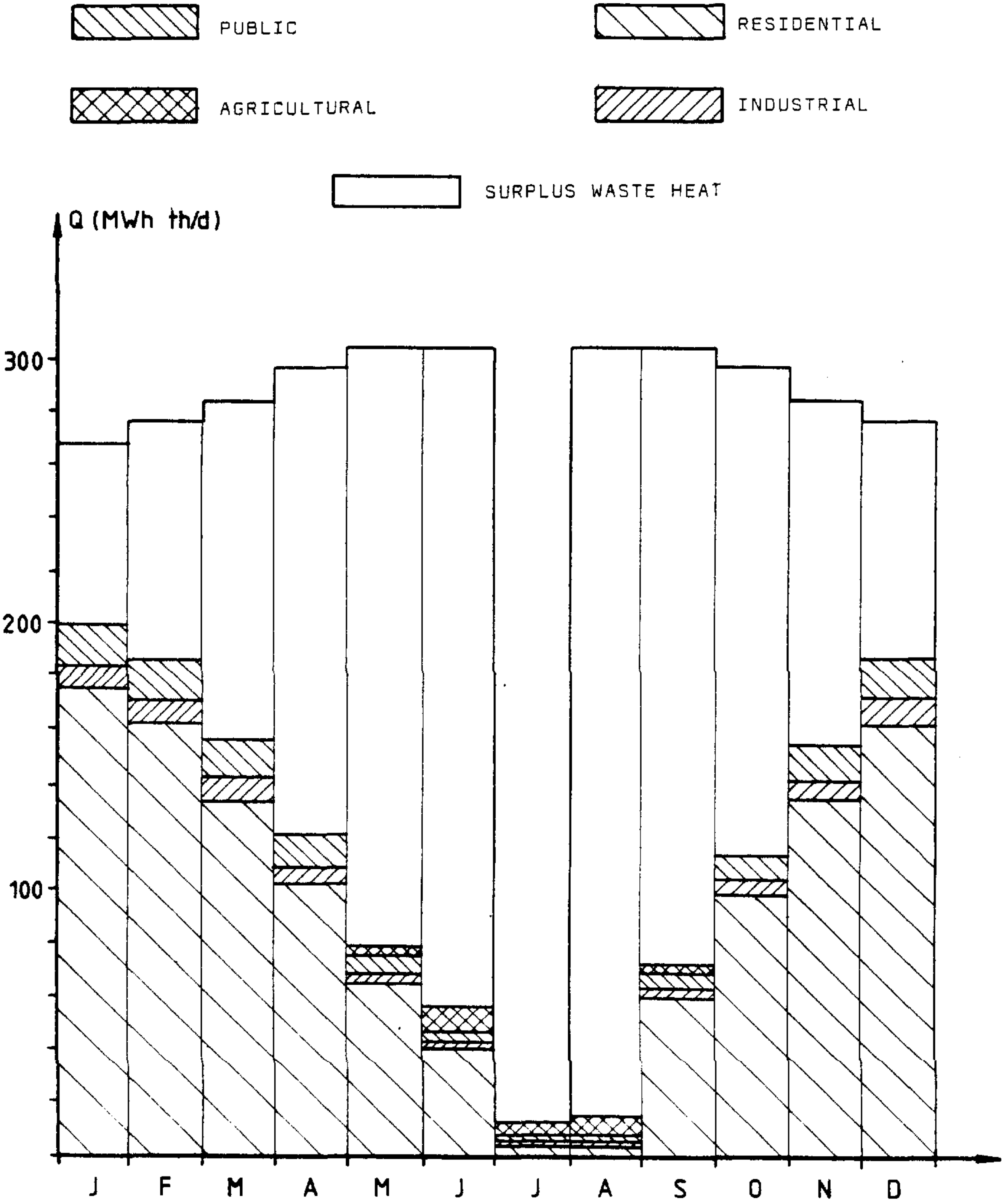


FIGURE 35. EBENHAUSEN PLANT: AVERAGE HEAT DELIVERED PER DAY (MWh th/d) AS A FUNCTION OF THE MEAN AMBIENT TEMPERATURE PER MONTH.

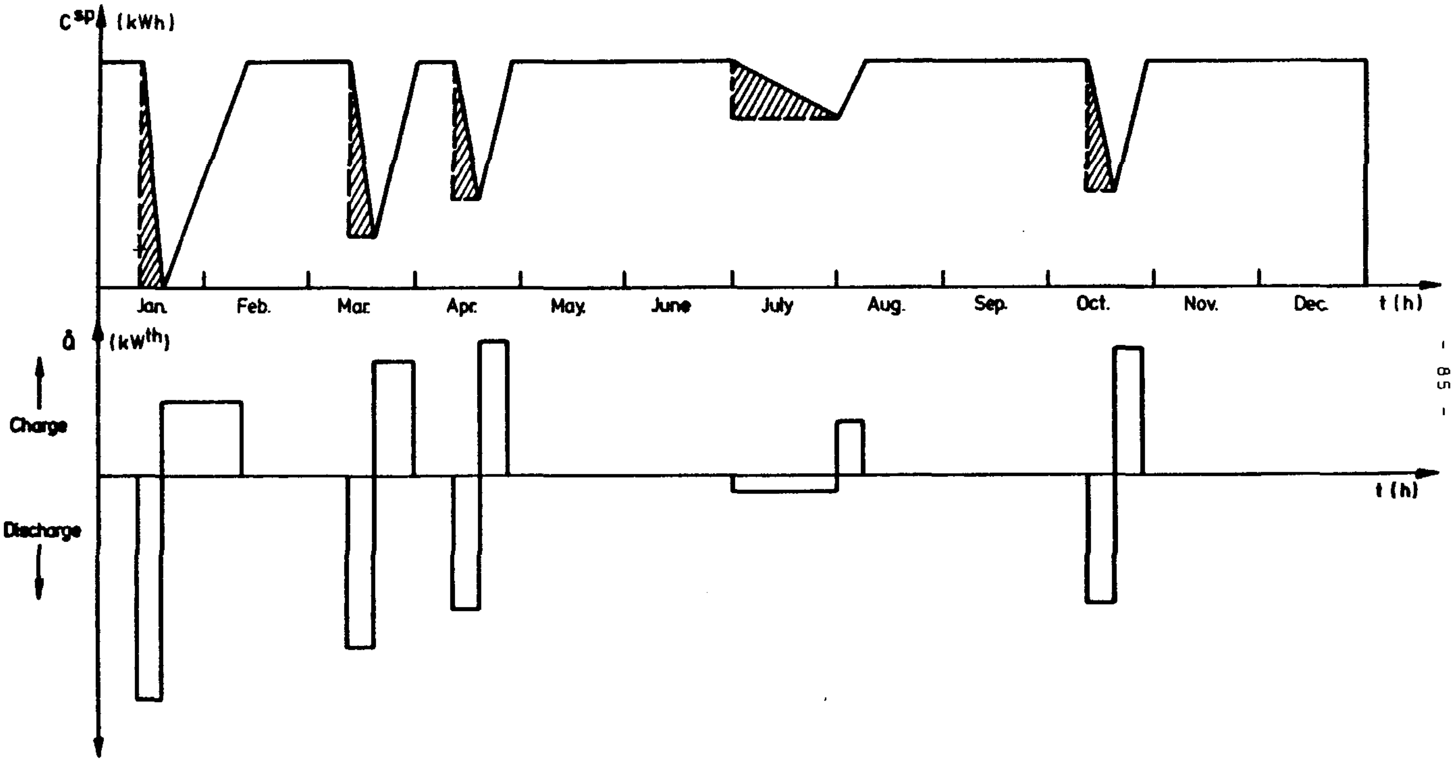


FIGURE 36. EBENHAUSEN PLANT : CYCLING ACCORDING TO THE FOLLOWING ASSUMPTIONS ON THE SHUT DOWNS TIMES OF THE INCINERATION PLANTS : 7 DAYS IN JANUARY AND OCTOBER (UNPLANNED)
31 DAYS IN JULY (REGULAR OVERHAUL PERIOD)

4.8.2. Economic data

The specific costs for the different storage-sizes given by MBB are the following :

7'150 m3 :	210 DM/m3
27'500 m3 :	170 DM/m3
39'900 m3 :	157 DM/m3

Even with constant fuel prices during the next 30 years, small store will almost prove economic. With 6 % annual increase of fuel prices, this option becomes a highly profitable investment. In this case options II and III can be expected to be economic.

It can be demonstrated that the benefit of TES (in monetary terms) depends strongly from the respective assumptions about fuel-price increase and interest rate.

4.8.3. Energy saving

Since the heat delivered by the incineration plant is completely waste heat, it makes not very much sense to describe the benefit of TES in terms of a percentage of the overall annual heat energy demand. Related to the heat energy saved by use of TES is 6,5 % for option I (7'150 m3) and 16,5 % using option II or III.

4.9. Studsvik Lake Magazine

4.9.1. Technical description

Studsvik Lake Magazine project includes construction of a pilot lake store of 300 meters in diameter and 15 meters deep. Source of heat will be 90°C reject heat. Other characteristics are :

- Duration : seasonal
- Temperature in store : maximum 90°C
  minimum 2°C
- Use of heat : connection with a district heating system
- Energy necessary for the store operating : 15,8 GWh for the heat pump
- Energy saved for every cycle and every year through :
  the concept 94,2 GWh
  the storage 78,4 GWh

Work is in progress concerning materials and design suitable for an insulated wall surrounded by water on both sides. The insulation must withstand 0,15 Mpa over pressure. A draining system for evaporated water in the insulation is tested. Tests are now run in a "micro-magazine" 1,5 m diameter and 15 m deep.

4.9.2 Project status

Work is now concentrated on studies of materials and design of the magazine wall. A test magazine of 1,5 meter in diameter and 15 m deep has been built for this purpose. The next logical step would be to build a magazine with 30 meters diameter. After that the full scale plant could be built if the results from the 30 meters magazine is successfull

4.9.3. Economics

Total cost for the Studsvik pilot project and associated piping system have been estimated at US $ 13 millions. The specific cost is thus of 13 $ pro cubic meter, heat pumps excluded.

On the basis of realistic economical assumptions the sum of the capitalized savings was calculated to be 18 millions US $ and the sum of the costs 13,5 millions US $.

giving a net saving of 4,5 millions US $. This corresponds to 45 % of the cost of the store itself.

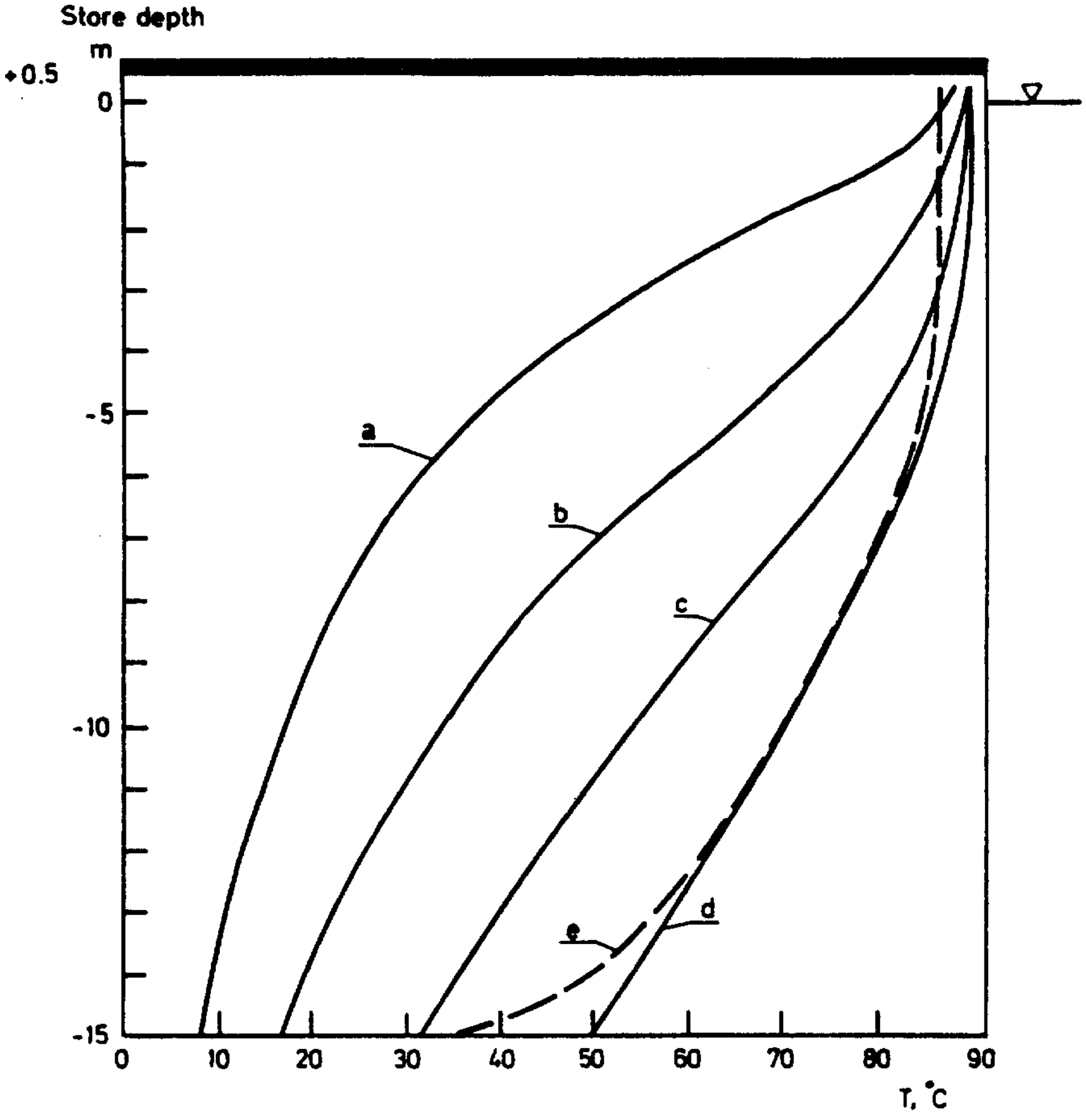
The most critical assumption is the expected future price of fuel or electricity.

Under the consideration the lake store will save considerable quantities of oil and be economically justified for long term storage.

4.9.4. Financing status

The lake magazine project is supported by the National Swedish Board for Energy Source Development.

FIGURE 37. LAKE HEAT STORE:
VERTICAL TEMPERATURE DISTRIBUTION IN THE POOL (SWEDEN)



Curve a) when 1/4 of the pool is charged
b) " 1/2 " ——
c) " 3/4 " ——
d) " the pool is fully charged
e) At start of discharge period e.g. after one month of storage in charged condition.

*) Charging 4 months. Storage 1 month. Discharging 4 months.

TABLE 3 : LARGE SCALE THERMAL STORAGE SYSTEMS EVALUATION

Technical data of IEA projects

Technical data	ST PAUL/MIN. US	DORIGNY Switzerland	HØRSHOLM Denmark	STIDSVIG Sweden
Type of store	Confined aquifer	Free aquifer	Confined aquifer	Free aquifer
Depth of stores top (m)	210	6	10	15
Type of plant	Pilot	Pilot +operating	Operating	Pilot + operating
System of injection	Vertical well(s)	Horiz. drains	Vertical well	Doublet(s)
Duration	Seasonal	Seasonal	Bimonthly + weekly	Seasonal
First year of operation	1983	1981	1981	1984
Medium		Silt + Sand	Sand	Sand
Aquifer permeability Horiz.	7 darcy	$9 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$	$1.0 \cdot 10^{-3} - 1.8 \cdot 10^{-3}$
(m/s) Vertic.	-	$5 \cdot 10^{-5} - 10^{-8}$	$1.5 \cdot 10^{-5}$	-
Store size: surface (m2)	61'500	1'600	3'700	90'000
height (m)	70	19	15	6
Volume of the store (m3)	4'300'000	30'000	56'000	500'000
Water equiv. volume (m3)	2'800'000	20'000	35'000	325'000
Maximum rate of injection (1/s)	75	5,5	17	25
Maximum rate of pumping (1/s)	80	7,0	18	28
Maximum heat recovery rate (MW)	17	0,44	6,5	1,2
Temperature of injection (° C)	150	70	100	35
Temperature of pumping (° C)	150-100	70-40	100-50	-
with heat pump (° C)	-	70-25	-	35-10
Energy annually stored MWh	115'000	1'500	3'750	6'300
Energy annually recovered MWh	81'000	750	2'650	3'800
Mean annual efficiency	0,7	0,5	0,58 (0,97)[1]	0,6
Source of heat	Cogeneration	Solar	Garbages	Industrial
Use of heat	District heating	Sp. heating	District heating	District heating

[1] Weekly

TABLE 3 (continuation) : LARGE SCALE THERMAL STORAGE SYSTEMS EVALUATION

Technical data of IEA projects (continuation)

Technical data	MUNICH EEC	MONS Belgium	EBENHAUSEN Germany	BELLINGHAM United States
Type of store	Artificial aquifer	Borehole2)	Steel container insulated	Cylindrical steel container, insul.
Depth of stores top (m)		surface	surface	surface
Type of plant	Pilot + operating	Operating	Operating	operating
System of injection	Horizontal drains	Vertical borehole	Heat exchanger	
Duration	Weekly + daily	Daily + weekly	Weekly3)	daily
First year of operation	1982	1982	1981	1985
Medium	Gravel	Water + surrounding terrains	Water	water
Aquifer permeability				
Horiz. (m/s)	$10^{-1} - 10^{-2}$	-	-	-
Vertic. (m/s)	$10^{-1} - 10^{-2}$	-	-	-
Store size: surface (m2)	1'370	3	1'070	700
height (m)	15	500	25	-
Volume of store (m3)	15'500	1'800	27'500	2 x 3'400
Water equiv. volume (m3)	9'600	1'500	27'500	6800
Maximum rate of injection (l/s)	300	40	60	
Maximum rate of pumping (l/s)	300	40	60	
Maximum heat recovery rate (MW)	5-7	5-8	11	
Temperature of injection water (° C)	28 (90)4	80-90	95	99
Temperature of pumping water (° C)	-	90-50	90	93
with heat pump (° C)	28-6 (90-5)4	-	-	
Energy annually stored MWh	247	701)	-	2600 (200)1)
" " recovered MWh	247	601)	-	2400 5)
Mean annual efficiency	95-100	80-90		92
Source of heat	Air conditioning	Undefined	Garbages	Aluminium factory
Use of heat	Space heating	Undefined	Didestrict Heating	District Heating

1) Daily

2) Included development of large diameter turbodrilling method which could be used as access to deep aquifers

3) Reserve of heat for emergency cases

4) Testing phase

5) Store full: 8345h/yr / Store empty: 78h/yr / Store in service: 337 hr/yr

TABLE 3 (continuation II) : LARGE SCALE THERMAL STORAGE SYSTEMS EVALUATION

Technical data of IEA projects (continuation)

Technical data	STUDSVIK
	Sweden
Type of store	Lake magazine[2)]
Depth of stores top (m)	surface
Type of plant	pilot
System of injection	At the surface
Duration	seasonal[1)]
First year of operation	1984
Medium	lake or sea water[2)]
Aquifer permeability	
Horiz. (m/s)	-
Vertic. (m/s)	-
Store size: surface (m2)	70'680
height (m)	15
Volume of store (m3)	$1,1 \cdot 10^6$
Water equiv. volume (m3)	$1,1 \cdot 10^6$
Maximum rate of injection (l/s)	160
Maximum rate of pumping (l/s)	214
Maximum heat recovery rate (MW)	36,3
Temperature of injection water (° C)	90° C
Temperature of pumping water (° C)	-
with heat pump (° C)	2° C
Energy annually stored MWh	108'000
" " recovered MWh	78'000
Mean annual efficiency (%)	60 - 90
Source of heat	Reject heat
Use of heat	District heating

1) 4 month charging period / 1 month in charged condition / 4 month discharge period / 3 month in discharged period

2) Location not yet decided

5. COMPARISON OF PROJECTS

5.1. Technical comparison

5.1.1 Objectives

The technical comparison of the projects is intended to supply the Executive Committee with information to enable it to choose one or several hardware projects on the basis of data which is as objective as possible.

A certain number of criteria which appeared to be the most important for the objectives of Annex I have been selected.

5.1.2 Type of store

Nine projects arrived early enough for an appraisal to be made. They can be classified according to the type of medium for energy storage :

- Free aquifer : Dorigny, Stidsvig
- Confined aquifer : Hørsholm, St Paul
- Artificial aquifer : Munich - Grosshadern
- Vertical boreholes : Mons
- Steel container : Ebenhausen, Bellingham
- Lake magazine : Studsvik

5.1.3 Duration

St Paul, Dorigny and Stidsvig are purely seasonal storage systems. Hørsholm operates on a weekly basis from June to September, and on a bi-monthly basis from August to November. Munich is a daily and weekly store, Ebenhausen is a weekly store, intended to compensate the interruption occuring in a garbage burning plant. The system proposed by Belgium is firstly a daily accumulator. It should be noted that the construction of this project will also allow a new boring technique to be developed. Bellingham is a daily storage.

5.1.4 Volume and thermal level

The water equivalent volume is the best criterion for comparing the projects.

They are, in decreasing order :

Location	Equivalent water volume	Temperature (°C)	
		Maximum	Minimum
St Paul	2'800'000 m^3	150	100
Studsvik	1'100'000	90	2 [1]
Stidsvig	325'000	35	10 [1]
Hørsholm	35'000	100	50
Ebenhausen	27'500		
Dorigny	20'000	70	40 (25)[1]
Munich	9'600	28	6
Bellingham	6'800	99	93
Mons	1'500	90	60

The largest accumulator proposed can store nearly 2'000 times more energy than the smallest. Hørsholm and Dorigny offer the minimal dimensions for seasonal storage without insulation. Thermal levels are very varied and it can be considered that nearly all possible cases are represented.

From this point of view, St Paul is an extremely interesting case since it can be linked to a conventional heat distribution system, whereas Hørsholm is a limit case. With the exception of Stidsvig and Mons, it will be noted that temperature increases with volume.

5.1.5 Technical risk and technological interest

The technical risk for each of the projects depends on the amount of information available concerning the system, the site and the physico-chemical phenomena which could create disturbances in the storage. The technical risk increases as the temperature rises, and with proximity to the surface.

St Paul

This is the most advanced project, by reason of its high temperature and its large volume. The technical risks are high, for example : chemical phenomena (clogging), thermal disturbance (tilting), badly known properties of the aquifer. This knowledge will be improved between now and the time of construction.

[1] With heat pump

On the contrary, ecological and biological effects are minimal, and the project's construction would make possible a great step forward in underground heat storage technology.

Dorigny

The main technological risk is linked to the very low vertical permeability of the aquifer, which could necessitate the placing of vertical drains. This system has been studied on a mathematical model, and should give good results. The top of the accumulator is at only 6 meters from the surface, giving rise to important thermal losses; it is also expected to have considerable effects on vegetation. These phenomena will be studied. The radial drain technology is interesting since it allows thermal disturbance to be restrained and tilting to be limited. It is a relative expensive technology, which is well adapted for small, high temperature accumulators. A detailed study of chemical reactions and the effects envisaged in the soil and on the heat exchangers has been made. Simulation of the system has been carried out very seriously on finite elements models. Ground characteristics are well known.

Hørsholm

The main technological risk lies in the guarantee of temperature which is necessarily high, for connecting the system to the district heating network. The water-tightness of the clay layer at the top of the aquifer appears to be guaranteed. Reaction may occur in the clay present in the covering layers and in smaller quantities in the porous matrix. Chemical reactions have been studied, and a frequent washing of the heat exchangers is envisaged. No biological effects are expected in the store. Changes in soil conditions above the store will be comparable to conventional district heating pipes. Natural groundwater flow will be controlled by means of two relief wells. A two dimensional mathematical model has been developed. It takes into account variations in density and viscosity as well as gravitational effects. No natural convection occurs in the store and thermal front tilting is moderate.

Stidsvig

The low temperature of the accumulator means that the technological risks of this concept are slight. The consequences of the installation of a store at 35°C on an aquifer which is considered as a domestic water reservoir, have not yet been studied. No thermal simulation has been carried out, and losses towards the surface are badly known. These points will be investigated during the coming months. The use of a heat pump ensures that heat will always be extracted with a high degree of efficiency. The displacement of the thermal disturbance can be foreseen with precision (no tilting). The problems of corrosion and clogging have not been studied, but they will probably be slight.

Munich

The artificial aquifer concept is intended to suppress the main technical risks encountered in natural aquifer. As the system operates on a closed circuit, all the chemical and biological problems inside the store are avoided. Disturbance control is ensured by a watertight foil. An optimal geometry for the injection and extraction installation can be chosen. The project presented can be well integrated to an energy-producing system. The remaining principal technical risks concern the system's watertightness and the thermal losses at the accumulator boundary, due to ground water flow.

Mons

Among the technical risks inherent in this project can be mentioned the problems caused by deep boreholes, the development of a new boring method and the reservoir's watertightness at long term. Cathodic protection of the reservoir should be envisaged. The stores productivity is high because it operates on a daily cycle basis. The single well system is not suitable for storage exceeding a few days. The effect of ground-water flow on productivity has not been studied. The technical advantages of a steel container are the same as for artificial aquifer storage : no chemical interaction, control of thermal disturbance.

Ebenhausen

The steel container concept undoubtly presents the lowest technical risk, since its technology is known. The advantages are the same as for all closed systems. Among the subsisting technological risks can be mentioned the geometry of the water injection and extraction system, if a good thermal stratification is to be maintained in the accumulator. The evolution at long term of the external insulating material can also be mentioned. Similar remarks can be made about the Bellingham project.

Studsvik lake magazine

Important technical risks lies in material and design suitable for an insulated wall surrounded by water on both sides. The insulation must withstand 0.25 MPa over pressure. For normal operation of the magazine, chemical, biological and environmental effects can be forseen by comparing results obtained from the surroundings of the outlet from power plants and industries. The consequences of an accident have not been estimated yet.

5.1.6 Connection to a producer-consumer system

Most of the projects presented (except Mons) are designed to be integrated in a producer-consumer system, either immediately (Hørsholm, St Paul, Stidsvig, Ebenhausen) or after a test phase of 1 or 2 years (Munich, Dorigny). The choice of the accumulation concept has most often depended on the power and temperature firstly of the producer and then of the consumer. St Paul is the project whose construction will take longest, but it is of the greatest interest since this concept is well suited to a conventional district heating system. The energy source (cogeneration) could be solar at medium term. Industrial waste heat is generally at lower temperature, and is better adapted for storage systems of the Stidsvig, Munich or Dorigny type. The concept proposed at Stidsvig is the most general, but presents drawbacks for the consumer because of the relative low temperature at the output of the heat pump.

In the case of Hørsholm, connection to a conventional system is possible presently, but a future lowering of the temperature in the district heating system will improve the system performance. Munich and Ebenhausen are short term accumulators, and are well combined with a producer-consumer system.

5.1.7 Time criterion

Dorigny, Hørsholm, Ebenhausen could be put into service at the beginning of 1982. After an experimental phase of 2 to 3 years, these systems could become completely operational. Munich and Mons are due to begin working in 1982. A test phase of 2 years is envisaged at Munich. These tests are particularly interesting for the project, since they will be carried out up to temperatures of 90°C.

St Paul (1983) and Stidsvig (1984) are constructions at medium term. Despite this relatively long time lapse, their technological interest is considerable due to size and temperature (St Paul) respectively size (Stidsvig).

5.1.8 Representativity criterion

This is the most difficult comparison to make, each project being adapted for the producer-consumer system to which it is connected, and to the geological and hydrogeological condition of the area in which its construction is envisaged.

Stidsvig is an example of thermal use of eskers, a Quaternary geological formation frequent in Sweden. At Dorigny, heat is stored in low permeability aquifer, because in Switzerland, the permeable aquifers are reserved for drinking water supply. The Munich store is well adapted for the large accumulations of un-satured gravel which are to be found at the periphery of the Alps. This concept could,for example, be applied in Switzerland. The Hørsholm concept could be less easily generalized than the Munich or Stidsvig does. It is well applicable to the medium permeability geological formation which are found in northern Europe (Germany, Holland, Denmark). The St Paul type of deep storage could be used in many IEA countries.

Its use is however reserved for cases where there is an important accumulation of terrain with intersticial porosity. The use of this concept can practically be excluded in Sweden, where the Quaternary layer is very thin.

The Mons and Ebenhausen projects are obviously the most easy to generalize. There is however probably less demand for weekly than for seasonal storage.

5.2. Economical comparison of IEA projects

5.2.1 Preliminary remarks

The aim of the economical comparison is to get a quantitative measure of the costs and benefits associated with each project participating in the evaluation. It is of interest to know the costs and benefits both for the actual projects, as well as for the concepts as such. In the latter case one has to disregard the restrictions or other conditions that are specific for the chosen site and the system associated with it.

A complete economical evaluation of the projects is not meaningful for several reasons

- The economic conditions (interest on loans, taxes, depreciation lifetimes, energy prices) differ widely from country to country.

- Opinions concerning the future development of important economic parameters (energy prices, inflation, interest on loans) also differ widely from country to country.

- Some projects use heat pumps in order to be able to utilize lower temperatures, thereby reducing the heat losses, while other do not use heat pumps. Therefore assumptions concerning the price of electricity will have very different impact on the different projects.

- Conditions (heat demand, temperature and cost of available heat, etc) at the various projects may impose restrictions that are site-specific and not concept-specific.

Therefore it was decided (1980,06,18-19) at the working group meeting in Denmark that the economic comparison should treat only costs of the storage as such, but not incomes from the use of heat storage.

In order to get a hint of the economic gains that could be achieved, a comparison is made with the marginal cost of heat produced by other alternative means.

5.2.2. Site-specific factors

The suggested projects cover a wide range of sizes (see tables 4 and 5), in fact the largest project has a storage size (in equivalent water volume) that is more than a factor 10^3 bigger than the smallest one. This means that there will be differences in the energy recovery factors and specific costs of the projects that do not depend on the concepts as such but on the "economy of scale". Also there are differences in number of storage cycles per year and length of the storage period (see table 6) that will affect the economy, without beeing tied to the storage concept, but instead related to the system connected to the storage.

Another factor that affects the economy, without necessarily being tied to the storage concept as such, is the temperature levels (see table 4). The reason could be e.g. use of solar energy (Dorigny), high return temperature in the system (Minneapolis) or use of heat pumps (Grosshadern, Klippan and Studsvik).

One method of taking care of these factors is to use adequate ordinates for diagrams comparing the projects. When plotting energy recovery factors the following arguments have been used (Cf Figure 38).

The dissipation of heat out of an insulated container is roughly proportional to time, to the area of the container and to the temperature difference between the water and the ambient medium. Since the heat content is proportional to the volume and some temperature difference, a suitable parameter to compare the recovery factor with could be $\Delta t/V^{1/3}$ where Δt is the length of the storage period and V is the equivalent water volume. The quantity $\Delta t/V^{1/3}$ has been named "heat loss parameter" in this report.

When plotting total and specific costs of storage, the size of the storage and number of cycles per year has been taken into account by plotting against total annual heat production and indicating the number of cycles per year or the length of storage.

5.2.3. Energy savings

The energy savings achieved by the various projects could be expressed in many different ways. The simplest is just to list the energy produced from the storage as shown in table 5. This, however, does not take account of the electricity used by pumps in order to transport water to and from the storage, and above all, it does not account for the energy used by heat pumps in some of the projects (Grosshadern, Klippan and Studsvik). The influence of these factors are illustrated in tables 7 and 8. Just subtracting the amount of electricity used gives an upper limit of the energy savings achieved. The electricity being used by pumps and heat pumps may be converted to an equivalent amount of thermal energy by dividing the amount of electricity by an energy conversion factor of approximately $n=0.4$. This gives the amount of fuel used by modern fossil fuelled an water cooled power stations in order to produce the electricity. Subtracting this amount of fuel from the heat production we get a (pessimistic) lower limit of the energy savings. As can be seen, the amount of energy used for ordinary pumping of water is almost negligible, while the energy used by heat pumps is quite significant. Therefore, one should check carefully, what kind or energy is really involved in the heat pump processes. Since this has not been possible within the time limits of the report, both the upper and lower limits of the energy savings have been given for the heat pump projects. A realistic value would probably be closer to the lower limit than to the upper limit.

In Figure 38 are shown the energy recovery factors versus $\Delta t/V^{1/3}$ (Cf section 5.2.1). If the amount of energy used by the heat pumps is not taken into account, this would give recovery factors that sometimes are at or above 100 % (Studsvik and Grosshadern). In Figure 38 the energy used to operate the heat pumps has therefore been subtracted in both ways described above. It is to be expected that the Klippan and Mons projects should have low values compared to the other projects in this way, since they have comparatively larger surface to volume ratio (Klippan because of the regional flow, Mons because of the high length to diameter ratio).

Through division of the amount of energy produced in each cycle by the equivalent water volume we arrive at the specific energy saving in kWh_t per m3 (see table 9). This could be converted to an "equivalent ΔT" through multiplication by 3600/4187 (No. of seconds per hour divided by Cp for water). This "equivalent ΔT" indicates the average temperature difference between the in-and outgoing water during production, scaled with the quotient between "active" amount of water and total amount of water. This number is essentially a help to understand "anomalies" in the energy production versus volume. For instance, the heat produced by the Studsvik system per m3 water equivalent is high compared with the Minneapolis value because of the high ΔT achieved by use of heat pumps in the Studsvik system. In the Minneapolis system there is a very high return temperature from the system.

The low value for the equivalent temperature in the Danish weekly case is due to the fact that only a part of the aquifer is used by the weekly system.

5.2.3. Economical scenarios

In order to make the comparison relevant not only for the actual projects but also for the class of projects they represent, irrespective of when and where such projects would be realized, three economical scenarios have been studied. Each scenario is defined by a set of different values for the most important economic parameters as shown in table 10.

Case 2 in table 10 is the base case. It assumes that the interest rate for loans will be 2 % higher than the annual inflation[1]. At the same time the energy prices will increase with 3 % per year faster than inflation. The technical and economical lifetime is assumed to be 15 years. The average cost of electricity 1980 for pumps and heat pumps is assumed to be 60 $\$/MWh_e$ and the marginal fuel cost 1980 for heat produced by oil-fired peak 35 $\$/MWh_t$.

These values correspond roughly to an average of the national values supplied by the participants in the evaluation.

The price of electricity is normally a very insignificant post in the total, except for the projects using electrically powered heat pumps.

Case 1 and case 3 are intended to represent conditions unfavourable and favourable for the economy of the storage. Similarly high prices for the alternative energy sources and low prices of the electricity used for pumps will be favourable. Since the price of electricity only affects part of the cost, energy price increases above the average inflation will be favourable for the storage when compating it with alternative sources of energy.

The values of economical parameters used for case 1 and case 3 correspond approximately to the extreme values among those submitted by the participants in the evaluation. This means that those cases might be not quite consistent. In particular, the price of electricity is rather close to the price of oilproduced heat in case 3.

It should be noted, however, that no estimate was obtained from the US participants. Since energy prices are much lower in the US than in Europe this could have affected the definition of case 1. On the other hand the marginal cost of energy is the interesting value, and this should be determined by world market prices and not average prices.

---

[1] Since all costs will be referred back to 1980 dollars, the rate of inflation is immaterial

5.2.4. Investments

In table 11 are listed the initial investments required for the projects, all data expressed in the same value or money (1980 US $). The numbers include construction cost, heat exchangers, pumps and other equipment necessary in order to connect the store with a heat distribution system. For some of the projects the investments in heat pumps are also included. As can be seen from the water temperature figures, heat pumps are required for three of the projects, the Grosshadern, Klippan and Studsvik projects. Inclusion of the cost of the heat pumps adds approximately 10-20 % to the investment. The following columns of table 11 illustrate the specific investment for the storage from different points of view. The specific investment per m3 of equivalent water volume (col 3) is the number most often seen in the literature. It does not, however, take into account that different storage concepts may set different temperature restrictions on the heat storage medium. Therefore the last two columns of table 11 show the investments per kWh_t produced from the storage, both per cycle, which takes into account the temperature levels, and per year, which also takes into account the number of cycles per year. The investments per m3 water equivalent are also shown in Figure 39. Here the investments for heat pumps are not included, since they have nothing to do with the volume of the storage. It is tempting to try to draw one straight line through the points denoting the aquifer storages and another one through the non-aquifer storages. This might be adequate, at least approximately for the aquifer storages, but certainly not for the non-aquifer storages, which all have quite different investment to size characteristics.

5.2.5 Annual costs for operation and maintenance

For a new concept like large scale thermal energy storage, the costs for operation and maintenance are hard to estimate. Indeed, some of the participants have not been able to give estimates on this point and other estimates are probably quite rough. It is also difficult to sort out the costs really needed for the operation of the store from other costs related to the whole system. Therefore the values given in table 12 are intended primarily to illustrate the order of magnitude of these costs. Some comments could however be made :

The relatively high operation cost of the Dorigny project is rather natural having in mind the small size of the store. Also a relatively high cost for operation and maintenance is natural for the lake magazine (Studsvik). The

Ebenhausen and probably also Mons and Grosshadern projects should be expected to have lower cost for operation and maintenance due to less problems of chemical, biological, geological and hydrological art. The comparatively low cost for the Klippan project is somewhat surprising, but might have to do with local conditions.

5.2.6. Total cost for the heat produced

The total cost for the heat produced includes capital charges (interest and depreciation) costs for operation and maintenance of the storage as well as energy (electricity) for pumps and heat pumps (if such are used). In the total cost, no reductions have been made for the capacity reductions achieved for peak boilers (see section 5.2.7.). No cost has been attached to the heat injected into the store.

In order to obtain a relevant cost comparison, irrespective of when the projects are going to be realized, all projects have been supposed to be constructed during 1980 and with start of operation in 1981. The total annual costs have been computed over a 20 year period. Annual and average total costs per unit of energy produced during the assumed lifetime have been computed in constant 1980 US dollar, see table 12.

The total costs for the base case over the lifetime are shown in Figure 42 as function of the amount of heat replaced. As a comparison is shown the average cost of fuel over the lifetime if the same amount of heat would have been produced by oil-fired boilers.

In Figure 43 is shown the corresponding average cost per MWh of heat over the assumed lifetimes for all three cases, Case 1 = "Unfavourable", Case 2 = base case and Case 3 = "Favourable".

5.2.7. Savings in boiler capacity

One aspect of the economy of heat storage, not accounted for in the total cost is whether it will be possible to reduce the total boiler capacity needed for peak and reserve purposes, or not. A more detailed assessment of this question in possible only by taking into account also the system to which the storage is connected. This was not possible (and maybe not quite relevant for the aim of the study) within the short time allowed for this study. Some general comments and estimates could through be made.

In order to be able to reduce the peak and reserve boiler capacity it is necessary that the storage is at least partially loaded during the time period when the peak heat demand is to be expected, normally december, january and february. This should be the case for most of the projects, with the exception of Hørsholm (storage only in autumn and beginning of winter) and possibly Grosshadern (cycling not completely defined yet).

In the first columns of table 13 are shown the maximum savings that could be achieved for the peak and reserve boiler capacity, using the maximum heat production rate specified by the participants. Normally only some fraction (say around 50 % ?) of that production rate could be used for the seasonal storages at the coldest day, due to decreased temperature in the storage. The last columns of table 13 contain a very rough estimate of the possible savings in boiler capacity that could be expected. The main aim is to give an indication of the order of magnitude of the savings that could be achieved.

5.2.8. Cost of injected heat

The cost of the injected heat is not included anywhere in the total costs. One reason for this is that in many of the projects the source of heat is waste heat, which is, at least from national point of view, free of charge. Sometimes it is in fact valuable to get rid of heat that has nonwanted impact on the environment.

5.2.9. Final remarks concerning economical comparison

Since the conditions for the participating projects are very different in particular concerning number of cycles per year, temperature levels and size of the storage, no attempt shall be made to construct a "rating list". Some general comments could however be made.

It is quite evident (and natural) that the lowest cost is attained by the aquifer projects (Dorigny, Hørsholm, Klippan and Minneapolis, see e.g. "investment per m3 water equivalent" in table 14). All the nonaquifer projects, except the Studsvik project, attain low cost levels mainly because the number of cycles per year is higher than 1 (3.2 to 130 full cycles per year). For the Studsvik project a low cost level is attained through "economy of scale".

TABLE 4 : Project characteristica

Project	Type	Start of constr.	First year of op.	Equiv. water volume V (10^3 m^3)	Temp. of injected water (°C)	Temp of water produced from store (°C)	Heat pumps needed (MW$_t$)
B, Mons	Giant borehole			1.5	80	75-80	No
CEC, Grosshadern	Art. aq.	1981	1982[1]	9.6	6-28	6-28	
CH, Dorigny	Conf. aq.	1980	1981	20.0	70-80	25-70	No
D, Ebenhausen	Steel tank	1980	1981	27.5	95	90-95	No
DK, bimonthly	Conf. aq.	1981	1982	35.5	100	75-100	No
DK, weekly	"	"	"	"	"	95-100	No
S, Klippan	Free aq.	1984	1985	125	30-35	10-35	1.60
S, Studsvik	Lake mag.			1060	90	2-85	28
US, Bellingham							
US, Minneapolis	Conf. aq.	1980	1983	4305	150	-150	No

[1] As test plant

TABLE 5: Heat storage and production (final years)

Project	Max. heat injected per cycle (GWh_t)	Max. heat prod. per cycle (GWh_t)	Max. heat prod. per year (GWh_t)	Heat prod. in 20 years (GWh_t)	Comments
B , Mons	0.070	0.059	7.67	153.8	
CEC , Grosshadern	0.247	0.247	4.90	98.8	Heat pumps
CH , Dorigny	1.5	0.750	0.75	14.4	
D , Ebenhausen	>1.40	1.40	4.43	88.6	Excess waste heat
DK, bimonthly	3.75	2.17	2.17	43.4	
DK, weekly	0.44	0.43	6.88	137.6	
S, Klippan	6.30	3.80	3.80	76.0	Heat pumps
S, Studsvik	89.0	94.2	78.4	1568	Heat pumps
US					
US	115	81.0	81.0	1579	

TABLE 6: Cycling data

Project	No of full cycles per year	Length of storage period Δt (Days)	Heat loss parameter[2] (days/m)
B, Mons	130	1.4[1]	0.12
CEC, Grosshadern	20?	9	0.42
CH, Dorigny	1	180	6.63
D, Ebenhausen	3.2	100	3.31
DK, bimonthly	1	60	1.83
DK, weekly	16	3.5	0.11
S, Klippan	1	180?	0.28
S, Studsvik	1	150	1.47
US, Bellingham			
US, Minneapolis	1	185	1.14

1) Computed as 0.5 * 360/130

2) Computed as $\Delta t/V^{1/3}$, where V = eq. water volume

TABLE 7: Annual energy savings (final years)

Project	Heat produced GWh$_t$	Electricity usage, GWh$_e$			Fuel[1] to produce electricity, GWh$_t$	Minimum saving GWh$_t$	Barrels[2] of oil eq. saved per year
		Pumps	Heat pumps	Totally			
B, Mons	7.67	Small	---	Small		<7.67	~5150
CEC, Grosshader	4.90	0.044					<3300
CH, Dorigny	0.75	0.010	---	0.010	0.03	0.72	~ 500
D, Ebenhausen	4.43	0.015	---	0.015	0.04	4.39	~3000
DK, bimonthly	2.17	0.016	---	0.016	0.04	2.13	~1500
DK, weekly	6.88	0.024	---	0.024	0.06	6.82	~3000
S, Klippan	3.80			1.10	2.75	1.05	700-1800
S, Studsvik	94.2	Small	15.8	~16	~40	54.5	37000- 52000
US							
US, Minneapolis	81.0	Small	---	Small		81	~54000

[1] When electricity is produced by thermal power plants with $\eta=0.4$

[2] Using boiler efficiency = 0.85 and 1 barrel of oil = 1.75 MWh$_t$

TABLE 8: Net heat recovery (final years)

Project	Annual heat storage GWh_t	With subtraction of electricity for heat pumps		With subtraction of fuel for heat pumps	
		Heat produced GWh_t	Recovery factor %	Heat produced GWh_t	Recovery factor %
B, Mons	9.10	7.67	85	Same, no heat pumps	
CEC, Grosshadern	4.90				
CH, Dorigny	1.5	0.75	50	Same, no heat pumps	
D, Ebenhausen	>4.43	4.43	<100	Same, no heat pumps	
DK, bimonthly	3.75	2.17	58	Same, no heat pumps	
DK, weekly	7.04	6.88	97	Same, no heat pumps	
S, Klippan	6.3	2.70	43	1.05	17
S, Studsvik	89.0	78.4	88	54.5	61
US, Bellingham					
US, Minneapolis	115	81.0	70	Same, no heat pumps	

TABLE 9: Specific energy savings and equivalent ΔT

Project	Gross energy saved per m^3 water equivalent (kWh_t/m^3)		Equivalent ΔT[1] (°C)	Net energy saved per m^3 water equivalent (kWh_t/m^3)		Equivalent ΔT[1] (°C)
	per year	per cycle		per year	per cycle	
B, Mons	5113	39.3	33.8	As	gross	
CEC, Grosshadern						
CH, Dorigny	37.5	37.5	32.2	As	gross	
D, Ebenhausen	163	51	43.8		"	
DK, bimonthly	61	61	52.5		"	
DK, weekly	200	20	17.2		"	
S, Klippan	30.4	30.4	26.1	8.4	8.4	7.2
S, Studsvik	89	89	76.4	51.4	51.4	44.2
US, Bellingham						
US, Minneapolis	18.8	18.8	16.2	As	gross	

[1] Computed as Energy saved per m^3 and cycle * 3600/4187

TABLE 10: Economical scenarios

Item	Case 1 (Unfavourable)	Case 2 (Base case)	Case 3 (Favourable)
Interest rate above inflation, %	4	2	0
Technical and economical lifetime, years	10	15	20
Energy price increase above inflation %	0	3	6
Fuel cost for heat produced by oilfired boilers 1980, $\$/MWh_t$	30	35	40
Cost of electricity 1980, $\$/MWh_e$	90	60	50

TABLE 11: Initial investments

Project	Total inv. M$ 1980	Inv. per m^3 water equivalent $\$/\mathrm{m}^3$	Inv. per heat prod. per cycle $\$/\mathrm{kWh}_t$	Inv. per heat prod. per year $\$/\mathrm{kWh}_t$
B, Mons	1.00	667	16.7	0.13
CEC, Grosshadern	2.47[1]	257	10.1	0.50
CH, Dorigny	0.432	19	0.51	0.51
D, Ebenhausen	2.29	83	1.64	0.52
DK, bimonthly	0.537	15	0.25	0.25
DK, weekly	"	"	1.22	0.08
S, Klippan	1.40[2]	11	0.37	0.37
S, Studsvik	14.35[3]	14	0.15	0.15
US, Bellingham				
US, Minneapolis	4-8	1-2	0.05-0.10	0.05-0.10

[1] Excl. heat pumps

[2] Incl. heat pumps (= 0.19 M$)

[3] Incl. heat pumps (= 1.86 M$)

TABLE 12: Annual and average total cost for base case

Project	Annual cost 10 years after start of op.			Average cost per MWh produced during assumed lifetime (15 years)		
	Op.and maint. 1) 10^3 \$	Capital cost 10^3 \$	Totally 10^3 \$	Op.and maint. 1) \$/MWh_t	Capital cost \$/MWh_t	Totally \$/MWh_t
B, Mons	---	78	78	---	10.1	10
CEC, Grosshadern 2)	7	192	199	1.3	38.9	40
CH, Dorigny	13	31	44	18.5	45.1	64
D, Ebenhausen	6	178	184	1.34	40.3	42
DK, bimonthly	19	42	61	8.8	19.3	28
DK, weekly	19	42	61	2.8	6.1	9
S, Klippan	92	109	201	23.1	28.7	52
S, Studsvik	1721	1117	2837	21.1	14.2	35
US, Bellingham						
US, Minneapolis	---	467 3)	467 3)	---	4-8	4-8

1) Excl. cost of waste heat

2) Excl. heat pumps

3) Based on investment = 4 milj \$. Inv = 4 to 8 milj \$ gives $311\text{-}622 \cdot 10^3$ \$/year

TABLE 13: Savings in peak and reserve boiler capacity

Project	Maximum savings			Expected savings (tentative)		
	Peak power MW_t	Reduction in boiler inv. 10^3 \$	% of inv for storage	Peak power MW_t	Reduction in boiler inv. 10^3 \$	% of inv for storage
B, Mons	3	150	15	3	150	15
CEC, Grosshadern	7	350	14	4	200	8
CH, Dorigny	0.44	22	5	0.3	15	3
D, Ebenhausen	11	550	24	11	550	24
DK, bimonthly	2.6	130	24	---	---	---
DK, weekly	6.5	325	60	---	---	---
S, Klippan	1.2	60	4	1	50	4
S, Studsvik	50	2500	17	35	1750	12
US, Bellingham						
US, Minneapolis	20	1000	17	15	750	13

Boiler investment: 50 $\$/kW_t$

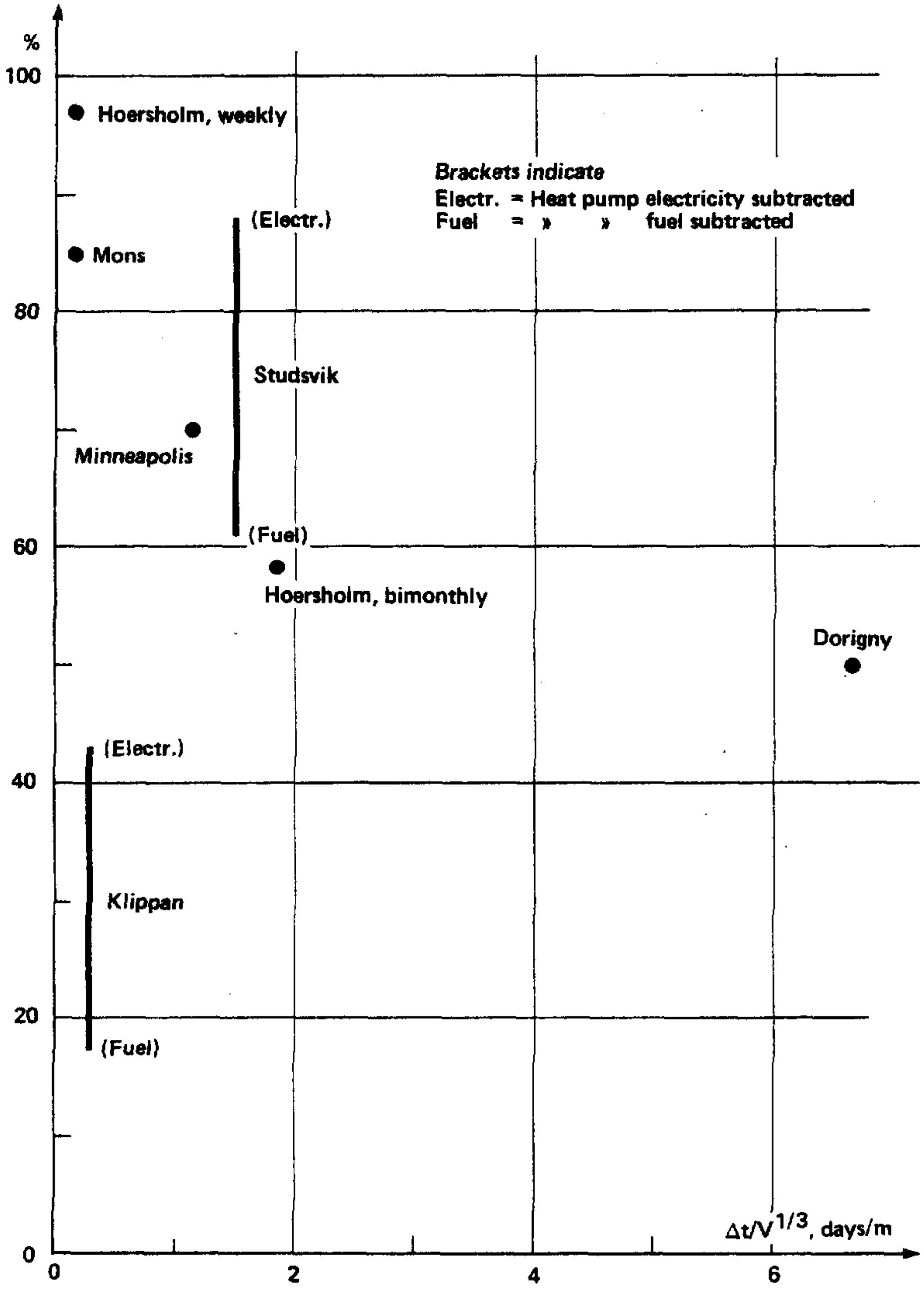


FIGURE 38. Heat recovery versus "heat loss parameter"

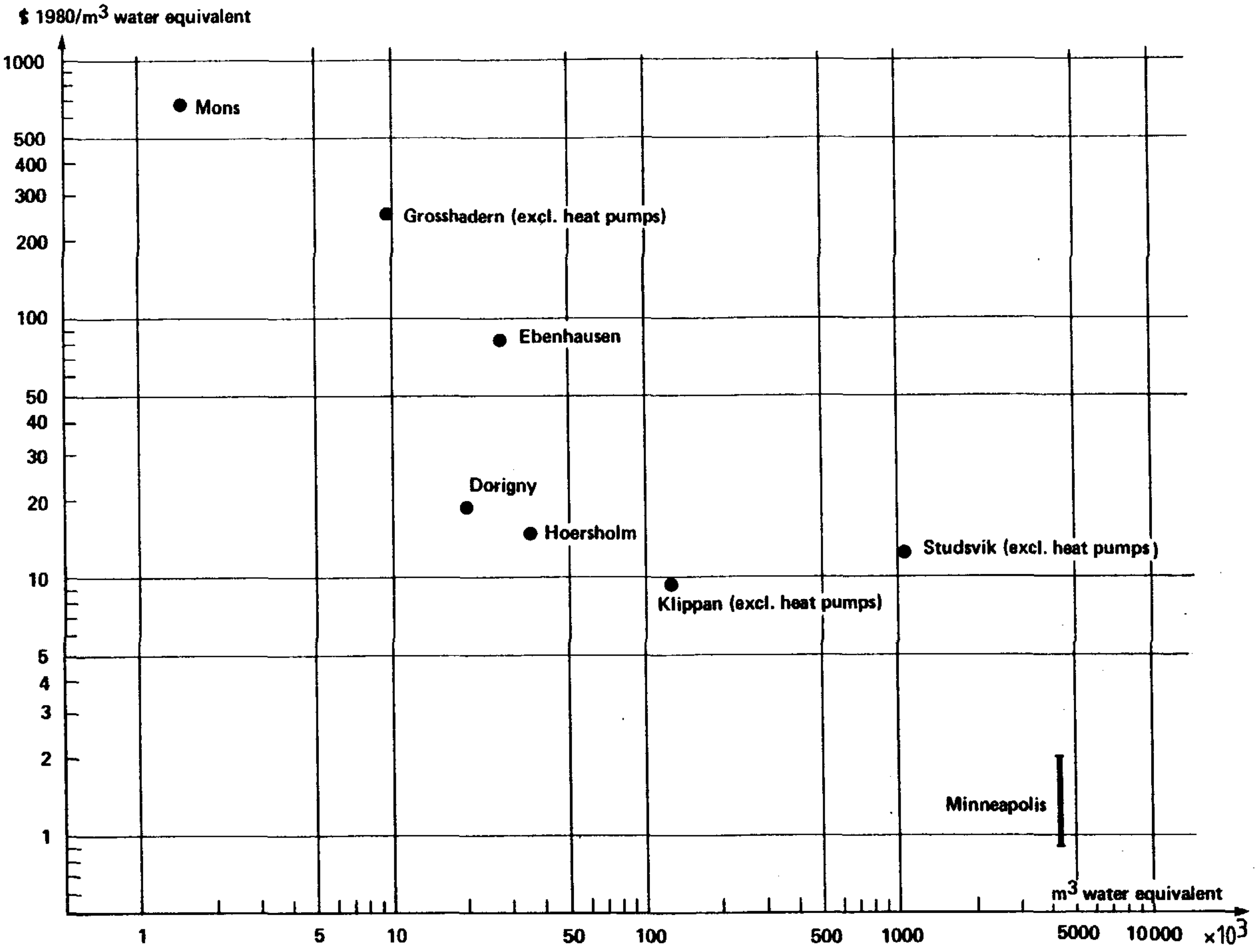


FIGURE 39. Investment per m^3 water equivalent versus storage size

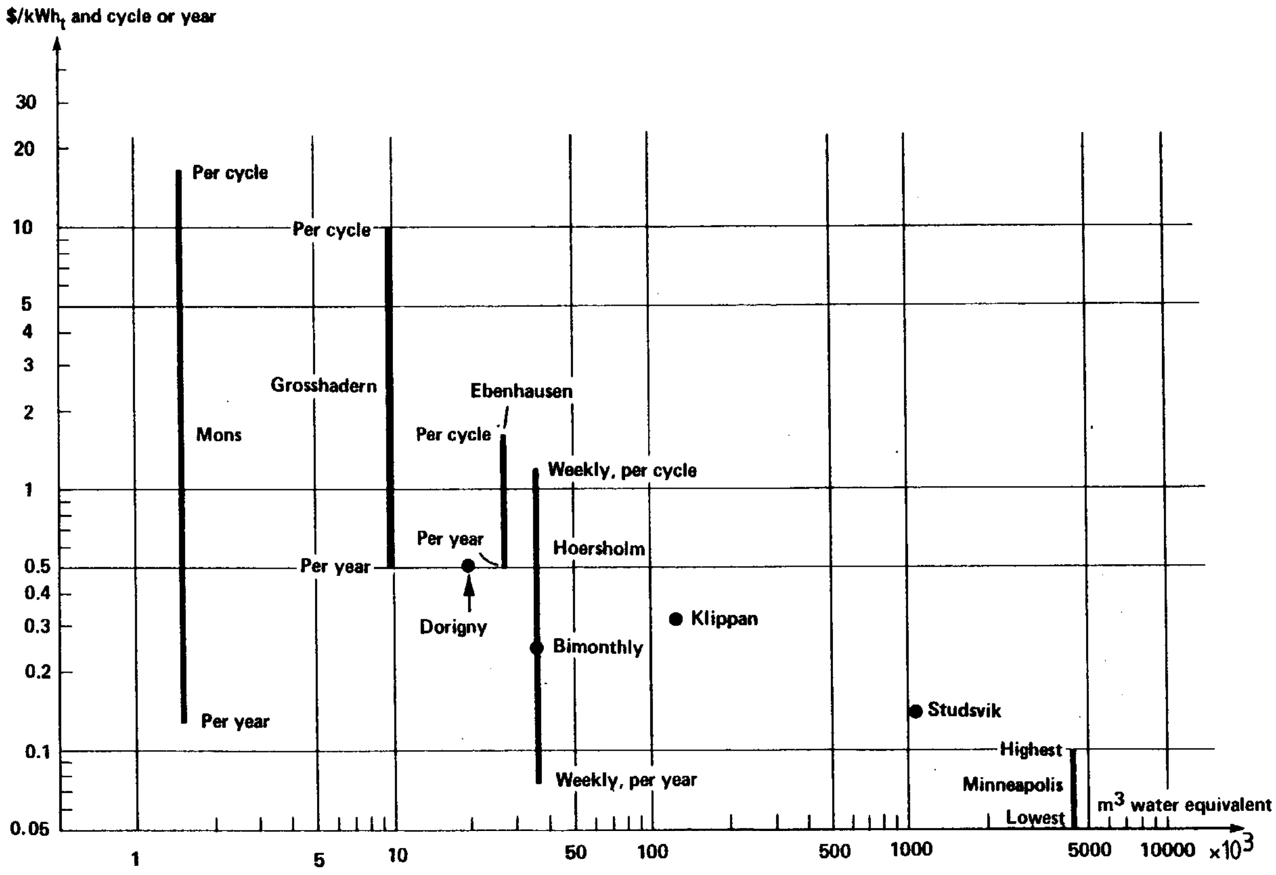


FIGURE 40. Specific investment versus storage size

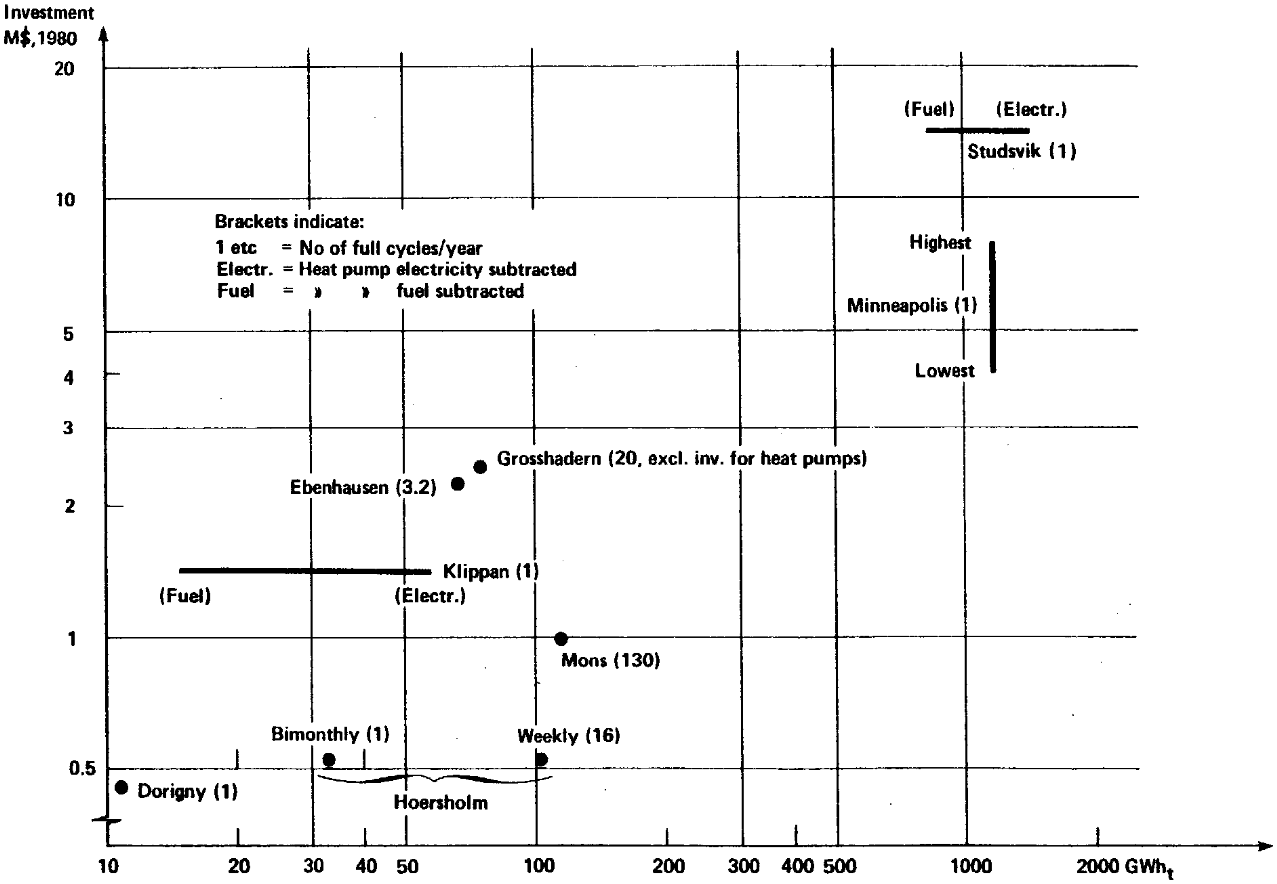


FIGURE 41. Initial investment versus heat produced during assumed lifetime

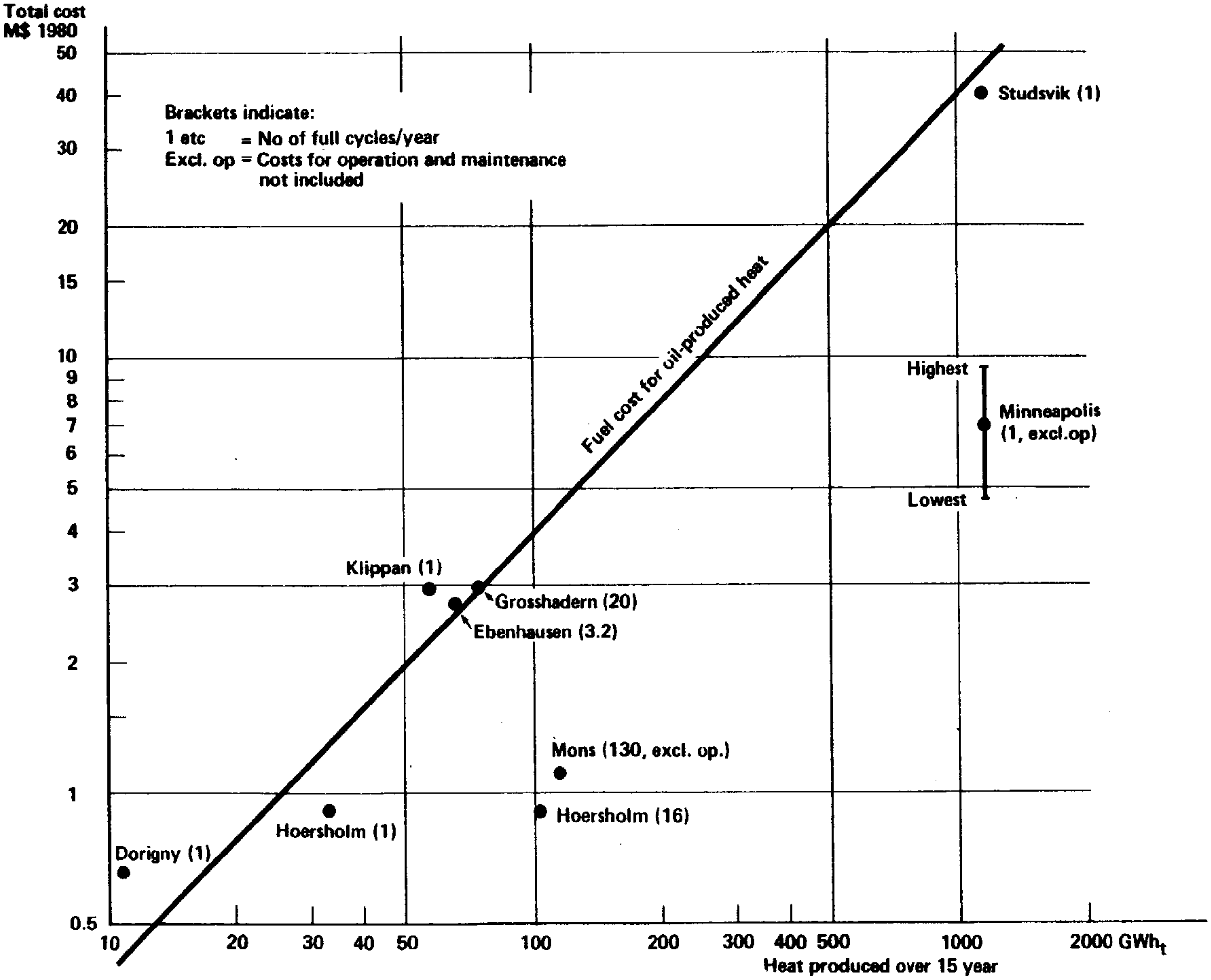


FIGURE 42. Total cost versus heat produced for base case

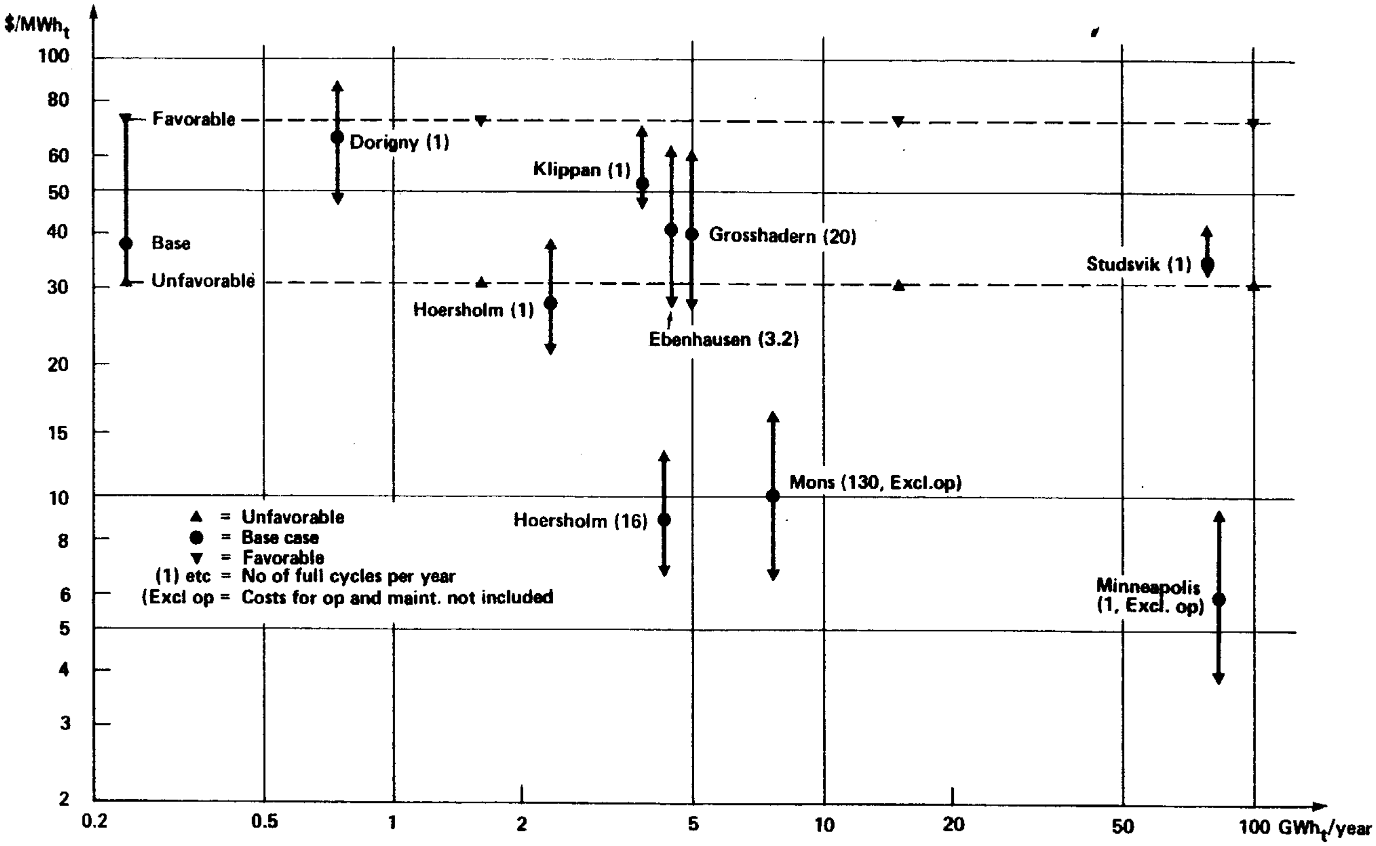


FIGURE 43. Average cost of energy produced over lifetime

5.3. Overall comments

The choice of a project among those presented is definitely a delicate matter. The persons who have made the technical and economic assessment consider that all the projects offer considerable technical interest.

If the economic criterion prevails, large scale accumulators (Studsvik, St Paul) will be preferred. The advantage of smaller accumulators (Dorigny, Hørsholm, Munich) is that they are short-term projects which can supply very precious technical information.

All the projects presented provide their contribution towards a solution in the thermal energy storage problem, at middle and long term. The concepts presented cover a great many needs and utilizations. The choice of a storage concept being largely dependant on local factors, it can be envisaged that most of the concepts presented will be widely realized in coming years. Up till now the lack of major constructions in the field of seasonal thermal energy storage is due to the technical risks presented by the prototypes. These risks prevent the project from being a guaranteed, and economically paying proposition. Those responsible for the evaluation of the projects, considering the important stack constituted by energy storage, advise the Executive Committee to favour the construction or several projects, and to assure their common financing on the basis of a distribution scale to be defined on each case.

6. CONCLUSION

6.1. Relationship between the participating countries

This report marks the end of the work carried out in the framework of Annex 1. The concluded agreement essentially provided exchange of information about the projects and research of each country participating in this task.

Fifty four (unpublished) technical reports have been exchanged between the participants through the Operating Agent from October 1978 - March 1980. The Operating Agent is glad to point to the excellent contacts between the designated persons and experts in Annex 1.

During the three meetings held by experts (Copenhagen, Neuchâtel, Paris) the scientists of each participating country were able to discuss their work and in this way complete their information concerning long term and large scale storage.

When a research project is limited to an exchange of information, it is not possible to show spectacular results. However Annex 1 was a necessary and indispensable step to suggest that large scale thermal storage systems are :

- Technically possible by the use of various methods

- Economically viable

- An important method of saving energy.

During the meeting of Paris on 9th October 1980, the members of the Executive Committee recognized that an exchange of information in this area is extremely important, and hope that these exchanges will continue in the future, and if possible in collaboration with the new countries signing the Implementing Agreement. The members of the Executive Committee also hope that new annexes will be defined and adopted in order to ensure the carrying out of jointly funded hardware demonstration projects. The Operating Agent expresses nonetheless one slight regret : The exchanges of scientists between Research Institutes of the participating countries have been almost non-existent. In the frame of new annexes it is to be hoped that certain funds could be attributed to such exchanges.

Taking into account the different stages of progress of projects, the level of informations received by the Operating Agent was relatively heterogeneous : Munich, Hørsholm, Dorigny for example are very advanced projects with a great number of technical data. Bellingham, St. Paul are projects in development which will not be completed before several years. For these projects information level is still relatively low.

In order to ensure the uniformity of this final report the Operating Agent had to reduce the number of data relative to certain projects. These data can be obtained directly from the participating countries, and they have been provided to the subscribing countries as technical reports.

6.2. Main results

Most important conclusions :

First : Techniques and systems at disposition or which are going to be developed for long term thermal storage on a large scale are very different.

Second : Construction of thermal storage on a large scale is now under certain circumstances economically interesting.

Third : Energy storage enables to save an important quantity of energy, which could amount to as much as 30 % of the consumption of the system to which the accumulator is linked.

The choice of an energy storage concept depends on the following technical parameters :

- Duration
- Quantity of energy to accumulate
- Number of cycles per year
- Temperature in the store
- Site conditions (from a geological point of view)
- Technical risks

Technicals parameters being clearly defined and evaluated, the final choice of a system has to be made in function of an economical analysis.

Daily and weekend storage can now be carried out economically and save a great deal of energy. This result is remarkable and was not obvious at the time of signing the agreement in 1978.

It is anticipated that a complete solution will be found for seasonal thermal energy storage in years to come. The economical efficiency of this type of storage is not always shown at the present time. The economical evaluation of the projects taken into condideration in the report has shown clearly that the specific cost of storage decreases with the volume of the accumulator. (See the case of St. Paul or Studsvik). Investment for the construction of a large accumulator is very high, which increases proportionally technical risks and delays the start of a first construction. There is a "barrier" to climb over, which takes a certain time, before being able to ensure the technical and economical success of a first large and efficient construction. The specific cost of seasonal storage (1 cycle per year) should be less than 0.30 dollars per KWh of accumulation. In this context a combined effort should be made concerning :

- The construction of prototype systems in order to acquire the necessary knowledge and control of all technical problems encountered in building a large sized seasonal accumulator.

The tests carried out at Auburn (Alabama) represent a good example of testing in order to obtain very precious information on one of the constructions of large size seasonal accumulators.

- A technical and economical cooperation in order to build one or a few seasonal stores of large size in which the economic aspect could be demonstrated.

Finally the choice of projects should be made more in terms of a concept rather than in terms of projects in the light of geological and site factors.

6.3. Final remarks and suggestions

The Swiss project designed as a classical aquifer project and the Munich project retained the interest of the participants. These 2 projects could be carried out in a short time, and they could help to solve the technical difficulties which arise during the construction of large sizes accumulators.

St-Paul (aquifer) and Studsvik (lake) projects are to be encouraged.

Exchange of data on the Hørsholm project and construction would be very welcome.

Exchange of information between associated countries must be maintened and cooperation with new countries encouraged.

7. ACKNOWLEDGEMENTS

We would particulary like to thank the members of the Executive Committee and their associates for the excellent collaboration which they have maintained over this period of two years.

In particular the following people have collaborated in the technical and economical evaluation of projects and also prepared the present final report :

- Rune HÄKANSSON	(Studsvik Energiteknik, Sweden)
- Reinhard JANK	(MITEC - München, for Kernforschungsanlage Jülich, Germany)
- Bernard MATHEY	(Consulting engineer, for the Centre d'Hydrogéologie de l'Université de Neuchâtel, Switzerland)
- Michel SIAT	(RPA - Paris, for US DOE)

We thank them for their efficient team work.

The Operating Agent for Annex 1

Centre d'Hydrogéologie
de l'Université de
Neuchâtel - Switzerland

A. Burger

Neuchâtel, October 1981.

8. SHORT BIBLIOGRAPHY

Belgium

BRYCH,J. / NEERDAEL,B. / PAREZ,A. / SAROT,J. — Large diameter wells for heat storage. Summary of the research work under the auspices of the International Energy Agency. Faculté polytechnique de Mons. Internal report. 21 p.

SAROT,J. — (1979) Stockage de chaleur. Théorie de la modélisation des réservoirs. Faculté polytechnique de Mons. Internal report. 33 p.

NEERDAEL,B. / VAN EYLL,M. — (1980). Modèle semi-industriel de réservoir de stockage de chaleur et de réacteur souterrain de méthanisation. Faculté polytechnique de Mons. Internal report. 33 p.

SAROT,J. / NEERDAEL,B. — (1980). Stockage de chaleur. Les réservoirs cylindriques verticaux souterrains. Etude thermique expérimentale. Faculté polytechnique de Mons. Internal report. 40 p.

BRYCH,J. / NEERDAEL,B. / PAREZ,A. / SAROT,J. — (1980). Stockage de chaleur. Approche économique de différents systèmes de stockage de chaleur. Faculté polytechnique de Mons. Internal report. 36 p.

Denmark

LETH,J.A. — (1978). Seasonal Storage of Heat Underground. Annual Progress Report for 1978. RISØ Engineering Dept. 771.112/K /bk. Konstruktionsafdelingen, Forsøgsanlæg Risø. 5 p.

ANDERSEN,L.J. — (1978). De Hydrogeologiske Forhold ved Randers Varmtvandslagring Status rapport. Danmarks geologiske undersøgelse København. 5 p. + dessin

RATHMANN,O. — (1978). Ground Water Flow Control by 2, 3, 4 or 6 Compensation Wells. Risø National Laboratory. Department of Reactor Technology - SOL. 13 p.

RATHMANN,O. — (1978). Porflow : A Computer Finite Element Model for Aquifer Simulation. Risø National Laboratory - Department of Reactor Technology - SOL. 58 p.

AMBO,K. — (1979). An Experimental Investigation of Cold and Hot Water Drives in Saturated Porous Media. Inst. of Hydrodynamics and Hydraulic Engineering. Techn. Univ. of Denmark. 182 p.

MELHUS,Ø. / QVALE,B. — (1979). Evaluation of warm water storage in the Aalborg - Nørresundby Area. Lavoratoriet for Energiteknik. 9 p.

MELHUS,Ø. / QVALE,B. —(1979). Varmtvandslagring i Aalborg - Nørresundby - Området. Laboratoriet for Energiteknik. 73 p.

ANDERSEN,L.J. — (1980). Field Investigation for Selection of Sites for Aquifer Storage of Heat in Denmark. Geological Survey of Denmark. 18 p.

REFFSTRUP,J. / WÜRTZ,J. — (1980). Mathematic Modelling of Thermal Energy Storage in Aquifers. Laboratory for Energetics. 8 p.

HAGELSKJAER,J. —(1980). The Danish Aquifer Thermal Energy Storage Project Demonstration Plant. Risø National Laboratory, Engineering Dept. 27 p.

European Communities

COMMISSION OF THE EUROPEAN COMMUNITIES. — (1978). Progress Report for 1978 on the theoretical and experimental feasibility study for an aquifer heat storage system.

Germany

MESSERCHMITT, / BÖLKOW, / BLOHM GMBH. — (1976). Studie über Jahreswärmespeicher niedrigen Temperaturniveaus Band 1 + Band 2. 26.5.1976. 281 (B.1), 302 (B.2) p.

FEDERAL MINISTRY OF RESEARCH AND TECHNOLOGY AND NUCLEAR RESEARCH FACILITY JÜLICH. — (1976). Study Report on Seasonal Heat Storage Systems in the Low Temperature Range. Summary. 11.10.1976. 46 p.

MESSERCHMITT, / BÖLKOW, / BLOHM, GMBH. — (1979). Entwicklung eines Aquiferspeichers Phase I. Periodisch Bericht Nr 2 für den Zeitraum vom 1.1.79 bis 30.6.1979.

Sweden

ALLMÄNNA INGENJÖRSBYRÅN AB, STOCKHOLM. — (1978). Heat Storage in natural groundwater basins. Report from NE-project 2060 261 Akviferer AIB.Apr 1978 191 p. (SSO)AT (NE/HETV--78/7)

BLOOM,F. / KÄRKER,S. / MARGEN,P. / MENON,S.(1978). A lake heat store for seasonal storage of hot water. Studsvik Energiteknik AB, Nyköping. STUDSVIK/K2--78-40. Final report from NE-project 2060 362 Sjömagasin AE Oct 1978 91 p. (SSO)AT (NE/HETV--78/13)

CLAESSON,J. / EFTRING,B. / HELLSTRÖM,G. / OLANDERS,P. — (1978). Theoretical analysis and computer simulation of solid-fluid heat storage systems in the ground, extraction of earth heat. Lunds Tekniska Högskola, Lund. Interim report inom NE-project 2060 371 Jordlagring. Oct 1978 Part I 115 p. and Part II 121 p. (SSO)AT [NE/HETV--78/15 (Pt.1 and Pt.2)]

LINDBLOM,U. / ADOLFSSON,K. HAGCONSULT AB, Göteborg. — (1978). Long term storage of waste and solar heat in clay (in Swedish). Slutrapport från NE-projektet 2060 471 Marklager Hagconsult. Dec 1978 12 p. (SSO)AT (NE/HETV--78/20)

HELLSTRÖM,G. / TSANG,C-F. / CLAESSON,J. — (1979). Heat storage in aquifers. Buoyancy flow and thermal stratification problems. Report from NE-project 2060 372 Jordlagring LTH. Lunds Universitet, Lund. Oct 1979 70 p. (SSO)AT (NE/HETV--79/17)

VBB, Stockholm och Malmö — (1980). Heat storage in ground water (in Swedish). Del 1: Studie av grundvattenmagasin 85 p. Del 2: Studie av distributionssystem 36 p. Bilaga: Geohydrologiska fältdata, 19 p. Final report from NE-project 2060 591 Akvifer VBB Jan 1980 (NE/HETV--80/1)

BOGDANOFF,I. — (1980). Block filled rock caverns for long term energy storage (in Swedish). Lägesrapport för NE-projektet 2060 571 Bergrum, CTH. Chalmers Tekniska Högskola, Göteborg. Inst för Geoteknik med Grundläggning. Maj 1980 105 p. (SSO)AT (NE/HETV--80/6)

ALLMÄNNA INGENJÖRSBYRÅ AB, STOCKHOLM. — (1980). Heat storage in natural ground water basins. Report from NE-project 2060 262. Sep 1980 210 p. (SSO)AT (NE/HETV--80/14)

Switzerland

DUCOMMUN,L. — (1978). Les rejets de chaleur dans les eaux suisses. Centre d'Hydrogéologie Université de Neuchâtel. Mars 1978 59 p.

CENTRE D'HYDROGEOLOGIE, UNIVERSITE DE NEUCHATEL. — (1978). Rapports scientifiques et techniques sur le comportement des nappes souterraines. Nov. 1978. 250 p.

JOOS,B. — Convection naturelle dans les aquifères, simulation du comportement du milieu par modèles numériques. IENER-EPFL-Lausanne. Internal Report. 20 p.

SAUGY,B. — Formulation de base, description et exemples d'application des modèles de diffusion transport par éléments finis. IENER-EPFL-Ecublens. 34 p.

MATHEY,B. — (1979). Le stockage intersaisonnier de l'énergie solaire dans le sol à l'échelle de l'habitat. Rapport Centre d'Hydrogéologie., Université de Neuchâtel. 16 p.

United States

Thermal energy storage in aquifer workshop. Proceedings. Berkeley. (1978). 126 p.

Third annual processing of thermal energy storage contractor's information exchange meeting. Springfield. Dec. 5-6 1978. 465 p.

US DEPT. OF ENERGY. — (1977-1978). Application of thermal energy storage to process heat storage and recovery in the paper and pulp industry. Final Report, Sept. 1977 - May 1978. 240 p.

Application of Thermal Energy Storage in the Cement Industry. — (1977-1978). Final Report, Sept. 1977 - March 1978. 197 p.

MOLZ, / WARMAN, / JONES, / PAPADOPULOS, / LARSON. Aquifer Storage of Heated Water. Part I and II. Réf.: Groundwater Nb 4, Vol 16, 1978. pp 234 - 248.

PETERSON,D.J. — Application of Thermal Energy Storage to process Heat and Waste Heat Recovery in the Iron and Steel Industry. Final Report. US DOE. 134 p.