Lawrence Berkeley National Laboratory

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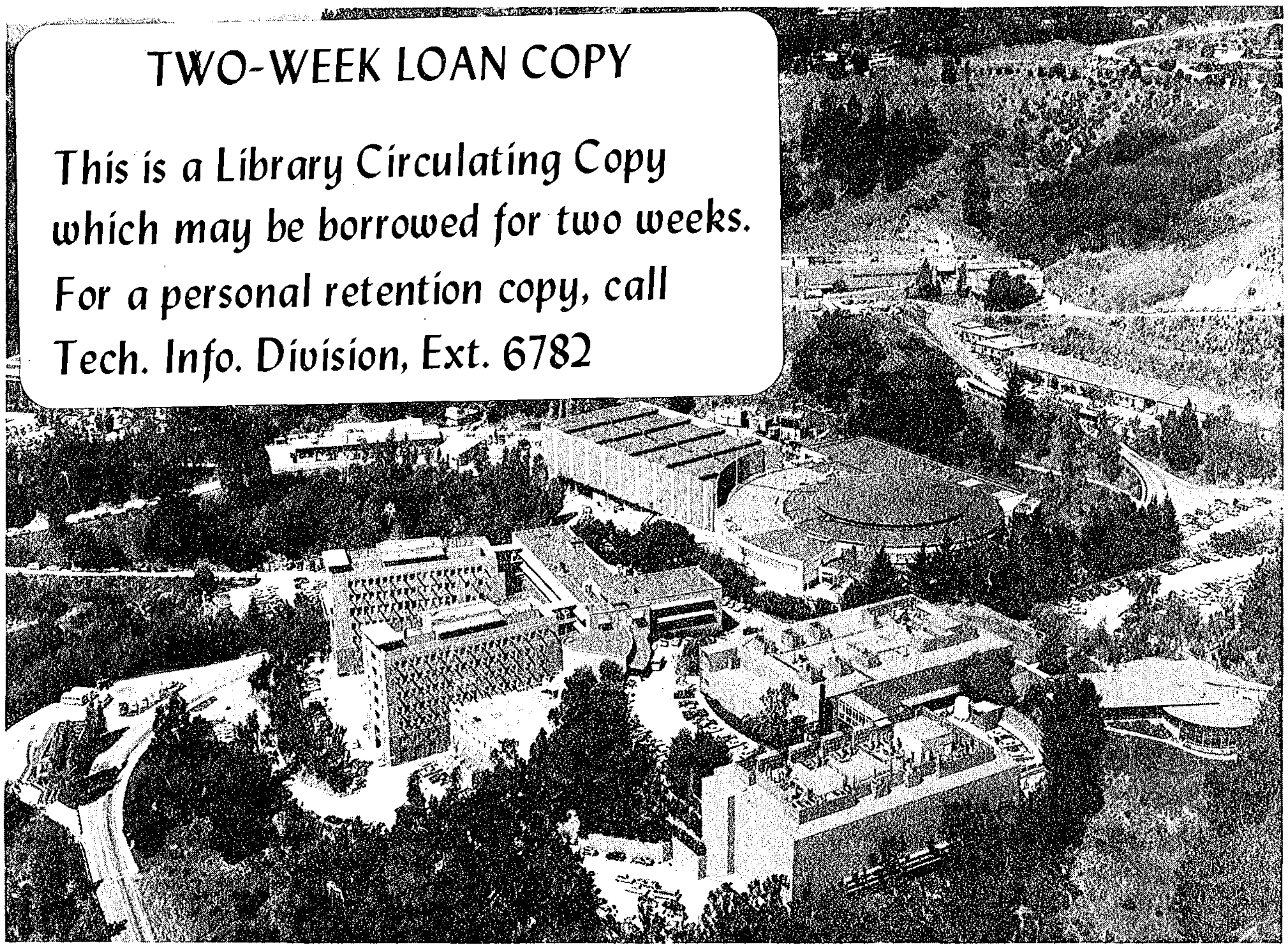
THERMAL ENERGY STORAGE IN AQUIFERS WORKSHOP

May 10-12, 1978
Berkeley, California

PROCEEDINGS



Sponsored by

U.S. Department of Energy Division of Energy Storage Systems, Through the Low Temperature Thermal Energy Storage Program of Oak Ridge National Laboratory

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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PROCEEDINGS OF THE THERMAL ENERGY STORAGE IN AQUIFERS WORKSHOP

May 10-12, 1978
Berkeley, California

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PREFACE

Although the concept of thermal energy storage in aquifers was suggested by several authors about ten years ago, only in the last three years or so has active interest been aroused and several field projects in the U.S. and abroad initiated to validate and demonstrate it. In mid-1978 it appeared appropriate to hold a workshop on this subject to review what has been accomplished and where future direction lies. The Lawrence Berkeley Laboratory (Earth Sciences Division), in cooperation with the United States Department of Energy (Division of Energy Storage Systems) and the Oak Ridge National Laboratory (Low Temperature Energy Storage Program), has taken the responsibility of organizing this workshop. The LBL Earth Sciences Division under the leadership of Dr. Paul A. Witherspoon selected Dr. Chin Fu Tsang as the Workshop chairman and Werner J. Schwarz as the Workshop coordinator.

The Workshop was limited to about 80 participants in order to allow a full exchange of ideas from all involved. In this volume, papers from outside the Lawrence Berkeley Laboratory were prepared for publication by the authors and are being reproduced without change. Lawrence Berkeley Laboratory papers were reviewed by the Earth Sciences Division's Publications Committee.

PROGRAM

SESSION I - 4:30 pm to 6:00 pm, Wednesday, May 10, 1978

CALL TO ORDER

Chin Fu Tsang, Chairman
Lawrence Berkeley Laboratory (LBL)

Welcome

Andrew M. Sessler
Director
Lawrence Berkeley Laboratory

DOE Perspective

George F. Pezdirtz
Director, Division of Energy Storage Systems
U.S. Department of Energy

Seasonal Storage - Prospects and Problems

C.J. Swet
U.S. Department of Energy

Aquifers for Seasonal Thermal Energy Storage: An Overview of the DOE-STOR Program

Herbert W. Hoffman
Oak Ridge National Laboratory

SESSION II - 8:30 am to 4:00 pm, Thursday, May 11, 1978

TECHNOLOGY REVIEW

Chin Fu Tsang, Chairman
Lawrence Berkeley Laboratory

Hydrogeology and Reservoir Engineering

Paul A. Witherspoon
Associate Director and Head of Earth Sciences Division
Lawrence Berkeley Laboratory

Aquifer Chemistry

L. Russell
Montgomery Engineering

Petroleum Industry Experience in Water Injection

Wayne J. Subcasky
Chevron Oil Field Research Company

Current Machinery for Solar and Geothermal Applications

R. Barber and K. Nichols
Barber-Nichols Engineering

Energy Management Objectives and Economics of Heat Storage Wells

Charles F. Meyer and Walter Hausz
General Electric - TEMPO

Institutional Aspects of Utilizing Heat Storage in Aquifers - A Proposal for a Prototype Test

John A. Carver, Jr.
Attorney General, American Samoa;
and University of Denver

Environmental Aspects of Low Temperature Thermal Energy Storage in Aquifers

Jay H. Lehr
The National Water Well Association

SESSION III - 4:00 pm to 9:30 pm, Thursday, May 11, 1978

REVIEW OF CURRENT DOE PROJECTS

R.J. Kedl, Chairman
Oak Ridge National Laboratory

Mathematical Modeling of Thermal Energy Storage in Aquifers

Chin Fu Tsang, Thomas Buscheck, Donald Mangold, and Marcelo Lippmann
Earth Sciences Division, LBL

BANQUET - W.J. Schwarz, Chairman

Banquet Address - California Energy Policy

Wilson Clarke
Assistant to the Governor on Energy, Planning and Research, State of California

SESSION III, continued - 8:30 am to 3:00 pm, Friday, May 12, 1978

Confined Aquifer Experiment - Heat Storage

Fred J. Molz and James C. Warman
Auburn University

Thermal Storage of Cold Water in Groundwater Aquifers for Cooling Purposes

D.L. Reddell, R.R. Davison, and W.B. Harris
Texas A & M University

Air Conditioning Kennedy Airport with Winter Cold

Henry J. Hibshman
Desert Reclamation Industries, Inc.

High Temperature Underground Thermal Energy Storage

R.E. Collins, J.R. Fanchi, and G.O. Morrell
University of Houston

K.E. Davis, T.K. Guha and R.L. Henderson
Subsurface, Inc.

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Aquifer Storage Projects in Sweden

G. Hellström
Lund Institute of Technology, Sweden

Aquifer Storage Efforts in Germany

Reinhard Jank
Projektleitung Energieforschung in der Kernforschungsanlage Jülich, Germany

The Danish Seasonal Aquifer Warm-Water-Storage Program

E.B. Qvale
Technical University of Denmark

Survey of Thermal Energy Storage in Aquifers Coupled with Agricultural Use of Heat Under Semi-Arid Conditions

A. Nir,
Weizmann Institute of Science, Rehovot, Israel

J. Schwarz
Tahal Engineering Ltd., Tel Aviv, Israel

Underground Heat Storage: Dimensions, Choice of a Geometry, and Efficiency

Bernard Mathey
Centre d' Hydrogéologie de l' Université, Switzerland

Heat Storage in a Phreatic Aquifer: Campuget Experiment (Gard, France)

P. Iris
Ecole des Mines de Paris, France

Seasonal Regeneration Through Underground Strata

T. Yokoyama
Nippon Chikasui-Kaihatsu Co., Ltd., Japan

SESSION IV - 3:30 pm to 5:00 pm, Friday, May 12, 1978

REACTION PANEL

David M. Eissenberg, Chairman
Oak Ridge National Laboratory

Panelists

1. S.S. Papadopulos, U.S.G.S., Reston, Virginia
2. C.W. Easton, Seattle Steam Corp.
3. S.P. Neuman, University of Arizona
4. M.F. Dorfman, University of Texas at Austin
5. K.C. Holte, Southern California Edison

CLOSING REMARKS AND ADJOURNMENT

Chin Fu Tsang
Lawrence Berkeley Laboratory

INTRODUCTION

The Thermal Energy Storage in Aquifers Workshop resulted from the need to gather active workers in this field to discuss the potential of thermal energy storage in aquifers; review efforts currently under way; and address the possible technical, environmental, and institutional problems associated with its implementation. The Workshop provided an information exchange to the 76 participants who are currently involved directly or indirectly in the field. These participants represented diverse areas: 18 from private industry and institutions; 13 from universities; 30 from national laboratories; 6 from government (USDOE/STOR, USEPA, USGS, the state of California); and 9 from foreign countries (Denmark, France, Germany, Iceland, Israel, Japan (2), Switzerland, and Sweden).

Workshop presentations were broadly classified into Overviews, Technology Reviews, Reviews of Current US/DOE Projects, and Summaries of Foreign Programs, followed by a discussion panel. Responding to the program, the discussion ("reaction") panel consisted of representatives from government, industry, utilities and universities. Papers presented in the Workshop as well as summaries of the comments by panel members are included in these Proceedings.

At the close of the Workshop, the need for further and continued information exchange was expressed in a meeting of DOE program managers, ORNL technical managers and foreign participants. LBL has been asked to take up the responsibility of publishing a bi-monthly Aquifer Thermal Energy Storage Newsletter, under the editorship of Dr. Chin Fu Tsang. The purpose of the Newsletter is to keep workers in this field informed of major results and the current status of aquifer storage projects throught the world. Further information about this Newsletter may be obtained from us.

The Workshop was sponsored by the U.S. Department of Energy (Division of Energy Storage Systems) and the Oak Ridge National Laboratory as well as Lawrence Berkeley Laboratory. Assistance and advice from many program and technical managers, particularly C. J. Swet, H. W. Hoffman and R. J. Kedl, are much appreciated.

Chin Fu Tsang
Chairman

Werner J. Schwarz
Workshop Coordinator

D.O.E. Perspective

George F. Pezdirtz
May 10, 1978
Thermal Energy Storage in Aquifer Workshop

Thank you and let me add my welcome to this group. I'm both surprised and pleased to see such a large group gathered to discuss thermal storage in aquifers. Within the Department of Energy, there is growing interest in aquifer storage. It is reassuring to see a matching interest in the private sector for our aim in the Department of Energy is to foster the commercialization of new technology developments in the private sector as rapidly as possible.

In fact, the Department of Energy possesses an entirely different type of operational attitude than any other department or agency in Washington, technical or otherwise. My previous experience was with NASA, and in that case the Agency is its own customer. NASA bought its own rockets, took its own folks to the moon, and brought them back again. The same is true of the Department of Defense. They buy their own tanks, planes, ships and other equipment. By contrast the DOE is not its own customer. The private sector, and private industry is actually the customer for the Department of Energy. If our products are not commercialized in the marketplace then we will not have reached "our moon". We will not have accomplished our main purpose. To do this we certainly need the university people, and we need the national laboratory structure. However, the major share of the action and the major commitment of funds will come not from the Department of Energy but rather from the private sector.

In order to provide some insight into the structure of DOE, the newest department within the government, I've included several organizational charts. Figure #1 is a chart of the technical and regulatory offices in the Department. The Secretary is Dr. James Schlesinger. He is supported by John O'Leary who came from FTA and Dale Meyers who was president of Rockwell International. They hold the positions of Deputy Secretary and Under Secretary respectively. The economic and regulatory functions are under David Bardin. To the Energy Information Administration under Lincoln Moses falls the difficult, but crucial job of providing reliable information on both current and projected energy supply and demand.

Department of Energy Technical & Regulatory Organization

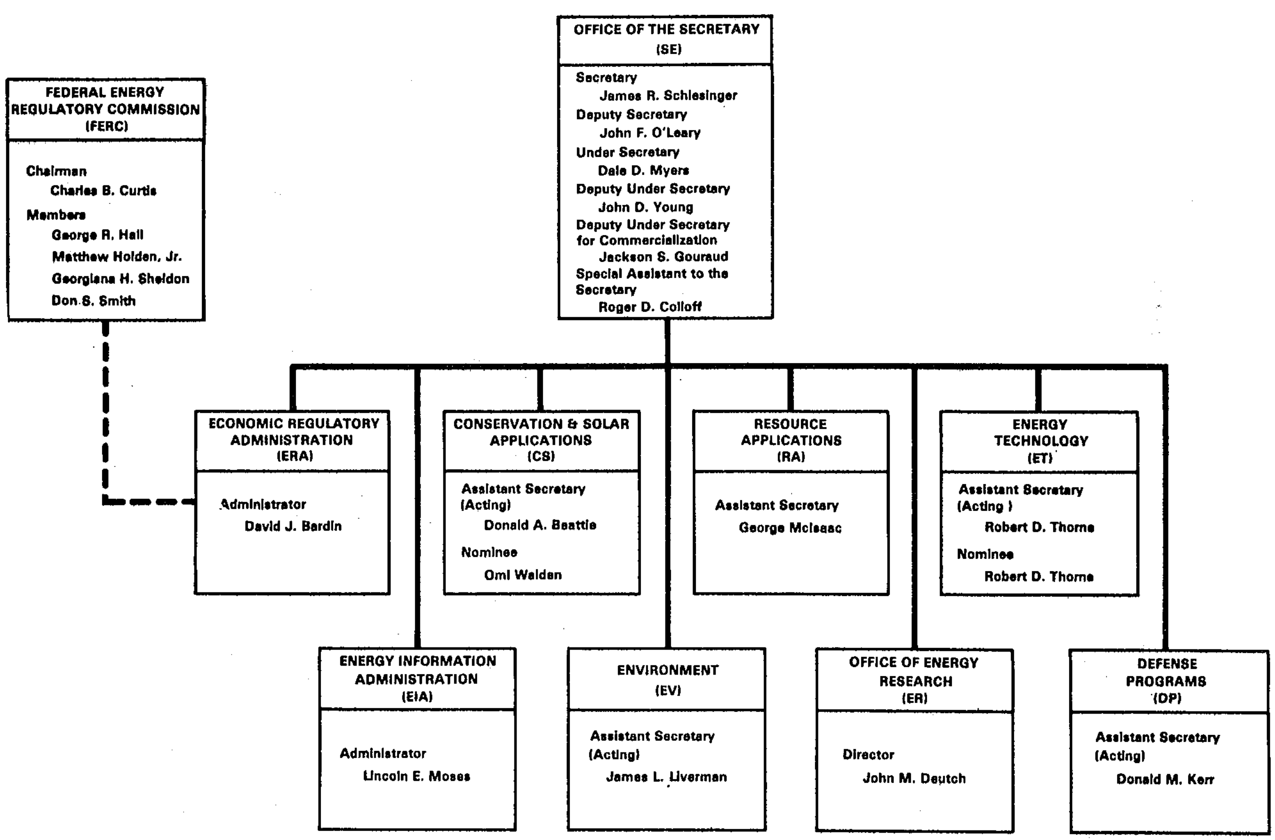

Figure 1

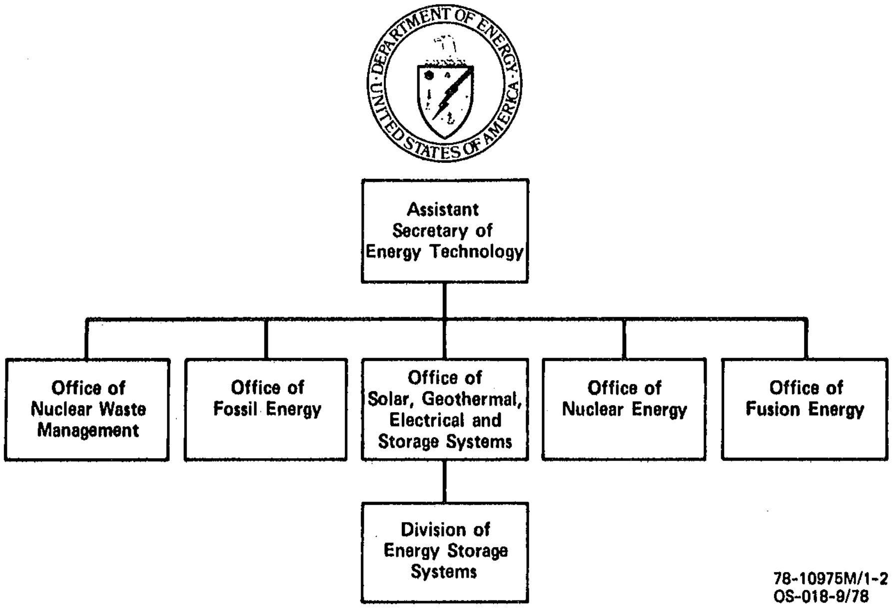

Figure 2

In the operational area, Don Beattie is the acting head of the Conservation and Solar Applications Program. Robert Thorne is Assistant Secretary for Energy Technology. His confirmation has only recently come from the Senate. Mr. Thorne, like all the Assistant Secretaries, is a Presidential Appointee who must be approved by Congress. Consequently, there is often a considerable delay during which these people must serve in an acting capacity as the approval process can be lengthy. George McIsaac is Assistant Secretary for Resource Applications, James Liverman is acting in the same position in Environment, and Donald Kerr holds the Assistant Secretary position in Defense Programs. Finally, John Deutch is the Director of the Office of Energy Research.

In ERDA, the Division of Energy Storage was located under Conservation. I'm very pleased that since the creation of DOE we have been placed in Energy Technology under Robert Thorne. Energy Storage is more technology-oriented than most programs under Conservation. For instance, Programs such as aquifer storage had to compete with programs such as driver education. The diverse nature of the activities under Conservation made programmatic, organizational and budgetary evaluations much more difficult to accomplish.

Figure #2 provides a more detailed view of part of the Energy Technology Organization under Robert Thorne. Eric Willis serves as the deputy assistant Secretary. The Division of Energy Storage is part of Solar, Geothermal, Electric and Storage Systems under Program Director Bennett Miller. Also under Energy Technology is the Office of Nuclear Waste Management, Fossil Systems, Nuclear Systems, and the Office of Fusion Energy.

The Solar, Geothermal, Electric and Storage Systems program is increasingly becoming the bright spot under Mr. Thorne. This program area of which we are a part, is experiencing increased emphasis from the President as well as throughout the Department. The third organizational Chart (Figure #3) which I have to show you provides a detailed view of this program under Bennett Miller. Hank Marvin heads the Solar Division, Rudolph Black is director of Geothermal Energy Systems, Fox Parry is director of Electric Energy Systems and I head the Division of Energy Storage Systems.

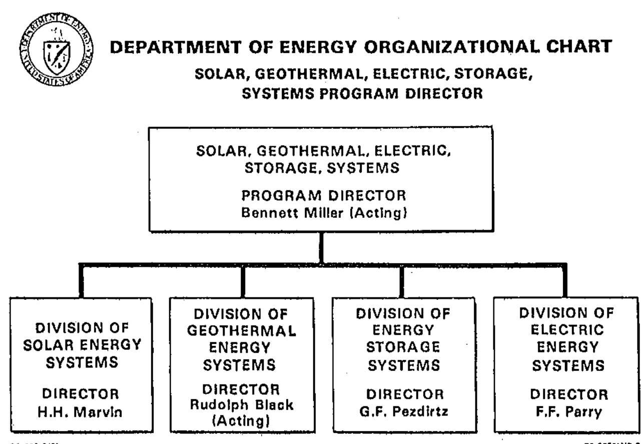

Figure 3

Within the Division of Energy Storage, as figure #4 illustrates, are two branches. The largest branch is the electrochemical group which is a rather homogeneous technology. We are spending approximately 17 million in the electrochemical program. The primary applications envisioned at this time are electric cars and utility load leveling. We also are sponsoring research into improving the efficiency of various electrochemical industrial processes such as occur in aluminum and chlorine production. As the chart shows, Maurice Katz serves as Assistant Director and under Katz are Kurt Klunder and Al Landgrebe as branch chiefs. Our other branch is headed by Jim Swisher who is assistant director for Physical Storage Systems. Under Jim are three

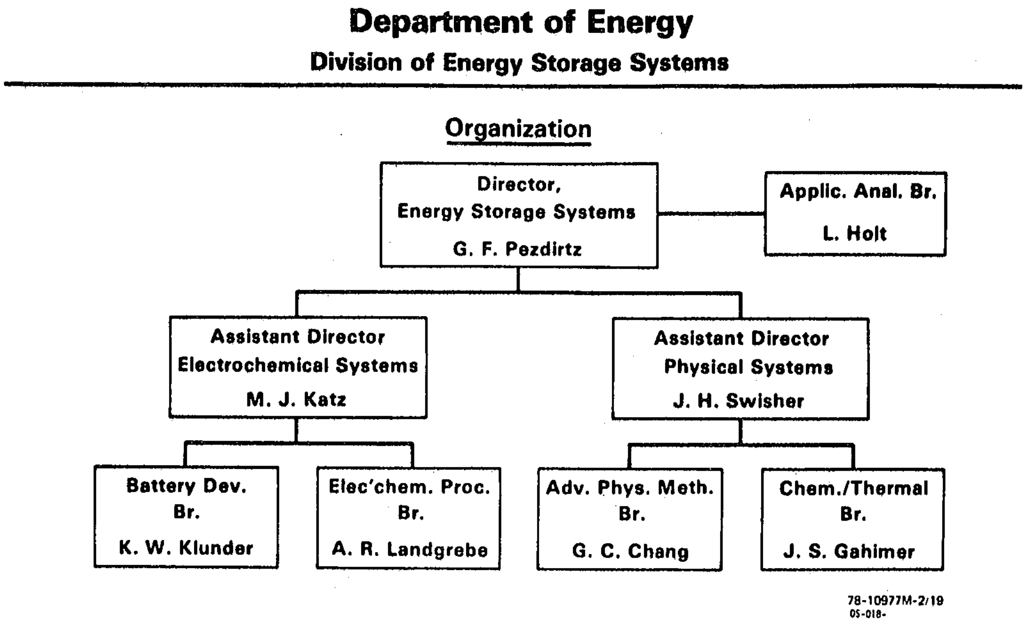

Figure 4

branches; Chemical and Thermal, Advanced Physical Methods, and Applications Analysis. In actuality, the Applications Analysis Branch reports directly to me and is responsible for a portfolio analysis of the whole division. This branch provides me with the data and methodology to evaluate where it makes the most sense to place your and my tax money. As a result of some of our evaluative studies, it appears that aquifer storage warrants increased emphasis in the future.

Returning to the Physical Systems Organization, John Gahimer is acting branch chief for Chemical and Thermal and under John is C.J. Swet as program manager for all Thermal Storage Activities. George Chang serves as Branch Chief for Mechanical and Magnetic Storage Projects.

We in the Division of Energy Storage have more technical interfaces than any other division within the Department. We have a rather small group of folks, about 16 professionals. We're managing a budget of a little over 50 million directly and another 20 million in joint projects with other divisions in DOE. We've also established some joint projects with the State of California, the State of Westphalia in the Federal Republic of Germany, and with several large corporations such as Ford and DOW.

Aquifer storage has the potential to fit neatly in with several projects being conducted by the Office of Conservation and Solar Applications in particular their Building and Community Systems Division. Also, the Industrial Conservation group also hold potential for active projects utilizing aquifer storage. In addition, under Energy Technology the Solar Technology group seems a natural fit.

Within the Chemical and Thermal Branch, we are investing in a number of projects. I use the term investing because we at DOE are definitely looking for a return on these "investments". As an example, in my division we have over a dozen patent waivers which give exclusive rights to an industry that is jointly sponsoring technology R&D with the government. This is a different arrangement than was common in the past. However, I believe this type of agreement will be used more frequently in the future. We view the patent waiver as an incentive to stimulate industry to get their act together and commercialize the results of current research and development. We realize that unless private industry can turn a profit on a new technology it will remain only a paper study and consequently will benefit no one.

Before concluding, I'd like to briefly discuss some of our current projects in the Thermal Storage program. At present the technical management of low temperature thermal storage (under 200° Centigrade) is being conducted at Oak Ridge while the management of high temperature storage is the responsibility of NSAS Lewis. Reversible chemical action work is being conducted our of SLL.

Our intent is to channel a significant portion of our funds to the private sector while retaining technical management at the national labs. The national labs have been instructed to pass on at least one half of their funding to private industry.

As you know, our purpose is to develop thermal and thermochemical storage technologies for a host of uses; in residential heating and cooling, in electric power systems, commercial and industrial processes and even perhaps transportation.

Seasonal storage in underground aquifers involving hourly, diurnal, weekly and extended storage appears to have very strong potential. One of the reasons that there is strong interest in seasonal aquifer storage even on the Assistant Secretaries level is that it appears that this type of storage can be implemented in the near term. This is a challenging area and to accomplish near term application we will need your help. However, in the environment of Washington, if there's one thing that stands out it's the desirability of accomplishing things during the current administration.

In the high temperature sensible heat area, solar thermal power generation is receiving increased attention and may get a fairly large boost in funding as well as increased emphasis within the solar program. Some of you may have noted that on Sunday at the Solar Energy Research Institute, the President announced that he had requested DOE to reprogram an additional 100 million into solar energy. We expect some of those funds to be allocated to the Division of Energy Storage for our storage activities.

In the thermal chemical energy storage program, there is the possibility of transportation applications. In Sweden, the Phillips Company has an automobile sterling engine coupled to a heat battery or heat cell of molten salt. However, one of the problems with this type of activity is that it becomes too diffuse. In Washington, DOE hopes to identify and focus upon a few technologies with a high likelihood of coming up as winners. I hope that some of your work here will provide us with the ammunition we need to go back and sell Congress and our own management on the desirability of emphasizing the thermal program.

Thank you for your attention. I'm sure this workshop will prove highly productive for you as well as helpful to us in our program planning. At this point, I'd like to turn things over to C.J. Swet who will provide you with more details on the Thermal Storage Aquifer program.

SEASONAL STORAGE: PROSPECTS AND PROBLEMS

C.J. Swet
U.S. Department of Energy

Thank you Chin Fu. I will try to act as a very short bridge, seeing how little time is left, between the general description that George Pezdirtz gave of what we are doing in thermal storage and what Herb Hoffman will be saying about aquifers after I sit down. I am going to try to place the aquifer storage program in perspective, against a backdrop of our seasonal storage program, which is really sprinkled through the activities of all three of the sub-programs George has described. Some of it is in the low temperature area, some is in the high temperature area and some is in thermochemical. In all of these areas, there are long-duration storage technologies that will be competing or perhaps complementing each other in the seasonal storage market. Although the title to my talk is "Seasonal Storage: Prospects and Problems", I think there will be enough problems raised during the next two or three days; so I will limit myself to the prospects and give you a brief rundown of the positive aspects of seasonal storage, make some comparisons, and show how aquifers fit in.

First, let us consider the major applications of seasonal storage listed in Figure 1. I use the term "seasonal storage" synonomously with "yearly averaging", "extended duration", and "interseasonal" as the spirit moves. The different terms represent minor variations on the general theme of very long duration storage that rides through seasonal fluctuations in the energy source demand. I think the comfort heating use is pretty evident. Seasonal storage can allow us to use the available heat more fully, whether it is for district heating on a large scale, or for individual buildings. Used for comfort cooling, it makes winter coolness available in the summer, when needed. For power generation, the prospect of autonomous solar-thermal power really rests on the feasibility of yearly averaging storage, or something approaching it. I added cooking because it is a favorite subject of mine, especially when the cooking is with stored solar heat. I do not claim it will have a profound impact on the U.S. energy economy, but the in the third world solar cooking is an extremely important thing, and I hope many of us take a broader view than the parochial outlook of many Americans. The problem of firewood depletion is a terribly important one, and making solar cooking viable by means of long duration storage is a truly worthwhile goal.

Seasonal Storage of Thermal Energy
Applications

- Comfort Heating
- Comfort Cooling
- Power Generation
- Cooking

Figure 1.

In Figure 2, we see where the heat, or absence thereof, comes from. Solar heat is one source and the winter environment is another. Power-plant cogenerated heat for district heating (otherwise described as power-plant reject heat) is the third source and, as I think George touched on before, seasonal storage of industrial waste heat makes its recovery more profitable.

Seasonal Storage of Thermal Energy
Energy Sources

- Solar Heat
- Winter Cold
- Power Plant Cogenerated Heat
- Industrial Waste Heat

Figure 2.

Now we move to Figure 3, which reads like a cigarette ad, but only because I do not have time or space to get into the subleties. So I will say that if we are using seasonal storage for comfort heating, and if the source is solar heat, then by extending the use of the collectors over the entire year, rather than trying to use them only in the winter when the heating is needed, but when they perform least efficiently, we can get by with smaller, hence cheaper collectors. Instead of the usual day or so of storage, with fifty or at most seventy percent solar contribution to the total energy demand, we can essentially get one hundred percent, and save all the fuel that would otherwise be needed. Once we have done that, and are using the sun for all of the energy, we of course avoid the need for a backup system. Many people view electric resistance heating as an inexpensive backup, but the capital investment is somewhere between $500 and $1000 dollars per kilowatt and somebody has to pay for it to assure the availability of this infrequently used backup. Seasonal storage provides the only hope for using solar energy for space heating in higher latitudes where the winters are long and dark. We have some people from Scandinavia who can verify this. Without seasonal storage, reject heat from thermal power plants can only be recovered during the winter, when needed for district heating. The rest of the year, when heat is not needed, the reject heat still must be dissipated. Only with yearly averaging storage can we solve the thermal pollution problem, and avoid the need for expensive cooling towers and fossil-fueled dedicated backup units. Many of the same arguments that justify seasonal storage with utility cogeneration also apply to industrial waste heat, because plants commonly discharge waste heat throughout the year. When the application is comfort cooling - you will hear more about this during the next day or two - there is exciting prospect of gathering and storing coolness from the winter ambient environment and then using it in the summer to reduce the requirement for electricity or heat, depending on whether you are using motor-driven vapor compression units, or thermally drive absorption chillers. This can also relieve the summer peaking problem. We go from these space heating and cooling applications to the generation of solar thermal electric power.

As I touched on before, potentially one can achieve grid independence (and when I say "grid independence", I do not mean "grid isolation"; there is a difference between the two) and a very high percent contribution of the sun to the electric energy demand. Also, as in the case of solar heating, seasonal storage offers the only real opportunity for using solar thermal power in high latitudes where there is not much sun available during the winter. For solar cooking, I think it is pretty evident that firewood depletion is as much of a problem during rainy seasons as when the weather is sunny.

These, then, are the good things about seasonal storage, mentioning the prospects but not the problems.

Benefits of Seasonal Storage (Simplistically Stated)

- For comfort heating
  - With solar heat
    - Smaller collector
    - Total fuel savings
    - No back-up investment
    - High latitude feasibility
  - With utility cogenerated heat
    - Year-round exploitation
    - No cooling towers
    - No dedicated peak heaters
  - With industrial waste heat
    - Year-round recovery
- For comfort cooling with winter cold
  - No chiller fuel or power
  - Summer peak relief
- For solar thermal power
  - Grid independence
  - Total fuel savings
  - High latitude feasibility
- For solar cooking (third world)
  - Relieve firewood depletion

Figure 3.

In Figure 4, I have listed the technologies that are being explored at the DOE Division of Energy Storage Systems and elsewhere. Aquifer storage, as you might surmise, is one of our favorite subjects these days. Artificial or natural lakes can be insulated and partitioned to convert them into large-scale thermal energy storage vessels. We are not supporting work on that concept here, but in northern Europe it is being examined both for cogenerated and industrial waste heat storage. Seasonal storage of hot water in buried constructed tanks (aquifers are unconstructed tanks), provided the tanks are big enough, may be economically viable. The economics become marginal for single family dwellings because of the poorer surface to volume ratios, and because constructed tanks can be made cheaply only in large sizes. In some size range yet to be determined, they may be economically competitive with aquifers and offer an alternative where neither aquifers nor lakes are available. Another approach is salt gradient ponds, which have inverted thermal gradients and essentially no convective losses. Salt gradient ponds can be used both as low loss collectors and as storage vessels. Heat storage in excavated caverns is being considered mainly for solar thermal power, using pressurized high-temperature water that flashes into steam. From earliest times, we have had seasonal storage in phase change material, by collecting and storing natural ice. Now we have what is known as ACES, which is being sponsored in the Division of Buildings and Community Systems. A.C.E.S. is the acronym for Annual Cycle Energy Storage. A heat pump is used to manufacture ice on its evaporator side during the winter while it is heating the house, then the ice is used for summer-time cooling.

Storage of heat in unsaturated earth is being examined less intensively here than storage in aquifers (saturated earth), but there is considerable interest in Europe, and some experiments are about are about to be started in the Netherlands. Storage in rock is another opportunity. We have looked at high temperature long duration storage in native rock using air as the heat transport medium. Finally, in reversible chemical reactions, there is a whole host of system concepts for solar heating or cooling of buildings, called chemical heat pump storage systems, and for high temperature decomposition and recombination for solar thermal power. Storage duration can be indefinitely long because the reactants are stored at ambient temperature.

Seasonal Storage of Thermal Energy

Technologies

- Aquifers
- Lakes
- Constructed Tanks
- Salt Gradient Ponds
- Excavated Caverns
- Ice
- Earth
- Rocks
- Reversible Chemical Reactions

Figure 4.

Now just a few examples of these technologies and then I will pass the baton to Herb who will tell you what we are doing about aquifers. Figure 5 is an example of a constructed tank, or constructed pool, if you wish. This one was built and tested at the University of Virginia. A trickle type of solar collector heats the water in the pool, which has an insulated top. This is what one might do when there is no aquifer handy, or the scale is too small. Figure 6 shows a solar pond of the salt gradient type, with a convecting storage section at the bottom. The coolest water is at the top instead of the bottom because of the salt density gradient, which means less heat loss up and out. Annual storage in such ponds has been proposed, but we are not sponsoring any work on salt gradient pond storage because this technology is being developed in the private sector and there appears to be no need for federal assistance. I mentioned the use of excavated caverns. Figure 7 shows a big hole mined out of the rock, filled with very hot solar heated water which flashes into steam to feed turbines when the sun is not shining. It has enough storage capacity to balance out the seasonal variations in insulation and electrical load. We funded a study on the feasibility of this for shorter duration storage and it is quite an attractive system providing the geology is favorable.

I mentioned that chemical heat pump storage systems can be used for annual storage. Figure 8 illustrates one of several approaches we are exploring. This one involves the heat of dilution of sulfuric acid. The water and the concentrated acid can be stored for an indefinitely long time at ambient temperature, then recombined when needed to produce heat. Notice that it has a heat pump function that magnifies the solar heat contribution. I also mentioned high temperature, reversible chemical reactions. Figure 9 shows a non-working model made of beer cans and tennis ball, that in real life would use high temperature solar heat to decompose sulphur trioxide into sulphur dioxide and water. The two products would be stored at ambient temperature and recombined to produce heat for steam generation or perhaps for a gas turbine. And lastly, Figure 10, shows a device that stores solar heat for cooking by means of an ammoniated salt chemical heat pump.

(See Figures 5 - 9 on following page)

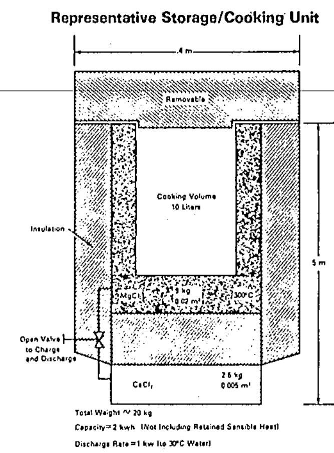

Figure 10.

In conclusion, let me suggest you read the series of letters between Amory Lovins and Hans Bethe on the subject of seasonal storage of solar heat, in which Bethe ultimately concedes that it might be an economically viable concept.

SOLAR POOL FOR ANNUAL COLLECTION/STORAGE

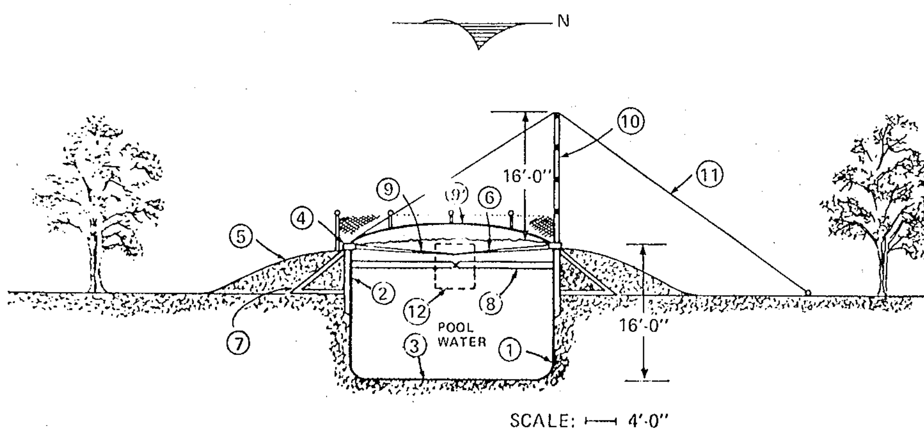

Figure 5.

SCHEMATICS OF SOLAR POND

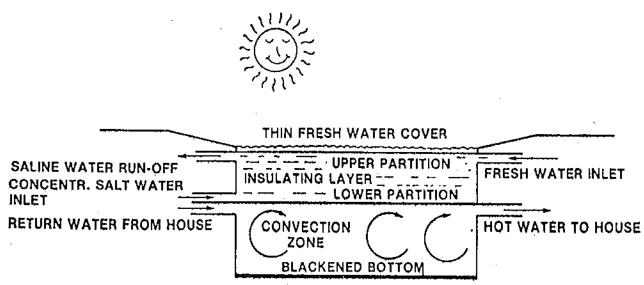

Figure 6.

PRESSURIZED WATER BLOWDOWN FROM EXCAVATED CAVITY (Seasonal storage)

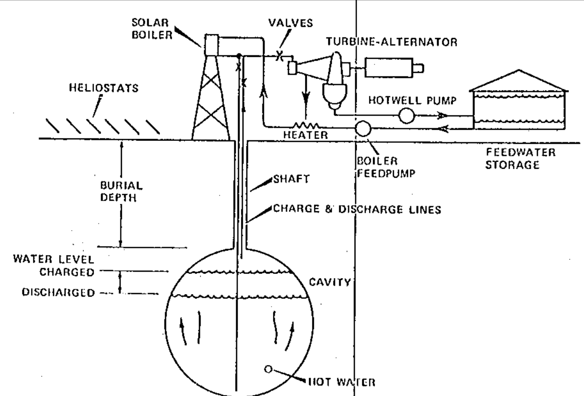

Figure 7.

Sulfuric Acid-Water Chemical Heat Pump

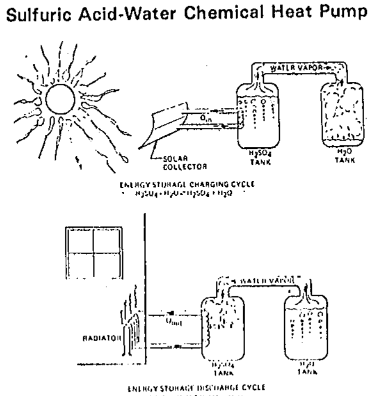

Figure 8.

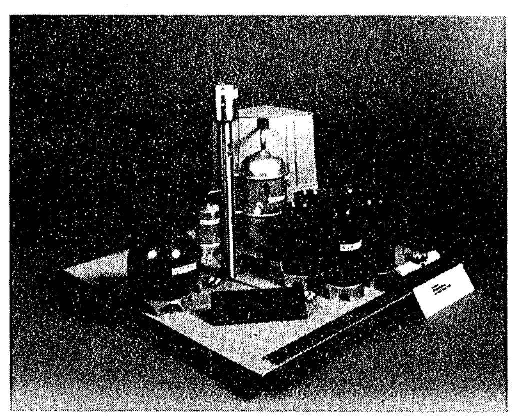

Figure 9.

AQUIFERS FOR SEASONAL THERMAL ENERGY STORAGE: AN OVERVIEW OF THE DOE-STOR PROGRAM*

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The U.S. Department of Energy (DOE), as a part of the activities of its Division of Energy Storage Systems (STOR), is examining the feasibility of cooling the terminal building at the JF Kennedy International Airport (Long Island, New York) by means of chilled water generated from winter cold and stored against summer use in an aquifer underlying the airport. This study is being carried out by Desert Reclamation Industries under a subcontract managed by the Oak Ridge National Laboratory through the Low-Temperature Thermal Energy Storage (LTTES) Program; Dames and Moore, architect-engineers, is assisting in this effort. If the results of this initial study indicate both technical feasibility and economic potential, a continuing phase in FY 1979 will drill wells at the test site to map the aquifer, develop the cold-water generation system, and design an injection/storage/recovery experiment. This program will conclude several years hence with demonstration, at least quarter-scale, of effective cooling of designated terminal areas.

The study described above is just one element in a broad DOE-STOR program to develop thermal energy storage technologies as means for conserving energy through substitution of solar, waste, and off-peak electrical energy sources for the exhaustible and costly oil and natural-gas fuels. Before proceeding to the further discussion of aquifers for seasonal storage, a brief digression to describe the total responsibility of the LTTES Program would provide some important perspective.

LTTES considers the utilization of alternative energies through thermal storage for application to residential and commercial heating and cooling and to certain industrial and agricultural processes. The LTTES objectives are twofold: the development of sensible and latent heat storage technologies for applications at temperatures up to about 250°C, and the determination of the potential of these technologies for energy conservation. While somewhat arbitrary, the boundary between "low temperature" and "high temperature" storage was chosen as 250°C to include absorption air-conditioning applications within the LTTES program scope. We are concerned with carrying technology development to a stage where commercial interests accept feasibility and perceive profitability; thus, encouraging economic characterization of a concept being developed can be as important as solving technical problems.

Over the several years since the inception of this effort, a number of primary thrusts have evolved. These thrusts have been enunciated by earlier speakers; and one - the seasonal storage of hot or cold waters in aquifers is, of course, the reason for this workshop. Energy sources being considered in association with aquifers are industrial reject heat, environmental (winter chill, summer heat), electric utility cogenerated heat, and solar heat from flat plate or concentrating collectors. The aquifer storage effort is still developing with studies now underway at three levels: (1) concept evaluation, (2) concept development, and (3) concept demonstration.

Concept evaluation considers the extent to which suitable aquifers are available (principally within the continental United States), where these are located with respect to significant energy sources, and the potential of areas having appropriate sources and aquifers for utilization of the hot or cold stored waters. Further, we have concern for environmental impacts. Throughout most of western U.S., there are strong water-use laws that control the amount of water that can be taken from below the surface and what its condition must be if this water is reinjected. Institutional problems need study. Who owns the heat being gathered? Who controls the charge-out rates? Who regulates the distribution systems? These questions, and many others, just being asked, need early answers in that they can control both the potential for application and the economics of energy supply systems involving aquifer storage.

The heart of the LTTES aquifer storage is at the moment in the area of concept development. Particularly involved are two field experiments of which you will hear more later in this workshop: one, being carried out by Auburn University, studies hot water storage in a confined aquifer; while the other (by Texas A&M University), examines winter chilling of water and storage in an unconfined aquifer. As a result of these experiments, we have come to an increased realization of the need for substantial and strong analytical and experimental support efforts on aquifer performance in re storage. Geochemistry, plugging, corrosion,

*Research sponsored by the Division of Energy Storage Systems, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

subsidence - these are among the problems of significance. Lawrence Berkeley Laboratory - our hosts for this workshop - is assisting in the application and development of models for predicting aquifer performance, in the design of appropriate field tests for evaluating such models, and in the interpretation of the field test data. The U.S. Geological Survey is a partner in this effort, providing invaluable support. Finally, we must concern ourselves with the capture of the energy. Studies are needed in the capture of winter chill as by spray ponds or cooling towers and of summer heat as by solar ponds or "heating towers"; some good engineering is needed in this area.

Moving to concept (prototype) demonstration, we are involved in the exciting JFK Airport (Long Island, NY) study described at the beginning of this paper; this will be considered in more detail later in this meeting. Beyond this, we are looking to industrial reject heat projects, where aquifer storage and subsequent heat reuse may be a viable alternative to current discard practices; and we will be examining the aquifer storage option for the ongoing Minneapolis-St. Paul district heating study.

Alternatively to aquifers, seasonal storage could be accomplished by storing water in surface ponds or by heating (or cooling) the earth itself. The LTTES Program has no current element on pond storage but is aware of major efforts ongoing or planned in Europe. For earth storage, we have pursued a limited study utilizing a heat pipe to introduce and recover solar-derived heat in a subsurface wet sand bed; if undisturbed earth could be used, this concept could be important to the heating and cooling of small clusters of residences or small office buildings.

For perspective, the area being accorded second highest attention in the LTTES Program deals with developing technologies for daily energy storage. Principally, this concerns utilization of solar heat for heating and cooling, though off-peak electricity through time-of-day pricing can be important. We are studying the possibility of incorporating phase-change materials (PCM) in concrete blocks for structural or partition wall use, into ceiling and floor tiles, and into wall panels. The building itself can thus be an enhanced storage element at costs that hopefully would be less than associated with independent storage units. Further, this configuration offers promise for "comfort zone" temperature conditioning, wherein by maintaining (say) 20°C boundaries 13°C air temperatures can be tolerated by room occupants. For short-term storage (up to 3 or 4 days), modular units - likened to furnace packages - using PCM's are indicated. Such units can take the alternative configurations of a tank filled with the phase-change medium through which pass tubes carrying the heat transport fluid or of macrocapsules (e.g., plastic pillows or metal cans) containing a PCM arranged within a duct such that the heat transport fluid passes over and around the capsules.

In closing this introductory session, let me address briefly the purposes of our workshop:

1. To display the DOE role in developing thermal energy storage systems, not in the sense of braggadocio, but to assure awareness that the Department of Energy considers thermal storage - and our particular interest, storage by means of aquifers - as important to achieving a stable national energy posture,

2. To mount a forum conducive to interaction between expert professionals of corollary interests such that problems can be matched against existing solutions, that impediments to implementing an aquifer storage technology can be aired, and that further information exchanges can be facilitated,

3. To provide positive and important input to LTTES Program planning, and finally

4. To engender an increased enthusiasm for working in this important area.

Why a workshop at this particular time? The sketch in Fig. 1 suggests an answer. Sitting here today, we know as a collective body - though not perhaps yet as individuals - from whence we come. Looking around at this audience today, we know where we are. We would like to explore the final direction of where we are going. Our program is organized thusly: Part 1 is a technology review to tell us "where from"; Part 2, a summary of current DOE-supported work and of collateral efforts in other countries addresses "where now"; and Part 3, a reaction panel and your interaction with this reaction will portend "where to".

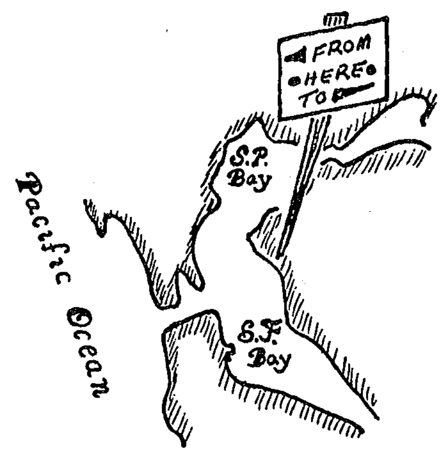

Fig. 1. Why a Workshop at this Time?

HYDROGEOLOGY AND RESERVOIR ENGINEERING

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The study of thermal energy storage in aquifers can benefit from examining the results of using aquifers for other purposes. There is considerable experience with storing natural gas underground. High production rates have been achieved proving aquifers to be an effective means of storing energy.

Locating suitable aquifers should not be a difficult problem. Sophisticated geophysical techniques, including resistivity and electromagnetic methods, have worked effectively in the field of groundwater hydrology. Information can also be obtained from existing water wells which are found in most residential and urban areas.

Experience suggests that problems affecting the efficiency of storage are site specific, mandating an appropriate amount of exploration to evaluate the aquifer. Testing is necessary to locate barrier boundaries and discontinuities, and to define aquifer parameters. Important aquifer parameters include depth, thickness, hydraulic conductivity, specific storage, regional gradient, heterogeneity, confining bed tightness, water chemistry, and hydraulic fracture pressure.

To determine hydraulic conductivity, the well is pumped at a constant rate and the change in reservoir pressure is observed. The pressure data thus obtained may be plotted several ways to determine the hydraulic conductivity and storativity of the aquifer. Methods have been developed to deal with non-constant pumping rates and barriers within the aquifer system.

There are several potential problems in developing an aquifer storage project that need to be examined. Evaluating discontinuities, regional gradient, and the vertical permeability of the confining bed is important in ensuring that injected water can later be retrieved. Experience has demonstrated that problems due to heterogeneity can often be successfully dealt with, particularly when detected early. Problems associated with water chemistry include scaling, carbonate and silica formation, compatibility of injected and produced water, and problems associated with changing the temperature of a system that has been at equilibrium over geologic time. For thick aquifers, gravity segregation becomes a concern.

An important consideration in completing the well is controlling fluid flow and pressure. Substantial experience in oil fields has shown that exceeding the hydraulic fracture pressure does not necessarily cause permanent damage to the system and can, therefore, be used to determine an effective operating limit.

Monitoring is important in determining recovery coefficients and detecting problems such as thermal pollution, contamination of natural water, and subsidence. Ways of monitoring include wells above or below the system to observe a pressure transient that would indicate vertical movement of water, and the use of tracers to monitor the temperature boundaries.

PETROLEUM INDUSTRY EXPERIENCE IN WATER INJECTION

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INTRODUCTION

Each day the petroleum industry injects hundreds of millions of gallons of fluids into subsurface formations. These fluids are not injected into aquifers which might be a source of potable water for drinking, industrial, or agricultural usage. The injection wells are carefully sealed where they might go through such aquifer and are inspected by regulatory agencies. Any materials discharged to a surface or subsurface water system are done so in full compliance with all laws, rules, and regulations.

Fluids discharged to subsurface formations may be injected to enhance oil recovery (waterflood, steam flood, caustic flood, polymer flood, etc.) or to dispose of unwanted fluids generated or produced with the oil. Because of the large volumes involved, pumping energy and power costs are significant. Factors of water quality which can affect the permeability of the receiving formation and hence the pumping energy are discussed and illustrated.

WATER QUALITY

Water quality involves those factors that could change the permeability of the receiving formation or affect the equipment used to process and inject the water. Any factor which could affect the energy requirements and/or cost of water injection is of concern. Many of these factors are interactive and have a synergistic effect upon each other. These factors and their interactions can be identified by on-site testing with the treated water and the receiving formation in question.[1] Factors of concern in a water quality investigation include, but are not limited to, water chemistry, water-rock interactions, particulate plugging, scaling, corrosion, bacteria, water treatment chemicals, and temperature effects.

Water Chemistry

Changes in water temperature or pressure can cause the precipitation of certain solid phases. Decreasing the pressure on a particular water may cause the release of dissolved carbon dioxide. Loss of carbon dioxide will raise the pH of the water and decrease the solubility of calcium carbonate.

$$Ca^{++} + 2\ HCO_3^- \rightarrow \underline{CaCO_3} + \overline{CO_2} + H_2O$$

The solubility of most materials in water is affected by temperature. For example, the solubility of calcium carbonate decreases with increasing temperature while the solubility of calcium sulfate (gypsum) increases with increasing temperature. Thus a solution saturated at one temperature may become supersaturated and form a precipitate at another temperature. The precipitate may form as an adherent deposit on the walls of the system and increase pressure drop or may form as a suspended solid which could plug the receiving formation.

In some instances one water source is not sufficient to satisfy the injection requirements and two or more sources of differing compositions or concentrations may be used, or the water being injected may be different from the in situ or connate water. These situations can lead to problems of chemical incompatibility upon mixing of the waters. For example, an injected water with a high sulfate concentration could form a plugging precipitate when mixed with a formation water with a high barium or calcium concentration.

$$Ba^{++} + SO_4^{=} \rightarrow \underline{BaSO_4}$$

$$Ca^{++} + SO_4^{=} \rightarrow \underline{CaSO_4}$$

Or mixing of a water with a high pH or alkalinity with another of high calcium or magnesium content could form calcium carbonate or magnesium hydroxide.

$$Ca^{++} + HCO_3^- + OH^- \rightarrow \underline{CaCO_3} + H_2O$$

$$Mg^{++} + 2OH^- \rightarrow \underline{Mg(OH)_2}$$

Water-Rock Interactions

Rock formations usually contain clays and other minerals which undergo physical and chemical changes when the electrolyte content of the water surrounding them is changed.[2,3] Thus the spacing between repeating layers of montmorillonite is altered when the degree of hydration is changed by changing the salt content. When mica containing the potassium ion (interplanar spacing 10°A) is contacted with a fluid low in potassium content, a cationic exchange or chemical reaction can occur with larger hydrated ions such as sodium or calcium. The spacing is now 15°A.[4] Breaking and sloughing of fines can occur. Since the dispersing types of clays are charged species, changing the electric field around the particles by changing the electrolyte composition can cause the particles to disperse or coagulate. Dispersed particles can migrate within the formation and plug narrow pores.

In other instances, the rock formation or a portion of the formation may have an appreciable solubility in the injected water if the injected water is not in equilibrium with the formation. Thus water unsaturated with respect to calcium carbonate can dissolve the cementing carbonate present in some formations. Fines which can plug the formation are liberated.[4] Nonequilibrium water at high pH and/or high temperature can dissolve considerable amounts of silaceous material.[5] Changes in pH and/or temperature can redeposit the dissolved materials and plug the formation.

Particulate Plugging

Particulate plugging can be from material present in the injection water prior to its introduction to the formation or from material formed or produced within the receiving formation. Possible sources of particulate matter in the injection water are silts, formation fines, corrosion products, scale deposits, bacteria, and precipitates from the mixing of chemically incompatible fluids. Through water-rock or water-water interactions within the formation, particles can be formed or dislodged. These particles can move through the pores and become lodged in pore throats or restrictions.

The possible particulate matter in an injection water would be expected to consist of varying numbers of particles of various sizes and shapes. Similarly the receiving formation could be expected to be composed of a series of pores of varying number, size, and length. The rate and degree of permeability damage to the formation would depend upon such factors as particle properties (number and size), pore properties (number and size), and flow rate.[6] The damage could be the result of the formation of a "filter cake" on the face of the injection well or of plugs or bridges within the pores of the formation.

Scaling

Scaling can be described as the formation of an insoluble deposit or precipitate from a physical (e.g., temperature) or chemical (e.g., loss of carbon dioxide) change in a water or from the mixing of two or more waters containing incompatible species. Depending upon kinetics and adhesion, the following cases might be distinguished: (1) formation of a deposit on the walls of the processing and injection equipment, (2) sloughing of this deposit to give particles in solution, (3) formation of a suspended solid within the injection water, and (4) precipitation of a deposit on the sand grains of the formation.

Corrosion

The extent of corrosion with injection water in a metal system depends upon the corrosivity of the water and the activity of the metal. The corrosivity of the water is affected by such factors as temperature, pH, types and amounts of salinity, velocity, and the presence of corrosive gases such as oxygen, carbon dioxide, or hydrogen sulfide. Corrosion leads to destruction and failure of processing and injection equipment. Corrosion products (usually iron oxides and sulfides) can plug the receiving formation.

Bacteria

Bacteria within an injection water are troublesome for several reasons. Bacteria can form slimes which plug a formation or filters. Colonies of bacteria on pipe walls can form oxygen concentration cells which accelerate corrosion and pitting. Certain bacteria (sulfate reducers) under the proper conditions can form hydrogen sulfide. Introducing sulfate reducer into an injection system or providing the proper nutrients to a system already containing the bacteria could result in production of hydrogen sulfide in the water. Hydrogen sulfide is extremely toxic and highly corrosive. It can cause problems in the injection system as well as the production and heat exchanger system.

Water Treatment Chemicals

Oil field injection water usually contains a variety of chemicals added for specific purposes. These might include scale inhibitors, corrosion inhibitors, biocides, demulsifiers, solvents, acids, etc. Many of these chemicals are incompatible with each other. They can react when mixed with other added chemicals or with material originally present in the water to form plugging precipitates.

Temperature Effects

Published results[7,8] indicate that under some conditions the absolute permeabilities of some sandstones decrease with increasing temperature. As the temperature of the injected fluid is increased, fluid density and hydrostatic head in the wellbore are decreased. Thus higher surface pressures are required to inject the water. Rock solubility and scaling tendencies are also temperature dependent.

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ENERGY MANAGEMENT OBJECTIVES AND ECONOMICS OF HEAT STORAGE WELLS

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ABSTRACT

Management of energy systems to achieve energy conservation and pollution control objectives can be significantly advanced if large amounts of useful hot water can be stored in aquifers, and withdrawn as needed. The major source of high-temperature water would be from power plants modified to produce both power and heat; i.e., from cogeneration. An energy-conservation target of 10 to 15 percent of national energy consumption is felt to be realistic, with concomitant reduction in air and water pollution.

Thermal energy storage in aquifers would solve the mismatch problem which limits the amount of cogenerated heat that can be used. Heat produced as electricity is generated could be stored during the summer, when electric production tends to peak, to be used during the winter for space heating. Hot tap water, air conditioning, and industrial process heat demands could also be readily satisfied, with high-temperature water carried through pipelines to urban areas up to 100 miles away from the cogeneration plant.

Cost savings of 20 to 30 percent appear feasible, making large-scale cogeneration with thermal energy storage a very attractive approach to energy conservation.

INTRODUCTION

TEMPO studies in 1972 showed that thermal pollution from electric power plants could be greatly reduced and substantial energy conservation — at least 10 percent of national consumption — could be achieved through large-scale cogeneration of power and heat; but to do so requires that a way be found to store large amounts of heat cheaply enough and long enough to accommodate seasonal variation in demands for heat. From these studies emerged the Heat Storage Well (HSW) system concept first described by Meyer, Todd, and Hare in 1972. The Heat Storage Well is a device for storing in aquifers large amounts of useful high-temperature water (HTW), at low cost and low loss, for long periods of time.

This paper comprises two major parts: a discussion of management of Heat Storage Wells to achieve energy conservation and environmental benefits, and a description of the economic formulation used to compare heat and power systems with and without seasonal thermal energy storage (TES).

The work upon which this paper is based was supported in part by the General Electric Company and in part by funds provided by the United States Department of the Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379, as amended.

MANAGEMENT OBJECTIVES

A major objective of national energy planning is to promote energy conservation. In particular, replacement of foreign oil consumption with use of domestic coal or nuclear fuel is an objective whose importance is evidenced by an unfavorable balance of trade now measured in tens of billions of dollars per year.

Energy Conservation Targets

Our analyses show that ambitious management goals should be set for conserving energy through application of large-scale cogeneration and thermal energy storage. We suggest the target be to conserve 10 to 15 percent of national energy consumption — equivalent to reducing oil imports by five million barrels per day.

Energy management to achieve this ambitious goal will require capturing and using heat now wasted by electrical power plants and by industrial processes; and replacing oil- and gas-fired home furnaces (efficiency = 50 percent) and gas-fired water heaters (efficiency = 61 percent) with more efficient systems using centrally-generated HTW, stored until needed (Meyer, Hausz, et al, 1976).

Roughly one-third of our requirements for heat can be served at relatively low temperatures — less than 350°F. These heat loads are

- Space heating
- Water heating
- Air conditioning
- Low-temperature industrial processes.

That water at temperatures up to 350°F can be stored in aquifers is illustrated by the existence of geothermal reservoirs. However, we have much to learn about how to inject and recover the hot water efficiently. We know there may be corrosion, scaling, and plugging of wells due to geochemical problems of compatibility between injected water and the native groundwater and aquifer matrix.

The important management objective at this point in time is to define and establish investigations which will fill information gaps and demonstrate feasibility of aquifer TES. These investigations can draw upon a broad base of knowledge gained from drilling and operating the more than 15 million water wells now in service in the United States; from the petroleum industry's experience with injecting fluids to enhance production; from designing and operating waste-disposal wells for petroleum brines and industrial residuals; from research on storing fresh water in saline aquifers; and from ongoing developments in the geothermal field.

COGENERATION OF POWER AND HEAT BY ELECTRIC UTILITIES

The prime target for energy conservation and environmental protection is the thermal electric power plant. Electric utilities accounted for 30 percent (22.5 quads) of national energy consumption in 1977, according to Department of Energy estimates. Of this amount, only 6.6 quads – 29 percent – was delivered as electricity (DOE/EIA *Monthly Energy Review*). A small fraction of the losses are due to transmission and distribution. Most of the losses are a consequence of fundamental heat-engine inefficiencies, which dictate that about two units of heat will be rejected for each unit of electricity generated. The reject heat is discharged, at considerable expense, through cooling towers or into bodies of water.

For 50 years or more, engineers have known how to design and build power plants which produce both electricity and useful heat. In an era of inexpensive, plentiful supplies of fuel, the appropriate engineering approach has been to extract as much shaft horsepower as possible from fuel energy. This translates into discharging reject heat at as low a temperature as possible – typically, 100 to 110°F. Although many units of heat are contained in 100-110°F cooling water, the heat is not thermodynamically available or useful except in a few special situations. Management of thermal energy requires reallocation of some of the fuel's heat: generate less electricity; increase the temperature of the cooling water from 100°F to 350°F. From five to ten units of thermal energy can be gained for each unit of electric energy sacrificed. Management decisions necessary for such a reallocation will be based on economic considerations, to be discussed later in this paper.

In Europe, where district heating systems using HTW are prevalent, utilities have found it economically attractive to configure power plants for cogeneration. The Federal Republic of Germany may be foremost in this respect (Scholten and Timm, 1977). In the USSR, which has by far the largest district-heating capacity of any nation, economic motivation no doubt is more closely coupled to national energy objectives than in most other countries. In Germany and also in Denmark, where about one-third of the populace uses district heating, privately owned utilities have competed successfully with alternative energy suppliers to capture the market they serve (Winkens, 1975; Kelsey, 1975).

Modern power plants are most efficient and cost-effective in large sizes, ranging upward from 500 megawatts electric output. To convert existing plants of such large size to cogenerating power and useful heat is not practicable. Neither is it realistic to expect large plants already well into the planning stage to be redesigned for cogeneration. However, smaller plants, in capacities up to perhaps 400 MW_e, are now candidates for conversion to cogeneration; and large plants 10 or more years in the future could be designed for cogeneration.

It is obvious that many non-technical institutional problems are faced by utility management in expanding from power only to cogeneration of power and heat. Financial capital must be raised, which is now particularly difficult for privately-owned utilities. Expansion of charters or franchises is required in many cases, with new regulatory requirements to be faced. Environmental and safety regulations must be satisfied. And, of course, there must be adequate assurance of a market for the heat to be produced. Such institutional problems have been studied (Meyer, Hausz, et al, 1976; Carver, 1975), but will not be further discussed here principally because of space limitations but also because the nature of institutional problems and management's solution to them will depend largely upon the new technology to be employed. The present discussion therefore will continue to focus on management of aquifer TES technology and its applications.

The Mismatch Problem

The scale of cogeneration by electric utilities is limited by the mismatch problem:

- Electricity must be generated in instantaneous response to demand. (No feasible way to store electricity is yet available.)
- Heat demand seldom corresponds to electric generation in
  - Time
  - Location
  - Magnitude

In district heating systems owned by electric utilities in the United States (all of which sell steam, not hot water), the mismatch problem is solved largely by avoiding cogeneration. Predominantly, steam is raised in old boilers, no longer suitable for efficient electric generation, located in urban areas where new, large electric plants could not be sited. Condensate is not returned, in general. Cogeneration, when employed, supplies baseload heating. Auxiliary boilers are used for peaking and backup. In steam systems, only a small amount of thermal energy is storable: in accumulators (pressure vessels comparable to boilers in construction and capacity), and in the thermal capacity of boilers and pipelines.

European district heating systems almost universally employ high-temperature water, not steam; they have evolved since World War II, during reconstruction which permitted adopting new schemes. HTW has a higher thermal energy density than steam, and provides thermal inertia which amounts to appreciable TES in pipelines and boilers. HTW can be stored in various other ways. At least one HTW district-heating system, in Sweden, uses steel-tank storage which can handle diurnal load variations. Even diurnal TES reduces the capacity of auxiliary peaking and backup boilers which is needed to supplement cogenerated heat during cold periods or outages of central station equipment (Margen, 1978).

Large-scale seasonal thermal energy storage would make it possible to produce heat as a byproduct of electric generation, so that

- The electric system could be managed (dispatched) essentially according to conventional electric-utility practice.
- Cogenerated heat that is surplus to prevailing heat-load needs could be stored until needed.
- When inadequate heat is being produced, stored heat could provide the needed additional supply.
- Auxiliary boilers would be largely or entirely unnecessary, with their functions being taken over by storage.

TRANSMISSION AND STORAGE NETWORK FOR HIGH-TEMPERATURE WATER

The most important and probably the most difficult aspect of Heat Storage Well management will involve a pipeline network to transmit HTW and an ensemble of Heat Storage Well fields to store it.

First, it is necessary to understand that HTW can be economically transmitted for long distances – 100 miles or more – if large enough amounts of hot enough water are involved. This point has been established beyond any reasonable doubt (Margen, 1978; Meyer, Hausz, et al, 1976). Dual pipelines are involved, in a closed system, to send out HTW and return cooled water.

Figure 1 illustrates schematically a network of insulated, dual pipelines transmitting HTW from a central cogeneration station to various load centers. In Figure 1, "DH" indicates district-heating systems which serve commercial and residential areas with HTW for space heating, tap water, and absorption-cycle air conditioning. Industrial plants may use HTW for low-temperature process needs as well as for the other uses just mentioned. Heavy lines show major transmission pipelines, perhaps one meter or larger in diameter. Lighter lines indicate sub-transmission, in smaller pipes.

Where should aquifer storage be used? First, at the central plant. If suitable aquifers are available (the plant may be sited where they are), well fields near the plant can store HTW production that exceeds immediate demands, and supply HTW when heat demand exceeds production. Dependable storage will make possible the elimination of cooling towers or water for condensers, and thus the capture of all useful heat produced.

HTW storage at the central plant, along pipeline routes, and at their terminal points will help to smooth load fluctuations and permit pipelines to operate at high capacity factors. The storage will also increase system reliability, serving as a backup source in case of pipeline outage.

Assuming a HTW transmission and storage system has been designed and installed, management of the system will require that heat be dispatched (controlled) in conjunction with electric generation. Experience in "conjunctive dispatch" is limited. Large, modern electric utility systems employ complex, computerized control systems to control the output of generating units needed to supply electricity. Historical load curves provide a basis for predicting need for generation capacity and bringing it on line. HTW district heating systems employing a combination of cogeneration and auxiliary boilers, in use in Europe, control the boilers

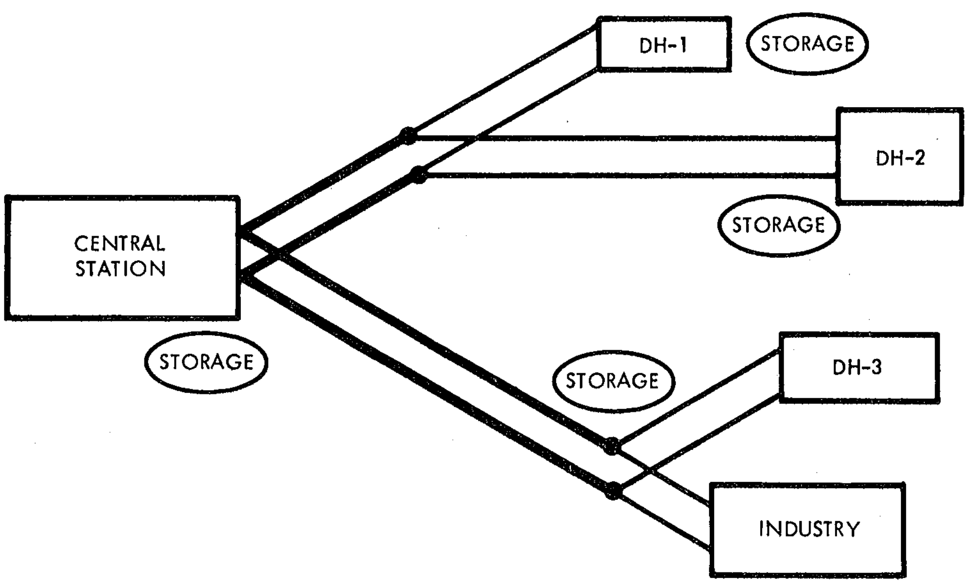

Fig. 1. Pipeline networks and storage locations.

to produce HTW both in response to and in anticipation of demand. But a combination of

- large-scale cogeneration, intended to supply more than baseload heat requirements,
- large-scale storage, to buffer heat load fluctuations ranging from diurnal to seasonal, and
- long transmission pipelines, to be operated at as high a capacity factor as possible,

comprises a new degree of complexity in system control. Experience with HTW cogeneration systems in the USSR, with up to 5 million gallons of HTW storage capacity at the central plant, is mentioned by Oliker (1977) and appears to be relevant.

HEAT STORAGE WELL DOUBLET

On a scale smaller than managing the power-and-heat system incorporating thermal energy storage is the problem of managing the use of an aquifer for TES. Figure 2 is a schematic diagram of the basic module, a Heat Storage Well doublet.* Two water wells comprise the doublet. Each well should be capable of serving as either an injection or a production well, with easy changeover between the two modes, and variable flow rate. (These degrees of flexibility are not standard features of water wells.)

In operation, the HSW doublet is a closed hydraulic system coupled thermally to a heat transmission system via a heat exchanger. When heat is to be stored, HTW from the pipelines flows through the counterflow heat exchanger and groundwater flows through the wells and heat exchanger as indicated by the open arrows in Figure 2. From the sendout HTW pipeline, HTW flows through the heat exchanger and into the return pipeline. Within the heat exchanger, heat from the sendout pipeline is transferred to water pumped from the warm well and injected into the hot well. When heat is to be withdrawn from storage, HTW is pumped from the hot well, through the heat exchanger, and into the warm well as indicated by the solid arrows. Water drawn from the return pipeline is heated and delivered to the sendout pipeline.

Breakthrough

A basic problem in managing operation of the HSW doublet is the possibility of breakthrough. Solid lines in Figure 2 suggest the shape of the

*The aquifer may be at a depth of 1000 feet. Valves, pumps, and control equipment, not shown in the diagram, will be required. Auxiliary wells may be needed to neutralize native, lateral flow of the groundwater.

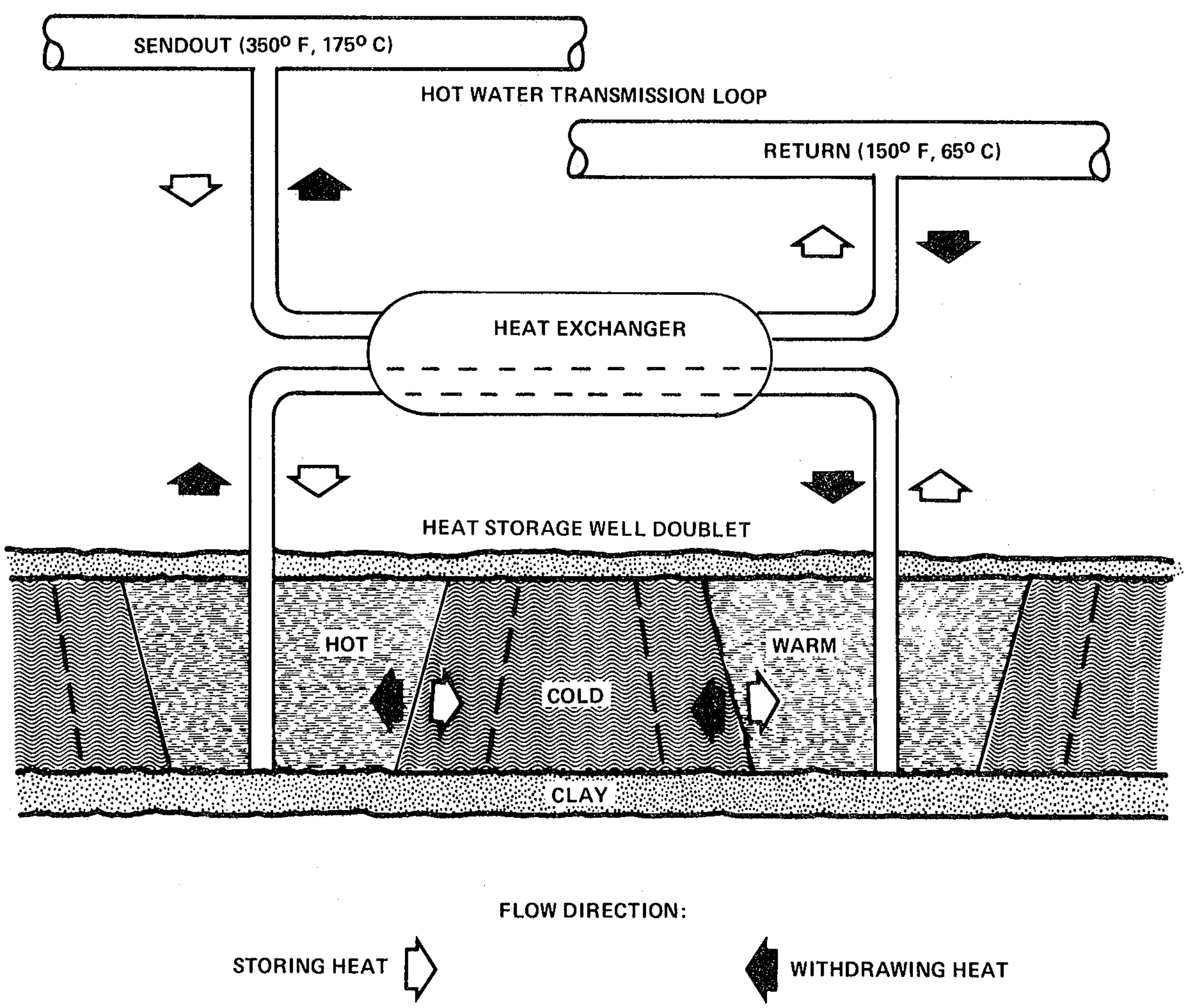

Fig. 2. Schematic diagram of Heat Storage Well doublet operation.

temperature inferfaces within the aquifer between hot, warm, and cold water. The hot and warm water, being less dense and less viscous than the cold native groundwater, will tend to override the cold water and cause the interface to tilt. The temperature interface does not coincide with the fluid interface where injected water meets native water. The location of the fluid interface is suggested in the diagram by a dashed line. A tracer in the injected water would move appreciably beyond the temperature interface because hot water moving outward from an injection well delivers heat to the aquifer matrix (porous rock and trapped water), and is cooled to essentially the ambient temperature.

The warm and the hot well must be far enough apart to prevent breakthrough of hot water to the warm well, or vice versa: the two temperature interfaces should not meet. The breakthrough effect in doublet wells has been analyzed by BRGM in France (1974) and others. The required separation between wells will depend upon the aquifer parameters, the maximum injection volume, and (probably) the injection rate. Managing operation of the HSW modules — of which there may be hundreds in a large system — will require keeping track of the approximate amount of hot water stored in each module, or the location of temperature interfaces.

Control

Both injection and production wells are in widespread use, but there is little if any experience in operating a single well with rapid switchover from one mode to the other. Ordinarily, an injection well has no pump installed except when it is being developed or redeveloped. Further, water-well pumps are not designed for variable-rate operation; they usually are turned on, to fill a reservoir, then turned off. Management of well modules may require similar operation, for greatest economy.

Heat Recovery

The amount of heat that will be lost during underground storage of HTW is an important factor in planning and managing a system. Computer models of fluid flow and heat loss will be needed. Some governing principles can be mentioned.

The fraction of stored heat that is lost will depend on the ratio of surface area, through which heat escapes, to the enclosed volume where the heat is contained. The ratio of surface area to enclosed volume decreases for larger volumes; hence heat loss will be higher for small-scale than for large-scale storage. This effect sets a lower bound on the applicability of aquifer TES (Meyer, 1978).

The effects of temperature on heat loss are not simply described. Not only will higher storage temperature cause larger heat-flow rates across temperature interfaces; the viscosity and density of the stored water will decrease, tending to cause greater tilt of the temperature interface within the aquifer, with corresponding changes in hydrodynamics.

More heat will be lost during early cycles of injection-storage-recovery than during later cycles, after the aquifer matrix has been warmed. A TEMPO estimate of heat recovery versus cycle is shown in Figure 3. Two cases are plotted. For the base case, water at 340°F is injected into the aquifer at a rate of one million gallons per day for 90 days. Then the stored water is withdrawn at the same rate until the temperature of the water being withdrawn has dropped to an arbitrary "lowest useful temperature" — in this case, 300°F. At the end of the first cycle, about 30 percent of the injected heat remains behind. The recovery ratio (efficiency) increases with successive cycles and levels off at about 80 percent after four or five cycles. (Other estimates, using more elaborate computer models such as LBL's, and different withdrawal-temperature criteria, usually indicate higher recovery efficiencies.) If the aquifer is prewarmed by injecting HTW for 90 days and leaving it in place rather than withdrawing it, the first-cycle efficiency is well over 90 percent. However, the cumulative recovery, shown by the dashed lines, is very nearly the same for both cases after about five cycles.

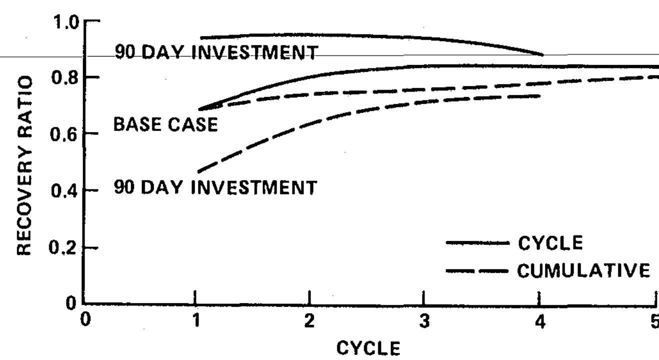

Fig. 3. Heat recovery.

SYSTEM APPLICATIONS

The proposed purpose of aquifer TES is to conserve energy and reduce pollution of air and water, which should also reduce the cost of energy. Two examples of applying seasonal storage of HTW to specific energy systems were analyzed: a relatively small cogeneration system using a gas turbine, and a larger system based on central coal-fired cogeneration. The results are summarized below; the economic basis for obtaining them will then be described.

Gas-Turbine System

Cogeneration of power and heat using a combustion gas turbine can be accomplished with standard equipment. These Brayton-cycle machines discharge exhaust gases at temperatures of about 1000°F. Heat-recovery steam generators are available which can be included in the initial installation of a gas turbine-generator or retrofitted at a later date. The usual application is for combined-cycle power generation, in which the steam produced from captured exhaust heat is used to drive a second turbogenerator.

Cogeneration of power and heat with a gas turbine obviously will reduce overall energy consumption, because otherwise-wasted heat is being utilized. The more interesting analysis is to compare gas-turbine cogeneration systems with and without thermal energy storage. Such an analysis, of a gas-turbine system generating 100 megawatts of electricity, shows that

- Cogeneration and seasonal TES, compared to purchasing electricity at industrial rates and producing heat from local boilers (heat load factor = 0.25), saves 35 percent in fuel and 25 percent in cost.
- Cogeneration with seasonal TES requires 28 percent less fuel and costs 25 percent less than the same gas-turbine cogeneration system without seasonal TES.

Large Coal-Fired System

Cogeneration of power and heat is well known for industrial plants. A fossil-fueled boiler produces steam which is first passed through a steam turbine to produce electricity and then, at reduced temperature and pressure, used for industrial process heat. These systems are often cost-effective if there is immediate use for all the power and all the heat that is produced; but in spite of ready availability of equipment, the fraction of industrial electricity that is generated in-plant has declined steadily. The industrial sector now produces only about 15 percent of the electricity it consumes (Dow Chemical, et al, 1975). Two reasons for this situation are that industrial managers prefer to invest capital funds in production facilities rather than in electric generation, and they find that reliability of in-plant electric generation often is inferior to the reliability of electric supply from a utility. Consequently, the cogeneration possibility with most promise for national energy savings and pollution reduction is in the large central stations operated by electric utilities. No such plants in the United States now cogenerate.

For analysis, an electric power plant rated at 600 to 800 megawatts of electric output is postulated. It is assumed to be designed for maximum effectiveness in heat production: the steam extracted and discharged from the turbine is at high enough temperature to heat water for district heating to 350°F, at a 1000 to 1200 megawatt rate. No cooling towers or water (other than the district-heating loop) are required. Such a cogeneration plant, with Heat Storage Wells, can produce heat and power at

- 30 percent lower cost than separate coal-fired heat and power plants at the same location,
- 20 percent less fuel consumption than for separate plants, and
- substantially lower investment.

The more meaningful comparison is to assume that the central coal-fired cogeneration plant will employ both TES and transmission pipelines to deliver heat to urban load centers. This comparison is particularly significant because heat from coal can be used to displace oil-fired furnaces and boilers, thus conserving oil and reducing air pollution in urban areas. The findings are that the central cogeneration plant with TES can deliver power and heat at

- 46 percent lower cost than separate power generation and local heat production, when the heat transmission distance is 15 miles, ranging downward to
- 6 percent lower cost when heat is transmitted 125 miles, with
- 20 percent lower fuel consumption than for separate products, when heat is transmitted 15 miles, or
- 14 percent lower fuel consumption when the transmission distance is 125 miles.

The oil conserved annually by central production of heat at one such plant would be 6.2 million kWh (3.8 million barrels) for 15 miles of heat transmission, or 5.3 million kWh (3.2 million barrels) for 125 miles of heat transmission. Only 3.3 million kWh of coal would be burned in either case.

ECONOMICS OF COGENERATION WITH STORAGE

The preceding section discussed the management of aquifer storage for cogeneration applications — the plant configurations, the interface with aquifer TES, the estimated performance of HSW doublets, some of the technical problems to be solved, and the amount of energy that can be saved. Commercial acceptance will ultimately depend on cost effectiveness — the economic comparison of a conventional or reference plant producing electricity only with a cogeneration plant producing heat *and* power, both without and with seasonal storage.

This section describes the economic formulation we have used to compare these alternative systems on a common basis over a wide range of alternative possible assumptions about the relative price of electricity and heat.

This paper draws heavily upon Meyer, Hausz, et al, 1976; Hausz, 1976; and Hausz, 1977. Two types of heat and power systems have been analyzed, with and without storage; and compared with separate product generation of electricity and of heat using boilers. One system was a simple-cycle gas turbine with recuperation of exhaust heat for district heating. The other was a central station coal-fired plant. The specifications and costs for these plants were taken from the Project Independence report on *Facilities*, for 1985 technology. They are given in 1974 dollars as is the whole Project Independence series, so this base year is used in the calculations in Table 1.

Table 1. Specifications for coal-fired plant.

Data Base: 1974 dollars, 1985 initial operation		
Project Independence *Facilities*, pages VII 48 & 72		
Plant:	800 MW, 0.62 capacity factor	
	3500 psia/1000°F/RH 1000°F, 3.5 in. Hg	
	Heat rate 8901, 38% efficiency	
	Costs: $380/kW, FCR 0.15	$10.5/MWh
	O&M	1.3/MWh
	Fuel: Coal at 0.75¢/MBtu	6.7 MWh
	Busbar Energy Cost:	$18.5/MWh

For brevity, only the coal plant example will be described. Basic description for conventional operation is given in the table. For this system, it was assumed that stack losses (and auxiliaries) were 15 percent, so the remainder is 38 percent electricity and 47 percent rejected heat for the conventional system.

When operated into high backpressure condensers or with steam extraction to generate HTW, the thermal efficiency of electricity generation is reduced, but the quality of thermal energy output is improved. By using a coolant temperature of 150-350°F, the fraction converted to electricity is slightly under 28 percent, so at full load 590 MW_e and 1000 MW thermal are generated. As electricity has a higher market value than heat, a three or more stage heater would be used, as in European practice, to achieve maximum thermal efficiency of electricity generation (Margen, 1978). One possible turbine configuration is that shown in Figure 4A. There is steam extraction at four temperatures to heat the district heating output successively to 200, 275, 325, and 350°F. In this figure the option of condensing at low backpressure is preserved for seasons when more electricity and less heat are needed.

Many other configurations are possible; some provide for no thermal discharge except to the district heating loop, as in Figure 4B. This implies that all the heat generated can be used, as the plant follows the electricity demand upon it. This ideal match may be attainable for one or two plants in a system, supplying base loads for both electricity and HTW. Alternatively, storage is required to buffer the differences between electricity and HTW supply and demand.

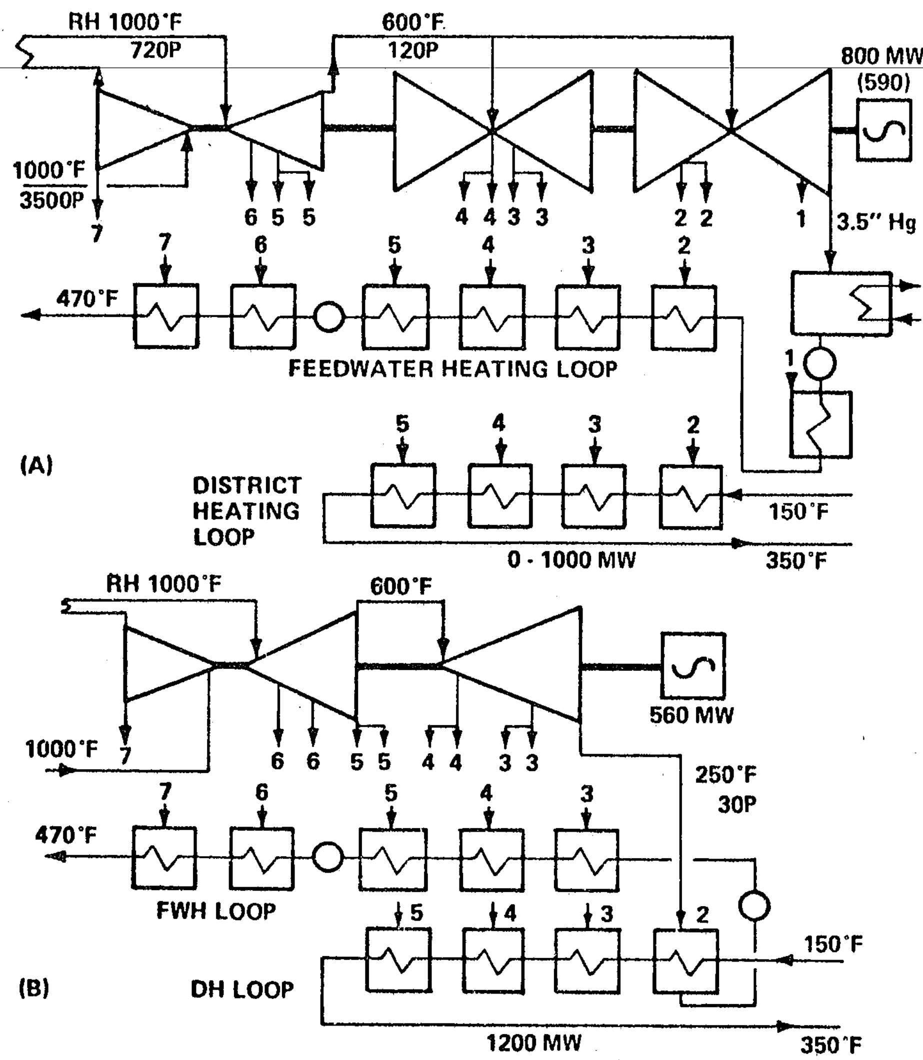

Fig. 4. Combined heat and power plants.

When both electricity and heat are generated and sold, there is considerable controversy in literature on the proper allocation of costs to electricity production and to heat production. Fundamentally, the sum of the revenues from electricity sales and heat sales must equal the sum of all costs, both annualized capital costs and variable cost, principally for fuel. This is a linear equation:

$$Q_e \bullet E + Q_h \bullet H = \text{Capital Costs} + \text{Variable Costs} = \text{Total Cost } (10^6 \, \$)$$

where

Q_e = annual quantity of electricity generated, in 10^6 MWh

Q_h = annual quantity of heat generated, in 10^6 MWh

E = assigned revenue for electricity in \$/MWh (at busbar)

H = assigned revenue for heat in \$/MWh (at plant output)

To compare alternatives, the line that this equation represents may be compared for each case of interest, as in Figure 5. Here the assigned unit revenue for heat is used as abscissa and the assigned unit revenue for electricity as ordinate: a line on these coordinates represents the family of all possible solutions to the above equation.

When electricity alone is generated in a plant ($Q_h = 0$), the graph, Line 1, is horizontal; the required revenue per MWh_e is independent of what value is assigned to heat. Conversely, when heat alone is generated by a "boiler" to give HTW, vertical Line 2 indicates that the required revenue per MWh_t is independent of the value of electricity. Line 1 represents the reference case of Table 1. Line 2 represents a supplementary coal-fired boiler assumed to cost \$80/kW_t including all provisions for pollution control. Both are shown for a capacity factor of 0.62. Equations 1 and 2 at the top of Figure 5 show the numbers used in each case.

The unit costs for both electricity and heat are sensitive to the capacity factor, as the annual capital costs must be allocated over fewer units of product for a lower capacity factor. For a capacity factor of 0.25 on the supplementary boiler, Line 3 results. Space heating is often the principal load demand of district heating systems; the International District Heating Association *Industry Statistics for 1974* show a range of load factors of 0.18 to 0.45, where the highest were for utilities fortunate in having some space cooling and industrial loads as well as space heating.

The conversion of the referenced system to both heat and power generation modifies both sides of Equation 1. If all the components of the referenced system are retained as in Figure 4A, so a maximum output of electricity can be generated when heat is not needed, the capital cost of the plant is increased by the added heat exchangers (condensers), and the steam extraction piping of the turbine system enlarged over what is normally provided for feedwater heating. These additions are estimated at \$10/kW rated thermal output of HTW. On the revenue side of Equation 3, the marketable heat, Q_h, is increased and the marketable electricity, Q_c, is decreased as steam is diverted from the low-pressure turbine in order to generate HTW. If electricity and heat are both generated at a capacity factor of 0.62, i.e., all the heat generated can be used, the equation and Line 4 on Figure 5 represent the joint-product cost allocation options.

This line can be compared to the intersection of Lines 1 and 2 representing the costs of separately generating electricity and heat for the same capacity factors. It can be seen that at the referenced busbar electric energy cost, the cost of HTW at the plant is \$4.09/MWh for joint-production, versus \$5.80/MWh for separate production. At

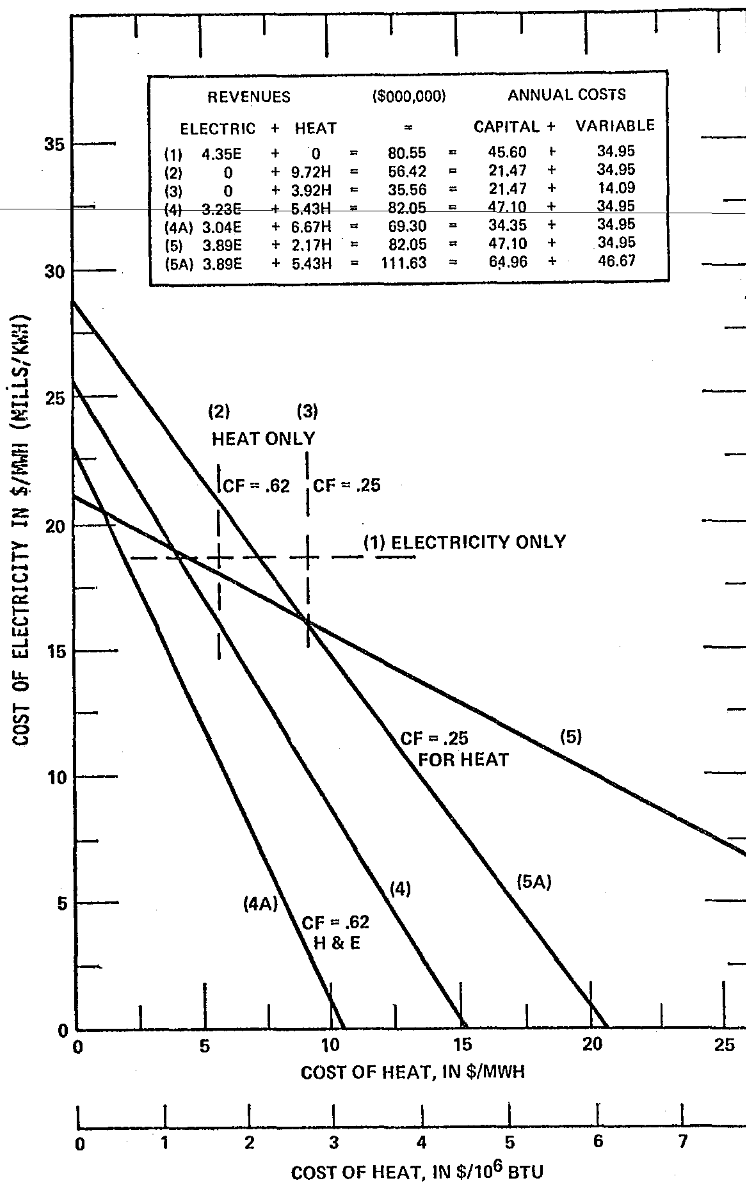

Fig. 5. Costs of conventional versus combined heat and power system.

the referenced (separate) production cost of heat, electricity as a joint-product can be produced at $15.70/MWh. Points between these two represent other cost allocation options for which both electricity and heat are cheaper than their separate product costs.

If the ideally matched demand patterns could be assured by load management or by storage of heat until needed, the capital cost of the plant could be reduced by using the configuration of Figure 4B in which the cooling tower and the low-pressure condenser are deleted, and the low-pressure turbine and the generator are reduced in capacity to match the reduced electricity output. This is illustrated by Line 4A. In addition to its economic effect, the elimination of thermal discharges to the air by cooling towers, or to water bodies by once-through cooling, would remove many environmental objections to otherwise desirable plant sites, giving greater flexibility in location.

However, practically, if the demand for heat has a load factor of 0.25, as in Line 3, the economics of joint heat and power production for the referenced system (Figure 4A) deteriorate. Assume, for simplicity, that the heat demand has a daily load factor of 0.62 for 4.8 months of the year and is zero for the remaining 7.2 months, giving an annual load factor of 0.25. For more than half the year maximum electric output is obtained; for 4.8 months the reduced output for joint production is obtained. The annual total will then be between that shown for Q_e in Equations 1 and 4 of Figure 5. This leads to Line 5 and the corresponding equation. If supplementary boilers are used to provide the balance of the annual heat needs in Equation 4, the equation and Line 5A are the result of the increased capital and fuel costs.

Lines 5 and 5A are to be compared to the separate product costs of electricity and heat given by the intersection of Lines 1 and 3; the latter has the 0.25 load factor for heat assumed in cases 5 and 5A. The reduction in the cost of heat, at the referenced level (Line 1) for electricity, is from $9.07/MWh for separate products, to $4.58 and $7.29/MWh for cases 5 and 5A. These are reductions of 50 and 20 percent. The comparable percentages for 4 and 4A were 29 and 66 percent.

Effect of Storage

The above provides some perspective on the advantages of heat and power production in which all heat available is used or stored until it can be used. For seasonal loads such as space heating and space cooling, these benefits can be achieved with seasonal storage, such as the Heat Storage Well, if the costs and the losses incurred in storage do not wipe out the benefits. Figure 6 portrays the effects of losses and the capital costs of wells and heat exchangers on the economics of case 4A, which was the most economically attractive of the cases considered in Figure 5.

If storage was available with no capital cost and with no losses, i.e., 100 percent energy recovery, the same economic factors would apply with matched demands of heat and electricity, or with storage to buffer short- and long-term differences in the demand patterns of these products. Line 4A in Figure 6 is then identical to that in Figure 5, and represents zero storage costs and 100 percent energy recovery from storage. Levels of energy recovery from storage of 75 and 50 percent are portrayed by Lines 6 and 7. For each of these, heat is used as generated for 4.8 months without loss. Heat is stored as generated for the 7.2 months and the amount stored, less losses, is recovered and used during the winter season.

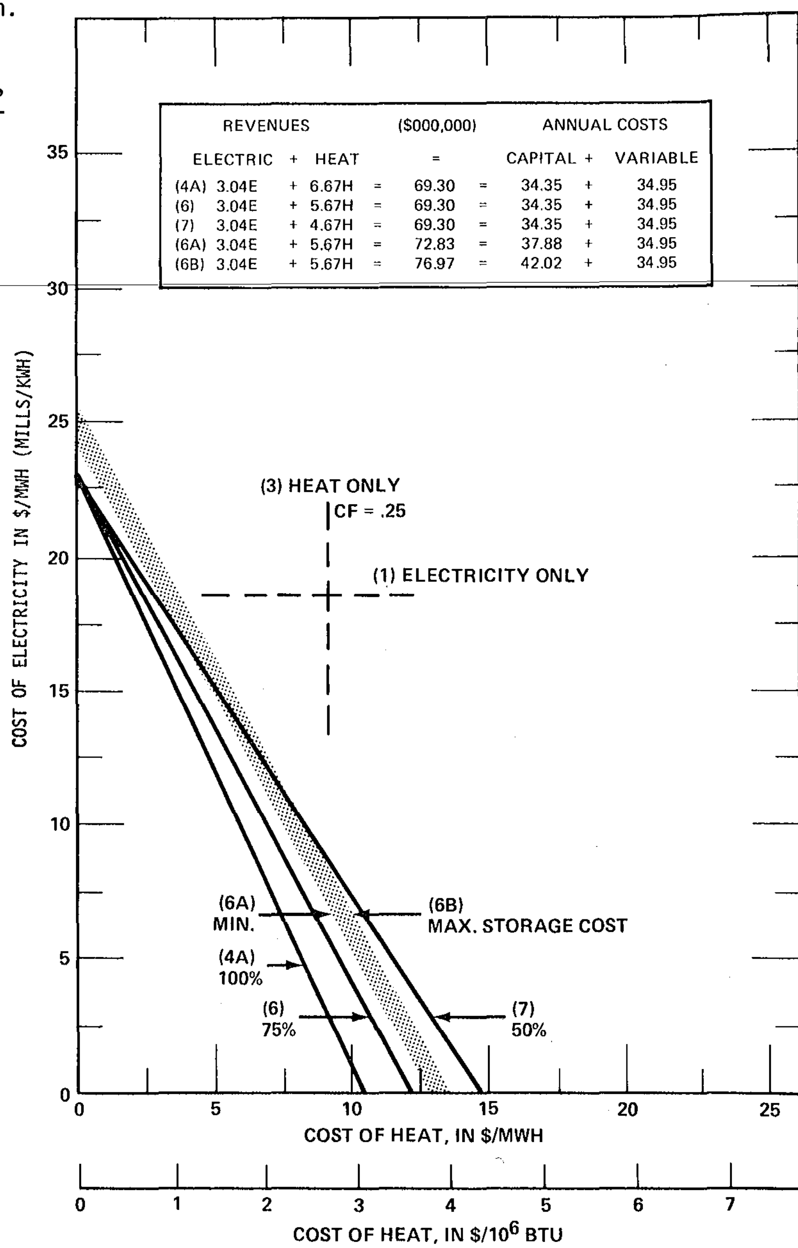

Fig. 6. Effects of storage costs and losses.

The energy-related costs of aquifer storage (in $/kWh of storage capacity) are truly negligible but the power-related costs are not. Estimating the $/kW (thermal) of capital investment needed for drilling and finishing a doublet well, with pumps, valves, pipes, and heat exchanger is highly speculative considering the wide range of geologic conditions that can be encountered across the United States. We have estimated $50,000 to $150,000 for a single million-gallon-per-day well to be a reasonable range, in 1974 dollars to be consistent with the plant data. For a doublet well plus heat exchanger and some contingency we assume $350,000 to $750,000. At one mgd capacity and a HSW temperature range of 150 to 350°F such a doublet has a capacity of about 20 MW_t, equivalent to 17 to 37 $/$kW_t$.

This cost will, when added to the costs in Equation 6, give the band bounded by Equations 6A and 6B. The 75 percent recovery case, Line 6, is taken as most typical from the previously discussed expectation of 70 percent recovery on the first cycle, and over 80 percent after many cycles. A band, similarly displaced from Lines 4A or 7, can be found to similarly describe the effect of storage cost and losses for 50 or 100 percent recovery.

It can be seen that even with the costs and losses of storage there is a considerable economic margin of superiority over separate generation of heat and power (intersection 1 and 3) over operating as a joint heat and power system without storage (compare Band 6AB with Lines 5 and 5A). If the price of electricity is held at the level for base load separate production of electricity, $18.52/MWh, the production cost of heat with storage is $2.91-3.65/MWh compared to $9.07, 4.61, and 7.29/MWh for Lines 3, 5, and 5A. Doubling the cost of storage, or assuming only 50 percent recovery from storage, or raising the heating load factor to 0.35, will not eliminate the economic advantage. This advantage can be used to reduce the price of electricity as well as heat, or permit district heating distribution into areas otherwise of marginal load density, or it can be used to transmit the heat to more distant load centers.

The tradeoff between the reduced cost of heat with cogeneration and storage, and a transmission distance from a non-urban coal plant to an urban district heating distribution center (where oil or gas is the fuel for district heating boilers, to keep pollution low), is graphically pictured in Figure 7. Here the coal plant is assumed to have the more favorable configuration of Figure 4B, i.e., it operates in a backpressure mode, producing proportional amounts of electricity and heat, each at a capacity factor of 0.62. Since the assumed demand for heat has a load factor (LF) of 0.25, the unused heat in the spring, summer, and fall is stored in HSW's. It is withdrawn from storage during the winter, to supplement the directly supplied heat from the coal plant.

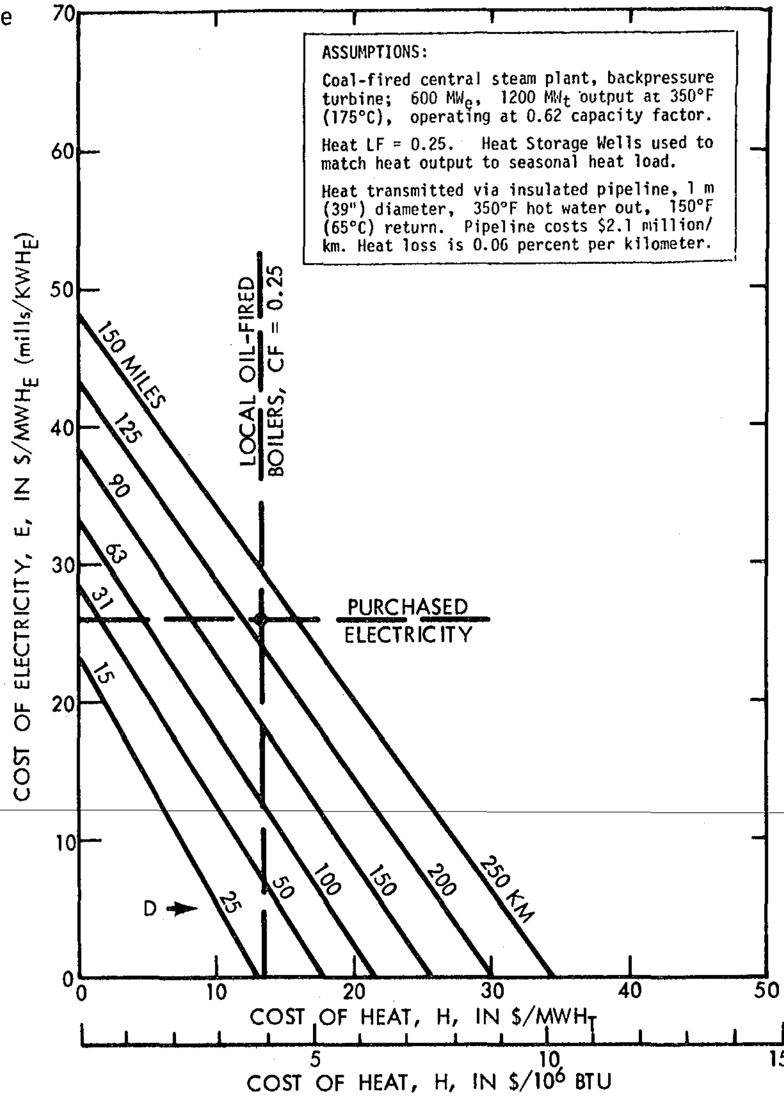

Fig. 7. Joint product costs: backpressure steam plant, Heat Storage Wells, and heat transmission.

The peak load that can be met is therefore up to 2400 MW_t, or higher if the HSW system has a pumping capacity greater than 1200 MW_t. As the HSW module was described as a doublet well with an input and output of roughly 20 MW_t, a well field of 60 such modules is needed to supply 1200 MW_t. These can be arranged as a line of hot wells surrounded on both sides by a line of warm wells, or as an inner circle of hot wells surrounded by an outer circle of warm wells as suggested by Despois and Nougarede (1977).

The capital cost of producing electricity and heat is reduced from that shown by Line 4A in Figure 6, because of the savings from the backpressure configuration. Use of one-meter diameter pipes capable of about 600 MW_t heat transport is estimated to cost $2.1 M$/km (1974 dollars). The amount this increases the capital cost of generation plus transmission is shown by the series of lines in Figure 7, each representing a transmission distance of the indicated number of miles or kilometers.

The vertical line shows the cost of heat derived from oil-fired boilers at the distribution center operated at 0.25 LF. It can be seen that the breakeven distance for this comparison is over 125 miles or 200 km.

As indicated earlier, the data sources for this paper used 1974 dollars and estimates of that period for future capital and fuel costs. Use of 1976 or 1978 dollars and more recent scenarios of capital and fuel cost escalation would change the numbers but not the methodology or the relative results for cogeneration versus non-cogeneration, and storage versus no-storage. In fact, if the fuel escalation rate of oil is significantly higher than that of coal, and both are greater than capital cost escalation, the case for storage and the breakeven distance for transmission of heat would be significantly greater.

QUESTIONS AND ANSWERS

Q. What about the cost of water purification?

A. We are using a heat exchanger so we are not contaminating the district heating water or boiler feedwater with the hard or saline groundwater. There would be operating and maintenance cost for cleaning the scale or fouling in the heat exchangers, which if large would reduce the advantage.

Q. Have you included the cost of pumping energy?

A. This is included and turns out to be fairly small, of the order of 0.2 mills per kW hour. Again we had to make assumptions. If the permeability of the aquifer is high the hot water buoyancy effect will be more noticeable than if it is low. We would prefer a uniform sandstone of moderately low permeability to reduce flotation effects but this increases pumping losses to the number I indicated. We want to use deep aquifers that may be slightly saline, so we do not compete with irrigation and municipal uses of groundwater. Our cost of pumping was based on having to use about 200 psi over and above the hydraulic head to inject and recover the water.

Q. Can you use aquifer storage for daily cycles?

A. I think we can do some of that. A current project we have indicates that if only a daily cycle is required, aboveground storage, or storage of HTW in excavated rock caverns may be more economic, but for seasonal storage or even for weekly cycles aquifer storage is less costly. When aquifer storage is installed, daily cycles can be superimposed on the seasonal cycle providing the maximum rates of energy extraction and injection, which determine the power-related costs of storage, are not exceeded.

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INSTITUTIONAL ASPECTS OF UTILIZING HEAT STORAGE IN AQUIFERS -- A PROPOSAL FOR A PROTOTYPE TEST

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ABSTRACT

The time has arrived to apply the prototype approach to some of the institutional problems attending utilization of heat produced in conjunction with the generation of electricity, particularly the rising cost of primary energy makes it possible now to encourage the combination of electric, gas, and water utility facilities under a common system to supply heating service at a level price, whether derived from gas, oil, or electricity, with the option of the user to select the mode of heating being withdrawn. This would make it possible to work our way through legal, political and institutional obstacles in a practical, step-by-step way, and would bring the household consumer into the experiment, something not now possible.

CONSERVATION AND HIGH ENERGY PRICES

The concept of thermal energy storage in aquifers is now getting serious consideration by those concerned with energy conservation in both the public and the private sectors. At one time, the non-technical constraints to this form of conservation were distinctly secondary to the technical constraints. The technical constraints are still primary, but we have advanced to the point where our consideration of the non-technical constraints has become more refined and differentiated.

Those concerned with national policy, and to a lesser extent those concerned with corporate strategy, traditionally regard institutional problems attending a particular kind of development as ultimately tractable. In their perspective, the necessary permits, the required access to land or water, and the general governmental and political support inevitably follow the successful demonstration of technological viability.

Efficiency, however, has been a less than precise term in projects involving energy and depletable natural resources. The engineers and the economists have been on different wavelengths in energy matters in the past, so that thermal efficiency and economic efficiency have meant different things. That is now changing, and although anomalies still exist, engineering efficiency now can more easily be explained in dollar terms. We can claim no particular credit, or take any real satisfaction in this development, for it is related mainly to the price of imported oil escalating by a factor of four or more in just a few years. This is a "real" price. Though not related to the regulated domestic price neither is it particularly related to assumptions about the behavior of "free" markets. For analytical purposes, it means that we can measure our efforts to conserve energy against a scale of at least $2.50 per million BTU.

In different terms, the concept of conservation has moved to the forefront of national policy. Some conservation is government-mandated, while other steps are related to the replacement of energy-wasting equipment by more efficient means, or adjustment of energy conversion methods to achieve greater efficiency. We have a new ability to translate these changes into energy terms as well as dollar terms. What has been accomplished so far by fuel-efficiency gains in automobiles will eventually by multiplied many-fold by the recovery of heat currently released to air and water in the process of generating electricity.

GOVERNMENT RESPONSE

However, improvements in the quality of our understanding of energy economics has not resulted in any perceptible improvement in the integrative process which is a prerequisite to the solution of institutional problems which could block this particular form of conservation. The federal government is not yet organized in such a way that rational choices can be made between spending money for facilities to remove heat as a pollutant, and spending it for facilities or systems which will enable the heat to be used. Only small steps in this direction are being made. One of these is the growing acceptance of the idea that air quality improvement measures can be accomplished by the purchase and retirement of existing pollution sources; another is the greater pragmatism about the desirability of retrofitting of control mechanisms to existing plants.

But the institutional (as distinguished from technical or technological) character of our thinking is still dominant. The Environmental Protection Agency still naively regards itself as a mission agency which does not have to worry excessively about energy efficiency, either from an engineering or an economic point of view.

As a nation we are still far from the centralized formulation of energy policy which the enactment of a Department of Energy Act was supposed to bring. The enactment of the President's National Energy Policy Act, when it finally comes, does not promise to improve things very much. The organization of the Congress to grapple with these challenges is not materially better than it was five years ago.

CHANGES IN INSTITUTIONAL OBSTACLES

One Phase of the non-technical side of the problem is psychological. As a British expert has observed, electrical engineers have not been content to produce and distribute a mere secondary product such as heat. Energy partisans rather than engineers still control a lot of policy making.

Some institutional obstacles to this form of conservation have become specific. The development of heat storage wells will be subject to the Federal Safe Drinking Water Act, 42 USC sec. 300f, which mandates the development of interim regulations for injection of water or other fluids into the ground. This problem, which once varied from state to state, is now specifically subject to a federal administrative superstructure.

Differences among the states in how they are likely to handle problems associated with heat storage in aquifers are not becoming any simpler. State regulation has not been displaced. Colorado's Water Quality Control Act, for example, authorizes the enactment of state rules for subsurface disposal systems. The rules which have been adopted are broad enough to include heat storage injections and withdrawals.

The constraining effect of the water law systems of the various states, particularly with respect to underground water and the utilization of aquifers for heat stoarge as a "use' will require state-by-state review. The only possible generalization is that this kind of "use" of water will be resisted by a coalition of interests, ranging from agriculture to competing energy sources.

THE PROTOTYPE APPROACH EXPANDED

A prototype approach is now being adopted to enable large scale tests to be made to demonstrate the feasibility of heat storage systems. The federal government might further encourage this by permitting experiments to go forward on government land, but the transfer of most energy functions from the Department of the Interior to the Department of Energy has created an adversary relationship within the heirarchy as to this use of public lands which will slow such a development. We are a long way from any federal government activity to facilitate private development of heat storage wells on leased government land, even to serve both environmental and energy objectives combined.

This country remains committed to utility-type regulation of those services which are natural monopolies or which are extremely capital-intensive, or both. The characteristics of the utility model of regulation include control on entry and price regulation, plus a considerable measure of financial control. Regulation of energy supply activites, chiefly electric and natural gas transmissions and distribution, is spread amoung a number of agencies at the federal level, and almost every state has a regulatory commission to regulate the local aspects of such activities.

Water for domestic and industrial uses is also generally regulated on the utility model, at the distribution level, or treated as a governmental function of municipalities. There are differences between regulated utility operations and municipally-owned systems, and the latter might be more amenable to the idea of district heating.

An extension of the prototype approach into the institutional area is an approach worthy of consideration. It would facilitate the physical prototype to test complete system, at a small sized city having its own generating and distribution facilities for electricity or gas or both, and its own water distribution system. It would furnish an improved opportunity to work our way through legal, political, and institutional obstacles in a practical way. Working from the federal government's current experimentation with some of the institutional components of programs to conserve energy, and with the possible assistance of federal grants, guinea-pig situations could be created for the utilization of jointly produced heat and electricity in a variety of combinations.

Heretofore, most tests of total energy systems have involved specialized industrial applications. If the ultimate use has been non-commercial (or at least non-profit), past applications have not generally involved individual householders, but rather large apartments or hotels, hospitals, and public buildings. This has been the experience in New Zealand, which has probably improved the thermal efficiency of their generating stations, whether geothermal or oil-fired more than most countries.

At the point of household consumption, the few past experiments have been undertaken to test the effect of more sophisticated metering or various experimental rate designs in order to control the time and manner of use of electricity. What is needed is a broadened experimental program which will enable a prototype system for utilizing the heat stored in aquifers.

In broad outline, the beginning point of such an experimental program would be to offer the customer only the product which he ultimately uses -- heating or cooling --without giving him his present option of choosing the method by which various forms of primary energy are converted to heating or cooling.

If the appropriate foundation were laid in authorizing legislation, the regulatory authority or the city agency operating such a program would have the tools to make it possible to eliminate price differentials as among various energy sources now utilized for heating and cooling. It would be challenging but not impossible for differentials based upon differing capital costs for various heating systems, differing factors of insulation or other construction characteristics, and differing prices of fuel to be eliminated at the point of use, so that there would be no false incentive to choose natural gas, and no disincentive for being "first on the block" to sign up for district heating service. Instead plans could be made for hooking up new hooking up new subdivisions, retrofitting apartments and other institutional users, and even changing the method of operating electric generating plants, looking toward greater conservation and use of all the available energy being supplied.

The greatest obstacle to such a program would be the indirect regulation of presently un-regulated fuel sources, particularly home heating oil. But it is not as long a step as it once seemed, indirect regulation of fuel oil is already in place. Public regulation required householders to give up burning coal in favor of natural gas many years ago. Federal Energy Administration regulations more recently required utilities to convert from oil to coal or from natural gas to oil or coal, without presenting insurmountable obstacles. In short, I do not believe there are serious institutional obstacles to a conservation-oriented experimental program which would be designed to demonstrate the feasiblity of using a substantial fraction of the 70% of the input energy in our electric generation plants now being wasted.

Even if the option of using heating oil could not be taken away from the household customer, the high price of oil probably permits a version of this proposal to be adopted on an experimental basis. The breadth of the experiment would be lessened in some geographic areas but this would not be significant.

Working with the existing gas, electric, and water-distribution utilities, the authority administering the experiment would arrange with the electric generating station to supply needed and available heating or cooling service, directly or from storage, to supply the requirements of customers who have been designated to take their heating or cooling service in this form. Those not so assigned would be designated to receive natural gas or electric heat service as circumstances warranted. Each customer would pay the same amount, on a BTU required basis whatever the source of energy. Potentially, any customer could be required to shift from one service to another, but this would have to be without the added burden of purchasing the new equipment. That cost would be rolled into the price of the heat service, or otherwise equalized if above a base level equivalent to the average cost for initial equipment chargeable to the cost of the structure being heated or cooled.

The advantages of this type of prototype program include the flexibility it would offer in terms of the size of projects and the speed of their implementation. The requisite legal machinery could be put in place without associated capital costs. Implementation could track the availability of this form of heat, with the added advantage of assuring a market for the heat on an assigned basis. The administrators (which could well be a municipality already operating basic utility services such as electricity, gas and water) would be able to assure that only the cost of the program in excess of the value of the energy supplied would be charged to the supplying utility.

There would be troublesome side effects, of course, particularly where the program might cut into established markets outside the regulated sector. It is conceivable that segments of the community denied access to an intrinsically superior form of heating and cooling service would complain of discrimination.

But these obstacles would have to be overcome if the commitment were left entirely to market forces. Ultimately they properly should be handled by market forces. But prototype experimental programs to speed the process of bringing this form of energy conservation into our national program are justified.

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ENVIRONMENTAL ASPECTS OF LOW TEMPERATURE THERMAL ENERGY STORAGE IN AQUIFERS

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Knowledge of the geologic and hydrologic characteristics of the subsurface environment at an injection well site and in the surrounding region is fundamental to the valuation of the site for low temperature energy injection and subsequent storage.

The subsurface rock units that are present are described in terms of their lithology, thickness, areal distribution, structural configuration and engineering properties. The chemical and physical properties of ground water and the nature of the local and regional subsurface flow system comprise the hydrologic environment for the storage system.

While nearly all rock types can, under favorable circumstances, be capable of receiving and storing water for use as thermal energy, sedimentary rocks are most likely to have suitable geologic and engineering characteristics. Their characteristics are sufficient porosity permeability, thickness and areal extent to act as a liquid-storage reservoir.

The temperature of the aquifer and its contained fluids is important because of the effect that temperature has on fluid properties. Likewise, the temperature of the injected fluid, whether it be hot or cold, may alter a variety of characteristics. Judgment as to whether water may or may not be permitted to be injected into a rock unit depends in part on the chemistry of the aquifer water and its potential reactivity with the injected water.

Temperature changes in an aquifer produced by injected water may alter solubility of the rock, it may reject gases in solution; it may promote biological activity, especially in the presence of nutrients. It may kill bacteria. Temperature changes may alter viscosity of the aquifer fluid; it may alter Ph thus affecting the solubility of metals in the rock formations.

Understanding the ultimate fate of injected waters and their environmental effect depends in part on knowledge of the regional and local subsurface flow system.

But all indications at present point to minimal if not insignificant negative impacts as a result of low temperature thermal storage, especially as one compares their impacts with the distinct environmental advantages to these systems.

By using heat-storage wells, thermal pollution could in fact be greatly reduced at the earth's surface. Energy can be saved and thermal pollution reduced if a total energy solution using aquifer stored energy were used. The day of massive energy generating systems is on the decline as the total energy approach using small generating systems becomes more popular.

A key question that must be considered when applying the total energy approach is the feasibility of storing large amounts of heat for several months in order to match the capacity for heat production to its seasonal demands. But all studies point to a reasonably efficient potential for doing exactly that, especially when comparing such a procedure to above ground storage of heat in huge insulated tanks which are aesthetically objectionable and enormously expensive. Recovery wells for underground storage on the other hand are unobstrusive, inexpensive, yet tap an incredibly large storage space.

It would appear then that the environmental impacts of low temperature thermal energy storage are probably of no negative significance and may in fact have major positive environmental impacts by reducing a variety of pollution producing procedures resulting from more convenient energy sources. That is to say that small aquifer temperature changes create insignificant fluid-aquifer alterations yielding no significant imbalance in the subsurface systems. But reduction of oil, gas and coal usage through the conservation of thermal energy helps to eliminate the myriad of pollution producing activities associated with petroleum refining, coal mining, and waste disposal.

It would appear at this time that high temperature geothermal energy utilization will not have such outstanding potential. High temperature geothermal resources are not found where they are needed while in contrast, low temperature energy storage can be sited with minimal limitations throughout the areas of need. Concurrently high temperature geothermal fluids are difficult to handle in conventional distribution and storage systems due to unusual corrosivity while low temperature fluid offers no such problems.

With space heating and cooling approaching 25% of our total energy consumption the easy availability of aquifer storage becomes environmentally attractive indeed. But perhaps we are overlooking the largest source of stored aquifer energy of all when we fail to recognize that ambient ground water itself, already resident in our vast subsurface aquifer-reservoirs has untold potential for energy extraction and recycling into the storage mode.

Ground water in its shallowest zone is still subject to the geothermal gradient which nearly always yields a shallow aquifer temperature equal to the mean annual air temperature of the land surface immediately above. This creates a favorable temperature differential for heating in the winter when the air is cooler and cooling in the summer when the air is warmer. Domestic dwellings and commercial buildings can continuously produce a ton of air conditioning through a water to air heat pump from a constant flow of three gallons per minute or less. Depending on the availability of ground water, large systems can be developed with all water recycled back into the acquifer for storage and future use either in a cooling or a heating mode.

It is estimated that 10 gallons a minute for a domestic energy system can be developed over at least 70% of the surface of the conterminous United States while large systems producing over 10 million BTU's for water to air heat pumps can be located over 25% of the countryside.

Thus it is not always necessary though perhaps always desirable to hunt down volumes of waste water with usable thermal characteristics whether it's hot waste water from an electrical generating plant or winter chill from a surface water body.

Just 125 years ago, in December, 1852, Professor William Thomson of Glasgow (later Lord Kelvin) pointed out that burning fuel is not the most efficient way to heat the air in a building. It can be done at a much lower cost in fuel, he calculated, by using a mechanical expansion and compression system that takes heat from an outside source to raise the temperature of the air circulated through the building. He noted also that the same mechanical system could be used for summer cooling in places like India where cooling "might be used with great advantage to health and comfort."

UNIT HEATING MODE

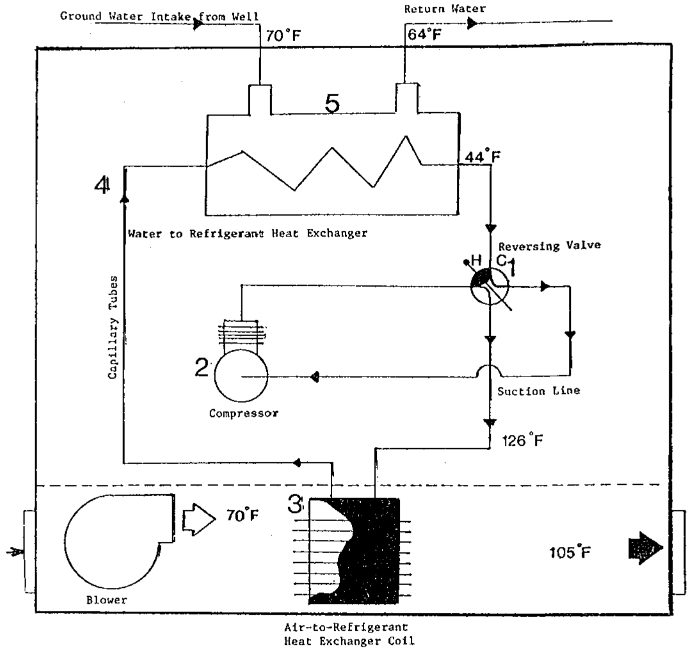

Figure 1

UNIT COOLING MODE

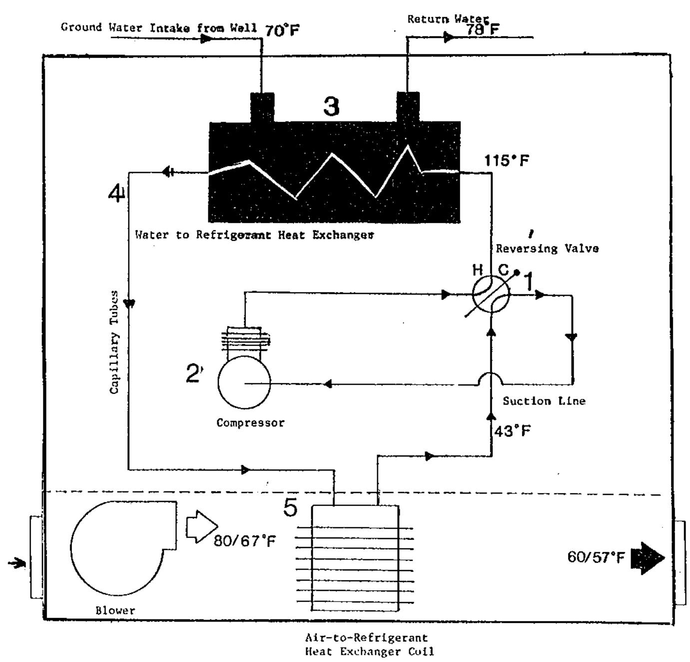

Figure 2

These possibilities were proposed about 25 years before the first successful use of refrigeration to freeze meat for shipping from Australia to Europe, and long before electricity and electric motors for power were generally available.

The heat pump is thus not a new idea, but it has now become a timely idea. Especially where ground water is available, it is now the lowest-cost means for heating buildings and hot water. It will probably remain so for some time to come.

Ground water to air heat pumps may offer the most perfect means of utilizing stored thermal energy from our nation's aquifers. The diagrams in Figures 1 and 2 illustrate the very simple mechanical device which extracts heat from ground water by means of a basic heat exchange system and transfers it to air in the heating mode (Figure 1) and operates in the reverse direction in the cooling mode (Figure 2). Capable of operating with a co-efficient of performance above 4.0 this system offers the most environmentally sound method of using thermal energy storage in our low temperature aquifers. Capable of operating on ground water temperatures between 40°F and 75°F normal reduction or increase of water temperature going through the cycle is less than 10°F and its ability to significantly alter overall aquifer temperatures is negligible upon recycling due to the relatively small volume.

The potential environmental consequences of the utilization of ground water for heat exchange must be carefully examined. Present designs call for withdrawal and recharge of all water used: there is no consumptive use and no consequent appreciable effect on the water table level. However, if the system is designed for possible water discharge into sewers or streams, the water available for recharge may be reduced and result in the lowering of the water table under certain hydrologic conditions.

In temperate climates where heating and cooling requirements are roughly equal, net alteration of the aquifer storage system will be zero. Where there is either a significant net cooling or heating requirement, long-range but slight alterations of aquifer temperatures can be anticipated.

Additional research on such thermal aquifer loading would be desirable to determine the density with which ground water source heat pumps can be counted on to perform without significant interference due to thermal alterations.

Research into ground water source heat pump systems has been directed towards finding methods for recycling or disposing of the ground water after it leaves the heat exchanger which would result in minimal thermal alteration. Although this water is not chemically contaminated in any way, its temperature has been raised or lowered a few degrees, posing questions of the possibility of thermal pollution. The fact that many systems have been designed but that few of them have so far been tested makes this problem hard to evaluate. The NWWA Research Facility has been investigating two systems that seem to merit further consideration: the storage tank system and the recharge/discharge well system.

In the storage tank design, a large storage tank, with a capacity of approximately 3000 gallons, would be installed underground immediately adjacent to the well. This tank would be insulated by the soil that would surround and cover it. The heat pump would utilize the water contained in this tank to heat or cool the house. Water that had run through the heat exchanger cycle would be discharged back into the tank, to be reused. If the heat pump were heating the house, the storage tank would eventually be filled with water whose original temperature had been lowered by several degrees. Heat would be extracted from this water until it reached approximately 40 degrees, when a heat sensor (thermoster) would kick on a solenoid that would start the well pumping again.

As the warmer ground water was pumped into the storage tank from the well, it would displace some of the cooler water, which would then be discharged from the system. Gradually the temperature of the stored water would begin to rise. However, since the heat pump would still be utilizing water from the storage tank, heat would also be extracted from the stored water. The temperature would therefore tend to reach a balance in the tank of between 40 and 45 degrees Farenheit during the heating cycle. Eventually the water would reach a set maximum average temperature and the heat sensor would signal the solenoid to cease pumping. This same control system would operate during the cooling cycle as well, only with higher maximum and minimum values. This control system reduces the amount of time that the pump has to operate and increases the efficiency of the system.

The greatest advantage of utilizing a storage tank system, however, occurs in the spring and fall when excessive amounts of heating and cooling are not needed. Since many times heating and cooling are required only occasionally during these seasons, the heat pump can often operate solely off the water contained in the storage tank. This presents two advantages. First of all, since not much heating or cooling is required, the temperature of the water is not raised or lowered to such a great extent as in other seasons. Secondly, the temperature of the ground below the frost line remains constant, so heat may move into the cooler water of the tank from the ground during the heating cycle and may move out of the tank into the ground during the cooling cycle, producing additional thermal efficiency. Either way, the amount of pumping required to supply heated or cooled air is substantially reduced.

The dual recharge/discharge well system will eventually be mandatory for water conservation reasons, but offers few problems and many advantages.

Water warmed or cooled can be stored in different aquifers or in different parts of the same aquifer. When heating becomes necessary, the well that had been recharged with warm water becomes the supply well, pumping water with a higher temperature than the surrounding aquifer to provide more efficient heating. During the cooling cycle, the well which had been recharged with cool water (the by-product of heating) becomes the supply well to assist cooling efficiency.

Research at the University of Wisconsin indicates relatively insignificant temperature declines of 1 to 2°C extending only to 10 to 20 meters from a discharge well after 10 years of operation. The well is part of a dual well domestic ground water source heat pump system where heating degree days were 5 times greater than cooling degree days.

To further improve its already high efficiency, the water withdrawn from the ground can be used for other non-polluting domestic purposes before being discharged. Possible uses include sanitary applications, water for cooling and drinking, domestic and commercial hot water use and various outdoor applications.

We all agree that new sources of energy must be found to meet our nation's requirements. Let's invest the time and effort to develop the vast, potential energy source that lies directly beneath our feet. Too often we look for some complicated solution when a simple solution is staring us in the face. We have an enormous supply of ground water energy and the technology to utilize it. The ground water source heat pump is that technology.

Widespread use of the ground water source heat pump will permit our nation to considerably reduce its consumption of fossil fuels and electricity.

Space heating and cooling accounts for 21 per cent of our nation's energy consumption. The ground water source heat pump is one alternative by which this figure can be lowered.

MATHEMATICAL MODELING OF THERMAL ENERGY STORAGE IN AQUIFERS

by

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Introduction

Aquifers have been suggested as one of the most promising solutions for long-term, low cost, seasonal storage of thermal energy. Aquifers are geologic formations which contain and conduct water. They are found at depths ranging from a few meters to several kilometers. Confined aquifers are those which are bounded above and below by impermeable layers and are saturated by water under pressure. For many years these types of aquifers have been used for liquid waste disposal and for storing fresh water, oil products and gas. Their use for hot water storage was first suggested in 1971. Initial studies were made by Rabbimov, Umarov and Zakhidov (1971); Meyer and Todd (1973); and Hausz (1974). These early works involve mainly analytic or semi-analytic calculations as well as economic and institutional considerations.

In 1976, Tsang, Lippmann, Goranson and Witherspoon, at LBL, presented the results of a three-dimensional numerical modeling of the fluid and heat flows in aquifers used for hot water storage. The results indicated a recovery storage ratio greater than 80%. At the same time, Molz et. al. (1978) completed their first set of field experiments on hot water storage. Their data were analyzed and used in a numerical simulation study by Papadopulos and Larson (1978). The present paper reviews the results of the numerical modeling work performed at LBL over the last one and a half years.

In the next section of the paper, the physical basis of the concept is briefly discussed and a qualitative description is given of a computer model developed at LBL and used in these studies. A careful validation of the model is then presented using three different examples for which either analytical or semi-analytical solutions are available. In the following section, the various cases for which calculations have been made are discussed and results described. The paper is concluded with a summary and some general remarks.

Mathematical Approach

The physical basis of the concept of aquifer thermal energy storage lies in the low heat conductivities of rock materials and also in the fact that aquifer volumetric capacity is normally on the order of $10^9 m^3$. Thus, large volumes of hot water may be stored under pressure. To estimate the feasibility and efficiency, as well as the optimal arrangements of such a storage system, the processes occurring during injection and withdrawal cycles must be understood. Processes of interest include: 1) thermal behavior and heat losses during successive cycles; 2) pressure changes throughout the aquifer including the possibility of the compaction of the aquifer and overburden formation which may result in land subsidence; and 3) chemical reactions and the resulting changes in aquifer permeability and porosity.

Most of our studies were made using a numerical model called "CCC" which stands for Conduction, Convection and Compaction. It is based on the so called Integrated Finite Difference Method (Edwards, 1972; Sorey, 1976; Narasimhan and Witherspoon, 1976). The model computes heat and mass flow in three-dimensional, water saturated, porous systems. Coupled with mass and energy flow is a calculation of the vertical deformation of the system using the one-dimensional consolidation theory of Terzaghi. Thus, the following physical effects are included in the calculations: a) effects of temperature on fluid heat capacity, viscosity and density; b) heat convection and conduction in the aquifer; c) effects of regional groundwater flow; d) spatial variations in aquifer properties; and e) gravitational effects.

For the validation of the numerical model, three different examples are used for which analytical or semi-analytical solutions are available. The first example is the Theis solution (1935) which describes the change of pressure head with time in a well flowing at a constant rate. Our numerical results follow closely the standard solutions in terms of the exponential integral (Figure 1). For comparison, numerical results obtained by a linear finite element method are also shown. A quadratic finite element method does not give any improvements. Only when a cubic finite element method is used are the results comparable to ours. The second example considered is a problem of evaluating the temperature distribution and radial distance as a function of time when cold water is injected into hot reservoirs. To solve the problem analytically, Avdonin (1964) assumed zero gravity and constant parameters. In Figure 2, the comparison between Avdonin's solution and our numerical results is shown. Again, good agreements are found. The small deviation corresponds to the finite size of the mesh. The third example is that of an injection-production doublet in which cold water is injected into one well and reservoir water is produced from another. The production temperature as a function of time, obtained by Gringarten and Sauty (1975), is compared with our numerical results (Figure 3). The agreement is surprisingly good.

Parameters Used and Mesh Design

In all our calculations we have assumed that the rate of injection and production is kept the same, equal to 10^6 kg/day (approximately 181 gpm).

The parameters used in the study are tabulated in Figure 4. These are property values taken from standard sources (Kappelmeyer and Haenel, 1974; Helgeson and Kirkham, 1974). We have performed calculations for both one-well and two-well systems. In the case of the single well, the mesh design is shown in Figure 5. The well is positioned at zero radial distance, the mesh having radial symmetry around that axis. One remark needs to be made here. In pressure calculations, mesh elements could be increased in size as one moves away from the well without significantly affecting the accuracy of the results. However, in heat calculations, the mesh elements should decrease in size as one moves away from the well, since for equal time steps, the injected hot water will move a smaller radial distance (assuming constant flow rate). We have chosen a compromise by assuming equal radial distance steps in the mesh, as shown in Figure 5. Furthermore, a finer mesh was used in an additional calculation to show the stability of our results against mesh changes. Another remark needs to be made concerning the design of the mesh in the caprock and bedrock. A very fine mesh is used close to the aquifer representing a rapid change in temperature in that region. A careless design will give a misleading value for the heat loss from the aquifer into the caprock and bedrock.

Results of Calculations

Calculations were made for the following cases:

1. Annual Cycle - Seasonal Storage

In this problem, each cycle of 360 days is composed of four periods: a) in summer, when supply exceeds demand, the hot water is stored in the aquifer; b) in fall, when supply and demand are approximately equal, the well is shut in; c) in winter, when demand exceeds supply, hot water is produced from the aquifer; and d) in spring, when supply and demand are approximately equal, the well is shut in. The calculated temperature distribution in the aquifer is shown in Figure 6 for two time periods: a) after ninety days of injection; and b) after ninety days of injection, ninety days of rest, and ninety days of production. The thermal front is not sharp because of heat conduction to the confining beds and to the aquifer system. It will be shown later that numerical dispersion is negligible in our results. Note, that after ninety days of injection, the 20° isotherm is about 30 meters from the well. The hydrodynamic front (the location of the injected water) is much farther away, approximately 60 meters from the well. The thermal front lags behind, representing the fact of the porous medium being heated and draining energy from the injected water. Figure 7 presents the radial dependence of pressure distribution at the horizontal center line of the aquifer, the initial pressure being 1.3×10^6 Pascals. After ninety days of injection, the curve is essentially an inverse Theis solution with a transition at about 30 meters. This transition may be understood as a separation between native and the warmer injected water, with significantly different viscosity values, on either side of the 30 meter point (see Figure 6). After ninety days of rest, the pressure distribution equilibrates to a smooth line. During the production period after this rest a typical Theis curve is seen again. The radial dependence of the temperature distribution at the horizontal center line of the aquifer is shown in Figure 8 for different times in the first cycle. This figure also presents the curve corresponding to five days into the next cycle, showing the effect of the aquifer having already been heated during the first cycle and thus resulting in a more efficient hot water storage system for later cycles.

To study how numerical dispersion affected our results, we performed the calculation again with a finer mesh. In one mesh design we divided the aquifer vertically into six layers and radially into steps of 2 meters. In another design, the corresponding quantities are four layers and 1.5 meter steps. As shown in Figure 9, the changes in temperature values are negligible. Figure 10 displays the water temperature at the well during the production period for successive cycles. The efficiency is increased for each successive cycle as the aquifer is heated up, making it a better storage system. The process will reach a quasi-equilibrium when successive cycles do not change the temperature appreciably. By integrating the production temperature minus the original aquifer temperature over the production period, the energy recovered can be calculated. The percentage of energy recovered, shown in Figure 11, is this calculated energy divided by total injected energy for each cycle. Further details are shown in Figure 12, which indicates the energy balance for the first cycle: a) heat loss from all the boundaries of our caprock-aquifer-bedrock system; b) total energy injected; and c) total energy produced. It appears that the external heat loss is negligible. The difference between injected and produced energies is mainly used to heat up the aquifer, making it a better storage system.

2. Different Cycle Periods

In addition to the annual cycle described above, we also looked at the semi-annual cycle, that is: storage in the fall, production in winter for space heating; and storage in spring, production in summer for air conditioning. Very similar results were obtained. The corresponding percentage of energy recovered for successive cycles is shown in Figure 11.

3. Well Partially Penetrating the Aquifer

Calculations were also performed assuming the well to be open only for the upper half of the aquifer. Figure 13 shows the temperature contours in the aquifer after ninety days of injection and after ninety days of subsequent production. The buoyancy effect of low density hot water is clearly seen. The percentage of energy recovered for successive cycles is only slightly affected.

4. Storage of Water of Different Temperatures

We have looked at storage of water at 120°C, 220°C and 320°C. We found that as far as the hydrodynamic and thermal behavior of the aquifer is concerned, the results appear to scale as $(T_S - T_O)$, where T_S is the temperature of water stored and T_o is the original aquifer temperature.

5. Effect of a Clay Lens in the Aquifer

In this case the aquifer is divided into two parts by a clay lens with a radius of twenty meters. If the well is open only below the lens, the result of hot water injection and production is as shown in Figure 14 which displays the temperature contours after ninety days of injection and ninety days of subsequent production. The effect of the clay lens on these temperature contours is clearly demonstrated. However, it is found that the percentage of energy recovered is not much affected (Figure 11).

6. Inhomogeneity of the Aquifer

If the aquifer is composed of two layers, one more permeable than the other, then the flow and the temperature contours will be changed. An example in which one region is twice as permeable as the other is shown in Figure 15. The water tends to flow into the higher permeable region as would be expected. However, again it is found that the percentage of annual recovery is not much affected (Figure 11).

7. Chilled Water Storage

In addition to the study of hot water storage, we have studied the concept of storage of winter chilled water (at say 4°C) to be used in summer for air conditioning. If we assume storage of 4°C water over ninety days in winter, and production for ninety days in summer, then the production temperature for successive cycles is shown in Figure 16. After a few cycles, the temperature is expected to be below 10°C for the whole production period.

8. Two Well System

In this case we study a system of two wells, where one well supplies the water that is heated and injected into the other well. In studies described above, the thermal front moves radially from the single well. However, in this case, because of the presence of the second well, the thermal front will be distorted. In Figure 17, the thermal fronts are shown as a function of the separation between the storage well and the supplying well. As indicated, if the two wells are at a reasonable distance apart, single well results are applicable. To study this case in more detail, we have performed a three-dimensional numerical modeling of the two well system. The mesh design is shown in Figure 18. A fine mesh is used near the storage well to ensure an adequate description of the temperature changes in that region. Results of our calculations are shown in Figure 19. Here, the effect of the supplying well and the gravitational buoyancy effect are clearly indicated. The production temperature as a function of production period in the first cycle is shown in Figure 20. For comparison, the corresponding single well curve is also plotted.

9. Possibility of Consolidation or Uplift

To demonstrate the capability of the model to calculate the consolidation or uplift effect, we have performed calculations based on two sets of arbitrarily chosen parameters. The results are illustrated in Figure 21 where we have assumed 10-day injection and production periods. One can see that consolidation and uplift are strongly parameter dependent.

Summary

In this paper, the hydrodynamic and thermal behavior of an aquifer used for thermal energy storage was studied and described for a number of possible situations. In all the cases studied, the percentage of energy recovery was surprisingly high, over 80% after only a few injection-production cycles. We have plans to simulate the production and injection history of an actual field experiment.

So far we have considered porous systems only. The existence of any fault, or large connecting fractures, will alter the picture. Chemical reactions will also be important because they may cause changes in porosity or permeability. Furthermore, water treatment is crucial to ensure the injectability of the storage well. Another effect which we plan to study is fingering caused by geological heterogeneities which would tend to reduce the energy recovery percentage.

In spite of these reservations, the results in this paper point to the potential of using aquifers for thermal energy storage. Problems outlined above might be minimized by careful engineering. Field experiments currently being carried out are important to verify the high recovery percentage predicted by these modeling studies.

Acknowledgements

The encouragement and interest of Paul Witherspoon are greatly appreciated. The assistance of Philip Fong and Debbie Hopkins in various aspects of this paper is gratefully acknowledged. Work is performed under the auspices of the Department of Energy (Division of Energy Storage Systems) through Oak Ridge National Laboratory.

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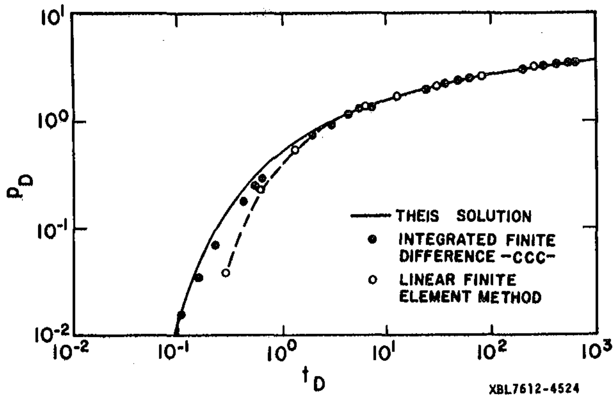

Figure 1. CCC compared to the Theis (1935) solution. Results obtained from the conventional finite element method are also shown.

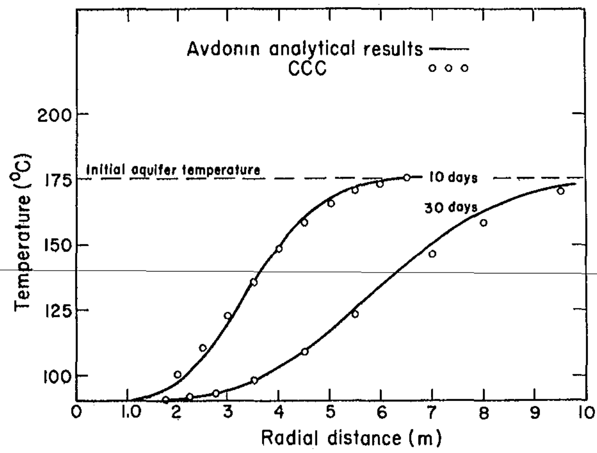

Figure 2. CCC compared to Avdonin (1964) solution. Water injected at 2×10^4 cm^3/sec into an aquifer 200m thick with 20% porosity.

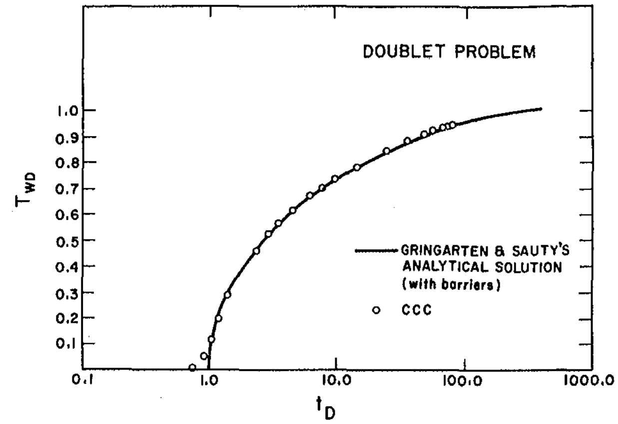

Figure 3. CCC compared to the Gringarten and Sauty (1975) doublet problem.

MATERIAL	POROSITY	DENSITY kg m^{-3}	HEAT CAPACITY J kg^{-1}°C^{-1}	THERMAL CONDUCTIVITY J $s^{-1}m^{-1}$°C^{-1}	PERMEABILITY m^2	SPECIFIC STORAGE $KN^{-1}m^2$
Reservoir (Sandstone)	0.20	2.6×10^3	9.70×10^2	2.894	1×10^{-13}	1×10^{-6}
Caprock Bedrock (Mudstone)	1×10^{-20}	2.7×10^3	9.30×10^2	1.157	1×10^{-40}	1×10^{-15}

FLUID PARAMETERS	VISCOSITY (CP)	T(°C)	HEAT CAPACITY C(J kg^{-1}°C^{-1})	T(°C)
	1.005	20	4.127×10^3	25
	5.45×10^{-1}	50	3.894×10^3	75
	2.80×10^{-1}	100	3.652×10^3	125
	1.82×10^{-1}	150	3.341×10^3	200
	1.35×10^{-1}	200		

EXPANSIVITY (°C^{-1}) 3.17×10^{-4}

Figure 4. Material and fluid parameters used in the hot water storage model.

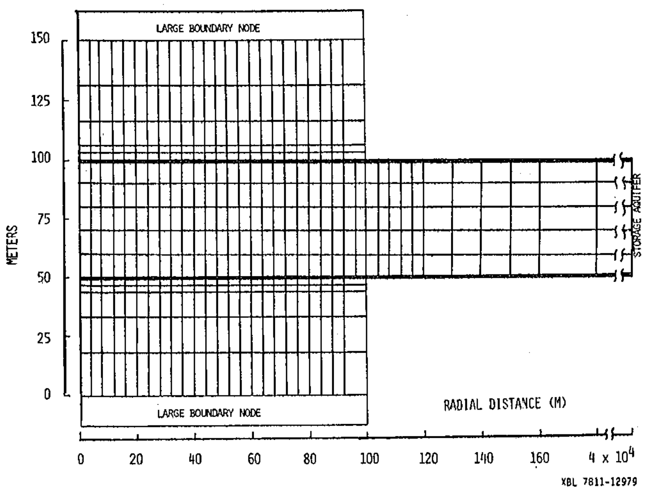

Figure 5. CCC mesh design for hot water storage: radial symmetry with well at zero radial distance.

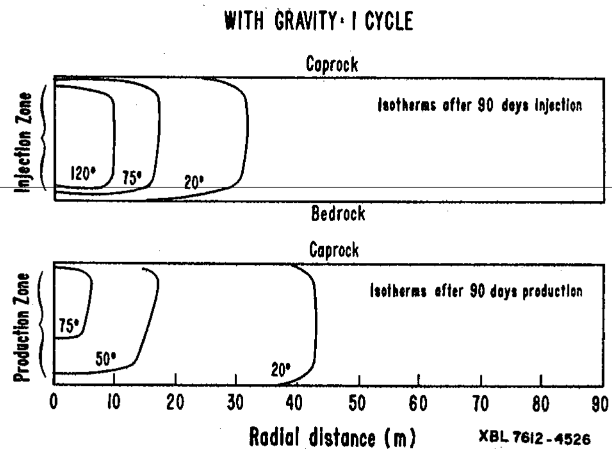

Figure 6. Temperature distribution in the aquifer after 90 days of injection, 90 days of rest, and 90 days of production (Cycle 1); t represents total time elapsed.

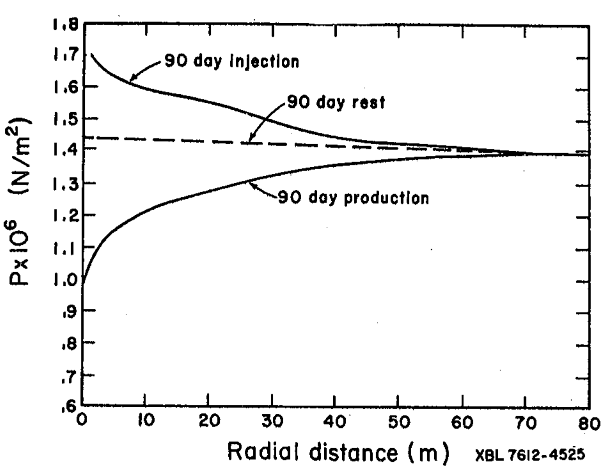

Figure 7. Pressure distribution in the aquifer as a function of distance from the well (Cycle 1), full penetration.

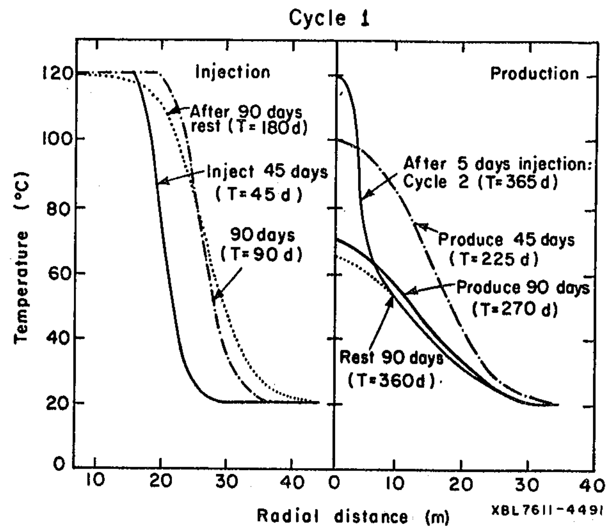

Figure 8. Temperature distribution in the aquifer as a function of radial distance for indicated times.

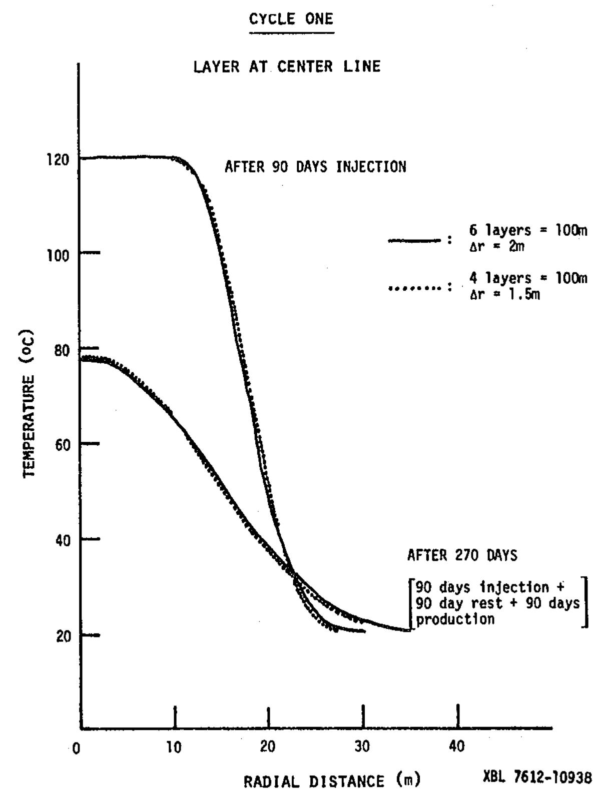

Figure 9. Effect of mesh size on calculated temperature.

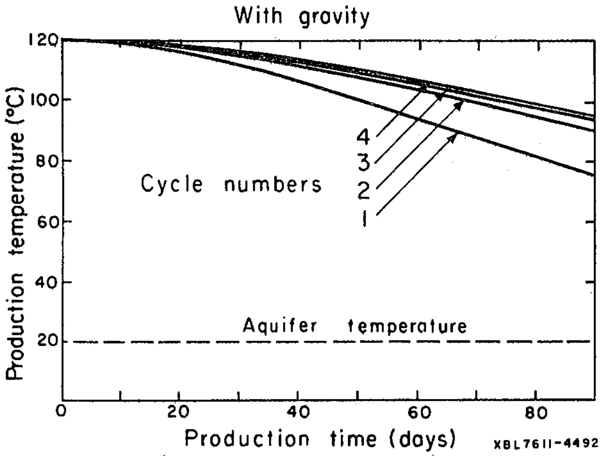

Figure 10. Temperature at the well versus production time for each cycle: full penetration case.

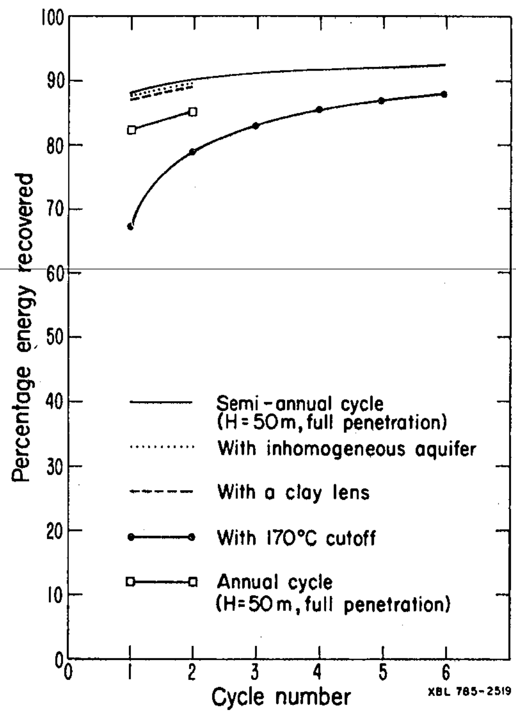

Figure 11. Energy recovered for different cycles.

FIRST CYCLE

Ti = 120°C

To = 20°C

Δr = 1.5m; 4 layers

Heat Loss Through Boundaries in One Complete Cycle	= 7.67 x 10^7 Joules
Total Energy Injected	= 3.97 x 10^{13} Joules
Total Energy Recovered	= 3.50 x 10^{13} Joules

Figure 12. Energy balance for first cycle. Note that energy lost through boundaries is negligible.

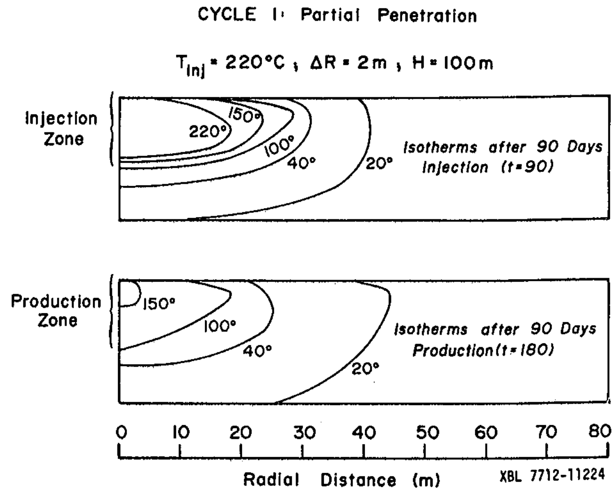

Figure 13. Isotherms for partial penetration after 90-day injection and production periods (Cycle 1).

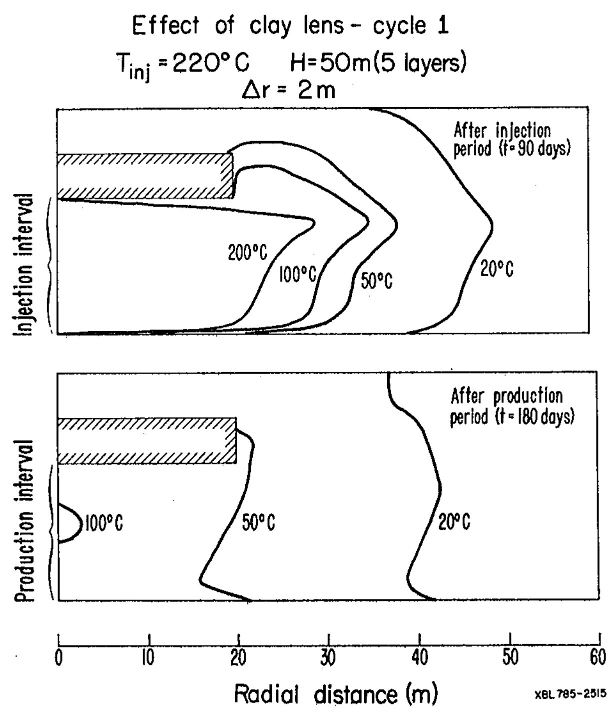

Figure 14. Effect of a clay lens (Cycle 1): 90 day production and injection periods.

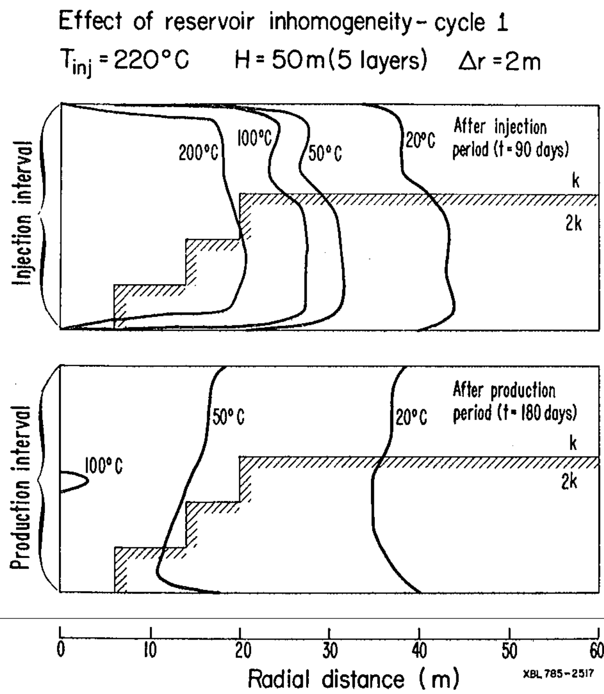

Figure 15. Effect of reservoir inhomogeneity (Cycle 1): 90 day production and injection periods.

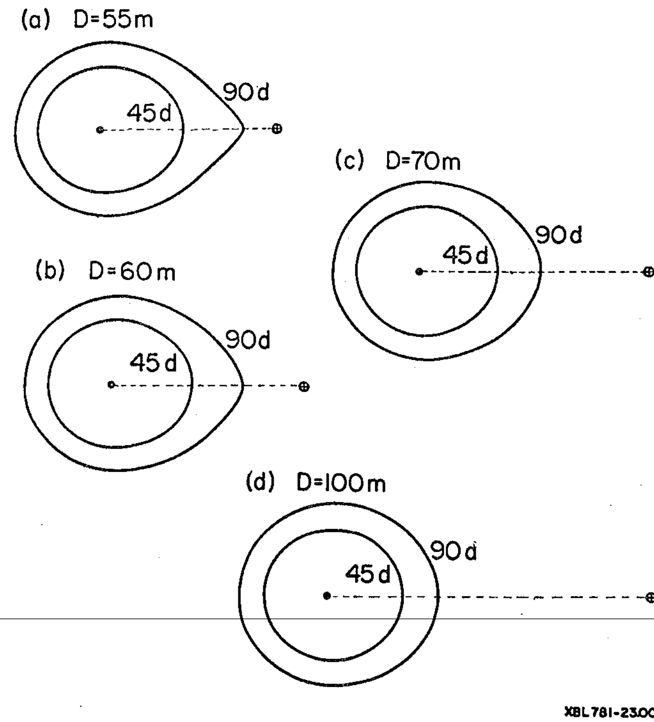

Figure 17. Effect of separation distance between storage and supplying wells at 45 and 90 days.

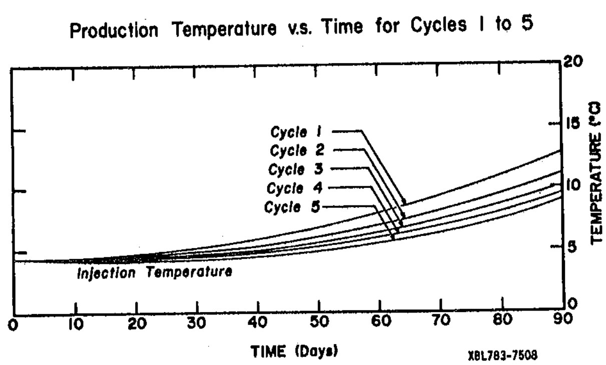

Figure 16. Chilled water storage: temperature at the well versus production time for five cycles.

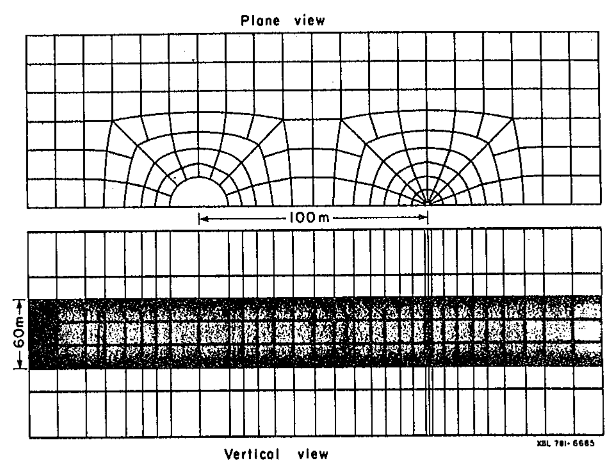

Figure 18. CCC doublet: mesh design.

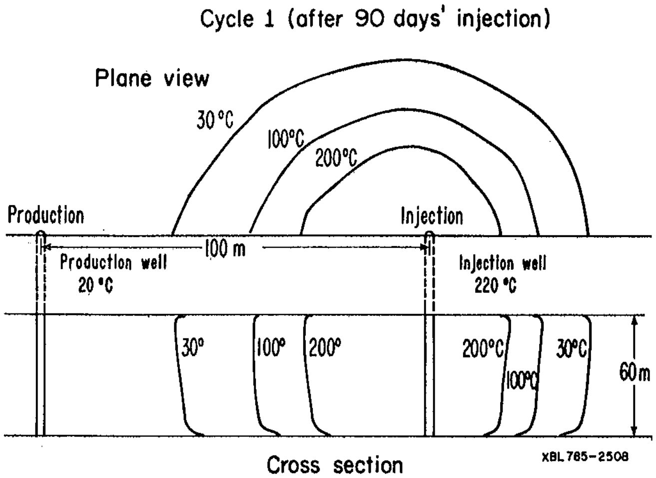

Figure 19. Isotherms for a two-well system after 90 days of injection. Plane and cross section views.

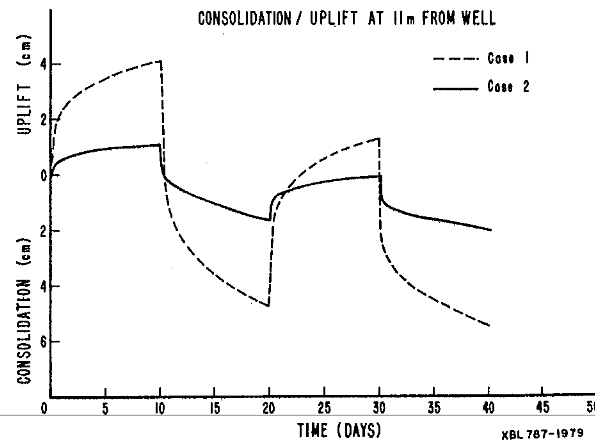

Figure 21. CCC Consolidation/Uplift: Case 2 has C_s and C_c values 1/5 of Case 1. (C_s and C_c are slopes of void ratio versus the logarithm of effective stress corresponding to recompression and virgin curves, respectively.)

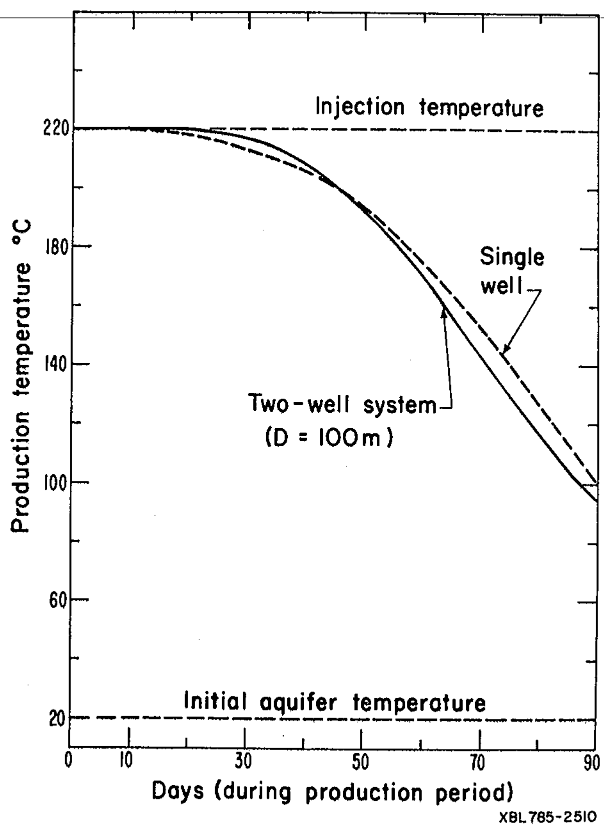

Figure 20. Production temperature during production period for a two-well system and the corresponding single-well case.

CONFINED AQUIFER EXPERIMENT - HEAT STORAGE

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INTRODUCTION

The possibility of using confined aquifers (saline or fresh) as natural containers for fluids such as gas, fresh water or a water-based solution has been considered seriously for the past decade [Esmail and Kimbler, 1967; Katz and Tek, 1970; Kimbler, 1970; Kumar and Kimbler, 1970; Moulder, 1970; Kazmann, 1971, 1974; Kazmann, Kimbler and Whitehead, 1974; Smith and Hanor, 1975]. More recently, however, much attention has been focused on the use of aquifers as temporary storage reservoirs for thermal energy in the form of moderate to high temperature water (140°F - 400°F; 60°C - 204°C) [Meyer and Todd, 1973; Hausz and Meyer, 1975; Meyer, 1976; Molz et al., 1976; Warman, Molz and Jones, 1976; Molz and Bell, 1977).

Studies of the Heat Storage Well Concept by the General Electric Company [Meyer, 1976] have as their interrelated principal objectives the conservation of large amounts of heat now wasted in generating electricity and the reduction of thermal pollution caused by discharge of this waste heat. Others have considered the possibility of using aquifer storage of heated or cooled water in conjunction with very large solar energy systems [Martin, Harris and Davidson, 1975]. The Heat Storage Well concept appears to make large-scale total-energy systems feasible. According to Meyer (1976), "Some 600 small total-energy systems are now in operation in the United States, but their total electrical generating capacity is only 0.4 percent of the national total. The technological innovation needed to make large-scale total-energy systems feasible is a means for storing large amounts of high-temperature water or steam for long periods of time--several months--at low cost and low loss. With such storage technology available, large thermal electric generating systems could produce high-temperature water as a joint product with electricity; storage of heated water makes possible the matching of electrical generation, which must instantaneously satisfy the demand for electricity, with the demand for heat."

Development of an adequate understanding of the hydraulics, heat transfer and geochemistry of Heat Storage Wells is essential if the concept is to be applied successfully. Therefore, in the seventies, the U.S. Geological Survey initiated an effort to develop a series of sophisticated mathematical models for describing the time-dependent transport of water and heat in a ground water system [Appel and Bredehoeft, 1976; Mercer et al., 1975]. In parallel with the modeling effort was an experimental study conducted by Auburn University. Funding for the experimental work was provided by the U.S. Geological Survey and the Energy Research and Development Administration. The objectives of the experimental program were to begin actual testing of the Heat Storage Well concept and to provide data for calibration of mathematical models. Since September, 1977, continuing experiments have been supported by the Department of Energy.

PROJECT DESCRIPTIONS

The initial research program started in June, 1975, and was composed of four phases. Phase I consisted of the drilling of an exploratory well at the selected field site by the Alabama Power Company. Phase II involved the construction of the central injection well, three observation wells, and the performance of preliminary pumping tests. Phase III was devoted to the construction of the remainder of the observation well field, performance of final pumping tests, and the measurement of aquifer thermal properties; while Phase IV was devoted to a cycle of warm-water injection, storage, and recovery.

The test facility was constructed in a soil borrow area at the Barry Steam Plant of the Alabama Power Company in northeastern Mobile County, Alabama. Warm water was obtained from the discharge canal for the condenser cooling water and pumped through a 3000 ft (914.4 M) pipeline to the injection well (Fig. 1).

At the end of Phase III, construction of the well field shown in Figure 2 was completed. The well field consists of an inner grouping of 10 observation wells (wells 1 through 10) and an outer grouping of 3 boundary wells (wells 12 through 14). All of this surrounds the central injection-production well, which extends 30 feet (9.14 M) into the storage aquifer. In addition, there is an observation well (well 11) that is screened just above the upper confining layer. Thermistors were positioned in the wells so that ground-water temperatures could be recorded at six depths in wells 1 through 10, at the top of the stiff clay in well 11, and near the middle of the bottom sand formation in wells 12 through 14. Wells 1 through 10 were located in the intended storage area, and hot water did not extend beyond well 10. The purpose of wells 12 through 14 was to record conditions at what is arbitrarily called the boundary of the system. Readings at these wells were intended to serve as boundary conditions for any mathematical models that might be tested. Hydraulic heads were recorded in all wells except the injection-production well.

The initial research program described briefly above was completed during the fall of 1976.

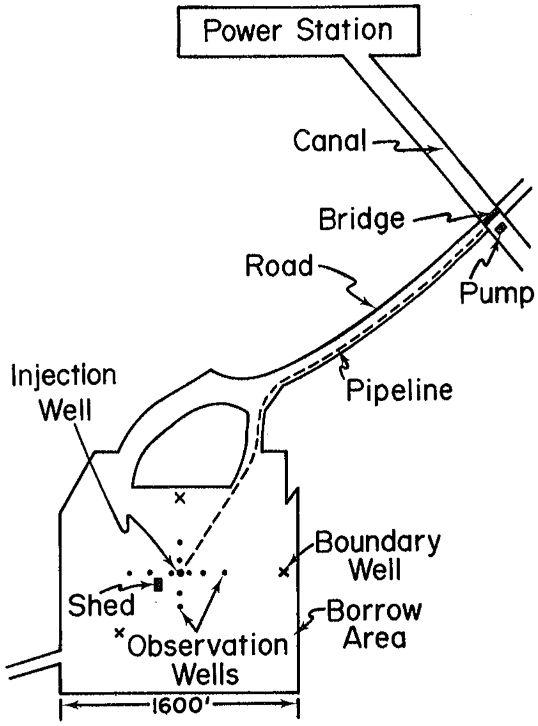

Fig. 1. Schematic diagram showing the details of the project site near Mobile, Alabama. In the present phase of the experiment, the pump in the canal is no longer used, and the pipeline is used only to dispose of warm water removed from aquifer storage.

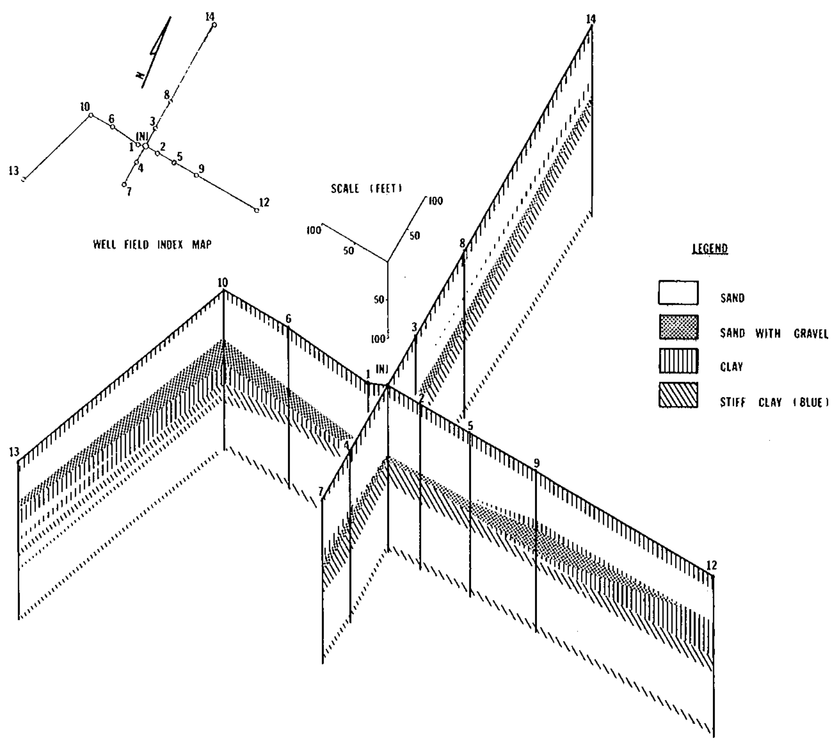

Fig. 2. Fence diagram of the well field penetrating the storage formation. The wells are screened in the bottom sand below the clay layers which serve to confine the aquifer. Temperatures are recorded at six equally-spaced depths in each of wells 1-10.

Ultimately, it involved storage of approximated 2×10^6 gal. of heated water for 36.6 days. A detailed description of the experiment, including a computer simulation, is given by Molz, Warman and Jones, 1978, and Papadopulos and Larson, 1978.

Using essentially the same well field as described previously, a second set of experiments were started on March 17, 1978. This set of experiments is still underway and consists of two injection-storage-recovery cycles. Six months will be devoted to the first cycle and 3 months to the second. The second set of experiments involves larger volumes of hotter water. Water from an aquifer above the storage formation (Fig. 3) is pumped through an oil-fired boiler which heats the water from 20°C to approximately 55°C. The heated water is then injected into the storage formation for later recovery. At the writing of this note, approximately 7 million gallons of water have been recovered after a 48-day storage of 14 million gallons. The temperature of the recovered water varied from 56°C at the beginning of recovery to 44°C at the present time (8/14/78).

Loss of permeability during injection has been observed with the second set of experiments, although the loss was not nearly as severe as with the first set. The permeability decrease appears to be due to clay particle swelling, dispersion, and migration in the storage formation. Migrating particles gradually clog the pores, and this leads to permeability loss. This loss was controlled during the 80-day injection period by surging the injection pump and by pumping water out of the formation for short periods of time.

Another important observation was that some type of convection or mixing in the observation wells caused erroneous temperature readings. This was corrected early in the experiment by backfilling the wells with coarse sand. At the present time, the temperature and hydraulic head data, which have been collected, are still being studied.

GENERAL OBSERVATIONS AND CONCLUSIONS

1. In selecting a site for a heat storage well, care must be taken to ascertain that natural movement of the ground water is very small. If a sufficiently large pore velocity exists, the site will be unacceptable unless the gradient is controlled artificially [Molz and Bell, 1977; Whitehead and Langhetee, 1978].

2. Long operation of a heat storage well will require use of heated water with extremely low suspended solids. (A hundred million gallons (3.785×10^8L) of water with suspended solids of one part per million contains 836 lbs (379 kg) of suspended material.) It is likely that clogging will be one of the most serious problems

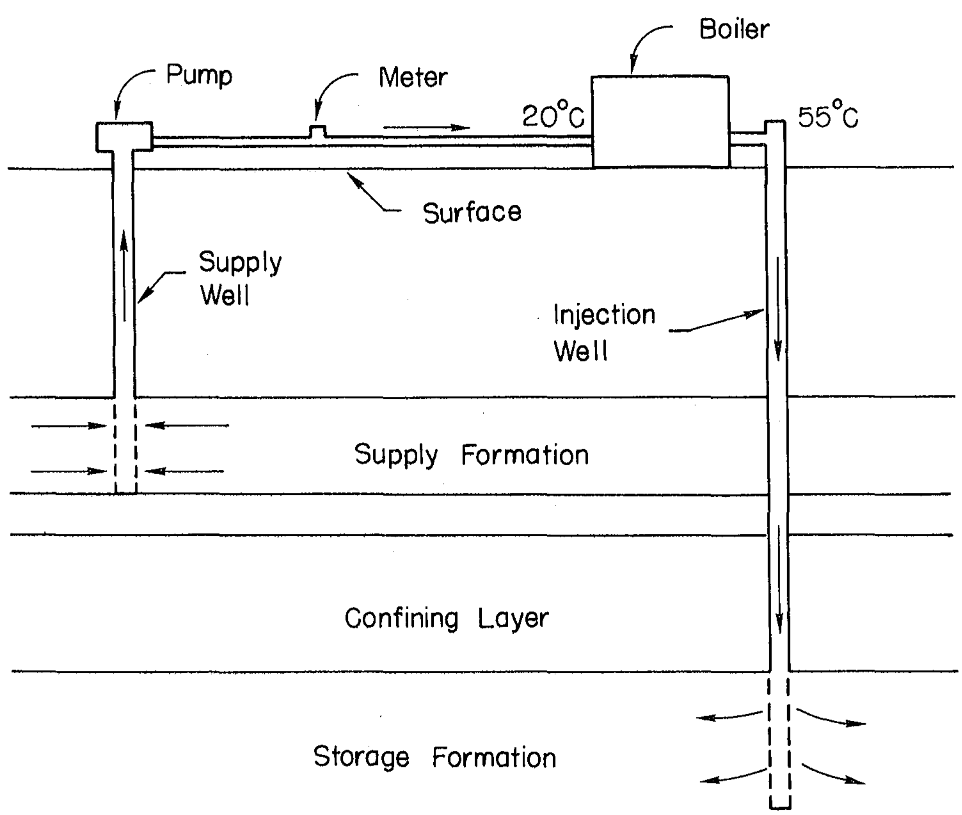

Fig. 3. Diagram showing how water is presently obtained from a shallow aquifer, pumped through a boiler for heating purposes, and injected into the storage formation.

concerning the intermediate to long-term operation of heat storage wells.

3. If a storage aquifer contains even small amounts of clay, one must not inject a fluid that will cause the clay fraction to swell. The pH and ion content of the water must be compatible with the particular clay mineral. Exposure to distilled water can cause clays to swell and disperse [Mitchell, 1976]. Also, the injected water must not precipitate any chemical compounds in the storage aquifer or onto the aquifer matrix or dissolve the matrix material.

4. Care must be taken not to create hydraulic conditions capable of causing the failure of a confining stratum if a confined aquifer is to be used for storage purposes. It may be that high-temperature water will weaken aquitard materials or or increase their permeability. The effect of temperatures in the 140 to 400°F (60 to 204°C) range on mechanical and hydraulic properties of aquitard materials should be studied.

5. Considering the relatively small injection volume and a partially penetrating injection well, the thermal recovery factor of 0.68 obtained in the first set of experiments is considered encouraging. Simulation studies [Papadopulos and Larson, 1977] predict high recovery factors for storage wells involving hundreds of millions of gallons of heated water.

6. Anomalous cooling effects can lead to errors in observation wells intended to measure ground water temperatures. The effects appear to be due to mixing between the hotter water in the lower portion of the well penetrating the storage formation and the cooler water in the casing above the formation. The problem can be eliminated by backfilling the well with porous material.

7. One procedure for minimizing the possibility of chemical or mechanical clogging of an injection well is to use formation water as an influent to the heating system. Ground water tends to be low in suspended solids, and the main difference between the injected water and the native water will be temperature.

8. In order to further develop the heat storage well concept, additional experimental studies are needed involving larger volumes of water and higher injection temperatures. The geochemistry-colloid chemistry problem must be studied carefully, and the effect of high temperatures on the mechanical and hydrualic properties of clay confining layers must be determined.

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THERMAL STORAGE OF COLD WATER IN GROUNDWATER AQUIFERS FOR COOLING PURPOSES

by

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SUMMARY

Objective

Design, develop and demonstrate a working prototype system in which water is pumped from an aquifer at 70°F in the winter time, chilled to a temperature of less than 50°F, injected into a groundwater aquifer, stored for a period of several months, pumped back to the surface in the summer time, and used to air condition buildings.

Scope

In Texas, about one-third of the residential energy load is used for air conditioning. During the winter, the mean Texas temperature has varied from 44°F in 1963-64 to 53°F in 1951-52. In the Bryan-College Station, Texas area, the temperature is below 50°F approximately 50 percent of the time from November through March. If the "cold" during this winter period could be collected and stored, it could be used for air conditioning purposes during the summer. Because it is clean, renewable and safe, the use of the winter's cold to air condition homes and businesses is a glamorous alternative energy source which should be explored.

To obtain sufficient quantities of thermal energy for air conditioning, large quantities of cold water must be generated during the winter and stored for several months. A natural water storage system exists in the form of groundwater aquifers under 80 percent of the land in Texas. Surface water has been injected, stored and recovered from groundwater aquifers for years; so the concept is technically sound. The question which needs to be answered is, "how much of the thermal energy stored in an aquifer can be recovered?"

This research will demonstrate the technical and economic feasibility of storing cold water in groundwater aquifers. A system consisting of a cooling pond, two wells and a network of observation wells will be constructed on the Texas A&M University Plantation Farm. The aquifer is the floodplain alluvium along the Brazos River. Wells 60 feet deep with water levels of only 20 feet and capable of pumping 400 to 600 gpm can be obtained. This system, when proven, could have an impact on all newly constructed air conditioning systems in Texas.

Although not proposed as a part of this study, aquifer storage of hot water during the summer for heating purposes during the winter is also possible with this system. Hot water storage using this system will be demonstrated at a later date.

INTRODUCTION

The energy crisis in the world has caused much attention to be focused on alternative energy sources. One of these alternative sources is the production and storage of cold water during the winter time for use in air conditioning buildings during the summer time. A major problem with this concept is finding a facility in which to store the collected cold water for several months until it is needed for air conditioning. One available storage facility is groundwater reservoirs, which are naturally insulated and have enormous storage volumes.

In this study, a concept for utilizing the winter's cold for air conditioning during the summer is proposed. Groundwater from a shallow aquifer (water temperature = 70°F) will be pumped from a well (Well A) to a cooling pond during the winter. When wet bulb temperatures drop below 50°F, the water will be pumped through a spray system and chilled to the wet bulb temperature. After chilling the water will be pumped to a nearby injection well (Well B), injected into the shallow aquifer, and stored until the summer time. During the summer, the cold water will be pumped from Well B and used in a heat exchange process to air condition buildings. After the heat exchange process, the water (warmed from the heat exchange process) will be returned to Well A and injected back into the aquifer.

Several design problems and environmental problems must be evaluated before the cold water storage system can be widely adopted. Potential heat losses from the aquifer and well must be evaluated. The general public will want any environmental problems adequately documented. To efficiently operate systems of cold water storage in aquifers over long periods of time, groundwater models are needed to predict the movement of water in aquifers, and the resulting temperature profiles. Several numerical models have been developed (California, Kansas, Texas and the U.S. Geological Survey) for analyzing heat transfer in aquifer systems. All of these models are theoretical, and very little field information is available with which to verify them. Data for designing and interfacing a cooling pond with an injection well is also needed.

Most of the heat losses in the proposed cold water storage system will occur during initial injection and recovery cycles. The native groundwater and rocks must be cooled to the injection water temperature. From preliminary heat transfer models of the system, this can probably be accomplished within three to five injection cycles. After this initial heat loss, approximately 85 percent of the injected cold water can be recovered at temperatures of 50°F or less. Most of the

15 percent heat loss occurs by conduction across the top and bottom of the aquifer. These losses will decrease with time, but no long term studies to evaluate the degree of reduction have been made.

Injected cold water will have different physical properties from those of the natural groundwater. Cold water will be more dense and viscous than the warmer groundwater. These differences will cause the cold water to go to the bottom of the formation and displace the native groundwater from the bottom of the aquifer upward in a wedge shape. In addition, the nonhomogeneous nature of the aquifer will cause "fingering" along the contact zone between the warm and cold water. Problems created by differences in fluid density and viscosity need to be carefully studied and their impact on the injection-pumping cycles and the efficiency of cold water recovery carefully evaluated.

A field study of the concept of storing cold water in aquifers for later use to air condition buildings is vitally needed. With such a study, the efficiency of storing cold water in groundwater aquifers can be evaluated. Cycles of injecting cold water, storing it underground for periods of several months, and then pumping the cold water to the surface must be studied to determine how much of the injected "cold" can be economically recovered. The collected field data can be used to verify available numerical models of the system. Using verified models, the effects of system parameters such as aquifer thickness, aquifer porosity and permeability, injection rates, length of injection and pumping cycles, nonhomogeneous nature of aquifers, temperature of injected water, confined versus unconfined aquifer systems, other geohydrological properties, and economics can be evaluated.

Research Objectives

The specific research objectives for this project are the following:

(1) Design, construct, and operate a cooling pond to chill water from 70°F to less than 50°F and evaluate the operation of the cooling pond when interfaced with an injection well,

(2) Evaluate in detail the transmissivity, storativity, heat transfer coefficients, and heat storage properties of a groundwater aquifer located near Texas A&M University in Burleson County, Texas,

(3) Perform a field test in which cold water produced by the cooling pond is injected into the aquifer, stored in the aquifer for several months, and then pumped out of the aquifer for air conditioning purposes, and

(4) Monitor the resulting water movement and temperature profiles in a system of observation wells, use the results to verify available numerical models, and evaluate the concept of storing cold water in groundwater aquifers during the winter time for use in air conditioning buildings during the summer time.

PROCEDURE

Research Location

We propose to use a site located on the Plantation Farm of Texas A&M University in Burleson County, Texas to test the concept of storing cold water from a cooling pond in groundwater aquifers. The site is about 10 miles west of the main campus of Texas A&M and is convenient for supervision by the A&M staff.

Hydrologic Conditions

Both Brazos and Burleson Counties are drained by the Brazos River and its tributaries. Several groundwater units underlay these counties. We are interested in using the shallowest of these units called the floodplain alluvium. These deposits exist extensively along the Brazos River. The floodplain alluvium rests unconformably on the eroded bedrock surfaces of older formations and represents deposits laid down by the Brazos River and its tributaries in comparatively recent geologic time. Deposition of the floodplain alluvium resulted from meandering stream channels and overbank flows.

The alluvium is composed of fine to coarse, red to tan sand, gravel, silt and clay. In general, the finer grained material is above the coarse material. Gravel, whether mixed with sand or clean and well sorted, occurs mostly in the lower part of the alluvium. Gravel ranges from pea size or less to cobbles about 5 inches in diameter and from clean and well sorted to poorly sorted.

The depth of the floodplain alluvium reaches a maximum of about 85 feet and averages about 50 to 60 feet below land surface. Floodplain deposits yield small to large quantities of fresh to slightly saline water, mostly to irrigation wells along the Brazos River. Well yields, range from about 250 gpm to more than 1,000 gpm. About 50 percent of the wells probably yield between 250 and 500 gpm. A very large percentage of the groundwater used for irrigation in Brazos and Burleson Counties comes from the floodplain alluvium of the Brazos River.

The transmissivity of the floodplain alluvium which is under watertable conditions, is about 7,000 to 10,000 ft^2 per day. The storage coefficient is about 0.15. The depth to the water level in the floodplain alluvium varies from less than 10 to more than 30 feet. Most of the water levels are about 15 to 25 feet deep. The natural water temperature in this aquifer is about 65 to 70°F. The groundwater in the floodplain alluvium is in general not of a good quality. The water is high in sodium, calcium, chloride and iron.

Research Design

We have constructed a cooling pond of approximately 5,000 ft^2 in area to produce an average of 100 gpm of water at a temperature of 40 to 50°F over a period of approximately 5 months. Any time water of 50°F or colder exists in the pond, it will be injected into the aquifer and stored.

Two wells were drilled to operate the cooling system, one a water supply well and the second a cold water storage well. However, both wells are capable of being pumped and having water injected into them. Water is pumped from the aquifer, chilled in the spray pond, and injected into a cold water zone of the aquifer. During the summer, the cold water is recovered by pumping, circulated through a building for air conditioning purposes, and reinjected into the cool water zone of the aquifer.

Twelve observation wells will be drilled around the two wells. These observation wells will be used to monitor water levels and temperature profiles in the aquifer. With this system of wells and the cooling pond, the utility of storing cold water in groundwater aquifers can be evaluated. The water movement and temperatures can be determined and available numerical models of the system evaluated. The heat recovery efficiency of the system can also be evaluated. We propose that this system be studied for at least a period of three years. Calculations indicate that the heat recovery efficiency improves with each injection-pumping cycle up to three to five cycles. The reason for this is that some of the "cold" injected in the first cycle is used to cool the aquifer rock material.

Records of the volume and temperature of water injected and pumped from both the cold and cool wells will be kept. These data will be used to evaluate the heat recovery efficiency of the system. Periodic water level measurements will be made in the observation wells to determine the rate and direction of water movement. Also, water temperature profiles in each of the observation wells will be maintained to evaluate heat movement in the aquifer and locate the sources of heat losses.

When drilling the observation wells, formation samples were taken every 2 feet of depth. In addition, the formation samples were supplemented by taking some cores from throughout the section. Laboratory determinations of porosity, specific yield, permeability, heat transfer coefficient, and heat storage properties are being determined from the cores and formation samples.

Prior to injecting any cold water, a long term pumping and recovery test will be conducted to evaluate the permeability and storage coefficient of the floodplain alluvium. These data will be useful as inputs into the numerical models describing heat and mass transfer. In addition, they will be useful in explaining and interpreting the water movement and water temperature data when injection is initiated.

Water temperature will be measured as a function of distance from the cold water injection well and depth below ground surface. Temperatures will be measured in each observation well using a temperature logging procedure.

Water at rates up to 200 gpm will be pumped from the production well to the cooling pond. The quantity of water pumped from the production well and its temperature will be recorded. Upon entering the cooling pond, the water will be circulated and cooled to a temperature below 50°F. When the water is sufficiently chilled, it will be injected into the cold water injection well. The quantity of water injected and its temperature will be recorded. The cooling and injection procedure will begin about the first part of October and continue through March. The system will be inactive from April through May. Starting on June 1, the cold water injection well will be pumped and the cold water recovered for air conditioning. The volume of cold water pumped and its temperature will be recorded. The warmer water from the air conditioner would then be injected down the production well and stored until the winter time. The volume of warm water injected and its temperature will also be recorded. The pumping of cold water for air conditioning and injection of warm water would continue until the first of October.

The collected data on the volumes and temperatures of the water pumped and injected at each of the two wells along with the water temperature profiles and water level data collected at each of the eleven observation wells will allow an evaluation to be made of the efficiency and economics of storing the winter's cold in groundwater aquifer. In addition these data will provide an excellent opportunity to verify several existing numerical models of heat and mass transfer in groundwater aquifers.

Since preliminary calculations indicate that three to five injection and pumping cycles are needed to achieve optimum efficiency, it is proposed that this study be conducted for 3 years. This time period will also allow for some statistical variation of weather data to evaluate the overall long-term efficiency of the system.

Immediate benefits of this project would be the establishment of a viable method for long-term storage of winter cold for small air conditioning requirements, such as single family residences. The project would demonstrate the concept in its entirety. It would also provide the opportunity to test the entire system and locate system interface problems. The project could also be used as a demonstration for possible users to visit and see first hand the potential of the cold water storage concept.

REPORT OF PROGRESS

The detailed design of the cooling pond was initiated in early September of 1977 and completed by mid-October of 1977. The excavation of the pond was accomplished in November of 1977. The pond liner was designed and ordered in September of 1977 and was received in November of 1977. The liner was placed in the pond in early December of 1977. Construction of the water spray system was initiated in mid-December of 1977. However, due to the severe winter (the coldest on record) in the College Station area, very little work was done on the spray system during January and February of 1978. Good weather during March allowed the construction of the spray system to be completed.

The designing, drilling and equipping of the the production and injection wells is 80 percent completed. In September of 1977, meetings were held with Department Heads and Administrators at Texas A&M to select some potential sites for the experiment. Two sites were tentatively selected. These areas were mapped and geologic, hydrologic and space limitation evaluated. A site was selected in late September near a major highway with sufficient space for the well installations. It was desirable to drill some test wells in the area and run some logs before finalizing the site selection. A well driller was contracted in late September, and the test wells were drilled in late October. Results from the test wells were very encouraging. A thick clay existed from 0 to about 38 ft, a fine sand from 38 to 42 ft, and an excellent gravel from 42 to 55 ft. Beneath the gravel was a very tight blue shale. Using the logging information and sieve analysis from the formation sand samples, a well design was finalized by the latter part of November. A meeting with personnel of well drilling companies in Houston resulted in an estimated well drilling cost of $275 per foot. This was slightly over twice the amount allocated in our budget for well drilling. A decision was made at that time for us to become the primary well drilling contractor. In December, we placed orders directly with well casing and well screen companies to obtain bids. A fiberglass screen and casing were selected and ordered in January. Because it was made to our specifications, some delays were experienced in constructing the well screen and casing. They were not delivered to us until the latter part of March 1978.

A local well driller was contacted in December about drilling the wells using a reverse circulation rig. It is the only reverse circulation rig in this area. In March, we drilled, set and grouted in the surface casing to a depth of 18 ft below land surface. We are presently waiting for the well driller to move his drilling rig to the site, drill the wells out from 18 to 55 ft, set the screen and casing, place the gravel pack, develop the well, and perform a pumping test. Once the well driller arrives, it will probably take about 3 to 4 days to complete the wells.

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AIR CONDITIONING KENNEDY AIRPORT WITH WINTER COLD

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INTRODUCTION

A feasibility study is underway for a possible conversion of the air conditioning system of the J. F. Kennedy International Airport (JFK) in New York City from a conventional refrigeration machine system to a system using winter cold stored as cold water in an aquifer under the airport. The stored water would be chilled by either winter air or near freezing Jamaica Bay water, and would be used during the following summer to air condition the airline terminal buildings. To put the scale of the air conditioning load in perspective, it is enough to centrally air condition every home in a city of 25,000 population.

Desert Reclamation Industries (DRI) proposed the conversion and has been sponsored by the Department of Energy since October 1977. The Port Authority of New York and New Jersey is providing the study site, relevant data, and miscellaneous services.

Figure 1 illustrates how the system would work using cooling towers for winter cold capture.

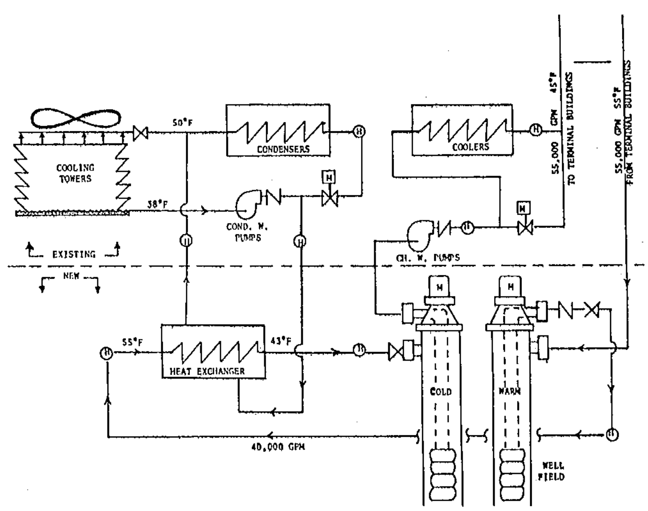

Figure 1. Schematic Diagram: Cold from Cooling Towers.

As presented in this paper, work on the feasibility study, Phase I of a four phase conversion plan, divides logically into the following parts:

- Natural Resource Studies
  - Geohydrologic
  - Atmospheric
  - Oceanic
- Engineering Studies
  - Sensitivity Analysis
  - Preliminary Design
- Economic Studies
  - Investment
  - Operating Cost

NATURAL RESOURCES

Geohydrologic

Based on interpolated data, the aquifer under JFK Airport holds promise for storing all the chilled water needed for only the cost of well pumping and capturing the free winter cold.

The hydrology of Long Island is among the most extensively and intensively studied in the world. More than 50,000 wells supply water to most of the island. Since the ambient temperature of the aquifer is 56°F there should be little objection to storing water at 43°F.

However, there is a paucity of data on the aquifer under JFK. Figure 2, showing the geologic information available along the northern boundary of the JFK Airport, illustrates the information available outside, but close to, the JFK site.

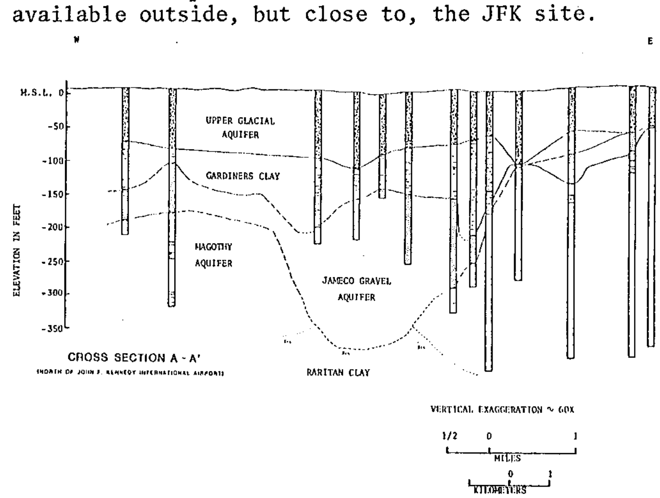

Figure 2. Cross Section A-A' (North of John F. Kennedy International Airport)

Figure 2 shows the profile of the storage aquifers, Jameco and Magothy, and the aquitards which seal the top and bottom of the aquifers, Gardiners and Raritan Clays. The location of the cross section A-A' in Figure 2 is shown on Figure 3.

It is apparent from the wide range of published aquifer parameters that the number of wells and pumping rates per well could vary at least several fold over the range of uncertainty which exists at JFK. A test well drilling program is planned in the near future to reduce this high

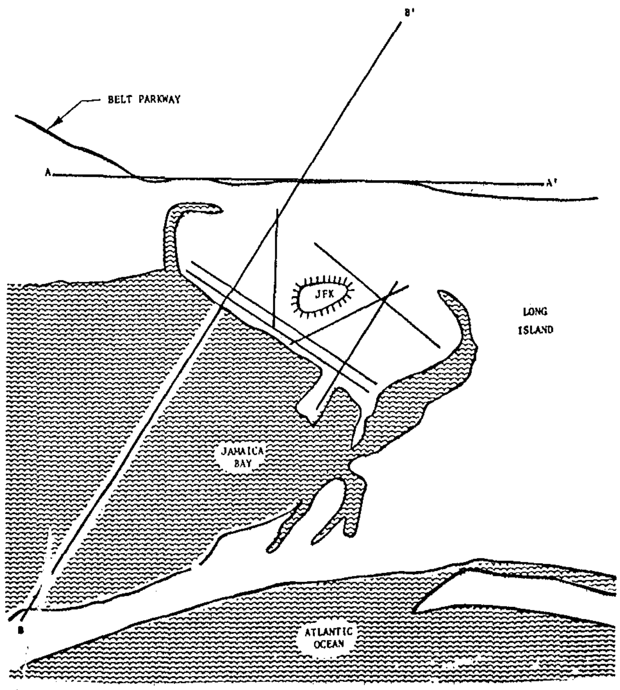

Figure 3. Location of the Profile Cross-Section A-A' and B-B'.

degree of uncertainty. Table 1 lists the aquifer parameters according to the information available.

Table 1. Aquifer Parameters Selected as Typical of Parking Oval Area at JFK Airport, for Use in Analytical Model

Parameter	Jameco Fm.	Magothy Fm.
Elevation of top of formation (FT. above M.S.L.)	-200.	-350.
Elevation of bottom of formation (FT. above M.S.L.)	-350.	-400.
Thickness (FT.)	150. ±100	50. ±200
Horizontal hydraulic conductivity (GPD/FT^2)	1000. +2000 - 500	+400 -200
Transmissability (GPD/FT.)	150,000.	20,000.
Storage coefficient	1.0×10^{-4}	
Hantush's Leakage Factor, B (FT.)	5,000.	
Static Piezometric Head (FT. above M.S.L.)	-5.0	
Land Surface Elevation (FT. above M.S.L.)	+10.	

Atmospheric

There is an abundance of free cold in the air at JFK in the winter. Three ways of capturing this cold are being considered: in cooling towers, in dry coolers, and in cooling ponds. The first two depend solely on air temperatures; cooling towers on wet bulb temperatures, and dry coolers on dry bulb temperatures.

Figure 4 shows the average dry bulb and wet bulb temperatures at JFK. It also shows the number of days during which dry coolers and cooling towers can be operated at or below the temperature determined by engineering considerations.

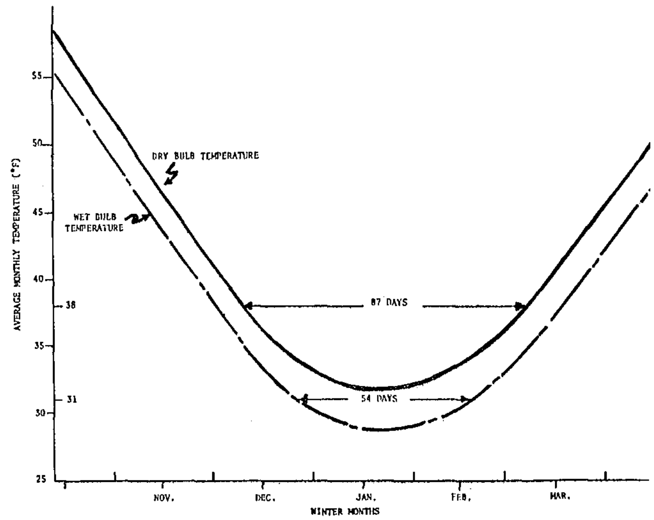

Figure 4. Average Air Temperature at John F. Kennedy International Airport.

Cooling pond operation depends upon a complex relationship of about 10 parameters. Use of cooling ponds has been eliminated because of space limitations at JFK and the hazard to aircraft from attracting birds and creating fog.

Oceanic

JFK is surrounded on virtually three sides by Jamaica Bay. JFK is at the head of the bay which extends for 12 miles behind barrier beaches to its only connection with the sea. Jamaica Bay is, in effect, a giant cooling pond with the complications of tidal flows and a variety of warm inflows, but with the advantage of a freezing point depressed to 28°F by salty sea water.

There is a paucity of data on Jamaica Bay winter temperatures. A seven year record of continuously recorded temperatures from the Long Island Lighting Company for the inlet cooling water to their power plant on Jamaica Bay is shown on Figure 5 as an average for the seven years. The data have been corrected several degrees for known recycling of warm discharge.

Selection of a site on Jamaica Bay for a possible pump station will be influenced by both man-made and natural variations in Jamaica Bay water temperatures at different locations around JFK. Figure 6 shows temperatures at several places taken the same day. Critical uncertainties remain which need further analysis by a computer model such as the estuarine model with 7 parameters developed by the MIT Parsons Water Resources Laboratory.

ENGINEERING

Sensitivity Analysis

Neither Jamaica Bay water nor cooling tower

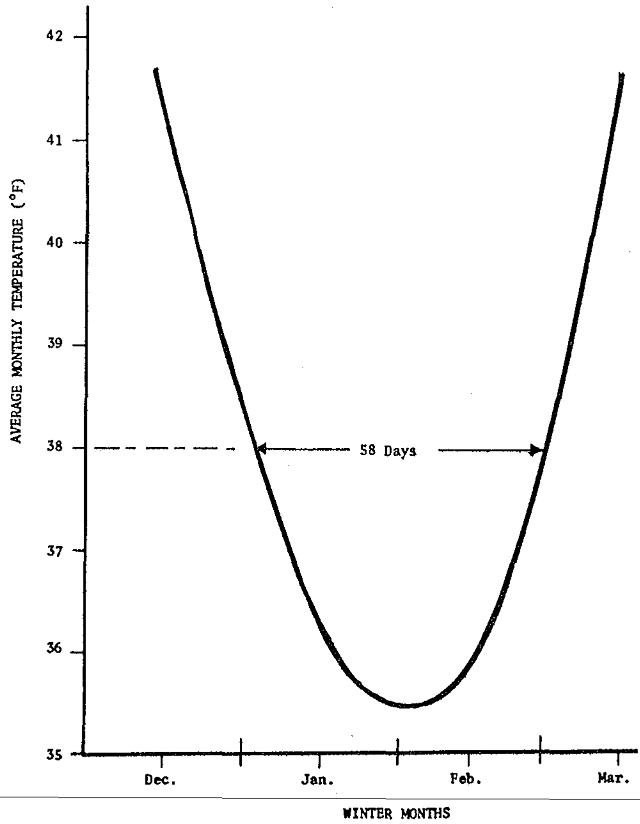

Figure 5. Average Jamaica Bay Temperatures near J. F. Kennedy International Airport.

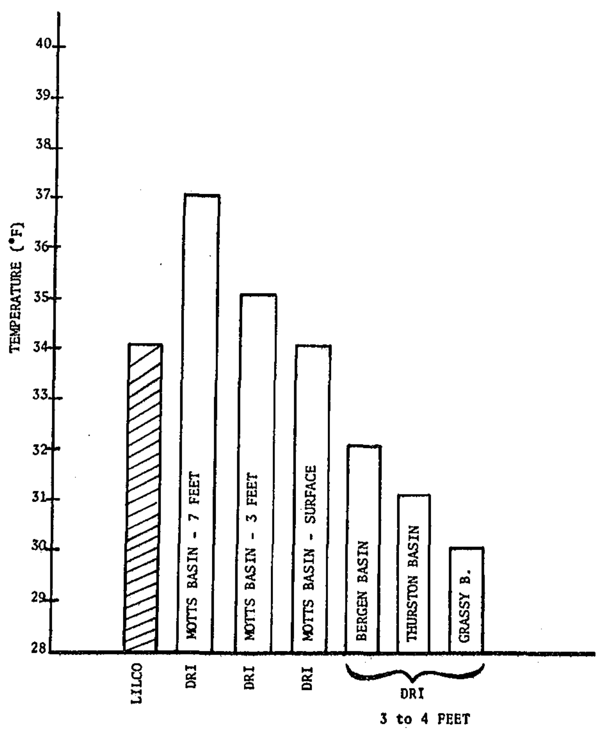

Figure 6. Jamaica Bay Temperatures, February 3, 1978.

water are clear enough to store in wells without clogging the wells. Thus a heat exchanger between either cold source and well water is necessary on the input to storage side. Many air conditioning systems on Long Island operate without corrosion problems when circulating well water directly through air-water heat exchangers. However, in case corrosive well water is encountered at JFK, it would be desirable to use a heat exchanger between the well water and a non-corrosive chilled water circulating system such as already exists at JFK. Such a double heat exchanger system is shown in Figure 7.

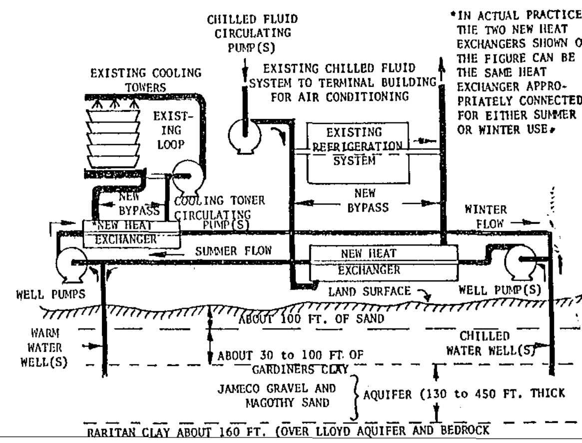

Figure 7. Schematic Diagram Showing Aquifers, Proposed Wells and Heat Exchange Systems at JFK Airport.

Using overall average daily temperatures, the second heat exchanger mentioned above may be ruled out as indicated by a sensitivity analysis on air and water temperatures as follows:

The airline terminals require a 45°F water. To produce 45°F water in a heat exchanger would require at least 40°F well water, which allowing for 2°F loss in storage and piping requires charging 38°F water into the wells for storage. To produce 38°F well water requires exchange with cooling towers or Jamaica Bay water at least as cold as 33°F. This may not be possible for a long enough period, even though air temperatures extend below 33°F every year and Jamaica Bay occasionally freezes from shore to shore, because heat exchanger surface becomes prohibitively large long before 33°F is reached, as illustrated by the sensitivity curve shown on Figure 8.

However, nighttime air temperatures are usually significantly colder than daytime air temperatures. A similar analysis will be made using average nighttime temperatures. Other possible solutions exist: (1) Store excess cold from the coldest years to make up for the warmest years; (2) Make up the difference with the existing JFK air conditioning system.

The second most sensitive factor is aquifer characteristics. The number of wells needed is directly related to aquifer transmissivity. Transmissivity is the product of the hydraulic

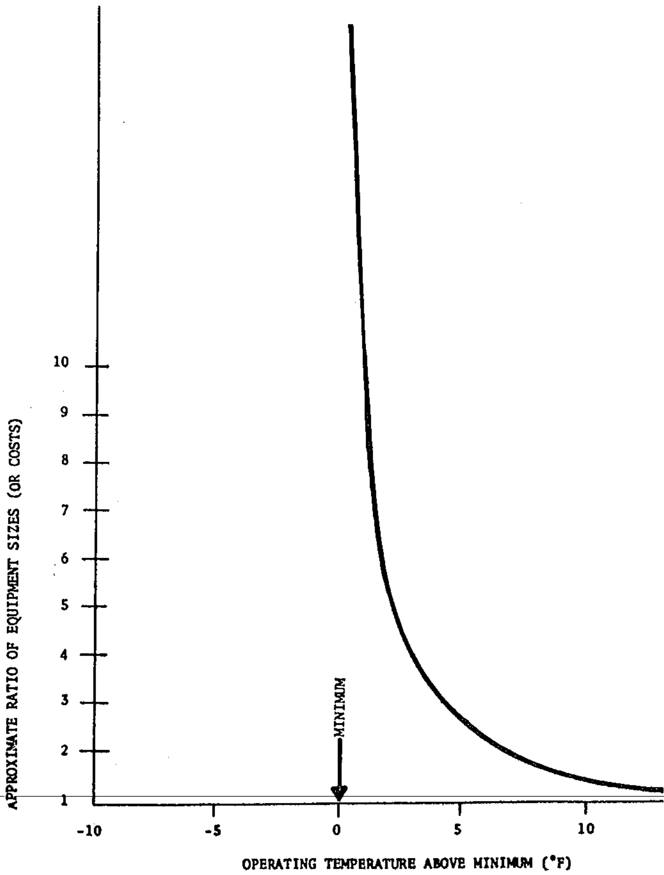

Figure 8. Temperature Sensitivity Analysis.

conductivity and the aquifer thickness. Neither of these two parameters are known for the JFK site. Hydraulic conductivity varies over ten fold throughout the Jameco and Magothy aquifers as a whole. Similarly the thickness of both the Jameco and Magothy vary from near zero to around 300 feet within a few miles of the site. Based on these ranges, shown in Table 1, the number of wells needed is probably between 24 and 80.

The cost of lifting water from wells and of recharging wells is inversely related to both transmissivity and the number of wells.

It is planned to reduce the uncertainties regarding aquifer parameters by a test well program to be sponsored jointly by the New York State Energy Research Authority and the U.S. Department of Energy in the near future.

Design

Following the sensitivity analysis, flow sheets were established for three alternate designs: using cooling towers, dry coolers or Jamaica Bay water as cold sources. The flow sheets are shown on Figures 1, 9, and 10.

Individual items of equipment such as heat exchangers, cooling towers, piping, etc. were then sized and cost estimated using general industrial budget estimating methods. Specifications were written for each item and sent to vendors for competitive budget estimates.

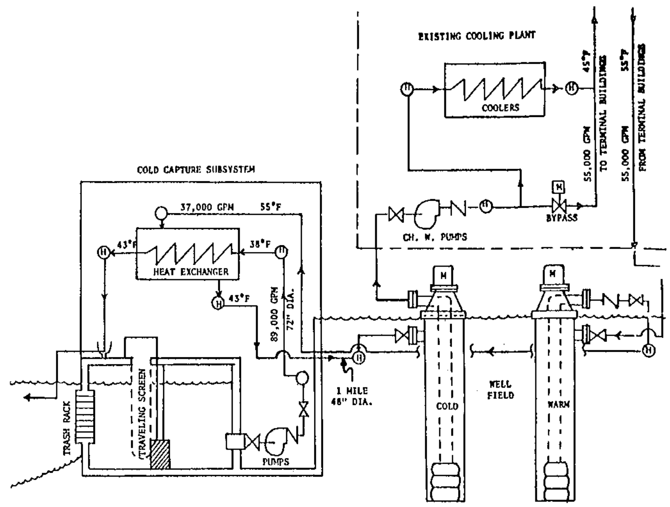

Figure 9. Schematic Diagram: Cold from Jamaica Bay.

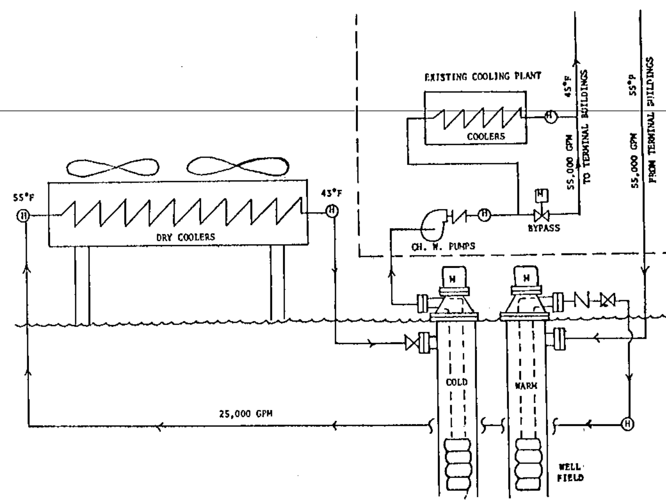

Figure 10. Schematic Diagram: Cold from Dry Coolers.

A well field was sized and laid out as shown on Figure 11. The piping network for connecting the wells was designed for a maximum velocity of 7 feet per second.

ECONOMICS

Investment

The total investment required for complete conversion of JFK to the new system, broken down into major items is shown on Table 2A and 2B. In view of uncertainties previously discussed, investments on a high, low, and most probable (target) basis are shown.

All investment estimates are on an installed basis, including materials and labor. Piping costs include insulation with polyurethane foam.

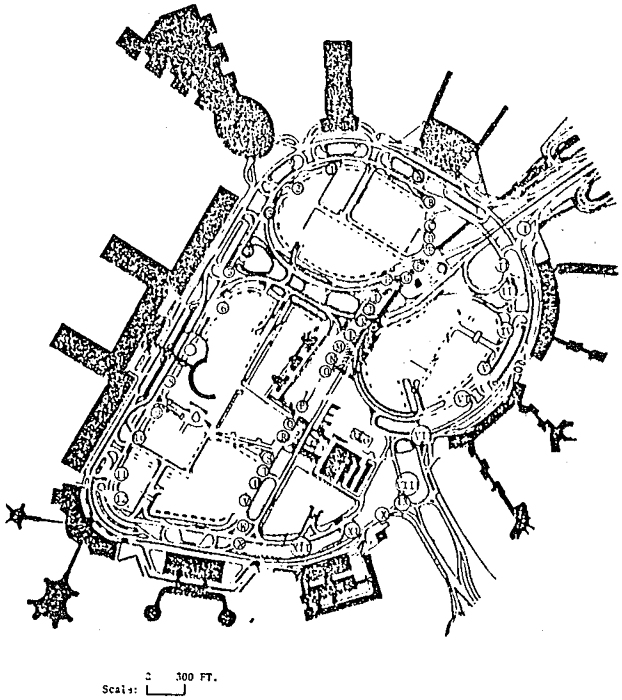

Figure 11. Preliminary Well Layout at JFK.

Table 2B. Investment Cost of Jamaica Bay Case.

	Cost in millions of $		
	High	Target	Low
Wells, including casing and screen	7.400	4.000	2.800
Well pumps and motors	.700	.300	.200
Well field piping and fittings	.820	.820	.820
Well field valves	.570	.570	.570
Subtotal	9.490	5.690	4.390
Shell and tube heat exchangers	1.500	.500	.200
Traveling screen	.080	.050	.040
Trash bars	.001	.001	.001
Pumps	.350	.350	.350
Concrete work	.500	.500	.500
Piping	.700	.700	.700
Subtotal	3.131	2.101	1.791
Total	12.621	7.791	(.181

Table 2A. Investment Cost of Cooling Tower Case.

	Cost in millions of $		
	High	Target	Low
Wells, including casing and screen	7.400	4.000	2.800
Well pumps and motors	.700	.300	.200
Well field piping and fittings	.820	.820	.820
Well field valves	.570	.570	.570
Subtotal	9.490	5.690	4.390
Shell and tube heat exchangers	1.500	.500	.200
Additional cooling towers	3.300	3.300	3.300
Total	14.290	9.490	7.890

The investment figures do not include contractor and engineering fees.

Operating Costs

Operating costs for both the cooling tower case and the Jamaica Bay case have been estimated for energy consumption only. The present electric rate is 4¢/KW Hour at JFK and is the basis of the operating costs shown on Table 3. For comparison, it is estimated that a conventional air conditioning system such as presently being used at JFK would consume about $1,300,000 per year of energy.

Economic Viability

A simplified cash flow analysis reflecting cumulative energy saved is shown for the cooling tower case on Figure 12, and for the Jamaica Bay case on Figure 13.

These cash flow cases assume that energy costs inflate at the rate of 7% each year.

Table 3. Annual Cost of Energy Required to Operate the JFK Aquifer System.

I. Cooling Tower Case		
Winter Cooling Tower Operation		$365,000
Winter Well Pumping		59,000
Winter Well Field Pumping		15,000
Summer Well Pumping		106,000
Summer Well Field Pumping		20,000
Summer Chilled Water Pumps		136,000
	Total	$701,000
II. Jamaica Bay Case		
Winter Bay Pumps		$ 81,000
Winter Well Pumps		49,000
Winter Well Field Pumping		13,000
Summer Well Pumping		106,000
Summer Well Field Pumping		20,000
Summer Chilled Water Pumps		136,000
	Total	$405,000

Note: 1) Assumes 60% efficiency for horizontal pumps
2) Assumes 70% efficience for vertical pumps

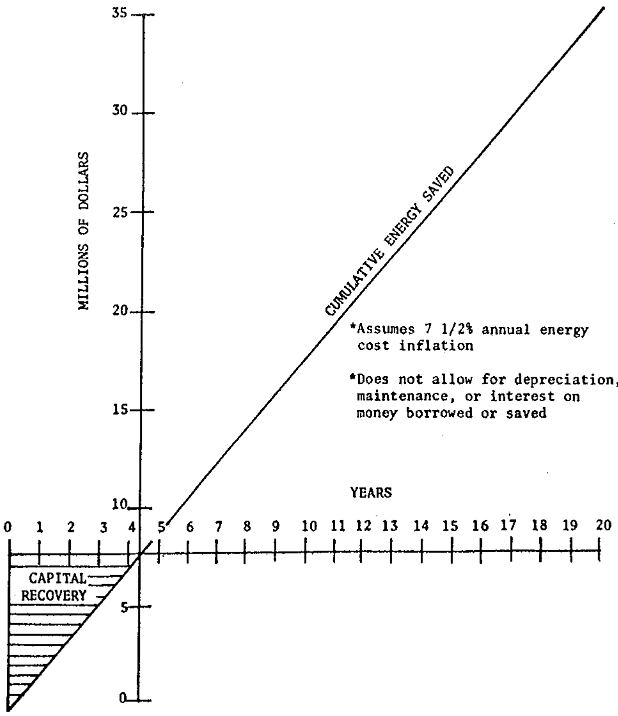

Figure 12. Economic Analysis of Jamaica Bay Case.

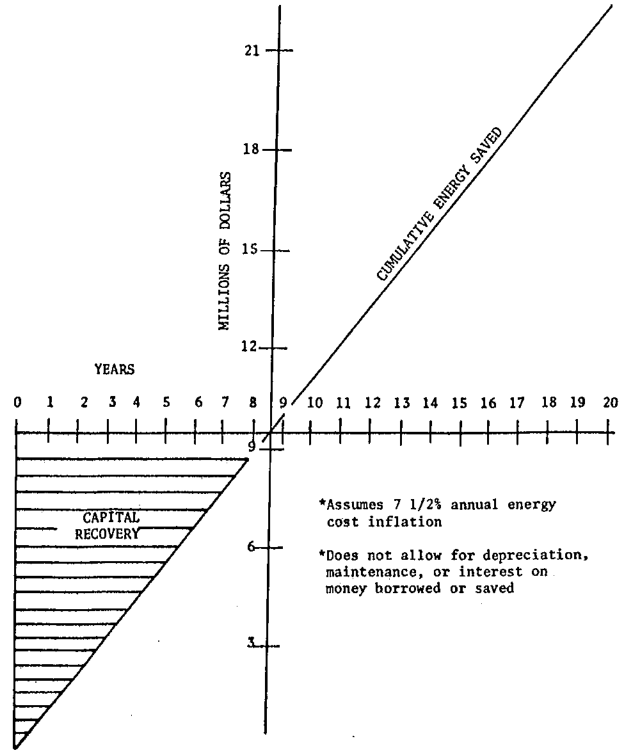

Figure 13. Economic Analysis of Cooling Tower Case.

CONCLUSIONS

Capture of winter cold for summer air conditioning can be technically and economically viable.

The viability of capturing winter cold for summer air conditioning depends upon local climatic and geohydrological conditions.

Further analysis is required to establish the technical and economic viability of capturing winter cold for summer air conditioning of the John F. Kennedy International Airport in New York City.

Preliminarily and subject to change, for 100% conversion of a typical site such as JFK, capture of cold from a large body of water such as Jamaica Bay with a payout period of about 4 1/2 years is preferable to use of cooling towers chich has a payout period of about 8 1/2 years.

Preliminarily and subject to change, for 25% conversion of a site such as JFK with already existing cooling towers, capture of cold with cooling towers is preferable to use of a large body of water for cooling.

Preliminary analysis indicates that dry coolers may be preferable to cooling towers in new installations.

HIGH TEMPERATURE UNDERGROUND THERMAL ENERGY STORAGE

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INTRODUCTION

A major problem associated with the efficient utilization of energy sources is the storage of heat in a system that minimizes heat loss. One possible solution to this problem is to store the heat underground[1-8]. The unique aspects of the systems discussed in this paper are their capability of achieving thermal storage at sufficiently high temperature and pressure, and with sufficient transfer rates, that electric power generation on a large commercial scale using heat from storage is possible. The two methods under study are deep aquifer storage of very high pressure hot water and deep cavern storage of hot oil utilizing solution caverns in massive salt deposits. Of these two methods the cavern storage appears to be the more feasible on the basis of our preliminary studies.

Currently computer simulators are being developed for detailed studies of thermal losses and pumping requirements associated with deep aquifer storage (superheated water, 650°F, 2700 psi) and deep cavern storage. These studies will also address other aspects of such geothermal storage systems, in particular the solution and transport of minerals, in the case of aquifer storage, and thermo-mechanical stresses on earth and well components. The present status of these ongoing studies will be discussed below.

STORAGE SYSTEMS

In order to achieve maximum heat storage efficiency it is necessary to minimize heat loss. Previously[1,2] it has been shown that deep underground storage of thermal energy, using a working fluid at high temperature and pressure, can be achieved with relatively small conduction losses for cyclic injection and withdrawals if the system is sufficiently large. In particular, the asymptotic loss ratio is estimated as,

$$\frac{\text{Heat lost per cycle}}{\text{Total Heat Stored}} = \frac{3\kappa\tau_C}{R^2} \qquad (1)$$

where κ is the thermal diffusivity of the rock, τ_C is the period of injection-withdrawal, and R is the equivalent radius of the cyclicly heated region. Thus only large storage systems should be considered.

If the working fluid is to remain in the liquid phase, an important requirement for maximizing the energy density, a high pressure in the storage region is necessary. This, in turn, dictates a deep storage zone if only the earth overburden pressure is to confine the fluid; in other words, the pressure in the storage region must be less than the fracture pressure which, for high pressure storage, can only be achieved at great depths. A rough rule of thumb assigns 0.75 psi per foot of depth as the fracture pressure.

Storage systems meeting the constraints necessitated by these considerations can be realized by using water as the working fluid and injection through a well into a porous aquifer or using oil as a working fluid and injection through a well into a solution cavern within a massive salt deposit.

GEOLOGICAL FEASIBILITY

Geologically two types of aquifer storage[9] can be considered: shallow, for aquifer depth ranging from 3000 ft. to 5500 ft.; and deep, for depths exceeding 5500 ft. The 5500 ft. division has been set based on a charged aquifer pressure of 2700 psi. Areas where the thickness of the sedimentary column above the basement rock (igneous and metamorphic rocks of all ages) are over 5500 ft. are potential regions for deep aquifer storage. Shallow aquifer storage is the same as deep aquifer storage except that the temperature and pressure of the injected fluid will be comparatively less depending on depth. This system is suggested where no other alternative is available.

As with aquifer storage, two types of cavern storage[9] are distinguishable: solution cavity and excavation cavity. Artificially created solution cavities in subsurface salt deposits are made using water to dissolve the salt. The fact that most rock salt has a low porosity and permeability, and exhibits semi-plastic properties, tending to close small fractures and openings made in it, makes massive salt formations ideal storage sites. Consequently, caverns in salt should be useful for thermal storage using some fluid other than water as the working fluid.

Recent advances in drilling and mining techniques now permit the use of deeply buried rock cavities for storage of water or steam. Rock types suitable for constructing underground excavations are crystalline and massive rocks. Dooley, et al[6] have shown that economics, environmental effects, and safety are favorable to this thermal storage system with power output being quite satisfactory.

On the basis of our geological study[9] it has been found that underground storage of high temperature and high pressure fluid is geologically feasible in approximately 80% of the United States, with the exception of the West Coast and areas of mountain intrusions. Many of the areas suitable for underground storage coincide with regions of good solar insolation or sites of significant heat supply from industries or nuclear power plants.

AQUIFER STORAGE

A mathematical model of steam injection into a permeable earth stratum containing brine has been formulated and programmed for computation on a high speed digital computer to evaluate thermal losses, thermal degradation of retrieved heat, and injection and retrieval pumping requirements in various operational modes. The model is similar to the two-phase model of Faust and Mercer[10], significant differences being that here gravity is included and the model represents the axially symmetric geometry of a single well. This program is now in the final debugging stage.

In addition to the comprehensive numerical model described above a simple analytical calculation has been performed to provide a preliminary evaluation of the back-flow capability of an aquifer storage well. On the basis of these calculations it appears that for a single aquifer storage well in an unbounded aquifer pumping would be required for backflow. Further calculations with the simple analytical model indicate artesian backflow is only possible from totally enclosed aquifers; a result which diminishes the applicability of the aquifer storage system. However, a downhole pump could be installed to achieve backflow conditions. This technology is currently being developed in the geothermal industry.

In addition to the backflow problem, the problem of mineral solubility and scale formation, particularly silicate minerals, appears to be a major problem confronting aquifer storage systems. Silica scale deposition, especially if occurring in high temperature, high pressure steam turbines, could have detrimental economic effects in brine systems associated with deep sandstone aquifers. It is anticipated[2], however, that through careful startup techniques (i.e. repeated flushing with pure hot water, chemical treatments, etc.) and the cyclic nature of the system whereby the retrieved water is reinjected after heating, such scale problems can be minimized with subsequent enhancement of the viability of aquifer storage systems.

CONSTRUCTION OF STORAGE CAVERNS

Solution caverns in salt domes have been used for storage of a variety of products — from crude oil to radioactive waste. Massive salt is an ideal storage medium for bulk liquids because of its very low porosity and permeability[11]. The essential geologic requirements for suitable and safe underground storage in salt masses are known and easily satisfied, for example, by the many salt domes of the Gulf region of the United States. The cavern construction requires an adequate supply of fresh water and an acceptable means of brine disposal. Fresh water is injected into the well and circulated, causing dissolution of the salt to form brine. As this brine approaches saturation, it is displaced from the cavity by incoming water. The dissolution of salt and removal of brine creates the cavern. Using these techniques, many caverns of multi-million barrel capacity have been developed[12].

The actual construction of a salt dome hot oil storage cavern would require approximately 9 months, with the well being constructed in about 60 days and the remaining time spent creating the cavern. The well design is relatively complex in that it would be installed under ambient conditions and operate at temperatures in excess of 600° F. This creates tremendous stresses on the cement to casing bond, as well as the cement to formation bond. Experience with steam stimulation of oil wells indicates that these problems can be overcome through the use of special cements and expansion joints on the outer casing.

A cavern storage well would be configured as a series of concentric pipes set at various depths as in conventional injection wells. The first pipe is called the conductor pipe and is generally driven into place with a diesel hammer. The conductor pipe usually extends to approximately 100 feet below ground level and protects the shallow fresh water aquifers as well as supplying a conduit for the drilling fluid to return to the mud tanks. The second pipe installed is the surface casing. This casing is set below the base of the fresh water aquifers and prevents their contamination from drilling fluid, salt water, and possibly oil and gas. For a heat storage well this casing would be cemented to the surface with a high quality heat resistant cement. The next pipe installed is the protection casing. It is usually set and cemented approximately 200 feet into the salt. This casing protects the caprock and other salt water aquifers. There will be two additional pipes installed, however these will not be permanently fixed with cement. The innermost tubing string will be used to obtain the proper cavity configuration by moving it up and down during the leaching process. The other casing will be used to protect the roof of the salt cavity. A hydrocarbon such as kerosene or diesel fuel is placed in the annular space between this casing and the protection casing. This prevents water contact with the salt cavern roof and thus prevents it from being leached.

After the cavern is developed, the free hanging casings will be repositioned so that the innermost casing is near the bottom of the cavern and the other casing near the top. The hot oil would be pumped into one and the resident fluid displaced through the other.

The configuration of the cavity can be confirmed through the use of a sonar log. From this data, we can calculate the configuration of the cavity and its exact volume.

Once the well and cavity are drilled and completed, the maintenance problems and costs will be minimal. However, routine checks on the integrity of the wells should be made at least once a year. This can be accomplished with various geophysical logging techniques.

CAVERN STORAGE OPERATION

We have used a simple mathematical model to study the operation of a cavity heat storage system. The cavern is partially filled with gas (nitrogen) which is compressed during injection. Expansion of the compressed gas forces the fluid out during retrieval. For preliminary studies of the thermal losses and pumping requirements the cavern is approximated as a spherically symmetric heat source embedded in an infinite earth of uniform thermal diffusivity. Numerical integration of the heat conduction equation and a coupled heat balance equation for the cavern is used to compute the temperature, the heat loss rate and the pressure as functions of time.

A complete cavern storage system would consist of the high temperature cavern, an additional cold fluid reservoir, which might also be a cavern, and appropriate heat exchangers and circulating equipment.

The optimum operational parameters for a cavern storage system have not yet been determined, but preliminary numerical results have been generated based upon the parameters in Table I using the computer simulator described above. These parameters correspond to a heat transfer rate of 74 megawatts. The assumed operational procedure consisted of displacing the brine from the completed cavern with nitrogen then injecting hot oil, compressing the nitrogen, and subsequently initiating cyclic injection and withdrawal of hot oil.

TABLE I. Cavern Operation Parameters
(These parameters correspond to a transfer rate of 74 MEGAWATTS.)

Q	= 2000 gal/min	Injection flow rate
τ	= 480 min.	Injection Period
T_{inj}	= 648°F	Injection Temperature
T_o	= 130°F	Ambient Temperature of Rock Salt
κ	= 0.00533 cm^2/sec	Thermal Diffusivity of Rock Salt
$C_o \rho_o$	= 0.49 cal/cm^3°C	Specific Heat Density of Oil

CAVERN STORAGE SIMULATOR RESULTS

Minimum heat losses from the cavern are of critical importance in cavern heat storage. The loss ratio, defined as the ratio of the heat lost per cycle to the total heat stored in the cavern, must be kept small. The loss ratio is defined by the equation

$$\text{Loss Ratio} = \frac{\text{Heat Loss Rate} \cdot \tau_c}{\text{Total Heat Stored}} \qquad (2)$$

where the heat loss rate and total heat stored are determined by computer simulator and τ_c is the time period of one storage cycle. The loss ratio as a function of time is shown in Figure 1 for a 100 ft. radius cavern and a one day storage period. The different curves correspond to initiating cyclic storage and retrieval at different times. The loss ratio at 70 weeks of cyclic operation is still well above the limiting, asymptotic value as given by Equation (1) while the cavern temperature has risen to between 2°F and 10° below injection temperature. However, the loss ratio does fall to a reasonably small value after just a few weeks, thereafter it decreases more slowly with time while cavern temperature continues to rise slowly.

We also determined the ratio of the heat lost per cycle to the heat input per cycle given by

$$\frac{\text{Heat Loss per Cycle}}{\text{Heat Input per Cycle}} = \frac{\text{Loss Rate} \cdot \tau_c}{f\, Q\, C_o \rho_o (T_{inj} - T_o)}. \qquad (3)$$

Values of this ratio at the end of one year of cyclic operation are plotted in Figure 2 versus the dimensionless ratio of oil volume transferred per cycle to total cavern volume. The heat lost per cycle is seen to be less than 4% of the heat input per cycle for any cavern radius less than 100 ft. at an injection flow rate of 2000 gpm. The asymptotic value of the ratio of the heat lost per cycle to the heat input per cycle goes approximately, as R/Q. Therefore, the minimum cavern size consistent with desired storage performance should be used in order to minimize heat losses and provide for maximum electric power production.

CAVERN STORAGE WORKING FLUID

The ideal fluid for use as in a high temperature, cavern storage system must have a high boiling point, high temperature stability, reasonable cost, and a reasonably high value of specific heat (per unit volume) to maximize the heat stored per volume of fluid. Of course, these fluids must not dissolve the salt as

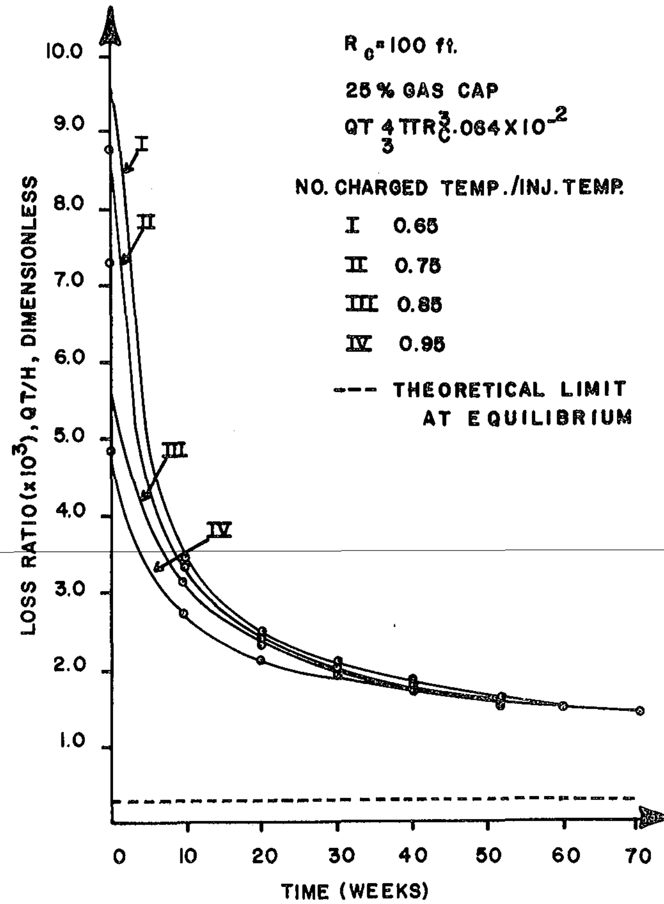

Figure 1. Loss Ratio as a function of time.

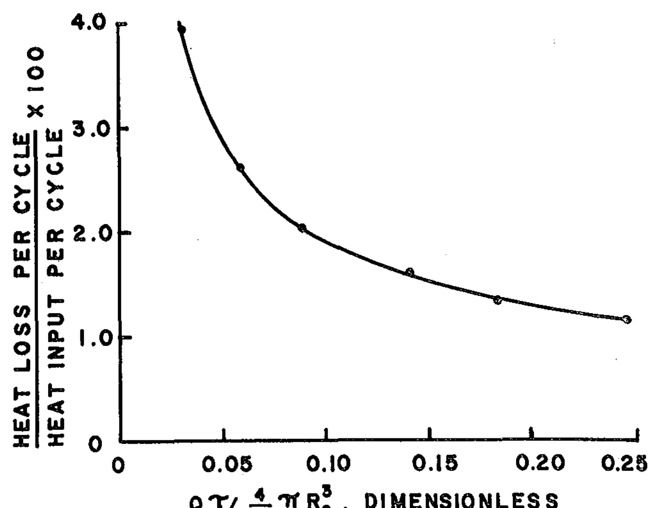

Figure 2. Ratio of heat lost per cycle to heat injected per cycle after 52 weeks of cyclic storage as a function of the ratio of oil injected per cycle to cavern volume.

continued cavern growth is undesirable. Some commercially available fluids being considered are listed in Table II along with values for some of their properties.

TABLE II. Working Fluids[13]

Liquid	Usable Temp. °F	Boiling Point °F	Specific Heat x Density cal/cm^3°C at 100°F/700°F	Cost $/gal
Dowtherm A	55 to 750	495	.405/.440	.61
Therminol 44	60 to 700			6.60
Dowtherm G	12 to 650	572	.430/.467	.67
Therminol 66	25 to 650		.370/.497	.72
Humbletherm 500	-5 to 600	720-950	.412/.476	
Mobiltherm 600	-5 to 600	650	.365/.494	
Therminol 55	25 to 600	650	/.428	.137

FUTURE CONSIDERATIONS FOR CAVERN STORAGE

Some of the topics now being studied include:

1. The gas pressures and pumping requirements for various operating conditions.
2. The effects of shutdown on heat losses from the storage system.
3. Feasibility of multi-day storage and seasonal storage.
4. Thermo-mechanical stresses on the well, salt, and above ground equipment.
5. Introduction of gravel or sand into the cavern in order to reduce the volume of storage fluid required and possibly raise the density of heat stored.
6. Requirements for the cold fluid storage reservoir.
7. Above ground equipment for cavern storage operations.
8. Economic considerations, especially in regard to best operating conditions, overall scale, and surface equipment required.
9. Environmental considerations.

ECONOMIC CONSIDERATIONS

An aquifer storage well capable of handling 2000 gpm would cost approximately $1,200,00.00. This price does not include the support surface facilities such as pumps, heat exchangers, etc. However, this equipment would be similar, if not the same, for a cavern storage system. A cavern storage well would cost approximately $700,000.00 to drill and complete, $100,000.00 to leach out the cavity, and $400,000.00 for a disposal well to dispose of the salt water created during the leaching process. Thus the total cost for a cavern well is also $1,200,000.00. A 75 foot radius cavern filled with gravel would require about 2.5 million gallons of oil. At $.60/gallon this volume of oil would cost $1,500,000.00.

Operational costs will probably be lower for the cavern storage system than for an aquifer storage system. We anticipate that an aquifer well will have to be pumped in most cases. Also, there is a strong possibility that there will be a silica scale problem associated with an aquifer storage well. These factors would add considerable costs to aquifer storage systems.

CONCLUSIONS

The preliminary studies completed to date indicate that underground thermal storage can be interfaced with a variety of high temperature heat generating systems, e.g. nuclear power plants and producers of industrial waste heat as well as large central focus solar collectors. Furthermore, much of the technology necessary for the design and construction of underground thermal storage facilities already exists. Consequently the underground storage of thermal energy, particularly cavern storage, appears to offer a promising near-term method of storing heat at temperatures high enough to permit reasonably efficient electric power generation.

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AQUIFER STORAGE PROJECTS IN SWEDEN

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SUMMARY

This paper presents two Swedish projects on thermal energy storage in the ground. The first project investigates the possibility of storing hot-water in so-called eskers (long and narrow glacial deposits of high permeability). A simple computer model and results on the energy efficiency of the storage system are presented. The question of a tilted thermal front caused by spatial variations in viscosity and density is discussed.

The second project focuses on theoretical aspects of heat storage in the ground, including the development of computer programs for this and similar problems. The performance of a vertical aquifer storage system is discussed. Numerical methods in geothermal aquifer simulation are mentioned.

INTRODUCTION

Thermal energy storage in aquifers is a very fresh subject in Sweden. The controversial nuclear-power technology and the heavy dependence on imported oil (60%) have brought considerable attention to solar and wind power. The use of solar energy and industrial waste-heat calls for methods to store energy during a long-term.

THERMAL ENERGY STORAGE IN ESKERS

Eskers are gravelly and sandy drift formations deposited by subglacial streams. Their length (up to 200 km), frequent appearance, and high permeability make them a potential for hot water storage. The investigation is lead by Allmänna Ingenjörsbyrån (Engineering Consultants) and financially supported by the National Swedish Board of Energy Source Development (NE). In a simple model the water is extracted at a distance of 300 m in each direction from the injection well.

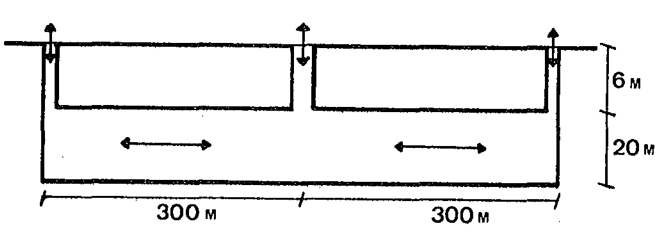

Figure 1. Storage in eskers.

Numerical model

A computer program has been developed to obtain an estimation of the energy balance. The water flow is of a very simplified character in that we assume the flow at a given time to be equal in all parts of the aquifer. The calculation is then carried out in a vertical cut along the length of the aquifer. This is a two-dimensional problem in a rectangular (x,z)-plane. The flow is given as $\bar{q}=q(t)\cdot\hat{x}$ ($m^3H_2O/(m^2,s)$). The ground above and under the aquifer may consist of arbitrary horizontal layers with different heat transfer properties. At the surface we have a fluctuating air-temperature. At the two vertical boundaries water is either supplied or withdrawn. The injected water has a temperature of 90 ^oC (194 F) when charging and 50 ^oC (122 F) otherwise. The temperature of the extracted water is taken as an average over the depth. The energy equation is solved using the explicit finite difference method. To avoid "numerical diffusion" the timestep DT is always chosen so that the thermal velocity $V_T(t)$ always moves one cell-length DX in the x-direction.

$$DX=V_T(t)\cdot DT \qquad (1)$$

The area is divided into 7200 cells. To begin with we made a comparison between different pumping strategies.

A. Waterflow always in the positive x-direction, i.e hot-water injected at x=0 and extracted at x=300 m.

B. Waterflow in the positive x-direction during the first 6 months of charging and in the other direction during the following 6 months, i.e hot-water injected and extracted at x=0.

In this case the temperature of the cold water was 40 ^oC.

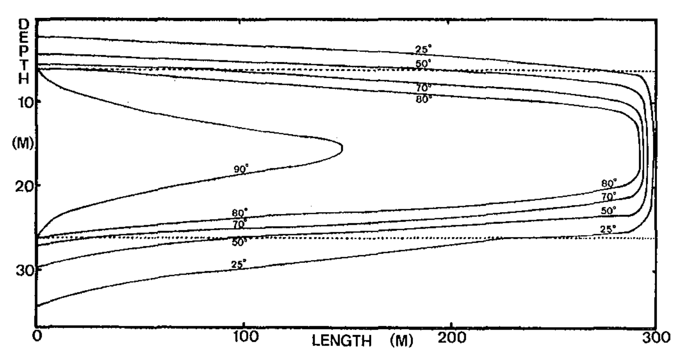

Figure 2. Temperature distribution after 6 months of charging.

Figure 2 displays the calculated isoterms after 6 months and Figure 3 the temperature of the extracted water during first-year cycle.

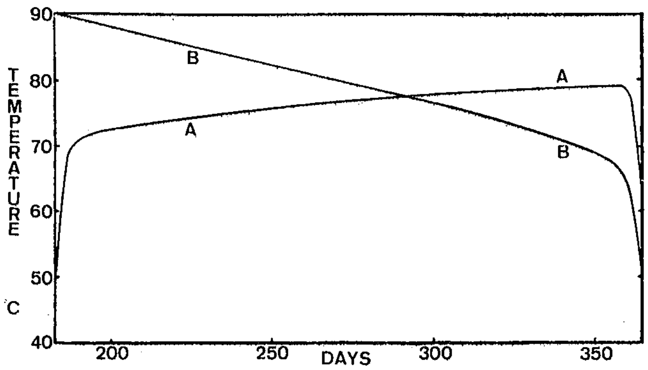

Figure 3. Temperature of recovered water.

The average temperature of the extracted water is 75.3 °C and 78.9 °C in case A and B respectively. Strategy B is obviously the better one. During the first half-year the matrix around the aquifer is heated and this works as a "shield", which is less efficient with increasing distance form the injection well. In case A the hot-water in the first part of the aquifer flows into the area with a bad shield whereas in case B the hot-water in the second part retreats to the good shield.

Then we proceeded to study a more complex situation where the thermal velocity was proportional to the actual need or supply of energy. The thermal front was moved 300 m when charging and 275 m back when discharging, in order to avoid the cooled water close to the thermal front. Considering an aquifer as in Figure 1 with 2x300 m length, 20 m height and a width of 100 m we obtain the following results for the first six years.

Table 1

Year	$Energy_{in}$	$Energy_{out}$	Energy efficiency
1	$2.70\cdot10^{14}$	$0.85\cdot10^{14}$ (J)	0.32
2	$1.38\cdot10^{14}$	$0.93\cdot10^{14}$	0.67
3	$1.32\cdot10^{14}$	$0.97\cdot10^{14}$	0.74
4	$1.29\cdot10^{14}$	$0.98\cdot10^{14}$	0.76
5	$1.27\cdot10^{14}$	$0.99\cdot10^{14}$	0.78
6	$1.27\cdot10^{14}$	$1.00\cdot10^{14}$	0.79

The additional heat loss from the vertical boundary areas is estimated to about 20% of the loss from the horizontal areas. This will reduce the energy efficiency with about 5%. The energy effect is proportional to the temperature difference between injected and extracted water. A typical value of the maximum effect during the sixth year is 9 MW. Some reservations must be made against the validity of this model although it definitely gives an upper limit to the energy efficiency. The main problem is the assumption that the flow is equal and in the x-direction in all parts at the aquifer. This prevents the possibility of thermal stratification, i.e. the tendency of the hot water to spread out over the cold water due to differences in viscosity and density. The behaviour of the thermal layering effect is of vital importance in this project, since the length/height ratio is very large.

Thermal stratification

A simple model (Figure 4) with linear flow in the x-direction and a sharp interface between hot and cold water gives some clues to the tilt of the thermal front.

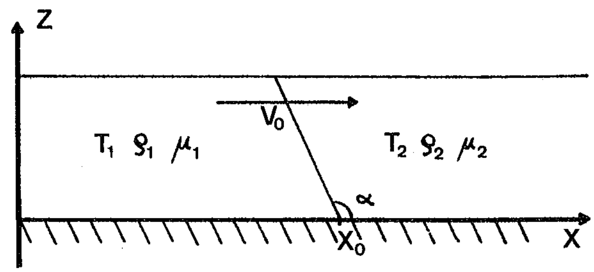

Figure 4. Tilting of a sharp thermal front.

Darcy's law

$$\bar{V} = -\frac{k}{\mu}(\nabla p + \rho g\hat{z}) \qquad (2)$$

The waterflow is constant and parallell to the x-axis throughout the aquifer

$$\bar{V} = V_0\cdot\hat{x} \qquad V_0 > 0 \qquad (3)$$

At the thermal front we have

$$z = \tan\alpha\cdot(x-x_0) \qquad (4)$$

The energy and mass balance equations are fulfilled if the angle α is given by

$$\tan\alpha = -\frac{V_0}{kg}\left(\frac{\mu_1-\mu_2}{\rho_1-\rho_2}\right) \qquad (5)$$

The term between the brackets is positive for all values of T_1 and T_2. This implies that the angle α is larger than 90°. We get the same angle when T_1 and T_2 are shifted. Further analysis show that the angle α represents a stable equilibrium when $T_1 < T_2$ and an unstable when $T_1 > T_2$. The heat diffusion at the sharp front is here neglected.

The effect of tilt becomes less pronounced for stratified flows and when the interface between hot and cold water is diffuse.

ENERGY STORAGE IN THE GROUND

This project, supported by NE and the Swedish Council for Building Research (BFR), deals with the long-term storage of low-temperature energy. The main object is to develop computer programs for heat and flow processes in energy storage system. These mathematical models will be used by applied Swedish projects in this field. The scope of this project is

- heat storage in ground-water regions
- storage in an earth-volume penetrated by waterpipes
- heat storage by freezing in soils
- extraction of geothermal energy
- heat storage in the ground combined with heat pumps and solar collectors

Vertical cylinder storage system

Consider a storage volume in the form of a vertical cylinder. (Figure 5).

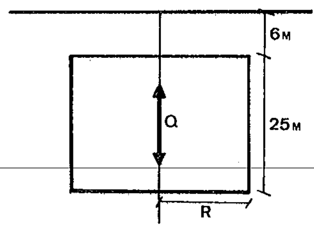

Figure 5. Storage in a cylindrical region. Vertical water flow.

The main assumption is that the water flow is equal and parallell to the z-direction in all parts of the storage volume. The hot-water (90 °C, 194 F) is charged and discharged at the top in order to avoid the undesired effects of thermal stratification. This idealized model sets an upper bound for the energy efficiency. In a typical case we obtain the following results during the first five years:

Table 2

Year	E_{in}(J)	E_{out}(J)	E_{out}/E_{in}	
1	$0.178 \cdot 10^{13}$	$0.251 \cdot 10^{12}$	0.141	
2	$0.116 \cdot 10^{13}$	$0.336 \cdot 10^{12}$	0.290	
3	$0.108 \cdot 10^{13}$	$0.367 \cdot 10^{12}$	0.341	R=10m
4	$0.104 \cdot 10^{13}$	$0.383 \cdot 10^{12}$	0.368	
5	$0.102 \cdot 10^{13}$	$0.393 \cdot 10^{12}$	0.387	
1	$0.703 \cdot 10^{13}$	$0.162 \cdot 10^{13}$	0.231	
2	$0.422 \cdot 10^{13}$	$0.193 \cdot 10^{13}$	0.458	
3	$0.385 \cdot 10^{13}$	$0.202 \cdot 10^{13}$	0.526	R=20m
4	$0.370 \cdot 10^{13}$	$0.207 \cdot 10^{13}$	0.559	
5	$0.360 \cdot 10^{13}$	$0.210 \cdot 10^{13}$	0.582	

In another test the vertical sides of the R=20m cylinder was covered by insulations. This gave a minor increase of the energy efficiency to 0.588 during the fifth year (R= 20m). The heat resistance of the insulation equals that of a 0.4m thick layer of the surrounding matrix. The main heat loss flows through the top of the cylinder. This could perhaps be used for house-heating by circulating air through an adjacent bed of gravel.

Computational methods in geothermal aquifer simulations

The object of the geothermal energy program in southern Sweden is the extraction of hot-water at 70 °C (158 F) from aquifers at a depth of about 2000 m. The physical process is very similar to that of energy storage in aquifers. The computational methods can be used in both cases. One of the computer programs developed calculates the temperature and the pressure distribution when operating with two holes (production and reinjection). We assume that the horizontal extension of the aquifer is very large compared to the distance between the holes. The calculations are performed in new coordinates given by a bipolar conformal mapping. Heat conduction is neglected, hence the energy transport becomes very simple. The numerical method to describe the movement of the thermal front is such that the reinjected water has to cool one cell completely before it initiates the cooling of the next cell down-stream. This procedure avoids the "numerical diffusion" and gives excellent agreement with analytical solutions. The viscosity is allowed to vary with the temperature and this proves to be important when calculating the lifetime of the well.

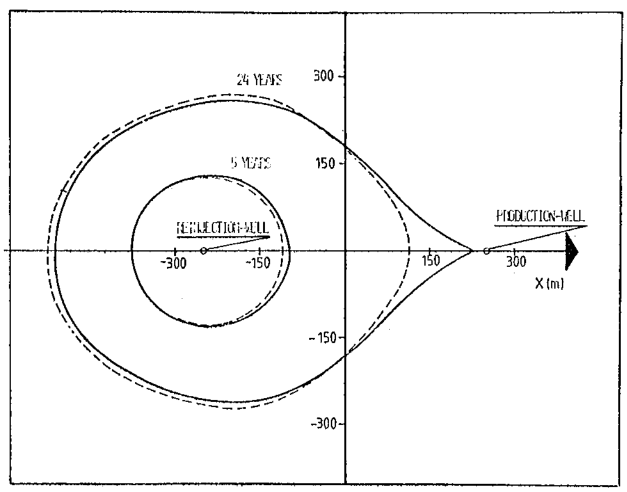

Figure 6. Thermal front in geothermal heat extraction.

Figure 6 displays the location of the thermal front with (dashed line) and without (bold line) the temperature dependence of the viscosity included in the calculation. The resulting relative increase in the wells lifetime is given as a function of the viscosity-ratio in Figure 7.

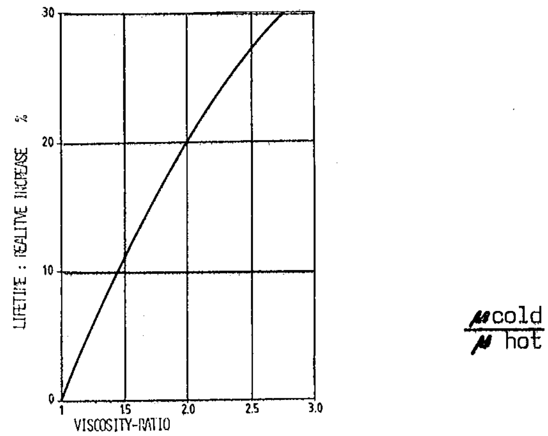

Figure 7. Increase of lifetime when the effect of different viscosities is considered.

Aquifer Storage Efforts in Germany

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Large-scale thermal energy storage (LSTES) with the goal of saving or substituting energy is in discussion in Germany since the early sixties. While being viewed as an exciting, but nevertheless somewhat exotic idea until 1973, LSTES has catched increasing attention among descion makers in energy politics since then. In order to improve the basis of R + D decisions in the field of LSTES, three major studies have been made since 1974. The final results of these studies are now on the table. The studiese I am talking about are the following:

- "Seasonal Heat Storage" by Messerschmitt-Bölkow-Blohm in cooperation with the Bundesanstalt für Geowissenschaften und Rohstoffe, Berlin (700 pages, treating laketype storage systems as well as aquifer-type storage systems).

- "Development of a Concept for a large-scale Warm Water Storage Facility" by Kraftanlagen Heidelberg in cooperation with the Kernforschungsanlage Jülich (180 pages) and

- "Energy Storage in the System with Combined Production of Heat and Electricity" by Messerschmitt-Bölkow-Blohm in cooperation with BBc, Kraftanlagen Heidelberg and Prof. Bach from the University of Stuttgart (2000pages).

Besides that, a meeting was organized in October 1977 in Stuttgart, where the present activities in Germany in the fields of warm water storage, aquifer storage and latent heat storage were reviewed. A report of that meeting with a volume of 180 pages was published /1/.

In the following I will outline a very brief review on the present oponion in Germany on the whole heat storage problem. To do so, I will give answer to three important questions, based on the work mentioned earlier:

1) What is the influence of heat storage on the energy demand?
   The answer is of course, that the energy saving potential of heat storage depends on the extent to which district heating is realized. District heating has already developed remarkably large in countries like Sweden or Denmark, but also in some Eastern European Countries. In Germany, district heating covers at present about 7 % of the heating demand. It is desirable to increase this portion to 25 % or more within this century.

   To realize that goal, small-scale heat storage, that means storage that covers periods of up to 10 days would be important already. However, substantial energy savings are only achievable by LSTES, which is illustrated

by 4 numbers:
The overal heating power in Germany is at present 280 Tcal/h with an annual heating demand of about 420 . 10^3 Tcal. On the other hand, if all power plants in Germany, which at present have condensating turbines, would be changed into combined heat and electricity producing power stations with equal electric output, this would allow for heating power of about 140 Tcal/h, producing an annual heat energy of about 580 . 10^3 Tcal. But the larger portion of this would be produced not during the heating period.

Of course, the economic potential of energy savings is much lower, because district heating is confined to high density population areas. But whithin such areas the use of LSTES can lead to energy savings of 20 % compared to conventional (high temperature and high pressure) district heating systems. The use of short-time storage, operated in combination with a peak-load gas turbine can lead to energy savings of about 4 %.

2) What are the limiting investment costs of LSTES?
The answer to that question is quite complex, because it depends largely to a number of general assumptions as well as to local conditions. The main features of the calculation are the balancing of the LSTES investment costs against

- substitution of the peak-load heating facility,
- the reduction of dimension of the heat-transport pipeline and
- the reduction in energy costs.

(The storage has more positive consequences like substitution of certain energy sources or reduction of emission but it is difficult to account for that).

To give a short answer to the question (which should be regarded only as an order-of-magnitude answer) I give the following figures:

- The limiting costs of short-time storage (being used up to 30 times per year) are
  7 500,-- DM/Gcal or 6. 5 DM/kWh.

- The corresponding figures for LSTES are only
  260,-- DM/Gcal or .35 DM/kWh.

The conclusion of this is, that short-time storage which is aloso desirable perse, can be introduced already today without problems of economics. The low limiting costs of LSTES, however, lead to the question if LSTES, at present boundary conditions, is a desirable facility from an economic point of view.

3) What is the best way of storing large amounts of heat?
As very well known to all of you, water has with respect to its mass as well as with respect to its volume a comparable very high heat capacity. In addition to that, it is usually cheap and easy available and causes no ecologic stresses (at low temperatures). Therefore, water should be the best medium for storing large amounts of

heat.

The energy saving potential by combined production of electricity and heat is the higher the lower the temperature of the removed water. So, heat storage by water with a temperature slightly below 100^{o} C should in general be the most favorable solution.

The possibilities to do this are at present in discussion in Germany:

(a) The first one is the artificial lake with a volume of up to 2 Million m^3 or even more. For that lake, the costs are estimated to be in the range of 35 to 50 DM per m^3. This is well above the limiting costs. In a project started at the end of 1977 ("Großwärmespeicher Mannheim") it shall be found out which components of the storage can be made cheaper without impairing its adequate functioning.

(b) The second possibility is the aquifer. To present knowledge, this seems to be the cheapest possible solution. There are cost estimates between 15 and 25 DM per m^3. To compare these figures to the artificial lake costs, they have to be devided by .6 according to the lower specific heat capacity of the aquifer. There are lots of unsolved problems with the aquifer solution which prevents us from preferring it to the artificial lake solution. Therefore, a laboratory-scale research project will be started on 1^{st} of October 1978. This project covers experimental investigation of chemical transport, corrosion and biology as well as the erection of small-scale pilot plant for testing purposes only. The result of that project - if successful - will be the definition of the location of a real-size aquifer storage to be operated within a district heating system. The project is supported by the Federal Ministry for Research and Development and by the European Community.

I should add a word to the general aquifer philosophy followed in Germany at present. It consists of the following main components:

i) Erection of two narrow vertical walls which confine the aquifer, 5 m distant of each other, constructed in a special and very cheap technique (Schlitzwand). The walls serve as separation of the warm water inside the aquifer from the cold groundwater outside. The gravel in between is a good thermal insulation.
ii) Removal of a layer of 2 m thickness from the surface.
iii) Construction of wells and pipes for the charging/discharging system.
iv) Introduction of a vapor barrier.
v) Introduction of a gravel bed of 2 m thickness.
vi) Covering of the surface with gravel and humus.

The aquifer described has horizontal temperature layers. Its capacity is of the order of magnitude of 50 Tcal. This means - with a temperature of less than 80^{o} C and an average specific heat capacity of 600 kcal m^{-3} k^{-1} - that the aquifer has a surface of about 300 x 300 m.

The most important questions which shall be investigated in the project mentioned are:

- Investigation of chemical transport of matter by use of typical limestones and primitive rocks,
- investigation of the physical properties of representative soil material,
- precise chemical analyses of soil water,
- necessity of chemical water treatment,
- theoretical description of the solubility as a function of temperature and other parameters,
- investigation of the corrosivity of the water to the components used and
- investigation of the biological processes in the aquifer and its surroundings.

c) The third possibility is a system which is perhaps a very promising one. But this has still to be checked. The system I am talking about is an intermediate solution between aquifer and an artificial lake: An aquifer with artificial bulk material. Here, the storage volume is extracted as in the lake versions, but afterwards refilled with coarse-grained material. This has the advantage to save the very expensive covering construction of the lake on the one hand and to have a much higher permeability than the natural aquifer on the other. Therefore, it may also be used as a short-time storage device.

Conclusion:

A large amount of theoretical work has been done recently in Germany as well as in some other countries in the field of large-scale thermal energy storage. The threshold has now been achieved, where hard-ware R + D - projects can be justified on the basis of the theoretical results. In both directions, the artificial lake on the one hand and the aquifer solution of the problem on the other hand, hard-ware projects have been started or will be started within 1978 in Germany.

Literature

/1/ "Rationelle Energienutzung durch Wärmespeicherung", VDI-Bericht Nr. 288, Proceedings of the Stuttgart-Meeting October 1977

/2/ Statusreport "Rationelle Energieverwendung", Berlin 1978, published by Projektleitung Energieforschung der Kernforschungsanlage Jülich, D - 5170 Jülich, Postfach 19 13, W. Germany.

THE DANISH SEASONAL AQUIFER WARM-WATER-STORAGE PROGRAM

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SUMMARY

The background for the Danish aquifer warm-water storage program is reviewed. The program itself is presented together with budget and schedule.

BACKGROUND

A significant part of the demand for both heat and electricity in Denmark is met through combined generation. About 10 percent of the residential heating requirements are presently being supplied from combined generation plants and efforts are presently made to increase this part significantly in the future. On a short time range, existing power plants are being converted to combined generation, or existing systems are being expanded. On a long time range, plans are being developed along which future conversion to combined generating plants and the establishment of new installations can be made without undue conflict with alternative supply sources (refuse burning, simple heating plants, natural gas etc.).

In systems containing combined heat and power generating units the use of diurnal and seasonal storage of warm water may lead to sizable savings of fuel, installed power capacity, and money. This is, in particular, due to the climatic conditions, characterized by a fairly long winter heating season and a reasonable warm summer without large cooling requirements, and with the heating requirements of residential areas limiting itself to the supply of hot water.

Seasonal storage of warm water has to be very cheap. The economic balance of seasonal storage shows that only the very cheapest solutions could be considered. Our inclination, therefore, has been to look for the presence of potential natural sites for storage of warm water. Furthermore, these have to be located very near existing or planned district heating pipelines.

Two alternatives have been found to exist. The one is represented by lakes and deserted quarries, the other is represented by aquifers. In Denmark the top soil practically always rests upon layers of sand, gravel or clay (50 to 500 metres) which in turn rest upon a thick layer of chalk (1000 to 3000 metres). The layers of sand, gravel and clay practically always carry water and is the main supply source for the water system. The chances of finding useable geological structures at suitable sites are, therefore, considered very good.

THE PROGRAM

The program consists of several parts:

The development of mathematical models; the design and construction of a demonstration plant; the operation of the demonstration plant; and a general nation-wide geological and hydrological survey.

MATHEMATICAL MODELS

The development of mathematical models has now been under way for about 2 years. Until now, one- and two-dimensional models have been developed. The one-dimensional model has been used only to get first-order estimates of storage requirements and losses, but is now abandoned. The two-dimensional model gives a rotationally symmetrical approximation to the reservoir. The condition of rotational symmetry will later be relaxed to expand the model into the desired three-dimensional model. This work is expected to last another year and a half.

Both the two- and the three-dimensional descriptions are finite-element models.

ESTABLISHMENT AND OPERATION OF A DEMONSTRATION PLANT

The establishment of the demonstration plant includes geological and hydrological investigations of the selected site, design and construction of the demonstration plant and operation of the plant over a period of two years. The first part, the geological and hydrological investigation, may have to be repeated if the selected site, for some reason, is found to be ill suited for the planned installation. Preliminarily, the aim is to convert a closed-down water supply well loacted close by a district heating main into the demonstration plant.

The size of the reservoir is about $10^5 m^3$ with a depth of about 30 metres, the ground water temperature about 8^oC, the storage temperature around 80^oC, the district heating return temperature about 50^oC, and pumping capacity about 30 m^3/hr. The design and construction of the plant is expected to run over 18 months and is hoped to include no particularly interesting or challenging problems.

OPERATION OF THE DEMONSTRATION PLANT

The operation of the demonstration plan comprises several interesting aspects. Aside from the usual problems of collecting and digesting data, and correlating these with the theoretical model, the modification and expansion of the model, etc., there will be the problem of recovering the stored heat at a time when the district-heating system needs heat at the available temperature. If this is done successfully, the expenditure could be held at about 50,000 U.S.

dollars. If unsucessful, the bill for expended energy will be double. The system considerations that are important in this context are also studied in connection with a couple of other projects and the results of these are expected to benefit the aquifer program.

GENERAL NATION-WIDE GEOLOGICAL AND HYDROLOGICAL SURVEY

Towards the end of the program a general geological and hydrological survey will be carried out. The aim of this is to identify sites that are suitable for aquifer storage, and that, at the same time, are located sufficiently close by existing or future district heating systems to make them interesting in this context. The survey will be limited to a systematic search of existing files of information on well drillings and geological and hydrological surveys.

This part is a minor, but important part of the entire program encompassing about one man year.

BUDGET

The entire program is expected to cost 6,65 million D.kr. (Danish Kroner, 5,50 to one US dollar).

The total is divided as follows:

Mathematical models	1,95 mill.D.kr.
Design, construction and operation of demonstration plant	4,50 - -
Geological and hydrological survey	0,10 - -
Travel expenses	0,10 - -
Total	6,65 mill.D.kr.

The program is planned to run over a period of 4½ years.

PARTICIPATING INSTITUTIONS

The participating institutions are:

The Technical University of Denmark (mainly Laboratory for Energetics)
RISØ National Laboratory
Danish Geological Survey

The program will be managed by the RISØ National Laboratory. Other institutions will participate in an advisory capacity.

SURVEY OF THERMAL ENERGY STORAGE IN AQUIFERS COUPLED WITH AGRICULTURAL USE OF HEAT UNDER SEMI-ARID CONDITIONS

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SUMMARY

Semi-arid zones have difficulty in inland location of power stations due to limited water resources for direct or wet tower cooling. A total energy system which utilizes the heat of the cooling cycle needs a year round user of low heat, which is generally not available in semi-arid zones. The only identified potential user so far is winter agriculture. The large scale uses considered are for hothouses and soil heating in open areas to increase yields of present crops and allow introduction of new ones. The short period of heat utilization makes seasonal storage mandatory. Aquifer storage of heat provides a possible solution if its location is within economic heat transport distance to power station and agricultural areas.

A preliminary survey of this concept is undertaken with respect to a specific area in Southern Israel with the following objectives (a) providing a general description of the proposed system and major sub-systems. (b) indicating the coupling between the various components. (c) identifying the critical parameters for technological and economic feasibility. (d) indicating gaps of knowledge which require detailed evaluation (e) specifying the scientific and technological disciplines and the amount of effort required to close these gaps.

The outcome of this survey is expected to lead to a decision whether to undertake a detailed feasibility study of this system.

1. BACKGROUND

1.1. Siting of power stations in semi arid zones

The general concept of a total energy system (TES) based on storage of reject heat from a power station in ground-water aquifers was described by Mayer, 1976 (11). Our survey limits the analysis to semi-arid zones emphasizing their specific problems and possibilities, including possible significance of this concept to the solar-thermal-electric concept (STEC). An example of a specific area in the northern Negev in Israel is given as a test of the approach to such an analysis.

The aquifer storage of reject heat has to be considered in a dual role as a component of a cooling system and as a phase transformer of the heat delivery cycle in order to fit the temporal needs of the users.

In a semi-arid or arid zone, with limited coastal sites the dissipation of waste heat becomes one of the key factors in determining the site and influencing the economics of the power producing plant. If dissipation through the intermediary of an aquifer storage is to be considered it has to be competitive with presently considered alternatives, which albeit costly and beset with open technological problems have been already tested to some extent: dry cooling system, wet systems and cooling ponds. There are however two prior conditions that such a system has to satisfy (a) the existence of suitable aquifer structures for storage of an average seasonal cooling requirement of the power plant (b) the existence of a heat sink that will dissipate the accumulated reject heat, preferably in an economically useful way; both within economic heat transport ranges from the power plant. The relative advantages of such a system are that there is no loss of water in the cooling process (even the relatively small amounts required by the wet tower of evaporation ponds may not be available) and that there is a significant energy conservation and associated economic benefits that may compensate for the larger costs. In case of the STEC, climatic factors favor such locations. In that case the avoidance of environmental effects associated with evaporative processes may be of significance: this subject deserves however a more specific study.

1.2. Objectives of the preliminary survey

In order to justify further study of this concept with relation to the areas considered, we had to have at least a tentative bases for the existence of the two associated factors. A suitable aquifer structure and a heat sink. In the following we describe the type of knowledge available at this preliminary stage and of the proposed approaches toward the next decision stage. In particular we provide a brief survey of (a) a general description of the proposed system and main subsystems (b) coupling between the various components (c) identification of critical parameters for technological and economic feasibility (d) gaps of knowledge requiring further evaluation (e) scientific and technological disciplines involved and the estimate of effort needed to close these gaps.

2. DESCRIPTION OF THE PROPOSED SYSTEM

2.1. The conceptual structure of the system is illustrated in Fig. 1a and 1b. During the warm period which lasts 8 months, the power station draws cold water from the aquifer and returns warm water in a closed cycle, to a warm region of the aquifer. During the cold period, there is an additional cycle, in an opposite direction with respect to the aquifer. It draws warm water from the aquifer and delivers it to the user, glasshouse air and soil. The average yearly heat input has to be balanced by the heat delivered to the users and lost to the environment.

2.2. Unit sizes and operational parameters.

The values selected for the unit sizes and leading operational parameters represent a reasonable initial guess which will be subject to subsequent optimization within appropriate constrains.

Power plant electrical capacity -800 MW(e)
Power production efficiency <1> - 0.33
Plant operation power factor - 0.8
Cooling water temp. rise, Δt - 35°C
Reject heat - 312 Mcal/sec
Condenser temperature - 58°C
Cooling cycle water flow - 770 · $10^3 m^3$/day
Heat losses in storage - 10%
Heat losses in transport - 20%
Heat delivered to user - 225 Mcal/sec = = $6.75 \cdot 10^9$ Mcal/y
Oil equivalent of heat delivery to user <2> -$870 \cdot 10^3$ TOE
Aquifer storage capacity - $400 \cdot 10^6$ m^3 (water)

<1> Corrected for increased condenser temperature

<2> Assuming boiler efficiency of 0.8

2.3. Environmental considerations

The inland site of power station will be remote from densely populated areas. It will also prevent additional heating of coastal waters. The use of reject heat to replace fossil fuels will prevent the associated air pollution. However if coal fired station will be selected, environment problems may be created by the transport of coal inland.

2.4. Economics and management

The investment and operational costs seem to be very sensitive to the depth of the storage aquifer and the number of wells required. That last parameter depends on the type of crops and on climatic variability. In an arid zone, agriculture requires heat input mostly during winter nights. This increases the number of wells and size of the distribution system, as compared with a system designed for a more extended period of use. The ability to select crop varieties for extended period of heat use is therefore an important element in economics of the project. Also of economic and managerial significance is the capability of the system to dissipate heat efficiently under emergency or transient periods, in excess of agricultural requirements.

3. OPEN PROBLEMS-SUMMARY

While the planned survey should define the open problems with more certainty and in greater detail, we can indicate some of them at this stage of investigation. They may be subdivided into those requiring (a) additional basic knowledge (b) technological development and material testing (c) pilot operation (d) system integration and optimization.

Problems of type (a) include: studies of plant response to heat input into surrounding soil, water and air; modeling of aquifers with time varying, high gradients of temperature; heat dissipation from soils with time varying heat sources and under vegetative cover, under various weather conditions.

Those of type (b) include: materials and configurations for efficient heat transfer from water to soil. Pilot operations(c)include recharge in specified geological formations; aquifer operation with controlled storage and recovery of heat; control of greenhouse and uncovered soil temperature, with warm water heat sources; power plant condenser operation with high temperature rise and with variable water quality.

Problems of type (d) include: planning of stages for sequential decision making; dealing with uncertainties and risks associated with changing energy prices and agricultural subsystems and their operation in the transient period and in emergencies.

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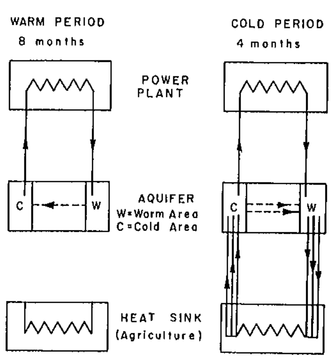

Fig. 1. Summer and winter operational scheme.

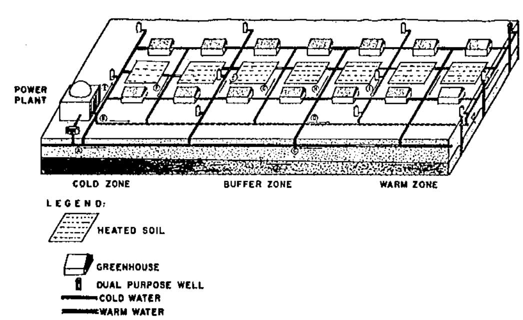

Fig. 2. Simplified graphic presentation of the interrelation between the various components of the system.

UNDERGROUND HEAT STORAGE : DIMENSIONS, CHOICE OF A GEOMETRY, AND EFFICIENCY

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ABSTRACT

Different methods for the calculation of the thermal efficiency of an underground heat accumulator are examined. The thermal convection which may appear when heat is injected into groundwater is, for the moment, difficult to control by numerical modelling.

INTRODUCTION

Underground heat storage is at present the most interesting solution economically and technically for the seasonal storage of thermal energy. When the groundwater is not used for water supply or irrigation, it may form a considerable reservoir of heat. Our aims in this work are to take into consideration a few possible techniques for the underground storage of heat.

AIMS, ADVANTAGES AND DISADVANTAGES OF UNDERGROUND HEAT STORAGE.

The aim of underground heat storage is to adjust production and consumption of thermal heat. Among low temperature production sources(T 100°C) we can mention: solar power plants, thermal power plants(fuel, nuclear), geothermal boreholes garbage burning plants, and industrial thermal waste water. In Switzerland, the energy necessary for district heating represents 50% of total energy consumption. It is estimated at 25 Gcal per year per inhabitant, i.e. 12 Gcal per year per inhabitant for heating. In Europe, air-conditioning is not generally thought of.

Under these conditions and when energy is constantly produced, 30% of the yearly consumption must be stored (Fig. 1). Whith solar production, this quantity goes over 50% at 45° latitude(Fig.2)

Table 1 shows the main advantages and disadvantages of heat accumulators in function of their dimensions. Geological criteria are probably the most constraining ones; their importance grows with the size of the accumulator. Environnmental conditions also limit the choice of possible sites, particularly in regions with a high population density where the use of groundwater for the supply of drinking water is the main issue. The permeability of the geological formation and the natural groundwater flow are 2 parameters which must be examined at first when looking for a storage site.

ANALYTICAL LAWS FOR THE TRANSFER OF HEAT IN POROUS MEDIA.

DAGAN (1972) formulates the general equation expressing the simultaneous transfer of heat and water in a saturated medium. The equation contains a term for diffusion, convection, loss of heat through friction, thermal dispersion, and thermal exchange between the water and the grains of sand. GREEN'S work (1963) shows that when heat is stored underground, diffusion and convection are the two predominant phenomena. This gives us :

$$\mathrm{div}(\lambda\, \mathrm{grad}\, T) - \rho_f C_f\, \mathrm{div}(\bar{V} T) = \rho C \frac{\partial T}{\partial t} + p$$

where

- λ thermal conductivity of the medium
- $\bar{V}$ Darcy velocity
- p density of the thermal source
- ρC Volumetric heat of the medium
- $\rho_f C_f$ Volumetric heat of the fluid

This equation includes in particular natural convection, which is unfortunately a phenomenon difficult to control by analytical or numerical techniques. The presence of natural convection during the injection of warm water into an aquifer, fig.3, has been observed by MATHEY,(1977 I).This phenomenon causes the efficiency of the storage to decrease a great deal. We should try to avoid that by a well-adjusted geometrical disposition of the injection and pumping apparatus. Attempts at numerical modelling of natural convection have given good results for the reproduction of experiments in the laboratory (KLARSFELD, 1970) where checking is easy. It appears more difficult to treat this problem in the case of big dimensions, on the field, where measurements are rare and the media are often heterogenous.

FORSESEEING EFFICIENCY OF UNDERGROUND HEAT STORAGE

The engineer has at his disposal a great variety of methods for forseseeing the thermal efficiency of a heat accumulator. Analytical techniques lead us to results allowing us to estimate expected efficiency. Numerical techniques taking into account the discretisation of the media are much more precise but longer to develop.

Table 2 shows the main functions and parameters used in a computer for the calculation of the thermal balance of a heat accumulator in a small reconstituted site (family house or small appartment house) Fig.4. Particular care has been taken in the calculation of solar heat production and heat consumption in the building. Loss of heat by diffusion has been expressed by a simple exponential taking into account the volumic heat of the accumulator, its volume and its surface.

The graph of Fig. 5 shows the general characteristics of an underground heat accumulator supposing it is spherical. The parameters have been calculated from analytical laws in a stationary regimen for increasing dimensions. Curves have been obtained by the interpolation of calculated points. The soundness of these graphs should however be tested experimentally. A numerical example is given on Table 3.

MENJOZ and JOOS (1977) give us a numerical method for calculating an accumulator. The accumulator consists in a well with a large diameter provided with horizontal radial drainage systems 50 meters apart from one another, Fig. 6. The choice of this geometry is intended to limit loss of heat through natural convection.

These models with finite elements allow us to analyze heat transfer in porous media in three dimensions and in function of time. Numerous successful tests have been made with thermal pollution.

SOME PROJECTS

Fig. 4 shows a heat accumulator for a family house, already mentioned. Fig. 7 represents an accumulator of 10 Tcal functioning between 70 and 30°C, using industrial warm waste water. In that case, heat may be recuperated by a heat pump.Since the system functions as a closed circuit, there is in principle no need to fear clogging of the terrain. The technical characteristics are given on Table 4. The greatest difficulty consists in finding simultaneously a favorable site from the geological point of view - a heat producer - a low-temperature heat consumer. The storage and heat exchanger parts are estimated at a cost of 3 million Swiss francs. A detailed study of this project will be made and it is financed by a private research fund.

CONCLUSION

Wherean research on underground heat storage has made great progress since the first publication of MEYER and TODD (1974), experimental proof of the validity of our models and foreseeing calculations is unfortunately lacking. Further, the phenomenon of natural convection mustbe studied as a priority so that it may be introduced into the models.This phenomenon a very important unsettled point as to the thermal efficiency of underground heat accumulation.

ACKNOWLEDGEMENTS

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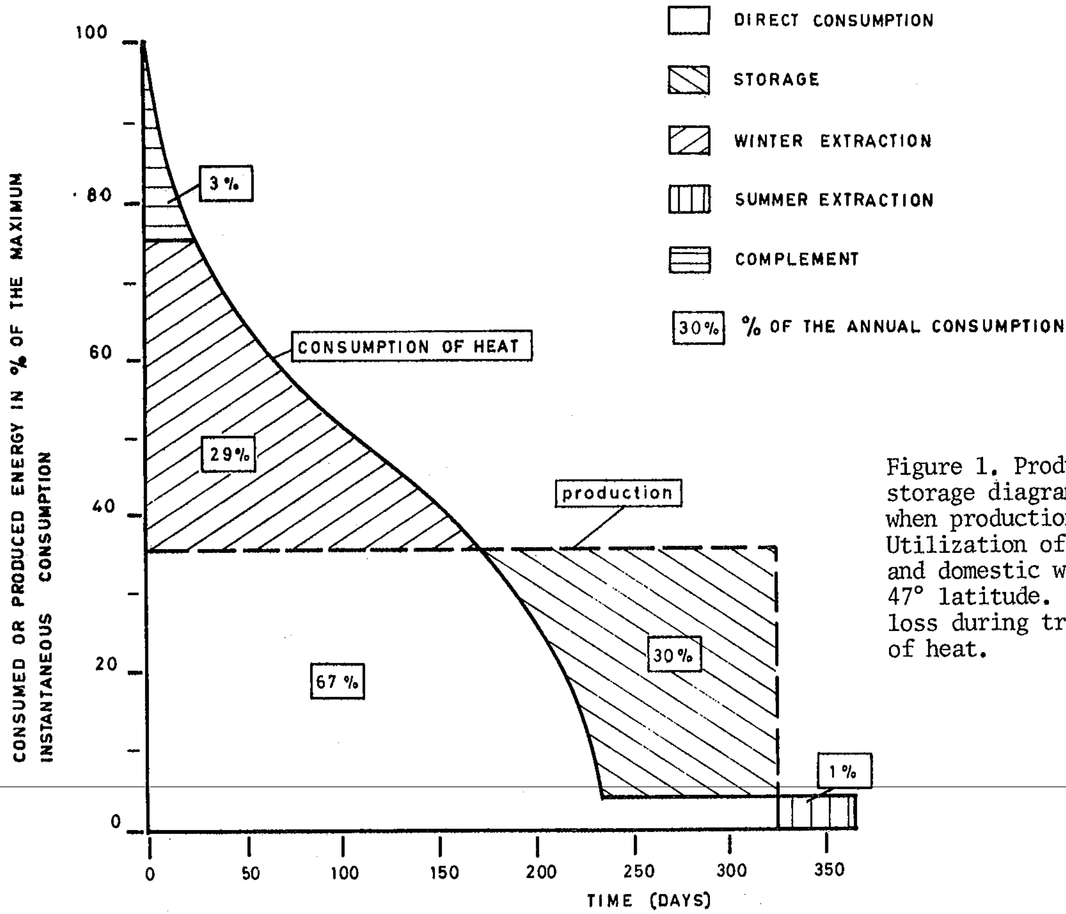


Figure 1. Production-consumption-storage diagram of thermal heat when production is unvarying. Utilization of the heat: space and domestic water heating at 47° latitude. Hypothesis: no loss during transport and storage of heat.

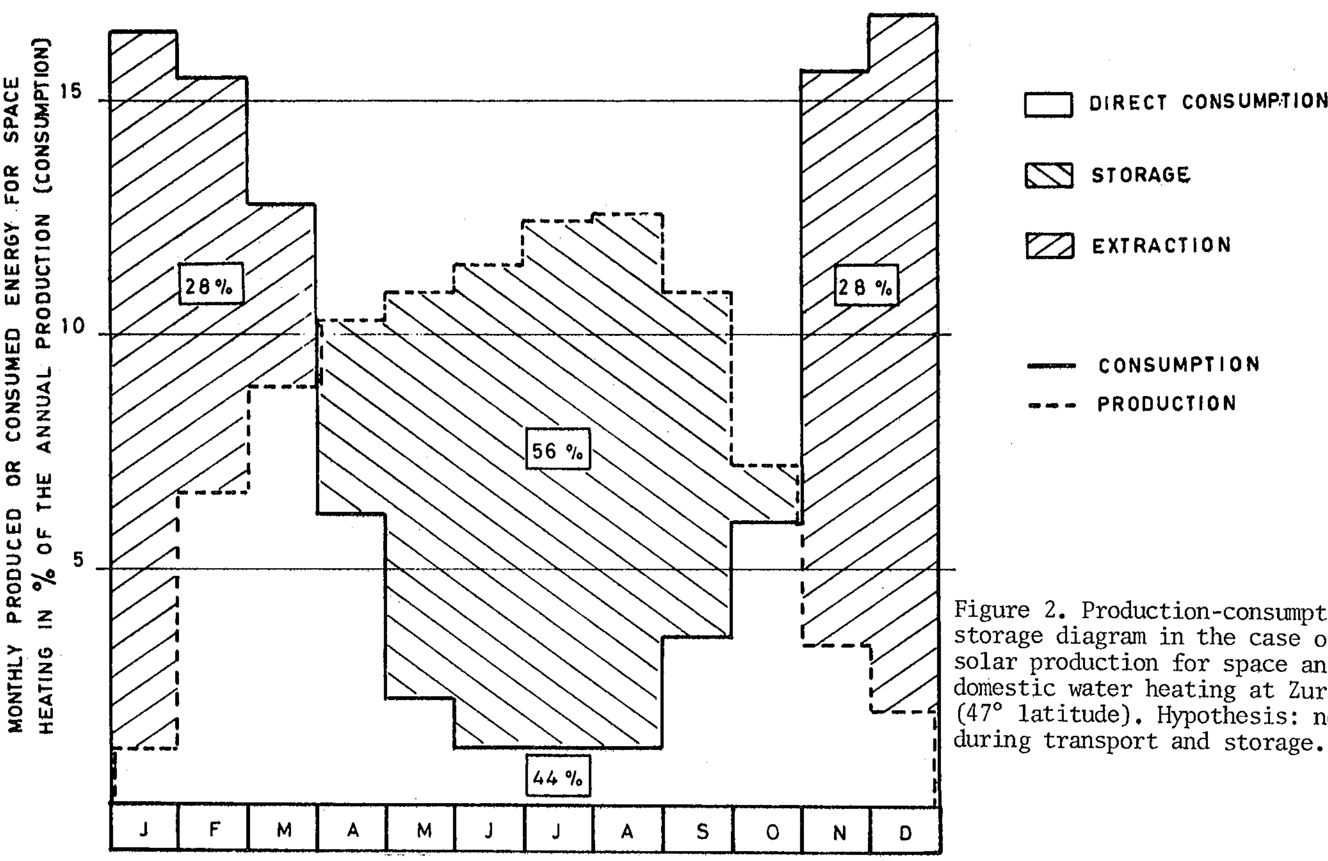


Figure 2. Production-consumption-storage diagram in the case of a solar production for space and domestic water heating at Zurich (47° latitude). Hypothesis: no loss during transport and storage.

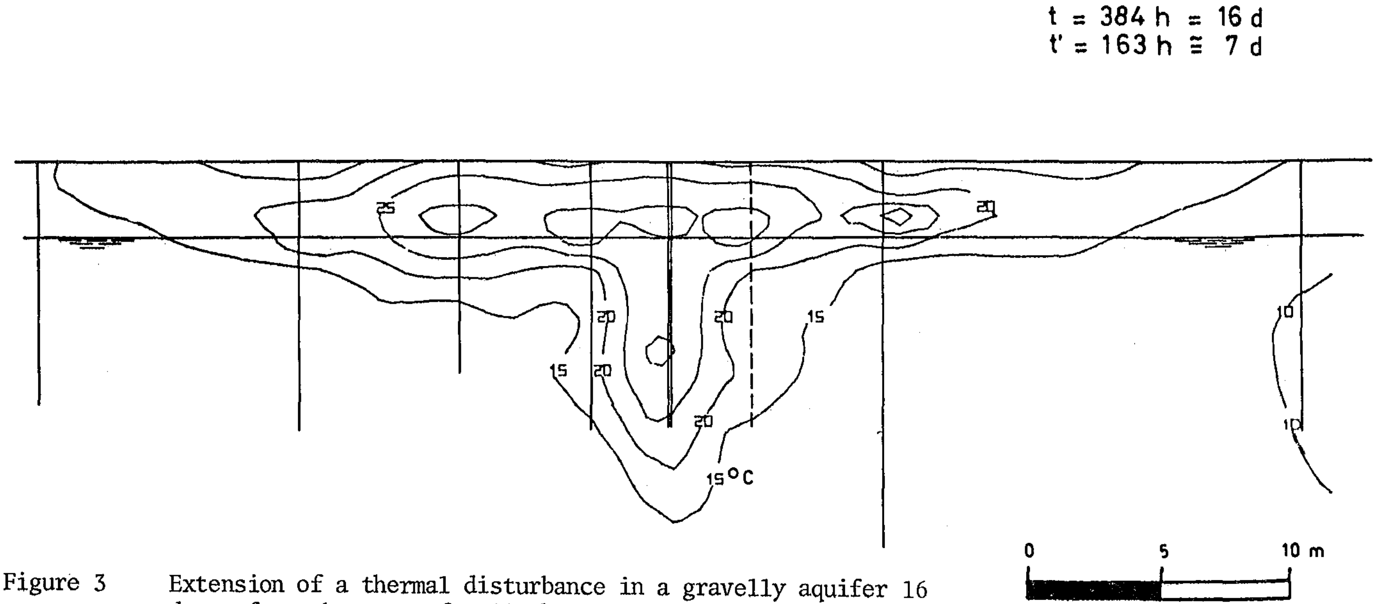


Figure 3 Extension of a thermal disturbance in a gravelly aquifer 16 days after the stop of a 223 hours injection (37 l/min) of water at 51°C into the Colombier-Robinson well(MATHEY, B., 1977 I). We can interpret the form of the isotherms as the effect of natural convection.

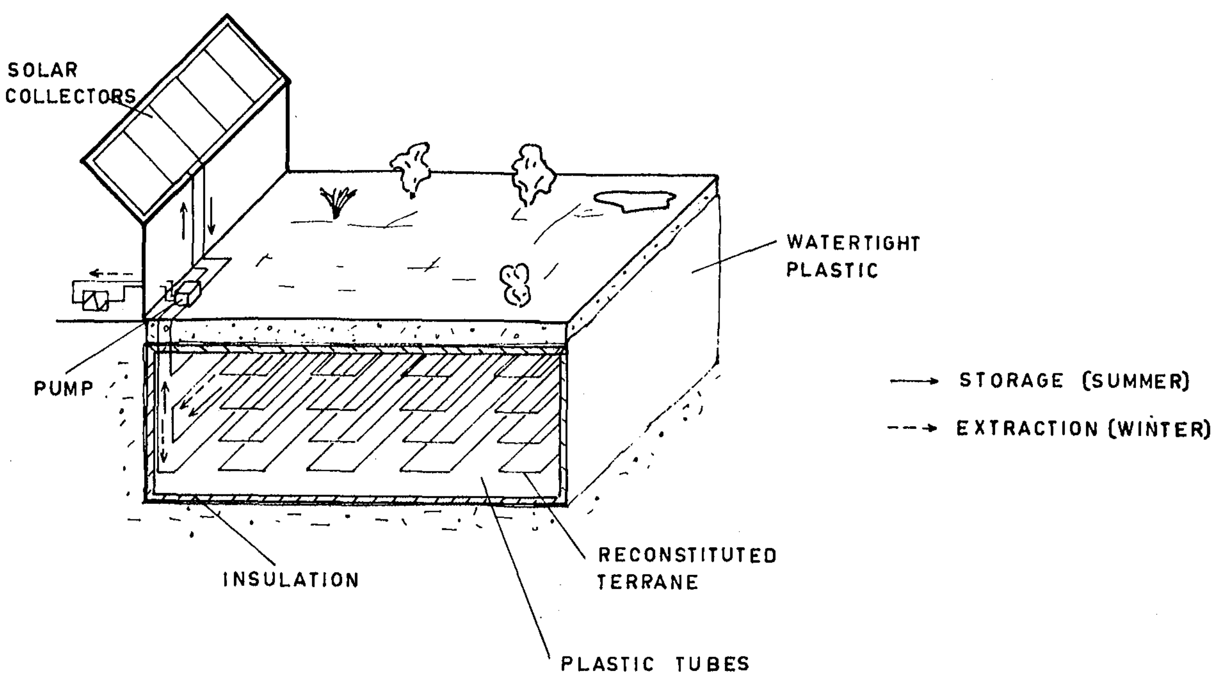


Figure 4 Project of heat accumulator in a rehandled terrain for a family house or small appartment with overall insulation.

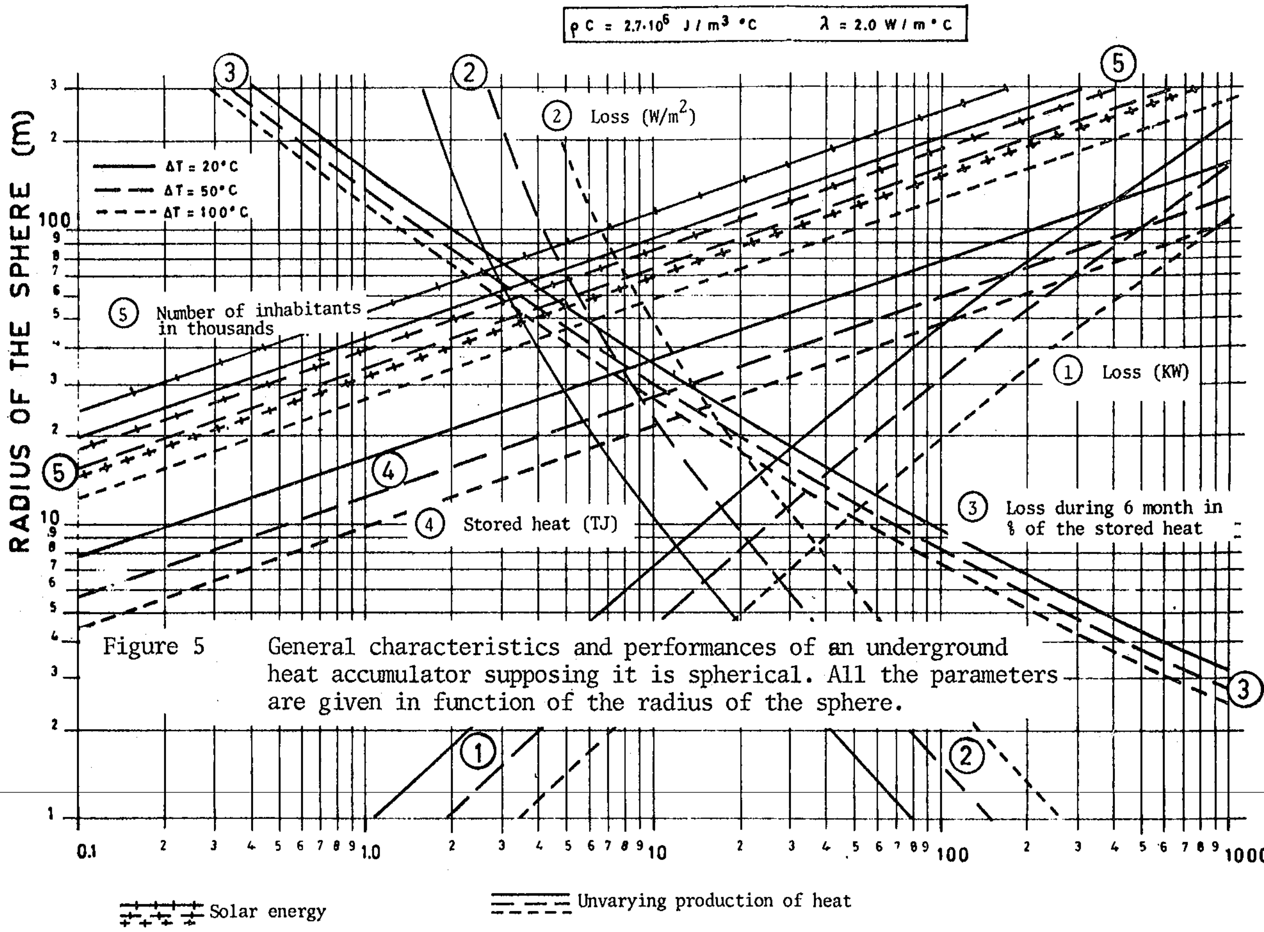
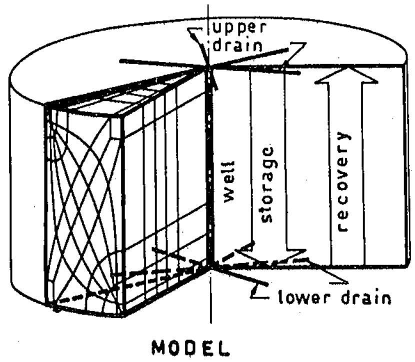


Figure 5 General characteristics and performances of an underground heat accumulator supposing it is spherical. All the parameters are given in function of the radius of the sphere.



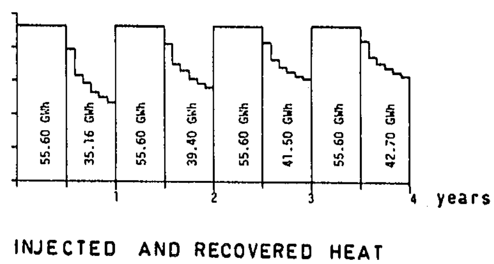
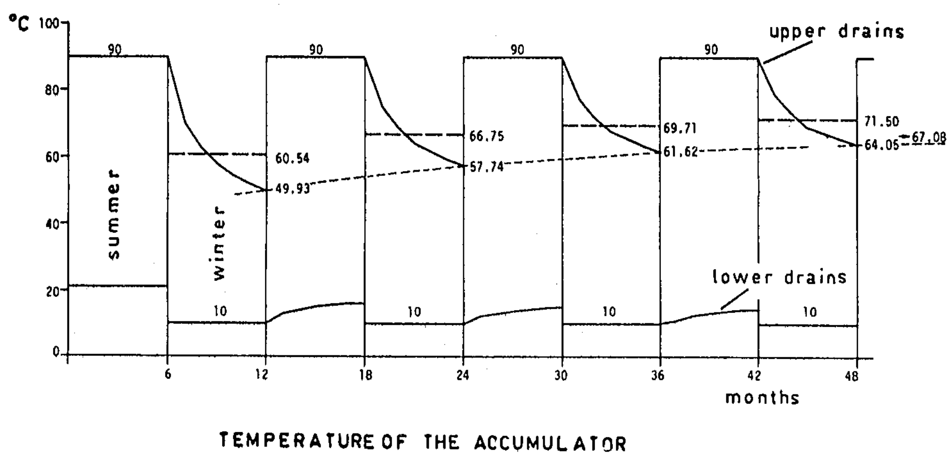


Figure 6

Heat Accumulator project tested numerical by MENJOZ and JOOS (1977), consisting in a well with a large diameter and two levels of drains for injection and pumping.



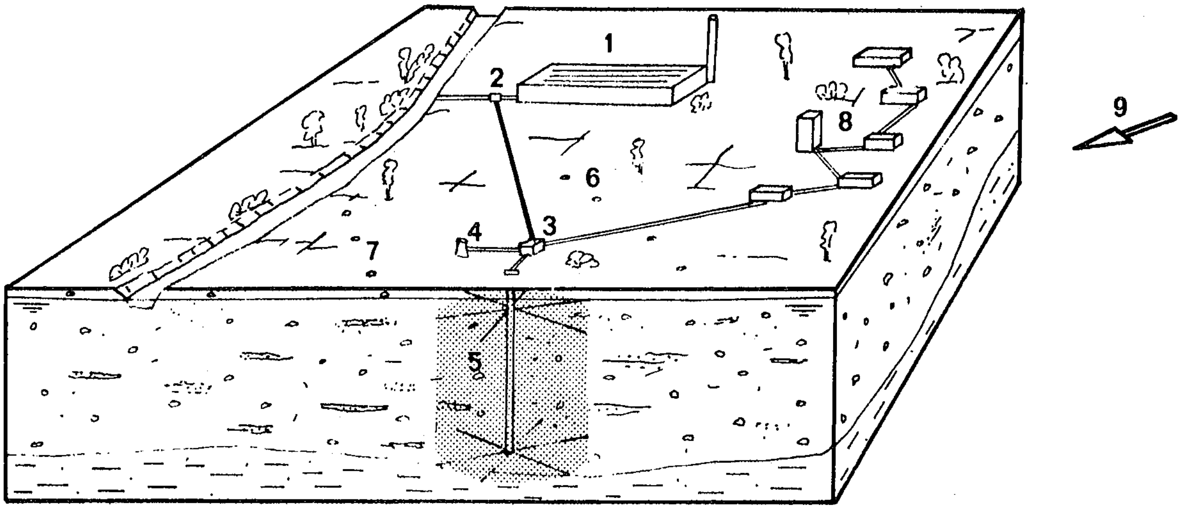


Figure 7 Project of a heat accumulator of 10 Tcal at low temperature (70°-30°C) Using industrial warm waste waters. 1. Industrial zone. 2. Heat exchanger. 3. Valve regulating and distributing heat. 4. Cooling tower(temporary) 5. Underground accumulator. 6. Pumping wells to prevent natural underground outflow. 7. Injecting wells for water pumped in 6. 8. Buildings with low temperatur heating systems. 9. General direction of the flow in the aquifer.

50 m

Table 1. Main advantages and disadvantages of underground heat storage in function of the dimensions of the accumulatoı

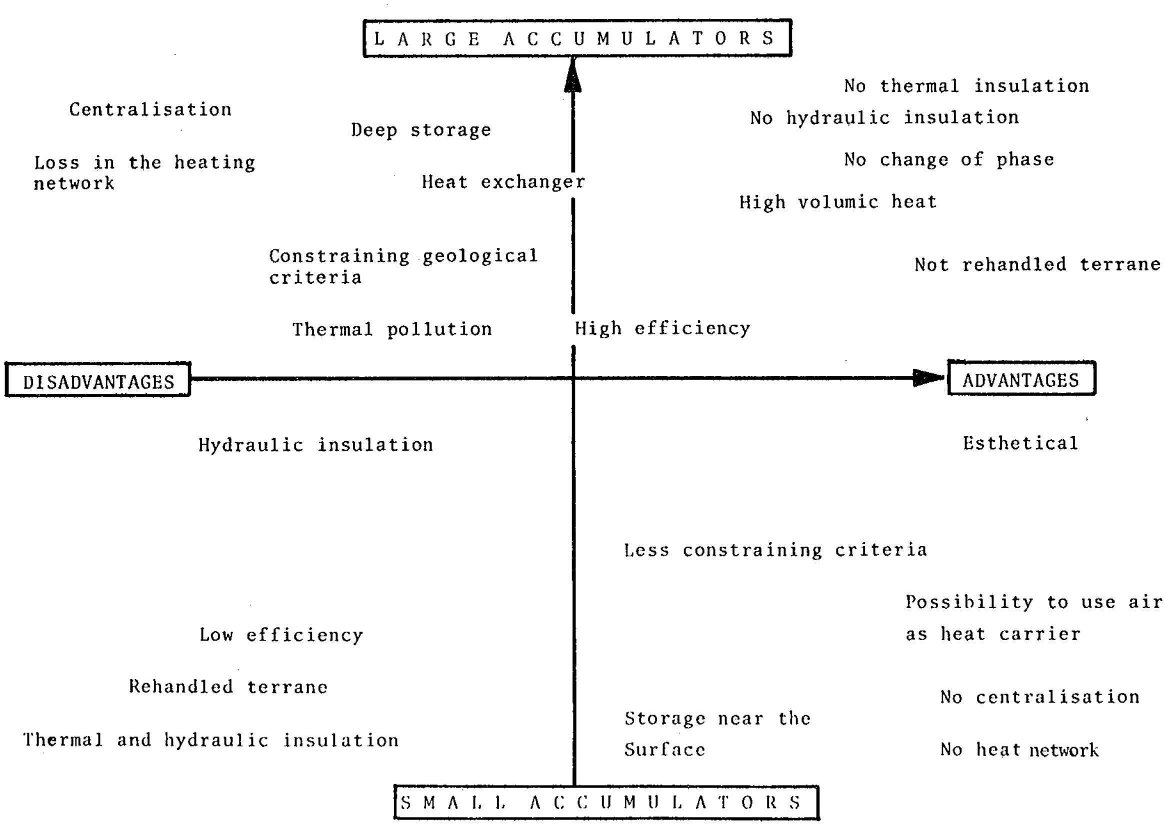


Table 2 - Main functions used in the SOLAC model to calculate the thermal balance of a small accumulator (family house or small apartment house).

Solar energy to the collector

$$E = S_c \frac{N_H \cdot N_j}{N_{th}} E_o$$

Energy produced by the solar collectors

$$E' = E \cdot A - K \cdot N_H \cdot S_c \left[\left(T_{AC} + \Delta T/2 \right) - \left(T_A + \Delta T_j \right) \right]$$

Heat consumption of the house

$$E'' = C_1 \left(T_{MIN} - T_A \right)^{1,5} \cdot H + C_o H$$

Thermal balance of the accumulator

$$T_{AC} = T_{AC} + \left(E' - E'' \right) / \rho C \cdot V$$

Decrease of the temperature of the accumulator

$$T_{AC} - T_S = \left(T_o - T_S \right) e^{-\beta t} \qquad \beta = \frac{\lambda \cdot S}{e \cdot \rho C \cdot V}$$

Water temperature in the heating system

$$T_{Ci} = T_{ZER} - T_A$$

Identification of the variables :

E	:	Energy to the Collectors
E'	:	Energy produced by the collectors
E''	:	Heat consumption of the house
S_c	:	Surface of the collectors
N_H	:	effective hours of sun pro month
Nth	:	Theoretical monthly sunny hours
Nj	:	Days in the month
Eo	:	Energy brought by the sun
A	:	Optical efficiency of the plate collector
K	:	Coefficient of thermal loss of the collector
T_{AC}	:	Temperature of the accumulator
ΔT	:	Temperature difference of the fluid input and output
T_A	:	Mean temperature of the air
ΔTj	:	Temperature difference between the mean temperature of the air and the mean temperature of the air during the functioning of the collectors.
T_{MIN}	:	Temperature of the air below which the space heating is functioning
H	:	Number of inhabitants
C_o	:	Constant giving the used for domestic water heating
C_1	:	Constant giving the consumption of energy for space heating pro inhabitant
ρC	:	Volumic heat of the accumulator
λ	:	Thermal conductivity of the insulation
S	:	Total external area of the accumulator
β	:	Coefficient of decreasing temperature of the accumulator
t	:	Time
e	:	Thickness of the insulation
T_{Ci}	:	Temperature in the space heating system
T_{ZER}	:	Temperature in the space heating system for $T_A = 0^oC$
T_s	:	Temperature of the soil around the accumulator
V	:	Volume of the accumulator
T_o	:	Initial temperature of the accumulator

Table 3 - Dimension of an heat accumulator for space heating and domestic water heating for a city of 20'000 habitants. Latitude 47°, $\Delta T = 100°C$. Hypothesis: the accumulator is spherical.

	Unvarying production	Solar production
Radius of the accumulator (if spherical)	73 m	88 m
Volume of the accumulator	$1,6.10^6$ m^3	$2,8.10^6$ m^3
Stored heat	350 Tj	600 Tj
Loss of heat	575 KW	750 KW
Loss pro square meter	8,0 W/m^2	7,2 W/m^2
Loss during 6 month in % of the stored heat	2,2%	1,7%
Rate of temperature decrease in % pro 100 days	1,3	1,0

The values of this table were obtained with the graph of the figure 5

The values can be thought as too optimistic.

Table 4 - Technical characteristics of an underground a seasonal accumulator of heat in project.

Ground volume concerned	: $6 \cdot 10^5$ m^3
Height	: 40 m
Drains	: 2 x 6 drains of 35 to 40 m
Diameter of the well	: 2,20 m
Geology	: Uncemented gravel and sand
Permeability	: K (Darcy) > 10^{-5} m/s
Depth of the aquifer	: -2 à -10m
Maximum flow (injection or discharge)	: 3000 lit/min
Accumulated energy	: 10 Tcal
Storage temperature	: 70°
Withdrawal temperature	: 35 - 60°C
Source of heat	: industrial wastage
Estimated cost for the construction	: 3 million swiss francs

HEAT STORAGE IN A PHREATIC AQUIFER: CAMPUGET EXPRIMENT (GARD, FRANCE)

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SUMMARY

In recent years, heat storage in aquifers has been considered in France for several purposes:

- interseasonal storage of solar heat,
- recovery of unused industrial thermal effluents (e.g. from power plants),
- storage of energy from a thermal nuclear reactor during the summer,
- thermal "recharge" of a depleted geothermal field.

The purpose in all these cases is space heating in winter.

Several theoretical calculations and efficiency estimations have been made, which show, in some cases, that these projects are economically and technically feasible. But it was felt that experimental evidence of this efficiency was necessary before proceeding further along this line.

The first experiment was performed in 1976-77 by the BRGM (Bureau de Recherches Géologiques et Minières) jointly with the CENG (Centre d'Etudes Nucléaires de Grenoble) and the Ecole des Mines de Paris (Centre d'Informatique Géologique, Fontainebleau), at Bonnaud (Jura).

A small quantity of hot water (1400 m^3 at 40°C) was injected during 20 days, and recuperated after 4 months in a confined aquifer, 3 m thick. The aim of this experiment was : i) to measure in situ thermal parameters of the aquifer, and ii) to experiment with heat storage. Only 30 % of the heat was recovered, at an average temperature of 15°C, for a withdrawal of 3000 m^3, and a normal temperature of 14°C in the aquifer. This was not surprising, considering the size of the experiment.

The Campuget experiment (1977-78), which we are going to describe, aims at a real-size storage (e.g. storing heat for the needs of 100 housing units) in an ordinary phreatic aquifer. This type of aquifer is very common in our country, and therefore the method could be widely applicable.

This research was sponsored by the Ministère de l'Equipement, Plan Construction, and carried out jointly by Electricité de France, Direction des Etudes et Recherches, Département Application de l'Electricité, and Ecole des Mines de Paris, Centre d'Informatique Géologique, Fontainebleau.

The Plan Construction sponsors research in the field of solar energy for space heating, and is interested in the use of low temperature water from phreatic aquifers for heat pumps, and also interseasonal heat storage in these aquifers.

Electricité de France has a research program on the use of electric heat pumps (for space and greenhouse heating), and is therefore interested in their association with water stored at low temperature (20°-40°C) and solar energy.

Ecole des Mines has research activities both in heat transfer in porous media and in solar energy.

CAMPUGET EXPERIMENT (Gard, France, July 77-March 78)

The research proceeds along two lines:

1. Realization of a large interseasonal storage in a phreatic aquifer - Study of its evolution - Measuring of the efficiency of the recovery - Numerical simulation.

2. Utilisation of the stored heat in the framework of already existing greenhouses - Application to space heating.

The experiment is now finished. We are beginning to interpret our measurements concerning the thermo-hydraulic mechanisms in the aquifer (the thermal measuring was made in nine observation wells distributed over 10000 m^2 around the injection center).

Description of the aquifer

It is an unconfined aquifer in quaternary alluvial deposits (pebbles, gravel, sand and clay) located between 3 and 10 meters under the surface (permeability 10^{-3} m/s); a pumping well in activity at a distance of 200 m to the west creates a 2 ‰ local gradient. The average initial temperature is 14°C.

Description of the experiment

July 3, 77 - Sept 28, 77 (3 months) (Continuous storage of 400,000 therms by 20,200 m^3 of water at the average temperature of 33.5°C. The water is withdrawn from the aquifer at a distance of 200 m, heated by rough solar captors and heat pumps, then injected into the aquifer at a depth of 7 to 10 m (position of well screens).

Sept 28, 77 - Nov 8, 77 (1,5 month): first waiting period: no intervention on the storage. The temperature decreases from 33,5° to 30°C in the center.

Nov 8, 77 - Dec 20,77 (1,5 month): withdrawal of 5000 m^3 at a temperature decreasing from 30°C to 21°C (average 24.5°C), which represents 14 % of the total heat stored, with a temperature efficiency above 50 %

$$\text{(efficiency} = \frac{\text{average withdrawal temp. min. } 14°C}{\text{average injection temp. min. } 14°C}\text{)}$$

Dec 20, 77 - Jan 20, 78 (1 month): Second waiting period: no intervention on the storage. The temperature decreases from 21°C to 19°C at the center.

Jan 20, 78 - March 15, 78 (2 months): withdrawal of 12,000 m^3 at a temperature decreasing from 19°C to 14°C (average 16°C) representing 4,5 % of the total heat stored, with a 8 % temperature efficiency.

On the whole, we have recovered 17,000 m^3 of water, at a temperature falling between November and March from 30°C to 15°C. The energy recovered represents approximately 20 % of the total heat stored in the summer.

14 % have been recovered after 2 months waiting with a 52 % temperature efficiency.

Comments and present interpretations

Storage period: We observe, during the summer, a vertical gradient of temperature in the observation wells which are located at a short distance from the injection center (Fig.1:thermal logging at 20 m from the injection center - summer). The hottest zone is situated between 3 and 7 m under the surface where the permeability of the aquifer seems to be the greatest. This hypothesis has been confirmed by a first experiment of tracing with salt.

First waiting period: The heat is globally dispersed over a 50 m range, with an asymetry in the west (toward the well pumping at a distance of 200 m); we also observe a tendency toward the south due to an increase of permeability (horizontal heterogeneity) in the southern part of the storage zone. The average pore velocity of the water in the aquifer is on the order of 20 cm/day; in spite of that, the hottest zone remains at the injection center during the waiting period, the heat is maintained by the solid matrix.

Pumping period: The main phenomenon observed is the efficiency decrease between the first and the second period of withdrawal. This phenomenon is correlated to the following observations:

- accumulation of rainfalls (700 mm between October and March),
- decrease of the thickness of the unsaturated zone (3 m in October, 1 m in January),
- important decrease in air temperature (16°C in October, 6°C in January).

It seems that the heat losses by horizontal dispersion and convection have been notably increaseed by a thermal exchange across the thin unsaturated zone. This exchange increased during the winter. We can observe from December on, a vertical thermal gradient between 2 and 7 m, in the most permeable zone (Fig.1: Thermal logging at 20 m from the injection center - autumn and winter) On the other hand, we observe a progressive thermal recharge of the underlying clay.

We have also noticed a difference between the temperature of the solid matrix near the pumping well, and the temperatures of the water pumped at the same time. This difference increased during winter (Fig. 2). That last phenomenon seems to confirm the combined reasons of heat loss: on one hand, a preferential circulation in the upper part of the aquifer, and on the other hand, thermal exchange across the unsaturated zone.

Water quality

- Chemical: The main problem was the possible precipitation of carbonates (in equilibrium in the water at 14°C) with the increasing temperature, which could clog up the injection wells. This depended on the cinetic of the chemical reaction; such a precipitation was never detected by chemical analysis, nor did any clogging occur during the storage period. The carbonates precipitation must have been absent or very slow.

- Bacteriological: We observed an important local bacterial development (escherichia coli,...) which was treated by moderate chlorine injections (10 cl/week). No clogging was observed.

CONCLUSION

Quantitative interpretation of the experiment by mathematical modelling of the combined flow of heat and water in the aquifer is currently in progress, using a 3-D finite element model of the diffusion-convection equation.

Once the model is calibrated on the observed set of data, it is expected to provide estimates of:

- heat losses through the unsaturated zone (present evaluation: 20-35 %),
- heat losses in the substratum (present evaluation: 10 %),
- heat losses by convective transport toward the pumping well at 200 m (present evaluation: 10-30 %),
- heat losses by unrecovered heat left inside the rock mass (present evaluation: 10 %).

We will then be able to use the model to predict the efficiency of the storage for a series of years of operation, or for a larger amount of heat stored, or even for a different configuration: thicker or deeper aquifers (with the same properties), or influence of thermal and/or hydraulic isolation on the soil surface, or optimal distribution of injection and withdrawal wells, etc...

The two main difficulties of this effort concern (i) the representation of heat and water transfer in the unsaturated zone, which are moisture-content dependent, and will require in situ measurements of hydraulic and thermal conductivity as a function of saturation, and (ii) the important influence of heterogeneities inside the formation on the actual behavior of heat. More tracing experiments will be performed.

Although the present state of heat recovery (20 %) is not very high, we believe it to be rather encouraging for future work, as it can certainly be increased by:

- repetitive storage over several years (we have computed theoretically before the experiment, that at least five years are necessary, in our geometry, to obtain annual stabilisation, with a decreasing heat loss each year);
- increase, by a factor of 2 or 3, of the amount of heat stored;
- well pattern optimization, soil surface isolation, or deeper aquifer conditions.

Combined with the use of heat pumps, we have estimated that such low temperature inter-seasonal heat storage for space heating can be economical down to a heat recovery of 50 % with a highly positive total energy balance, provided that the capital cost is small (which is true for shallow aquifers), and the heat injected is cheap (rudimentary solar captors, thermal effluents, low cost energy during slack hours,....).

We are, at present, looking for such a project involving the actual heating of 100 to 500 housing units.

APPENDIX: OTHER CURRENT RESEARCH IN FRANCE IN HEAT STORAGE IN THE GROUND

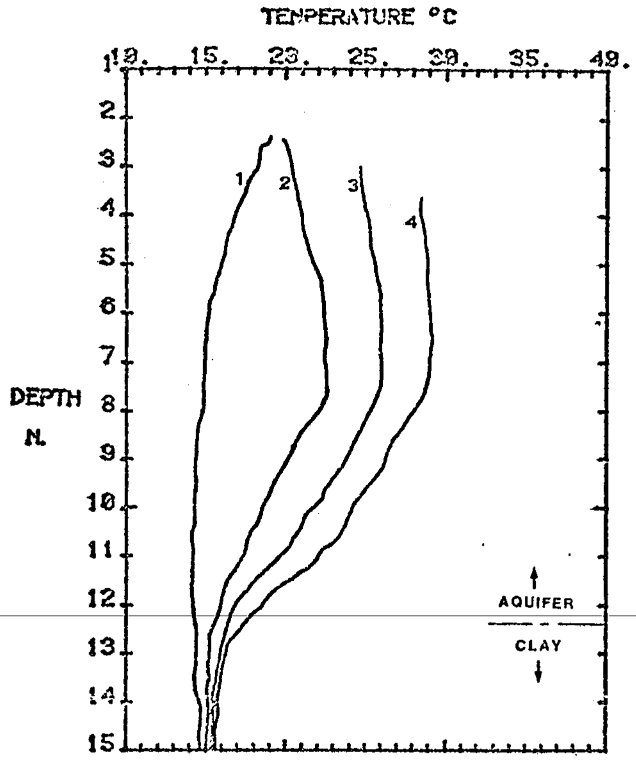
- M. JOUANNA, University of Montpellier: Theoretical and experimental study of heat flow in a two phase medium (for evaluation of behavior in the unsaturated zone, heat losses, heat storage and ecological and mechanical impact), (sponsored by Plan Construction).
- M. SAUTY, BRGM: Modelling of heat storage in aquifers (sponsored by Plan Construction). This research takes into account the regional flow and the conductive heat loss, for seasonal heat storage and also alternative heating-cooling systems.
- MM. VACHAUD, VAUCLIN, AUSSEUR, CNRS, Institut de Mécanique de Grenoble: Moisture dependent heat and water flow in the unsaturated zone: a theoretical result, which has been recently obtained, concerns the effect of rain infiltration on the thermal recharge: in the case of a water table aquifer at a depth of 3 m at a temperature of 60° overlayed by a fine sandy soil, in hydrostatic equilibrium, with the soil surface temperature at 15°C. It is shown that the heat reaching the aquifer after a two day rainfall of 50 mm/day, is equivalent to the heat loss by conduction through the unsaturated zone during six days. This result has been obtained by numerical simulation of the transient flow equation of heat and water in the unsaturated zone, coupled with temperature and water content as dependent parameters. Also heat storage in dry soils with heat exchangers.
- M. TORENTI, CEA: Storage in excavated cavities in the unsaturated zone.
- MM. DESPOIS (CEA) and NOUGAREDE (ELF-Aquitaine): Storage of hot pressurized water (170°C) from a thermal nuclear reactor in deep aquifers.
- M. GUIMBAL, SGET: Heat storage in dry cristalline rocks through a large number of well serving as heat exchangers.
- E.D.F.: Use of heat pumps with plastic pipes buried in the ground as heat exchangers.
- B.R.G.M. and D.D.E. of Vaucluse: Use of water-water heat pumps for space heating in the phreatic aquifer of Avignon.

For further references, refer to:

G. de MARSILY: Peut-on stocker de l'énergie dans le sol ?
Les Annales des Mines, April 1978.

FIG.1 - EVOLUTION OF A THERMAL LOGGING

AT 20 M. FROM THE INJECTION CENTER



← Summer-storage

-1 July, 3, 1977 - Initial conditions

-2 July, 31, 1977 - After one month storing

-3 August, 18, 1977 -

-4 Sept, 28, 1977- End of the storage

(Continuous storage from July, 3, 1977 to August, 9, 1977 - 240 m^3 per day at 33.5°C).

Autumn and winter - Waiting period and heat recovery

——— -1 Sept, 28, 1977 - Beginning of the first waiting period

——— -2 Oct, 20, 1977 - Waiting period

- - - -3 Nov, 18, 1977 - Beginning of the first heat recovery

— — — -4 Dec, 15, 1977 - End of the first heat recovery

• • • • • -5 Jan, 1, 1978 - Beginning of the second heat recovery

• • • • • -6 Feb, 21, 1978 - During the second heat recovery

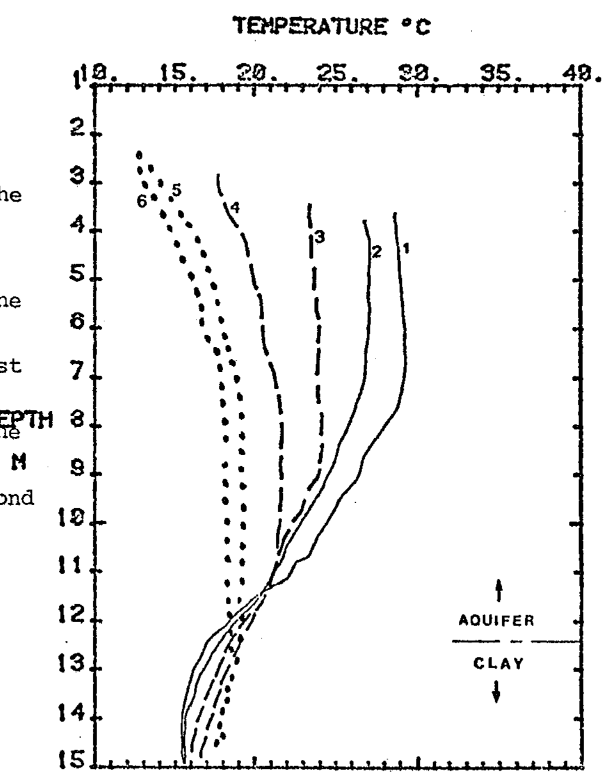
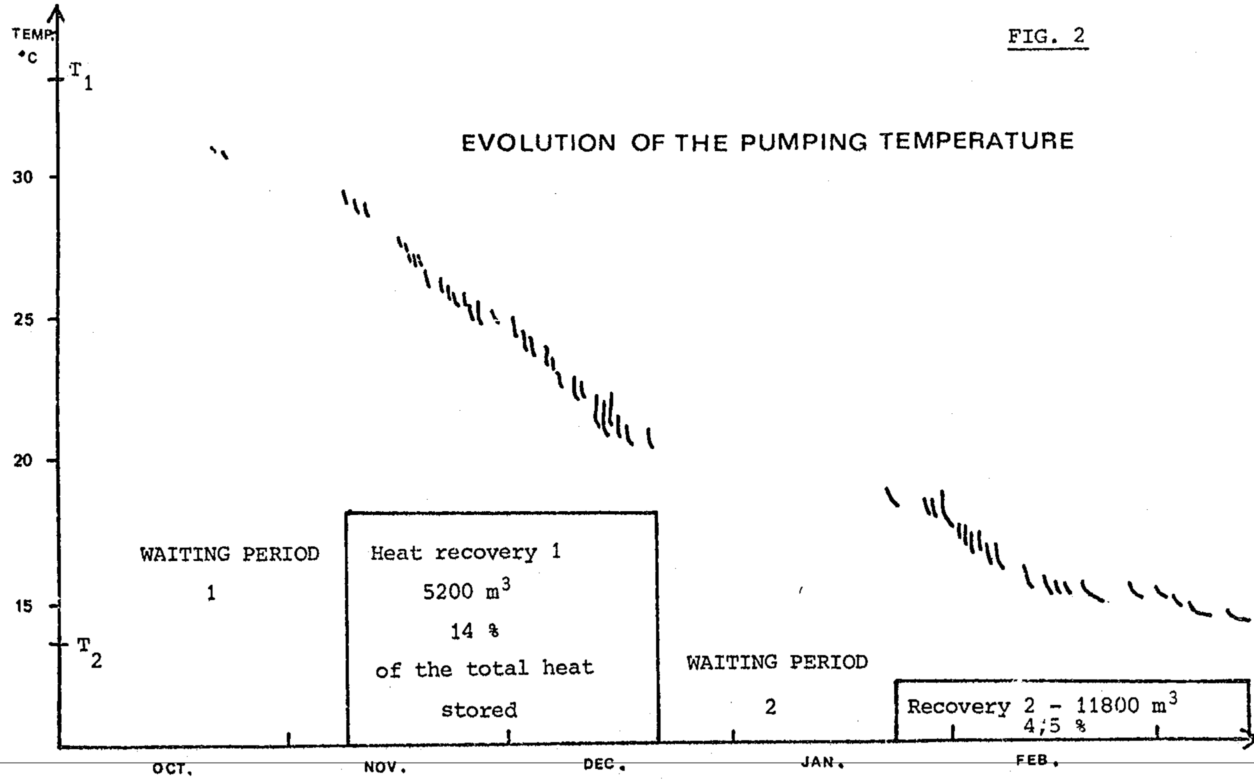
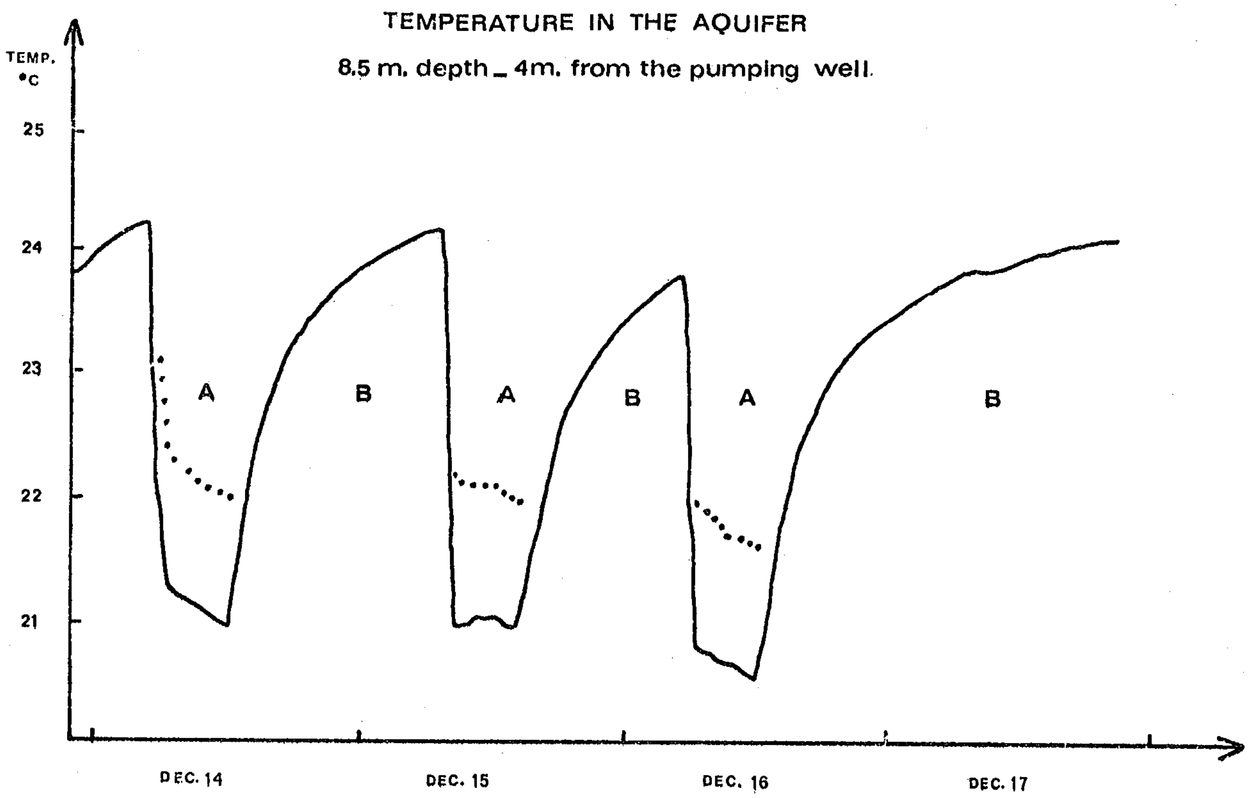


FIG. 2



T_1 33,5°C average injection temperature (summer-storage)
T_2 14°C initial temperature of the aquifer



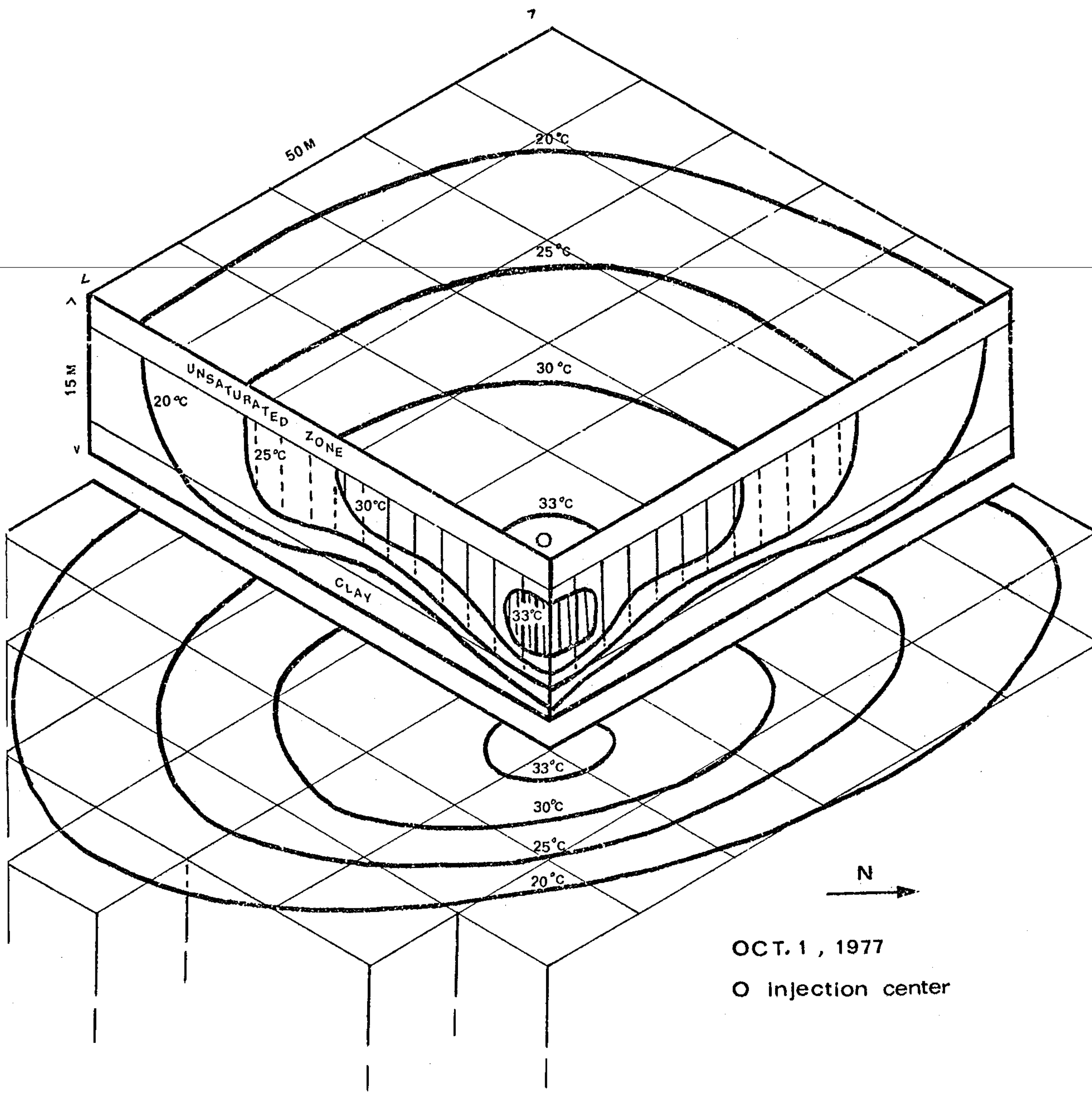
A With pumping

B Without pumping

—— Temperature measured in the aquifer (8,5 depth) in the observation well, 4 m from the pumping well

•••• Temperature of the withdrawal water during a pumping phasis.

FIG.3 - HEAT REPARTITION IN THE AQUIFER
AT THE END OF THE STORAGE
(autumn 1977)



SEASONAL REGENERATION THROUGH UNDERGROUND STRATA

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ABSTRACT

Different from present Solar energy system, which use only heat energy and regenerate daily at most, our system makes good use of not only heat but also cold, which are stored until the next available season, namely "Seasonal Regeneration".

Inhabitants of Temperate Zones, such as Japan, struggle with cold weather in winter, while they are suffering from hot sultry weather in summer. From another point of view, in this area the Sun supplies an enormous amount of heat energy in summer, but on the contrary in winter an enormous amount of cold energy, namely the "Condensed Cold" of snow and ice is delivered. Therefore, both hot and cold heat sources are available in the same places.

It seems to us that underground strata stores each season's heat source until the next available season because of its insulation effect composed of impervious layers, and its huge heat capacity. This enables us to obtain the hot originated in summer and the cold originated in winter, provided that the waste "Cool Heat" (in winter) and "Hot Heat" (in summer) are alternately stored, and then these heat sources can be regenerated permanently. In addition to air conditioning, we can also use this energy for agriculture and fish breeding.

In fact, our field experiments and theoretical analysis show this to be possible.

1. INTRODUCTION

Large amounts of low concentrated Solar energy reach the earth. Temperatures are neither high nor low, furthermore the energy varies by regions and seasons. So we have not been able to make good use of it, but have only suffered from its influences.

Especially in the Temperate Zone, e.g. Japan, such as an enormous amount of heat energy is given in summer so that cooling is needed for many months. In winter cold weather or what we might call "Condensed Cold" i.e. snow, necessitates heating for many months. Presently most heating is done by petroleum. In Japan, 12% of all oil is used for heating. Oil heating is at present relatively inexpensive but in future, shortages of petroleum will require us to find alternate heat sources.

From another point of view, the weather during each season, i.e. the hot in summer and the cold in winter, represent permanent heat sources and heat sinks not found anywhere else. Furthermore even where Solar energy systems cannot be used in winter, we may collect heat energy by a Solar system or a refrigerator during the summer months for heating in winter.

Different from the usual Solar Energy System which uses only a heat source and achieves, at most, daily regeneration, if each season's weather is regenerated for availability next season, we can make good use of seasonal variations. To be concrete, the regenerated hot heat originated in summer carries out heating in winter directly or by heat pump, and out snow melting in heavy snow fall area. In return, the regenerated cool heat originated in winter carries out cooling directly or by refrigerator during the summer.

Just below the earth's surface is known to be of constant temperature throughout the year. This characteristic is due to the fact that the earth consists of less thermal diffusive material such as soil. In the absence of underground water flow, we can show this insulating effect is sufficient for seasonal regeneration by Carslow's vertical one dimensional solution [1]. From injection of a heat source with Θj°c into a layer of thickness 2b initially $\Theta\infty$°c, then unsteady temperature distribution is given below,

$$\frac{\Theta a-\Theta\infty}{\Theta j-\Theta\infty} = \frac{1}{2}\left(\mathrm{erf}\,\frac{b-z}{2\sqrt{kt}} + \mathrm{erf}\,\frac{b+z}{2\sqrt{kt}}\right) \quad \text{----------} \quad (1)$$

where thermal diffusivity of the soil is generally very small, at most in the order of $10^{-3}m^2/h$, so the temperature drop of the injected heat source over a half year period is,

$$\tilde{\Theta} a \equiv \frac{1}{b}\int_0^b \frac{\Theta a(z)-\Theta\infty}{\Theta j-\Theta\infty}\,dz \simeq 0.7 \sim 0.8 \quad \text{---------} \quad (2)$$

also shown in Fig. 1, where 2b = 19m, and $\frac{kt}{b^2} \approx 0.04$.

This insulating condition causes surface water penetrating with yearly cyclic temperature to be constant. Namely, a constant underground temperature is the result of natural seasonal regeneration.

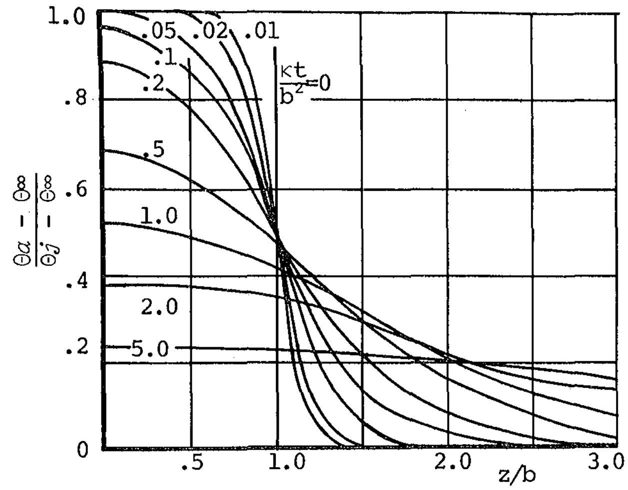

Fig.1 Temperature Propergation with $\kappa t/b^2$ (Carslow,et al.[1])

Man has always used wells, springs, etc. for drinking, cooling and other purposes because of their good quality and constant temperature. But, as we have not paid attention to recharging, we have suffered from land subsidence and sea water intrusion, not to mention drops in the water table. For this reason we must in future utilize these water sources paying attention to natural recharging as well as artificial rècharging.

From our idea, we discharge from one well and simultaneously recharge the waste water into the other well for storage. Adding the unconcentrated seasonal heat energy throughout the field to the recharge water, storing in the aquifer until available next season, we can ultimately use the recharged water and regenerated heat source or sink more effectively, for example as a regenerative heat pump such as that illustrated in Fig. 2.

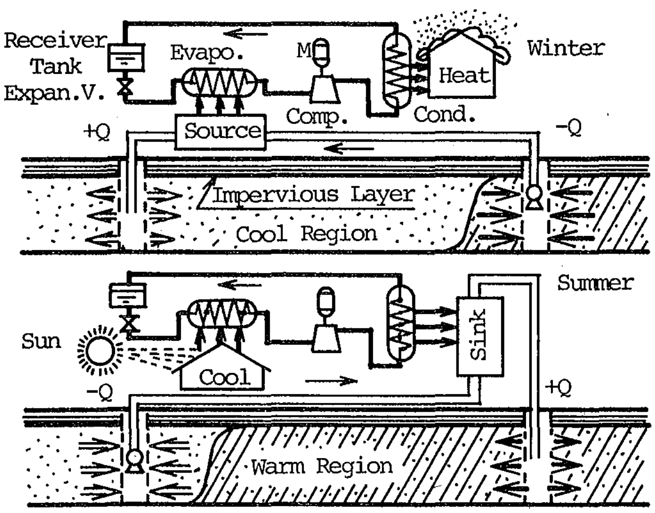

Fig.2 Scheme of Regenerative Heat Pump with Aquifer

But some problems resulting from injection arise. The first one is chemical pollution, and the second is thermal pollution in the aquifers. The former can be prevented by purification, and with less effort in the case of waste water from closed system. But for the latter to pretemper recharge water to the native level is not worth of thermal storage. Therefore the methods by which we can prevent thermal pollution and use the water for regeneration are that under the given natural conditions such as natural flow, aquifer depth, properties of layers, etc., we establish a suitable distance between the recharge well and the discharge well. For example, in the area of alluvial cones or basins where natural flow is not significant, thermal diffusion is not rapid and directed towards the pumping up well. Therefore we need a greater distance, but can expect long-run effective regeneration during seasons. Conversely, under rapid natural flow condition across the main well flow, thermal pollution can be easily cleared and we can use underground water as a constant heat source or sink.

In this paper, as a model field experiment on the above mentioned, we mainly testify seasonal regeneration less affected by natural flow, and thermal pollution caused by simultaneous recharge, on the supposition of practical heating for our building by heat pump in winter, and direct cooling or by refrigerator if need, in summer in an area subject to heavy snow fall in winter.

In addition to experiments, by the assumption of a simple underground strata-model and numerical analysis based on the divisions along with complex potential functions, we have tried to simulate the seasonal regeneration phenomena.

2. PREVIOUS WORK

2-1 Artificial Recharge

In many countries near the sea, i.e. the Netherlands, surface spread recharge is used successfully against sea water intrusion into coastal aquifers. In Europe, surface recharge is often used for water quality management [2].

In other which suffer from water shortage, underground storage is important. Especially in Israel, 10% of the annual fresh water supply is by artificial well recharge [3]. The most serious problem forced is clogging around the well, and this clogging phenomena of aquifers consisting of fractures and holes in rock such as limestone, sandstone, basalt, etc. was studied by Schwartz [4] both practically and with models.

In other countries such as Japan, rich in water resources but paying no attention to saving water resource and underground strata conservation, land subsidence and sea water intrusion in Quaternary deposits is occuring. Artificial recharge from wells is very useful as well as control of the discharge amount, for it is direct water delivery to the layer subject to subsidence. In fact, artificial recharge makes the piezometric surface up-lift as shown by Yokoyama [5]. Therefore in some places in Japan, artificial recharge installations are working. In unconsolidated aquifers composed of alluvial deposits, artificial recharge has been widely studied by the American Geological Survey and also Japanese Geological Survey. The clogging phenomena of unconsolidated aquifers was cleared by Price [6], and a recovery method for clogged wells proposed by Nagai, et al. [7]. Consequently we reached the point where recharge is possible if the quality of the water is similar to the native and if the flow rate of recharge is not forced.

2-2 Thermal Pollution Followed by Artificial Recharge

If contamination water such as sewage is recharged, chemical pollution may appear. By the same token, if the temperature is very different from the native, in time thermal pollution occurs, especially in the case of well recharge. Unlike geothermal sources, we cannot expect any heat source in an aquifer, not mention heat sink. For this reason we need to set a suitable distance between the recharge and discharge wells.

Under the parallel uniform flow caused by a group of injection wells of hot water into oil sand layer and the other group of production wells, Lauwerier [8] solved one dimensional unsteady state temperature distribution. Furthermore, Gringarton et al. [9] derived an approximate solution for any given flow pattern. Especially for pair wells of the same strength of sink and source he recognized the non dimensional parameters dominating temperature propagation, coinciding with that of Yokoyama, et al. [10]. Furthermore, Yokoyama tested his analysis in practical experiments and in scaled down model experiments [11]. Therefore we can predict temperature propagation and estimate a satisfactory distance between a pair of wells under simplified conditions.

2-3 Seasonal Regeneration

Constant temperature of underground water, which means truly natural seasonal regeneration, has been used as a heat source for heat pumps or heat sinks for refrigerators, but water wastage has caused underground water shortage. Therefore, we have lost the benefits of using it.

For the purpose of replenishment of underground water, this wasted hot or cool water was recharged, but this has been given up because of thermal pollution. From our opinion, by recharging with yearly cyclic temperature, 1) from an exclusive recharge well, 2) from alternately exchange wells, we can not only avoid thermal pollution but also make good use of these regenerating heat sources or sinks.

In Israel 10% of all fresh water is obtained by artificial recharge, mainly in winter. The temperature of discharge water in summer is cooler than the surface water as a result. Yokoyama, et al. repumped in summer 7°c water recharged the previous winter. After one year the discharge temperature shown in Fig. 3 was obtained. But no one has experimented with effective seasonal regeneration with quantitative data and a reasonable theory.

Regrettably, Gringarton's approximate solution cannot be applied to the entire range of seasonal regeneration, for a problem such as seasonal regeneration involves flow pattern change. Therefore it is difficult to predict seasonal regeneration through underground strata quantitatively.

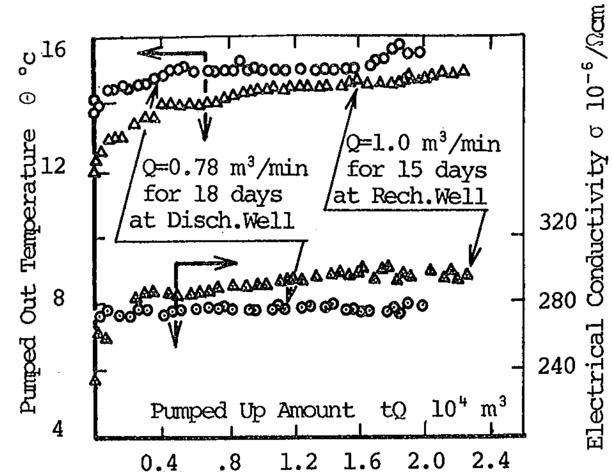

Fig.3 Obtained Cool Water after Regeneration during One Year

3. ASSUMPTION AND MODELING OF UNDERGROUND STRATA, AND FUNDAMENTAL EQUATION

Practically, the underground strata of the alluvial epoch spreads almost horizontally but at more or less non-uniform thickness. Due to the fact that in a confined aquifer, natural vertical flow, which is mainly caused by leakage of confining layers, is negligible compared with horizontal flow, in addition to the assumption of uniform thickness of an aquifer confined imperviously up and down as illustrated in Fig. 4, which is broadly adapted in hydrogeological analysis, we can use the following simple Laplace equation for potential field in confined aquifers.

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad (3)$$

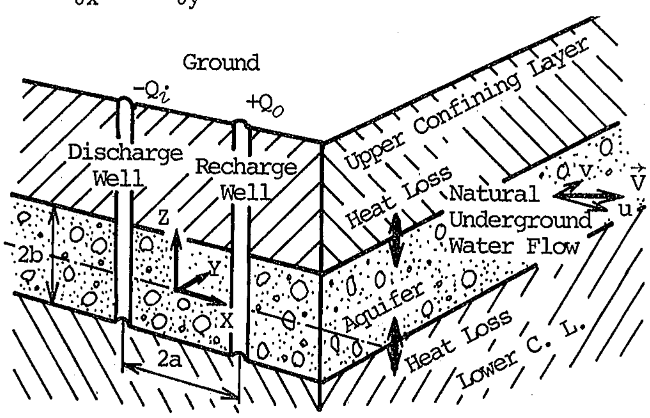

Fig.4 Underground Strata Model

Under natural horizontal flow, when one sink of $Q_i/2b$ strength corresponding to discharge well of Q_i m³/h is placed at (-a, 0), and one source of $Q_o/2b$ strength corresponding to recharge well of Q_om³/h is simultaneously placed at (a, 0) as illustrated in Fig. 4, water level distribution is given below,

$$h(x, y) \equiv \frac{\phi}{K} = \frac{1}{k}(ux + vy) + \frac{Q_i}{8\pi bk} ln[(x + a)^2 + y^2] - \frac{Q_o}{8\pi bk} ln[(x - a)^2 + y^2] \qquad (4)$$

Therefore, the complex potential function of this flow pattern is,

$$W = \phi + i\psi = sU + \frac{Qi}{4\pi b}ln(s+a) - \frac{Qo}{4\pi b}ln(s-a) \quad \text{---} \quad (5)$$

Where $s=x + iy$ is a complex variable, and $U=u + iv$ corresponds to the natural flow complex potential.

By the way, as the heat transfer phenomena in aquifers is dominated mainly by convectional term forced by well horizontal flow but negligibly by conduction and vertical natural convection term because of the small vertical temperature difference distinguished from Sahrock [12], only two horizontal directions are considered satisfactory for thermal diffusion of aquifers. In addition, to estimate heat loss into confining layers or heat recovery from them, vertical heat conduction at the interface between the aquifer and the confining layers is also considered. Then we can assume uniform thermal properties and the symmetry of vertical distribution. The energy equation of the aquifer is given below,

$$\lambda a\left(\frac{\partial^2\Theta a}{\partial x^2} + \frac{\partial^2\Theta a}{\partial y^2}\right) + c\rho\left(\frac{\partial\phi}{\partial x}\cdot\frac{\partial\Theta a}{\partial x} + \frac{\partial\phi}{\partial y}\cdot\frac{\partial\Theta a}{\partial y}\right) + \frac{\lambda c}{b}\frac{\partial\Theta c}{\partial z}\Big|_{z=b} = (c\rho)a\frac{\partial\Theta a}{\partial t} \quad \text{--------------} \quad (6)$$

In most cases, the horizontal heat conduction term is negligible compared with the convectional term, as simulated by Yokoyama, et al. [10]. Under typical conditions such as same strength of sink and source $Qi=Qo$, stagnant natural flow $U=0$, uniform initial temperature of the aquifer, and constant recharging temperature, Gringarton, et al. [9] determined an approximate solution.

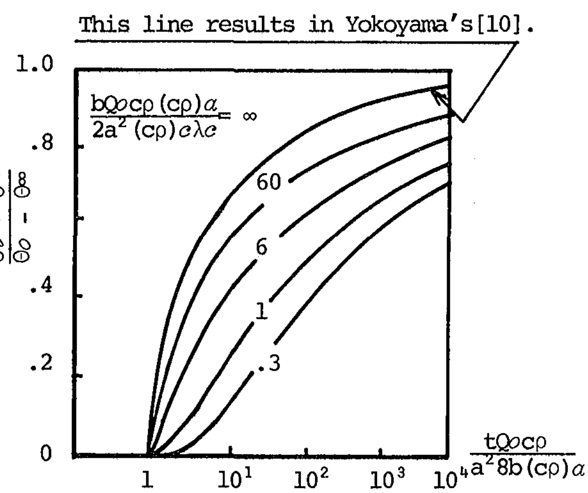

Fig.5 Discharge Temperature by Gringarton[9].

Also, Yokoyama, et al. [10] independently obtained the non-dimensional relation, then ensured it by a series of numerical analysis. Consequently, the combined results of Gringarton and Yokoyama are shown below and in Fig. 5,

$$\frac{\Theta a(x,y,t) - \Theta\infty}{\Theta o - \Theta\infty} = G\left[\frac{x}{a}, \frac{y}{a}, \frac{tQoc\rho}{a^2 2b(c\rho)a}, \frac{2bQoc\rho(c\rho)a}{a^2(c\rho)c\lambda c}\right] \quad \text{----------} (7)$$

Where each term on the right hand is a position relative to the well, non-dimensional time corresponding to apparent injected heat capacity ratio to overall heat capacity of the aquifer and coefficient of heat loss respectively. In this equation, tQ indicates the total recharged or discharged amount from t=0, therefore tQ can be substituted by summation ΣtQ of each interval amount t_1Q_1, t_2Q_2, ---, as long as daily interval, namely,

$$\Sigma tQ = t_1Q_1 + t_2Q_2 + \text{---} + t_nQ_n \quad \text{-----------} \quad (8)$$

But on the problem of un-equal strength of sink and source with natural flow, furthermore involving flow pattern changes such as in the case of seasonal regeneration, we can hardly obtain an approximate solution much less an exact one. For this reason, we have tried to solve the fundamental equation (6) by the numerical method.

In confining layers where convectional heat transfer does not exist, three dimensional heat conduction flow must be considered. Supposing that thermal properties are constant, the equation is given below,

$$\lambda c\left(\frac{\partial^2\Theta c}{\partial x^2} + \frac{\partial^2\Theta c}{\partial y^2} + \frac{\partial^2\Theta c}{\partial z^2}\right) = (c\rho)c\frac{\partial\Theta c}{\partial t} \quad \text{---------} \quad (9)$$

4. NUMERICAL ANALYSIS

4-1 Division Based on Complex Potential Function

In cases involving the convectional term, the Up Wind Difference Method is of considerable meaning in physics and stability as pointed out by Roache [13]. Also in our equation (6), convectional heat transfer dominates thermal diffusion. Therefore, we have simulated by the Up Wind Difference Method, though division is not simple equal division but based on complex potential function, $W = \phi + i\psi$.

Kroeger [14] is using changeable conformal mapping based on the moving interface of solids and liquids, and a fixed surface, solved the two dimensional propagation problem of interface with high accuracy. Gringarton, et al. [9] on the other hand obtained an approximate solution with coordinates based on complex potential functions.

Also in our numerical analysis, being based on the complex potential function of this flow, temperature propagation analysis is greatly simplified, and the accuracy of this analysis is raised. Furthermore we can shorten compuring time, as pointed out by Yokoyama, et al. [11].

When flow pattern changes are involved such as in the case of seasonal regeneration, we cannot avoid temperature replacing errors caused by sudden change in conformal mapping correspoinding to flow pattern change. Therefore, we must establish one conformal mapping most suitable for every flow pattern. For this reason, we selected the next conformal mapping equation (10), as indicated in Fig. 6.

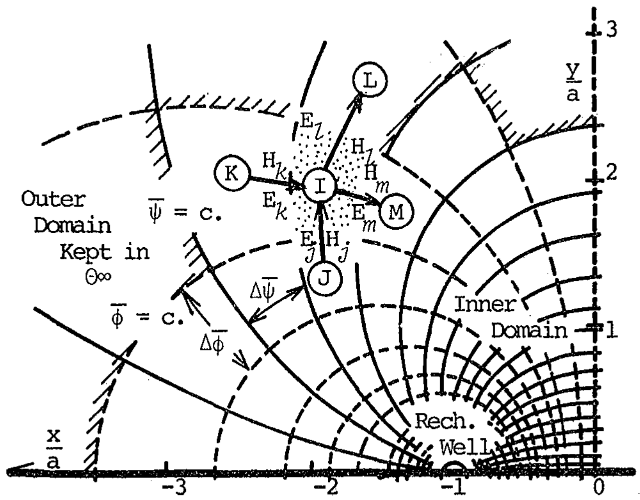

Fig.6 Mapping and Division Based on $\bar{W}=\bar{\phi}+i\bar{\psi}$

$$\bar{W} = \bar{\phi} + i\bar{\psi} = ln\frac{s-a}{s+a}, \qquad s = x + iy \quad \text{---------(10)}$$

Where $\bar{W}$ is the complex potential function for same strength of sink and source at (-a, 0), (a, 0). In this case, the surroundings of wells are divided into 44 cells, i.e. the approximate equi-potential line $\bar{\phi}$ is divided into 44 parts, and any space between wells, along with approximate flow line $\bar{\psi}$ is also divided into 44 parts.

By the way, as vertical heat transfer is simply only conduction, the number of vertical divisions is only 4, each with equal span. Finally we divided the inner domain of the entire strata into 44 x 44 x 4 ≃ 7700 cells.

4-2 Upwind Finite Difference Equation

We must prepare 2 types of equation, namely for the aquifer and for the confining layers. Among them, equations of the aquifer have convectional term forced by potential field eq. (4), and are complicated. On the other hand, the other equations of confining layers have a simple conducting term. Heat balance in un-equal division of the aquifer illustrated by Fig. 6 is,

$$A[i]a^2(c\rho)_a\frac{\Theta a^{\Delta t}[i]-\Theta a[i]}{\Delta t} = Ej + Ek - El - Em + Hj + Hk - Hl - Hm - 2Hc \quad \text{----------(11)}$$

Where E indicates the convectional term of which temperature is given upside of the potential flow, H indicates heat conduction flow, and subscript c indicates the component associated with the confining layers. E and H are estimated linearly by difference of values and distance between nodal points but are modified to have true flux because of non-rectangular divisions. Then the equation of the aquifer by Up Wind Difference Method is,

$$\Theta a^{\Delta t}[i] = \{1-Ma[i]\}\Theta a[i] + Ma[j]\Theta a[j] + Ma[k]\Theta a[k] + Ma[l]\Theta a[l] + Ma[m]\Theta a[m] + 2Mc[i]\Theta c[i] \quad \text{------------------ (12)}$$

Notice that the temperature coefficient M varies according to the situation and flow pattern. As a result this equation corresponds to a heterogeneous and unisotropic heat conduction problem (Yokoyama, et al. [11]).

Stability conditions are determined by the individual cell as below,

$$1 \geq Ma[i] \quad \text{----------------------- (13)}$$

But the overall stability condition, namely step time Δt, is limited in the cells surrounding the discharge well.

4-3 Flow Pattern for Each Season

With this method, though any flow pattern can be considered, with our experiments, where one sink and one source are considered in addition to uniform natural flow, then the sink and source are exchanged alternatively and these strengths are variable according to each season.

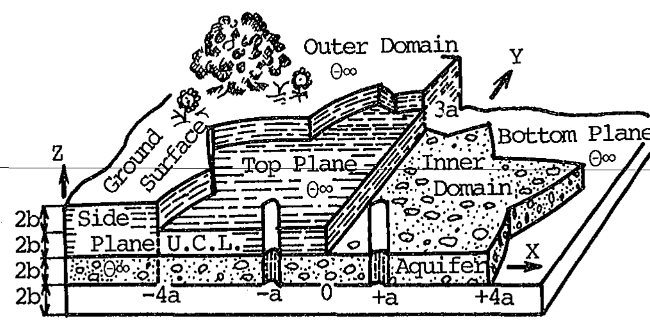

Fig.7 Simulation Domain and Boundary Conditions

4-4 Boundary and Initial Temperature Conditions

As illustrated in Fig. 7, vertical end planes are assumed to be kept in Θ∞. Here, vertical end planes are determined by one dimensional Carslow's solution eq. (1), sufficiently 2b away from aquifer.

Side planes are also assumed to be kept in constant Θ∞, and this assumption is in practice correct. Then, side plane is determined along with $\bar{W}$, eq. (10), about 3a away from each well by test-run simulation.

Each recharge well in summer or winter is kept in constant Θs or Θw. Initial temperature over the entire domain is to be Θ∞.

4-5 Computation

The computation flow chart is illustrated in Fig. 8. At the first stage unequal division based on $\bar{W}$, eq. (10), the second, area A [i], nodal point, etc. of each cell, the third, potential field ϕ corresponding to each season, the fourth, step time Δt, and lastly, temperature coefficient M[i] of each cell is given. Finally, an unsteady state temperature field is computed explicitly.

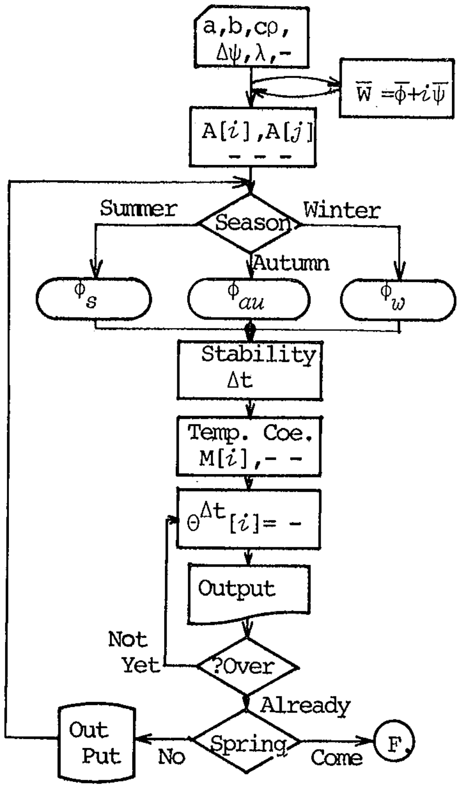

Fig.8 Computation Flow Chart

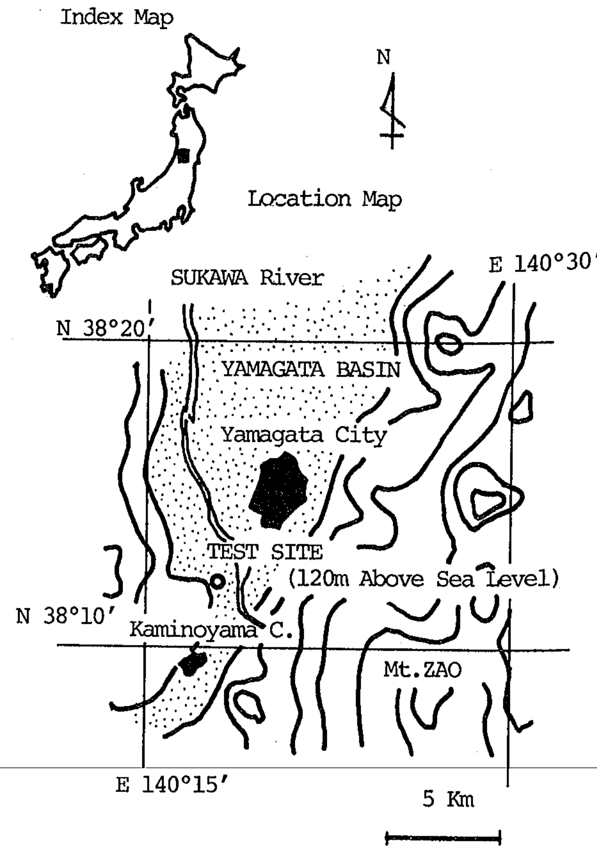

Fig.9 Test Site Location in YAMAGATA BASIN

5. EXPERIMENTAL APPARATUS AND ENVIRONMENTAL CONDITIONS

5-1 Natural Environment

Our test site is located in Yamagata Basin as mapped in Fig. 9 and surrounded by mountains. The underground strata is composed of alluvial deposits based on green tuff rocks of the tertiary period as shown in Fig. 10. Layers combine volcanic ash and mud flow originating from Mt. Ryuzan. Layers are not uniform and as well there are other usual edge deposits of alluvial corn. The wells have two strainer parts but the main permeable aquifer is limited in sand and gravel aquifer near 80m. We therefore regard the mean thickness of aquifer to be 19m. The lower confining layer is most certainly a bed of green tuff, but the upper one is not a complete silt layer being somewhat leaky. Nevertheless, we can regard the permeability of such alteration of sand, gravel and clay, and volcanic ash, as less than 10^{-1} times that of the main aquifer. Furthermore for practical analysis, we can assume the aquifer is confined and that no leakage exists.

The ground is close to the horizontal but slightly inclined toward the north-west. Besides the two dual purpose wells without any extraordinary construction for service as recharge wells,

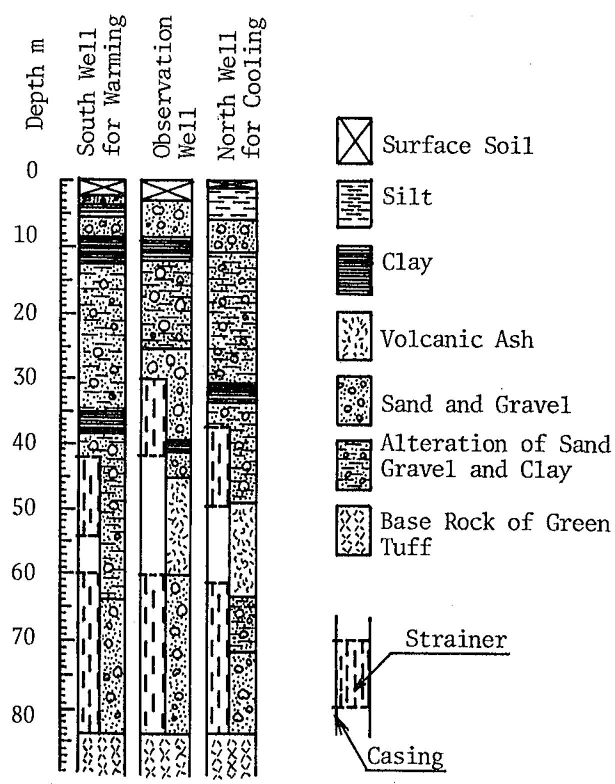

Fig.10 Geologic Columns of Wells at Test Site in YAMAGAYA BASIN

one observation well was drilled at the corner of the 22.4 m equilateral triangle. Natural underground water flow is estimated as almost uniform as illustrated Fig. 11, by the static water levels of the three wells in 1974 and 1977, and by permeability measuring of its aquifer tests. That is,

$$U = u + iv = -6.7m/y - i \cdot 16m/y \quad \text{--------} \quad (14)$$

which is a suitable value for this area.

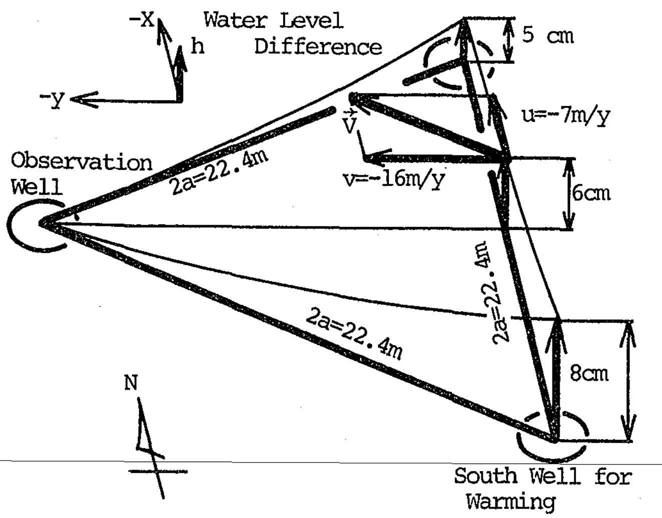

Fig.11 Well Situation and Estimated Natural Flow Where $K=1.6\times10^{-4}$ m/s

Our test building, NIPPON CHIKASUI KAIHATSU is floating, not pile mounted on the land. It consists of three floors with a total area of 1000 m^2. The ground and first floors are offices for about 50 men and the second floor is often used for meetings.

5-2 Climate of The District

The average yearly temperature is 11°c and precipitation is 1200 mm, of which 300 mm is snow in winter. In August the average temperature is 24.5°c, and a Summer days, days when the highest daily temperature is more than 25°c, 100 per year. In January the average temperature is -1.2°c, and a Winter days, days when the lowest temperature is less than 0°c total 110. Therefore we need heating for approximately 5 months and cooling for about 2. For example, our building required 160 l/day x 5 months/y heavy oil, namely 1.5 x 10^8 kcal/y considering a boiler efficiency 0.7 for heating, while we require cooling also.

5-3 Warm and Cool Water Requirements Regarding Heat Pump and Direct Cooling

In the case of underground water temperature lowering from 20°c to 10°c we can set the heat pump evaporation temperature at 5°c and the condensation temperature at 50°c. We can then gain a coefficient of performance based on shaft power of more than 4.0, as indicated in Fig. 12. Therefore running costs are cheaper than with an oil heater. The requirement for warm water totaled 9400~11000 m^3 for winter heating source, which supplied 3/4 of the 1.5 x 10^8Kcal heat required, and the remaining 1/4 is given by heat pump itself.

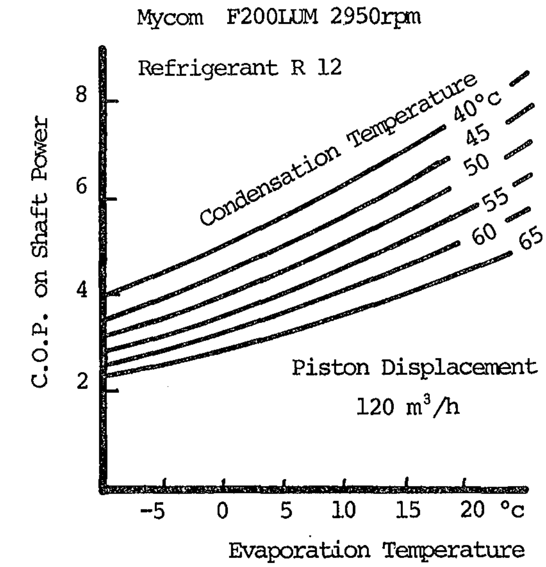

Fig.12 Coefficient of Performance of Heat Pump

By the way, presumed heat loss is 20 ~ 30% by conduction plus, further added natural flow out, etc., so perhaps a total of 50% of initial temperature difference (Θs-$\Theta\infty$) may be lost. Then we should recharge about 10000 m^3 with 24°c.

The wells are too close together to avoid thermal pollution when the recharge amount is more than 4000 m^3, for 4000 m^3 recharge amount corresponds to $tQc\rho/2a^2b(c\rho)\alpha = 3$, as indicated in Fig. 5. Avoiding this, we must gain 36°c hot water and decrease the total amount to 4000 m^3. But, in addition to our experimental limitations, to verify thermal pollution, we recharge about 10000 m^3 at 24°c for relatively easy heating.

On the contrary, if 10°c cool water is gained in summer, we can cool directly with the temperature increasing from 10°c to 16°c. Therefore the requirement for cool heat is,

$$0.023 \text{ USRT/m}^2 \times 6 \times 10^2 \text{ m}^2 \times 10 \text{ h/d} \times 2 \text{ months} =$$

$$0.62 \times 10^8 \text{Kcal} \quad \text{----------------------} \quad (15)$$

where 1 USRT = 3024 Kcal/h. The requirement for cool water is, therefore,

$$\frac{0.62 \times 10^8 \text{Kcal}}{6°c \times 10^8 \text{Kcal/m}^3{}°c} = 10^4 m^3 \quad \text{-------------} \quad (16)$$

For the purpose of experiments on thermal pollution, we recharge about 10000 m^3 in total at 6°c in winter on the assumption of an identical heat loss phenomena.

In this case the amounts of recharged water are balanced, and stored heat is also almost balanced.

5-4 Experimental Apparatus and Measurements

As shown in Fig. 13, cooling water is pumped from the North well and, after direct cooling, waste water is sprinkled on the roof for heat collection by convection and radiation without any ingenious equipment. Flowing through a filtration tower packed with fine sand and active carbon, water is additionally heated by a heat exchanger, and then recharged to the South well. (In winter, vise versa as shown later)

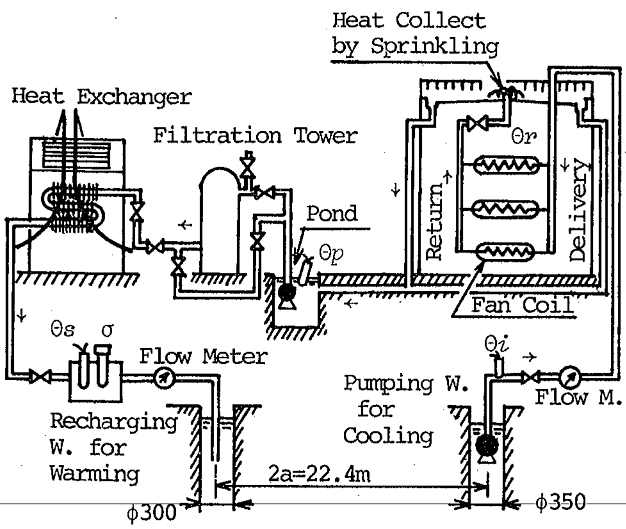

Fig.13 Model Apparatus in Summer

As the power of the submerged pump was strong, about 8 Kw, discharged water was heated, in the case of a discharging rate of less than 100 l/min., it amounted to about 1°c. Flow rates were measured by volume type flow meter, and water levels of wells were measured by probesensor type level meters. Water quality was inspected by an electric conductivity meter and sampling checks are carried out monthly. Temperatures at all point were measured with 0.5 mm C-C or Cr-Ar thermo-couples.

Data was gathered into the laboratory and recorded. Climate data such as atmospheric temperature, dew point, overall isolation, etc. are obtained from the Yamagata Meteorological Observation Center. It is situated several Km. away from our test site, so we can assume the same weather conditions. Besides the main pump, another small pump of 1 Kw. for drinking water and other purposes was included in the North well untill Autumn, giving a daily discharge of several m^3. In winter, this small pump is moved to the South well.

6. WARM WATER RECHARGE AFTER COOLING IN SUMMER

6-1 Recharging and it's effect

Experiments were carried out from July 16 to September 18, usually in the daytime, but occasionally at night. Experimental conditions and material properties are listed in Table 1.

Table 1. Material Properties and Conditions for Simulation

$(c\rho)a$		660 Kcal/m^3°c	predicted by measuring of resembling aquifer samples
$(c\rho)c$		300 Kcal/m^3°c	refer to that of JSME
$Qo/2b$	summer	0.303 m^2/h	mean value of total amount divided total hours of each season, including intervals between experiments
	autumn	0	
	winter	0.255 m^2/h	
$Qi/2b$	summer	0.340 m^2/h	(same above)
	autumn	0.0147m^2/h	
	winter	0.304 m^2/h	
u		-0.18 x 10^{-2}m/h	mean value of observation
v		-0.76 x 10^{-3}m/h	(same above)
λa		0.5 Kcal/mh°c	refer to that of JSME
λc		1.0 Kcal/mh°c	refer to that of JSME

JSME, Material of Heat Transfer, 1973, p.259

Injection went favorably and the total amount reached 8843 m^3, a little less than the total amount of discharge 9930 m^3 and that of the plan, as shown in Fig. 14. This was because the amount of discharge included the 3 m^3/day living water and backwash water for the filtration tower.

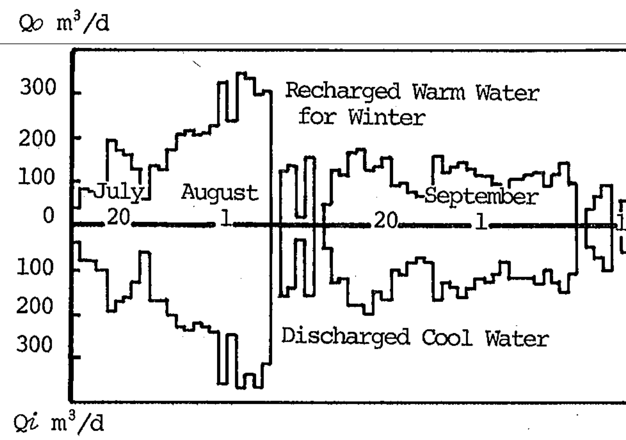

Fig.14 Pumped Up and Injected Amount in Summer,1977

In spite of daily discharging, water level recovery after experiments was smooth and water level was kept constant, as indicated in Fig. 15, due to the effects of injecting.

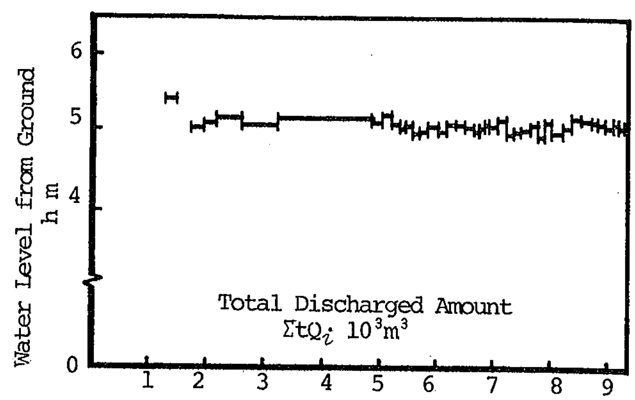

Fig.15 Recovery Effect of Water Level after Pumping,in Summer(1977)

Clogging of the aquifer was not in appearance and the apparent permeability by equation (4) did not decrease but remained constant, as shown in Fig. 16. Namely, the filtration tower trapped most organics (algae) and detritus, so we needed to back wash daily. The quality of the recharge water was kept nearly natural through all seasons and was suitable for drinking. Only zinc (Zn), increased from 0.1 ppm (natural) to 0.6ppm (recharge) once or twice due to piping but this was within allowable limits for drinking.

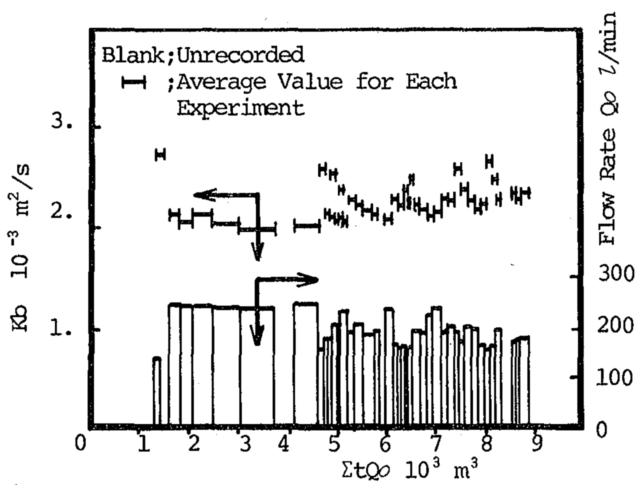

Fig.16 Constant Correlation Apparent Permeability & Total Recharged Amount,in Summer(1977)

6-2 Heating Pattern

As shown in Fig. 17, the heat exchanger was useful at night when there was no isolation, but the temperature could not be increased far over the dew point much less to atmospheric temperature. On the contrary, sprinkling, which is simplest, can heat water warmer over dew point under isolation. In addition to this, from other experiments in heating with only the exchanger and not including sprinkling, absorption of isolation is more important for heat collecting than convectional one. Nevertheless we injected 8843 m^3 at 23.7°c mean temperature, close to the expected 24°c value.

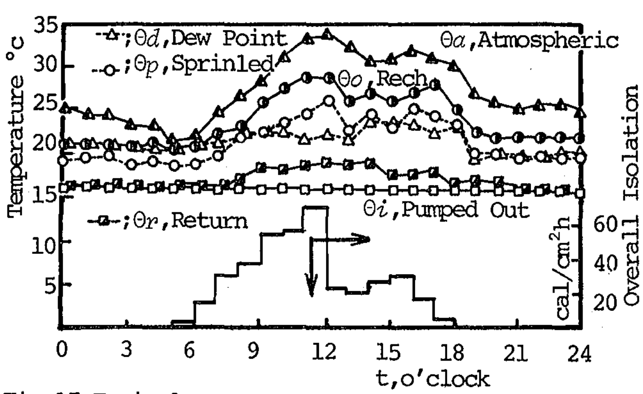

Fig.17 Typical Temperature Change Pattern through August 5 (1977)

6-3 Stored Heat Energy and Thermal Pollution

Daily stored heat energy heated from 16°c is shown in Fig. 18, and the total was 0.672 x 10^8 Kcal (6720 *l* of oil) with a temperature rise from 16°c to 23.7°c over summer. If the temperature drop by winter is within 50%, corresponding to 20°c from 23.7°c, supply of 0.88 x 10^8 Kcal heat source of heat pump using the heat of lowering from 20°c to 10°c is expected, but this is a little less than 1.1 x 10^8 Kcal of the plan.

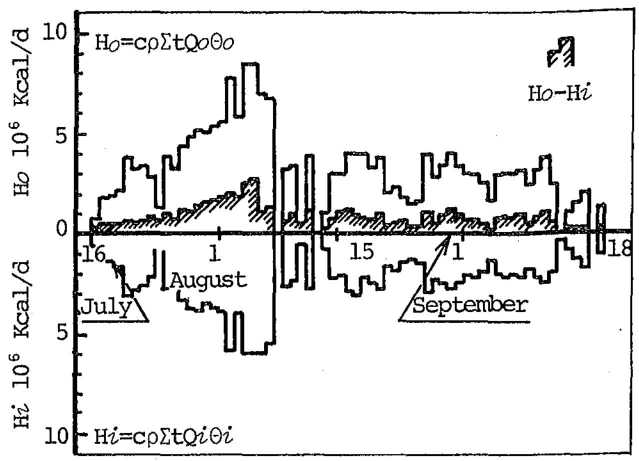

Fig.18 Stored Heat in Summer (1977)

Thermal pollution followed by warm water recharge has appeared in the north cool discharge well, as indicated in Fig. 19, since the time of 4000 m^3 discharged amount as predicted by equation (7) and Fig. 5. In spite of the fluctuation, however, experimental data coincided with the numerical value analyzed under the same conditions as experiments and with the rough assumptions for the underground strata.

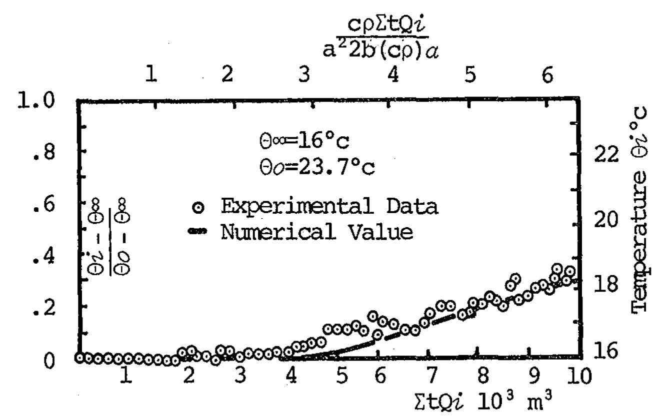

Fig.19 Thermal Pollution into Discharge Well in Summer (1977)

7. REGENERATION DURING AUTUMN

During the period from September 19 to December 25 injection was not carried out but the regeneration phenomena was subject to experiment. Drinking water of at most 6 m^3 per day, total 660 m^3, was discharged from North well.

From the numerical analysis, the temperature of the aquifer dropped slowly day after day by heat conduction to the confining layers, thermal diffusion in aquifer on the natural flow and discharge of drinking water. By the way, since the arrival of natural cool water with Θ_∞=16°c, the temperature drop accelerated, especially upstream of natural flow, namely the south-east area around South well. Therefore the temperature drop of the South well accelerated from November 10, while the temperature of the North well slowly decreased as indicated in Fig. 20. But the area with nearly 23.7°c still remains around the downstream area between the wells.

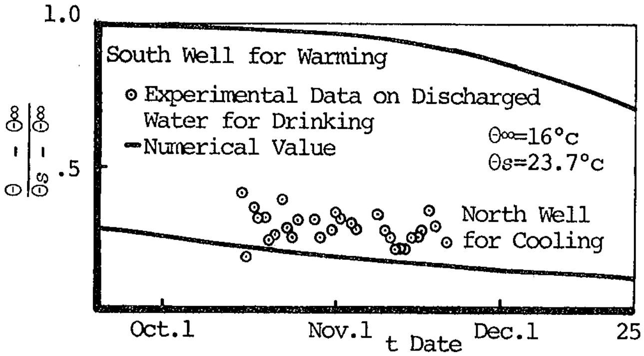

Fig.20 Thermal Storage Process during Autumn(1977)

Experimental data are not satisfactory to compare with numerical analysis, for the temperature of the discharge, which is measured in tank, is heated not only while passing through the piping in the building but also while remaining in the tank under the sun-shine, owing to the small flow rate. Nevertheless experimental data are at most 20% higher (about 1°c) than the numerical values and have the same tendency towards lowering with time, as does the numerical analysis.

8. RE-PUMPED WARM WATER IN WINTER AND RECHARGE OF WASTE COOL WATER

8-1 Model Apparatus in Winter

Conversely to that of summer, we re-pumped seasonally regenerated warm water from the South well, then recharged waste cool water into the North well, as shown in Fig. 21.

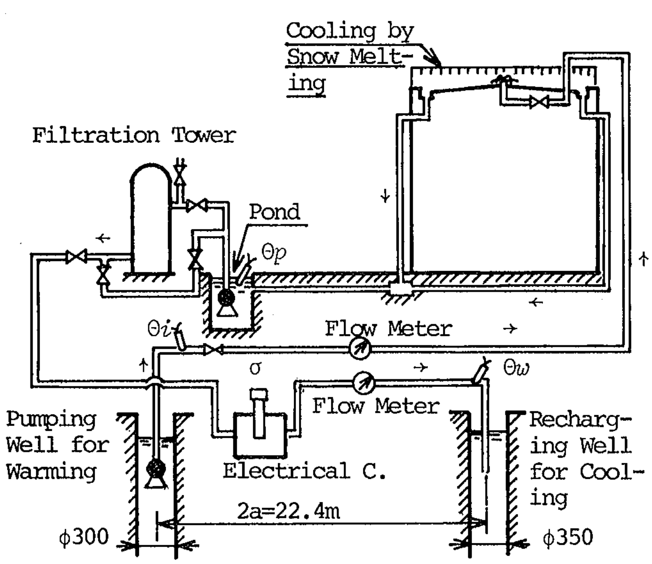

Fig.21 Model Apparatus in Winter

Instead of a heat pump, we used warm water for snow melting on the roof (300 m^2 area). The sprinkler type nozzles were replaced by a spray type. Therefore sprayed water was satisfactorily cooled without use of a heat exchanger. The other parts of the apparatus and measurements were the same as for summer.

8-2 Re-pumping Warm Water and Recharge of Waste Cool Water

Warm water was re-pumped from the South well for snow melting from December 26, 150 m^3 daily, total 11200 m^3, including drinking water. In return, waste cool water with 5.3°c mean temperature has been simultaneously recharged into the North well, 140 m^3 daily, total 9430 m^3, favorably as indicated in Fig. 22 but with slightly additional viscous resistance due to low temperature.

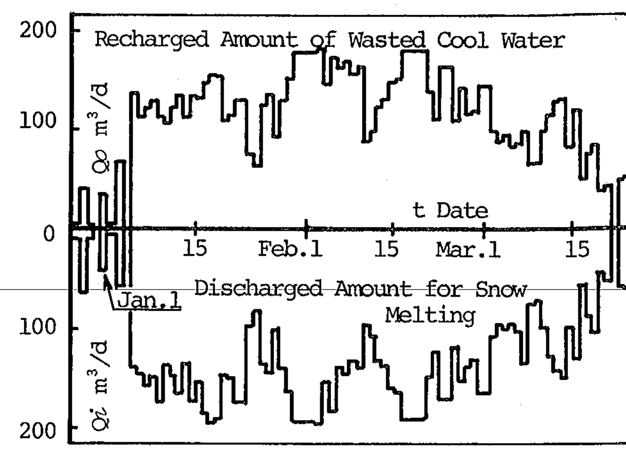

Fig.22 Daily Discharged and Recharged Amounts, Winter,1978

As shown in Fig. 23, with 20°c at the beginning, we obtained warm water at about 19°c untill the end of January, corresponding to discharged amount of 4000 m^3. Though re-pumped temperature drop in numerical analysis accelerated, due to the affect of recharged cool water, since the time corresponding to re-pumped amount of 5000 m^3, in the experiment the temperature drop did not accelerate quickly as the numerical value, but only slightly. The disagreement at the end of the season looks to be caused not only by non-uniformity of the aquifer but also by underestimating the heat loss into the confining layers and heat recovery from these layers. Nevertheless the numerical value coincided with experimental data within a 10% error over all the seasons. So, this numerical analysis with division based on complex potential function and with rough assumptions is suitable for long period and wide space heat conduction problems dominated by convectional terms such as seasonal regeneration through underground strata.

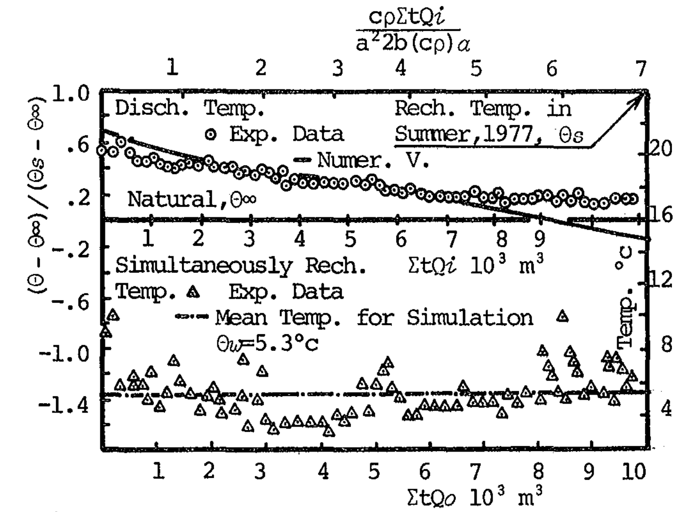

Fig.23 Discharged Warm Water and Recharged Cool Water after Snow Melting in Winter,1978

8-3 Recovering Heat Energy and Determing Suitable Distance between Wells

Until the time when the discharge well was affected by recharged cool water, re-pumped water temperature and its heat energy were kept at least 40% of the original temperature difference (Θs-$\Theta\infty$), which can be termed the Recovery Coefficient, or the original stored heat energy during the previous summer, in spite of about half year thermal storage. Since the arrival of recharged cool water, however, the recovery coefficient decreased, as indicated in Fig. 23. As a result we got warm water at 18.3°c mean temperature over all re-pumped water, more than the recharged amount in summer, then 0.26×10^8 Kcal among stored heat 0.672×10^8 Kcal in summer, namely 38%, was recovered. The warm water at 18.3°c, totalled 12000 m^3, corresponding to 0.91×10^8 Kcal for the heat source of heat pump in the case of lowering temperature from 18.3°c to 10°c; this heat energy is nearly satisfactory for our objective amount of 1.1×10^8 Kcal.

We therfore chose the distance between wells to be that not affecting distance from recharge well, which is estimated by equation (7) and Fig. 5 as testified already in summer. That is,

$$\frac{\Sigma tQc\rho}{a^2 2b(c\rho)\alpha} \leqq 3 \qquad \text{------------------------ (17)}$$

For example, at our test site, let ΣtQ be 11000 m^3, substituting the material properties of the test site listed in Table 1, then a suitable well to well distance without affects is obtained from eq. (17)

$$2a \geqq 40 \text{ m} \qquad \text{------------------------ (18)}$$

In this case, if the temperature in summer is highter than 23.7°c, the distance is less than 40 m.

9. DISCUSSION

Residual heat in the aquifer and confining layers is partly diffused in aquifer or directly mixed with the natural cool water, lowering its temperature. This might be partially recovered in the next winter season.

If natural flow is more significant than present, seasonal regeneration is not effective but we can more easily avoid thermal pollution. Vice versa natural flow being more stagnant, we can more effectively regenerate seasonally and so obtain a recovery coefficient of more than 40%, but we must pay more attention to thermal pollution.

By the way, this injected cool water in winter is expected to be re-pumped at 10°c within 4000 m^3 next summer on the assumption of identical conditions as initial summer experiment, and used for direct cooling as well as for a heat sink of a refrigerator.

Furthermore if high temperature water is originated by Solar Heating or refrigerator in summer, e.g. 50°c, we can get hot water of more than 30°c in winter even if the surface is covered with snow, or even if Solar Heating System is not used due to absence of sunshine. Therefore Seasonal Regeneration is very useful for saving energy and can be applied in many aspects, especially in the Temperate Zone.

10. CONCLUSIONS

Though the experiment results are not sufficient for generalizations and for quantitative analysis, a recovery coefficient of nearly 40%, coinciding with our numerical analysis, satisfactorily indicates that seasonal regeneration through undergound strata is possible and can be used for many application.

We have arrived at the following conclusions.

(1) Underground water can be successfully used as a low concentrated heat source without negative influence caused by a shortage of underground water if waste water is recharged. Supposing that well distance 2a is chosen, as below, under the given conditions such as thickness of aquifer 2b, etc.,

$$\frac{\Sigma tQc\rho}{a^2 2b(c\rho)\alpha} \leqq 3 \qquad \text{---------------------- (17)}$$

Then thermal pollution into the pumping well can also be avoided. Over this distance, the most effective seasonal regeneration can be expected.

(2) In fields of slow natural flow, compared to main well flow, horizontal and vertical thermal diffusion appear minor therefore, we can seasonally regenerate enormous amounts of heat sink or source wasted by a heat pump, originated by Solar Heating, etc.

(3) In spite of the rough assumptions on underground strata, numerical analysis based on division along with complex potential function carries higher accuracy and less efforts over a long period and wide space thermal problem dominated by convectional term.

ACKNOWLEDGEMENTS

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NOMENCLATURE

English

a	:	2a = distance between discharge and recharge well	m
A	:	Aa^2 = Area of each cell	m^2
b	:	2b = Thickness of aquifer	m
cρ	:	Heat capacity of water	$Kcal/m^3 °c$
E	:	Convectional heat transfer rate of each cell	Kcal/h
G	:	Temperature function of doublet	–
h	:	Water level	m
H	:	Conduction heat flow rate of each cell	Kcal/h
K	:	Hydraulic conductivity	m/s
M	:	Temperature coefficient of each cell	–
Q	:	Well flow rate	m^3/min
s	:	$= x + iy$, complex variable	m
S	:	Isolation	cal/cm^2
t	:	Time	h
u	:	x directional component of natural underground water flow	m/y
U	:	$= u + iv$, complex potential of natural flow	m/y
v	:	y directional component of natural underground water flow	m/y
W	:	$= \phi + i\psi$, complex potential function	m^2/h
(x, y, z)	:	Three dimensional Cartesian coordinates	m

Subscript

a	;	of aquifer
au	;	of autumn
c	;	of confining layer
i	;	of sink, namely discharge
j	;	of injection, namely recharge
i, j, k, l, m	;	of cells of I, J, K, L, M
o	;	of source, namely recharge
p	;	of sprinkling
r	;	of return of cool water
s	;	of summer
w	;	of winter
Δ	;	step value
–	;	of approximate complex potential function
∞	;	infinitive condition

Greek

Θ	:	Temperature	°c
κ	:	Thermal diffusivity	m^2/h
λ	:	Thermal conductivity	Kcal/mh°c
φ	:	Potential function	m^2/h
ψ	:	Flow line function	m^2/h
σ	:	Electrical conductivity	μ/Ωcm

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REACTION PANEL

S.S. Papadopulos
U.S. Geological Survey
Reston, Virginia

I was too busy listening to the papers presented here during the last two days to prepare any written comments, so I don't know if I can react to the workshop with the proper words of wisdom. At any rate, if you are expecting to get much wisdom out of my comments I hate to disappoint you. My being on this reaction panel reminds me of a brief comment I heard the other day on the American justice system. Someone was commenting that it is ridiculous to expect a wise decision from twelve people who are not smart enough to get out of jury duty.

I am going to limit my comments to the hydrologic aspects of thermal energy storage. First, because my area of specialty is hydrology, ground-water hydrology in particular, and second, because I represent a division of my agency that is involved in aquifer storage of energy primarily because of its hydrologic aspects.

First, I want to comment on a slide that was shown here which listed items of importance in aquifer storage. There were items such as power plants and pumps and finally at the bottom of the list there were geology and hydrology. I feel that geology and hydrology should have been at the top of the list. As Jay Lehr stated, there may be aquifers almost everywhere but not all of these aquifers are suitable for energy storage. To consider aquifer storage of energy at a site, we first have to determine if there are any aquifers at the site, and if there are any, if they are suitable for energy storage. Therefore, before we do anything else we have to study the geology and hydrology of the site.

The papers presented here demonstrate that we have most of the technology needed to implement thermal energy storage in aquifers. We have developed over the years the methodology necessary for evaluating the hydraulic parameters of aquifers. Professor Witherspoon gave us several examples of such aquifer testing techniques. We also heard researchers both from here and from Europe list mathematical modeling as an integral part of their aquifer storage program. Chin Fu Tsang presented an excellent paper summarizing the mathematical modeling efforts here at LBL. We at the U.S. Geological Survey have also developed several models for simulating both single- and two-phase energy transport in aquifers. The numerical techniques necessary for solving the particular equations are pretty well developed. However, as we are learning to solve more and more complex equations we find that the number of parameters that we need to know also increases. For example, in addition to the hydraulic parameters of the aquifers we need to know their thermal properties. Therefore, it appears to me that we need to design some field tests to improve existing techniques or to develop new methods for determining in the field these additional parameters. Finally, we have to consider the water quality aspects. We heard an excellent paper here on the problems that could develop because of quality differences between the ambient fluids and the injected fluids. In schemes where water from the same formation is to be used for injection these problems could still develop because of differences in temperature. I am not a water chemist and I may not be able to visualize all the complications, but what I have heard here leads me to believe that none of these water quality problems are insurmountable. It appears that the experience of the petroleum industry, where water injection for petroleum recovery has been practiced for quite some time, could provide us with insight on how to solve some of these water quality problems.

Normally, I should end my comments here, however, I will continue with a few more words with what I see as feasible aquifer storage projects in the near term. For immediate applications, I think we should be talking about water at low temperatures that can be stored in relatively shallow aquifers. By low temperatures, I mean temperatures that are below the boiling point, which is different than the definition given by C. J. Swet. I also think we should be considering applications such as air-conditioning and heating which directly use the thermal energy and avoid the great losses that are associated with conversion to some other form of energy. I believe that at the present time the economics would be unfavorable for projects that deal with high temperatures. Water at high temperatures will have to be maintained at high pressures and, therefore, will require storage in deep aquifers. The costs for wells and wellhead structures would be higher. In most projects, we might have to control the hydraulic gradient of the aquifer over the life of the project. The cost of gradient control wells will also be higher when we are dealing with deep aquifers. Also, we have heard about the well-clogging problems that may arise because of suspended solids or differences in water quality. These problems might be easier to control in shallow systems. For example, in a shallow system one could consider drilling a large diameter injection well to increase the surface area and lower the injection velocity and pressure, and thereby possibly reduce clogging or its effects.

To summarize my reaction to the workshop, I believe we have the tools to solve most of the problems associated with aquifer storage of thermal energy and that we need a simple but practical demonstration project that will put these tools into use. I disagree with the gentleman who stated that we cannot get the utilities interested in using aquifer storage. Maybe we cannot convince utilities in large cities such as New York but I believe that utilities in small communities, with populations of about 5,000, could be demonstrated the advantages of using aquifer storage for district heating and cooling.

C. W. EASTON
SEATTLE STEAM CORPORATION
SEATTLE, WASHINGTON

I am not the one here today that has been doing research or consultation on Aquifers as our friend from Germany said earlier, nor am I the one like D.O.E. providing the money for the research. Instead, I am simply the one, and maybe the only one, here today that is in the business of converting energy into other useful forms to furnish heat to customers, unless there is a man P.G. & E. in the audience. I mention that because the previous speaker, Mr. Ken Holte, was from Southern Cal Edison and they have no district heat plants and never have had any. P.G. & E. has one located in downtown San Francisco and if you walk around in the heart of the downtown area, you will see evidence of the small district heating system. I know something about the San Francisco system because about two years ago I met with representatives of their Company to discuss mutual problems.

Basically, I am in the district heating business and being in this business, we consider ourselves as energy converters and distributors. C.F. Meyer has excellently portrayed in his presentation the need for energy storage in order to increase energy efficiency, either through an electric co-generation system or the utilization of waste heat from industrial processes. I would like to confine my remarks to these two areas.

Professor Carver, in his statements, pointed out the great institutional restraints and the need for removing a persons options for the selection of heating sources. I have differed a little with the Professor in his saying that heating sources were not competitive. Heating sources have been highly competitive over the years, and the competition point has been artificially set by the government in their regulation of natural gas prices. That arbitrarily forced the price of oil downward for many years and, in some cases, the price of electricity also. I have worked closely with the electric industry the past fifteen years for the reason that the majority of the district heating companies in the United States are owned and operated by major electric utilities. Being very active in the district heating industry association, I have had the opportunity of working with these electric utilities. My Company is one of the few companies, maybe one of two in the United States in the district heating business and not owned by the electric industry, other than the district heating or college companies. I must mention these because the district heating on college campuses has been the only fast growing segment of the district heating industry here in the U.S. District heating generally has not been growing in our urban high density living, shopping and working areas.

When we talk about institutional restraints we more often than not think it means restraints brought about by the regulation of the utility industry and we think of government rules, regulations and controls. We blame the government for this and that and here at this Conference you have heard a great deal about the impediments to industry brought about by the bureaucracy. But curiously enough, I think we should point out that the restraints in district heating have not been brought about by government or by utility regulation necessarily. They have been brought about primarily by Corporate restraints and these Corporate restraints are the result of our electric industry's control of district heating, I believe. I have been trying to point this out to my colleagues in the district heating business and the electric industry for the past ten years.

I must confine these remarks to the electric industry here in the United States because in Western and Eastern Europe it is a rapidly growing industry and it is growing there because the electric utilities are promoting it. Most of the promotion has occurred in the European countries since World War II, however, the largest heat distribution system in the world is in Paris, France. Many do not realize that the Paris system was installed back in 1928.

You will recall that Professor Meyer said that the electric industry considered their wasted heat as "mere" secondary power, meaning it inconsequential and nothing for them to really be concerned about. Most of all electricity is generated by the heat process by the burning of fossil fuels or nuclear reactors for the generation of steam to drive turbines to drive electric generators. Almost all of electrical generation is accomplished in this manner except for the areas blessed with hydro-power. I believe the electrical industry fails to consider themselves as simply energy converters but instead call themselves power generators. They claim they take natural energy and convert it very efficiently into electricity. Let's take a look at their performance on a BTU basis.

It is generally accepted that conversion of the assailable BTU's in coal or oil to make steam to drive turbine generators sets for the production of electricity is about thirty eight percent efficient on the basis of BTU imput to BTU output. And by adding distribution losses, the average conversion efficiency probably is reduced to the neighborhood of 30%. So they are throwing some 70% of the available BTU's away at the present time. It is time that they started to think of themselves as energy converters rather than power generators.

I believe that the removal of institutional restraints could probably be most rapidly overcome or at least reduced by a municipal operation rather than by private enterprise and this may sound unusual coming from a free enterprise believer. But a municipal operation initially seems required simply to get some prototype projects started.

Mr. Holte of Southern Cal Edison spoke of the necessity to get all the various diciplines together and that is just what is being done by the D. O. E. people up in Minneapolis where what is known as the Twin Cities project is the way to develop a district heat system utilizing waste heat from electrical generation etc. They have recently added the subject of well storage and aquifers into their research program. I believe they have merged together all the disciplines as well as tackling the institutional restraint problems. But, this is a long range project and it is not one that you can get going on immediately. A smaller project and one that possibly could move much faster would be what I call the Bellingham project up in my part of the country. This project is being funded by D. O. E. and monitored by O. R. N. L. and is in the early stages. Essentially, the program is taking the waste heat from an aluminum plant for use in the development of a nearby industrial park and possibly to heat the city of Bellingham, Washington and a nearby State College. The waste heat from the aluminum process is relatively low level heat but there is a huge amount available and it would appear that an aquifer would solve the storage problem so necessary for meeting heating needs.

I believe the presentations were very excellent and that inviting a reaction panel like this one we are serving on should assist all of you that are in the research and development end of the business.

From what I have heard, I have to assume Aquifers will work and as Steve has just said they are going to work. So, lets get going on a prototype project! And as Professor Carver said, a small project. Perhaps the Bellingham project might be a possibility or find a small city having a close by electric generation plant for a co-generation program utilizing Thermal Energy storage.

The District Heating Industry was founded by the electric utilities on the co-generation principle but then discarded. They said its "good enough to only use 30% of the available BTU's effectively. In Europe, the electric utilities are not content with only a 30% efficiency.

I believe your program is excellent and I hope you will get going on a project soon.

Thank you.

S.P. Neuman
University of Arizona

For me, this workshop has been an educational experience as my past involvement with geothermal research has been quite limited. I wrote with Paul Witherspoon and Marcello Lippmann a survey paper on the modeling of geothermal resources, but that is about as far as my research has carried me into the area of heat storage and heat transfer underground. What I would like to do now is simply share with you some of what I think I learned during these two days, and then perhaps have you judge whether or not the ideas that have been raised here are indeed feasible, at least technically. I don't think that I'll be able to say very much about the economical feasibility of these ideas. The two major ideas that have been discussed are storage in aquifers and storage in deep caverns. I will not talk about storage in deep caverns although I was quite impressed by the possibilities and especially by the fact that in contrast to aquifer storage, storage in caverns may be accomplished without pumping; the fact that cavern storage deals with a closed system whereas aquifers storage will most of the time deal with open systems; and the fact that as a result of this, problems arising from the chemistry of the fluid will probably be of lesser importance than in aquifers. Concerning aquifer storage, it was said that our first goal is to develop the appropriate technology and our second goal is to demonstrate that this technology is feasible. I think that I'll generally agree with Steve Papadopulos that the technical tools for storing heat in aquifers are already available and therefore, what remains is to demonstrate the technical feasibility of the concept. I think that the theoretical basis for the aquifer storage concept is very sound. Let me recount the five major points which appear to provide theoretical justification for this concept. First, the high specific heat capacity of water. Second, the availability of large pore volumes for storage. Third, the fact that most rocks have a low thermal conductivity and therefore the loss of energy through confining layers will be relatively small. Fourth, the possibility to store water under high pressure and in this way maximize the density of the stored energy. Hot water can be stored in its liquid form by injecting it at low or intermediate temperatures to shallow depths or at high temperatures to greater depths. Finally, number five is the availability of suitable aquifers in a wide variety of geographical locations. What appear to be the potential benefits of aquifer storage? On the first day of our meeting here it was said that we would like to have large scale, long term energy storage systems at low loss and low cost. Well, the large scale effect, of course, is obvious. Large aquifers are large scale. As to long term and low loss, I think that the presence of confining layers having low thermal conductivity will insure low thermal losses and will make it possible to store energy for long periods of time. On the other hand, the question of cost and economic feasibility has not been answered to my satisfaction during this meeting, and we'll have to address ourselves to it in the future much more seriously than we have done in the past. Concerning environmental aspects, we heard two opinions. One of these opinions stated that aquifer storage will lead solely to environmental benefits. Indeed, it appears that there may be such benefits, for example reduction in thermal pollution above ground and alimination of the need for large unsightly storage reservoirs on the surface. More important may be the low level of environmental damage that one can expect, although one should be quite careful in making this conclusion because I can foresee such environmental problems as land subsidence and underground thermal pollution. In other words, it is quite possible that hot water injected at one point will move under the influence of regional gradients and pollute somebody's potable water supply. Another environmental aspect that I did not hear mentioned at this Workshop is the possibility of the movement of toxic materials, especially those that are being used for water treatment. A relatively remote and yet important environmental consideration is the possibility of triggering earthquakes. This happened in the past, although not exactly in the type of aquifers we are talking about here. Now in order to be able to say a little more about the technical feasibility of aquifer storage, we have to study several problems. We have to study heat transfer through rocks and how it affects heat loss. We have to study pressure distribution and how it affects pumping requirements. We have to study geochemistry and water-rock interaction. And we also have to study the state of stress in the rock, or thermo mechanical stresses. We heard a little about many of these problems, but not all of them. Let me run down very quickly through a list of possible physical and chemical phenomena that we have to understand at least to a fair degree in order to be able to say more about how aquifer storage projects will operate. As far as heat transfer goes, of course, we have to understand the processes of advection, conduction, and hydrodynamic dispersion both under saturated and unsaturated conditions. Prior to attending this Workshop I didn't realize that unsaturated conditions might be of importance in aquifer storage. It was interesting for me to learn that some people are considering very shallow aquifers as possible storage sites, in which case one cannot possibly overlook the properties of the unsaturated zone. Concerning hydrodynamic dispersion, we heard two different groups of papers. The first group described results of field experiments which clearly showed that there is a fair amount of hydrodynamic dispersion taking place in the field. The other group of papers showed results of modeling studies which seldom took hydrodynamic dispersion into account. I believe that in future modeling studies, this phenomenon will have to be accounted for. Pressure distribution and pumping requirements: We have to understand how pressure gradients affect aquifer storage. The effect of natural heterogeneity has been emphasized by quite a few speakers and there are, of course, different kinds of natural heterogeneity that have to be considered. The Workshop leaves the impression that the effect of layering is of paramount importance. It may cause large scale anisotropy and preferential movement in the lateral direction in one or more layers. It may retard vertical movement between layers. Other types of natural heterogeneities are those found on a smaller scale. Some people mentioned fingering. Fingering, of course, may cause hydrodynamic instability of the thermal front and the hydrodynamic front. None of the models presented here have taken this into account, and it is not clear how important the phenomenon may be. However, it appears that small scale heterogeneities may retard the establishment of thermal equilibrium. This was brought to our attention by the French study presented by Mr. Pascal which showed that local thermal equilibrium between the water and the rock doesn't always exist, most probably due to small scale heterogeneities. Heterogeneties may also be induced by man as a result of injecting water which affects the physical properties of the rock, such as hydraulic conductivity. It is important to be able to predict how waters of different chemical compositions will affect the properties of the aquifer as well as the equipment. Two phase flow: Most of the models discussed during the Workshop were single phase, although some two phase flow models have also been mentioned. To what extent is this important? At what depths, at what pressures, at what temperatures? Some people seem to think that under certain conditions two phase flow has to be taken into account and I have a similar feeling. Geochemistry: Here talk was centered around the effect of water quality on aquifer performance and on the equipment, the need for treatment, and the cost of treatment. What would be the effect of backflushing or pressure pulsing? How should this be done? How often? In what way? These, I think, are questions that have to be answered. And finally, the state of stress in the rock. What should be the maximum pressure in order to avoid cap rock failure, as might have actually happened in one of the experiments described here? What should be the maximum pressure in order to avoid hydraulic fracturing unless this is specifically desired? What may be the effect of thermo mechanical stresses on the equipment? We heard that this may sometimes be a problem. We heard about various models in one, two, or three dimensions, and I will not mention all of them. One of the questions that has to be answered is whether there is a true need for three-dimensional models, or whether one could perhaps get by with quasi-three dimensional models based on the concept of vertical equilibrium, such as that of Mercer and Faust. To what extent is the concept of vertical equilibrium applicable to heterogeneous and anisotropic situations? All of the models that we have seen are hydrodynamic in nature and none of them take into account water chemistry. During the first day, we heard about the possibility of relying on an existing chemical equilibrium model. To what extent is chemical equilibrium satisfactory in order to describe the chemical processes that occur in an aquifers, or should one perhaps consider kinetics? How much do we know about kinetics? My impression is that we know very little and should therefore study our chemistry more closely before trying to superimpose it on existing hydrodynamic models. All of the theoretical models seem to indicate that aquifers can be ideal for heat storage purposes. Unfortunately, few of these models have actually been verified against field data, although many have been tested against simple analytical solutions. This point has been stressed by Steve, and I fully agree with him about the importance of field verification. We must go out to the field and collect data, starting with small scale experiments but already keeping large scale projects in mind. Most of the field experiments that were described during the Workshop are on a very small scale and quite poorly instrumented. I believe that there would be advantage in spending larger amounts of money in the design of carefully instrumented experiments which could aid in the verification of mathematical models. I mentioned previously that in my opinion the technology for heat storage in aquifers exists. All one has to do is learn from the experience accumulated in recent years in connection with thermal recovery and water flooding of petroleum, underground storage of natural gas, large scale recharge of aquifers by injection wells as practiced for example in Israel, and deep well disposal of liquid wastes. In order to adopt this technology to heat storage in aquifers, there is a need for large scale pilot projects. Such projects can perhaps be developed more easily by direct cooperation with foreign countries in which institutional and political constraints are not as severe as they sometimes appear to be in the U.S. I think that this conference might have contributed toward the possibility of such international cooperation.

Myron H. Dorfman
The University of Texas
Austin, Texas

Please don't apologize. I'll just tell Aggie jokes. Actually, in deference to my friends from the pasture lands of central Texas, I will not do so. But, I want my friends at Lawrence Berkeley Laboratory to know that you will have benefits from having them here, as we do at the University of Texas; because when H.E.W. comes to see you about your affirmative action program, you can mention how well you treated the most discriminated against minority group in America--the agro-Americans.

I think Schlomo Neumann took away most of my act, but I want to reiterate a few of the things that he said and, perhaps, add a few more. Any time you talk about introducing exogenous fluids into an aquifer and withdrawing exogenous fluids from an aquifer, and attempting to utilize those fluids in some manner, you are not dealing with a purely hydrological problem. You are not dealing with a modeling problem per se. You are dealing with a system; and to deal with this particular system, you must consider it as a whole. You first need a resource assessment group to delineate the geology and perhaps the geophysics of the system; directional permeability and boundaries of the aquifer can be extremely important. Second, you need resource engineering which includes reservoir modeling, the well design, a knowledge of the rock mechanics, the geochemistry, etc. Third, you need resource utilization; how do you handle these fluids when you withdraw them from the aquifer? You will probably also need to consider the legal, institutional and environmental problems associated with solar thermal storage. Now this system can be developed by six people or by a hundred people, depending upon the size of the various problems, but if you don't cover these things you may waste a lot of time, effort, and money, because you will have blank spots and may miss some of the most important elements. If you constitute the type of structure I envision, you will find the interaction of the group will uncover unsuspected knowledge, and prevent many serious problems from developing. Each member of the group will be reading other disipline's literature and broadening perspectives. As a result, you will not talk about...I'll step on a few toes now...you will not talk about modeling water at 650°F introduced into an aquifer with a thin shale layer because you're not going to have a thin shale layer. At that temperature you're probably going to have a fractured zeolite in very short order (a greenish metamorphic rock which will react differently). Another researcher suggested introducing 650° fluids into a salt cavern under multiaxial stress; you may find that your salt at elevated temperatures has a viscosity slightly less than that of molasses. So there appear to be some blank spots in some of the presentations, and I would suggest to DOE that when they review these projects, they consider some of these things; these are not strictly hydrologic problems. They are system problems, with important parts to be considered--and I apologize if I've hurt anybody's feelings. I believe that the petroleum engineer, or the geothermal engineer, can be particularly useful in evaluating and working with systems of this type since they are accustomed to dealing with elevated temperatures as well as injection and withdrawal of exogenous fluids. Of course, the question of geochemistry and the effect of rock/water interaction is extremely important and that has been pointed out by several speakers.

I believe one important point, particularly, has been largely overlooked at this meeting. It sort of reminds me of the Kentucky Derby. If any of you watched the race on television, you know that after the race the jockey got up and praised the trainer. The trainer told how he planned the race and praised the owner. The owner praised the track, and the track officials praised the Governor. Nobody said a damned word about the horse! Well, we have casually talked about trouble in drilling a well and trouble with drilling contractors, but no one has talked about the importance of well design. When you plan to introduce exogenous fluids at high temperatures, you need to seriously consider the well drilling and design aspects--they are more than casual concerns, as any petroleum engineer knows. It is simply not enough to drill a conventional water well and grout a little pipe under these conditions. A good well drilling and design program can give modelers and others a wealth of information. For example, if you are involved with an operation costing multithousand or perhaps a million dollars, it would be worthwhile to consider running well logs of different types in each well. Among other things, you can obtain accurate information on porosity, rock type, cementation, and vertical bed thickness. It does not do much good to put out modeling data to eight significant figures if you are unsure of the exact thickness of the aquifer. So, I would suggest that the qeustion of well drilling and design be considered in addition to everything else that has been mentioned. It might even be useful to involve well drilling contractors and engineers familiar with oil well design at some future conference.

Now, on a more general level, early in the conference Dr. Hoffman enumerated several purposes of this workshop. First, to display the D.O.E. role; that has been done. Second to expose correllary interests; that has been done. Third, to identify impediments; that certainly has been done. Fourth, to impact program planning; I have suggested some ways in which that can be done. Fifth, to establish communications; that has been done very well. And, finally, to increase enthusiasm; and I don't know about that one, but I know the best way to find out. Publish all of this material as widely as possible and see what results. I would suggest more illustrations in some of these papers. I would much rather look at pictures than read second order partial differential equations, and you will find that most of your audience will, also. Then, if you generate sufficient enthusiasm, have another workshop or have a bigger conference and involve industry to a greater extent. That is the way to get things done. Thank you.

REFERENCES ON HOT AND COLD WATER STORAGE IN AQUIFERS

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INTRODUCTION

Since the beginning of my involvement in hot and cold water storage aquifers, I have found many reports and papers published all over the world on this fascinating subject. This bibliography, researched and compiled at the Lawrence Berkeley Laboratory, is available to everyone interested in aquifer storage in the hope that it will save time otherwise spent in "digging" through the stacks of engineering and earth sciences libraries.

In order to maintain a complete and updated version of this bibliography for the use of all researchers interested in the subject, I would appreciate reviewing reprints (or pre-prints) of relevant papers and reports as they are being published. I would also like to invite any corrections of, or comments upon the present version.

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