IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY
solar heating and
cooling programme
task VII

central solar heating plants with seasonal storage

cost data and cost equations for heat storage concepts

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INTERNATIONAL ENERGY AGENCY

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat, coordinates the energy research, development, and demonstration program.

Solar heating and cooling program

Solar Heating and Cooling was one of the technologies selected by the IEA for a collaborative effort. The objective was to undertake cooperative research, development, demonstrations and exchanges of information in order to advance the activities of all Participants in the field of solar heating and cooling systems. Several tasks were developed in key areas of solar heating and cooling. A formal Implementing Agreement for this Program, covering the contributions, obligations and rights of the Participants, as well as the scope of each task, was prepared and signed by 15 (now 20) countries and the Commission of the European Communities. The overall program is managed by an Executive Committee, while the management of the tasks is the responsibility of Operating Agents who act on behalf of the other Participants.

The tasks of the IEA Solar Heating and Cooling Programs and their respective Operating Agents are:

I Investigation of the Performance of Solar Heating and Cooling Systems - Technical University of Denmark

II Coordination of R & D on Solar Heating and Cooling Components - Agency of Industrial Science and Technology, Japan

III Performance Testing of Solar Collectors - Kernforschungsanlage Jülich, Federal Republic of Germany

IV Development of an Insolation Handbook and Instrumentation Package - United States Department of Energy

V Use of Existing Meteorological Information for Solar Energy Application - Swedish Meteorological and Hydrological Institute

VI Performance of Solar Heating, Cooling and Hot Water Systems Using Evacuated Collectors - United States Department of Energy

VII Central Solar Heating Plants with Seasonal Storage - Swedish Council for Building Research

VIII Passive and Hybrid Solar Low Energy Buildings - United States Department of Energy

IX Solar Radiation and Pyranometry Studies - National Research Council, Canada

Collaboration in additional areas in likely to be considered as projects are completed or fruitful topics for cooperation identified.

Task VII - Central Solar Heating Plants with Seasonal Storag Feasibility Study and Design

In colder climates solar energy for heating of buildings is least abundant when it is needed most - during the winter. A seasonal storage is needed for making solar heat gained during warmer months available for later use. From investigations of various storage methods two observations can be made: The choice of storage method will greatly influenc the working conditions for and the optimal choice of the solar collectors and the heat distribution system; and based on the technique that is available today the most economic solutions will be found in large applications. The objective of Task VII is to determine the technical feasibility and cost-effectiveness of such seasonal solar energy storage for large-scale district heating systems. The Participants will evaluate the merits of various componer and system configurations for collecting, storing and distributing the energy, and prepare site-specific designs for specific systems.

The work is divided in two phases, preliminary design and parametric study of design alternatives. The work during the first phase is undertaken in five Subtasks:

Subtask 1a: System Studies and Optimization
(Lead Country: Canada)

Subtask 1b: Solar Collector Subsystems
(Lead Country: USA)

Subtask 1c: Heat Storage
(Lead Country: Switzerland)

Subtask 1d: Heat Distribution System
(Lead Country: Sweden)

Subtask 1e: Inventory and Preliminary Site Specific System Design
(Lead Country: Sweden)

The participants in this Task are Austria, Canada, the Commission of European Communities, Denmark, Germany, the Netherlands, Sweden, Switzerland, the United Kingdom and the United States.

This report documents work carried out under Subtask 1c of this Task. The co-operative work and resulting report is described in the following section.

central solar heating plants with seasonal storage

cost data and cost equations for heat storage concepts

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This report is part of the work within the IEA Solar Heating and Cooling Programme,

Task VII: Central Solar Heating Plants with Seasonal Storage
Subtask 1c: Heat Storage

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The reports of Subtask 1c are the result of an international cooperative work within Task VII. Many Task participants - especially in Subtask 1c - have made significant contributions to this work, as well as several companies in their respective countries. Some of these, such as modellers teams and engineering companies, were not directly involved in Task VII.

Three different versions of the reports were prepared by Pierre Chuard and Jean-Christophe Hadorn, of Sorane SA, Lausanne, Switzerland, under contract with the Swiss Federal Office of Energy. The work has been sponsored by the Swiss National Energy Research Foundation.

These versions have been improved by the joint effort of the Subtask 1c participants.

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EXECUTIVE SUMMARY OF THE WORK UNDERTAKEN IN SUBTASK 1c

A. INTRODUCTION

Within the IEA Task VII, the Subtask 1c called "Heat Storage" has the specific goal to collect and co-ordinate research and engineering information on heat storage systems to be considered in the design, analysis, and optimization of Central Solar Heating Plants with Seasonal Storage (CSHPSS).

In Subtask 1c three main fields were covered:

1. Seasonal heat storage simulation models
2. Cost data and cost equations for heat storage concepts
3. Basic engineering information for seasonal heat stores

The basic information collected in the Subtask among the ten participating countries has been analysed and presented in three reports dealing with each identified field. The Subtask work concurrently allowed the participants to select heat storage models suitable to the needs of Subtask 1a: "System Studies and Optimization", as well as adequate cost equations and cost parameters describing the various types of storage systems considered in the Task.

The purpose of this Executive Summary is to give an overview of the work accomplished in Subtask 1c, and of the three detailed reports which resulted from the cooperation and discussions among participants.

B. HEAT STORAGE CONCEPTS CONSIDERED IN TASK VII

Dealing with large-scale seasonal heat storage for solar heating plants, and considering the past and present developments in this field, the participants in Task VII decided, in 1980, to consider storage systems in which:

- the sensible heat of materials only is used
- the transfer medium is a liquid
- the annual variations of temperature are between 10°C and 100°C approximately

Seven storage types were identified as concepts to be investigated. They are the following:

1.	Tank	insulated	and/or	uninsulated
2.	Pit	insulated	and/or	uninsulated
3.	Cavern	insulated	and/or	uninsulated
4.	Aquifer	confined	or	unconfined
5.	Earth	disturbed	or	undisturbed
6.	Rock		undisturbed	

7. Solar controlled gradient pond

As the interest in solar ponds was not widespread among participants it was later decided not to consider these.

Hence, six concepts, mainly underground storage, have been considered in Subtask 1c.

C. HEAT STORAGE MODELS AND THEIR SELECTION

The aim of this part of the Subtask work was to gather information concerning seasonal heat storage simulation models, their capabilities and availabilities, to present in some detail several models suitable to the needs of Task VII, and, finally, to select models compatible with the optimization tool (the MINSUN program) and the analytical tool (the TRNSYS program) chosen in Subtask 1a.

In the resulting report, a general overview of about 50 existing heat storage models in the ten participating countries in 1981 is presented.

The information was processed by Lead Country 1c, based on questionnaires which were distributed to the particpants at the beginning of the Task.

Considering this basic information, a more precise analysis was performed for about 20 models, which were identified as being available.

A detailed analysis was then executed for 15 models classified in 3 categories:

- models for water tank, pit, and cavern storage systems
- models for earth and rock storage systems
- models for aquifer storage systems,

and typical test cases were submitted to the authors of the models.

Considering the capabilities, size, and results of each evaluated model, and keeping in mind the specialities and constraints of Task VII, the participants decided to choose a set of programs developed in Sweden by Lund University. These are the following:

SST: Stratified Storage Temperature Model (for tanks, pit, and cavern)

DST: Duct Storage Model (for earth and rock storage)

AST: Aquifer Storage Model (for aquifer storage)

These models are based on 2-D explicit finite differences, and they basically solve the heat conduction equation in soils.

For water storage in tanks, pits, and caverns, vertical stratification is accounted for.

For earth and rock storage, the local processes around pipes or ducts, and the global processes (storage losses) are treated with a superposition method.

For aquifer storage, a special technique is used to take into account the convective terms in a one-well or doublet system with prescribed horizontal water flow.

The models have the basic advantage to be complete (with few restrictions), while not consuming too much computer time. Furthermore, they are at least partly validated.

The integration of the models into TRNSYS and MINSUN, by their authors directly, started in Sweden in 1982 with a lower priority for AST, due to time constraints.

D. COST INFORMATION AND COST MODELS FOR HEAT STORAGE CONCEPTS

The optimization program for Central Solar Heating Plants with Seasonal Storage needs storage models used as subroutines, as well as cost equations describing the various storage components to be optimized.

For this main purpose and also for storage cost comparisons, the Subtask participants were asked to provide cost information concerning the storage types they were mostly interested in, as well as the distribution of investment costs between the storage main components.

After a general cost comparison among participating countries, cost equations were developed describing in terms of the MINSUN independent variables the total investment cost for each identified type of storage.

Typical values of the parameters involved in the equations (mainly specific costs) were then given - using the basic cost information provided by the participants - to the Subtask group responsible for optimization studies.

This work should be considered as a first attempt to give future cost projections since few large-scale storage systems have been built in the participating countries in 1981/1982.

Furthermore, as a result of the IEA cooperation, the Task participants are able to investigate, with some restrictions due to national conditions, the economic competitiveness of storage types with which they do not have much experience.

E. HEAT STORAGE CONCEPTS AND ENGINEERING DATA

The purpose of this part of the Subtask work was to gather information among the participating countries about engineering aspects of some major concepts of seasonal heat storage considered in the Task.

The aim was not to produce a "heat storage handbook", but rather an overview of the applicability, the existing experiences, and the future of the storage concepts.

To reach these objectives, the final report is organized into three main parts:

- the general design, applicability, and past experience of each storage type is outlined in a brief description written by some participants
- an overview of the national activities and specific interest in seasonal storage of each participating country is presented
- and, finally, based on questionnaires that were distributed to the participants during the Subtask work, a compilation of some interesting heat storage projects in participating countries was made, using a summary sheet for storage projects developed in the framework of similar EC work

More than 25 actually constructed projects or design studies in the field of large-scale seasonal storage are briefly presented, together with references and contact persons.

1. INTRODUCTION

The main purpose of Task VII of the IEA Solar Heating and Cooling Program, "Central Solar Heating Plants with Seasonal Storage", is to determine the technical feasibility and cost effectiveness of seasonal storage combined with large scale solar district systems.

During the past ten years, a great deal of studies and experiments has been achieved over the world in the field of seasonal heat storage.

Seasonal storage can be considered, in colder climates, as the only way to reach high solar fraction of domestic heating loads in an active solar system, and even in a hybrid system.

Moreover, seasonal heat storage can allow important savings (30-50%) on the total amount of solar collectors needed to meet a given part of a heating load.

Within Task VII, the Subtask 1c called "Heat Storage" has the specific goal to collect and co-ordinate research and engineering information on heat storage systems to be considered in the design, analysis, and optimization of Central Solar Heating Plants with Seasonal Storage (CSHPSS).

In Subtask 1c three main fields are covered:

1. Heat storage simulation models
2. Cost data and cost equation for heat storage concepts
3. Engineering data for heat storage concepts

The purpose of this report, covering the second item of Subtask 1c, i.e. "Cost Data" is to gather information among the ten participating countries about the cost of heat storage, and to describe the cost equations developed by Lead Country 1c, to be used in Subtask 1a for the optimization of CSHPSS by the MINSUN program.

The report is organized in three main sections:

1) Comparison of cost data in the participating countries (Chapter 3)
2) Cost equations to be considered in the CSHPSS optimization process (Chapter 5)
3) Typical values of cost equation parameters for preliminary CSHPSS optimization studies (Chapter 6)

2. HEAT STORAGE CONCEPTS CONSIDERED IN TASK VII

Dealing with large scale seasonal heat storage for solar heating plants, and considering the past and present developments in this field, the participants in Task VII decided to consider storage systems in which:

- the sensible heat of materials only is used
- the transfer medium is a liquid
- the annual variations of temperature are between 10°C and 100°C approximately
- the charging temperature is between 10°C and 150°C

Seven storage types were identified as concepts to be investigated:

1.	Tank	insulated	and/or	uninsulated
2.	Pit	insulated	and/or	uninsulated
3.	Cavern	insulated	and/or	uninsulated
4.	Aquifer	confined	or	unconfined
5.	Earth	disturbed	or	undisturbed
6.	Rock		undisturbed	

7. Solar controlled gradient pond

As the interest in solar ponds was not widespread among participants it was decided not to consider these.

Hence, six concepts, mainly underground storage, have been considered in Subtask 1c.

3. COMPARISON OF COST DATA IN THE PARTICIPATING COUNTRIES

This section is devoted to a comparison of cost data for each storage concept. The data has been provided to Lead Country 1c by the participants in Subtask 1c.

We have tried to express the cost data on a common basis, i.e. - when possible - with a reference volume as parameter.

When comparing data one must keep in mind that:

1. The provided costs did not necessarily include the same components
2. The set of units was often different, and assumptions have been made for comparison purposes (average efficiency...)
3. The cost figures provided have not necessarily been developed for the same control strategies
4. Special features are involved in each country for each storage type
5. A reference volume of storage can be defined in different ways for non-contained storages (such as aquifer, earth, rock...)
6. Few large storages have been built yet, and the cost functions are mostly cost projections
7. The currency exchange rates have varied much during our study. For comparison purposes we have used the exchange rates of July 1980. These values are the following, expressed in national currency unit per US$:

Austria	12.40
Canada	1.15
Denmark	5.41
FRG	1.75
The Netherlands	1.91
Sweden	4.13
Switzerland	1.61
UK	0.422
USA	1.0

8. The cost level used is that of July 1980

9. The points shown on the cost curves in this chapter do not represent special built projects, except when specified.

3.1. Water tank storage

The cost function for this storage system is certainly one of the easiest to predict since quite a lot of experience can be found in many countries in the field of district heating or oil products storage.

Moreover, the storage efficiency is rather independent of the site, and a reference volume is obvious to define.

Figure 1 shows the total capital costs of tank stores in different participating countries as a function of storage capacity.

To produce single curves for water tanks, the participants have made several assumptions, namely about the aspect ratio of the tank, the choice and thickness of thermal insulation, as well as about foundation systems (Reference 6) and control systems. For instance, small steel tanks can be built with "optimum" aspect ratio, but for large volumes the height of the tank is restricted to a maximum of about 20 m by the strength of the foundation, and the maximum thickness of steel which can be welded on the site (Reference 7).

Furthermore, the basic cost of steel tanks seems to be proportional to the surface area of the tank to a higher degree of correlation than to the tank volume (Reference 6).

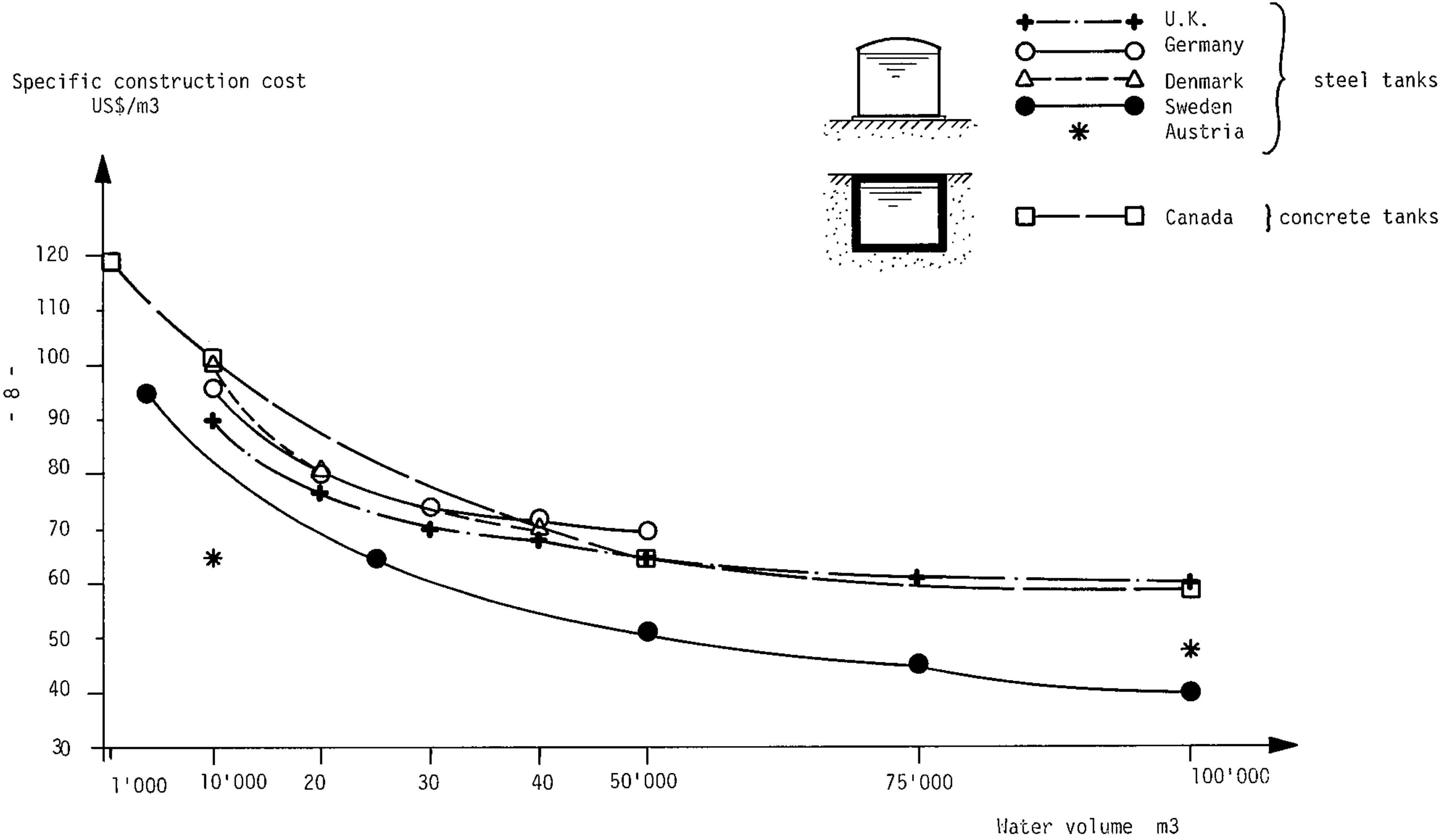
However, to assess a cost comparison in the Subtask, the storage volume has been used in Figure 1 as the reference variable.

The cost functions are quite close for Germany, Denmark, and U.K., whereas Swedish tanks appear to be cheaper. Data for buried concrete tanks based on a recent Canadian study (Reference 5) also compares well with the steel tank costs.

Figure 1: Cost function for steel and concrete tanks

Cost level and currency rate as per July 1980

IEA Task VII, Subtask 1c, 1982



Typical cost component breakdowns for water tanks are the following:

Steel tanks above ground between 10'000 m3 and 50'000 m3 (Germany)		Buried concrete tanks between 10'000 m3 and 100'000 m3 (Canada)	
Tank	40%	49%	Tank
Foundation	7%	6%	Excavation
Insulation	15%	10%	Insulation
Tubing, valves, pumps	29%	18%	Tubing, valves, pumps
Measuring and control	9%	14%	Measuring and control
Total	100%	100%	Total

These two cost distributions are represented in Figure 2 and 3.

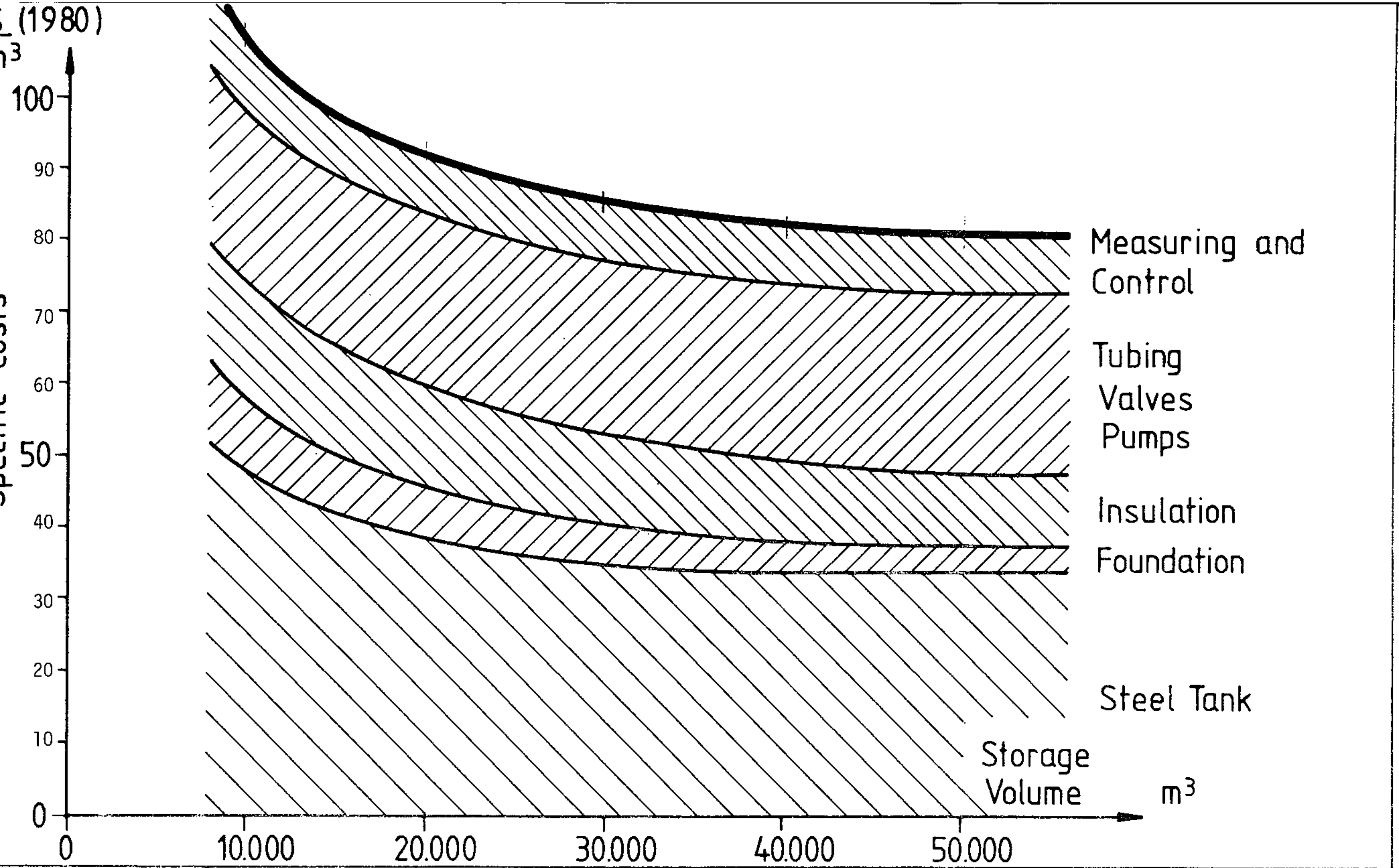


Figure 2: Germany

Costs of Hot Water Tank TES ($=2 DM)

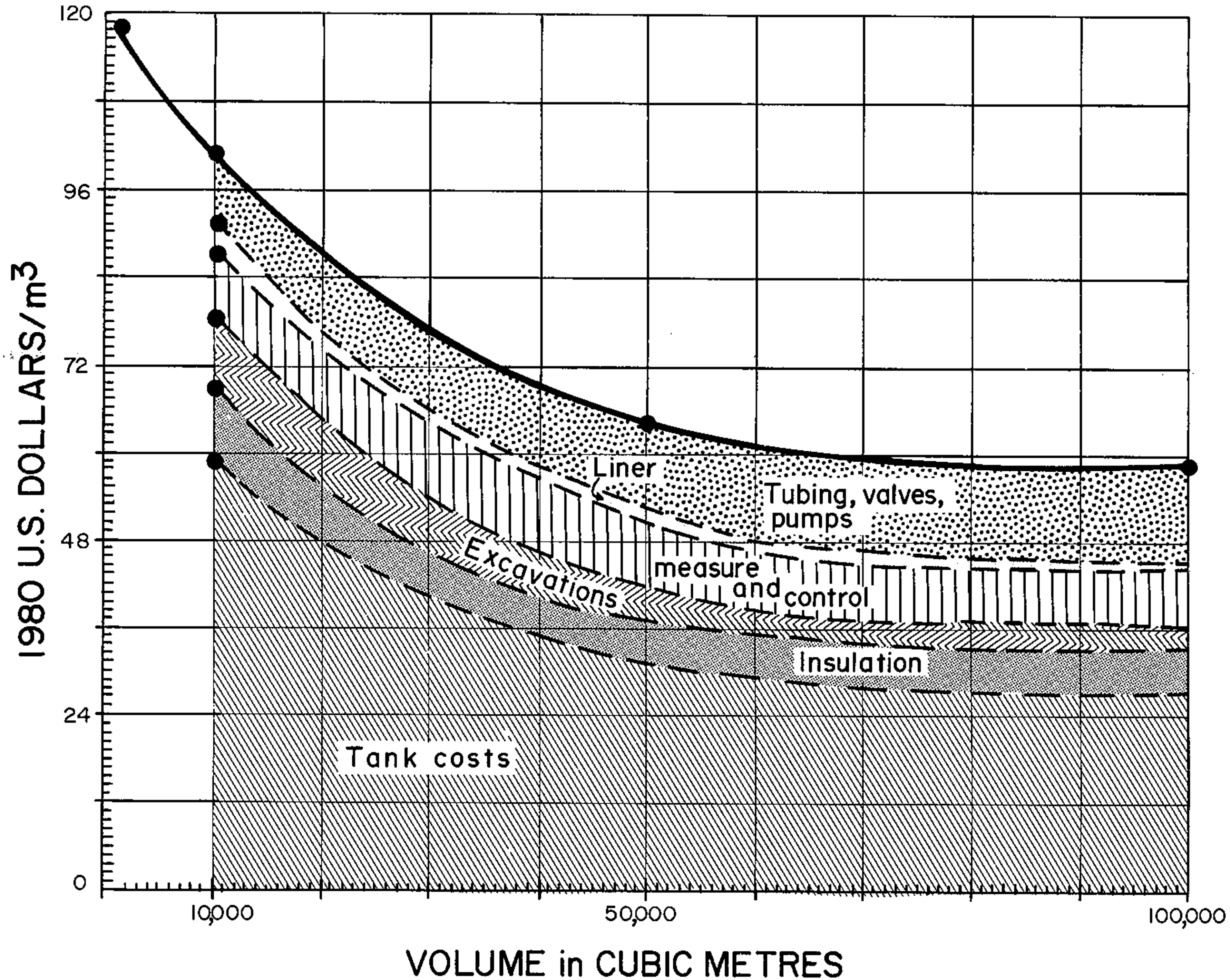


Figure 3: Plot of unit cost against Volume for Storage Tanks Canada

3.2. Water pit storage

Comparing cost functions for pit storage becomes more difficult since the design is quite different in each country, and for each particular system.

For example, the pit can be semi-excavated with retaining banks, or completely excavated, and insulated all around or with a floating insulated roof only, or with a support structure.

The cost functions plotted in Figure 4 mainly represent the following:

for Denmark:	semi-excavated pit with floating top insulation only and plastic liner, including heat exchangers, pumps and controls, without designing and land costs
for the United Kingdom:	semi-excavated pit with insulation on top, sides and bottom (polyurethan blocks), to give a storage time constant of five years, including a butyl liner with polyester, for a fixed depth of 10 m and sides of gradient 1 in 3, including heat exchangers, pumps, and control equipment, and a 10% consultancy charge
for Sweden:	gravel water basin (excavated, insulated and refilled), without land cost, interest during the construction period, operation and maintenance costs, and assuming an average yearly recovery factor between 0.5 and 0.8 for storage temperature variations between 30°C as a minimum and 85°C as a maximum
for the United States:	semi-excavated pit storage with steel frame roof, with 15 cm polyurethan top insulation, including rubber liner cost, engineering and contingencies.

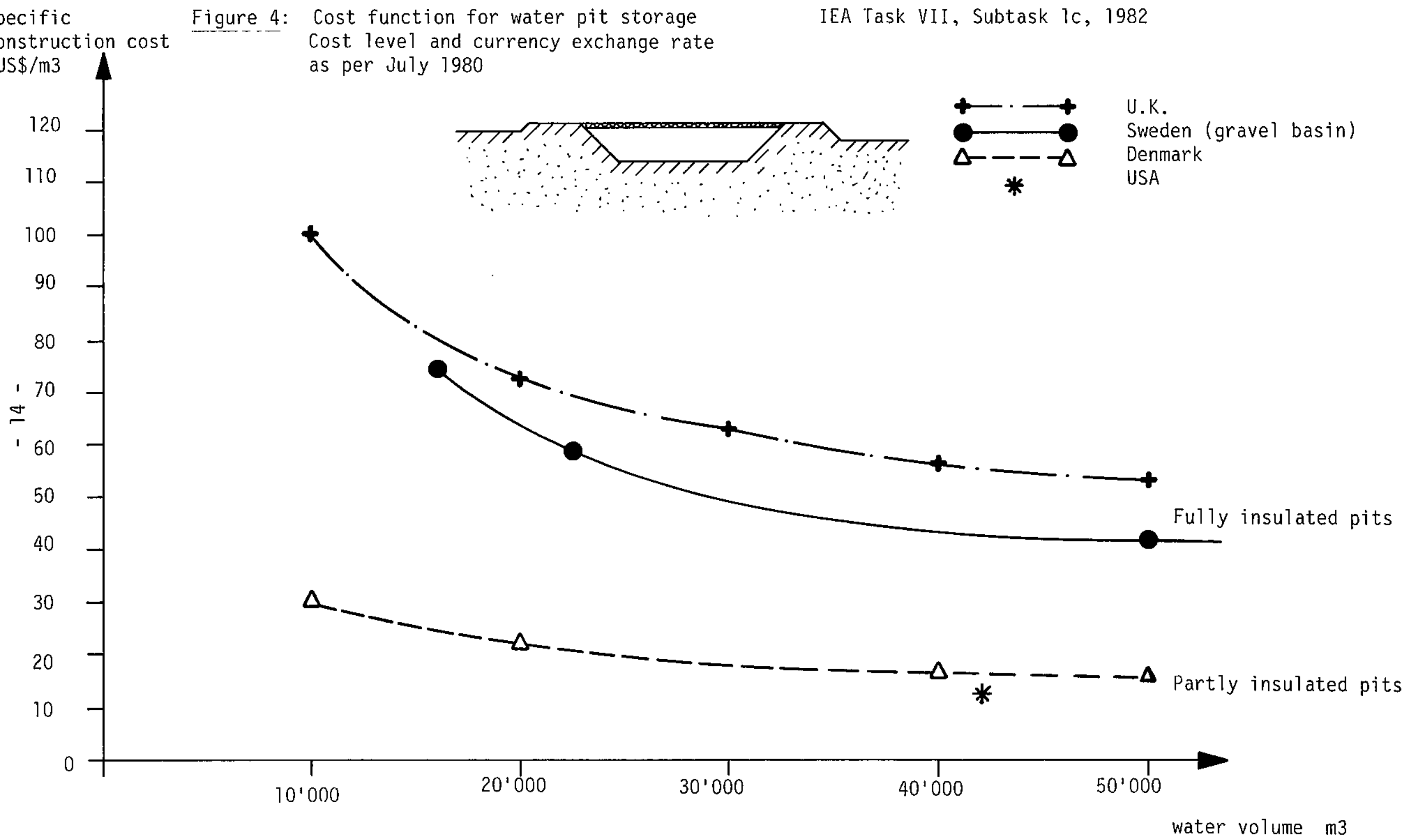
All costs given in Figure 4 are cost projections based on estimations.

A possible cost component breakdown for pit without side and bottom insulation is as follows (Denmark, pit between 10'000 and 40'000 m3):

Excavation	17%
Liner	15%
Floating top insulation	45%
Heat exchangers, pumps, controls	23%
Total	100%

Figure 4: Cost function for water pit storage
Cost level and currency exchange rate
as per July 1980

IEA Task VII, Subtask lc, 1982



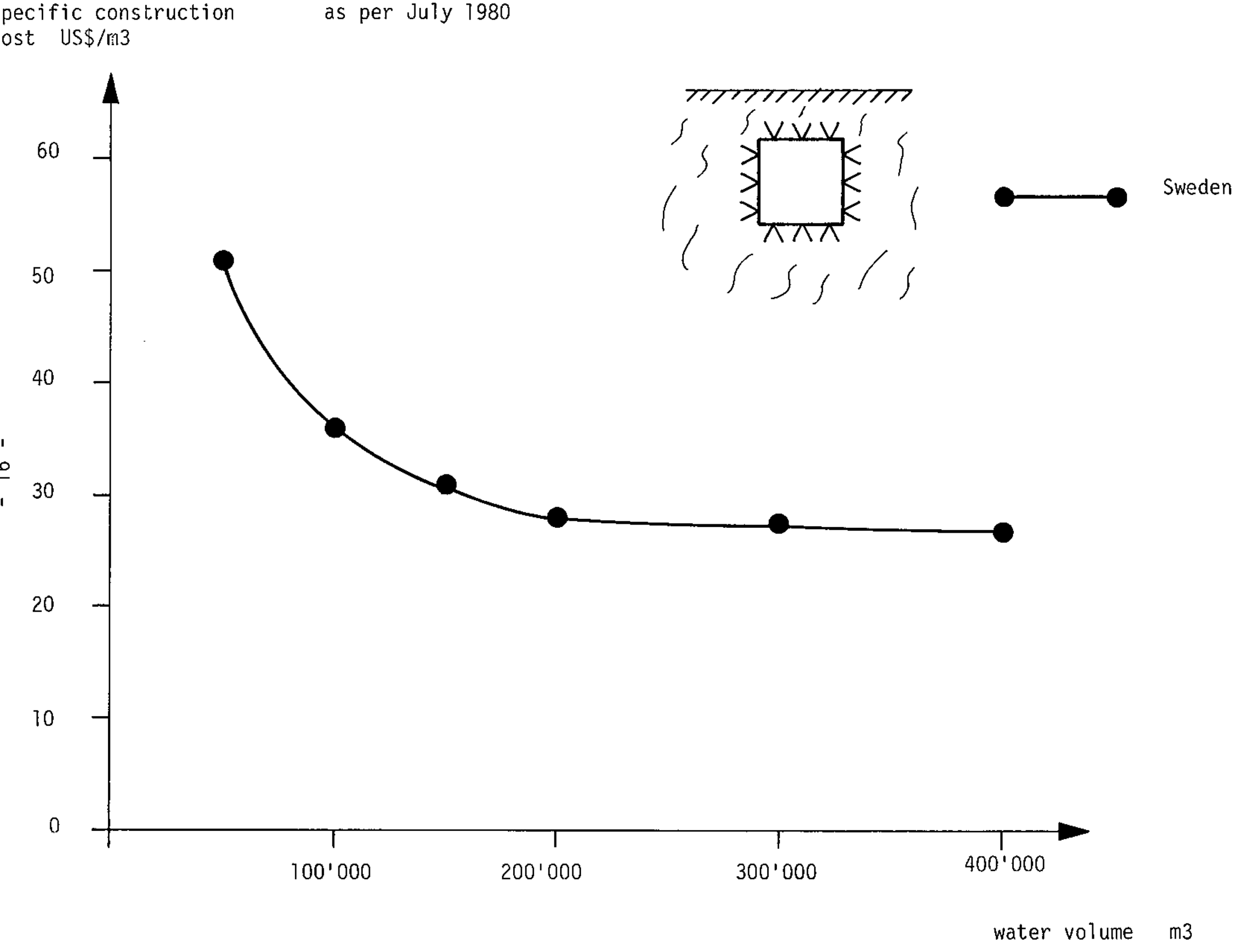
3.3. Rock cavern storage

Figure 5 shows a cost function given by Sweden for uninsulated rock cavern stores filled with water. The cost does not include costs for land use, interest during the construction period, operation and maintenance, and value added tax.

The information is based mainly upon existing rock caverns, since large scale underground cavern storage facilities have been designed and constructed in Sweden during the past twenty years, most of them for petroleum products.

Figure 5: Cost function for rock cavern
Cost level and currency exchange
as per July 1980

IEA Task VII, Subtask 1c, 1982



3.4. Earth storage

A cost comparison is difficult to achieve since earth storage systems are very dependent on local geological conditions.

The cost data gathered in Figure 6 for this type of storage concerns different systems, with the following main features:

- for the Netherlands: storage in sandy soil without excavation, with vertical plastic tubes inserted from the ground surface, with a top insulation consisting of 0.10 m of foamglass and 0.40 m of expanded clay, extending 7 m beyond the side of the storage;

  for this system, the specific cost decreases with the height of the storage due to the particular way of construction;

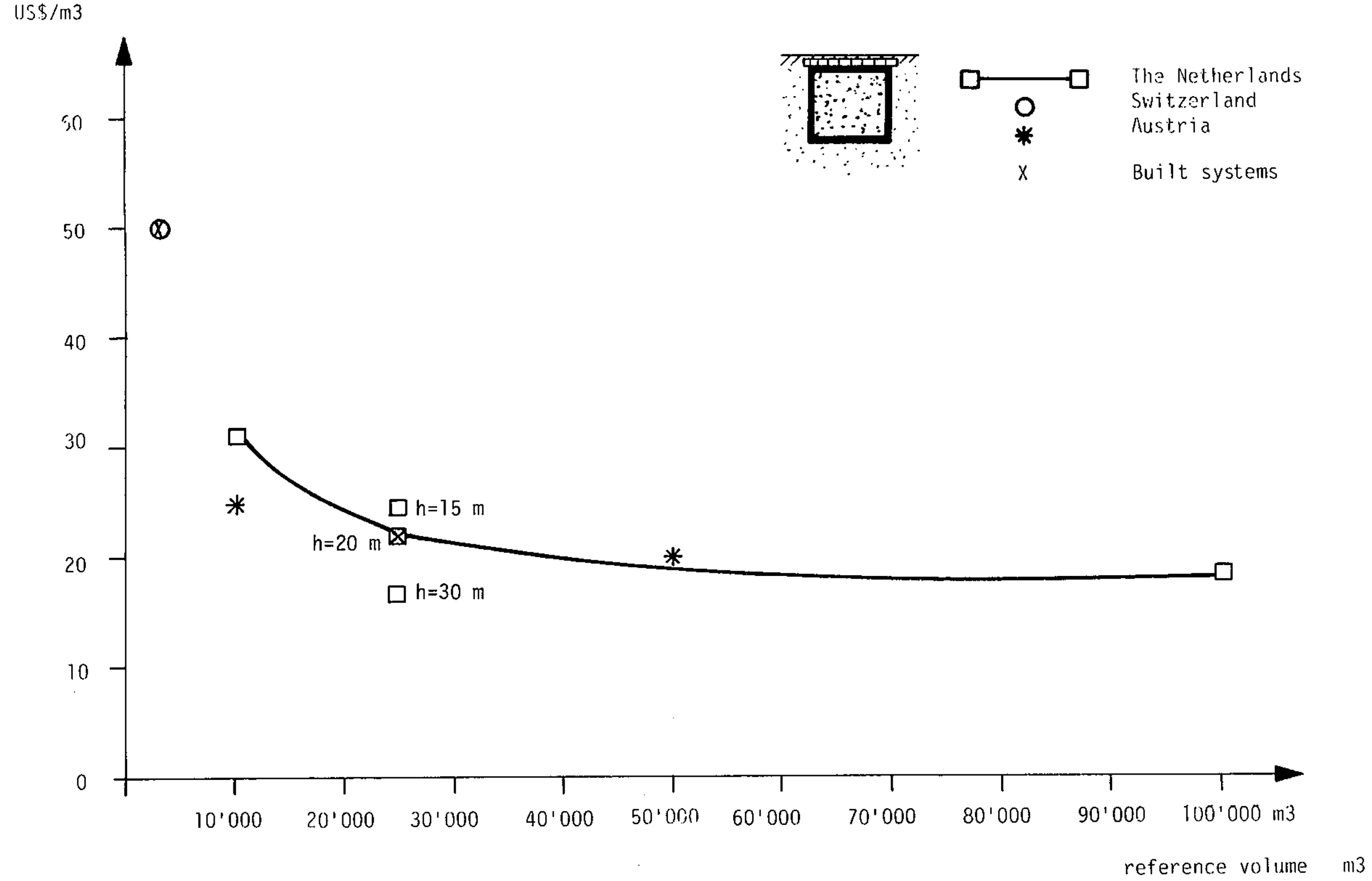
- for Switzerland: excavated storage with horizontal layers of plastic tubes, with side and top polystyren insulation (0.60 m on top, 0.30 m on side), and water-tightness.

The point given by Switzerland and the one given by the Netherlands, for 23'000 m3 and a height of 20 m, represent built systems.

Figure 6: Cost function for earth storage

Cost level and currency exchange rate as per July 1980

IEA Task VII, Subtask 1c, 1982



A possible cost component breakdown is as follows:

	The Netherlands (25'000 m3, not excavated)	Switzerland (3'500 m3, excavated)
Storage material (land price)	5%	3%
Ground works	3%	40%
Containment		12% (plastic sheets and vapour barrier)
Insulation	41% (foamglass and expanded clay)	20% (expanded polystyren)
Tubes and network	46%	22%
Miscellaneous	5%	3%
Total	100% (540'000 US$)	100% (170'000 US$)

For bigger systems, Sweden indicated 2 US$ / m3 in the range of volume between 50'000 and 1'000'000 m3 for vertical tubes systems in clay (low temperature storage).

The cost is almost independent of the volume for this kind of system.

3.5. Rock storage

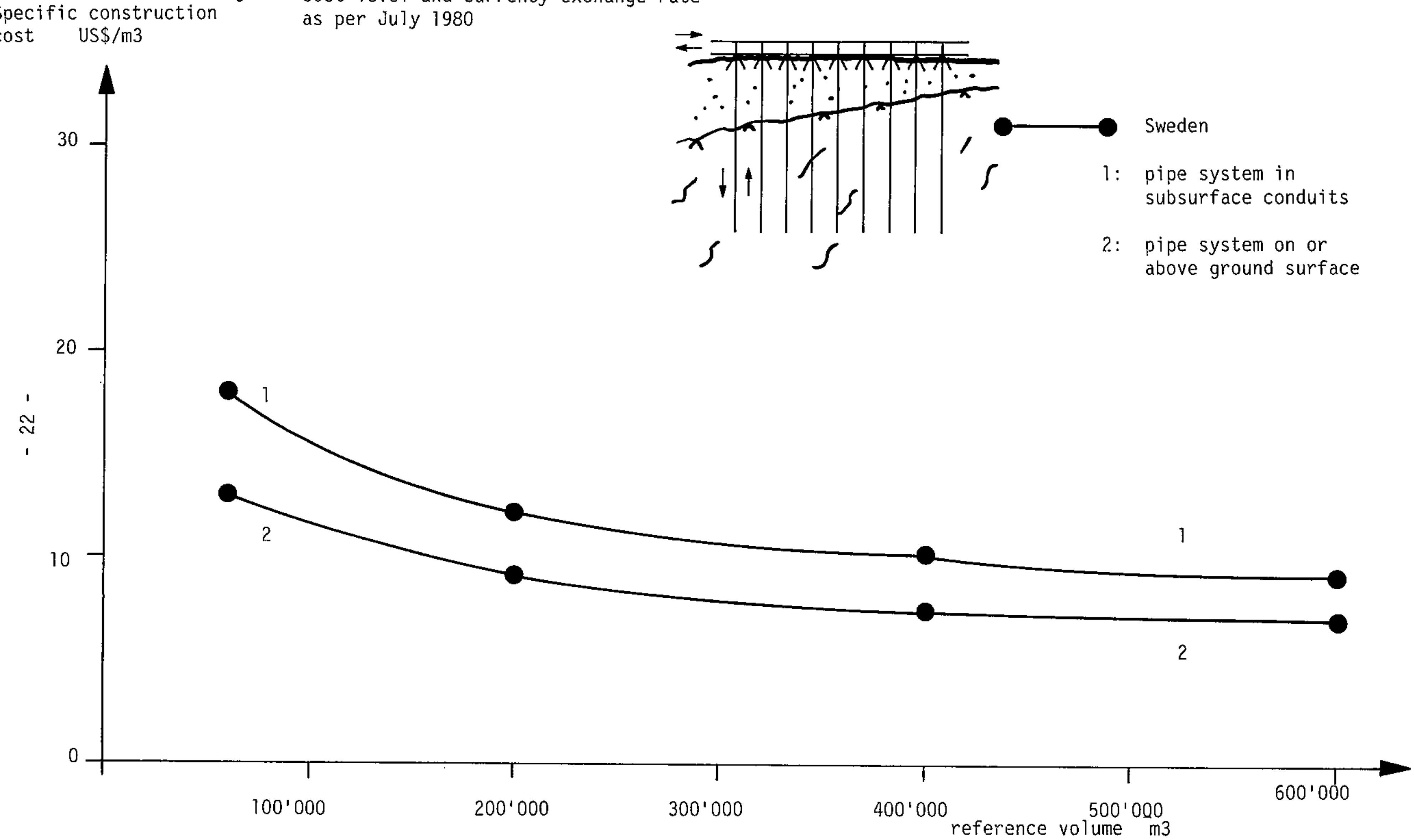
A cost function for multiple-well systems drilled in solid rock, given by Sweden, is represented in Figure 7.

The provided costs do not include costs for heat pumps installation, land use, interest during the construction period, operation and maintenance, and value added tax.

The information is based upon cost estimations for high temperature systems. When using low temperatures, the material for installations becomes significantly less expensive. Therefore, the costs per m3 for low temperature systems could be well below the curves indicated in Figure 7.

Figure 7: Cost function for high temperature drilled rock storage - Cost level and currency exchange rate as per July 1980

IEA Task VII, Subtask 1c, 1982



3.6. Aquifer storage

Cost data for aquifer thermal energy storage (ATES) is more difficult to assess in terms of "container" cost than the other storage technologies, because in most cases the use of the aquifer is essentially free. ATES "container" and storage costs are not directly related to the total stored water volume or to the aquifer volume or to the total amount of energy stored.

Rather, storage costs are proportional to the rate of water storage or retrieval. It is the rate of water injection and withdrawal that determines the number and size of wells, pumps, valves, and associated equipment. These costs constitute the largest portion of the capital cost for typical ATES systems. The major container/storage capital costs for the other storage technologies are related, as seen previously, to container materials, fabrication, excavation, and erection.

Although direct analogy cannot be made for ATES container/storage costs with the other technologies, a comparison can be made by assuming that the cost of obtaining access to the container (aquifer) is equivalent to a container cost, as defined for tank, pit, and cavern storages.

These costs include well drilling and completion, downhole pumps and land acquisition if necessary.

J.R. Raymond, from the USA, has made a cost assessment on this basis for a hypothetical ATES system to allow a rough comparison with the other technologies. The system factors and assumptions are as follows:

System parameters	
Operation temperature	144°C
Steady-state temperature differential	70°C
Aquifer thickness	30 m
Well depth	183 m
Well diameter	30.5 cm
Pumps, lineshaft turbine	20.3 cm
Water injection/withdrawal rate	44 l/sec
Injection/withdrawal time	90 days

Volume of stored water	3.45×10^5 m3
Required aquifer volume at 20% porosity	1.76×10^6 m3
Surface land requirements	2.5 hectares
Nominal system power (heat input/output)	12 MW
Total heat storage	26 GWh

With the following cost assumptions, typical for the US mid-continent, expressed in US$ July 1980:

Well drilling (Ø 30.5 cm)	480 US$/m
Pumps, valves, piping for one well	32'600 US$
Land cost	1'235 US$/m2

the system costs become:

Well doublet	176'000 US$	65%
Pumps, valves, piping	65'200 US$	24%
Land cost	30'900 US$	11%
Total cost of the system	272'100 US$	100%

Using these system parameters and assumptions, derived from ATES research and investigation in the USA over the past few years, the specific cost of storing water is 0.79 US$/m3, considering only the capital cost of the "container", or 0.15 US$ per m3 of aquifer volume.

The unit power cost is 22.7 US$/kW, and the unit energy cost is 10.5 US$/MWh.

If larger amounts of heat were needed, additional doublets would be required.

To give an idea of the considerable economies of scale possible for ATES systems, for a 6 MW system (half the nominal system power) with all parameters identical to the ones of the system described - except for the reduction of the injection/withdrawal rate to 22 l/sec - the cost of storing water would be 1.37 US$/m3.

Of course, the cost data given here can vary widely in time and space, and must be used with some caution in the evaluation of the proposed site-specific systems.

Costs for other items such as site exploration, monitoring wells and instrumentation, heat exchangers, control equipement, etc., are not included in the above discussion.

A more comprehensive evaluation of ATES costs linked to a system can be found under References 1, 8, and 9.

Further, cost information about ATES was provided by Austria, indicating the cost of access to a natural aquifer such as follows: 0.8 US$/m3 for an aquifer volume of 10^7 m3, and 4.0 US$/m3 for an aquifer volume of 10^6 m3.

In terms of volume of stored water, assuming a 20% porosity, these costs yield to:

4.0 US$/m3 for a water volume of 2.10^6 m3

20.0 US$/m3 for a water volume of 2.10^5 m3

For a man-made aquifer (artificial), Austria indicated a specific cost of 16 US$/m3 for aquifer volumes around 10^6 m3.

In Switzerland, the specific cost of the SPEOS pilot plant project is around 10 US$/m3 for a reference aquifer volume of 60'000 m3. The reference volume is twice that of the cylinder delimited by the two levels of horizontal radiant drains, the effectively influenced volume being 2 to 3 times larger.

Considering the volume of water injected and withdrawn (60'000 m3) the specific cost is around 10 US$/m3.

For a bigger system (aquifer volume over 10^6 m3) it is foreseen that the specific capital cost of such an ATES system could be divided by a factor of 5.

Due to the particularities of ATES systems compared with the other technologies, no reliable cost function in terms of a reference volume will be assessed in this report.

3.7. General cost comparison

What is interesting about gathering cost data is to try to assess a general comparison between each type of storage.

Curves of average specific construction costs as defined previously are plotted against a reference volume in Figure 8.

Since the storage cost functions have been derived with different assumptions for each storage type, one must be careful when interpreting the results of such a comparison.

Indicative points only are given for the aquifer storage due to the particularities discussed in Section 3.6.

Obviously, specific capital costs in terms of a volume cannot allow a direct comparison of storage technologies, even if the same components are included in the data, since the energy recovery factors of the various types of storage are different.

Moreover, these recovery energy factors are, for some of the heat storage technologies, site-dependent, and, for nearly all of them, system-dependent.

In addition to these difficulties, the temperature levels of the withdrawn energy play a special role in the definition and the choice of the back-up systems required. From this point of view a relevant cost comparison of storage technologies should involve an exergy recovery factor rather than a "simple" energy recovery factor.

This kind of exergy recovery factor being somewhat difficult to define, we have tried to use typical energy recovery factors to assess a more relevant cost comparison than the one based on reference volumes.

Figure 9 shows such a comparison of specific construction costs based on recovered energy. To define these specific costs, the following equation has been used:

$$SC_e = \frac{SC_v}{\rho Cp \cdot \Delta T \cdot \eta}$$

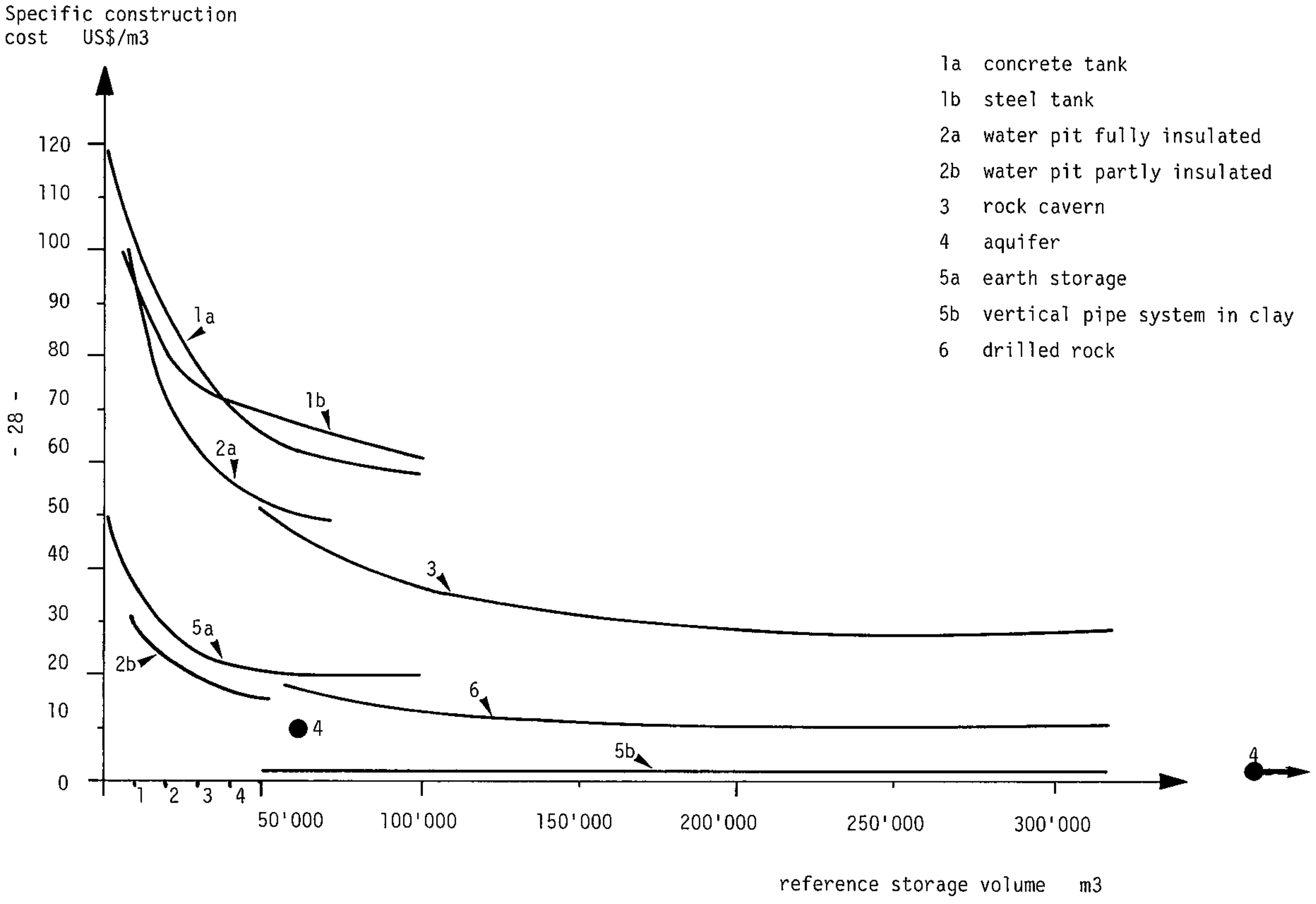
where:

SC_e = specific construction cost based on recovered energy US$/kWh

SC_v = specific construction cost based on reference storage volume US$/m3 given in Figure 8 for each type of storage considered

Figure 8: General comparison of specific costs based on a reference volume
Cost level and currency exchange rate as per July 1980

IEA Task VII, Subtask 1c
1982



ρ = density of storage medium kg/m3

Cp = specific heat of storage medium kWh/kgK

ΔT = reference useful temperature swing defining the energy recovered from the storage K

η = typical energy recovery factor for the storage considered

SC_e can be derived from SC_v by using the factor $f = \rho Cp \cdot \Delta T \cdot \eta$ [kWh/m3] which represents a conversion factor from 1 m3 of storage to 1 useful kWh.

The factors f used for each storage category to derive Figure 9 from Figure 8 are given in the next table.

Typical values have been considered to draw the table, with the following important comments:

- the volumetric heat capacity of the storage medium depends obviously on the medium itself, which can vary very much for storages using the soil as medium. The figures chosen in the table represent usual values for built systems;
- the reference ΔT will very much depend on the way the storage is built (insulation...), on its size, and on the whole system in which it is included (presence of heat pump or not...).

  A rather high reference ΔT has been chosen for all types of storage (55°C), except for the vertical pipe system in clay, where 15°C represents roughly a physical limit for this type of storage.

  For most of the storage types considered, 55°C can be regarded as an upper limit, even if a heat pump is present in the system, as it represents the ΔT over which the storage can be used during the production period. The charging ΔT should thus be higher than this value;
- the energy recovery factor - defined as the ratio of the energy withdrawn from the storage during the production period to the energy put into the storage during the charging period - is in fact very dependent on the size of the plant ("scale economies" of the heat losses), as well as on the way the storage is built.

  The figures chosen in the table can be considered as "target" values for big storage systems.

According to the assumptions described above and to the uncertainties in assessing storage cost projections in figure 8, Figure 9 represents a first estimation of specific capital cost per recovered energy during <u>one</u> cycle.

One must keep in mind that a lot of different assumptions have been made to derive the cost functions, and that capitalized cost for storage heat losses, heat pump electricity - when a heat pump is necessary to achieve the reference ΔT -, as well as capital cost for heat pumps have not been considered.

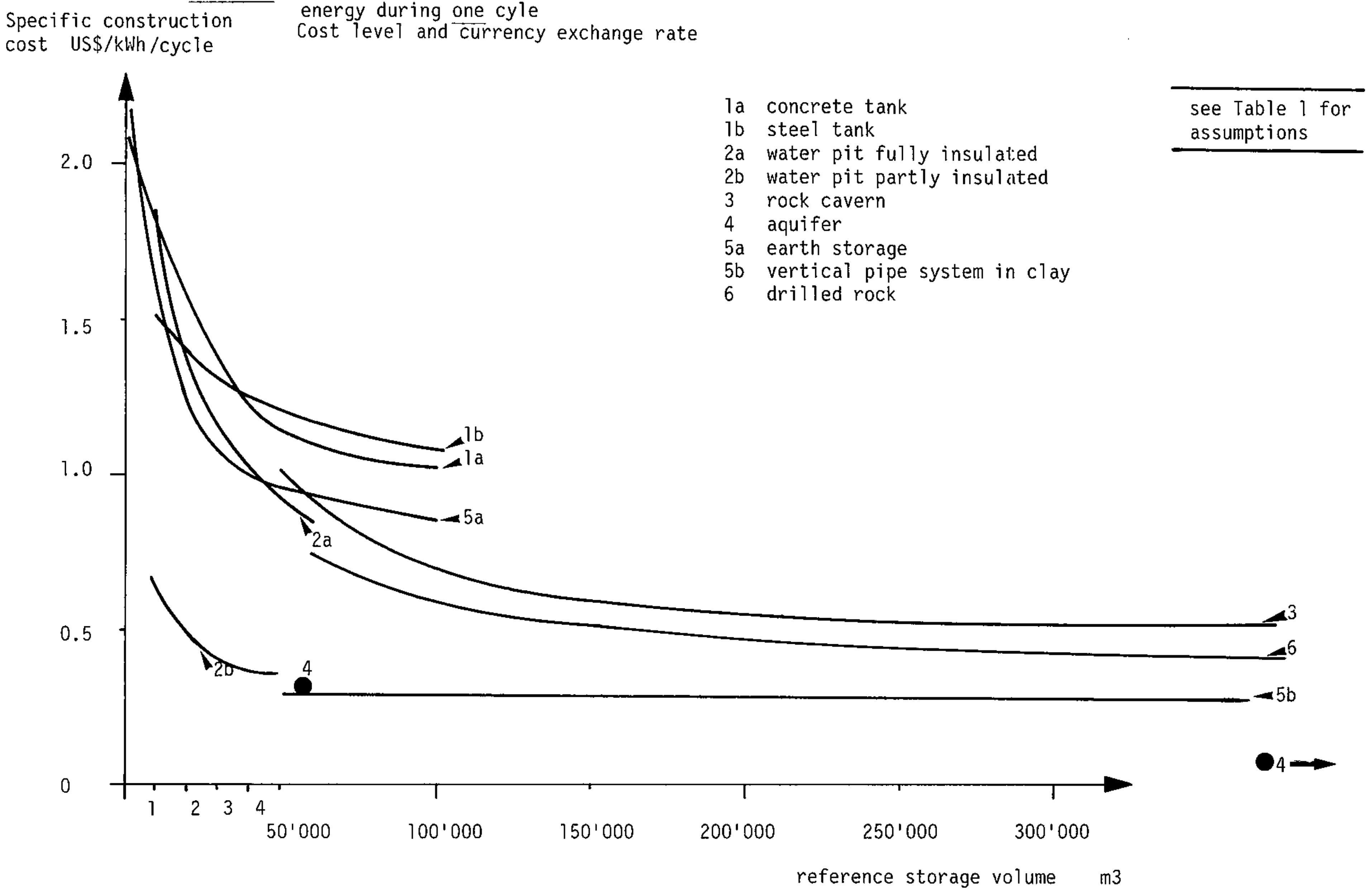
Table 1: ASSUMPTIONS FOR THE CONVERSION FACTORS BETWEEN REFERENCE VOLUME AND RECOVERED ENERGY

STORAGE TYPE	1 CONCRETE & STEEL TANKS	2a WATER PIT FULLY INSULATED	2b WATER PIT PARTLY INSULATED	3 ROCK CAVERN	4 AQUIFER	5a EARTH STORAGE	5b VERTICAL PIPE SYSTEM IN CLAY	6 DRILLED ROCK
Storage medium volumetric heat capacity ϱCp [kWh/m3K]	1.16	1.16	1.16	1.16	0.75	0.70	0.80	0.63
Reference ΔT 1/ [°C]	55	55	55	55	55	55	15	55
Typical energy recovery factor 1/	0.90	0.85	0.70	0.80	0.75	0.60	0.70	0.70
Conversion factor [kWh/m3]	57	54	45	51	31	23	8	24

1/: very dependent on the size of the plant, of the system...

Figure 9: General comparison of specific capital costs based on recovered energy during one cyle
Cost level and currency exchange rate

IEA Task VII, Subtask 1c, 1982



see Table 1 for assumptions

3.8. Other cost information

In the IEA program for "Energy conservation through energy storage", Annex 1 deals with large scale thermal storage systems. In the final report of this annex (October 1981) the cost functions provided by the participating countries (Belgium, EEC, Denmark, Germany, the Netherlands, Sweden, Switzerland, USA) are given (reference 12).

They concern underground concrete tanks, man-made aquifers, steel or concrete tanks above ground, aquifer storages and large diameter vertical reservoirs.

The functions (Figure 10) express specific construction costs pro equivalent water volume versus equivalent water volume of the storage system.

The cost functions for steel tanks (N° 3) are close to the ones proposed in our Task (Section 3.1.), represented by dots.

The information given in Figure 10 is complementary to the information gathered in our Task since it concerns other types of storage and is expressed in terms of the same parameter (water equivalent volume).

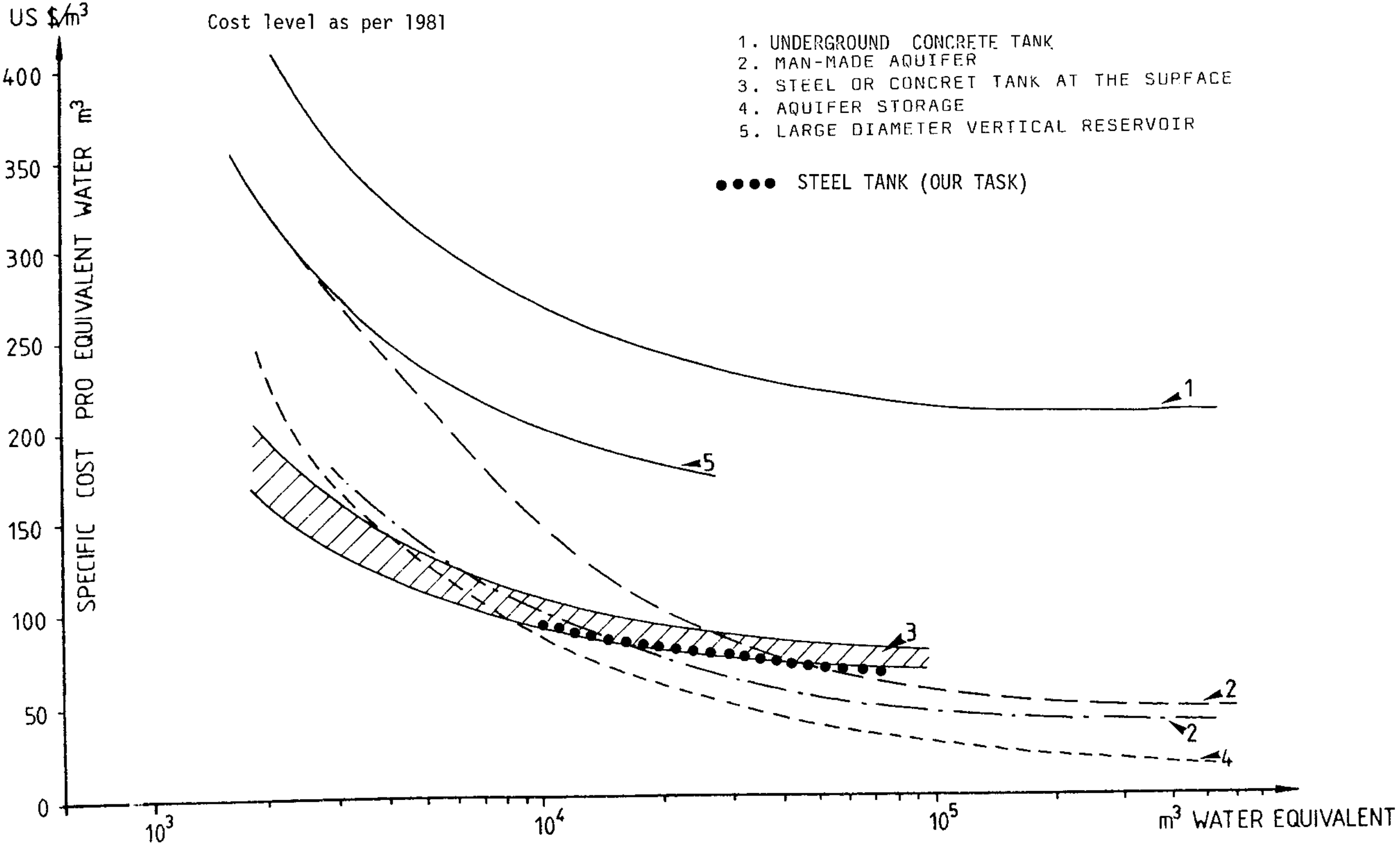


Figure 10: CONSTRUCTION COSTS FOR DIFFERENT HEAT STORAGE SYSTEMS IN FUNCTION OF EQUIVALENT WATER CONTENT (1981)

From IEA Annex 1: Large Scale Thermal Storage Systems

3.9. Cost information for built storage projects

The previous information was elaborated during 1980 and 1981, and mainly represents cost projections for future big storage projects. This information was based on very few plants existing at the time, and on engineer estimations.

In 1983 some big storage projects have been built in the participating countries, and the Subtask participants felt that a presentation of cost data for these projects would be very useful.

Tables 2a and 2b present the basic technical data of ten storage plants that have been built since 1980, and for which reliable cost information could be obtained. This cost information is given in terms of specific capital cost per m3 of reference volume, as well as in terms of specific capital cost per kWh of recovered energy during one cycle or - when not available - per kWh of heat capacity.

These figures are given in the concerned country currency unit with mention of the price level year.

In order to compare the cost data, a common basis has been used in Tables 2a and 2b in terms of US$ 1980.

The cost expressed in US$ 1980 was derived from the cost expressed in national currency unit, using the following relation:

$$\text{Cost in 1980 US\$} = \frac{\text{Cost in national currency unit}}{I_F \times E_R}$$

where:

I_F is the inflation factor with an inflation rate assumed to be 9% per year in every country, so that:

$I_F = 0$ for cost given in 1980

$I_F = 1.09$ for cost given in 1981

$I_F = 1.19$ for cost given in 1982

$I_F = 1.30$ for cost given in 1983

E_R is the currency exchange rate in July 1980 used as a reference and given in page 5 for each currency

This procedure is rather arbitrary and has been used only to allow a more or less rough and rapid comparison between very different projects. The currency exchange rates have varied very much during the past two years, especially when considering the US$ as the reference.

Therefore, the specific costs indicated in Table 2 in terms of US$ and in Figure 11 do not allow one to say that the types of storage discussed in the table could be realised in the US for the indicated cost.

They are only meaningful for comparison purposes and no absolute conclusion should be taken out of the last two lines of Table 2 and of Figure 11.

Tables 2a and 2b are followed by notes presenting the major features included in the given costs and main references.

Reference to the Summary sheets describing the projects with more details and enclosed in the Subtask 1c report entitled "Heat Storage Systems: Concepts, Engineering Data and Compilation of Projects" (see List of Task VII Reports) is also mentioned when available.

Figure 11 shows the cost comparison in terms of US$ for the 10 storage projects considered.

In general, Figure 11 compares well with Figures 8 and 10, the cost of the built projects being slightly lower than indicated by the projections, except for experimental research storage plants.

TYPE OF STORE	STEEL TANK	ROCK CAVERN		AQUIFER		
NAME OF PROJECT	District heating STOCKHOLM Sweden	LYCKEBO Sweden	AVESTA Sweden	Cold storage SCARBOROUGH Canada	Hot storage SCARBOROUGH Canada	SPEOS Switzerland
STATUS	Completed 1981	Completed 1982	Completed 1982	Construction started February 1983		Completed 1982
REFERENCE VOLUME m3	40'000 height 33 m	100'000	15'000	~ 750'000	~ 50'000	~ 60'000
$T_{min} \div T_{max}$ °C	40 ÷ 95	40 ÷ 90	70 ÷ 115	4 ÷ 13	20 ÷ 43	30 ÷ 60
HEAT CAPACITY MWh	2'500	5'500	800	2'900	260	
or ENERGY RECOVERED PER CYCLE MWh						1'000
in national currency unit COST/m3 1)	284 SEK 81	150 SEK 82	850 SEK 82	0.27 CDN$ 83	0.40 CDN$ 83	17 SFr 82
COST/kWh per cycle 2) (for seasonal storage)	5 SEK 81	2.73 SEK 82	16 SEK 82	0.07 CDN$ 83	0.08 CDN$ 83	1 SFr 82
COST/m3 1) 1980 US$	63	30	173	0.18	0.27	10
COST/kWh.cycle 2) 1980 US$ (for seasonal storage)	1.11	0.56	3.26	0.05	0.05	0.53
NOTES & REFERENCES SEE (pp. 39-40)	A	B	C	D	D	E

1) The cost used in this table is the storage capital cost with features described in notes

2) The energy recovered, when available, is the energy output from the storage during <u>one cycle</u>

Table 2a): Cost information for built projects

TYPE OF STORE	EARTH STORAGE			DRILLED ROCK
	VERTICAL TUBES		HORIZONTAL TUBES	
	IN CLAY	IN SATUR. SAND		
NAME OF PROJECT	SUNCLAY Sweden	GRONINGEN The Netherlands	VAULRUZ Switzerland	LULEÅ Sweden
STATUS	Completed 1980	Completed 1983	Completed 1982	Completed 1983
REFERENCE VOLUME m3	85'000	23'000	3'500	120'000
$T_{min} \div T_{max}$ °C	$7 \div 15$	$25 \div 60$	$5 \div 45$	$25 \div 60$
HEAT CAPACITY MWh	695			
or				
ENERGY RECOVERED PER CYCLE MWh		450	108	1'700
in national currency unit				
COST/m3 1)	12 SEK 80	40 DFL 83	85 SFr 82	50 SEK 82
COST/kWh per cycle 2) (for seasonal storage	1.4 SEK 80	2 DFL 83	2.8 SFr 82	3.5 SEK 82
COST/m3 1) 1980 US$	2.9	16	45	10.2
COST/kWh.cycle 2) 1980 US$ (for seasonal storage)	0.34	0.81	1.47	0.85
NOTES & REFERENCES SEE (pp. 39-40)	F	G	H	I

1) The cost used in this table is the storage capital cost with features described in notes

2) The energy recovered, when available, is the energy output from the storage during <u>one cycle</u>

Table 2b): Cost information for built projects

Table 2a): Notes and references

Project A: Steel tank in Stockholm

The tank is a hot water storage tank designed and built in Stockholm, for short-term storage (~1 day), in a district heating plant.

For seasonal storage, the tank cost will rise due to the higher amount of insulation needed, but it may decrease according to reduced need for piping, valves, and pumps.

The cost component breakdown for the short-term storage is the following:

Foundation:	12%	
Steel tank:	40%	
Insulation (300 mm):	12%	
Tubing, valves, pumps:	28%	
Design and control:	8%	
Total:	100%	(12.5 MSEK 1981)

Project B: Rock cavern in Lyckebo

Costs include heat exchangers, pumps, water filling, and hardness softener. Refer to References 14 and 15, and to Summary sheet 5.3.2.

Project C: Experimental rock cavern in Avesta

The plant is basically intended for short-term storage (weekly) and is a research plant.

The costs given in Table 2a) include heat exchangers, pumps, water filling, hardness softener, control equipment, connection to district heating, engineering cost, and experimental features (such as a "research tunnel"...). Refer to References 16 and 15, and to Summary sheet 5.3.1.

Project D: Cold and hot aquifer storage in Scarborough

The costs given in Table 2a) include drilling of 4 cold wells (60 m deep), and 2 hot wells (40 m deep). Refer to Reference 17, and to Summary sheet 5.4.4.

Project E: SPEOS - Experimental aquifer storage

Costs include drilling of a central well (25 m deep) and 12 horizontal drains (25 m long), heat exchangers, pipes, control equipment, and experimental features (pilot test plant). Refer to Reference 18, and to Summary sheet 5.4.2.

Table 2b): Notes and references

Project F: Project SUNCLAY in Kungsbacka

The costs given in Table 2b) include installation of pipes and connection to load. Refer to Reference 19, and to Summary sheet 5.5.3.

Project G: The Groningen project

Costs include insertion of pipes in the sand, a 100 m3 buried steel tank for short-term storage, connection between pipes, and top insulation. Refer to Reference 20, and to Summary sheet 5.5.1.

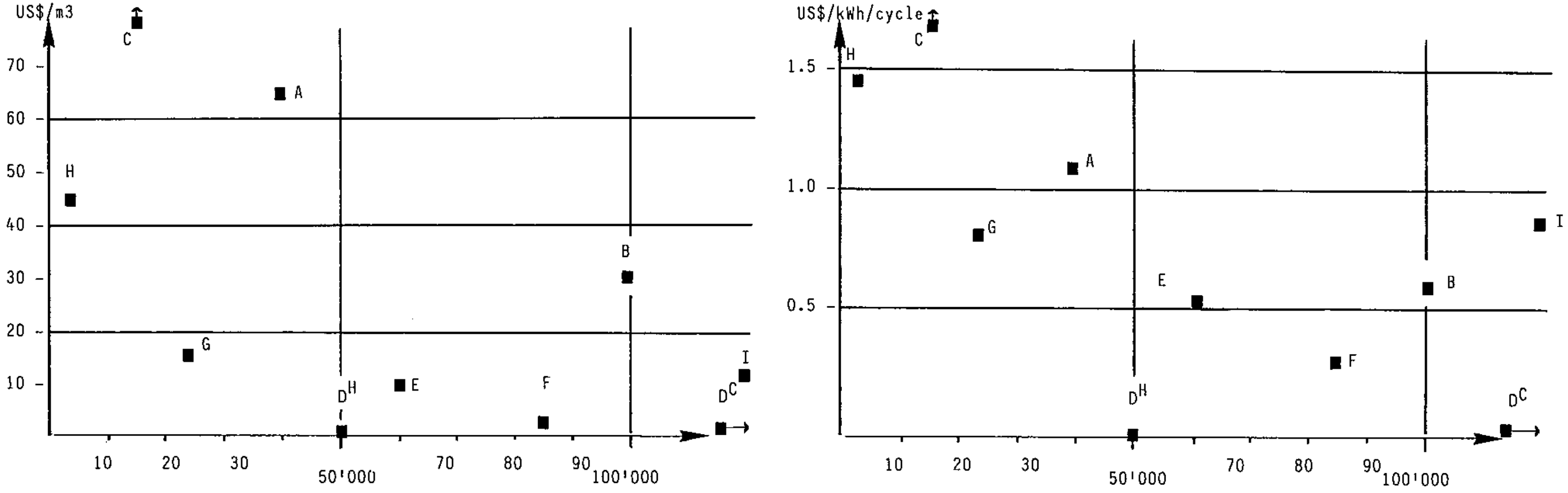
Project H: The Vaulruz project

Costs include ground works, plastic pipes, containment, insulation, connection to the load. Refer to Reference 21, and to Summary sheet 5.5.2.

Project I: Drilled rock in Lulea

Costs include drilling of boreholes, plastic tubes insertion, connecting pipes, pumps, heat exchangers, control equipment, engineering, some experimental features, and a heat pump. Refer to Reference 22, and to Summary sheet 5.6.1.

Figure 11: Cost comparison for built storage projects
Cost level July 1980
Currency exchange rate per July 1980


Specific capital cost based on reference volume

Specific capital cost based on energy recovered during one cycle

REFERENCE STORAGE VOLUME m3

REFERENCE STORAGE VOLUME m3

A = Steel tank in Stockholm 1981
B = Rock cavern in Lyckebo 1982
C = Rock cavern in Avesta 1982
D^C = Cold aquifer storage in Scarborough 1983
D^H = Hot aquifer storage in Scarborough 1983

E = SPEOS aquifer storage 1982
F = Vertical pipe system in clay, SUNCLAY 1980
G = Earth storage in sand in Groningen 1983
H = Excavated earth storage in Vaulruz 1982
I = Drilled rock in Luleå 1983

4. OBJECTIVES OF GATHERING COST DATA

Within Subtask 1a of Task VII, the optimization process needs, as input data, the various costs involved in the CSHPSS.

The subsystems of the solar plant can be related to many configurations within the solar system, the size of which is to be optimized.

The MINSUN program, chosen as the optimization tool in Subtask 1a needs cost functions for each storage concept in an appropriate form.

This means that a cost structure for each storage type should be taken out of the cost data gathered in Subtask 1c.

As soon as we try to get cost variations with the relevant parameters of a storage system, in order to optimize the whole system, problems arise:

- the relevant parameters must be known or defined
- the cost functions should be given in terms of these relevant parameters
- the cost functions should be suitable to the optimization process in MINSUN

As we have seen, the cost functions provided were all expressed in terms of a single parameter such as a reference volume.

The volume is certainly not the only parameter to optimize in the system, since the storage models incorporated into the MINSUN program can take into account other relevant and independent variables defining a storage.

For these reasons, cost functions for optimization purposes could not be taken out of the previous information (Chapter 3).

Considering this point and the capabilities of the optimization part of both the MINSUN and the LUND storage models selected within Subtask 1c (see the report concerning heat storage models), Lead Country 1c developed cost equations suitable to the needs of Subtask 1a.

These cost equations are developed in the next chapter, including the equations proposed by some participants.

5. COST EQUATIONS FOR HEAT STORAGE CONCEPTS SUITABLE TO MINSUN

Introduction

This section presents the proposed cost equations for several types of storage to be considered in the optimization process of CSHPSS (Subtask 1a).

The cost equations are given by formulaes to be incorporated into the MINSUN program. The set of parameters needed should be given by each country considering its specific design and local conditions.

A set of parameters to be used for test purposes is given, but it should be taken as a first attempt to give mean values to be considered when there is a lack of data in someone's country. These parameters are based on the information given in the previous sections.

For the proposed equations, we have tried to take into account the capabilities of LUND models for heat storage in the definition of the independent variables, and the requirements for smooth curves in MINSUN.

The first type of storage will be treated in more details to present the basic philosophy.

Warning:

In this report the so-called "independent variable" is a variable which:

- is independent (usual meaning)
- affects strongly both the thermal behavior of the storage and the cost of the storage type considered
- is a parameter for the heat storage models chosen in our Subtask for MINSUN (LUND models basically), which can be easily changed during the optimization process within the MINSUN program.

5.1. Storage in buried tanks or tanks above ground

5.1.1. Identification of the independent variables to be optimized

1 Volume of storage tank

2 Height of storage tank

3 Thickness of insulation on top

4 Thickness of insulation on sides

5 Thickness of insulation at the bottom

5.1.2. Comments

Variables 1 & 2:

- Define also the shape of the tank (stratification effects)
- It is assumed that the earth cover above the tank is rather independent on height or volume. Thus it will not be a parameter and we will assume, for buried tanks:

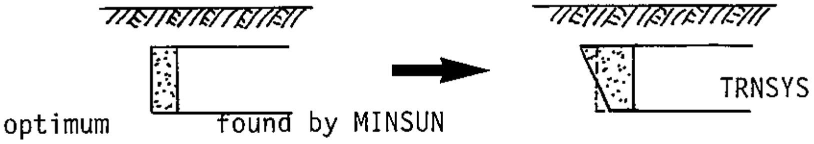
  max. depth = height + constant

- The cost will depend on the depth of the store (i.e. its height) and on the volume of the store: for a same depth the specific cost of the tank can be smaller for a big tank than for a small tank. The dependence on volume can be avoided, when desired, by setting the appropriate set of values for the regression parameters

Variables 3, 4 & 5:

- The volume of insulation is not chosen because in this case, with a model such as LUND-SST, an assumption on the repartition of the insulation around the tank should be made internally
- Moreover, MINSUN capability to optimize this repartition appears to be very interesting
- It will be assumed that the insulation is placed with a constant thickness: any other distribution should be "optimized" around the optimum found by MINSUN, using TRNSYS (Figure 12)

Figure 12: Example of a TRNSYS detailed analysis using MINSUN results



- The thickness or volume of concrete or steel will not be optimized as it is more a technical problem than a thermal one: its cost will then have to be included in the cost of storage Costvol (Section 5.1.4.).

5.1.3. Proposed cost function

According to the above remarks we propose for water tanks the following breakdown for the capital cost:

$$\text{Cost} = \text{Vol} \times \text{Costvol} \times e^{\alpha H} \qquad (1)$$

+ Insulation thickness on top x Top surface x Cost of insulation/m3

+ Insulation thickness on walls x walls surface x Cost of insulation/m3

+ Insulation thickness on bottom x Bottom surface x Cost of insulation/m3

+ A_{ground} x Cost of ground/m2

+ Constant Cost

where Costvol is the specific cost of storage (US$/m3) excluding insulation and ground cost

To express this equation in terms of the independent variables, we will assume:

$$A_{ground} = A_{top} = A_{bottom} = \frac{\text{Vol}}{H} \qquad (2)$$

5.1.4. Expression for Costvol

As the dependence of the storage cost on the volume is not well known before a project starts we will consider a simple general expression, which can be used in all the cases where economies of scale can occur.

This formula - schematically shown in Figure 13 - is the following:

$$\boxed{\text{Costvol} = C_b + \frac{C_o - C_b}{\left(\frac{Vol}{Vo}\right)^{\beta}}} \quad \text{US\$/m3} \qquad (3)$$

with:

C_b = asymptotic cost US$/m3 or basic cost

C_o = specific cost for a small volume V_o US$/m3

V_o = small volume (start point) m3 for which C_o is known

Vol = tank volume m3

β = scale factor $0 \leq \beta \leq 1$, expressing economies of scale

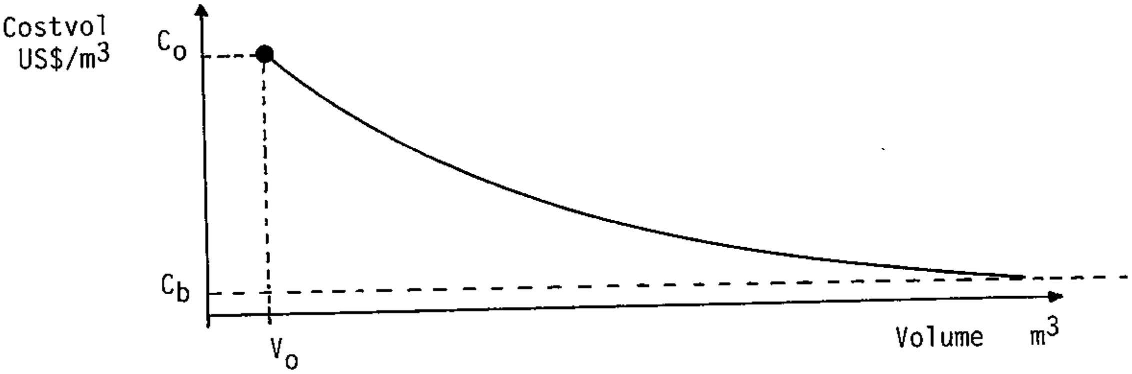


Figure 13: Parameters defining the specific cost of storage Costvol

In most projects one point is known (V_0, C_0), based on a small system already built, and can be considered as a starting point for cost projections for larger projects.

The higher the value chosen for β, the stronger will be the dependence of the specific cost on the storage volume (Figure 14)

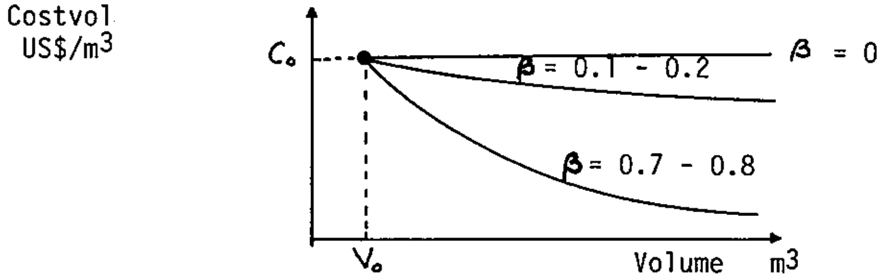


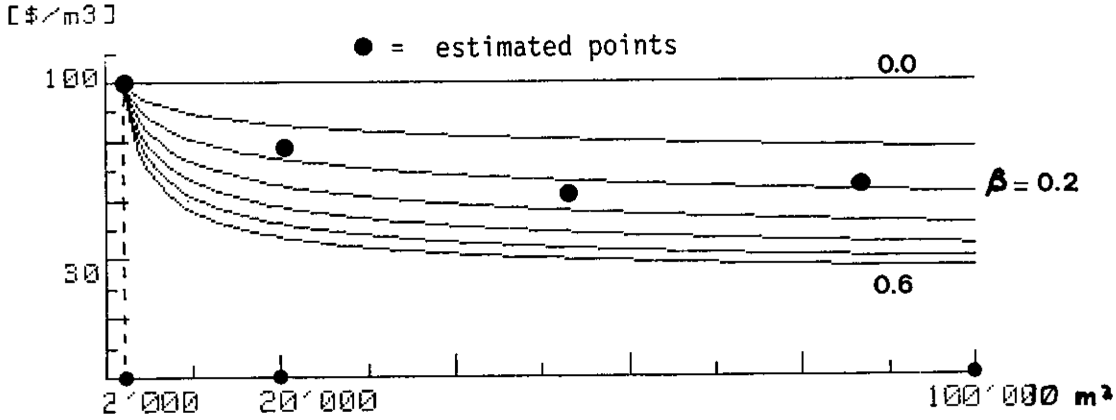
Figure 14: Influence of the scale factor β on the specific cost

A sensitivity study can thus be done using different values for β, when only one point is known (V_0, C_0).

To optimize a system with MINSUN, the user must then fix for Costvol:

$$C_b \; ; \; C_0 \; , \; V_0 \; ; \; \beta$$

This can be done by hand if 3 or 4 ponts are known for a specific case (Figure 15)



The estimation of the parameters yields to:

Co = 100 $/m3 Vo = 2'000 m3 Cb = 30 $/m3 β = 0.2

Figure 15: Example of by-hand procedure to define the parameters in Costvol

5.1.5. Cost equation in terms of independent variables

$$\boxed{\begin{aligned} \underline{\text{Cost}} = {} & \text{Vol} \times \left[C_b + \frac{C_o - C_b}{\left(\frac{\text{Vol}}{V_o}\right)^{\beta}} \right] \times e^{\alpha H} \\ & + I_t \times \frac{\text{Vol}}{H} \times C_{it} \\ & + I_s \times A_s \times C_{is} \\ & + I_b \times \frac{\text{Vol}}{H} \times C_{ib} \\ & + \frac{\text{Vol}}{H} \times C_g \\ & + C_c \end{aligned}} \qquad (4)$$

with:

$$A_s = A_{walls} = 4\,H \sqrt{\frac{\text{Vol}}{H}} \quad \text{for a cubic tank}$$

$$= 2\,\pi\,H \sqrt{\frac{\text{Vol}}{H}} \quad \text{for a cylindrical tank}$$

Nomenclature:

Cost : total cost of storage US$

Vol : internal volume of the tank m3

C_b : specific cost for a very large tank US$/m3

C_o : specific cost for a tank of volume V_o US$/m3

V_o : internal volume of a small tank for which the specific cost C_o is known m3

β : scale factor $0 \leq \beta \leq 1$ (see Section 5.1.4.)

α : coefficient expressing the increase of specific cost with depth 1/m

H : height of the tank (depth $\simeq$ height + constant)

I_t	:	thickness of top insulation m
I_s	:	thickness of wall insulation m
I_b	:	thickness of bottom insulation m
C_{it}	:	specific cost of top insulation US$/m3 of insulation
C_{is}	:	specific cost of wall insulation US$/m3 of insulation
C_{ib}	:	specific cost of bottom insulation US$/m3 of insulation
A_{side}	:	area of the sides of the tank defining the volume of sides insulation m2
C_g	:	ground cost US$/m2
C_c	:	constant cost independent of the identified variables US$

Note:

If the area of land occupied by the storage appears to be larger than Vol/H, C_g should be majored.

The independent variables are:

Vol	H	I_t	I_s	I_b
1	2	3	4	5

These variables are defined in Figure 16 for buried tank systems.

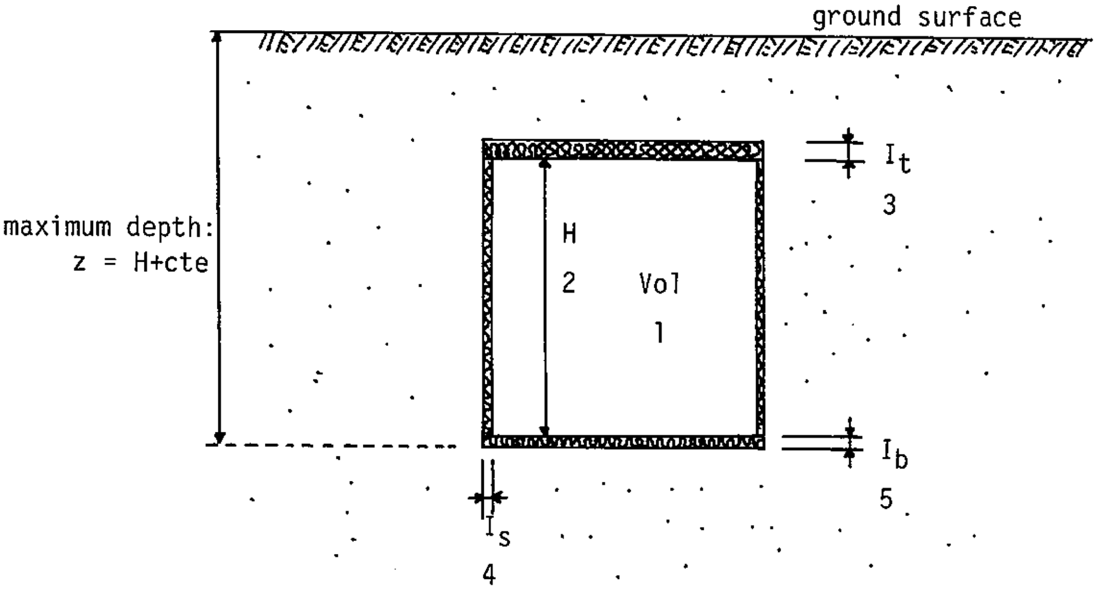


Figure 16: Definition of the independent variable for buried tanks

For tanks above ground the same definitions are applicable except that z is equal to zero.

Note:

In C_b and C_o, one must obviously not consider the insulation cost and the ground cost, but all other elements of cost (installation of machines, excavation, ground works, concrete or steel, tubes and valves, liners, drainage...).

With the equation (4) one can consider:

- different costs per m3 for the insulation, depending on its position (top, sides or bottom)
- buried tanks ($\alpha > 0$) or tanks above ground, setting $\alpha = 0$ (this way there is a dependence on the volume only)

A small storage (daily storage or buffer storage) has not been considered explicitely: it could be included in C_b, C_o, or even in C_c if necessary.

For buried tanks, the dependence of the specific cost Costvol will not be strong on the volume, but on the depth or height of the tank (Figure 17).

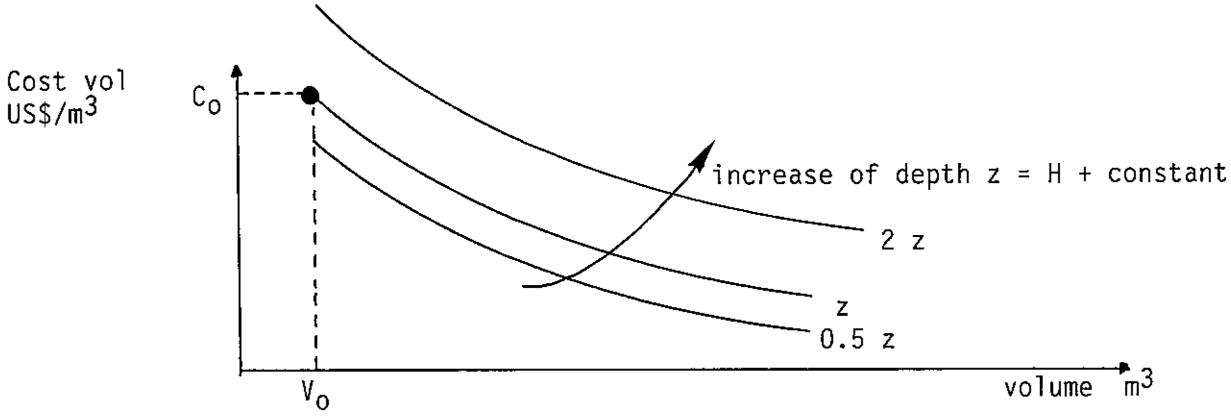


Figure 17: Influence of the storage depth on Costvol for a given value of the parameter β

If, on the other hand, increasing the depth will decrease the specific cost Costvol for some reason or another, one has to set $\alpha < 0$.

In Figures 18 and 19 two examples show how the term "Costvol" can be affected by the parameters β and H.

Figure 18: Specific cost "Costvol" for different values of β

Example: Costvol $= \left[C_b + \dfrac{C_o - C_b}{\left(\frac{Vol}{V_o}\right)^{\beta}} \right] \times e^{\alpha H}$

with:

C_b = 35 US\$/m3

C_o = 80 US\$/m3

α = 2.10^{-2}

V_o = 5'000 m3

H = 15 m

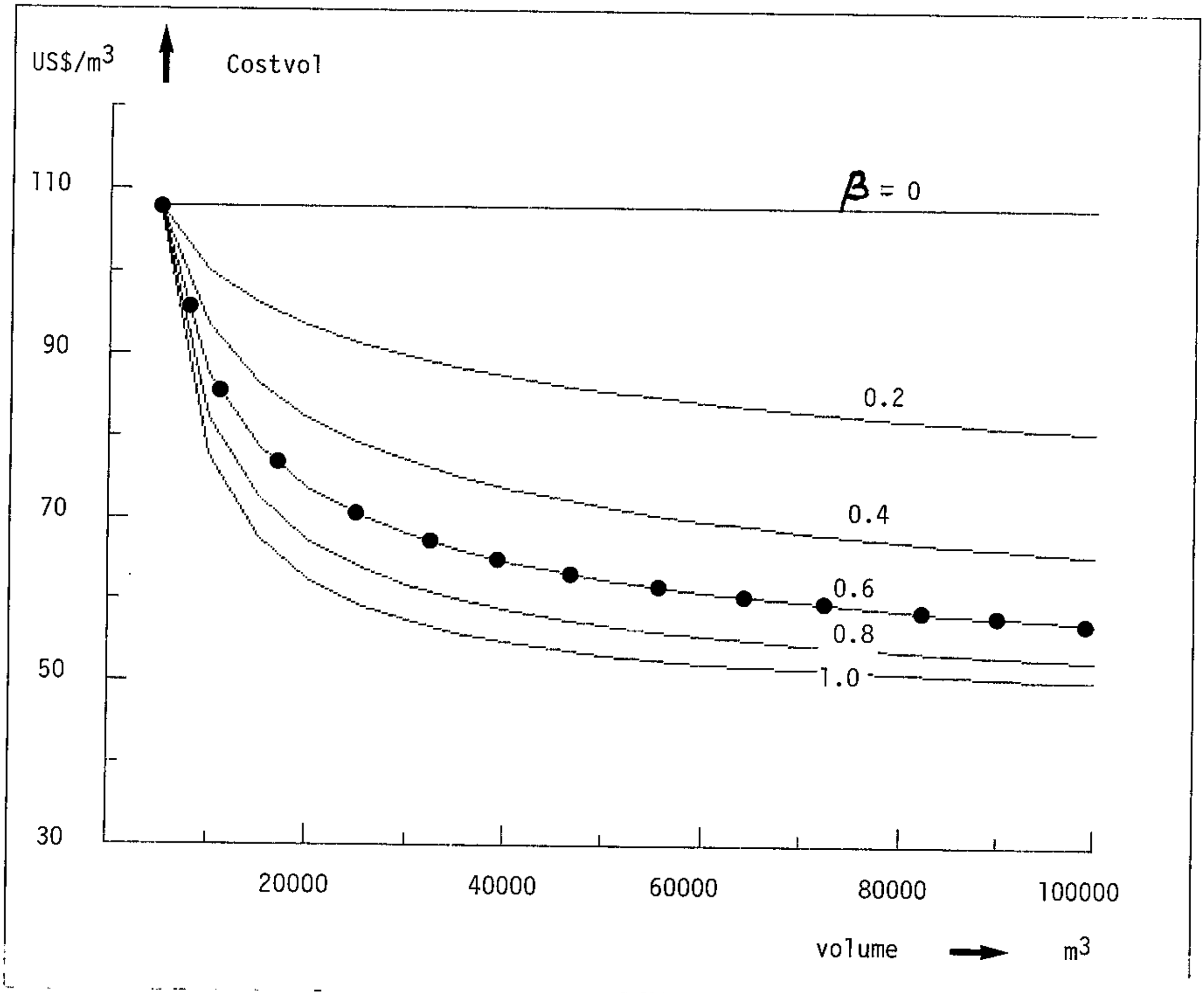


Figure 19: Influence of the height H on the specific cost "Costvol"

Example:
$$\left[C_b + \frac{C_o - C_b}{\left(\frac{Vol}{V_o}\right)^{\beta}}\right] x\ e^{\alpha H}$$

with:

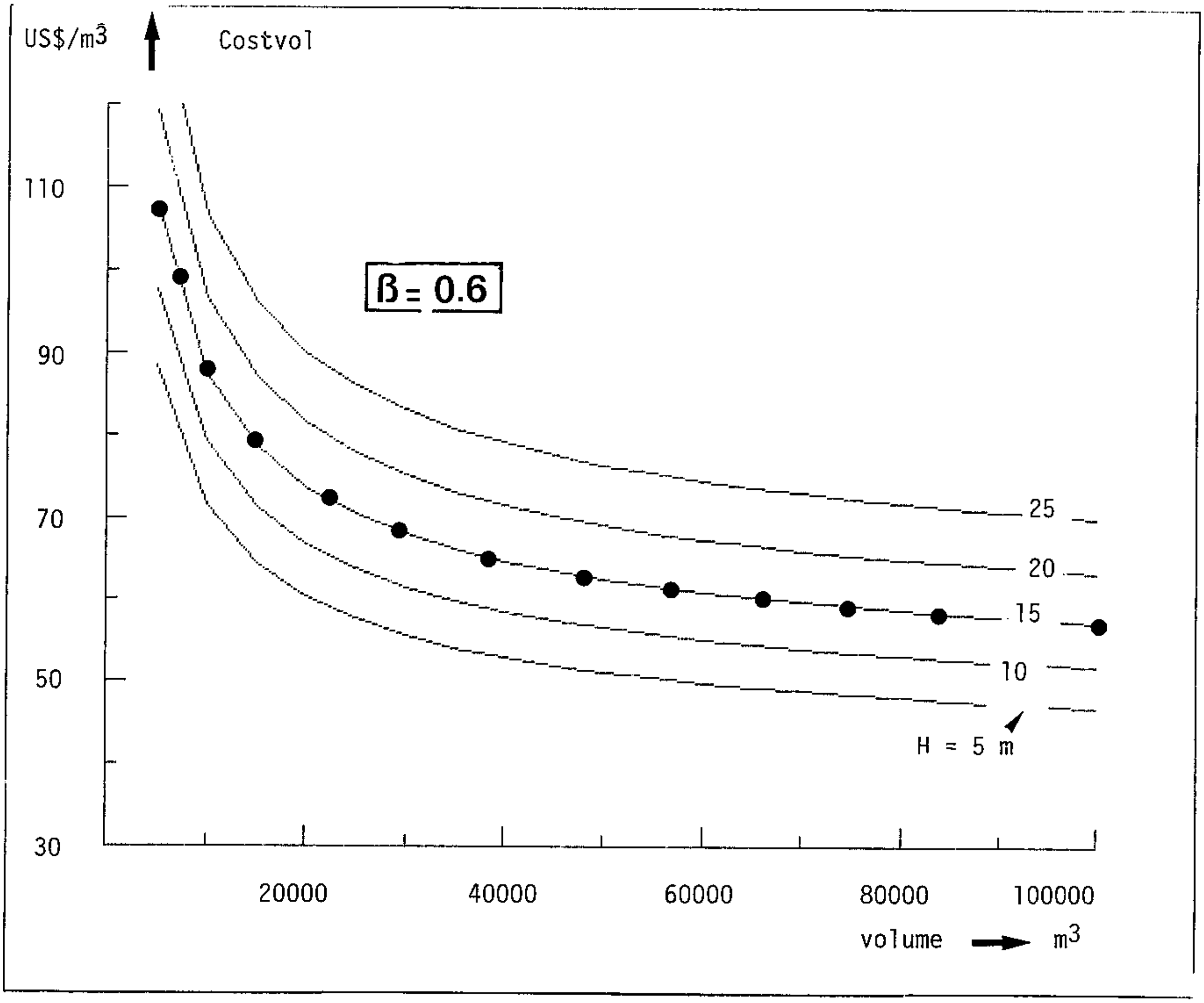
C_b = 35 US\$/m3

C_o = 80 US\$/m3

α = 2.10^{-2}

V_o = 5'000 m3 (for H_o = 15 m)

β = 0.6



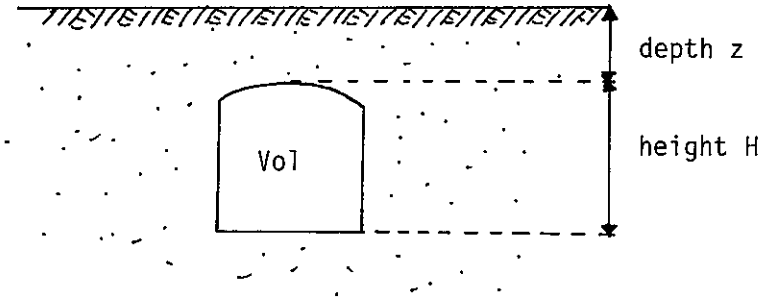
5.2. Rock cavern

5.2.1. Identification of the independent variables

1 Volume of the cavern

2 Height of the cavern

3 Depth



5.2.2. Comments

Variables 1 & 2:

- Define the shape

Variable 3:

- Important for heat losses and mechanical stresses (i.e. affecting strongly the cost)

If the dependence on z is small, one can consider it with the appropriate set of coefficient in the cost function.

5.2.3. Proposed cost function

$$\boxed{\underline{\text{Cost}} = \text{Vol} \times \left(C_b + \frac{C_o - C_b}{\left(\frac{\text{Vol}}{V_o}\right)^{\beta}}\right) \times e^{(\alpha H + \gamma z)} + C_c}$$

Nomenclature (see also 5.1.3.):

γ : coefficient expressing the increase of specific cost with depth 1/m

z : depth of the cavern m

α : coefficient expressing the increase of specific cost with the height of the cavern 1/m

H : height of the cavern m

Note:

One can also consider H + z as the independent variable if z cannot vary too much in a specific design. Thus one has to set $\alpha = \gamma$.

5.3. Drilled rock

5.3.1. Identification of the independent variables

As discussed with the LUND team, responsible for heat storage models in MINSUN, the independent variables to consider for this kind of storage can be:

1 Number of boreholes

2 Depth of boreholes

3 Volume of storage

4 Thickness of insulation on top

5.3.2. Comments

Variables 1 & 2:

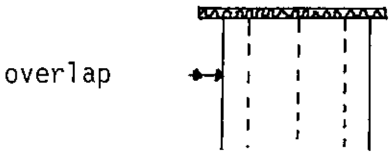
- The boreholes have a fixed diameter in this case

Variables 2 & 3:

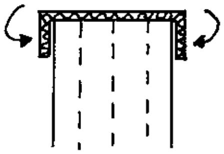
- Define the shape

Variable 4:

- A disposition of insulation is assumed, i.e.:



or



These four parameters can easily be changed in LUND-DST (Duct Storage Model) and are the most relevant ones to define a cost function. (The volume, depth, and number of boreholes could be aggregated to a "density" of boreholes per m2, but this parameter would not be convenient to use.)

5.3.3. Proposed cost function

Cost = Cost of installation and preparation (Vol)

+ Cost of boreholes

+ Cost of insulation

+ Ground cost

+ Constant cost

We assume that the cost of boreholes will not depend on the volume.

5.3.4. Cost equation

$$\boxed{\begin{aligned} \underline{\text{Cost}} \; &= \text{Vol} \times \left(C_b + \frac{C_o - C_b}{\left(\frac{\text{Vol}}{V_o}\right)^{\beta}}\right) \\ &+ N^{\gamma} \left(C_{bh} \cdot z^{\alpha} + C_{grout}\right) \\ &+ I_t \times \frac{\text{Vol}}{z} \times C_{it} \\ &+ \frac{\text{Vol}}{z} \times C_g \\ &+ C_c \end{aligned}}$$

Nomenclature (see also 5.1.3.):

C_{bh} : base cost per meter of 1 borehole US$/m

C_{grout} cost per borehole for grouting of casing rock US$/m

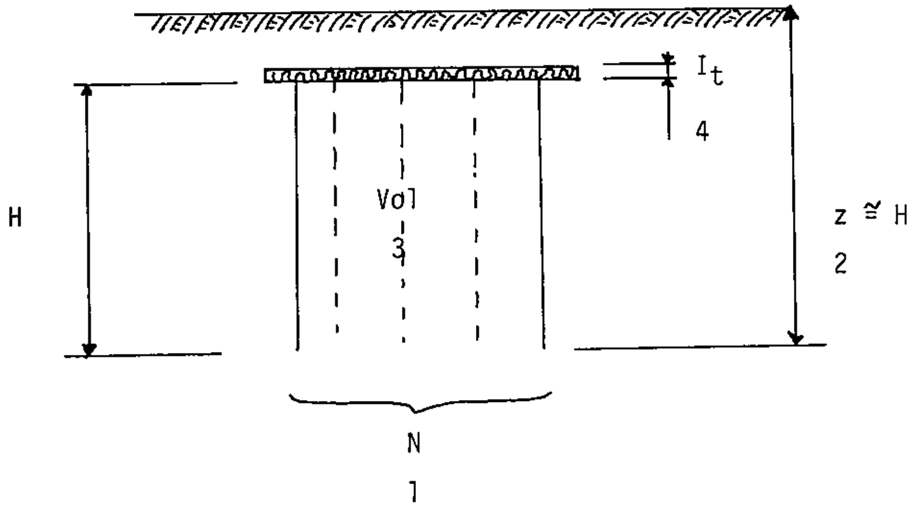
z : depth of boreholes m
(we assume depth of boreholes = height of storage)

α : coefficient expressing the increase of cost with depth for boreholes

N : number of boreholes

γ : coefficient expressing an eventual economy of scale on the number of boreholes (or an eventual increase)

Figure 20: Definition of the 4 independent variables for drilled rock systems



Note:

It the cost does not depend much on the volume one can set $C_b = 0$, and $V_o = \beta = 1$. Thus, the first term is C_o, which stands for a constant installation cost.

If the cost of boreholes is linear with depth, one has $\alpha = 1$.

If the cost of boreholes is "broken" because of a change in the quality of rock, one can have the following approximation:

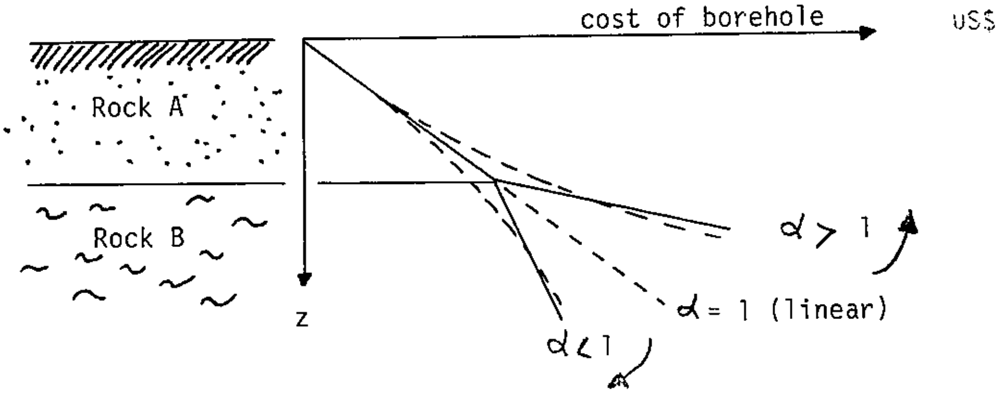


Figure 21: Variation of the cost of boreholes with depth

This approximation allows a smooth curve which is more suitable for the MINSUN optimization procedure.

In most cases, one has $\gamma = 1$ (linear dependence of cost on the number of boreholes). But, for instance, the quality of the rock could change if a certain size is reached:

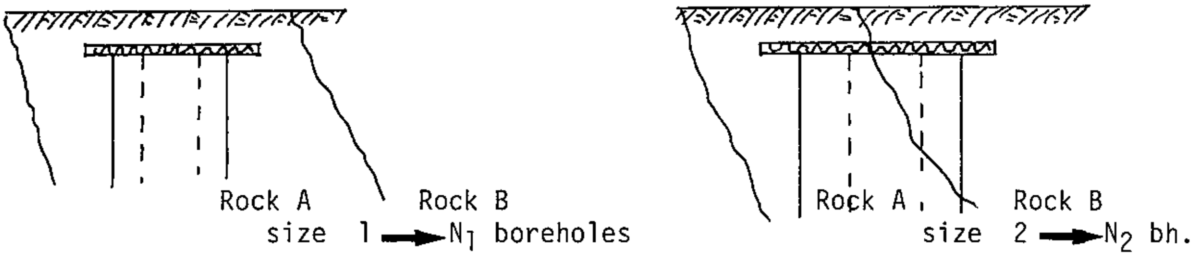


Figure 22: Two different rock qualities reached, as the number of boreholes is increasing

and thus γ could be > 1 or < 1.

5.4. Undisturbed earth (in clay or sand, for example)

For a vertical pipe system in clay the same formula as the one for drilled rock is applicable.

For a vertical pipe system in sand, as for the system developed in the Netherlands for the Groningen project, the Netherlands suggest the following:

Cost = Land cost

+ Ground works cost

+ Containment cost

+ Insulation cost

+ Buried heat exchanger cost

+ Constant cost

Expressed in terms of independent variables, one gets:

➡

$$\boxed{\begin{aligned} \underline{\text{Cost}} &= \frac{\pi}{4}(D+20)^2 \,.\, (C_g + C_{gw}) \\ &+ \pi \,.\, D \,.\, H \,.\, C_t + \frac{\pi}{4}(D+10)^2 \,.\, I_t \,.\, C_{is} \\ &+ (a - b \,.\, H) \times \frac{\pi D^2}{4} \,.\, H \\ &+ C_c \end{aligned}}$$

Nomenclature:

D : diameter of the store m

C_g : ground cost US$/m2

C_{gw} : ground works cost US$/m3
(the land area needed is assumed to be the top surface plus 10 m around)

C_t : cost for containment (proportional to the circumference and the height of the reservoir) US$/m2

I_t : thickness of top insulation m (overlap of 5 m assumed)

C_{is} : specific cost of insulation US$/m3, including labour cost

a,b : coefficient expressing the cost function for the tubes, their insertion and the interconnection network on top

H : height of the reservoir m

C_c : constant cost US$

a and b are dependent on $l_{tube} \cdot (\frac{d}{do})^{1.3}$ where l_{tube} is the length of the plastic tubes and d the tube diameter.

The volume of the reservoir is given by $V = \frac{\pi D^2}{4} \cdot H$ m3

The independent variables are in this case:

D	I_t	H
1	2	3

The cost calculated with this formula agrees within 5% with the engineer's estimations of costs for volumes between 10'000 and 100'000 m3, and heights between 15 m and 30 m, with the following set of parameters given by the Netherlands:

C_g : 10 US$/m2

C_{gw} : 6.7 US$/m2

C_t : 41 US$/m2 for a height of 20 m, with a bentonite wall

C_{is} : 390 US$/m3 (foamglass) for 0.30 m of insulation on top

$$\left.\begin{array}{lll} a & : & 12.3 \text{ US\$/m3} \\ b & : & 0.19 \text{ US\$/m3} \end{array}\right\} \text{for 1.2 m of tube, diameter 20 mm, per m3 of earth}$$

C_c : 63'000 US$

This equation is basically linear due to the specific way of building the storage. Note that the specific cost decreases with the height (or the depth).

5.5. Excavated earth

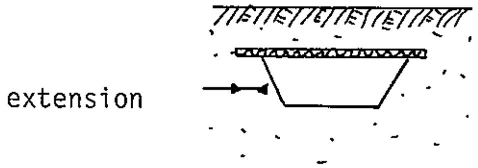
5.5.1. Identification of the independent variables

1 Volume of storage

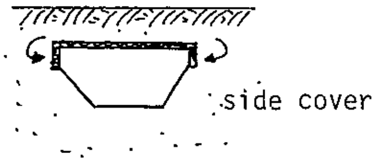
2 Height of storage

3 Thickness of insulation on top

4 Thickness of side insulation



or



We assume a variable extension or side cover, and a constant earth cover.

In most cases, the height is limited by local conditions (rock or water table...).

5.5.2. Proposed cost function

$$\boxed{\begin{aligned}\underline{\mathrm{Cost}} &= \mathrm{Vol} \times \left(C_b + \frac{C_o - C_b}{\left(\frac{\mathrm{Vol}}{V_o}\right)^{\beta}} \right) \times \alpha\, p \\ &+ I_t \times \frac{\mathrm{Vol}}{H} \times C_{it} \\ &+ I_s \times A_s \times C_{is} \\ &+ \frac{\mathrm{Vol}}{H} \times C_g \\ &+ C_c\end{aligned}}$$

Nomenclature (see also 5.1.3.):

αp : coefficient expressing the increase of cost due to an increase of the length of pipes beyond the length used to define C_b and C_o. Example: C_b and C_o have been established for 1 m of pipe per 0.5 m3 of storage. For a given case one wishes to put 1 m of pipe per 0.25 m3 of storage (i.e. length x 2). The cost of pipes represents 10% of the volume cost. Thus one has approximately $\alpha p = 1.1$.

Vol : reference volume of the storage (excavated volume beneath the insulation for instance) m3

H : fixed height of the store

A_s : wall surface where insulation is present m2 or surface of top extension with insulation

Independent variables:

Vol H I_t I_s

Note:

As for the other cases, we have used $\frac{Vol}{H}$ to define the ground surface occupied by the storage. If it is in fact more, one has to major C_g.

5.6. Pit

Independent variables

1 Volume

2 Height

3 Thickness of insulation on top

4 Thickness of insulation on sides

5 Thickness of insulation on bottom

➡ The same cost equation as the one for tanks (5.1.) is applicable.

5.7. Aquifer

5.7.1. Identification of the independent variables

The cost and the energy recovery factor of an aquifer storage system will be very dependent on the local geological conditions, the depth of the well, and the peak demand to be supplied.

Due to the special capabilities of the LUND-AST model chosen as the analytical tool for aquifer storage, two independent variables can be considered:

1 well depth

2 maximum flow rate (which defines the diameter of the well and the pumping-injection equipments). LUND-AST assumes a radial flow from the injection-production well, no doublet effects, no buoyancy effects and impervious bed and caprock. Thus an assumption will have to be made if the well depth is considered as a variable. That is, the bedrock is always supposed to reach the bottom of the well as the depth varies.

Example: the aquifer configuration given by the first field tests on a specific site is schematically represented in Figure 23.

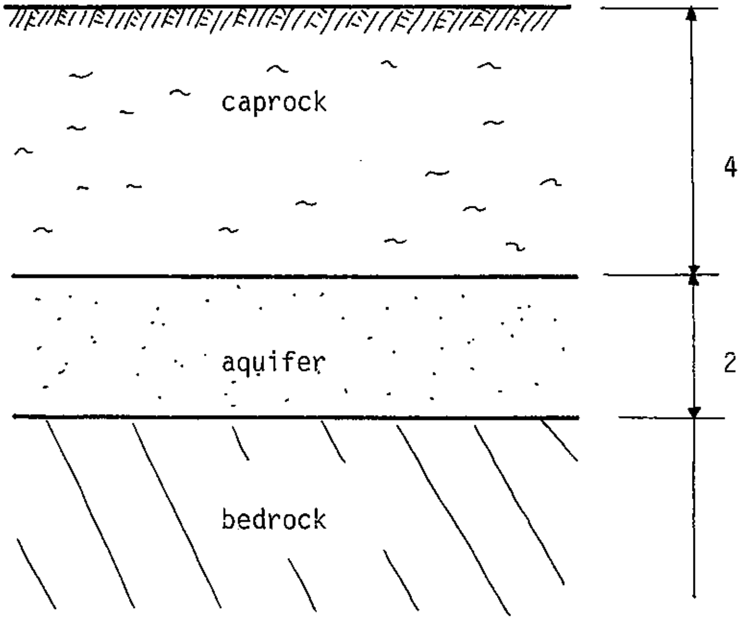


Figure 23: Example of a typical aquifer configuration

If the well depth is taken as a variable, the model will have to assume the following configurations as the depth is increased with a 5 m step.

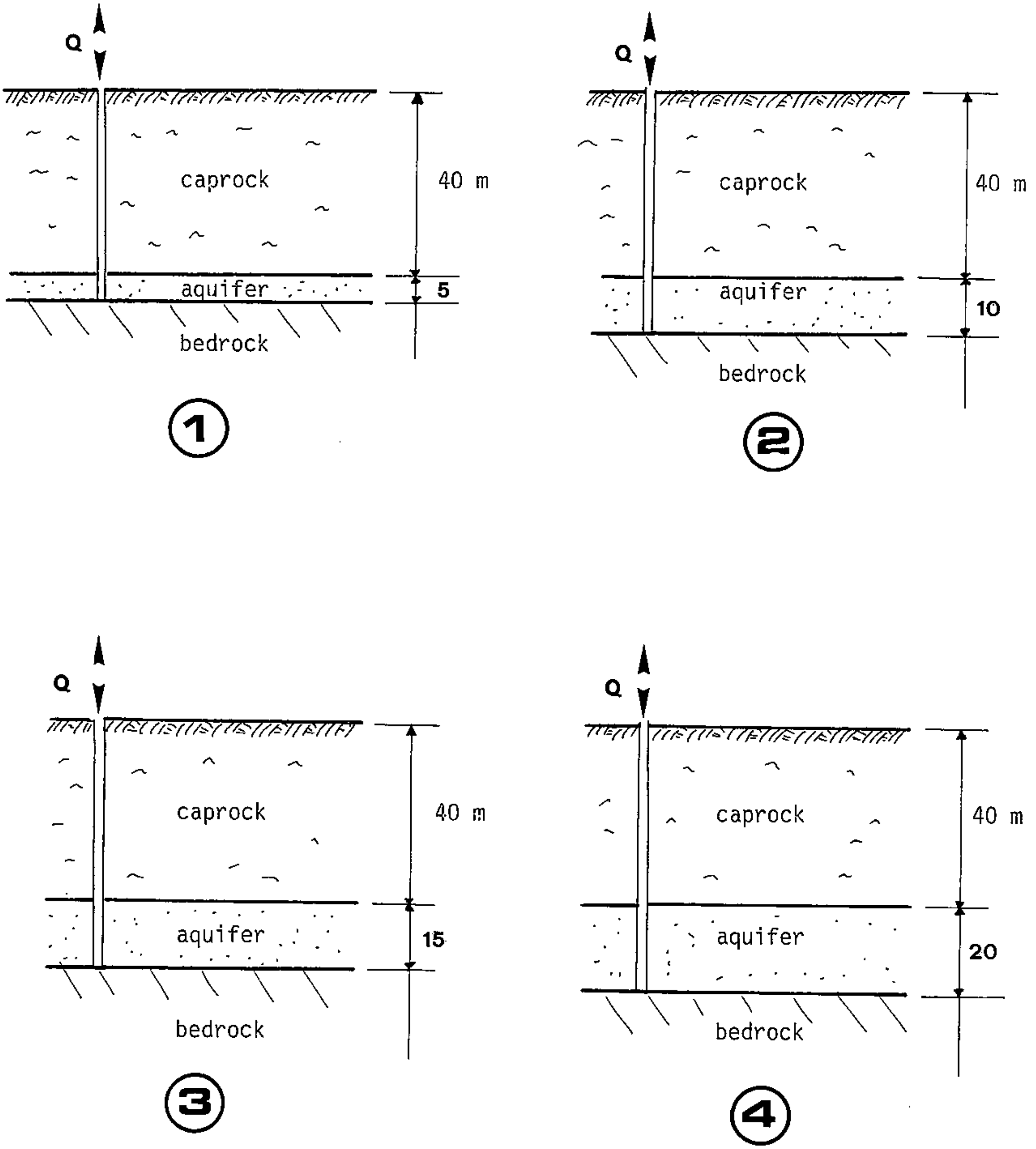


Figure 24: Examples of aquifer configurations assumed by the LUND-AST model, as the well depth is increased

5.7.2. Proposed cost function

Cost = Cost of well(s)

+ Cost of equipments depending on maximum flow rate

+ Ground cost

+ Constant cost

Note that the cost of a well depends also on the well diameter, and therefore on the maximum flow rate.

5.7.3. Cost equation

$$\boxed{\begin{aligned} &\underline{\text{Cost}} = C_{bho} \times z^{\alpha} \times N^{\gamma} \times \left(\frac{Q}{Q_o}\right)^{a} \\ &+ C_{eo} \times \left(\frac{Q}{Q_o}\right)^{b} \\ &+ A_g \times C_g \\ &+ C_c \end{aligned}}$$

Nomenclature (see also 5.3.3.):

C_{bho} = base cost per meter of well for the maximum flow rate Q_o US$/m (specific cost)

z = well depth

α = coefficient expressing the eventual non-linearity of cost with depth

N = number of wells

γ = coefficient expressing an eventual non-linearity of cost with the number of wells

Q_o = given flow rate for which the cost C_{bho} is valid (this flow rate determines the diameter required for the well, once the hydraulic head is known)

a = coefficient expressing an eventual non-linearity of the specific well cost with the flow rate, i.e. the diameter

C_{eo} = cost of equipments (pumps...) for the flow rate Q_o US$

b = coefficient expressing an eventual non-linearity of the cost of equipments with the flow rate

A_g = ground surface required to be bought m2

C_g = ground cost US$/m2

C_c = constant cost US$, i.e. independent of well depth and flow rate (i.e. diameter)

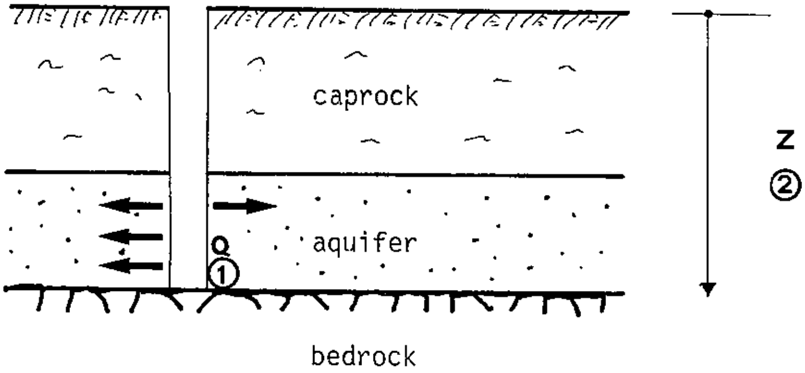


Figure 25: Definition of the 2 independent variables for aquifer systems **Q, Z**

6. TYPICAL VALUES OF COST EQUATION PARAMETERS FOR PRELIMINARY OPTIMIZATION STUDIES

This section presents typical values of the parameters involved in the cost equations described under Section 5.

Due to the difficulty of assessing a precise cost structure for each storage concept, several assumptions were made to obtain typical values of the cost parameters.

The cost data given in this section has therefore to be considered as an order of magnitudes and should be used for preliminary optimization or sensitivity studies within the IEA Task VII.

For design studies it is recommended to derive an appropriate set of parameters, depending on the national and local conditions. This set of parameters should be adapted to the proposed cost equation.

```
*********************************************
*       BURRIED  CONCRETE  TANK             *
*********************************************
```

Cost equation

```
Cost   =  Vol * [Cb+(Co-Cb)/(Vol/Vo)^Beta] * EXP(Alpha*H)
          +  It * Vol/H * Cit
          +  Is *   As  * Cis
          +  Ib * Vol/H * Cib
          +  Vol/H * Cg
          +  Cc
```

Nomenclature

Cost : total construction cost $

Vol : internal volume of storage m3

Cb : asymptotic specific storage cost without insulation, ground surface and constant cost $/m3

Co : specific cost of storage Vo without insulation, ground surface and constant cost $/m3

Vo : internal volume of storage for which Co is given m3

Beta : scale factor expressing economies of scale 0 <= Beta <= 1

Alpha : coefficient expressing the increase of specific cost with the height of the tank 1/m

H : storage height (assuming depth=height+constant) m

It : thickness of insulation on top (lid) of storage m

Is : thickness of insulation on sides (wall) of storage m

Ib : thickness of insulation on bottom of storage m

Cit : specific cost of insulation on top of storage $/m3

Cis : specific cost of insulation on sides of storage $/m3

Cib : specific cost of insulation on bottom of storage $/m3

Cg : ground surface cost $/m2

Cc : constant cost (independant of the others variables)$

With the following Assumptions :

1. Cylindrical geometry
   - Shape = Diameter / Height = 4
   - Height = H =(4*Vol/(PI*Shape^2))^.333333333
   - Side area = As =2*PI*H*SQR(Vol/(PI*H))

2. Insulation thickness
   - Top = It = 0.30 m
   - Side = Is = 0.30 m
   - Bottom = Ib = 0.30 m

Typical values of Parameters are :

Cb = 25 $/m3

Co = 88 $/m3

Vo = 10'000 m3

Beta = 0.4

Alpha = 0.005 1/m

Cit = 100 $/m3

Cis = 100 $/m3

Cib = 100 $/m3

Cg = 0 $/m2

Cc = 0 $

STEEL TANK

Cost equation

```
Cost  =  Vol * [Cb+(Co-Cb)/(Vol/Vo)^Beta] * EXP(Alpha*H)
         +  It * Vol/H * Cit
         +  Is *   As  * Cis
         +  Ib * Vol/H * Cib
         +  Vol/H * Cg
         +  Cc
```

Nomenclature

Cost	:	total construction cost	$
Vol	:	internal volume of storage	m3
Cb	:	asymptotic specific storage cost without insulation, ground surface and constant cost	$/m3
Co	:	specific cost of storage Vo without insulation, ground surface and constant cost	$/m3
Vo	:	internal volume of storage for which Co is given	m3
Beta	:	scale factor expressing economies of scale 0 <= Beta <= 1	
Alpha	:	coefficient expressing the increase of specific cost with the tank height	1/m
H	:	storage height	m
It	:	thickness of insulation on top (lid) of storage	m
Is	:	thickness of insulation on sides (wall) of storage	m
Ib	:	thickness of insulation on bottom of storage	m
Cit	:	specific cost of insulation on top of storage	$/m3
Cis	:	specific cost of insulation on sides of storage	$/m3
Cib	:	specific cost of insulation on bottom of storage	$/m3
Cg	:	ground surface cost	$/m2
Cc	:	constant cost (independant of the others variables)	$

With the following Assumptions :

1. Cylindrical geometry
   Shape = Diameter / Height = 4
   Height = H =(4*Vol/(PI*Shape^2))^.333333333
   Side area = As =2*PI*H*SQR(Vol/(PI*H))

2. Insulation thickness
   Top   = It = 0.30 m
   Side   = Is = 0.30 m
   Bottom = Ib = 0.30 m

Typical values of Parameters are :

Cb = 40 $/m3
Co = 85 $/m3
Vo = 10'000 m3
Beta = 0.4
Alpha = 0 1/m
Cit = 100 $/m3
Cis = 100 $/m3
Cib = 100 $/m3
Cg = 0 $/m2
Cc = 0 $

```
*********************************************
*                WATER PIT                  *
*********************************************
```

Cost equation

```
Cost  =  Vol * [Cb+(Co-Cb)/(Vol/Vo)^Beta] * EXP(Alpha*H)
         +  It * Vol/H * Cit
         +  Is *   As  * Cis
         +  Ib * Vol/H * Cib
         +  Vol/H * Cg
         +  Cc
```

Nomenclature

Cost	:	total construction cost	$
Vol	:	internal volume of storage	m3
Cb	:	asymptotic specific storage cost without insulation, ground surface and constant cost	$/m3
Co	:	specific cost of storage Vo without insulation, ground surface and constant cost	$/m3
Vo	:	internal volume of storage for which Co is given	m3
Beta	:	scale factor expressing economies of scale	0 <= Beta <= 1
Alpha	:	coefficient expressing the increase of specific cost with the height of the tank	1/m
H	:	storage height	m
It	:	thickness of insulation on top (lid) of storage	m
Is	:	thickness of insulation on sides (wall) of storage	m
Ib	:	thickness of insulation on bottom of storage	m
Cit	:	specific cost of insulation on top of storage	$/m3
Cis	:	specific cost of insulation on sides of storage	$/m3
Cib	:	specific cost of insulation on bottom of storage	$/m3
Cg	:	ground surface cost	$/m2
Cc	:	constant cost (independant of the others variables)	$

With the following Assumptions :

1. Cylindrical geometry
   Shape = Diameter / Height = 4
   Height = H =(4*Vol/(PI*Shape^2))^.333333333
   Side area = As =2*PI*H*SQR(Vol/(PI*H))

2. Insulation thickness
   Top = It = 0.30 m
   Side = Is = 0.30 m
   Bottom = Ib = 0.30 m

Typical values of Parameters are :

Cb = 15 $/m3
Co = 85 $/m3
Vo = 10'000 m3
Beta = 0.5
Alpha = 0.005 1/m
Cit = 100 $/m3
Cis = 100 $/m3
Cib = 100 $/m3
Cg = 0 $/m2
Cc = 0 $

ROCK CAVERN

Cost equation

```
Cost  =  Vol * [Cb+(Co-Cb)/(Vol/Vo)^Beta] * EXP(Alpha*H + Gamma*Z)
          +  It * Vol/H * Cit
          +  Is *   As  * Cis
          +  Ib * Vol/H * Cib
          +  Vol/H * Cg
          +  Cc
```

Nomenclature

Cost	:	total construction cost	$
Vol	:	volume of storage	m3
Cb	:	asymptotic specific storage cost without insulation, ground surface and constant cost	$/m3
Co	:	specific cost of storage Vo without insulation, ground surface and constant cost	$/m3
Vo	:	internal volume of storage for which Co is given	m3
Beta	:	scale factor expressing economies of scale	0 <= Beta <= 1
Alpha	:	coefficient expressing the increase of specific cost with the height of the cavern	1/m
H	:	cavern height	m
Gamma	:	coefficient expressing the increase of specific cost with depth of top of storage Z	1/m
Z	:	depth of top of storage below ground level	m
It	:	thickness of insulation on top (lid) of storage	m
Is	:	thickness of insulation on sides (wall) of storage	m
Ib	:	thickness of insulation on bottom of storage	m
Cit	:	specific cost of insulation on top of storage	$/m3
Cis	:	specific cost of insulation on sides of storage	$/m3
Cib	:	specific cost of insulation on bottom of storage	$/m3
Cg	:	ground surface cost	$/m2
Cc	:	constant cost (independant of the others variables)	$

With the following Assumptions :

1. Cylindrical geometry
   Shape = Diameter / Height = 4
   Height = H =(4*Vol/(PI*Shape^2))^.333333333
   Side area = As =2*PI*H*SQR(Vol/(PI*H))
   Depth below ground surface = Z = 10 m

2. Insulation thickness
   Top   = It = 0 m (no insulation)
   Side   = Is = 0 m (no insulation)
   Bottom = Ib = 0 m (no insulation)

Typical values of Parameters are :

Cb = 10 $/m3
Co = 48 $/m3
Vo = 50'000 m3
Beta = 0.7
Alpha = 0.005 1/m
Gamma = 0 1/m
Cit = 0 $/m3
Cis = 0 $/m3
Cib = 0 $/m3
Cg = 0 $/m2
Cc = 0 $

DRILLED ROCK

Cost equation

```
Cost  =  Vol * [Cb+(Co-Cb)/(Vol/Vo)^Beta]
         +  It * Vol/H * Cit
         +  N^Gammab * (Cbh*Z^Alphab + Cgrout)
         +  Vol/H * Cg
         +  Cc
```

Nomenclature

Cost	:	total construction cost	$
Vol	:	reference volume of storage	m3
Cb	:	asymptotic specific storage cost without insulation, boreholes, ground surface and constant cost	$/m3
Co	:	specific cost of storage Vo without insulation, boreholes, ground surface and constant cost	$/m3
Vo	:	reference volume of storage for which Co is given	m3
Beta	:	scale factor expressing economies of scale	0 <= Beta <= 1
H	:	storage height	m
It	:	thickness of insulation on top of storage	m
Cit	:	specific cost of insulation on top of storage	$/m3
N	:	number of boreholes	
Gammab	:	coefficient expressing an eventual economy of scale on the number of boreholes N	
Cbh	:	specific cost per 1m of borehole without Cgrout	$/m
Z	:	boreholes maximum depth	m
Alphab	:	coefficient expressing the eventual increase of borehole cost with depth	
Cgrout	:	cost per 1m of borehole for grouting of casing	$/m
Cg	:	ground surface cost	$/m2
Cc	:	constant cost (independant of the others variables)	$

With the following Assumptions :

1. Cylindrical geometry
   Shape = Diameter / Height = 4
   Height = H =(4*Vol/(PI*Shape^2))^.333333333
   Maximum Depth = Z = H + 1m

2. Insulation thickness (only on top)
   Top = It = 0.50 m

3. Number of boreholes
   N = Vol/(Z*5) (1 borehole per 5 m2)

Typical values of Parameters are :

Cb = 1 $/m3
Co = 7 $/m3
Vo = 50'000 m3
Beta = 0.4
Alphab = 1
Gammab = 1
Cit = 100 $/m3
Cbh = 30 $/m
Cgrout = 0 $/m
Cg = 0 $/m2
Cc = 0 $

EXCAVATED EARTH

Cost equation

```
Cost  =  Vol * [Cb+(Co-Cb)/(Vol/Vo)^Beta] * Alphap
         +  It * Vol/H * Cit
         +  Is *   As  * Cis
         +  Ib * Vol/H * Cib
         +  Vol/H * Cg
         +  Cc
```

Nomenclature

Cost	:	total construction cost	$
Vol	:	reference volume of storage	m3
Cb	:	asymptotic specific storage cost without insulation, ground surface and constant cost	$/m3
Co	:	specific cost of storage Vo without insulation, ground surface and constant cost	$/m3
Beta	:	scale factor expressing economies of scale 0 <= Beta <= 1	
Alphap	:	coefficient expressing pipes cost variations around the pipes length used to define Cb and Co	
H	:	storage height (assuming depth=height+constant)	m
It	:	thickness of insulation on top (lid) of storage	m
Is	:	thickness of insulation on sides (wall) of storage	m
Ib	:	thickness of insulation on bottom of storage	m
Cit	:	specific cost of insulation on top of storage	$/m3
Cis	:	specific cost of insulation on sides of storage	$/m3
Cib	:	specific cost of insulation on bottom of storage	$/m3
Cg	:	ground surface cost	$/m2
Cc	:	constant cost (independant of the others variables)	$

With the following Assumptions :

1. Cylindrical geometry
   Shape = Diameter / Height = 4
   Height = H =(4*Vol/(PI*Shape^2))^.333333333
   Side area = As =2*PI*H*SQR(Vol/(PI*H))

2. Insulation thickness
   Top = It = 0.50 m
   Side = Is = 0 m
   Bottom = Ib = 0 m

3. Pipe density
   1 m of pipe (diameter 20 mm) per 0.5 m3 of earth

Typical values of Parameters are :

Cb	=	12	$/m3
Co	=	45	$/m3
Vo	=	5'000	m3
Beta	=	0.6	
Alphap	=	1	
Cit	=	100	$/m3
Cis	=	100	$/m3
Cib	=	100	$/m3
Cg	=	0	$/m2
Cc	=	0	$

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Cost equation

```
Cost  =  PI/4 * (D+20)^2 * (Cg + Cgw)
         +  PI * D * H * Ct
         +  PI * D * H * Is * Cis
         +  PI/4 * (D+10)^2 * It * Cit
         +  PI/4 * (a-b*H) * D^2 * H
         +  Cc
```

Nomenclature

Cost	:	total construction cost	$
D	:	storage diameter	m
Cg	:	ground surface cost	$/m2
Cgw	:	ground works cost	$/m2
H	:	storage height (assuming depth=height+constant)	m
Ct	:	cost for sides containment	$/m2
Is	:	thickness of insulation on sides (wall) of storage	m
Cis	:	specific cost of insulation on sides of storage	$/m3
It	:	thickness of insulation on top (lid) of storage	m
Cit	:	specific cost of insulation on top of storage	$/m3
a	:	coefficient for pipes and network	$/m3
b	:	coefficient for pipes and network	$/m4
Cc	:	constant cost (independant of the others variables)	$

With the following Assumptions :

1. Cylindrical geometry
   Diameter = (4*Vol/(H*PI))^.5
   Height = H = 20 m

2. Insulation thickness (only on top)
   Top = It = 0.3 m
   Side = Is = 0 m

3. Pipe density
   1.2 m of pipe (diameter 20 mm) per m3 of earth

Typical values of Parameters are :

Cgw = 6.7 $/m2
Ct = 41 $/m2
Cis = 0 $/m3
Cit = 390 $/m3
Cg = 10 $/m2
a = 12.3 $/m3
b = 0.19 $/m4
Cc = 63'000 $

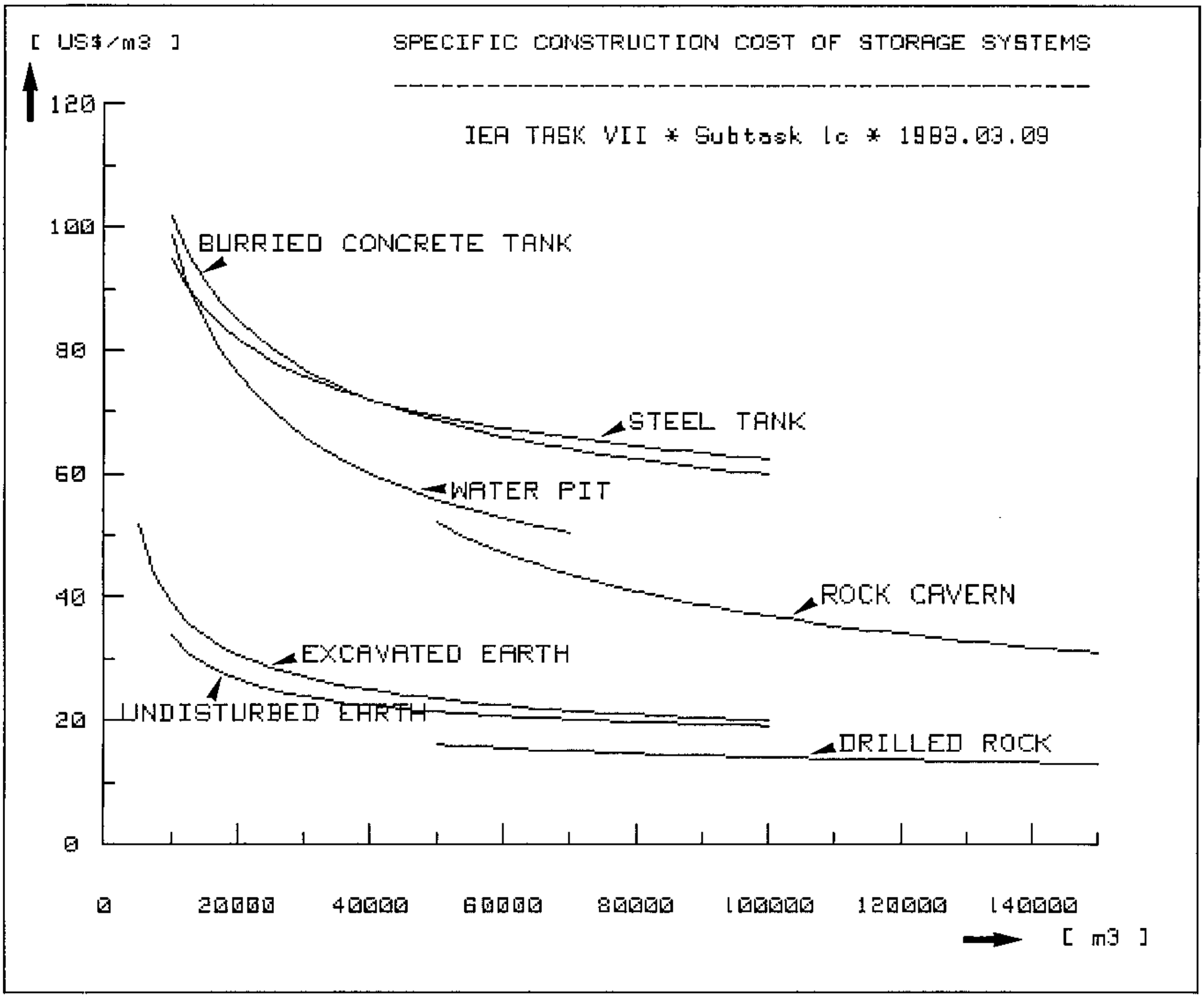

Figure 26: Specific construction costs of storage systems derived using the cost equations and the typical values for the parameters provided in Section 6

Cost level per July 1980

7. CONCLUSION

In the first part of this report, cost data for different heat storage concepts provided by the participants in Subtask 1c have been gathered and compared.

Cost projections, as well as cost data for ten storage projects built in the participating countries during the period 1980 to 1983.

Important economies of scale can be found in seasonal heat storage technologies.

Cost equations suitable for the MINSUN program and corresponding to the needs of Subtask 1a have been developed in terms of independent variables. The set of parameters to be used in a national design should be defined by each participant due to the specific features involved in any kind of storage project.

Typical values of the parameters involved in the cost equations are given for each type of storage for preliminary optimization studies with the MINSUN program.

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8. Central Solar Heating Plants with Seasonal Storage - Preliminary Designs for Ten Countries,
Subtask I(e) - 1983
Distribution: see Report N° 7

This report is part of the work within the IEA Solar Heating and Cooling Programme,
Task VII : Central Solar Heating Plants with Seasonal Storage
Subtask 1c: Heat Storage

This report deals with the cost of the seasonal heat storage concepts considered in the IEA Task VII for Central Solar Heating Plants with Seasonal Storage (CSHPSS).

The aim was to gather basic cost data for heat storage from the participating countries, and to give cost equations for the optimization process of the CSHPSS with the MINSUN program, to be used as a common tool in Task VII.

The report gathers the cost data given by the participating countries, compares the given cost for each storage type, and presents the cost equations suitable to MINSUN, developed by the Subtask 1c Lead Country.

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