IEA

SOLAR R&D

INTERNATIONAL ENERGY AGENCY

solar heating and
cooling programme

task VII

central solar heating plants with seasonal storage

heat storage models - evaluation & selection

june 1983

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 Storage: 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 influence 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 components 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

heat storage models - evaluation & selection

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and the participants in Subtask 1c of the IEA Task VII

June 1983

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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ACKNOWLEDGEMENTS

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.

The authors also wish to acknowledge the encouragement and support provided to Subtask 1c by the Task Operating Agent: Arne Boysen, of Sweden.

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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 objectives of this report - covering the first item of Subtask 1c, i.e. "Heat Storage Models" - are the following:

- to gather information from the ten participating countries about Seasonal Heat Storage Simulation Models, their capabilities and availabilities

- to present some models chosen with respect to the needs of Task VII

- to describe and explain

    a) the evaluation process performed by Lead Country 1c, and

    b) the final selection of models suitable to the purposes of Task VII

The report is organized into three parts:

1) presentation of the general information collected

2) the selection process and its results

3) detailed description of the evaluated models and of the selection work

The aim of the report is firstly to present a general overview of existing heat storage models in the participating countries, and secondly to describe the selection process achieved in Subtask 1c.

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

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

1.	Tank	insulated	and/or	uninsulated
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4.	Aquifer	confined	or	unconfined
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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.

3. CONTEXT AND PURPOSES OF A SELECTION OF HEAT STORAGE MODELS

At the beginning of Task VII, it was decided that the basic tools for the Task would be:

1) the TRNSYS program (University of Wisconsin, USA), as the analytical tool for the detailed simulation of the physical behaviour of the CSHPSS

2) the MINSUN program (Studsvik, Sweden) as the optimization tool

The responsibility for adapting these programs into a general framework for the needs of Task VII was assigned to Subtask 1a.

As the above programs did not include seasonal heat storage routines concerning the considered storage types (see Chapter 4), one of the objectives of Subtask 1c was to provide Subtask 1a with the "best available simulation model" for each type of storage.

The responsibility for evaluating, selecting, eventually simplifying, and providing these programs be incorporated into TRNSYS and MINSUN belonged to Subtask 1c.

Thus, after a collection of information about storage models in the participating countries, Lead Country 1c was able to evaluate and propose a selection of models to be considered in Subtask 1a for the simulation of the heat storage system.

The present report describes this process.

4. THE STORAGE MODEL IN TRNSYS AND MINSUN IN 1981

4.1. TRNSYS 11.1 (reference A.19)

The current routine Type 4 in TRNSYS models is, basically, a short-term cylindrical storage with stratification. The model has already been used for sensitivity analysis on the storage capacity in a solar system covering daily and seasonal storage (A.16).

The routine describes the conductive interactions between layers or segments of fluid within a tank, as well as conduction losses to the environment of the tank (Figure 1).

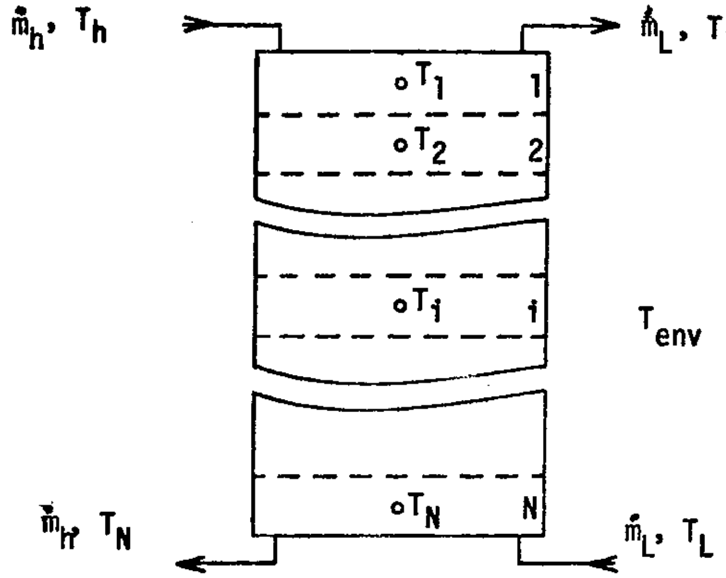

Figure 1: Typical storage tank in TRNSYS routine Type 4

Natural convection effects (cells) are not treated, the model assuming a perfect vertical stratification in the tank. The fluid inlet and outlet are located in the top and in the bottom layers.

Improvements of this type of model can be obtained through the CSU and SOLSYS models (A.15) where a variable inlet position can be handled.

The computing time, as well as the accuracy of the model, are very sensitive to the number of segments assumed. Usually, 5 to 10 segments are chosen, although validations of the model against experimental data for a 2 m3 storage tank in a simple water heating solar system showed that 50 to 100 layers should be assumed to meet a good agreeement with the experimental results.

4.2. MINSUN 1.0 (A.20)

In the MINSUN optimization program a subroutine called STORES is currently available, which models a perfectly stratified tank. It has been adapted from the routine Type 4 of TRNSYS.

This model only handles the steady heat losses of the storage through walls, top, and floor, and variable positions of inlet and outlet in the storage volume are assumed, according to the general control strategy of the MINSUN program (Figure 2).

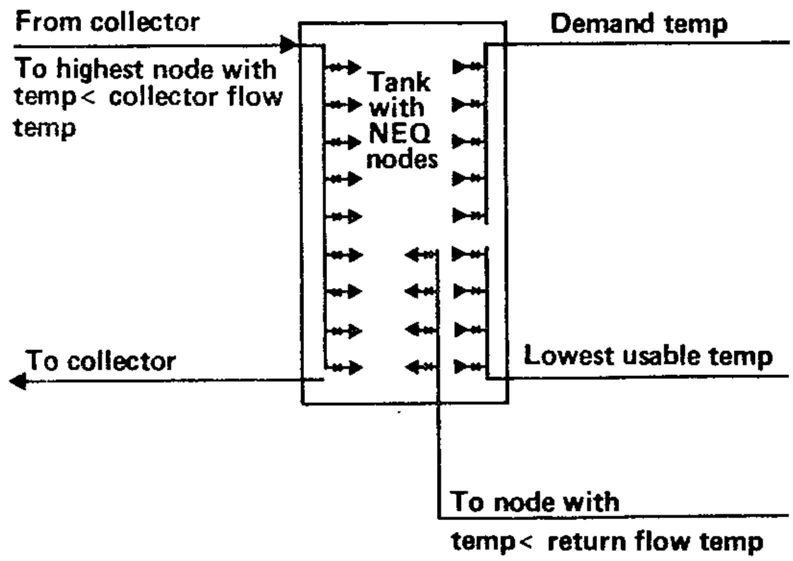

Figure 2: STORES model of a perfectly stratified tank in MINSUN 1.0

However, in this model as well as in the storage routines developed for TRNSYS, the heat losses to the environment are computed using an equivalent heat transfer resistance through the tank walls and the insulation. This procedure was found not to be suitable to the Task VII needs since mainly underground storage systems had to be considered where high heat capacity effects outside the storage region were to be expected.

Only well insulated tank or pit storage systems could be modelled using these routines, and the Subtask 1c participants decided that further investigations of storage models were necessary.

5. HEAT STORAGE MODELS - GENERAL INFORMATION

5.1. First step: General look

The first step of the work within Subtask 1c was to gather information about existing storage models, since these have been developed in many countries for about 5 to 7 years.

Basic information was required regarding the following points:

1. Name, country
2. Availability (available = public)
3. Transient or steady state simulation
4. Language
5. Validated: against analytical results and field experiments
6. Memory size required for a typical application
7. User's manual (exist or not)
8. If transient, typical timesteps for accuracy
9. Input data required and typical output produced
10. Flexibility (flexible = easy to adapt or modify)

After an analysis of the information provided by each participant, Lead Country 1c was able to compile it into the following Tables - 1 to 6 - (status mid 1981) as "rough" information.

Table 1: STORAGE COMPUTATION PROGRAMS FOR WATER TANK AND CAVERN SYSTEMS

STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	COMPUTER MATH. SOLUTION: STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
PCL	UNT			X	FD	FO		Y		UK
LT-TPD-F	UNT		X	PARTLY	FD	FO		N		NL
ASTEP	NO DOC AV		X		FE	PL1		Y	AV	CAN
SOLANSIM	NO DOC AV		X		FE	PL1		Y		CAN
SUSYM	NOT PUBLIC AV	X			FD	FO				CAN
EBA Geothermal	DOC AV NOT AV		X		FE	FO		Y		CAN
SOLANSIM	AV					FO		IN PROGR.	PRPL	USA
COMMIX - SA 3 - dim	AV	X	X	X	FE	FO	LARGE	PARTLY IN PROGR.		USA
BOEING 1 - dim	AV	X		X		FO	SMALL	Y		USA
NTACT-1	AV		X		FD	FO	MEDIUM	Y	ETR-5	CAN
ETR-5	AV		X		FD	FO	SMALL	Y	AV	CAN

CAPTION:
AV = AVAILABLE
UNT = UNDER TEST
PRPL = PROGRAM PLANNED
FE = FINITE ELEMENT
AN = ANALYTICAL SOLUTION
FD = FINITE DIFFERENCES
FO = FORTRAN
AL = ALGOL
BA = BASIC

Table 1 (continued): STORAGE COMPUTATION PROGRAMS FOR WATER TANK AND CAVERN SYSTEMS

STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	COMPUTER MATH. SOLUTION: STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
?	AV		X	X	AN	FO		Y		AUS
LUND-SST	AV		X	X	FD	FO	MEDIUM	IN PROGR.		SWE
KFA-STE	UNT		X	X	FE	FO		Y	UNT	GER
TU-München	UNT		X	X	FD	FO		Y	UNT	GER
IKE-Stuttgart	AV		X	X	FD	FO	LARGE 110 K	Y	AV	GER
GROCS	AV		X		FD	FO	MEDIUM	Y		USA
STORAGE	?									CAN
INTRANS	?									CAN
WELL	NOT AV		X		FD	FO	MEDIUM	N		SWE

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FO = FORTRAN
AL = ALGOL
BA = BASIC

Table 2: STORAGE COMPUTATION PROGRAMS FOR PIT SYSTEMS

STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	COMPUTER MATH. SOLUTION								
		STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
LT-TPD-I	UNT		X	PARTLY	FD	FO		N	AV	NL
EBA Geothermal	NOT AV				FE	FO		Y		CAN
WATERPIT	AV		X		AN+FD	FO		N		DAN
LUND-SST	AV		X	X	FD	FO		IN PROGR		SWE

CAPTION:

AV	= AVAILABLE	FE	= FINITE ELEMENT	FO	= FORTRAN
UNT	= UNDER TEST	AN	= ANALYTICAL SOLUTION	AL	= ALGOL
PRPL	= PROGRAM PLANNED	FD	= FINITE DIFFERENCES	BA	= BASIC

Table 3: STORAGE COMPUTATION PROGRAMS FOR EARTH SYSTEMS

		COMPUTER MATH. SOLUTION								
STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
Th INVESTIGATION	AV		X		FD	FO	SMALL	N	AV	UK
LT-TPD-I	UNT AV	X	X	PARTLY	FD	FO	SMALL	N	AV	NL
LT-TN-I	UNT		X	X	FE	FO	LARGE	N	NOT POSS.	NL
NRC	?			X						CAN
EBA	NOT AV			X	FE	FO		Y		CAN
GEOG. WASHINGTON UNIVERSITY	?									USA
COLORADO STATE UNIVERSITY	AV	X	X		AN	FO	SMALL	Y		USA
GROCS	AV	X	X		FD	FO	MEDIUM	UNT		USA
SPIPE	AV		X		FE	FO	70 K	Y	PRPL	CH
ADES-STORE	AV				FD	FO	SMALL	N		E.C.
DT2/DT3	NOT AV	X	X	X	FE	FO	LARGE 60÷100K	Y		CH

CAPTION:

AV	= AVAILABLE	FE	=	FINITE ELEMENT	FO	=	FORTRAN
UNT	= UNDER TEST	AN	=	ANALYTICAL SOLUTION	AL	=	ALGOL
PRPL	= PROGRAM PLANNED	FD	=	FINITE DIFFERENCES	BA	=	BASIC

Table 3 (continued): STORAGE COMPUTATION PROGRAMS FOR EARTH SYSTEMS

STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	COMPUTER MATH. SOLUTION: STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
?	AV		X	X	AN	FO		Y		AUS
?	UNT		X	X	AN	FO		N		AUS
LUND-DST	AV		X		FD	FO	SMALL	PARTLY		SWE
TUBE	UNT		X	X	FD	FO	SMALL	N		UK
ENERGY	AV	X	X		FE	FO	LARGE	N		SWE
WELL	NOT AV		X		FD	FO	MEDIUM	N		SWE

CAPTION: AV = AVAILABLE; UNT = UNDER TEST; PRPL = PROGRAM PLANNED
FE = FINITE ELEMENT; AN = ANALYTICAL SOLUTION; FD = FINITE DIFFERENCES
FO = FORTRAN; AL = ALGOL; BA = BASIC

Table 4: STORAGE COMPUTATION PROGRAMS FOR ROCK SYSTEMS

STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	COMPUTER MATH. SOLUTION								
		STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
UNIVERSITY OF MINNESOTA M. RIAZ	AV	X								USA
EBA	NOT AV									CAN
DCT 3 3-dim	NOT AV	X	X	X	FE	FO	100 - 200 K WORDS	Y		CH
?	UNT		X	X	AN	FO		N		AUS
LUND-DST	AV		X	X	FD	FO	SMALL	PARTLY		SWE

CAPTION:

AV	= AVAILABLE	FE	= FINITE ELEMENT	FO	= FORTRAN
UNT	= UNDER TEST	AN	= ANALYTICAL SOLUTION	AL	= ALGOL
PRPL	= PROGRAM PLANNED	FD	= FINITE DIFFERENCES	BA	= BASIC

Table 5: STORAGE COMPUTATION PROGRAMS FOR AQUIFER SYSTEMS

		COMPUTER MATH. SOLUTION								
STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
PT (CCC) BERKELEY 3-dim	AV	X	X	X	FD	FO		Y	AV	USA
AQUASTOR	UNT	X		X		FO				USA
CFEST	AV		X		FE	FO	LARGE	Y		USA
DCT3 3-dim	NOT AV	X	X	X	FE	FO	200 K	Y		CH
?	AV		X		FE	FO	LARGE	UNT		DAN
?	UNT		X	X	AN	FO		N		AUS
LUND-AST	AV		X		FD	FO	SMALL	Y	AV	SWE
SFM-LBL	AV		X		FD	FO	SMALL	Y	AV	USA
SHAFT 79	AV		X		FD	FO	LARGE	Y		USA
LBL CHARTS	AV		X		GRAPH			Y	AV	USA
COMMIX-SP	?									USA

CAPTION:
AV = AVAILABLE
UNT = UNDER TEST
PRPL = PROGRAM PLANNED
FE = FINITE ELEMENT
AN = ANALYTICAL SOLUTION
FD = FINITE DIFFERENCES
FO = FORTRAN
AL = ALGOL
BA = BASIC

Table 6: STORAGE COMPUTATION PROGRAMS FOR SOLAR POND SYSTEMS

STORAGE TYPE / PROGRAM NAME	PROGRAM COMPUTATION AV/UNT/PRPL	COMPUTER MATH. SOLUTION								
		STEADY	TRANSIENT	STRATIFIED	MATH MODEL FE/AN/FD	COMPUTER LANGUAGE FO/AL/BA	MEMORY REQUIRED	VALIDATION OF MODEL Y / N	SIMPLIFIED AV/UNT/PRPL	COUNTRY
SOL POND SERI	AV	X				FO				USA
COMMIX - SP 3-dim	PRPL	X	X	X	FE	FO		PRPL		USA
OHIO STATE UNIVERSITY	AV	X		X		FO		PARTIAL		USA
UNIVERSITY OF NEW MEXICO	AV	X		X		FO		PARTIAL		USA
CARDIFF	AV		X	X	FD	FO		PARTIAL		UK

CAPTION:
AV = AVAILABLE
UNT = UNDER TEST
PRPL = PROGRAM PLANNED
FE = FINITE ELEMENT
AN = ANALYTICAL SOLUTION
FD = FINITE DIFFERENCES
FO = FORTRAN
AL = ALGOL
BA = BASIC

5.2. Second step: More detailed information

The review of the existing or under test computer codes in the previous pages could give us only a general idea of the different types of storage models.

More detailed information was then required for the models that could be considered (i.e. those available) concerning:

1. the validation tests already done

2. the level of precision

   - complete model

   - multidimensional representation with various simplifications

   - fast computer codes

   - rough model for rapid estimation

3. the real capabilities

4. the compatibility with MINSUN AND TRNSYS (language, memory size, time limitations...)

This detailed information may be positively taken out of three sources: a general description of the model, a user's manual, and a computer listing.

The models for which we received these documents or part of them are identified in the next three tables.

PROGRAM

Table 7: AVAILABLE GENERAL INFORMATION

COUNTRY \ STORAGE TYPE	WATER	PIT	EARTH AND ROCK	CAVERN	AQUIFER
USA	Boeing Commix GROCS		GROCS	GROCS	PT (C.C.C.) SFM SHAFT 79 CFEST LBL CHARTS
CANADA	ASTEP E.T.R. 5		E.B.A.		
UNITED KINGDOM			TUBE		
SWEDEN	WELL LUND-SST	LUND-SST	ENERGY WELL LUND-DST	WELL LUND-SST	ENERGY LUND-AST
THE NETHERLANDS			LT-TPD-I (description) LT-TN-I		
GERMANY	KFA-STE IKE				
EC			ADES-STORE		
SWITZERLAND			SPIPE		

PROGRAM

Table 8: AVAILABLE COMPUTER LISTINGS

COUNTRY \ STORAGE TYPE	WATER	PIT	EARTH AND ROCK	CAVERN	AQUIFER
USA	Boeing (Fortran) GROCS (Fortran)		GROCS (Fortran)	GROCS (Fortran)	PT (C.C.C.) (Fortran) SHAFT 79 (Fortran)
CANADA	ASTEP (PL-1)				
UNITED KINGDOM			TUBE (Fortran)		
EC			ADES-STORE (Fortran)		
SWEDEN	LUND-SST (Fortran)	LUND-SST (Fortran)	LUND-DST (Fortran)	LUND-SST (Fortran)	LUND-AST (Fortran)
SWITZERLAND			SPIPE (Fortran & basic)		
THE NETHERLANDS			LT-TPD (Fortran)		

PROGRAM

Table 9: AVAILABLE USER'S MANUALS

STORAGE TYPE / COUNTRY	WATER	PIT	EARTH AND ROCK	CAVERN	AQUIFER
USA	Boeing GROCS		GROCS	GROCS	PT (C.C.C.) LBL CHARTS SHAFT 79
CANADA	ASTEP				
UNITED KINGDOM			TUBE		
SWEDEN	LUND-SST	LUND-SST	Energy LUND-DST	LUND-SST	Energy
EC			ADES-STORE		
SWITZERLAND			SPIPE		
THE NETHERLANDS			LT-TPD-I		

Two programs were already compatible with TRNSYS and, in fact, developed for it (Boeing for water tanks above ground, and GROCS for buried water tanks or ground coil). The LUND programs were found to be in the process of being incorporated into TRNSYS by the LUND team in Sweden.

At this stage of the evaluation, it was very difficult to get a good idea of the capabilities of each program and their limitations.

Hence, a detailed investigation of the models by Lead Country 1c became necessary.

Moreover, the participants decided after a proposition made by Lead Country 1c that a better comparison between models should involve a common run of a test case for each main type of storage.

6. HEAT STORAGE MODELS - EVALUATION AND SELECTION

This section presents a summary of the selection process for the heat storage models identified as available in October 1981 and for which detailed information has been provided by the participants in Lead Country 1c.

Three main families of models for storage systems were considered, as they could represent all the others for modelling purposes:

1. Models for water tank, pit, and cavern storage systems

2. Models for earth and rock storage systems

3. Models for aquifer storage systems

The detailed description of each model is given for each category in Appendix 1, 2, and 3.

The test cases and their philosophy, as originally distributed by Lead Country 1c to the participants, are explained in Appendix 4.

The results of the test cases are given in Appendix 5, 6, and 7 for each storage family.

6.1. Models for water tank, pit, and cavern storage systems

6.1.1. Introduction

As pointed out in Section 4, the storage subroutines incorporated into TRNSYS and MINSUN only take into account the steady heat losses to the environment or to the ground at fixed temperature for MINSUN. If heat capacity effects of the ground are to be considered - particularly during the warm-up period - other types of models are needed.

In fact, heat losses are significant in annual heat storage cycles. The heat recovery factor will be directly dependent on the heat losses, and on the general system. The size of the storage and the way the energy is made available to the consumers (directly or by means of heat pumps) are important factors as well.

As an example, the "thermal recovery factor" will be varying from 60% for a single family storage system to above 90% for a large storage.

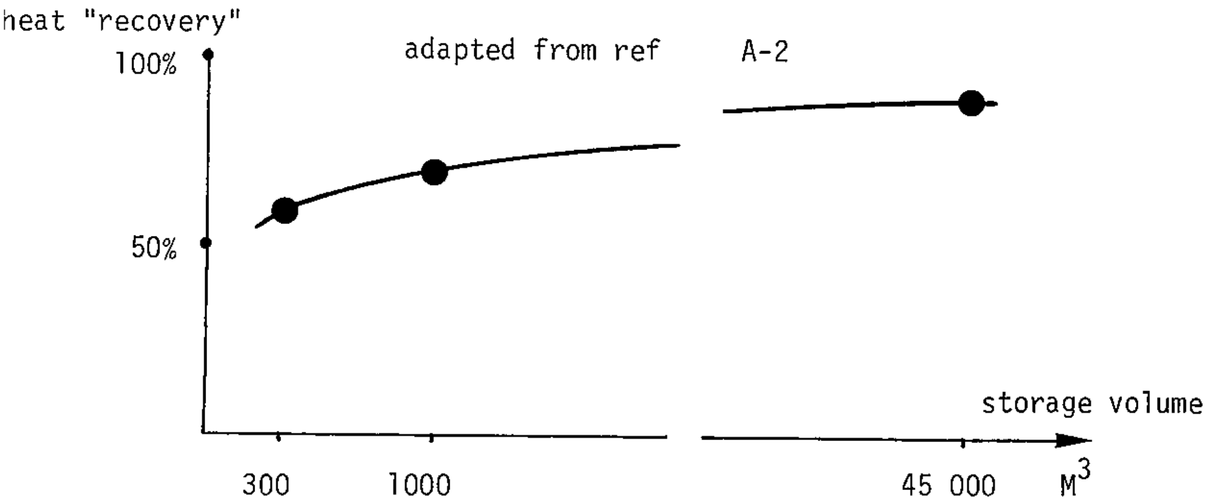


Figure 3: Water tank annual heat recovery factor vs. storage volume

The heat recovery factor from the storage tank is largely determined by the geometry of the tank, the thermal resistance of the insulation and surrounding soil, the climate, and the annual average storage water temperature. The influence of the stratification on the heat losses and on the recovery factor is not clear to date.

6.1.2. Available information

In Table 10, we have pointed out the different levels of information provided to us about water tank storage models.

As can be seen, there is quite a wide dispersion in the provided information.

The Commix program will not be considered in our Subtask, due to its huge size and the difficulty to couple it with the TRNSYS and MINSUN programs.

The detailed description of each model and the results of the test cases are given in Appendix 1 and 5.

Table 10: WATER TANK, PIT, AND CAVERN STORAGE MODELS

LEVELS OF INFORMATION PROVIDED TO LEAD COUNTRY 1c

Date: October 1981

1) COMMIX (USA)

2) BOEING (USA)

3) GROCS (USA)

4) NTACT 1÷3 (Canada)

5) ASTEP/ETR-5 (Canada)

6) LUND-SST (Sweden)

7) ENERGY (Sweden)

☐ Not available

■ Available

⊡ Yes

	1	2	3	4	5	6	7
Short description	Available	Available	Available	Available	Available	Available	Available
User's manual	Not available	Available	Available	Available	Available	Available	Not available
Computer listing	Not available	Available	Available	Available	Available	Available	Not available
Code complete description	Not available	Available	Available	Available	Available	Available	Not available
Test case run	Not available	Not available	Not available	Available	Not available	Not available	Not available
Other test cases	Not available	Not available	Not available	Available	Available	Not available	Not available
Original validation	Available	Available	Not available	Not available	Not available	Not available	Not available
Tested by CH				Yes	Yes	Yes	

6.1.3. Summary of test case results (see Appendix 5 for a detailed presentation)

Two models have run the proposed test case (NTACT and LUND-SST). Great discrepancies between the simulation results of the two codes were found. These were mainly due to the fact that both models did not simulate the same installation (NTACT could not handle the original test case without several important simplifications).

No reliable conclusion could be made from this test case run, except that the typical geometry proposed could be handled by LUND-SST without any modification. Therefore, further validations of the LUND-SST model were needed.

6.1.4. General comparison between models

In the next table, the "quality levels" of the models - established with respect to the Subtask 1a needs - are reported.

The diagram key is the following: the darker the column representing a model, the better the model.

As can be seen, LUND-SST presents a high number of advantages with respect to our needs, but it is a complete model which requires bigger memory size and computing time than the others.

Note that none of the models were completely validated against field experiments (status mid 1981), but most of them were in the process to be.

Figure 4 shows the spatial description of a typical storage case for three evaluated models.

Table 11: QUALITY LEVELS OF WATER TANK, PIT AND CAVERN STORAGE MODELS (1981)

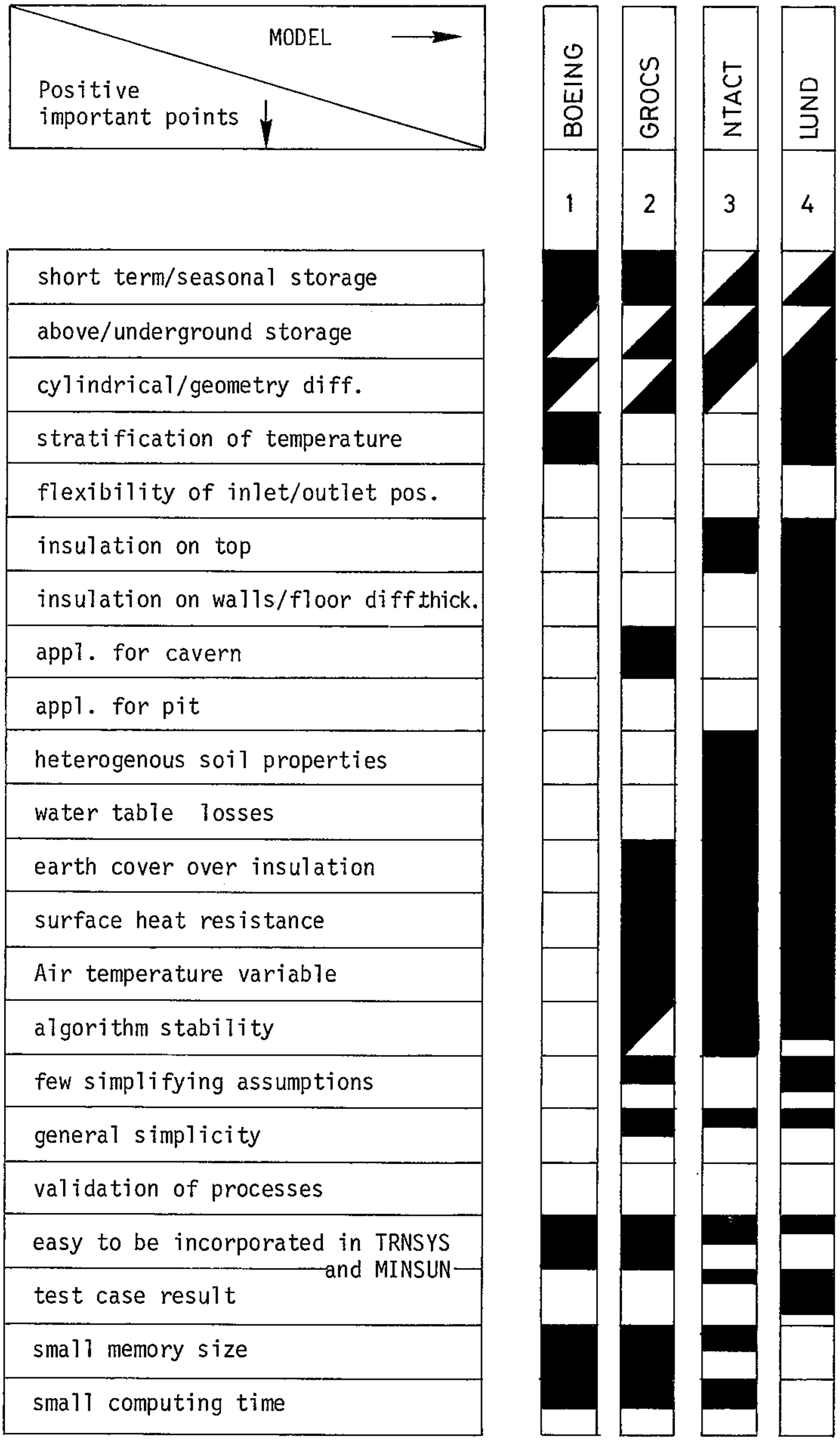
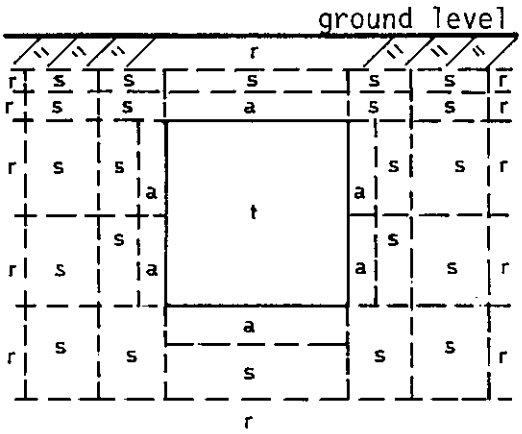
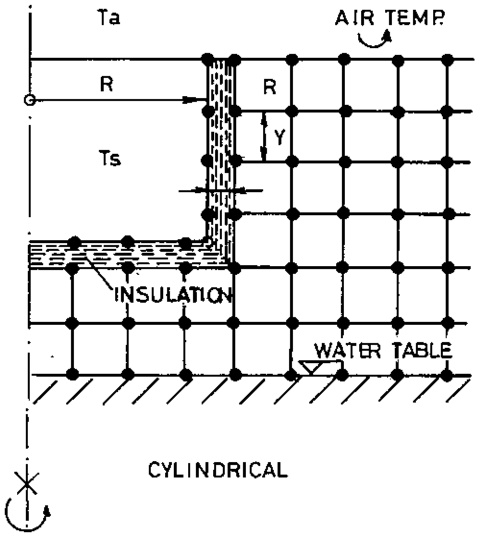
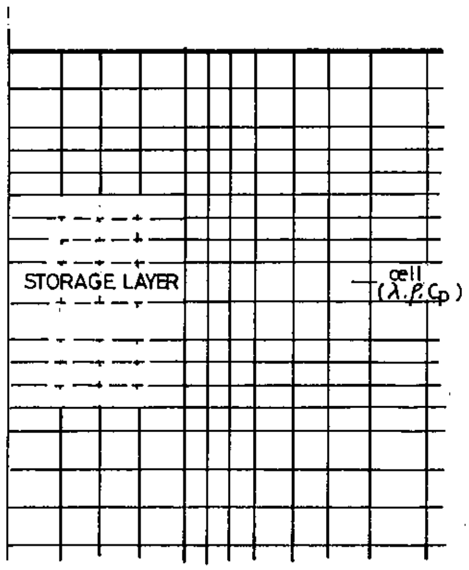


Figure 4: Water tank, pit and cavern storage models - Schematic spatial discretization of the models considered in the selection process

MODEL	GLOBAL PROCESS	STRATIFICATION
2 GROCS (buried tank and cavern)		fully mixed
3 NTACT-1 + ETR-5 (buried tank and pit)		fully mixed
4 LUND SST (buried tank, pit and cavern)		stratified (one-dimensional vertical distribution)

6.1.5. Selection

As a model was needed, which could simulate either a water tank with different parameters, or a cavern, or a water pit, LUND-SST exhibited several advantages.

For optimization purposes, which require simplified models, it could be interesting to modify the NTACT and ETR-5 models, in order to account for vertical stratification.

With respect to the main capabilities of the models, the participants decided, during the 3rd Expert Meeting (October 1981), to choose the LUND-SST model for water tanks, cavern and pit storage.

The SST model will be used as the analysis tool for both the simulation work with TRNSYS and the optimization work with MINSUN. For the latter, a simplified version of SST has to be developed by the LUND team.

6.2. Models for earth and rock storage systems

6.2.1. Introduction

For the earth storage system, the model must be able to take into account a local process (interaction between circulating fluid and ground), and a global process (interaction between the storage zone and the surroundings).

The local process determines the heat flow rate that may be injected in or withdrawn from the store: it is a short-term process on an hourly or somewhat shorter timestep.

The global process determines the general exergetic quality of the store and is concerned with losses to surrounding ground and air, and with heat distribution in the whole domain of investigation: it is a longer term process which can be treated in large scale systems with daily or weekly timesteps.

These two phenomena cannot be treated simultaneously in general with the same timesteps because of the difference between their spatial scale (the discretization process leads to big meshes generally not reasonable without any geometrical or topological transformation).

On the other hand, the two identified processes can be treated separately by using the superposition principle, valid for the linear Fourier law of conduction, or assuming that they can be studied separately with some simple interaction effect.

Most models separate the local and global processes.

Another important point must be noted: heat losses cannot be reasonably defined during one annual cycle for underground storages that are not thermally confined all around. In fact, the surrounding ground can actively participate in the storage and its contribution will depend on the temperature levels of the injected or extracted heat. Therefore, one should never overestimate the importance of the figures given for heat losses during one cycle, for storage only partly confined.

6.2.2. Available information

Table 12 represents the levels of information provided to us, concerning the 8 models identified as available during the 2nd Expert Meeting of the IEA Task VII (March 1981).

As can be seen, the information about models is quite heterogenous. We were able to get an idea of 7 models, and could study 6 of them in more detail.

The proposed test case, discussed in Appendix 4, has been run by 3 models only (LT-TPD-I from the Netherlands, DST from Sweden, and TUBE from the United Kingdom).

The most important point to bring into light is that one model only (SPIPE) was originally validated in 1981, and the validation was only partial (global processes). We had no original information about the other models'validation.

Therefore, in order to get our own feeling about the general quality of the models, we decided to implement and test 4 models we could reasonably study during the time at our disposal until the 3rd Expert Meeting.

As we shall see, this procedure has allowed us to detect errors in the computer listing provided to us (TUBE), and to perform a partial validation of LT-TPD-I, which leads to some modifications to the original version. We were, therefore, also able to perform an indirect kind of validation for the models which had run the proposed test case.

Table 12: EARTH AND ROCK STORAGE MODELS

LEVELS OF INFORMATION PROVIDED TO LEAD COUNTRY 1c

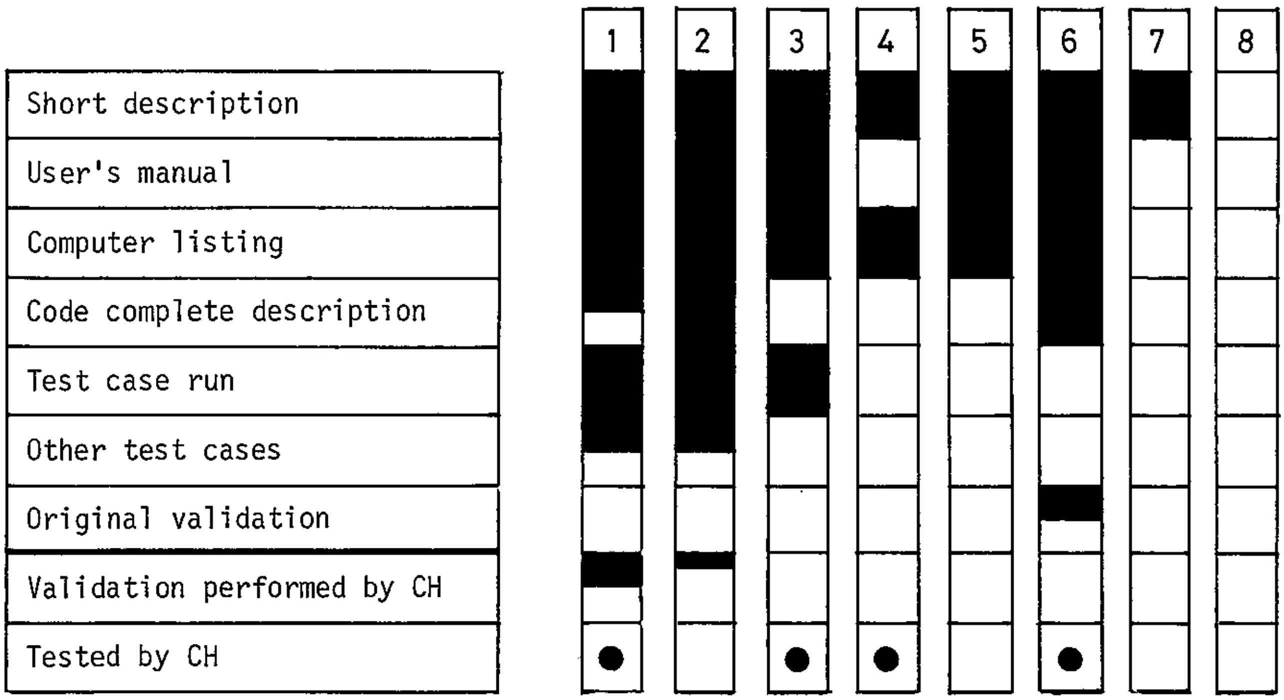
Date: October 1981

1. LT-TPD-I (the Netherlands)
2. LUND-DST (Sweden)
3. TUBE (United Kingdom)
4. ADES-STORE (EC)
5. GROCS (USA)
6. SPIPE (Switzerland)
7. ENERGY (Sweden)
8. EBA (Canada)

☐ Not available

■ Available

⊡ Yes



6.2.3. Summary of test case results (see Appendix 6 for a detailed description)

Three models have run the test case: LT-TPD-I, LUND-DST, and TUBE.

The SPIPE, GROCS and STORE models could not handle the proposed geometry without some important modifications.

A modified test case was proposed by the LUND team and run by LUND-DST, as well as by a modified version of the LT-TPD-I model.

In general, LT-TPD-I and LUND-DST gave comparable results, whereas TUBE could be qualified as "approximate". Even though the test case was found not to be significant enough, it has allowed to get a more precise idea of what geometry the models could handle, as well as of their relative performances in a typical case.

6.2.4. General comparison between models

In Figure 5, the spacial discretization process has been schematically represented for the six identified models. In Table 13, the "quality levels" of the models established with respect to the Subtask 1a needs, and earth storage relevant parameters are reported.

Figure 5: Earth and rock storage models

Schematic spacial discretization of the models considered in the selection process

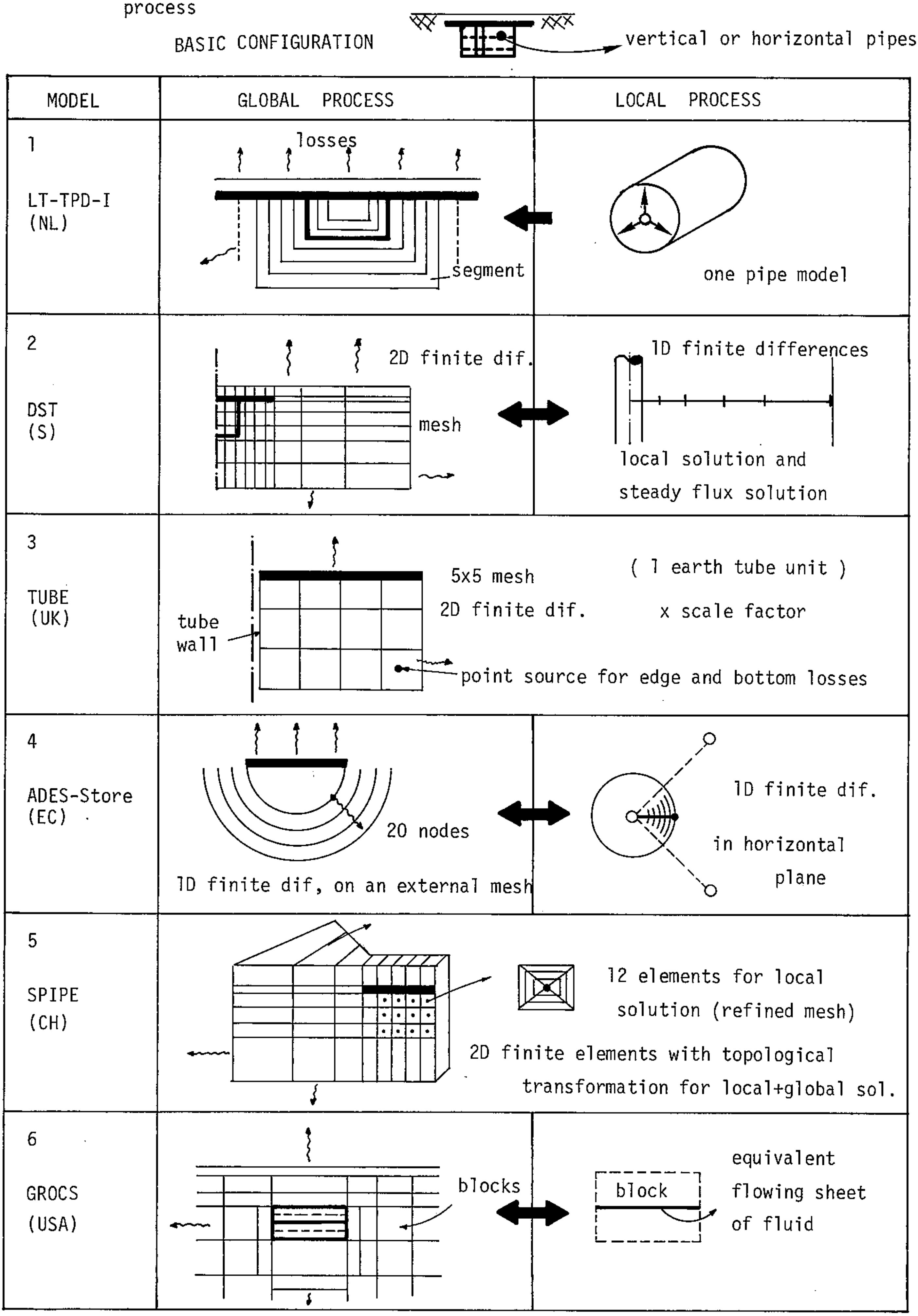
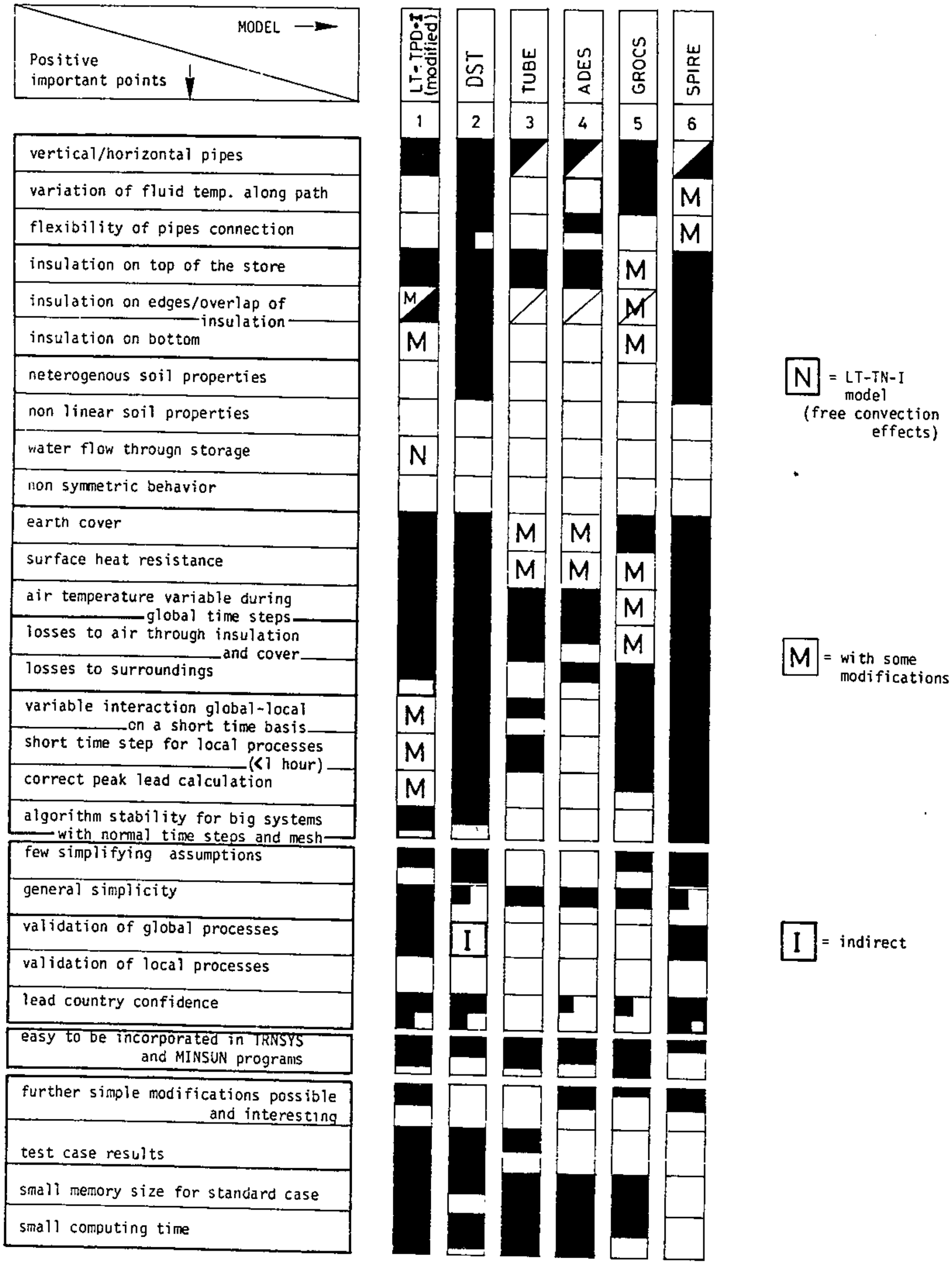


Table 13: QUALTIY LEVELS OF EARTH AND ROCK STORAGE MODELS (1981)



6.2.5. Selection

As two accurate models for earth storage system (LT-TPD-I and LUND-DST) were available, we could consider:

1) the modified version of LT-TPD for optimization purposes which require simple and fast codes

2) LUND-DST for system design purposes

Because of the great capabilities of LUND-DST compared to its size, memory, and run time required, the participants decided, during the 3rd Expert Meeting (1981), to choose LUND-DST as the basic model for optimization and system design purposes.

A simplified version of the DST model will be integrated into the MINSUN program by the LUND team.

6.3. Models for aquifer storage systems

6.3.1. Introduction

In aquifer storage systems two main heat transfer processes dominate: the thermal diffusion, and the thermal convection due to the water flow.

The complete models should be able to take into account buoyancy effects and kinematic dispersion effects. The more simplified models can neglect these effects when the permeability and the dispersion lengths of the storage layer are not too high.

The heat losses through caprock and bedrock should be accounted for.

Generally, a restricting assumption concerns the dimension of the system: usually, the real system is three-dimensional and care must be taken when using two-dimensional models.

6.3.2. Available information

Information about 4 models, and one graphical method were available in 1981. These are the following (Table 14):

1. CCC from the USA, renamed PT in 1981
2. SHAFT 79 from the USA
3. CFEST from the USA
4. LUND-AST from Sweden
5. Graphical method: LBL Chart, from the USA

The first three models are complex, and the fourth is a simplified one.

Number 5 is not a model, but a graphical method predicting the energy recovery factor for standard aquifer configurations and injection conditions.

Table 14: AQUIFER STORAGE MODELS

LEVELS OF INFORMATION PROVIDED TO LEAD COUNTRY 1c
Date: October 1981

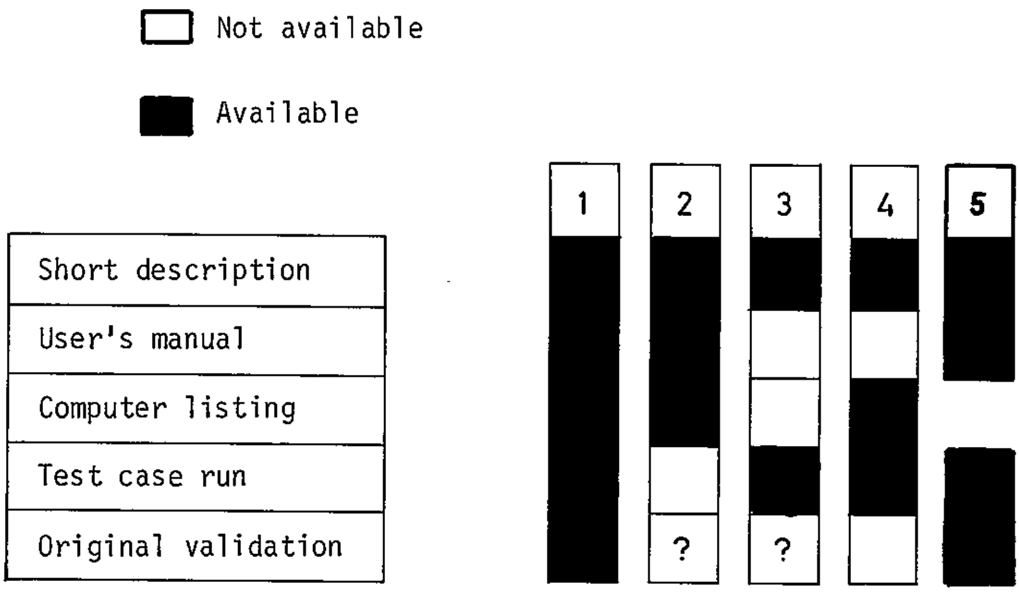
1. PT. CCC (USA)

2. SHAFT 79 (USA)

3. CFEST (USA)

4. LUND-AST (Sweden)

5. LBL Chart (USA)



6.3.3. Summary of test case results
(see Appendix 7 for a detailed description)

Three models have run the proposed test case: PT (CCC), CFEST, and LUND-AST. Very detailed results were provided by the three modelling teams.

Some discrepancies were found between the results, mainly due to different interpretations of the given input data.

The Lawrence Berkeley Laboratory (PT model) also proposed the use of a very simple model (SFM, Steady Flow Model) developed in cooperation with the LUND team - this model is essentially identical to LUND-AST -, and the use of the graphical method (LBL Charts) derived from SFM and PT simulations for standard aquifer configurations.

For the proposed test case, the results of these simple models agreed well with the results of complete models such as PT.

6.3.4. Selection

A real choice was not in fact possible. Only one simplified model could be considered due to its relatively small size: the LUND-AST model.

This model is a simplified one, and it cannot handle any kind of configuration, but mainly the ones in which:

- buoyancy flows are negligible
- cap and bedrock permeabilities are small, compared with permeabilities in the aquifer
- the process is axi-symmetrical around a single well
- a steady radial fluid flow can be defined in a homogenous and horizontal aquifer.

The participants decided to choose this model, being aware of its restrictions and limitations. It was then suggested to use this model basically in the optimization process, and to check and refine the results with a more complete national model.

This choice was mainly due to the complexity and important site specific conditions of an aquifer storage system.

Should a participant think that the AST restrictions - namely concerning the buoyancy effects - are too important for his own case, he may alternatively use the LBL Charts by means of a table of values or regression curves.

Within our Task it was decided that the AST model would be incorporated into TRNSYS, and a simplified version of it in MINSUN, as the aquifer analysis tool. The responsibility for developing a routine using the LBL Charts belongs to each interested participant.

7. CONCLUSION

A great effort has been made by the participating countries in gathering information concerning seasonal heat storage computer models.

Only a few models could be studied and evaluated in a selection process, due to the special needs of the work within Task VII.

The selection process had to be done relatively quickly, in order to provide Subtask 1a with suitable storage models. Moreover, it took place at a time when most of the models were in the process of being validated.

However, learning in detail each selected model for each type of storage systems considered in the Task, as well as studying the results of the proposed test cases, has allowed the participants in Subtask 1c to select a class of storage models to be integrated into the TRNSYS and the MINSUN programs.

The three models from Lund University were chosen (LUND-SST for water tank, pit, and cavern storage, LUND-DST for earth and rock storage, LUND-AST for aquifer storage) for both optimization and system design analysis of CSHPSS.

These three models are, in the opinion of Lead Country 1c, the "best available" ones for the Task VII purposes.

For water tanks above ground, the current MINSUN and TRNSYS tank storage models are applicable.

Furthermore, the models have similar general framework and computation procedure, which will simplify their incorporation into TRNSYS and MINSUN.

The final validation of the three models against field experiments has finally been undertaken by their authors during 1982 and 1983 (reference D-1), after this report was prepared.

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17) M. JOHANSSON, J. CLAESSON:
"Continuous heat source model for ground heat storage"
Department of mathematical physics
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C - Models for aquifer storage systems

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2) C.F. TSANG, T. BUSCHECK, D. MANGOLD, M. LIPPMANN:
"Mathematical modeling of thermal energy storage in aquifers"
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3) K. PRUESS R.C. SCHROEDER:
"SHAFT 79, User's manual"
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LBL-10066, November, 1979

5) J. BENNET, J. CLAESSON, B. EFTRING, G. HELLSTRÖM:
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Editors: J. CLAESSON, B. EFTRING, G. HELLSTRÖM:
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7) L.W. VAIL, C.T. KINCAID:
"CFEST Simulation of the I.E.A. Solar Energy
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Pacific Northwest Laboratory, Richland, Washington , Oct. 1981

8) C. DOUGHTY, T.A. BUSCHECK, G.S. BODVARSSON, C.F. TSANG:
"A Numerical Study of a Two-Well System: IEA Test Problem
for Code Comparison"
LBL, Berkeley, California, October 1981

9) C.T. KINCAID / Battelle PNL:
"Discrepancies between LBL and PNL Simulation Results for
the IEA Aquifer Storage Test Case"
Letter dated October 13, 1981

10) G. HELLSTRÖM, C.F. TSANG, J. CLAESSON:
"Heat Storage in aquifers - Buoyancy flow and Thermal
Stratification Problem" - Oct. 1979
Dep. of MathematicalPhysics University of LUND - Sweden

D - General matter

1) G. HELLSTRÖM:
"Comparison between theoretical models and field experiments for ground heat systems"
International Conference on Subsurface Heat Storage in Theory and Practice, Stockholm, June 6-8, 1983, Proceedings, Part I, pp. 102-115, Document Swedish Council for Building Research D16:1983

E - Detailed description of LUND models (1983)

In 1983, three basic versions of the three LUND models have been prepared by the LUND team for the Task VII needs, that is for SST, DST and AST: an independent version, a TRNSYS version, and a MINSUN version. Detailed information concerning these versions and their users'manuals can be found in the following reports (available from the authors; addresses on page iv):

1) B. EFTRING:
"Stratified Storage Temperature Model (SST)"
Manual for computer code, Lund, November 1983 (116 pages)

2) G. HELLSTRÖM:
"Model of Duct Storage System (DST)"
Manual for computer code, Lund, March 1982, updated September 1983 (116 pages)

3) G. HELLSTRÖM & B. EFTRING:
Description of storage subroutines in TRNSYS form:
- Aquifer Storage (AST)
- Duct Storage (DST)
- Stratified Storage (SST)
Lund, November 1983 (approx. 50 pages)

Appendix 1: MODELS FOR WATER TANK, PIT, AND CAVERN STORAGE SYSTEMS - DESCRIPTION OF AVAILABLE MODELS

From the provided information, and for the Task VII needs, four models were considered for a detailed analysis.

These are the following:

1. GROCS (USA)
2. NTACT-1 (Canada)
3. ETR-5 (Canada)
4. LUND-SST (Sweden)

A.1.1. GROCS (ref. B-12)

A.1.1.1. Original description

GROCS solves the heat flow finite difference equations over a system of "blocks" of earth. Each block is a volume of earth whose size and shape are determined by a hand-drawn model. One such model is illustrated in the following figure:

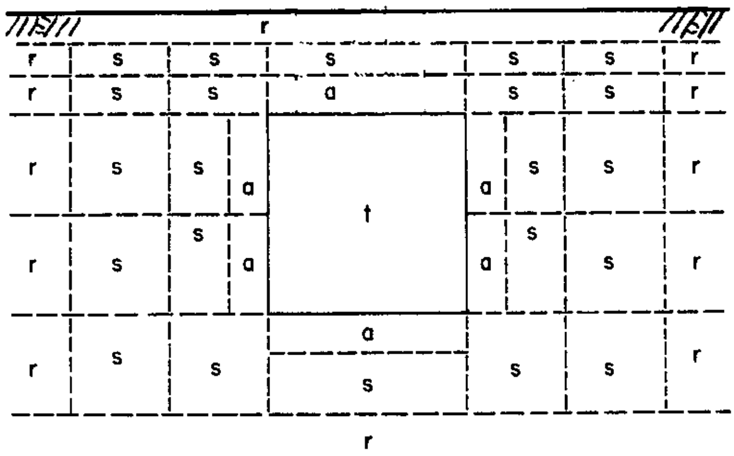


Figure 6: GROCS/Ground-coupling model schematic (adapted from ref. B-12)

GROCS uses two different kinds of blocks, called "rigged blocks" and "free blocks". the rigged blocks surround the free blocks and provide the necessary spatial boundary conditions. The temperatures of the rigged blocks are determined at each timestep by a function subprogram called TINTERP which requires a table of experimentally measured average ground temperature at a number of different depths spanning the portion of the ground to be simulated, for each month of the year. At every timestep in GROCS, the subprogram is told the time of year and the depth of the center of the block whose temperature it is to compute. TINTERP then determines the temperature of the block by linearly interpolating with respect to time and depth between the relevant table entries.

The free block temperatures are initially determined by specifying them as data input or, if a default value is specified (which is a timesaver), by TINTERP as described above. At all future timesteps, however, the free blocks have their temperatures determined by their thermal interaction with each other and with the rigged blocks, and by heat inputs placed in them to simulate the effect of a solar heating system and load.

A number of physical parameters of the model must be specified for input to GROCS. These include the numbers of free and rigged blocks, the initial temperature or the default temperature, the volume and volume heat capacity for each free block, the depth of each block, all nonzero heat transfer areas, and center-to-center distances of adjoining blocks.

A.1.1.2. Integration of GROCS with TRNSYS

In order to merge GROCS successfully into TRNSYS it was necessary to make provision for the simulation processes going on in each program to proceed without interfering with the other, and yet to allow appropriate thermal interactions to occur between them. To make this possible, subroutines were written in the same format as other component TYPE subroutines in TRNSYS, which model solar components and building loads and in some cases perform various algebraic manipulations necessary to a simulation. These subroutines, TYPE33 for the buried tank, in turn communicate with GROCS. During each simulation timestep, the TYPE subroutines are called in turn by a central "command" subroutine in TRNSYS called EXEC. As each TYPE subroutine is called, its inputs are adjusted to reflect the outputs of previously called subroutines, and after it finishes processing, its outputs in turn affect the inputs of subroutines to be called later. After (usually) several passes through the set of subroutines which constitute the system to be simulated, the inputs and outputs of all the subroutines converge to a set of mutually consistent values.

A.1.1.3. Buried tank model

During the course of simulating a given timestep, TRNSYS "sees" a mixed tank of a specified volume with the same inputs and outputs as a conventional tank. After convergence has been obtained for that timestep, however, the flows of heat between the tank and its surroundings are calculated differently. During the iterative process within a timestep, thermal interaction occurs between the tank (t in Figure 6) and the rest of the system. At the end of the timestep, the heat transferred between the tank and the conceptual blocks of earth (a) adjacent to the tank are calculated by TYPE33 and made available to GROCS. Then GROCS is called by TYPE33; it computes the heat flows between all pairs of blocks, including both the adjacent blocks (a), the surrounding nonadjacent free blocks (s), and the rigged blocks (r). The usefulness and accuracy of this model depend on the use of timestep short enough so that the change in tank temperature during any timestep is much less than the mean temperature difference between the tank and adjacent blocks.

A.1.2. NTACT (ref. A-2)

NTACT-1 (numerical thermal analysis of cylindrical tanks/ 1st version) is a two-dimensional explicit form transient heat transfer computer program designed to calculate heat loss factors of cylindrical thermal storage tanks.

The formulation allows the variation of soil thermal conductivity with position and time.

A.1.2.1. General description

NTACT-1 utilizes an explicit form of finite difference representation. A three point central difference formula and a two point forward difference formula are used to formulate the finite difference expression for the space and time derivatives, respectively.

The nodal representation for thermal analysis is given below.

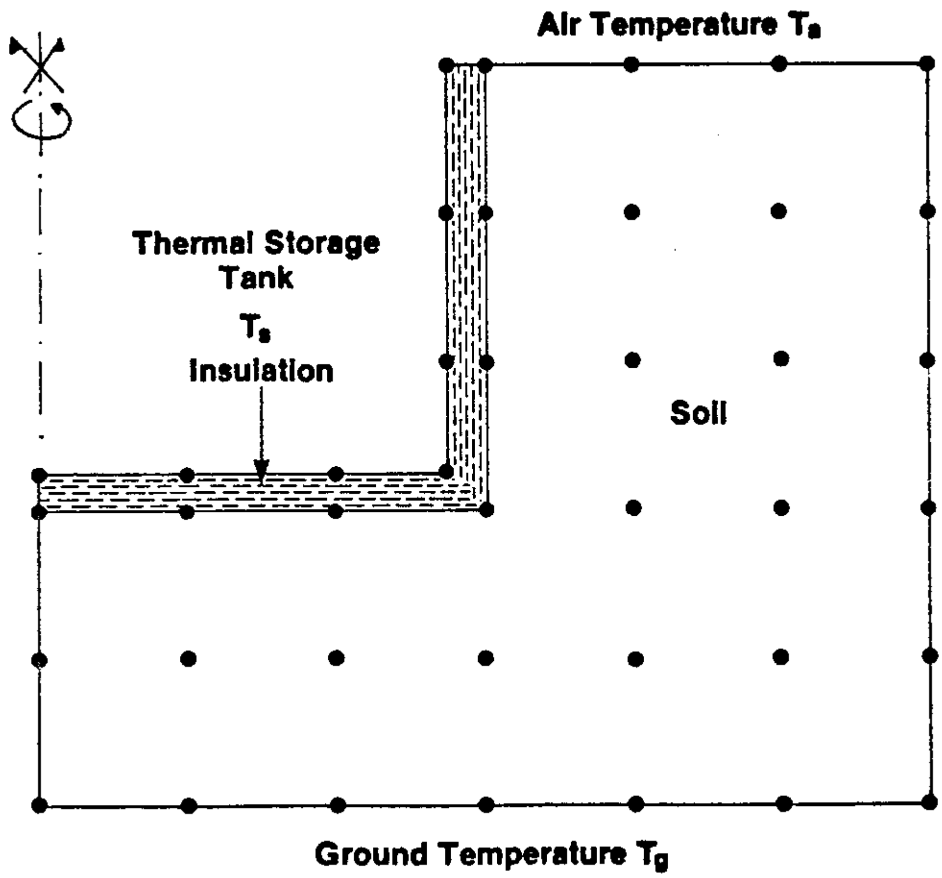


Figure 7: NTACT/Typical nodal representation for thermal analysis of a buried cylindrical tank (from ref. A-2)

The geometry of the general case is given in Figure 7. It is limited to a buried cylindrical tank with insulation all around. The thickness of the insulation can be different for the top, wall, and floor. This model has been developed at the University of Toronto with the objective of validating a simplified lumped model, to calculate the annual heat losses in the ground from the second year of operation, because solutions then correspond to the nearly sinusoidal temperature variation in the system over a one-year period. After the start-up transients, usually significant only in the first year of operation, a repeating cycle is closely approached.

The complete NTACT model can be used to prepare in advance tables of heat losses parameters for use within the simple parameter ETR model of thermal storage. This parameter characterizes each tank soil configuration for which the net change in the earth heat contents over the period is zero. This is typical of annual storage cycles, often the initial warm-up period, where the tank temperature variation is approximately sinusoidal over a given year (see Section A.1.3. for details).

A.1.2.2. Limitations of the model

Geometry

In the current version, the geometry of the tank must be cylindrical.

The thickness of insulation must be the same on the walls and on the floor. The bottom insulation cannot be suppressed. Heat capacity effects of the soil above the tank are not computed. Only the thermal resistance of the cover (insulation and ground) is accounted for.

Stratification

The water in the storage volume is assumed to be fully mixed.

It is assumed that the yearly mean variation of the average storage temperature has a sinusoidal form.

A.1.3. ETR-5 (ref. A-1)

A.1.3.1. General description

Tanks for annual storage are characterized as of cylindrical form and below grade construction, with the tank top either flush with the ground surface or directly below the conditioned building. Heat loss calculations for this type of tank are separated into two components; heat loss through the tank lid, and heat loss from the walls and floor through the earth surrounding the buried tank. The heat loss from the tank lid (LID_LOSS) as shown by the following equation is calculated neglecting thermal transients, assuming the tank top surface of the insulated tank is exposed directly to the ambient air (outdoor or indoor).

$$\text{LID\_LOSS} = \frac{\text{TANK\_TEMP} - \text{AMB\_TEMP}}{\text{ETR\_LID}}$$

where TANK_TEMP = storage temperature of well mixed contents of tank;

AMB_TEMP = outdoor dry bulb temperature or indoor thermostat setting;

ETR_LID = resistance to heat flow by conduction through the insulation. Resistance to heat flow by convection from the surfaces is assumed to be negligible. (For an uninsulated tank a small insulation thickness equivalent to the film coefficient must be assumed.)

Heat losses through the walls and floor of the buried tank are calculated based on the electrical analogy shown in Figure 8.

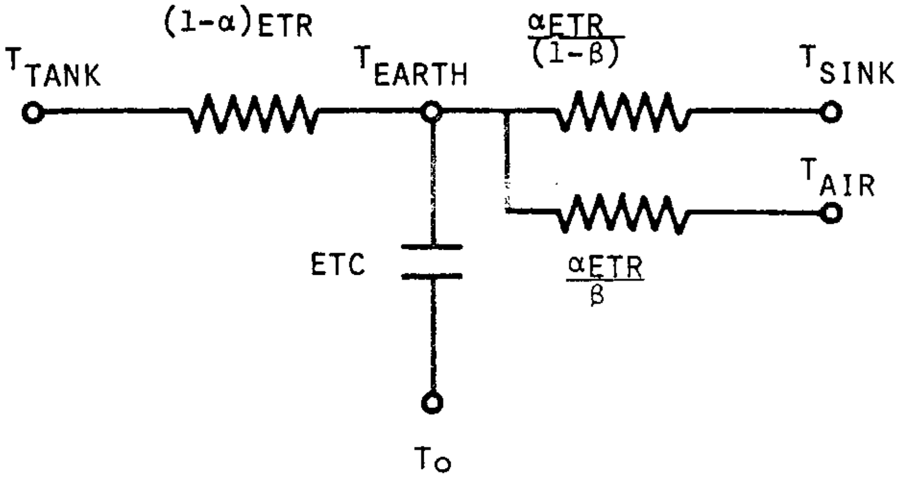


Figure 8: ETR-5/Analogous electrical circuit for the lumped parameter model

The lumped parameters, ETR, ETC, α, and β, are calculated using NTACT, a computer model incorporating the thermal transients of the surrounding soil. This model utilizes a finite difference method whereby the characteristic differential equation for transient heat flow is replaced by an equivalent expression in finite differences for each node in an assumed soil grid. Assumptions of the model include:

1. A vertical axi-symmetric cylindrical tank with top flush with ground surface

2. Conductive heat transfers only

3. A vertical isothermal soil boundary at a distance radially outward from the tank wall equal to the depth below grade of the assumed horizontal isothermal boundary (or water table)

4. A value for the depth of the lower horizontal isothermal boundary

5. Constant soil thermal properties

6. Insulation so distributed that the heat loss per unit of its surface area is equal at every point on the surface (this has been shown to be the optimum distribution of a fixed volume of available insulation)

To illustrate the utility of the ETR method, the heat loss predictions of the ETR model on a daily basis were compared with those from the very much more complete NTACT model. The case chosen for comparison is that of the same storage tank proposed for the test case (see Appendix 4), except that a uniform distribution of the insulation was assumed.

Also an annual cycle was followed rather than a forty day cycle. The major system parameters are summarized in Figure 9. In Figure 10b the comparison is made between the ETR prediction and that of the NTACT model for the seventh year of operation. The agreement is remarkably good.

Figure 10a shows the first year of operation, as predicted from NTACT, in comparison with the ETR model prediction which ignores the transient factors. It will be seen that after a few months the ETR predictions begin to approximate closely those of the more complete model.

A.1.3.2. Limitations of the model

They are essentially the same as for NTACT.

PARAMETER SUMMARY

```
GENERAL SPECS
-------------
  AIR TEMPERATURE FUNCTION  - AMPLITUDE                -        15.0  C DEGREES
                              MEAN                     -        10.0  DEGREES C
                              PERIOD                   -        8760  HOURS
  TANK TEMPERATURE FUNCTION - AMPLITUDE                -        25.0  C DEGREES
                              MEAN                     -        55.0  DEGREES C
                              STARTING PT.             -      3.1416  RADIANS
  TANK INSULATION - THICKNESS                          -      0.2500  METERS
                    SPECIFIC HEAT                      -      1000.0  J/KG C
                    DENSITY                            -        20.0  KG/CUB.M.
                    THERMAL CONDUCTIVITY               -      0.0400  W/M C
  TANK LID THERMAL RESISTANCE                          -      0.0260  C/W
  TANK RADIUS(TO OUTSIDE OF INSULATION)                -      10.425  METERS
  TANK HEIGHT(INSIDE TANK LID TO UNDER FLOOR)          -      10.400  METERS
  ITERATION TIME STEP                                  -       24.00  HOURS
  SIMULATION RUN TIME                                  -           0  YEARS

GROUND SPECS
------------
  GRID SPACING    - RADIAL DIRECTION                   -        2.00  METERS
                    AXIAL DIRECTION                    -        2.00  METERS
  WATER TABLE DEPTH BELOW TANK                         -       10.00  METERS
  VERTICAL SOIL BOUNDARY DISTANCE FROM TANK WALL       -       20.00  METERS
  TANK DEPTH BELOW GROUND SURFACE                      -      12.400  METERS
  SOIL - SPECIFIC HEAT                                 -      1000.0  J/KG C
         DENSITY                                       -      2000.0  KG/CUB.M.
         THERMAL CONDUCTIVITY                          -     LAYERED  W/M C
  GROUND-AIR HEAT TRANSFER COEFFICIENT                 -      10.000  W/SQ.M. C
  INITIAL SOIL TEMPERATURE                             -     LAYERED  DEGREES C
```

Figure 9: NTACT / Example of computer printout of parameter summary

NTACT SIMULATION RESULTS - YEAR 1

ETR = 7.702 C/KW (4.063 F HR/KBTU)

UNIT R = 7.688 SQ.M. C/W (43.657 SQ.FT. F HR/BTU)

TANK SURFACE AREA = 998.3 SQ.M. (10745.2 SQ.FT.)

TANK NODE UNIT R-VALUES
SQ.M. C/W (SQ.FT. F HR/BTU)

TANK SURFACE	POSITION OF CELL	R-VALUE INSULATION	R-VALUE SOIL
WALL	DEPTH (M)		
	0.00 - 1.40	6.250 (35.489)	0.164 (0.929)
	1.40 - 3.40	6.250 (35.489)	1.233 (7.002)
	3.40 - 5.40	6.250 (35.489)	1.644 (9.334)
	5.40 - 7.40	6.250 (35.489)	1.730 (9.823)
	7.40 - 9.40	6.250 (35.489)	1.592 (9.040)
	9.40 - 10.40	6.250 (35.489)	1.177 (6.683)
FLOOR	RADIUS (M)		
	0.00 - 1.42	6.250 (35.489)	2.116 (12.013)
	1.42 - 3.42	6.250 (35.489)	2.092 (11.880)
	3.42 - 5.42	6.250 (35.489)	2.035 (11.558)
	5.42 - 7.42	6.250 (35.489)	1.917 (10.884)
	7.42 - 9.42	6.250 (35.489)	1.677 (9.524)
	9.42 - 10.42	6.250 (35.489)	1.177 (6.683)

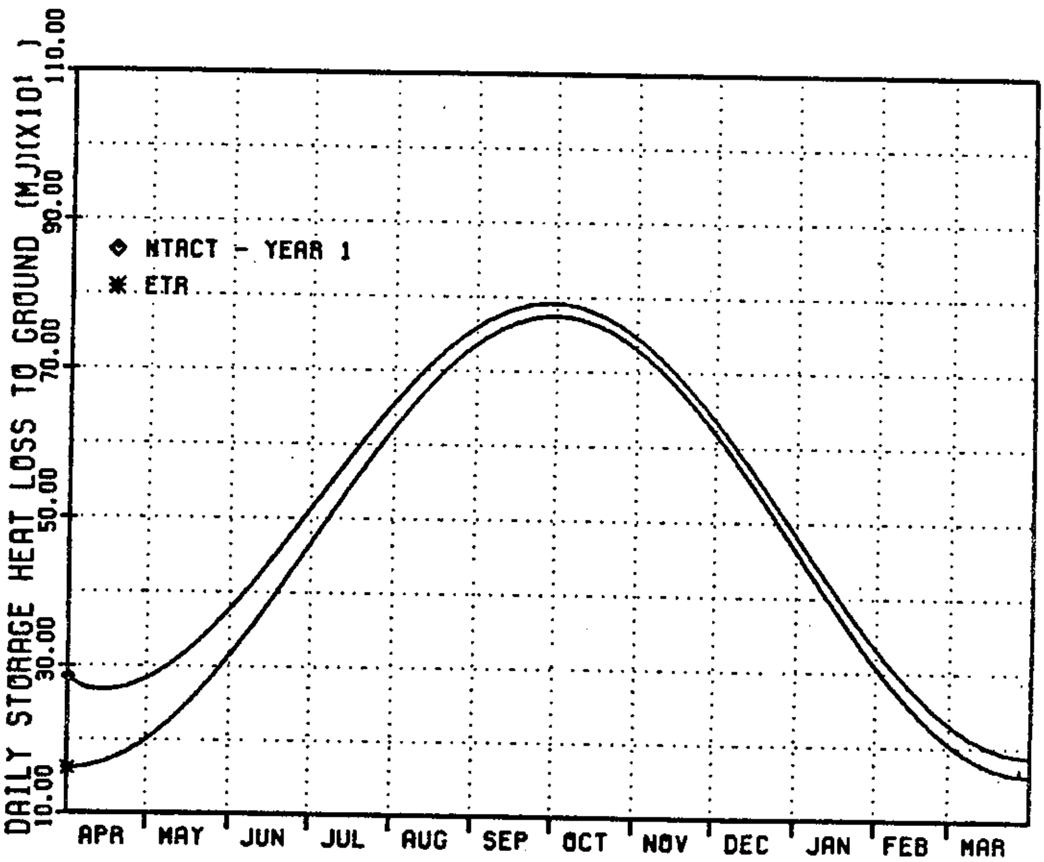


Figure 10a: Comparison of NTACT and ETR models heat loss
Calculation year 1

NTACT SIMULATION RESULTS - YEAR 7

ETR = 8.298 C/KW (4.377 F HR/KBTU)

UNIT R = 8.283 SQ.M. C/W (47.035 SQ.FT. F HR/BTU)

TANK SURFACE AREA = 998.3 SQ.M. (10745.2 SQ.FT.)

TANK NODE UNIT R-VALUES
SQ.M. C/W (SQ.FT. F HR/BTU)

TANK SURFACE	POSITION OF CELL	R-VALUE INSULATION	R-VALUE SOIL
WALL	DEPTH (M)		
	0.00 - 1.40	6.250 (35.489)	0.178 (1.013)
	1.40 - 3.40	6.250 (35.489)	1.431 (8.124)
	3.40 - 5.40	6.250 (35.489)	2.027 (11.512)
	5.40 - 7.40	6.250 (35.489)	2.302 (13.071)
	7.40 - 9.40	6.250 (35.489)	2.291 (13.011)
	9.40 - 10.40	6.250 (35.489)	1.925 (10.931)
FLOOR	RADIUS (M)		
	0.00 - 1.42	6.250 (35.489)	3.565 (20.241)
	1.42 - 3.42	6.250 (35.489)	3.497 (19.858)
	3.42 - 5.42	6.250 (35.489)	3.353 (19.038)
	5.42 - 7.42	6.250 (35.489)	3.095 (17.574)
	7.42 - 9.42	6.250 (35.489)	2.666 (15.136)
	9.42 - 10.42	6.250 (35.489)	1.925 (10.931)

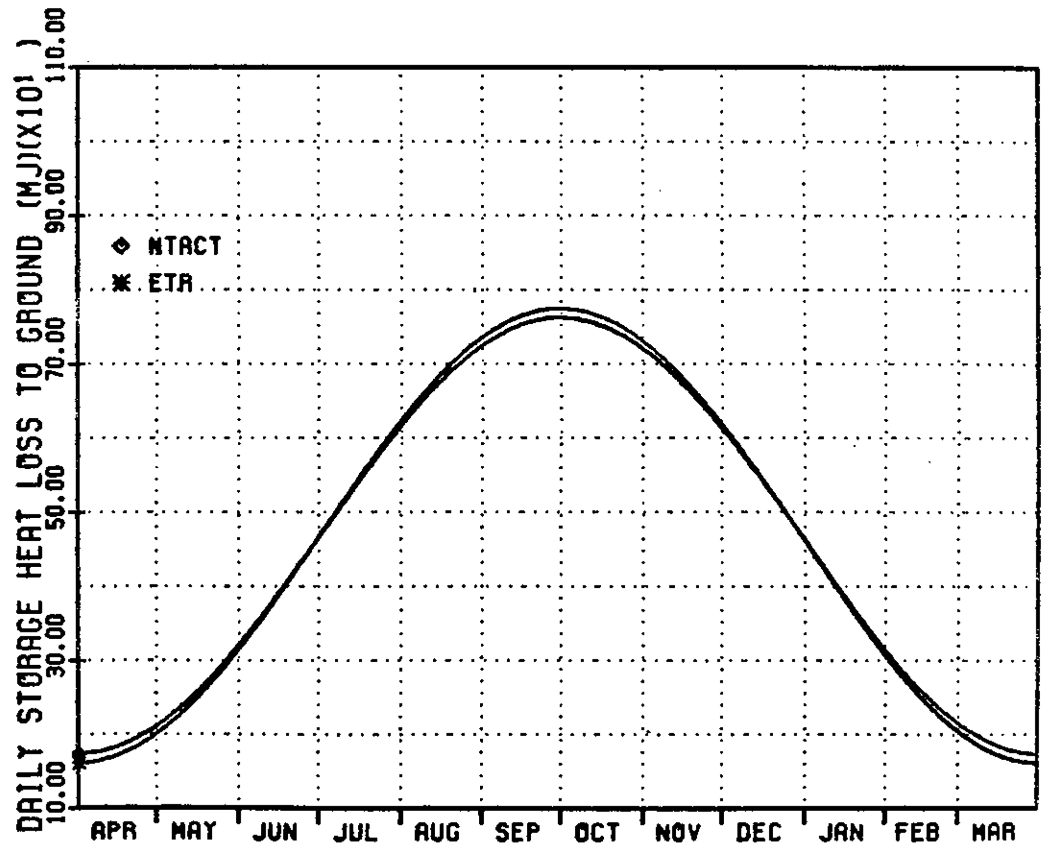


Figure 10b: Comparison of NTACT and ETR Models Heat loss Calculation - Year 7

A.1.4. LUND-SST (Stratified Storage Temperature) (ref. B-12)

A.1.4.1. Application of the model

The model presented may be appropriate in the following cases:

- rock cavern with water
- rock cavern with water and stone
- buried water tank
- water pit
- pit with stones and water
- high-permeability aquifer with horizontal temperature stratification

A.1.4.2. Geometry of the model

The geometry of the storage is plane or cylindrical (two-dimensional or cylindrical)

(x, z) or (r, z).

Inside the storage volume there is a vertical one-dimensional temperature field. The temperature is stratified, that is: T water = T (z, t). The computer code can handle the following shapes: (ref. A-14)

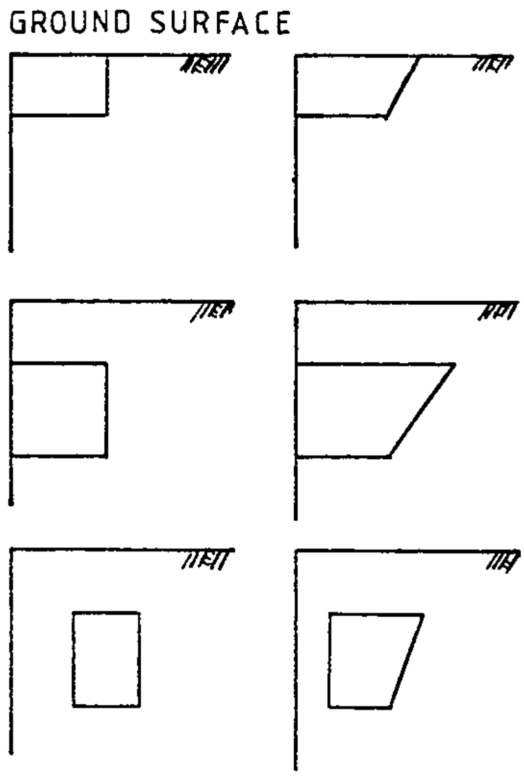


Figure 11: LUND-SST / Typical geometries handled

A.1.4.3. Heat transfer processes

Thermal resistances may be introduced anywhere between the cells.

At the ground surface the temperature is given. It may vary with time.

A certain number of cells form the storage region. The calculation of the thermal process is different.

Heat transport in the storage region

During the heat injection period, fluid is pumped through the storage volume from the top to the bottom.

The temperature in the storage volume is represented by a one-dimensional distribution in the vertical direction. The storage volume is divided into a number of horizontal layers. The layers have the same heat capacity.

Conductive heat transfers

At a given time the heat flows through all boundaries of all layers of the storage volume are calculated. These heat flows are constant during a given timestep.

Free convection is not implemented in the code but the effect of it is dealt with in different approximate ways. Insulation may be put anywhere in the ground.

The program does not consider water transport in the ground outside the storage volume.

Heat transport in the ground outside the storage volume

The time dependent equation that describes the conduction heat transport present in the ground is solved by a method using explicit forward difference.

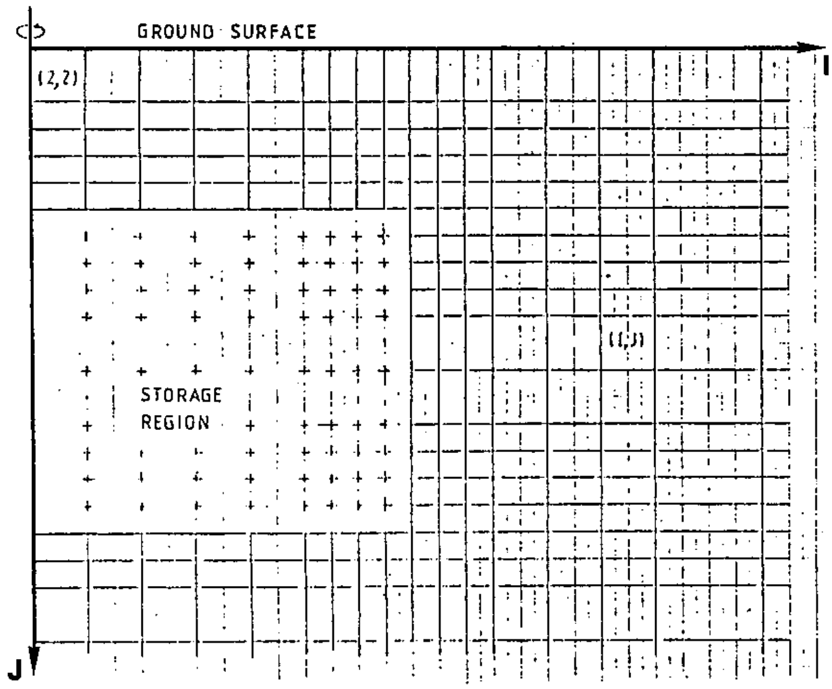


Figure 12: LUND-SST/Cell structure for the ground problem. The cell dimensions may vary over the cross section

For each cell the thermal properties (λ, ρ, C_p) can be defined.

The heat flow between two layers is calculated in the following way:

$$Q = \frac{T_{i-1} - T_i}{\frac{d_i}{2\lambda_i} + \frac{d_{i-1}}{2\lambda_{i-1}}} \cdot A$$

Q : heat flow (W)

T_i: temperature of layer i (^oC)

d_i: thickness of layer i (m)

λ_i: thermal conductivity of layer i (J/sm^oC)

A : area between layer i-1 and i (m2)

If the storage content is pure fluid the λ- value of the fluid should be used. If the storage volume contains solid and fluid the λ- value of the stagnant solid/fluid mixture should be used.

If the storage volume contains stones or blocks a dispersion effect will appear because of the fluid transport around the blocks. This effect may be described as an increased effective thermal conductivity ($\bar{\lambda}$) in the storage volume.

In the model $\bar{\lambda}$ is given as:

$$\bar{\lambda} = \lambda + \ell \cdot q_f^n \cdot C_f$$

λ : thermal conductivity for stagnant solid/fluid mixture (W/m°C)

ℓ : thermal dispersion length (size of blocks) (m)

q_f: fluid flow through the storage volume ($m3_f$/m2s)

n : user specified power. Usually n equals 1 or 2

C_f: volumetric heat capacity of the fluid (J/$m3_f$°C)

$\bar{\lambda}$ is time-dependent since it is a function of q_f. The area of the horizontal cross-section of the storage volume may vary in the vertical direction. Thus, q_f and $\bar{\lambda}$ may be a function of the depth.

Convective heat transport

The water transport through the storage volume is treated in the following way:

the total water flow rate Q_f ($m3_f$/s) and the inlet water temperature T_f (°C) are given at each timestep. There are no restrictions on the time variation of Q_f and T_f.

Free convection will occur in the fluid. It strives to place warmer water on top of heavier cold water.

The buoyancy stratification requires that the temperature is not increasing downwards. This model does not account for the buoyancy flow in the water except in an approximate way.

Run time, program size

The execution time depends on the number of cells in the system. For example: if there are 600 cells in the ground and 21 layers in the storage, with a dimension of the smallest cell of 1 x 1 m in the cross section, the CPU time on a UNIVAC 1100/80 is about 5 seconds, for a simulation period of one year, during which the routine WST is called for every hour.

Simulation of larger storage volumes will need less CPU-time, since the cell dimensions will be larger (timesteps are longer).

The program size is about 20k in this case. If the number of cells is 1600, the size should be about 30k.

Appendix 2: MODELS FOR EARTH AND ROCK STORAGE SYSTEMS - DESCRIPTION OF AVAILABLE MODELS

Our aim, in this section, is not to give a complete description, which should be found in a user's manual, but to emphasize the peculiarities of each earth storage model.

Only the first 6 models identified will be treated, as there is too big a lack of basic information for the others.

These models are the following:

1. LT-TPD-I from the Netherlands
2. LUND-DST from Sweden
3. TUBE from the United Kingdom
4. ADES-Store from EC
5. GROCS (buried pipe model) from the USA
6. SPIPE from Switzerland

In order to take advantage of the work performed by each Subtask 1c group, we preferred to reproduce the original short description of the model, when available. In the other cases, we have given a short description, based on the provided user's manual.

A.2.1. LT-TPD-I (ref. B-1)

A.2.1.1. General information

The computer simulation program is a simple one. In the computer simulation model heat transfer takes place only by conduction.

At present the program is available; validation of the model is yet to be done.

It is a transient model with a solution by finite differences. The computer language is Fortran IV; the required memory is small (= 2 k).

A.2.1.2. Description of the model

In the computer simulation model the seasonal heat storage reservoir in the soil is considered a semi-cube, which is covered at the top by an insulation layer (see Figure 13).

Four regions, partly overlapping each other, are distinguished:

- the heat exchanger region
- the hot region
- the transition region
- the cold region

In the heat exchanger region heat is supplied to or withdrawn from the soil.

Because of heat transfer from the heat exchanger region to the surrounding soil there is a temperature gradient at the outer part of this heat exchange region.

In the centre of the heat exchange region this heat loss to the surrounding soil is not noticeable; in this region the temperature is homogenous: the hot region.

The region with the temperature gradient is the transition region. Outside this region the temperature is assumed to be constant: the cold region.

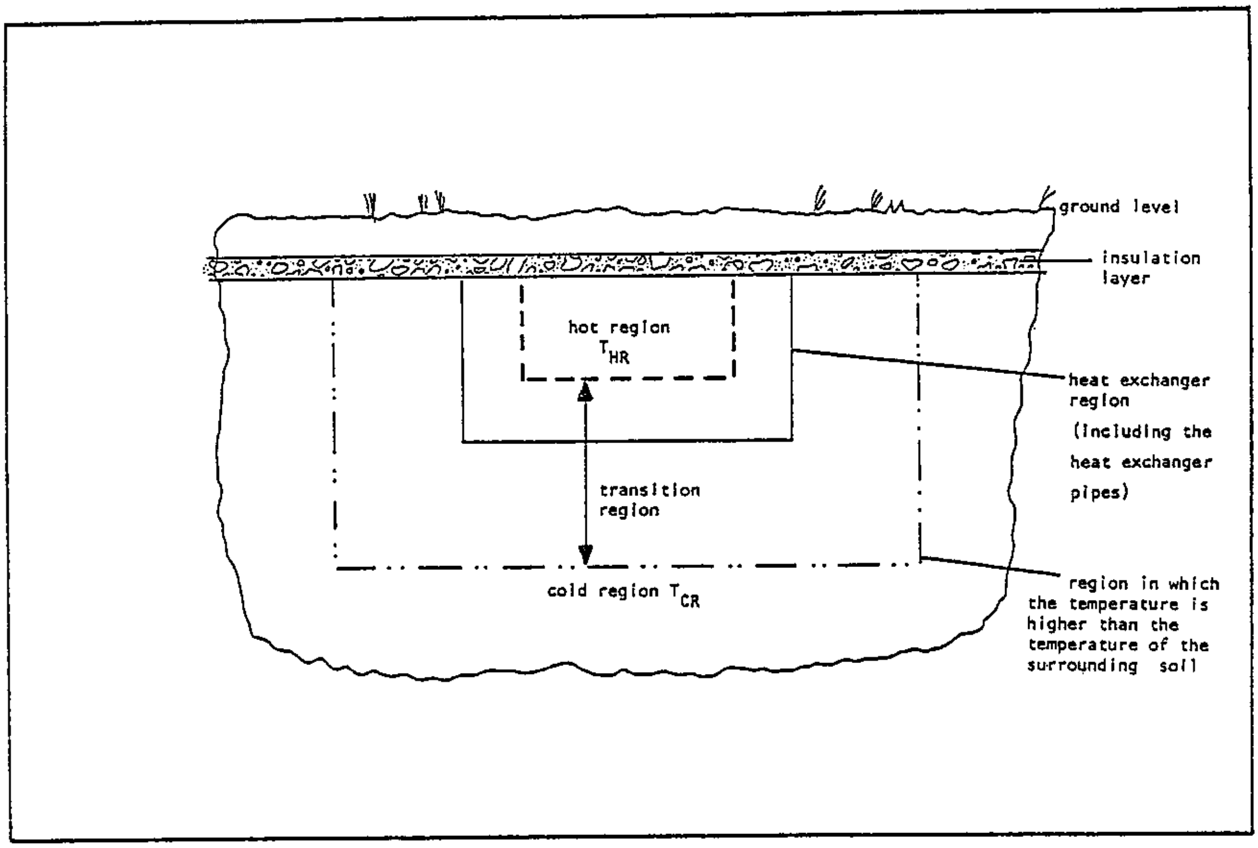


Figure 13: LT-TPD-I/Dvision of the seasonal heat storage reservoir into regions

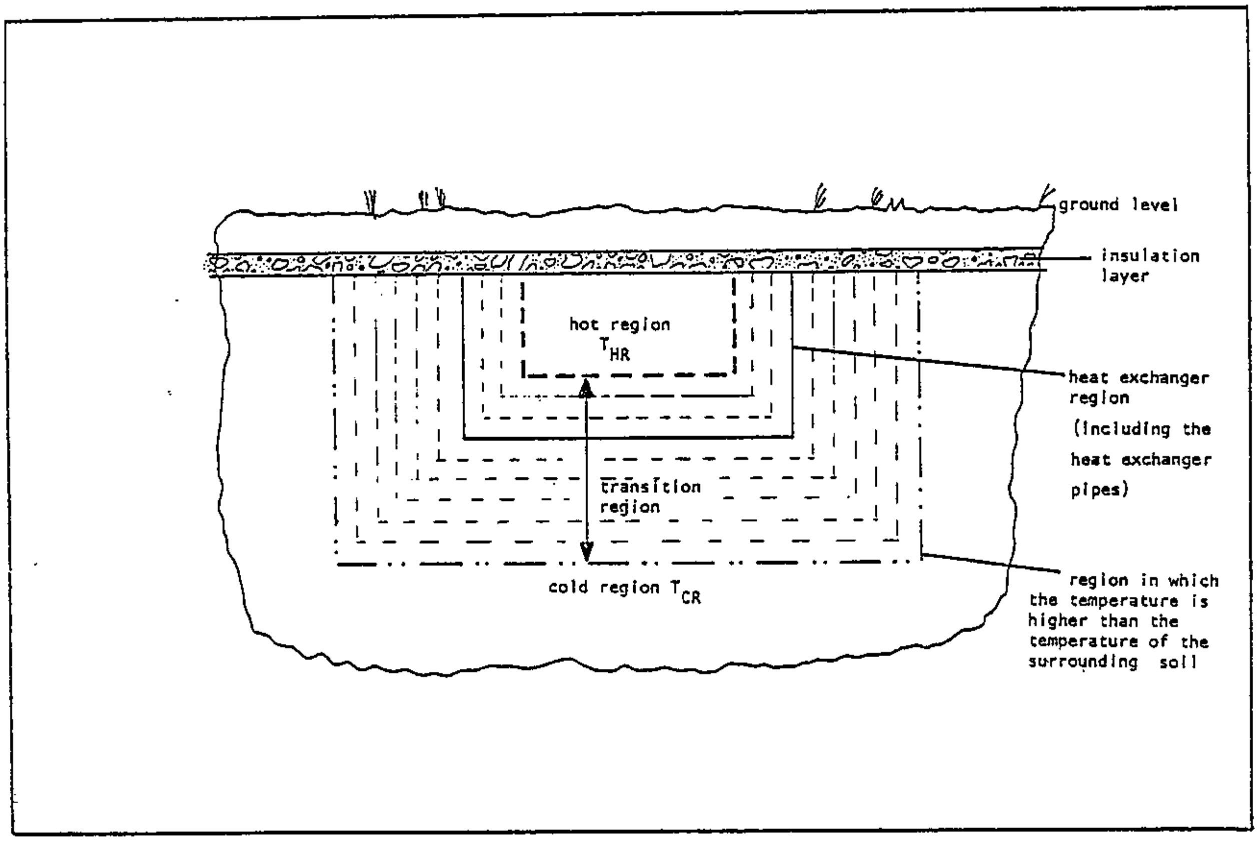


Figure 14: LT-TPD-I/Division of the transition region into a large number of layers

The transition region is divided into a large number of layers, each with a heat capacity corresponding with the volume of the layer (see Figure 14).

Between two neighbouring layers heat transfer takes place by conduction.

In the heat exchange region heat is supplied to or withdrawn from the soil. The exchanged heat Q_{exch} is calculated by the relation:

$$Q_{exch} = \varepsilon . \phi . \rho c_p \, . \, (T_{inlet} - T_{HR})$$

in which:

ε = efficiency of the heat exchanger

ϕ = volume flow of heat transfer medium (m3/s)

ρ = specific weight of heat transfer medium (kg/m3)

c_p = specific heat of transfer medium (J/kg K)

T_{inlet} = temperature heat transfer medium at the inlet of the heat exchanger (°C)

T_{HR} = temperature of the soil in the hot region (°C)

The exchanged heat is assumed to be proportionally distributed over the heat exchange region.

Remark: if this model is coupled with a simulation model of a solar house the exchanged heat is calculated every hour. During the day, however, the temperature in the reservoir and the surrounding soil is assumed to be constant. At the end of the day the temperature changes in the soil are calculated from the daily exchanged heat and the heat loss to the surrounding soil.

Input data is required concerning:

- properties of the soil: thermal conductivity, specific weight and specific heat

- dimensions of the reservoir: are determined by the number of houses, the heat storage capacity per house and the properties of the soil

- top insulation layer: thickness, thermal conductivity

- rate of the heat exchanger: proportional to the number of houses.

A.2.1.3. Limitations of the model

- The model is based on heat transfer in the soil by conduction only
- The exchanged heat is calculated without taking into account temperature stratification in the reservoir
- The rate of the heat exchanger (W/K) is assumed to be constant. In practice it is determined by heat penetration into the soil.

A.2.1.4. Flexibility of the model

The following heat storage reservoirs can be modelled:

- the reservoir in the soil with an insulation layer around the entire reservoir. To the heat resistance of the soil layer at the edge of the reservoir an extra resistance of the insulation layer is added
- a water reservoir (with or without insulation) in soil. In the heat exchange region the material properties of water are used

Remark: with a few changes a reservoir with a semi-sphere shape can be modelled.

A.2.1.5. Typical configuration handled

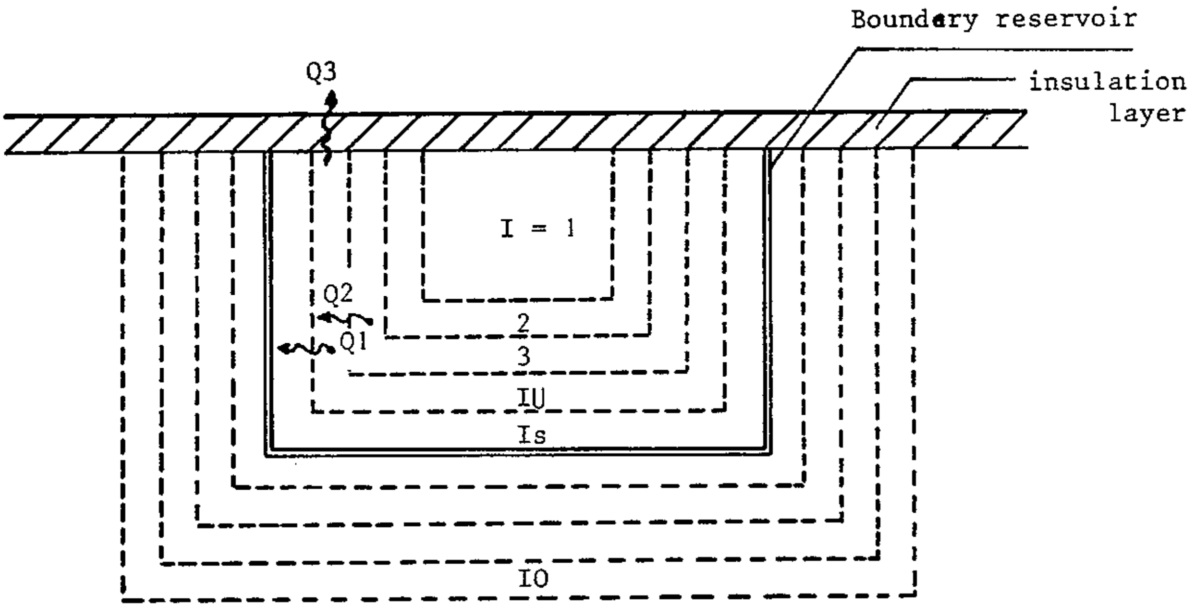


Figure 15: LT-TPD-I/Typical discretization scheme

I = number of the segments: $1 \leq I \leq IO$

Is = number of the last segment in the reservoir

IU = $1 \leq IU \leq Is$

Heat can be taken from segment 1 → IU due to the fact that temperature in segment IU (and inner segments) is higher than the return temperatures of the space heating system.

- The daily heat input is distributed over the whole reservoir ($1 \leq I \leq Is$) proportionally to the volumes of the segments
- The daily heat output is withdrawn over the segments $1 \leq I \leq IU$, again proportionally to the volumes of the segments
- The temperature changes in the reservoir by heat loss, heat input, heat output, are calculated from the heat balances over the several segments.

IO = total number of segments (typically 40 to 60)

A.2.1.6. Note by the lead country concerning the calculation of the local process

As outlined in the original text, in the heat exchange region the heat supplied to or withdrawn from the soil is calculated by the relation:

$$Q_{exch} = \varepsilon \cdot \emptyset \cdot \rho Cp \cdot (T_{inlet} - T_{HR}) \qquad (1)$$

The energy balance for the circulating fluid yields to:

$$Q_{exch} = \emptyset \cdot \rho Cp \cdot (T_{inlet} - T_{outlet}) \qquad (2)$$

Combining (1) and (2), one obtains for the "efficiency" of the heat exchanger:

$$\varepsilon = \frac{T_{inlet} - T_{outlet}}{T_{inlet} - T_{HR}} \qquad (3)$$

Considering the usual heat exchanger efficiency definition, one can define:

$$\varepsilon = 1 - \exp - \left(\frac{\alpha}{\emptyset . \rho cp}\right) \qquad (4)$$

where α is a heat transfer coefficient in W/m2k.

Combining (3) and (4), one obtains:

$$\underline{T_{outlet} = T_{inlet} (1 - \varepsilon) + \varepsilon T_{HR}} \qquad (5)$$

The heat transfer coefficient α is calculated using the so-called "TPD one pipe model"; it is assumed to be constant during the periods of simulation (injection or production).

A.2.2. LUND-DST (Duct Storage Model) (ref. B-4)

The DST model is a rather complete program, which can handle nearly all configurations of earth or rock storage. We refer to the original description of the code dealing with the global process (the ground outside the storage region) and the local process (duct storage model in this section).

Further details for the computation of the global process outside the storage region can be found in the previous description of LUND models (Appendix 1).

A.2.2.1. The ground outside the storage region

The heat transfer process in the ground is governed by the ordinary heat conduction equation. Convective heat transfer due to ground water migration is not considered.

The ground is divided into a number of cells with a mesh of rectangular type. Explicit forward differences are used in the computation of the temporal development of the temperature in each cell.

Three coordinate systems are used: plane (x,z), three-dimensional (x,y,z), and cylindrical (r,z). The geometrical shape of the heat transfer region may be of a rather general character. It is generated by an arbitrary set of rectangles (plane and cylindrical case) or parallelepipeds (three-dimensional case).

Each cell may be assigned an individual thermal conductivity and heat capacity. This means that the thermal properties of the ground may vary at will. It is also possible to insert thermal insulation layers anywhere between two cells.

At each boundary point the temperature or the heat flux is a prescribed function of time. So at the ground surface there may be a given air temperature and a certain surface resistance between air and ground. The boundary conditions in the ground far away from the storage pose no problem. Let L be the maximal linear dimension of the storage region below the ground surface. L could be the width, depth or the distance from the bottom of the storage region to the ground surface. Then it suffices to put the boundaries 5L away outwards and downwards. Normally, it is quite sufficient to have zero normal heat flux at these boundaries.

A representative cylindrical (or plane) mesh can use 25 x 25 points. The smallest cells close to the storage or the ground surface can have linear size 0.3 - 0.6 m. The timestep for the computation is from a few hours to one day. The computer time for a simulation of one year will require no more than a few seconds.

A.2.2.2. Duct Storage Model

A region of rock or soil is used for heat storage. Heat is injected and extracted via a duct system in which a heat carrier fluid is circulated. An example with vertical pipes or bore holes is shown below.

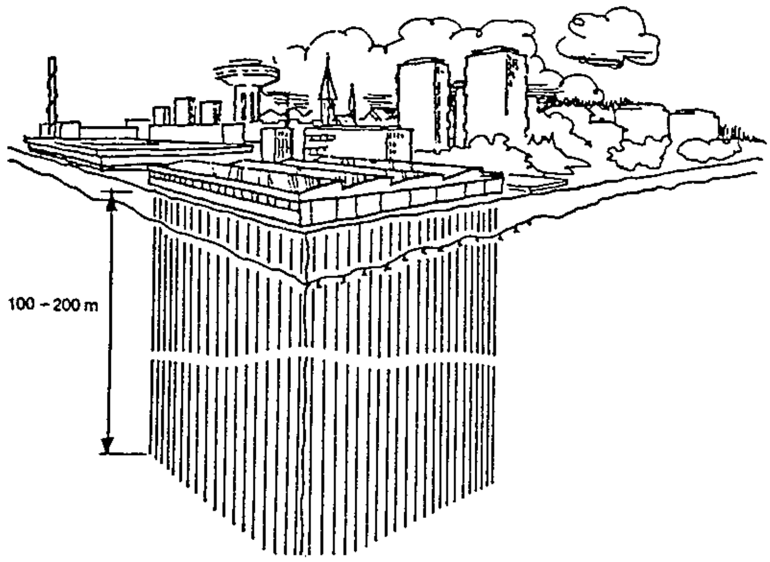


Figure 16: Duct system for ground heat storage

The thermal process outside the storage region with possible protecting insulations around and above the storage is dealt with as described above.

The thermal process in the storage region with its duct system, where the heat carrier fluid is circulated, is quite complex. There is a "global" temperature variation from the center of the store out to the boundaries and into the surrounding ground. Then there is an important and often violent heat transfer process around the ducts. Finally, there is a variation along the ducts, which is coupled to the heat exchange between fluid and ground. One also has to consider the flow pattern for the fluid through the storage.

All these processes shall be fitted together. The local processes are important in order to obtain the right heat exchange between fluid and ground. But the local process depends on the global temperature level. The global temperature on the other hand is strongly influenced by the local injection/extraction of heat at the ducts.

The temperature in the storage region is represented by three parts: a global temperature, local solutions, and a steady-flux part. The total temperature at a point is obtained by superposition of these three parts.

The global temperature is the solution of the heat conduction equation with a variable heat source/sink from the local solutions and the steady-flux solution. It shall also fit to the temperature outside the storage.

The storage region is divided into a number of sections. There is one local solution around a duct for each section. In the basic case the local solution is radial around a pipe. The heat carrier fluid flows through the sections consecutively. The variation of the fluid temperature within a section is obtained with the use of an analytical expression. There is a heat balance for the fluid from section to section.

The fluid that passes a section will feel a variable global temperature for the different mesh points of the section. A redistribution of heat within each section in accordance with this is made with the use of the steady-flux solution. In this part a particular analytical solution is used. The idea is the following: consider a situation of constant heat injection from the duct to the surrounding region. After a certain transient period there is a state of steady-flux. This means that the temperature at each point increases at a constant rate. The heat flux is constant in time at each point. There is a fixed temperature profile around the duct. This profile is just lifted at a constant rate. In this steady-flux regime there is a simple relation between the injection rate and the difference between fluid and ground mean temperature. The relation is obtained by solving analytically the local problem in the steady-flux regime. This result is used in the steady-flux redistribution of heat within each section.

The Duct Storage Model takes into account the variable temperature through the storage region and its interaction with the surrounding ground. The local process around the ducts at different points in the storage and the variation of the fluid temperature along the ducts are also considered. The ducts may be distributed at will through the storage region.

The pumping rate of the fluid is a prescribed function of time. The inlet fluid temperature is also a given function of time. Alternatively the rate of heat injection or extraction can be prescribed. The inlet temperature is then chosen accordingly.

The basic computer code concerns a cylindrical storage region. A representative case can use 30 x 30 points to represent the global temperature in the storage and the temperature in the surrounding ground. The storage can be divided into, say, 2 - 10 sections. For each section there is a local, one-dimensional, radial solution around the heat (pipe case). The local problems can use, say, 10 cells. The smallest cell near the pipe can have the size 0.05 m. The timestep of the global and steady-flux parts are around a few hours, while the local problems can have a timestep of a few minutes. The computer time for a simulation of a year is then less than one minute.

A.2.3. TUBE (ref. B-8)

A.2.3.1. General information

The Tube program is a simple one, which can treat vertical pipes in earth or rock (conductive processes).

The typical configuration the Tube program can handle is represented in the following figure:

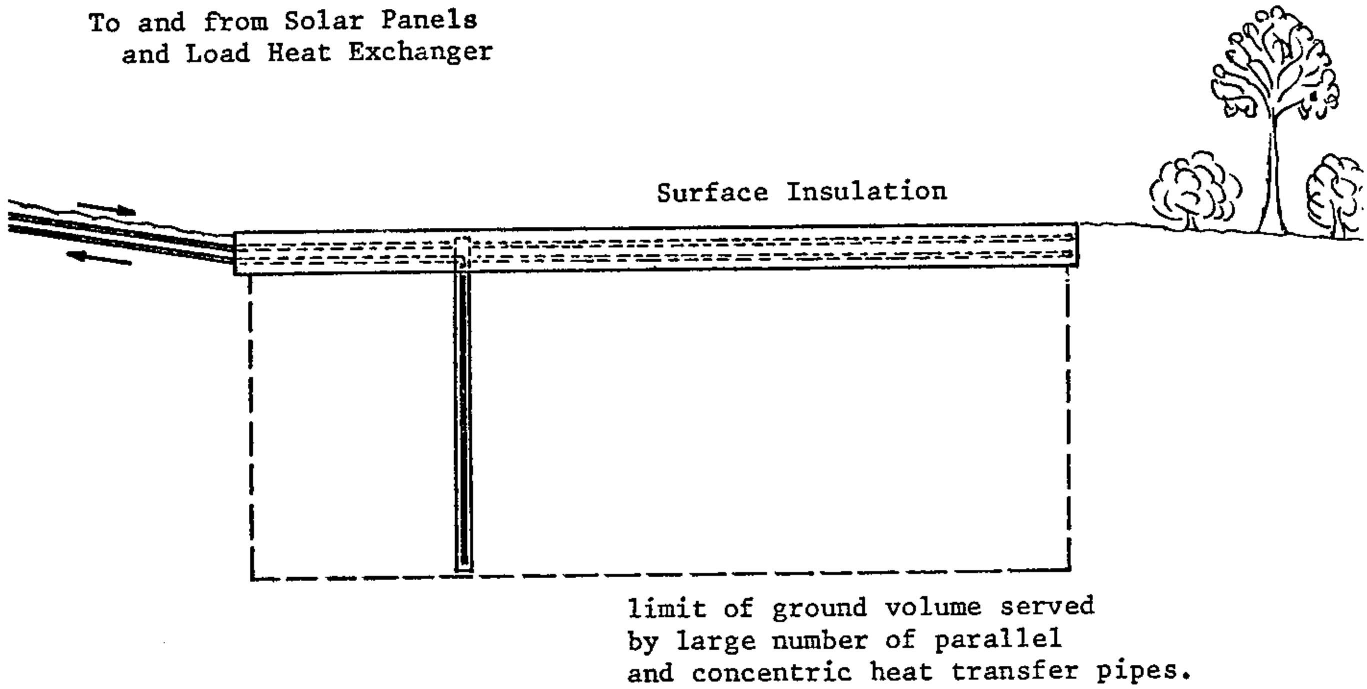


Figure 17: TUBE/Typical storage representation

The model has not yet been validated.

A.2.3.2. Basic assumption of the model

- Heat transfer takes place by conduction only
- The behavior of the whole storage is supposed to be equivalent to the behavior of one "earth tube unit" including one pipe and its range of influence (delimitated by the geometrical configuration of the tubes) with a scale factor equal to the number of tubes
- No heat capacity effects are considered outside the heat exchanger region!
- No global gradients are considered in the storage (scale factor assumption)

A.2.3.3. Description of the model

The model uses explicit finite differences with a 5 x 5 points mesh to represent a vertical tube and the surrounding soil in axisymmetry.

Local and global processes are treated simultaneously: as one boundary of the mesh represents the tube wall, a heat transfer coefficient between circulating fluid and tube wall is considered. The original version gives an expression valid only for laminar flow.

Heat losses are referenced to the outside air temperature:

- convection losses occur on top of the store through the insulation (modified version, reference B-9)
- conduction losses are calculated from a point source (T(5,5)) to ambient temperature through a hemisphere of radius, the equivalent radius of the total store. This procedure is difficult to justify, as it neglects heat capacity effects outside the heat exchanger region. Moreover, the substraction of these heat losses is uniformly distributed over the store, thus giving an irrealistic prediction of the temperature distribution within each ground-tube unit
- hourly variation of air temperature is accounted for
- the typical timestep for both local and global processes is one hour or more

A.2.4. ADES-STORE (ref. B-10)

A.2.4.1. General information

The store model is a simplified model which can handle vertical pipes configuration.

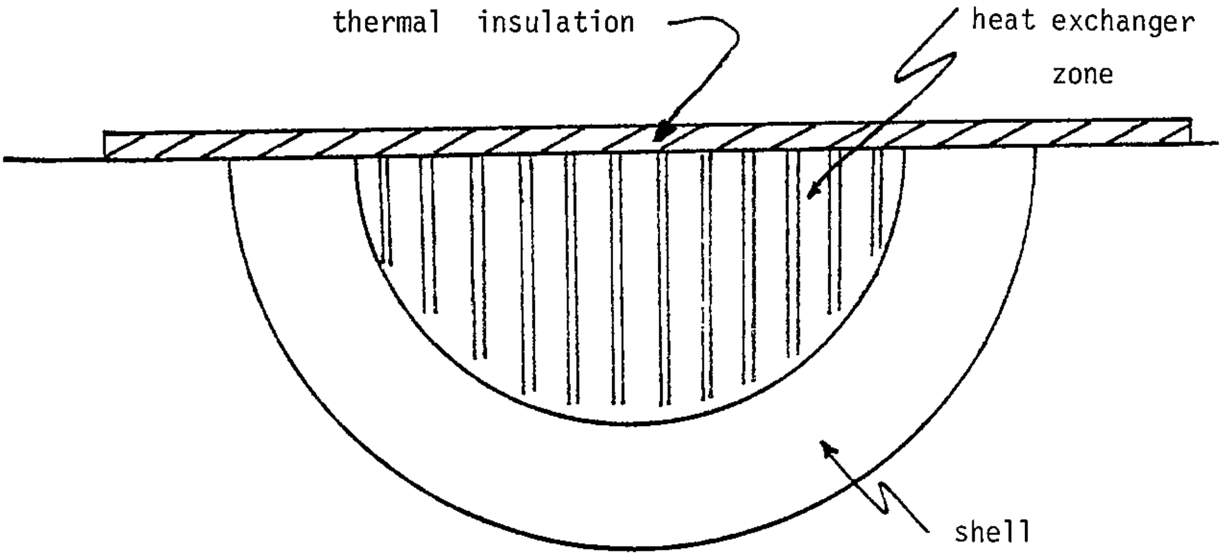


Figure 18: ADES-STORE/Typical storage representation

A.2.4.2. Basic assumptions of the model

- in the original version, an upper adiabatic boundary condition (no heat losses to air) was assumed. A modified version was developed in order to account for heat losses (ref. B-11)

- the boundary condition for surrounding ground consists of a fixed temperature on a hemispherical shell (see Figure 18)

- side extension of insulation cannot be considered

- the storage volume is divided into three concentric classes of equal temperature, in which one pipe is considered

- a control system addresses the water flow towards the class having a contact soil-tube temperature, the nearest to the water temperature.

A.2.4.3. Description of the model

- for each class, the temperature distribution in the soil is calculated using Fourier's law of conduction in an infinite cylindrical geometry with a finite difference model

- this local heat transfer process is considered to occur in an horizontal plane: the first node is the tube wall and the last one is the medium point between tubes

- the global losses are calculated using a mean storage temperature and the far surrounding ground with a finite difference discretization: the points represent hemispherical shells. These losses are then redistributed over the storage zone nodes, proportionally to their volume of influence. This procedure does not give a realistic prediction of the local temperature field, nor considers the influence of the air temperature variations for the surrounding soil

- the heat exchanged between water and soil is calculated without using a heat transfer coefficient between water and tube wall, and assuming that all tubes of one class are at the same temperature

- the usual timestep is one day for both local and global processes

- in order to assure the stability of the algorithm, the typical mesh size for a daily timestep should be greater than half a meter for usual soils.

A.2.5. GROCS (ref. B-12)

A.2.5.1. General information

A buried pipe model can be used with GROCS in order to simulate the local process.

This model deals with horizontal coils in the ground without any insulation, but some modifications can be done to account for vertical pipes and insulation layers.

The GROCS model is already incorporated in TRNSYS. As the global process has already been explained in the chapter devoted to the water tank models, we shall only treat here the local process by reproducing parts of the GROCS user's manual.

A.2.5.2. Buried pipe model

The simulation of a serpentine array of buried pipe presents problems not encountered with the buried tank. Most of these problems are related to the fact that the typical pipe diameter is small enough to require very small block sizes, and therefore timesteps much shorter than the 15-min. typical for TRNSYS runs. Straightforward modelling of the pipe along the same lines as the tank would require inordinate amounts of computer time. For this reason it was decided to model the pipe field as a thin sheet of water flowing in the plane of the pipe field.

The heat flow from a sheet will not in general be the same as that from a set of pipes. The sheet assumption, as described so far, does not take into account the radius of the pipes or the distance between them. However, it is possible to take these factors approximately into account. at least for quasi-steady-state heat flow, by reducing the effective heat transfer area between the plane sheet of water and the adjacent blocks of earth, making it less than the geometrical surface area. The determination of the correct factor by which the heat transfer area must be reduced is discussed below.

Because the amount of water resident in a pipe field is generally one to two orders of magnitude less than that in a buried tank, it is not feasible to defer the accounting of temperature changes within the pipes to the end of the timestep. Instead, the heat flow from the water to the ground is calculated on the basis of the inlet water temperature and the temperatures of the earth blocks adjacent to the pipe field. The change in water temperature along the flow path, as it transfers heat to the soil, is accounted for to first order. As with the buried tank model, calculation of heat transfer between blocks of earth by GROCS is deferred to the end of the timestep.

A.2.5.3. Approach

The major approximation made in the TYPE32 buried pipe model is the substitution of a flowing plane sheet of fluid for the buried pipe field (Figure 19). This approximation was introduced above. The method for correcting the model to take into account the pipe radius and spacing is considered in more detail below. The incorporation of the flowing sheet approximation into the model is now discussed.

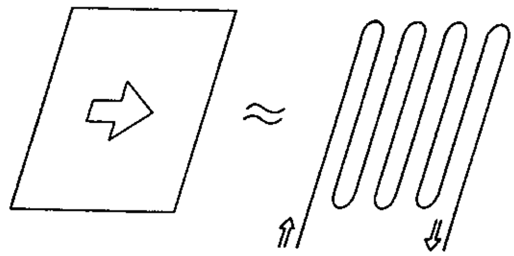


Figure 19: GROCS/Flowing sheet approximation to pipe field

A.2.5.4. Flowing sheet approximation

A cross section of the geometry of this approximation is shown in Figure 20. For simplicity, only two adjacent blocks of earth are shown, although the model will also accomodate multiple pairs of adjacent blocks. The adjacent blocks must be set up in pairs, one on each side of the flowing sheet, and both members of a pair must have the same length Y_E in the direction of flow. Different pairs may have different lengths, as long as both members of each pair are directly opposite one another and have the same length.

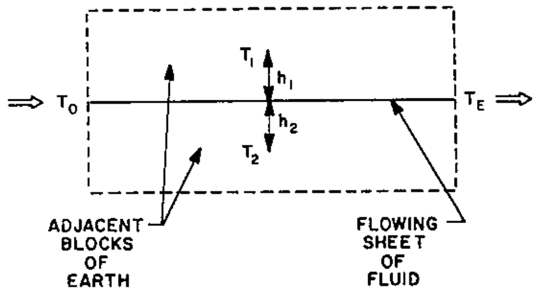


Figure 20: GROCS/Geometry of flowing sheet approximation

Knowing the temperature T_0 at the beginning of the flow and the mass flow rate M (which are INPUTS to TYPE32), the distances h_1 and h_2 and the heat transfer area A (which are PARAMETERS), and the block temperatures T_1 and T_2 (which are obtained from GROCS), one can calculate the pipe fluid temperature T_E after the fluid has passed by the pair of earth blocks, and the rates of heat flow into (or from) the adjacent blocks. A first-order assumption is made...

If a second pair of adjacent blocks is used, then the value of T_E obtained from the first calculation is used as the initial temperature T_0 for the second. The final temperature T_E from the last pair of blocks is the oulet temperature from the pipe field as a whole.

A.2.5.5. Correction for the difference between a flowing and an array of pipes

The approach to making this correction is to consider the thermal resistance of a half-block of earth with a constant temperature boundary on one side and a planar array of pipes on the other. This resistance is compared with that for the same half-block of earth with the same constant temperature boundary, but now with the sheet of fluid on the other side in place of the pipe array. In general, the resistance in the case of the plane sheet is the lesser of the two. To correct for the difference, the heat transfer area from the sheet to the adjacent block is reduced by a factor equal to the ratio of these resistances, so that the resistance for the flowing sheet case, with the reduced heat transfer area, is the same as for the actual pipe array.

A.2.6. SPIPE (ref. B-13)

A.2.6.1. General information

SPIPE is a complete model which can handle earth storage system with horizontal layers of buried pipes.

It is a specific finite element model which has been validated against the experimental results of the Marly earth storage (ref. B-16).

A.2.6.2. Basic assumptions

- the local and global processes are treated simultaneously with the same timesteps in the original version, using a topological transformation
- heat transfer takes place by conduction
- the behavior of the store is supposed to be symmetrical

A.2.6.3. Description of the model

- the model is based on an implicit finite element discretization: a rough mesh is used for the global process and a refined mesh for the local process
- the meshes are generated automatically in order to reduce the input data
- all pipes are supposed to be identical with the same flow conditions
- insulation can be put everywhere
- inside pipes two boundary conditions can be considered: either a heat flux condition or an inlet temperature condition with a heat resistance coefficient which has to be calculated separately
- the model has been developed in order to investigate the interaction of the local and global processes on the same timestep basis. Thus, it could be possible to say in which cases these two influences can be treated separately

- the run time is quite important: the authors indicate that for a daily timestep, the computing time is the same as for the TRNSYS program for a yearly simulation of a normal solar installation, with an hourly timestep, on a CDC 7600

- the model requires 70.000 B words on a CDC 7600

- the timestep is optional: in order to reduce computational costs, a daily timestep should be chosen and one could use heat flux condition on pipes by computing the daily injected or extracted energy using the pipe temperatures of the previous day

- the model does not take into account variations of fluid temperature along the path.

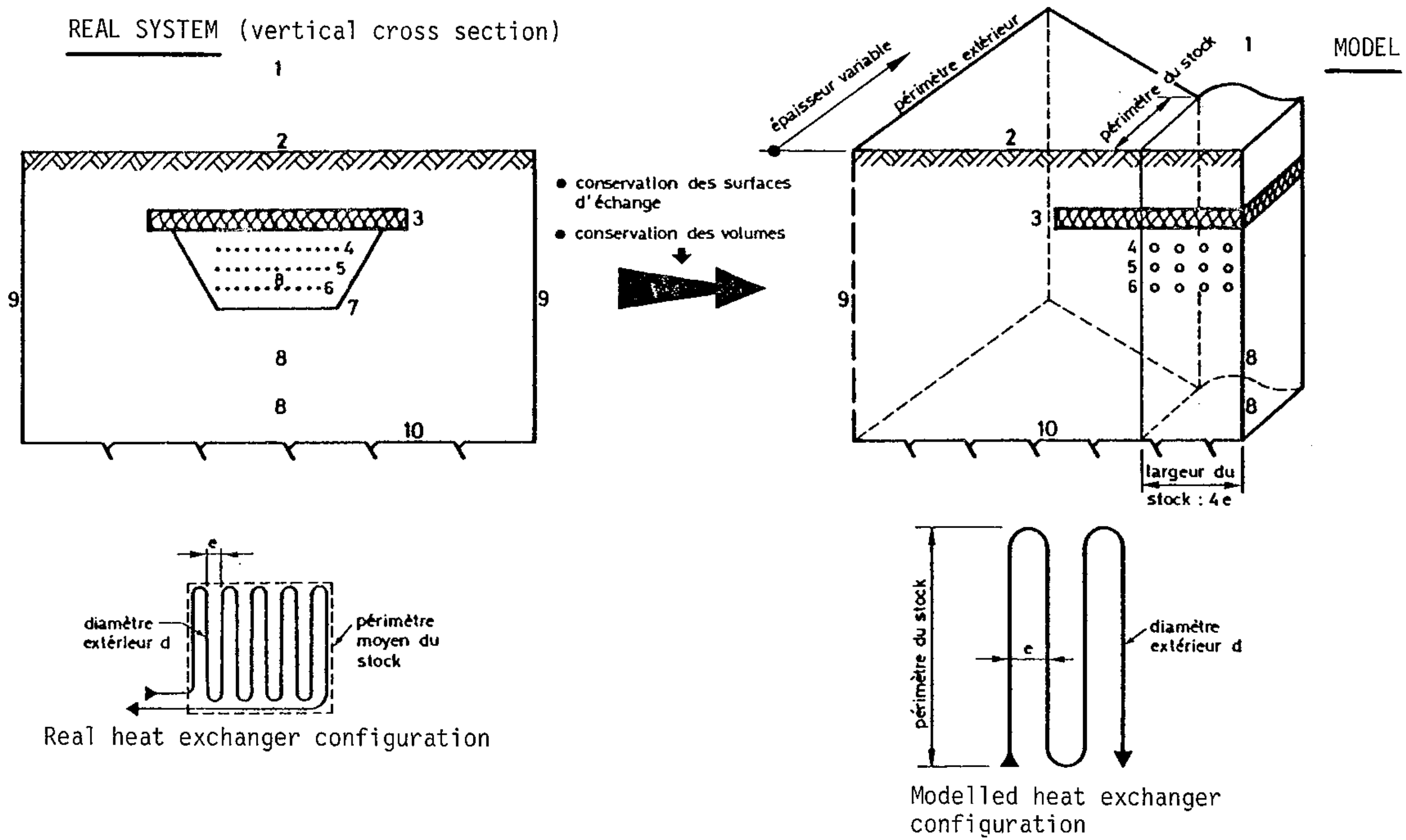


Figure 21: SPIPE/Typical configuration handled and topological transform

A.2.7. MODELS VALIDATION

As mentioned in Section 4.3., only one model out of the six identified has been validated.

The SPIPE model has been verified on the Marly earth storage experiment described in detail in reference B-16. But the validation must be qualified of partial, because the real injected energy in the store has been considered as boundary condition for the pipes: hence, the very local process has not been validated yet.

As we have implemented the LT-TPD model on our computer, it was possible for us to check the model with the Marly input data.

This short section is devoted to this "validation".

A.2.7.1. LT-TPD-I/Original version

As we only have daily temperature measures for a two-year period of experiment in Marly, a simulation of the local process is not possible. So we have only been able to study whether or not the LT-TPD-I could reproduce the global process.

For the simulation we have used a daily timestep with the following data and parameters:

- the injected energy is given by the measures every day
- the thermal properties of the soil and the insulation are taken from the simulations of the Marly storage by the SPIPE model.

Figure 22 represents the comparisonbetween LT-TPD-I and measures, where:

- T1, T3, T4, are the measured temperatures at the top, in the middle, and at the bottom of the heat exchanger region
- the two black full lines represent the calculated temperatures of the first segment (the warmer), and the last segment (the colder, which is the 8th in our case), in the heat exchanger region.

It is obvious that the original LT-TPD-I model underestimates the heat losses of the storage system.

This can be due to two main effects:

- the provided version does not take into account air temperature variations

- the original model assumes a top insulation over the whole domain, and the earth cover is equal to the dimension of segments

Therefore we have modified the model to account for these two effects (in Marly there is a side extension of the insulation of 3 m).

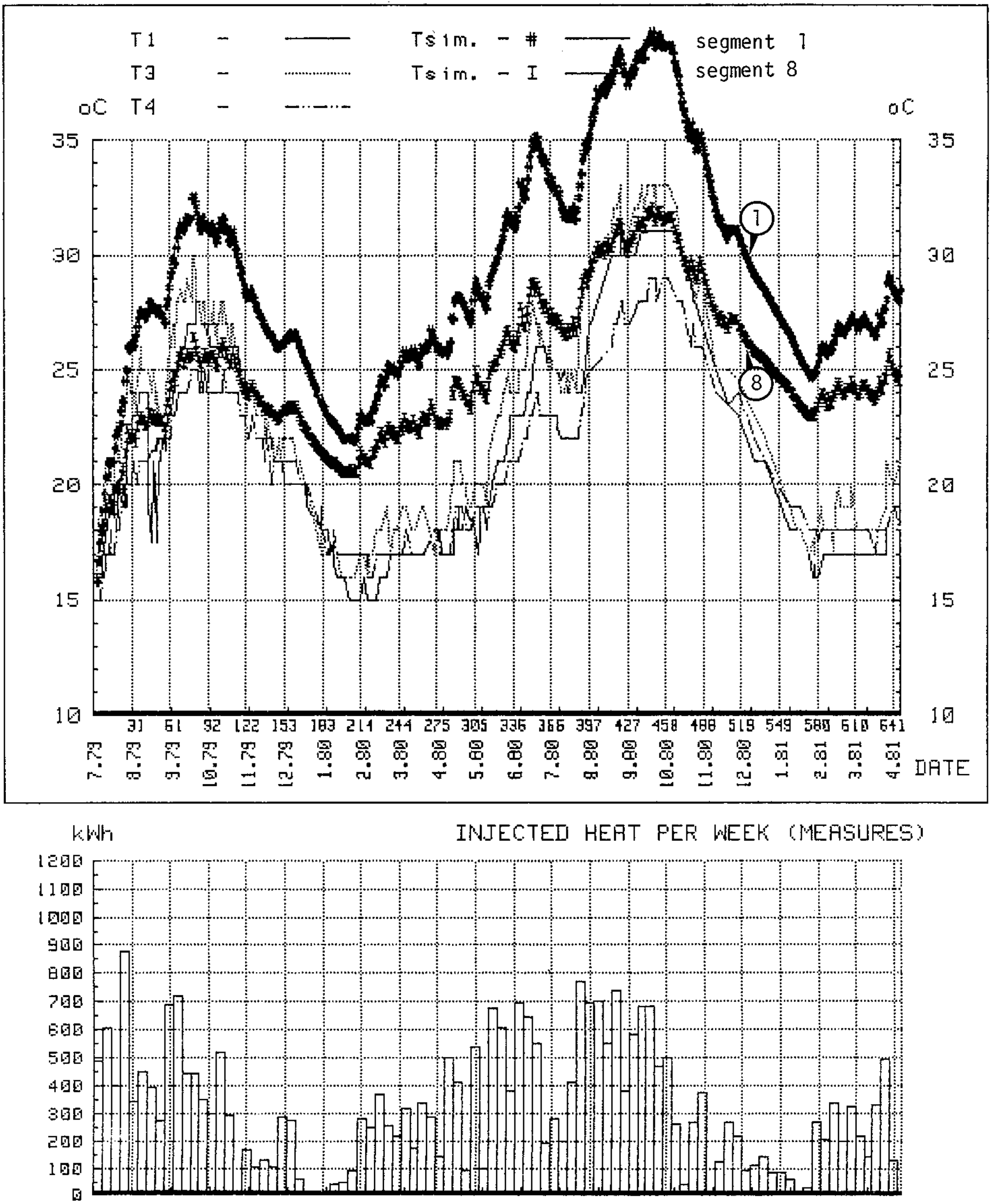


Figure 22 : Comparison of the LT-TPD-I original version with Marly experimental results

A.2.7.2. LT-TPD-I/Modified version

Figure 23 shows the situation when accounting for air temperature variations (measured in Marly) and Figure 24 for air temperature variations and limited insulation.

One can see that in this last case, the model compares well with the measurements (it must be precised here that during the first two months of experiment irrigation water has been injected into the store. This explains the more important differences between measures and calculations for the first seven months).

Thus, this modified version of LT-TPD-I can be considered as "tested" (without calibration, because we have used thermal properties with SPIPE), at least for the global process simulation.

Moreover, it will be possible, within some limits, to "validate" indirectly the models which have run the common test case.

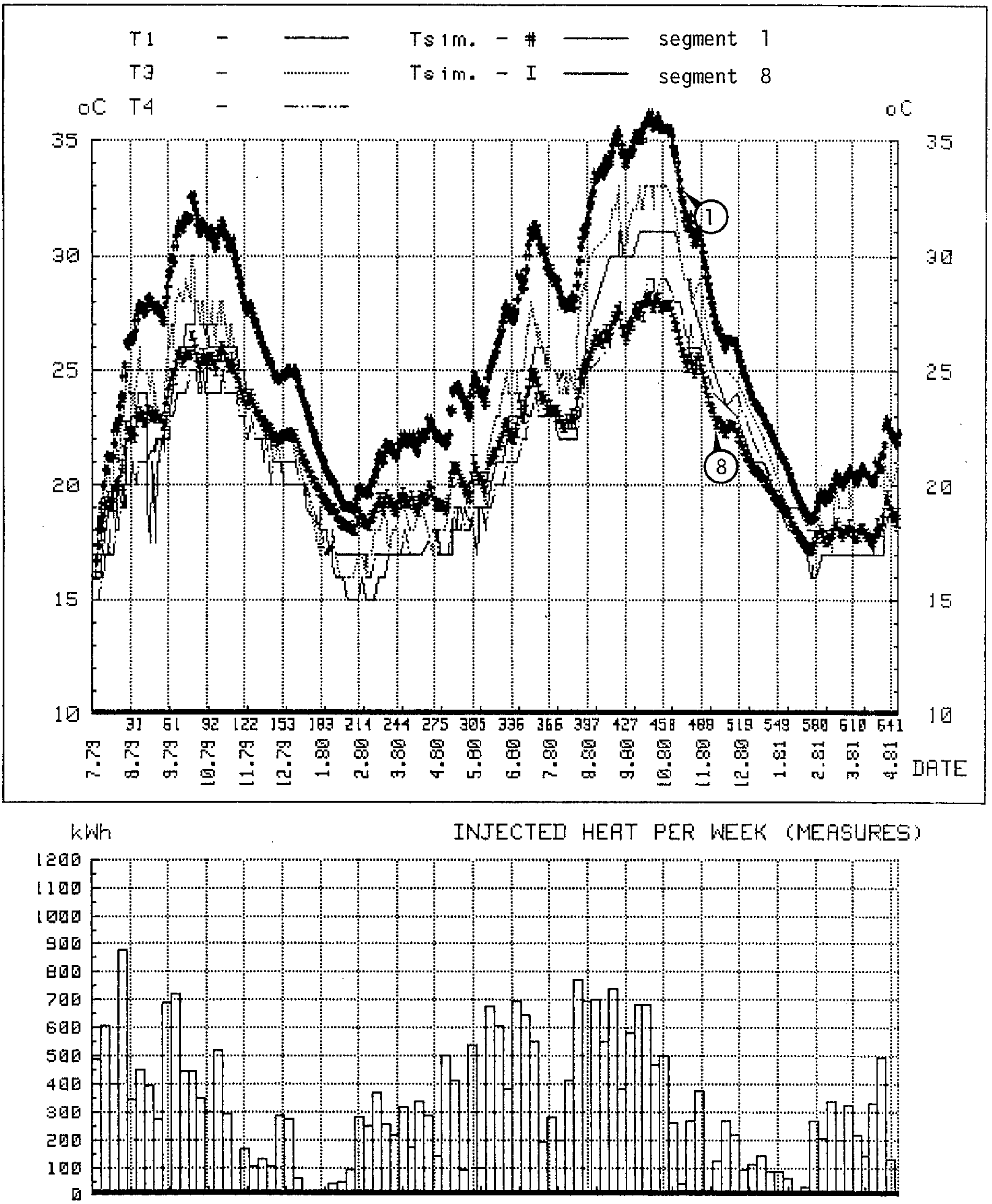


Figure 23 : Comparison of the LT-TPD-I modified version (air temperature variations) with Marly experimental results

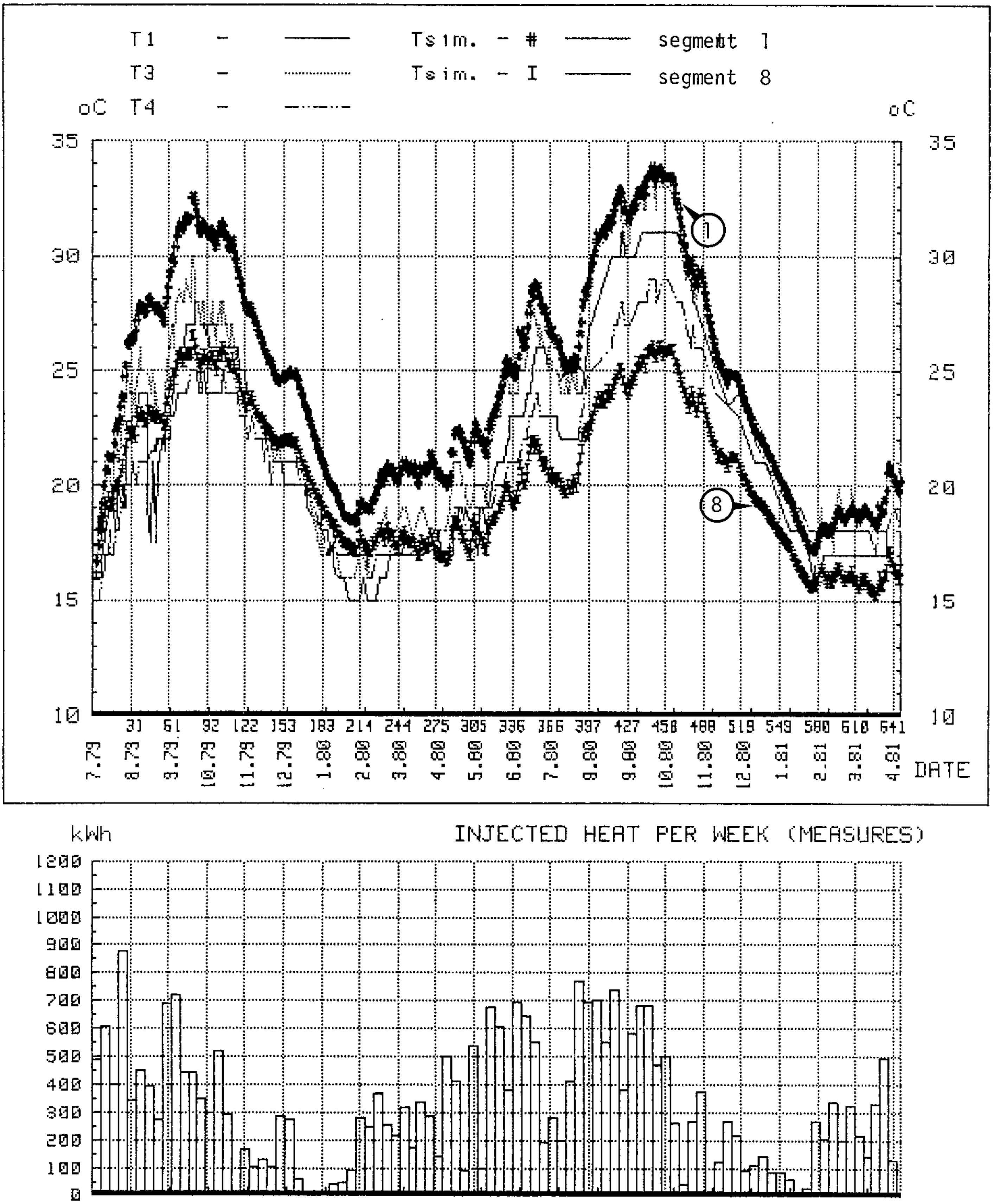


Figure 24 : Comparison of the LT-TPD-I modified version (air temperature variations and limited insulation) with Marly experimental results

Appendix 3: MODELS FOR AQUIFER STORAGE SYSTEMS - DESCRIPTION OF AVAILABLE MODELS

A.3.1. PT (CCC) (ref. C-1)

The numerical model CCC (Conduction - Convection - Consolidation) is a complete code which solves numerically the heat and mass flow equations in three dimensions for a liquid saturated medium and the one D consolidation equation of the simulated systems.

The model uses the integrated finite difference method.

The temperature and pressure non-linearities are accounted for (buoyancy effects...).

The time iterations for energy calculations are performed with a larger timestep than for flow calculations.

CCC is a 3-D model which can handle all the configurations of aquifer storage such as single well systems, doublet systems, several wells systems, vertical piston systems.

The model has a large capability and is one of the more complete that can be found in the field.

A.3.2. SHAFT 79 (ref. C-3)

SHAFT 79 (Simultaneous Heat and Fluid Transport) is also a complete model with a capability comparable to the one of CCC code.

As it has originally been destinated to the study of geothermal reservoir, vapor phase is accounted for.

It does not take into account the variations of density with temperature.

The numerical procedure is also based on integrated finite difference formulation.

A.3.3. CFEST (ref. C-7)

CFEST (Coupled Fluid, Energy, and Solute Transport) is a finite element complete model, which has quite the same capabilities as the first two models. As an example of such big models, we reproduce a short description of CFEST capabilities in the following lines.

Coupled Fluid, Energy, and Solute Transport (CFEST):
Finite element multidimensional code

The code solves partial differential equations describing: single phase fluid flow, energy transport by conduction, dispersion and convection, and solute transport by dispersion, diffusion and convection. Vertical heat loss/gain to confining rock strata is also simulated.

Capabilities:

Multidimensional (planner, radial or three-dimensional) simulation to suit varied field situations

Staged execution to verify nodal and element geometry and fluid low prior to simulation of transport

Simulation combinations of fluid, fluid and energy, fluid and solute, or all three (fluid, energy and solute) dependent variables

Interactive input preparation of input data files

Automatic grid generation for STES applications

Interactive plotting for verification of input, visualization of results, and monitoring of simulations.

Assumptions:

1. Darcian flow (steady or transient)

2. Fluid density and viscosity are functions of temperature and solute concentration

3. Hydrodynamic dispersion is a function of fluid velocity

4. The porous medium and fluid are compressible

5. The fluid and porous media are in thermal equilibrium

6. Rock density and heat capacity remain constant

7. Permeability and coordinate axes are collinear

8. Injection fluid is miscible with the aquifer resident fluid

9. Aquifer properties (porosity, permeability, thickness and elevation) vary spatially

10. Vertical conduction within impermeable layers

11. Continuity of temperature between adjacent geologic strata

Input data:

Properties of aquifer fluid: compressibility, thermal expansion, heat capacity, reference density and absolute viscosity of fluid

Hydrogeologic properties: permeability, porosity, compressibility or specific storage, dispersivity length, thermal conductivity, heat capacity

Thermal properties of confining rock: thickness, vertical heat conductance, heat capacity, held temperature at outer edge and initial vertical temperature distribution

Regional groundwater: geologic stratigraphy, discontinuities, fault zones, groundwater gradients, surface waterbodies and recharge/withdrawal

Initial conditions: initial hydraulic head, temperature, and solute concentration distribution

Boundary conditions: Dirichlet, Neumann, and/or mixed boundary conditions according regional hydrological data and proposed injection/withdrawal

Output:

Contour plots of horizontal and vertical cross sections for all dependent variables

Production well temperature

Plots of hydrogeologic detail

Note: As these three models are rather big and complex, they cannot be considered without any interface in our task. But they could be used as check tools since they are really complete.

A.3.4. LUND-AST (Aquifer Storage Model) (ref. C-5)

This model is a simplified one which can be considered as a simple tool.

The Aquifer Storage Model focuses on the thermal process in the aquifer and surrounding impermeable layers. The ground water flow is not computed; it is given as radial flow, dipole flow and so on.

The basic case concerns a single well in aquifer stratum of constant thickness. The water flow is radially outwards during injection and radially inwards during extraction. The second well should not lie too close so that the radial flow pattern is disturbed in the thermally active region.

Buoyancy flow is neglected. This requires that the permeability of the aquifer is low.

The rate of injection/extraction of water is any prescribed function of time. the temperatures of the water during injection are also arbitrary.

The thermal process in the impermeable strata above and below are dealt with as described above.

The aquifer is in the basic case homogeneous. The thermal conductivity may be different in the horizontal water flow direction and in the vertical direction. By chosing high values of the conductivities the effect of so-called macrodispersion may be approximately simulated.

A representative mesh may contain 20 x 20 cells. The smallest cell can be 1 x 1 m2. In the aquifer there can be 10 cell layers in the vertical direction and 20 layers radially outwards. The radial mesh is variable with smaller cells in the important thermal front region. The mesh size increases outwards until undisturbed conditions are obtained. A simulation of an annual cycle requires around 1 minute computer time and often less.

A particular problem for the simulation of the thermal process in the aquifer is the so-called "numerical dispersion". This effect is due to the convective heat transfer, when the water flows from cell to cell. The result is an erroneous extra spreading of the thermal front region. The effect is that of too high a value of the thermal conductivity. A new technique is used in the numerical model in order to avoid this problem. The idea here will be only indicated.

When water flows from a cell to the next one downstreams, there is a mixing between the old temperature in the cell and the temperature that the water carries. This mixing corresponds to an entropy production. But the real entropy production is only due to diffusion and not to convective heat transfer. A method that does not contain this erroneous numerical dispersion must in some way suppress the heat mixing due to the convective process. This is done in the following way: the cell is divided into two parts in the water flow direction through the cell. The two parts are ascribed independent temperatures. So each cell is characterized by three quantitites; two temperatures and a temperature front position. The mean temperature in the cell is used for the diffusive process as before. The convective heat transfer is more complicated. The new values after a timestep of convective heat transfer for the three quantitites are determined by three relations. There is an energy blance as before. Secondly, the new values are chosen so that the entropy does not change. The third relation is given by a requirement on the convective heat flux during the following timestep.

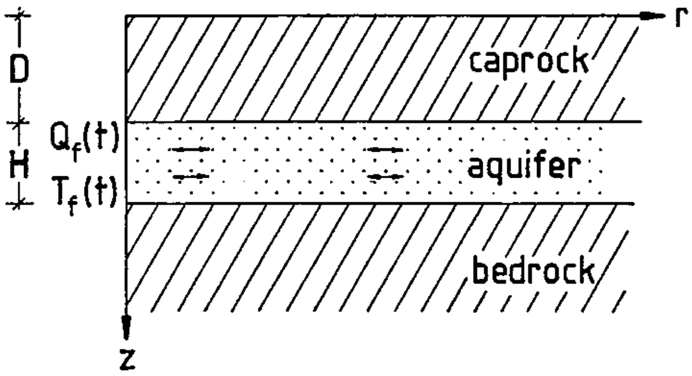


Figure 25: AST/Heat storage around a well that lies along the z-axis

The basic assumption of the model is that the ground water flow is essentially radial in the thermally active region around the well. There are three conditions that must be fulfilled:

1. Negligible natural ground water flow

2. Negligible disturbance from the second well

3. Negligible buoyancy flow

A.3.5. GRAPHICAL METHOD: LBL CHART (ref. C-8)

As an alternative to the use of big computer models, the Lawrence Berkeley Laboratory has developed a graphical method based on detailed computer simulations for a variety of parameters describing standard aquifer configurations (single or double well systems).

The original description of the method is given in the following lines (from Reference C-8).

The purpose of our graphical characterization schemes is to develop some general parameters or procedures whereby the energy recovery factor may be predicted readily for a given problem without doing a detailed numerical simulation. Two graphical characterization schemes have been developed, the first neglecting buoyancy flow, the second including it.

The first scheme is based on the SFM assumptions[1/]. With these assumptions, the thermal behavior of the system can be described in terms of the following four dimensionless parameter groups.

$$Pe = \frac{C_a R^2}{2\lambda_a t_i} \qquad \Lambda = \frac{C_a^2 H^2}{C_c \lambda_c t_i} \qquad Bi = \frac{\lambda_c C_c}{\lambda_a C_a} \qquad \frac{C_a}{C_c}$$

where $R = \sqrt{C_w/Qt_i/C_a \pi H}$ is called the thermal radius, Q is the flow rate; H is the aquifer thickness; λ_a and λ_c are the aquifer and confining layer thermal conductivities; C_w, C_a, and C_c are the water, aquifer, and confining layer volumetric heat capacities, and t_i is the injection time period.

The SFM has been used to calculate recovery factors and temperatures as a function of these parameters. The ratio C_a/C_c is nearly constant for ATES applications, so we concentrate on λ_a/λ_c, rather than Bi. Some of the results are shown in Figures 26 and 27.

Figure 26 shows the calculated energy recovery factor as a function of Pe and Λ numbers for the first cycle. Results for subsequent cycles have also been calculated. Note that the large initial increase in recovery factor is followed by a more gradual increase as Pe and Λ are increased.

Figure 27 displays the temperature of water extracted during the production period of the first and fifth cycles for different values of Pe and Λ . For values of Pe larger than 200, the production temperature shows little dependence on Pe.

[1/] SFM is similar to AST (A.3.4.)

Other factors ave also been considered through the introduction of several additionl parameters. Thermal dispersion has been modelled by creating an effective aquifer thermal conductivity, $\tilde{\lambda}_a$, which adds a dispersion term to the usual aquifer thermal conductivity. This additional term may be constant, proportional to fluid velocity, or proportional to fluid velocity squared. Unequal length periods within a cycle are dealt with by introducing a parameter, τ, defined as the average time a fluid particle spends in the aquifer.

Both $\tilde{\lambda}_a$ and τ can be incorporated into the basic four parameter groups. A finite thickness caprock, overlain by a constant temperature boundary representing the ground surface or another aquifer, can be included in the analysis by introducing a parameter d, the ratio of the caprock thickness to the aquifer thickness. Figure 28 shows the effect of the caprock thickness on the recovery factor as a function of Λ for a range of values of d. This variation is independent of Pe.

To investigate the effect of thermal front tilting caused by buoyancy flow, a second scheme has been developed. Calculations have been conducted over a wide range of aquifer permeabilities and injection temperatures using the numerical model PT (CCC) which takes into account temperature-dependent parameters and the buoyancy flow process. In each case, an energy balance was kept for various times, separating radial diffusive losses in the aquifer and the vertical losses to the confining layers. A study of these results shows that over a wide range of conditions, the radial and vertical heat losses can be decoupled. Thus the energy recovery factor ε may be expressed as the product of two factors, $\varepsilon = (1 - \Delta E_a)(1 - \Delta E_c)$ where ΔE_a is the normalized energy lost radially when the aquifer is insulated from the confining layers above and below, and ΔE_c is the normalized energy loss due to vertical conduction into the upper and lower confining layers.

The decoupling of radial and vertical heat losses reduces the number of parameter groups required to describe the system to three: Pe, Λ, and Bi. However, the thermal front tilting influences both the radial and vertical losses, since the tilting modifies the area over which heat conduction occurs. An empirical shape factor based on the thermal front angle of tilt, α, is introduced to modify the parameter groups. Thus ΔE_a depends on the modified Pe number, Pe*, while ΔE_c depends on Λ^* and Bi*.

ΔE_c as a function of Λ^* and Bi* is calculated from a one-dimensional heat conduction problem in which heat diffuses from aquifer to aquitard. The effect of a constant temperature boundary overlying a finite-thickness caprock is also included. Using values of Pe*, Λ^*, and Bi* obtained from field input data, ΔE_c and ΔE_a may be determined and combined to form ε. Although not mathematically rigorous, the method has been shown to yield accurate predictions for a wide range of conditions when compared with CCC-simulated results.

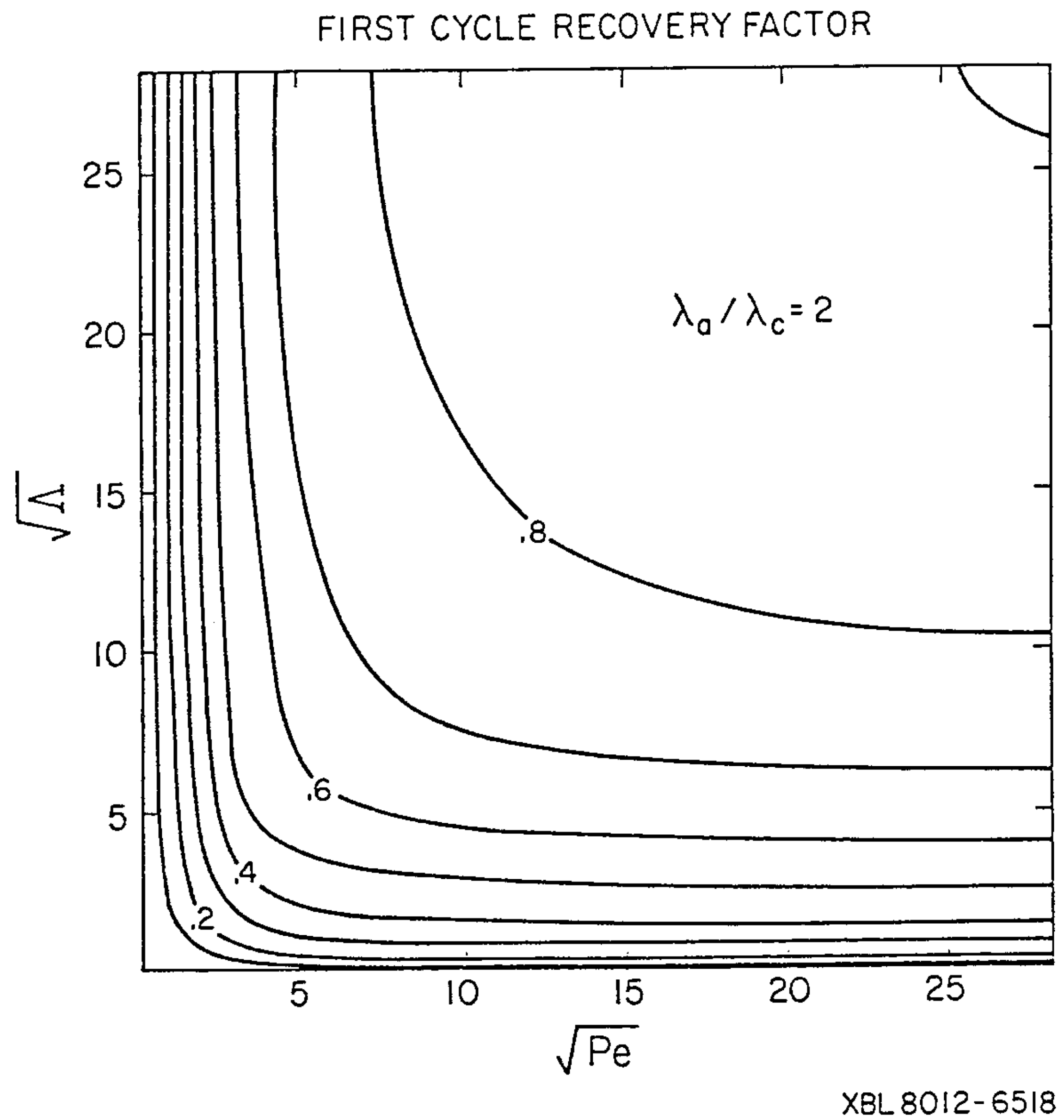


Figure 26:
LBL/ Nonbuoyant characterization scheme - recovery factor as a function of $\sqrt{Pe}$ and $\sqrt{\Lambda}$ for the first cycle, when $\lambda_a/\lambda_c = 2$.

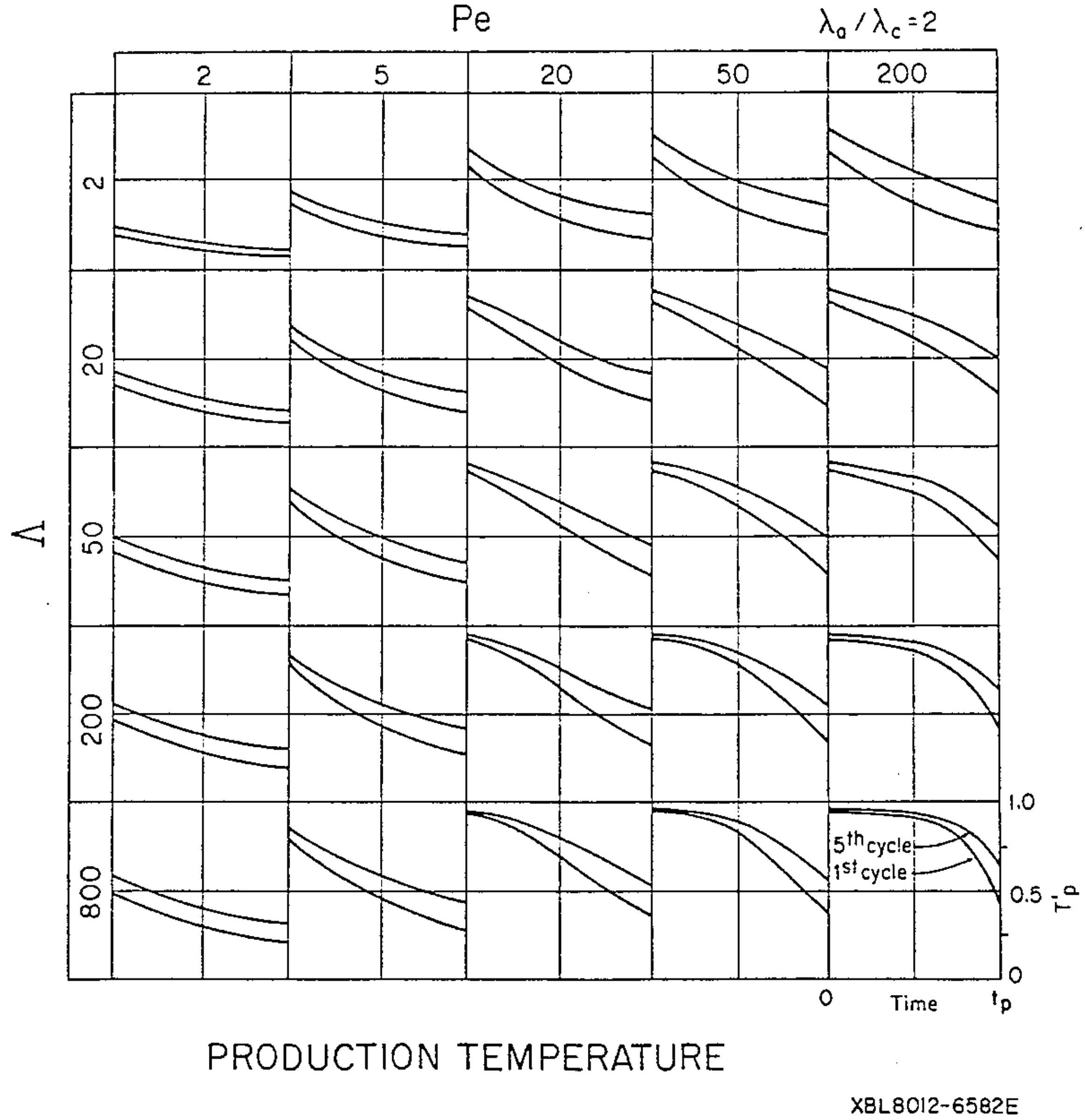
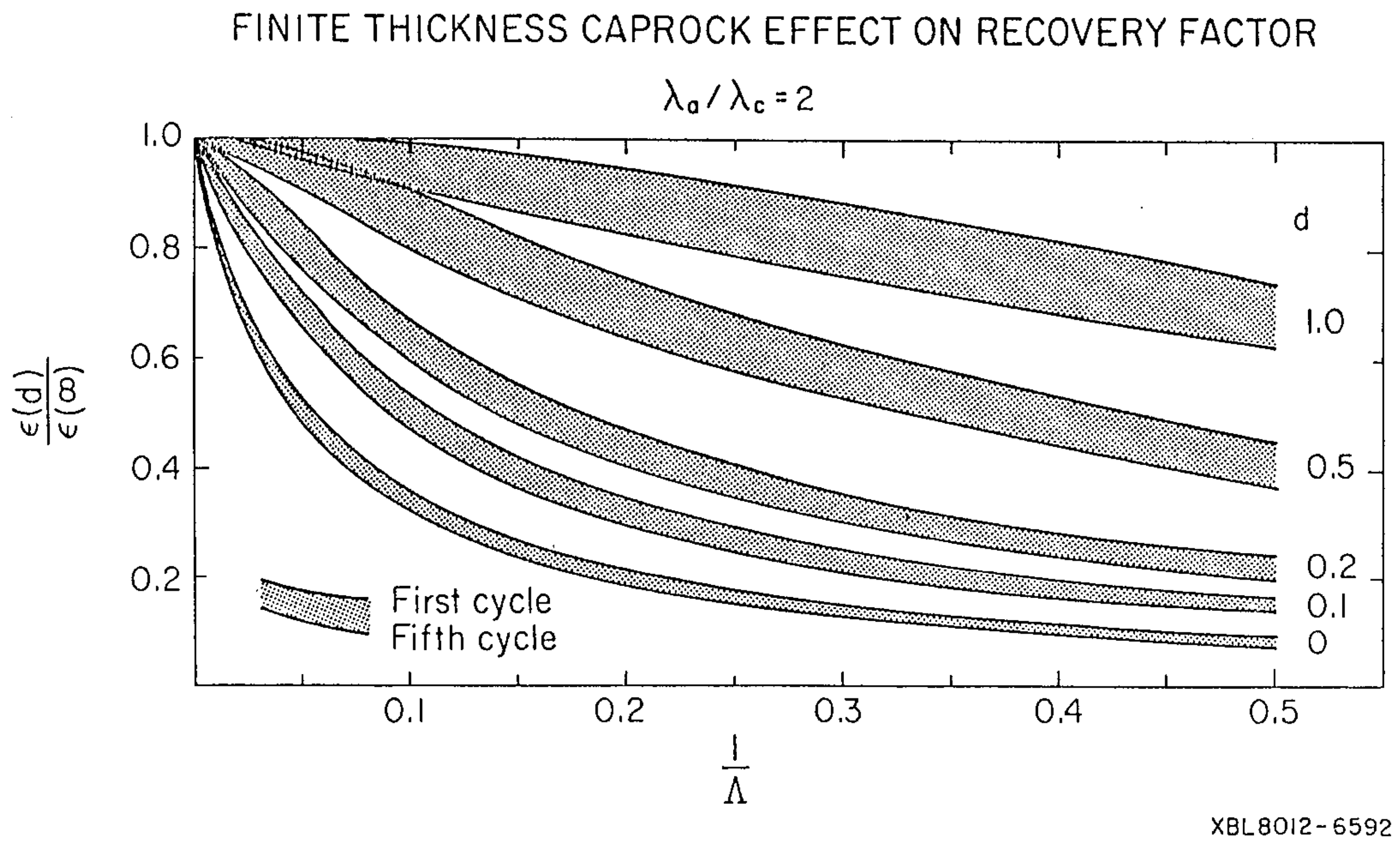


Figure 27:
LBL / Nonbuoyant characterization scheme - first and fifth cycle production temperature versus time for a range of Pe and Λ when $\lambda_a/\lambda_c = 2$.

Figure 28: LBL/ Nonbuoyant characterization scheme - finite thickness caprock effect for the first and fifth cycle recovery factors as a function of Λ when $\lambda_a/\lambda_c = 2$.



Appendix 4: DATA FOR THE IEA TASK VII TEST CASES

A.4.1. SELECTION PROCESS

The purpose of the selection process is to find out how accurately each program performs, based on input data, which should be as realistic as possible.

The underlying assumption was first that the models should be validated and that the measured data from existing storage types, which could serve as the input data, could be used easily. Basically, this means that we expected to obtain with one set of measured input data from each storage type to the different models, sets of output data, which were all similar within some limits of accuracy and precision. If this were true, then we just might take the simplest program.

We might expect differences in the results due to significant differences in the assumptions made for the model itself. Whether the spread in the differences can be accepted, or improvement can be obtained by modifying a program, this becomes a matter of further investigation.

As regarded what kind of measured data to use, problems arose. First of all, little reliable data was available concerning existing storage types, because most of the existing storage systems have been functioning only for a few years. Secondly, the measured storage types did not correspond necessarily to representative cases related to the Subtask 1c needs.

Another problem was that much of the gathered data was available in a draft form and was not processed yet, or was in the stage of being processed. It has to be recognized that the processing alone of this data by the researcher takes a very long time, hence this could not be made available to Subtask 1c early enough. Furthermore, certain storage types have been analysed over a longer period than others.

That is why for water tanks the USA could propose the use of complete input data from the "Nebraska School" and the FRG from the "Stuttgart water tank" experiment.

For aquifers the Auburn data was proposed. Switzerland proposed for earth storage systems data from the Marly experiments. However, the data from the "Nebraska School" was not available to us in a useful format. Adapting this data for a representative period would have delayed the whole selection process substantially.

Because much time was involved in running and testing the various available programs, it became clear that the testing could best be performed by those who made the programs or, in other words, by the persons who are at present more familiar with them.

For all these reasons, the selectioner decided to establish a hypothetical test case, and to submit it to all participating countries. The test case should be chosen such as it would most likely apply for all programs and should gather all relevant parameters of a typical storage configuration.

There remains a minor problem: this way of acting does not allow to conclude whether a simplified program is validated or not, because the test case is not a real case, and the output data obtained does not correspond to the real physical state. Therefore, as long as it has not been proved that the simple program has been validated, validation should be done by comparing the simplified program with a validated complete program.

A.4.2. GENERAL PURPOSE OF THE TEST CASES

The purpose of selecting a simplified model is to save execution time and memory size. If there is a lack of accuracy and precision in applying a simplified program, the test case should be able to detect this. The test case should comprise all the relevant parameters including initial conditions and boundary conditions.

If the test case contains too many parameters, the researcher (analyst) should adapt or simplify the input data as much as necessary to run the test case effectively with his model. However, the original test case should then be simulated by a complete model as well in order to give a reference output.

A.4.3. CONCEPTION OF THE TEST CASES

With the conception of the test case, a distinction has been made between the more general conditions which apply to all three storage categories, and the more specific requirements which apply individually for each category.

A.4.3.1. General conditions

a) Typical daily injection and production patterns, which the model should be able to handle for a solar system simulation, were given. At the end of the day (3-4 pm), water is injected into the storage at a rather low temperature (30°C) compared with the inlet temperature at noon (60°C). Thus, it will be interesting to see which models are able to predict whether or not this situation leads to a heat withdrawal at the end of the day.

   The simulation period is rather short (40 and 80 days) and is divided into three typical periods: injection, storage, production (figures 29, 29a, and 30).

   A simulation period shorter than a year, which was more typical of seasonal storage systems, was intentionally chosen to avoid the use of simplified models where assumptions of the storage temperature variations (such as sinusoidal curves) are made. This type of model would not be suitable to our needs, since the MINSUN program has a daily timestep.

b) It is assumed that all storage types are underground. As boundary condition on top was given, the air temperature, the use of a daily variation and a heat-transfer coefficient were recommended.

A.4.3.2. Specific conditions

a) For the water tank case, a cylindrical concrete tank has been assumed of 3000 m3, and an average depth of 7 m. This corresponds roughly to a case given in the Astep user's manual.

b) For the earth storage case, we assume a 5000 m3 storage volume with a vertical pipe heat exchanger configuration. Most models were able to handle this case (LT-TPD-I, ADES-Store, DST, TUBE, ENERGY).

GROCS and SPIPE cannot handle a vertical pipe system without important modifications.

The geometry of the test case corresponds to a given case in the user's manual of the TUBE program.

The pipes connection has not been fixed.

c) The aquifer test case deals with a doublet system, using a 10 meters thick confined aquifer located at an average depth of 25 meters.

   Because no existing simplified model can deal with a three-dimensional storage configuration, we assume that the doublet system could be considered as a two-dimensional system. This corresponds for example to a system having theoretically two lines of injection/production wells, so that one horizontal dimension is eliminated.

The hydraulical and thermal characteristics have been chosed, based on our experiences as well as on information from the IEA Annex I (Large Scale Thermal Storage Systems).

The charging mode for all test cases corresponds roughly to a solar heating system.

For the production period, a return temperature of 20°C has been set, because we expected that all storage systems - after the injection and storage period - would at least reach this temperature. Should it not be the case, injection of heat will occur during this period, and some models will not be precise enough to detect it.

On the other hand, the analysts might do some sensitivity analyses around this outlet temperature and consider the 20°C outlet temperature as an indication only.

Further, because most models cannot deal with non-linear situations, a rather low average temperature in the store is acceptable.

A.4.4. INPUT FOR THE PROPOSED TEST CASE

The following pages define the input data for the three categories of models to be tested.

A.4.4.1. General conditions for all categories

Boundary conditions on top

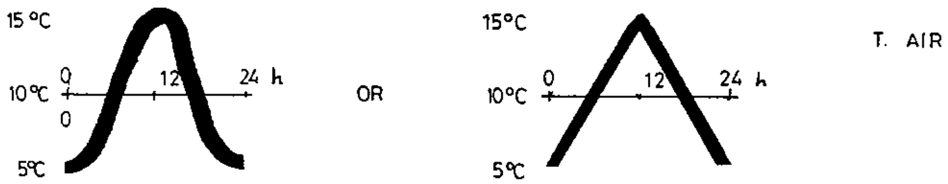
- Air temperature

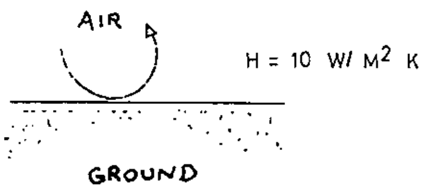
  5°C at 00.00 for each day of simulation

  15°C at 12.00

- Assume a daily sinusoidal variation of the air temperature (min. 5°C, max. 15°C) if the model can handle it, or a linear variation if not

- Assume a heat transfer coefficient between ground surface and air of 10 W/m2°C if possible. If not, use air temperature as ground surface temperature





Inlet/Outlet

For the water tank case and for the aquifer case, the outlet becomes the inlet during a production period.

Output required

1. Evolution of the outlet temperature during the period of simulation

2. Evolution of the mean temperature or of the temperatures of stratification in the store

3. An energy balance for the three periods (injection, storage, production) given, namely the heat losses through the top, bottom, and sides of the store

4. All results available given by the model are welcome

Figure 29a: DAILY INJECTION PATTERN FOR SUBTASK 1c TEST CASE

(variation of inlet temperature)

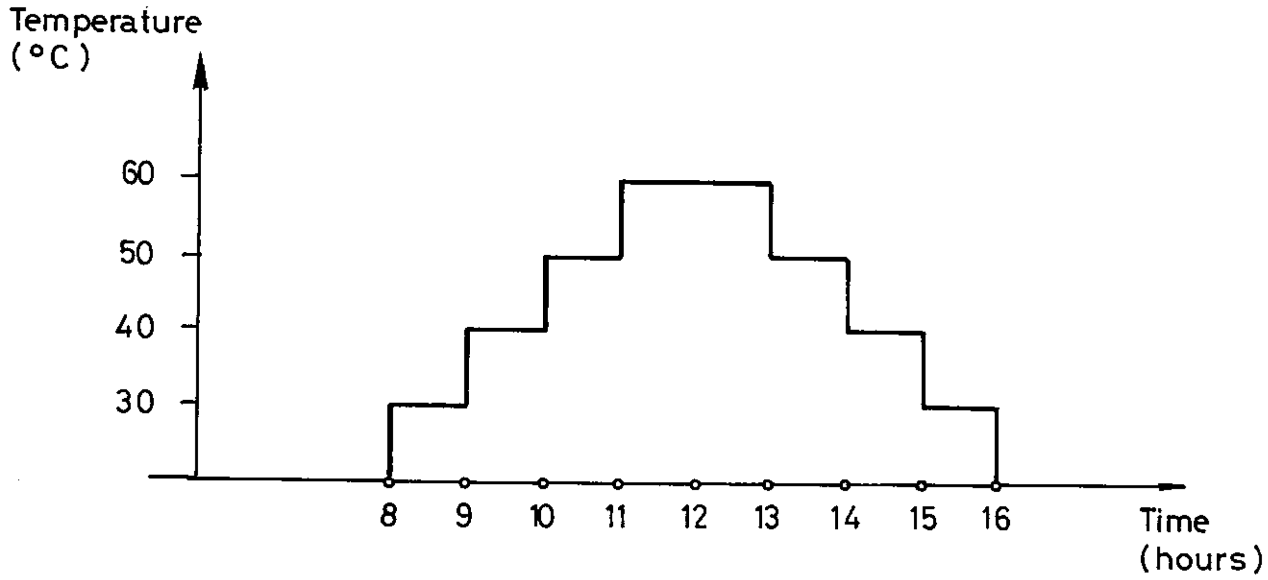


Figure 29b: DAILY PRODUCTION PATTERN FOR SUBTASK 1c TEST CASE

(constant inlet temperature)

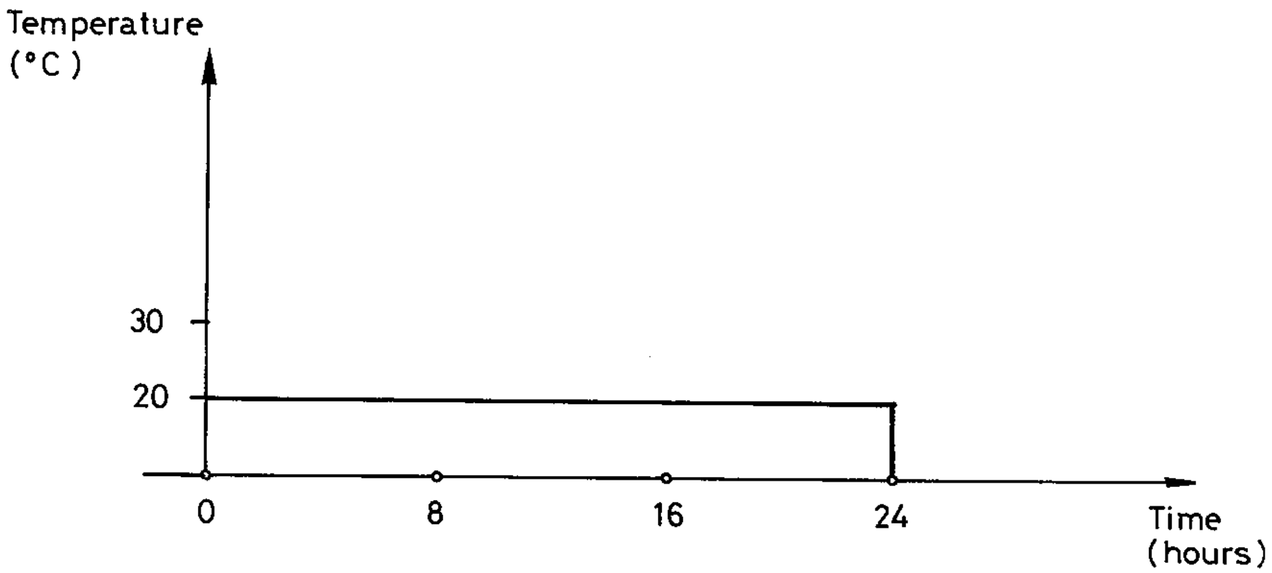
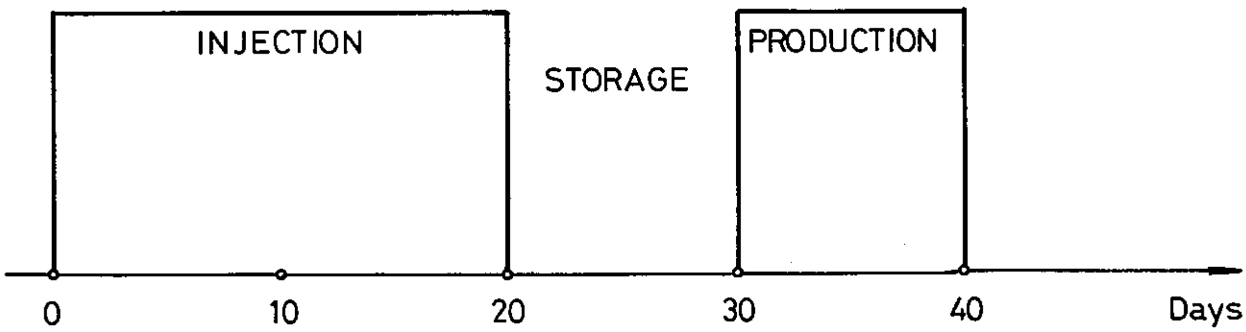
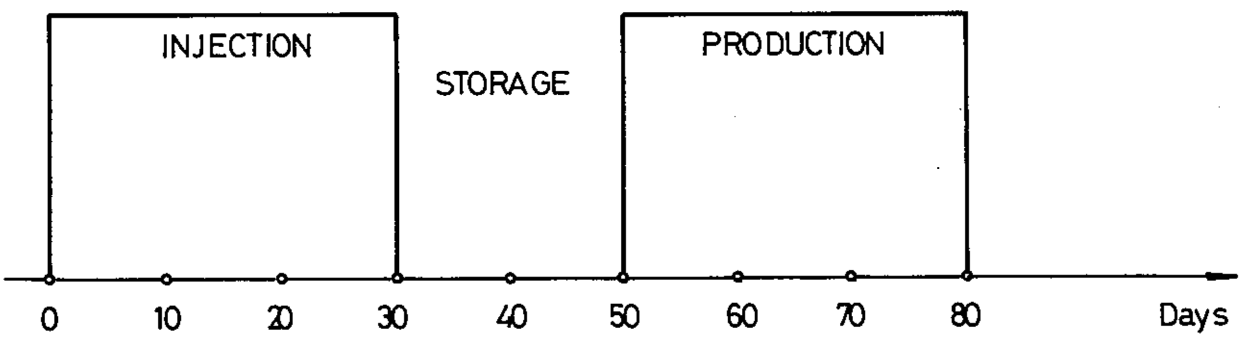


Figure 30: GENERAL PATTERNS FOR SUBTASK 1c TEST CASE

40 DAYS PATTERN for
- water tank
- earth



80 DAYS PATTERN for - aquifer



A.4.4.2. Specific data for the water tank case

WATER

STORAGE	: CYLINDRICAL
DIAMETER	: 19.50 m
HEIGHT	: 10 m
VOLUME	: 3'000 m3

INSULATION

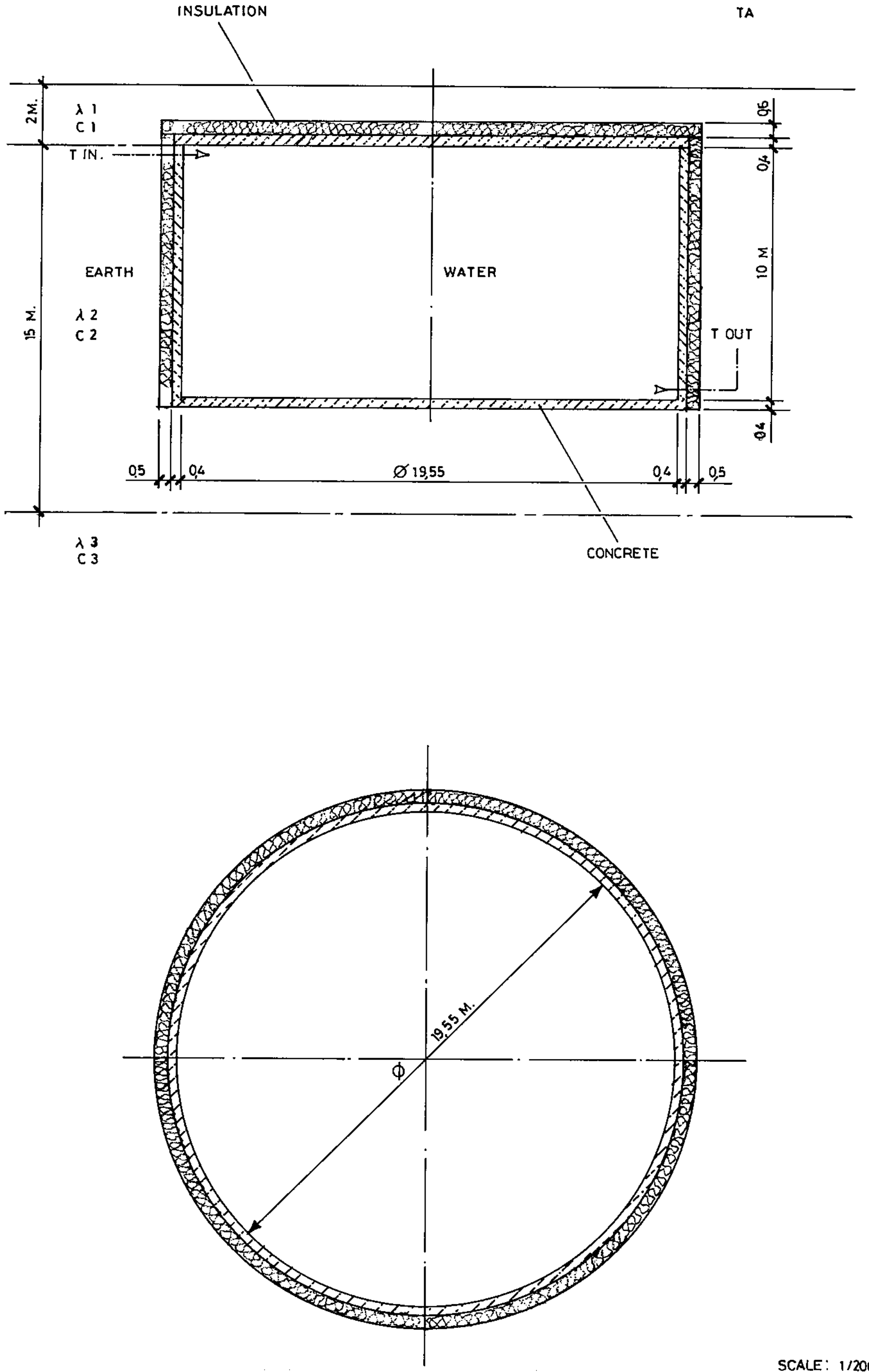
ON THE TOP	: 0,6 m
ON THE SIDES	: 0,5 m
THERMAL CONDUCTIVITY	: 0,04 W/mK

GROUND

INITIAL SOIL TEMPERATURE		
DEPTH	: 1 m	: $5^{o}C$
	2 m	: $8^{o}C$
	4 m	: $10^{o}C$

SOIL DENSITY	: 2 t/m3
THERMAL CAPACITY	: 2.0 10^{6} J/m3 K = C1 = C2 = C3
THERMAL CONDUCTIVITY	: $\lambda 1 = 1.5$ $\lambda 2 = 2.0$ $\lambda 3 = 2.5$ W/mK
INITIAL TEMPERATURE OF WATER IN THE TANK	: 15°C
WATER FLOW RATE	: 20 m3/h, constant during injection time (8 hours/day) and production time (24 hours/day)

Figure 31: WATER TANK CONFIGURATION FOR SUBTASK 1c TEST CASE



A.4.4.3. Specific data for the earth storage case

VERTICAL PIPES

VOLUME	: 5'000 m3
NUMBER OF PIPES	: 61
RADIUS OF GROUND UNIT	: 1.30 m
RADIUS OF PIPE	: 0,05 m
DEPTH OF GROUND UNIT	: 15 m

INSULATION

THICKNESS OF TOP INSULATION	: 0,6 m
SPECIFIC HEAT	: 1000 J/kgK
DENSITY	: 20 kg/m3
THERMAL CONDUCTIVITY	: 0.04 W/mK

GROUND

SPECIFIC HEAT	: C1=C2=C3=2.0 10^6 J/m3^{o}K
DENSITY	: 2.0 t/m3
THERMAL CONDUCTIVITY	: λ1=1.5 λ2=2.0 λ3=2.5 W/mK

INITIAL SOIL TEMPERATURE

DEPTH	: 1 m	: 5^{o}C
	2 m	: 8^{o}C
	4 m	: 10^{o}C

TOTAL WATER FLOW RATE : 50 m3/h constant during injection time(8 hours/day) and during production time (24 hours/day)

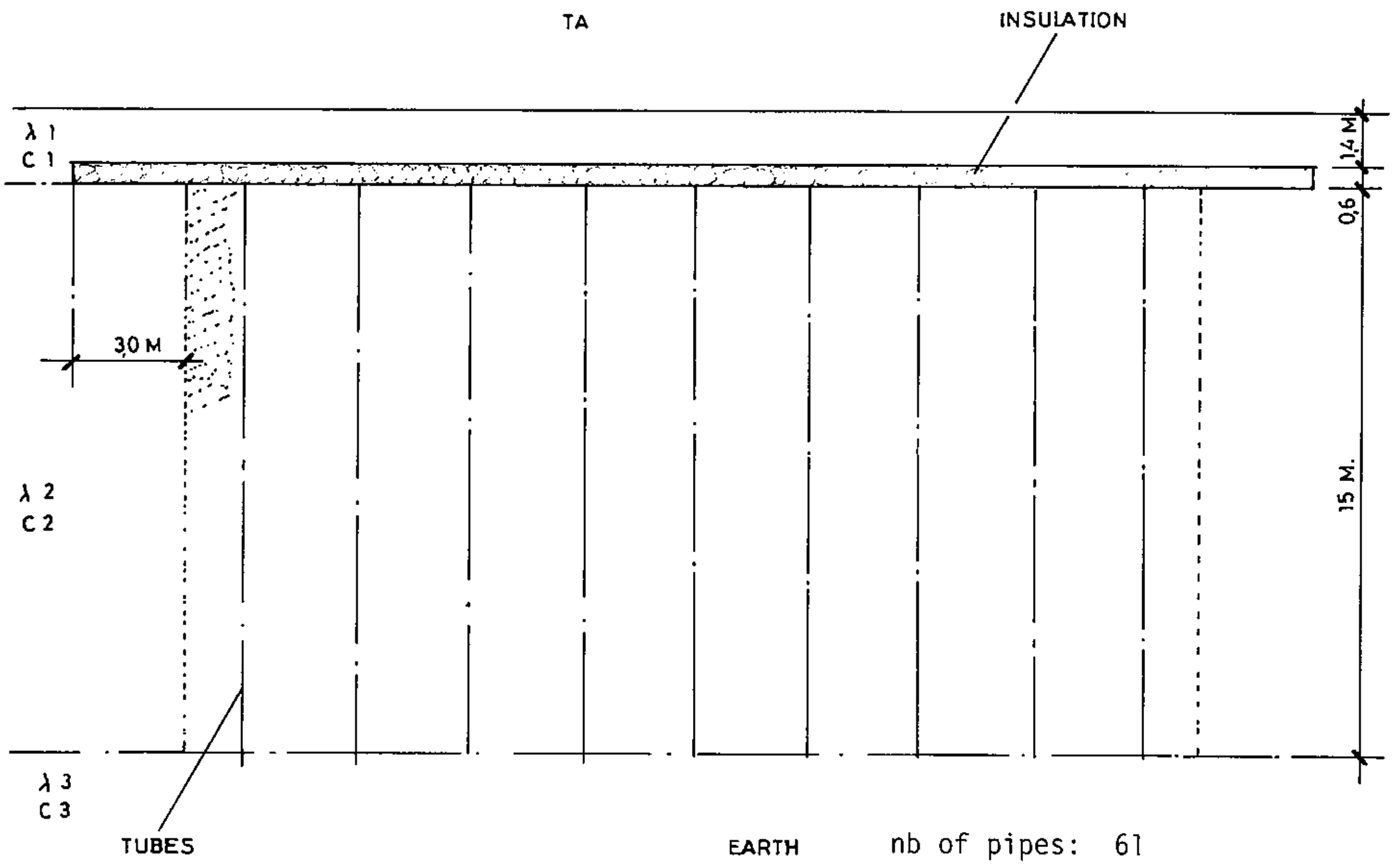
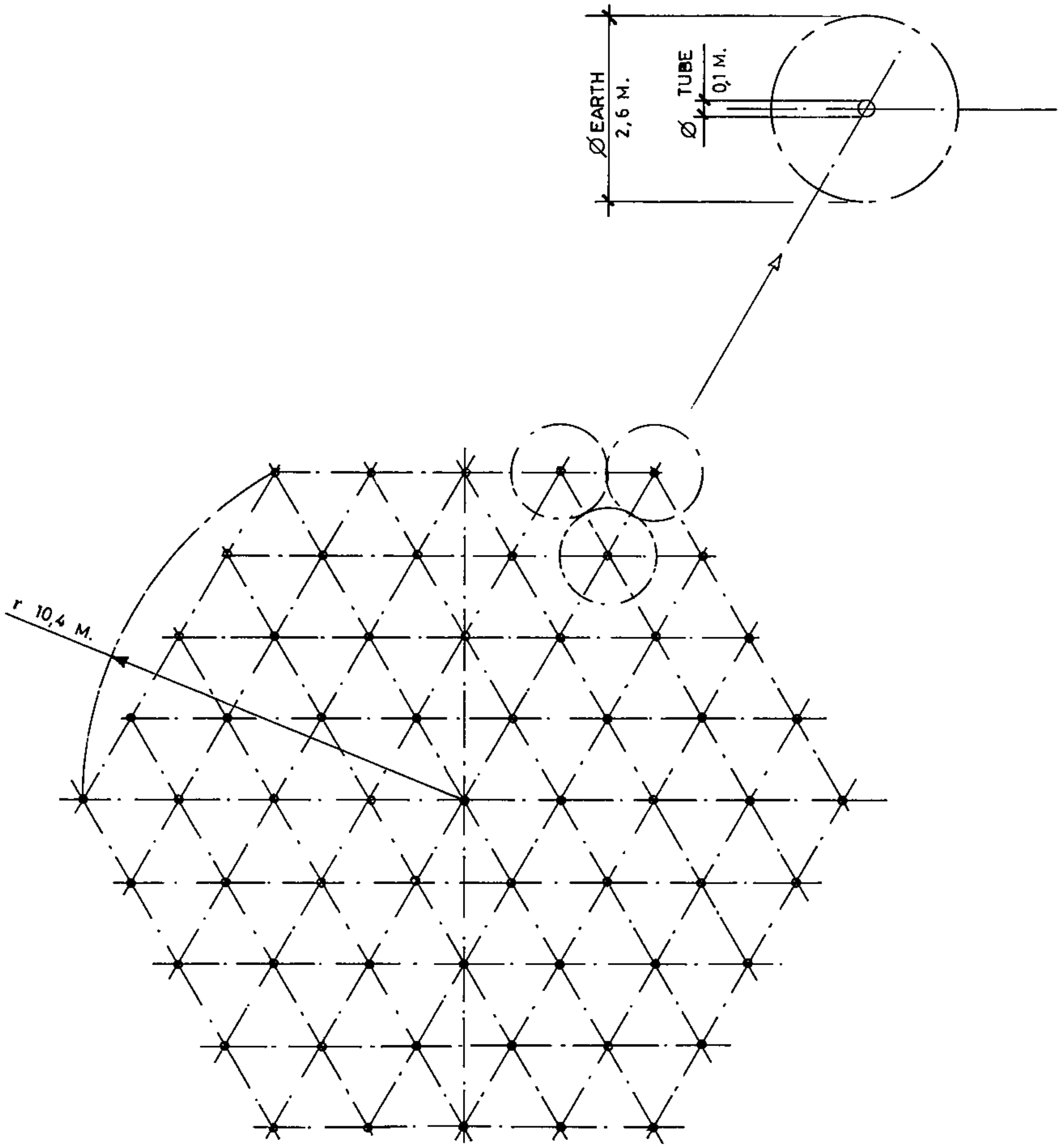


Figure 32a: Earth storage configuration for Subtask 1c test case - Cross section



nb of pipes: 61

Figure 32b: Earth storage configuration for Subtask 1c test case - Plane view

A.4.4.4. Specific data for the aquifer storage case

CONFINED AQUIFER

Layer (1) : Bedrock

Horizontal permeability	: 10^{-7} m/s
Vertical permeability	: 10^{-8} m/s
Specific heat	: 2.0 10^{6} J/m3K
Horizontal thermal conductivity	: 1.5 W/mk
Vertical thermal conductivity	: 1.5 W/mK

Layer (2) : Aquifer

Horizontal permeability	: 10^{-4} m/s
Vertical permeability	: 10^{-5} m/s
Specific heat	: 2.5 10^{6} J/m3K
Horizontal thermal conductivity	: 3.0 W/mK
Vertical thermal conductivity	: 2.0 W/mK

Layer (3) : Caprock

Horizontal permeability	: 10^{-6} m/s
Vertical permeability	: 10^{-7} m/s
Specific heat	: 1.7 10^{6} J/m^{3}k
Horizontal thermal conductivity	: 1.3 W/mk
Vertical thermal conductivity	: 1.5 W/mk

Layer (4) : Unsatured zone

Horizontal permeability	: 10^{-3} m/s
Vertical permeability	: 10^{-3} m/s
Specific heat	: 1.0 10^{6} J/m3K
Horizontal thermal conductivity	: 2.0 W/mK
Vertical thermal conductivity	: 2.0 W/mK

Water Flow Rate : 0,5 m3/h (per 1m of aquifer thickness)

Initial temperature : 11 ^{o}C (assumed constant)

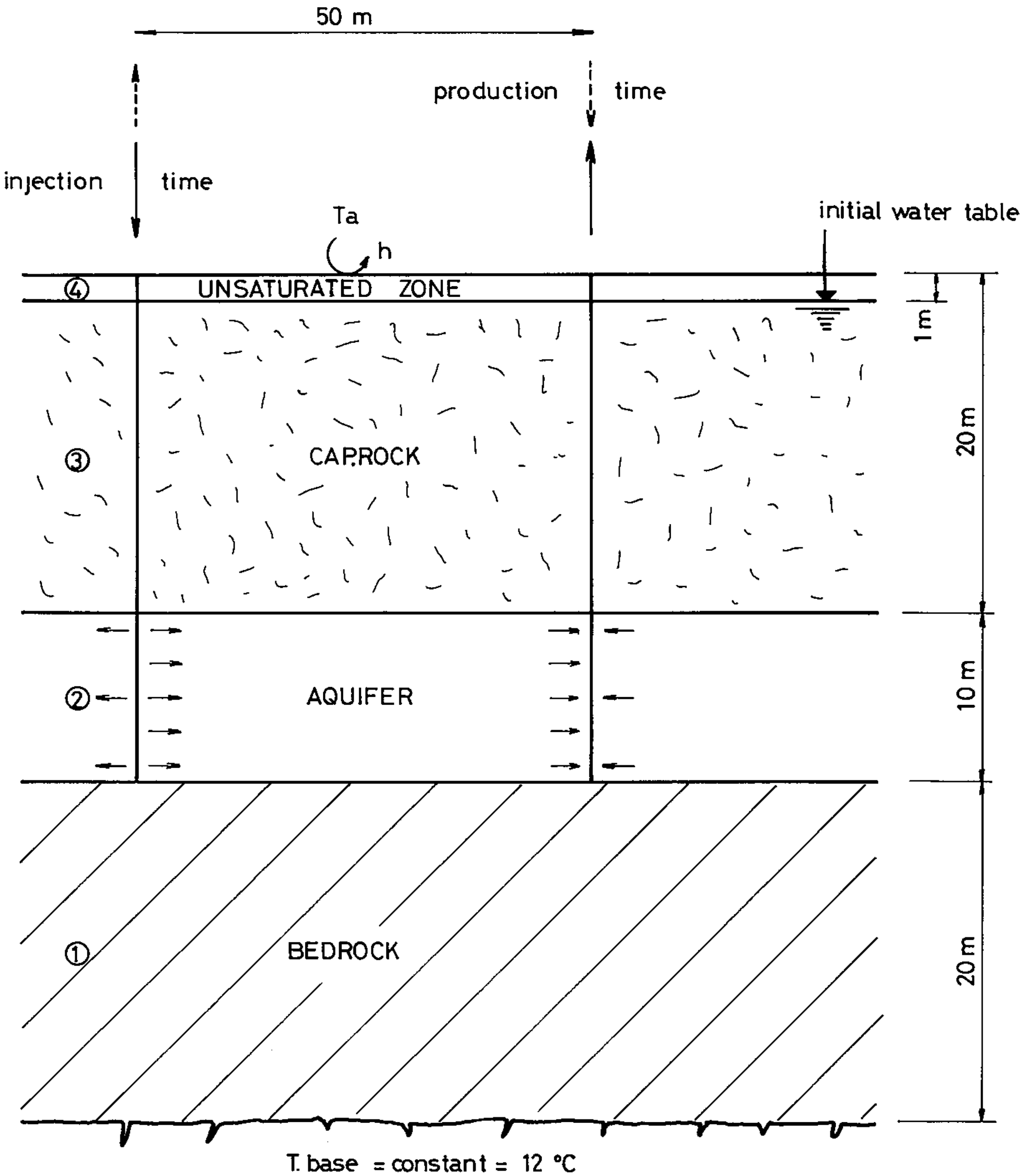


Figure 33: CROSS SECTION OF A DOUBLET SYSTEM FOR SUBTASK 1c TEST CASE

Appendix 5: TEST CASE RESULTS FOR WATER TANK STORAGE MODELS

The original test case and its conception are described in Appendix 4 of this report.

Only two models have run the proposed test case. These are NTACT from Canada, and LUND-SST from Sweden.

A detailed analysis of output was provided by each modeller team and this can be found under References A-3 and A-12.

A comparative summary will be presented after a short description of the results provided by each team.

A.5.1. LUND-SST (ref. A-12)

The program can handle all the specifications of the given case. The concrete and the insulation are represented by two cell layers of the mesh in the ground. The three soil layers are accounted for. The water is assumed to be vertically stratified with the warmest water on top. A mesh with 25 x 31 cells is used for the ground. The smallest cells at the vicinity of the storage have the linear size of 0.4 m. The vertical temperature profile in the water tank is represented by 20 cells.

The temperature at the ground surface varies sinusoidally above a surface resistance.

The water pumping rate is 20 m3/h during injection (8-16 hours each day) and during extraction (0-24 hours each day). A buffer cell is used at the inlet and at the outlet of water. The buffer has the same volume as a cell in the water tank. The moment the inlet buffer is completely filled, the water is put into the first cell. The water of the first cell is displaced to the second cell and so on. The water of the outlet cell leaves the tank and is put into the outlet buffer. This displacement procedure is introduced in order to avoid a so-called numerical dispersion for the diffusive-convective thermal process of the water.

The timestep is 4 hours and the computation requires 14 seconds in total and 3.6 seconds CPU time on a UNIVAC 1100/80.

Some vertical temperature profiles in the water tank are given in Figure 34. Radial temperature profiles at the depth z = 7 m are shown in Figure 35.

The mean temperature of the water in the tank, averaged on the 20 stratification layers, is given in Figure 36.

There is a bump at t = 16 days, due to the discrete cell-size injection from the buffer. The volume of injected water per day is 160 m3, while the water cells have a volume of 150 m3 (1/20 of the total). So, during the 16th day two cells are injected instead of one.

The outlet water temperature during the injection and production period is shown in Figure 37. It is somewhat below 15°C during injection, except for the last days when the injected heat is felt.

Finally, Figure 39 shows the energy balance. Accumulated energies are shown during the 40 days.

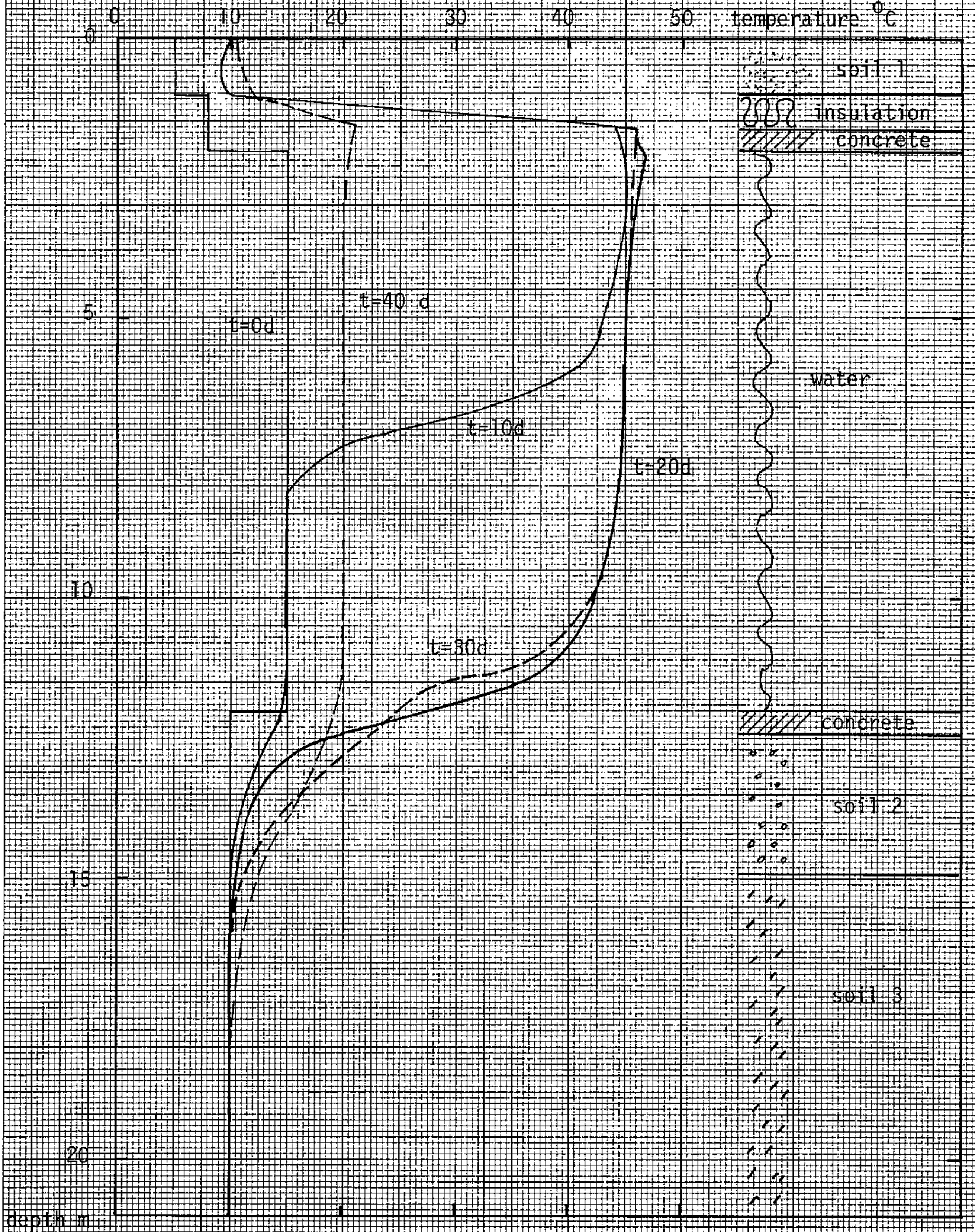
Accumulated heat losses from water to concrete, and soil through top, side and bottom are shown as negative contributions.

During production, there is a gain of heat from the surroundings which is shown as positive contributions.

Water tank
SSI

Vertical temperature profile along the cylinder axis
t= 0 , 10 , 20 , 30 and 40 days

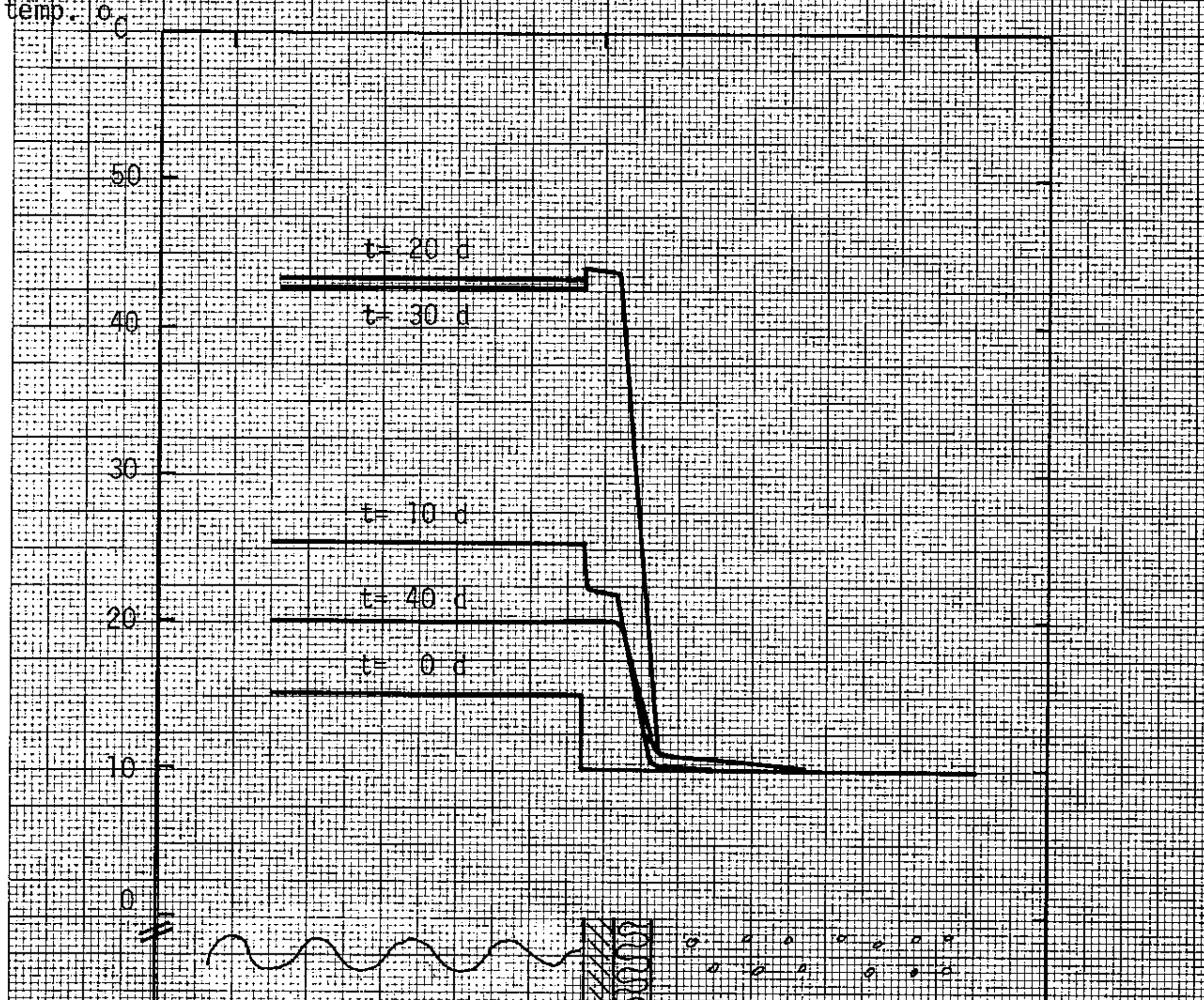
Figure 34



Water tank SST

Horizontal temperature profile at the depth z = 7 m t=0 to 40 days

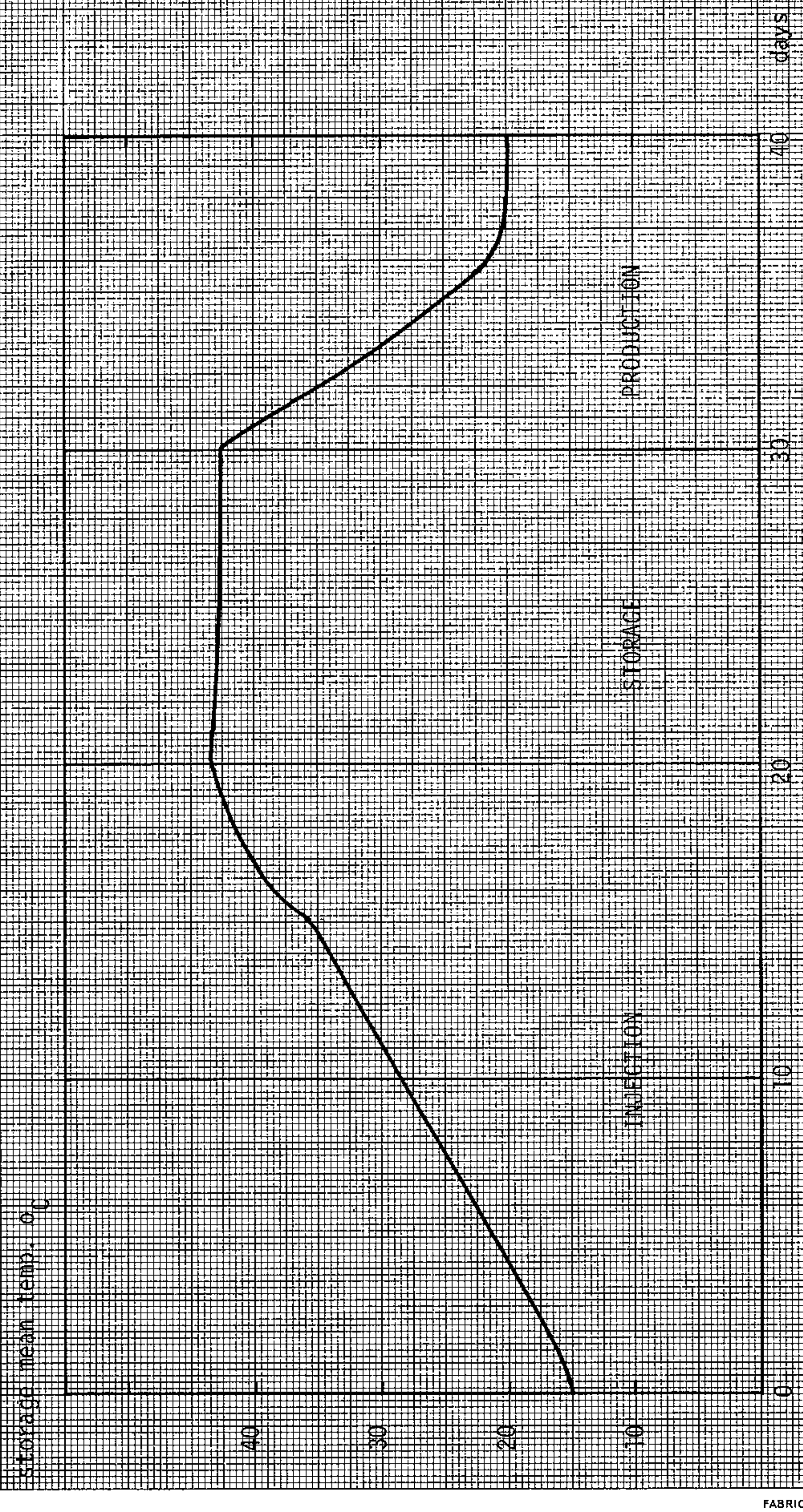
figure 35



Water tank
SST

Storage mean temperature

figure 36

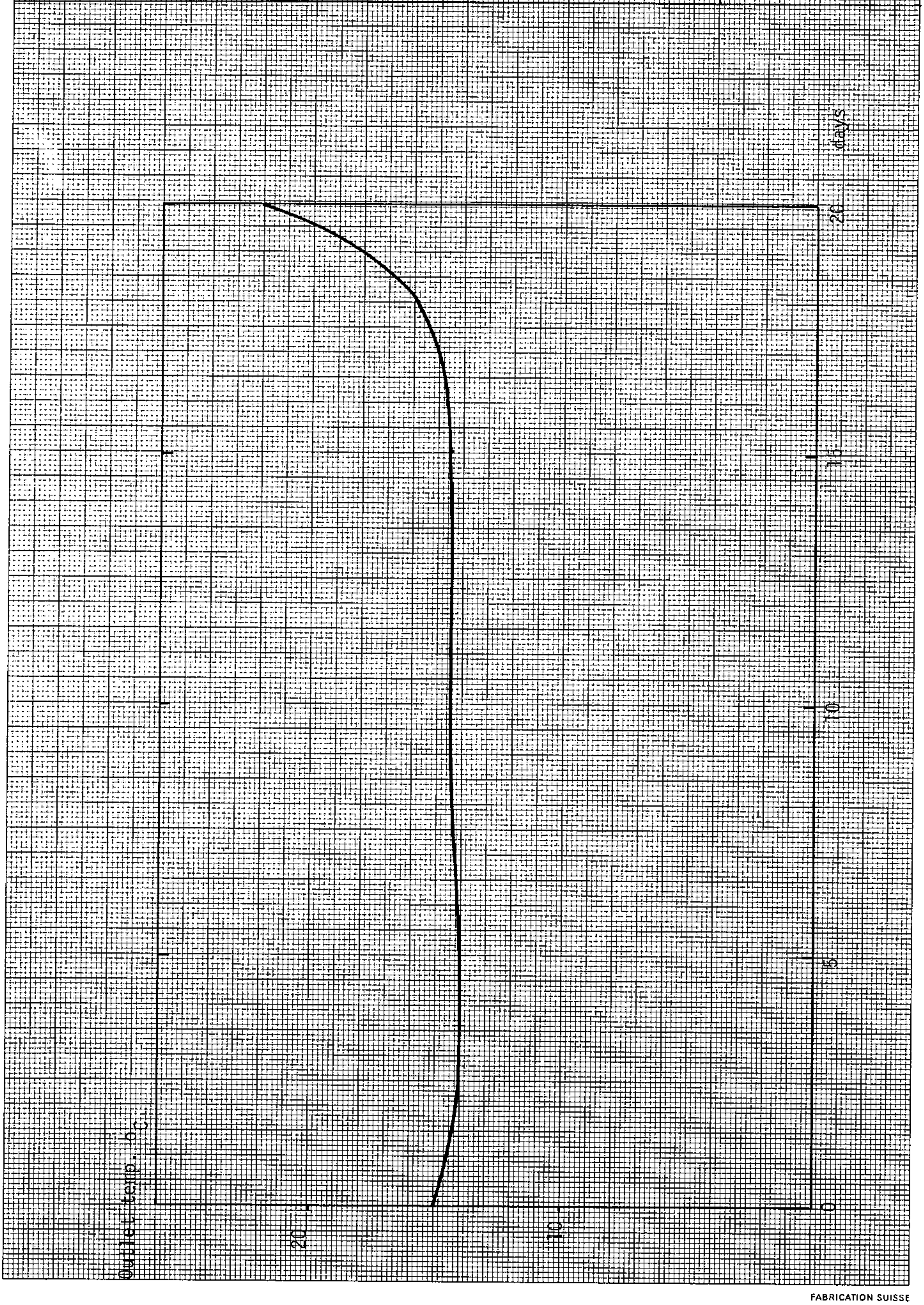


FABRICATION SUISSE

Water tank
SST

Outlet water temperature during injection

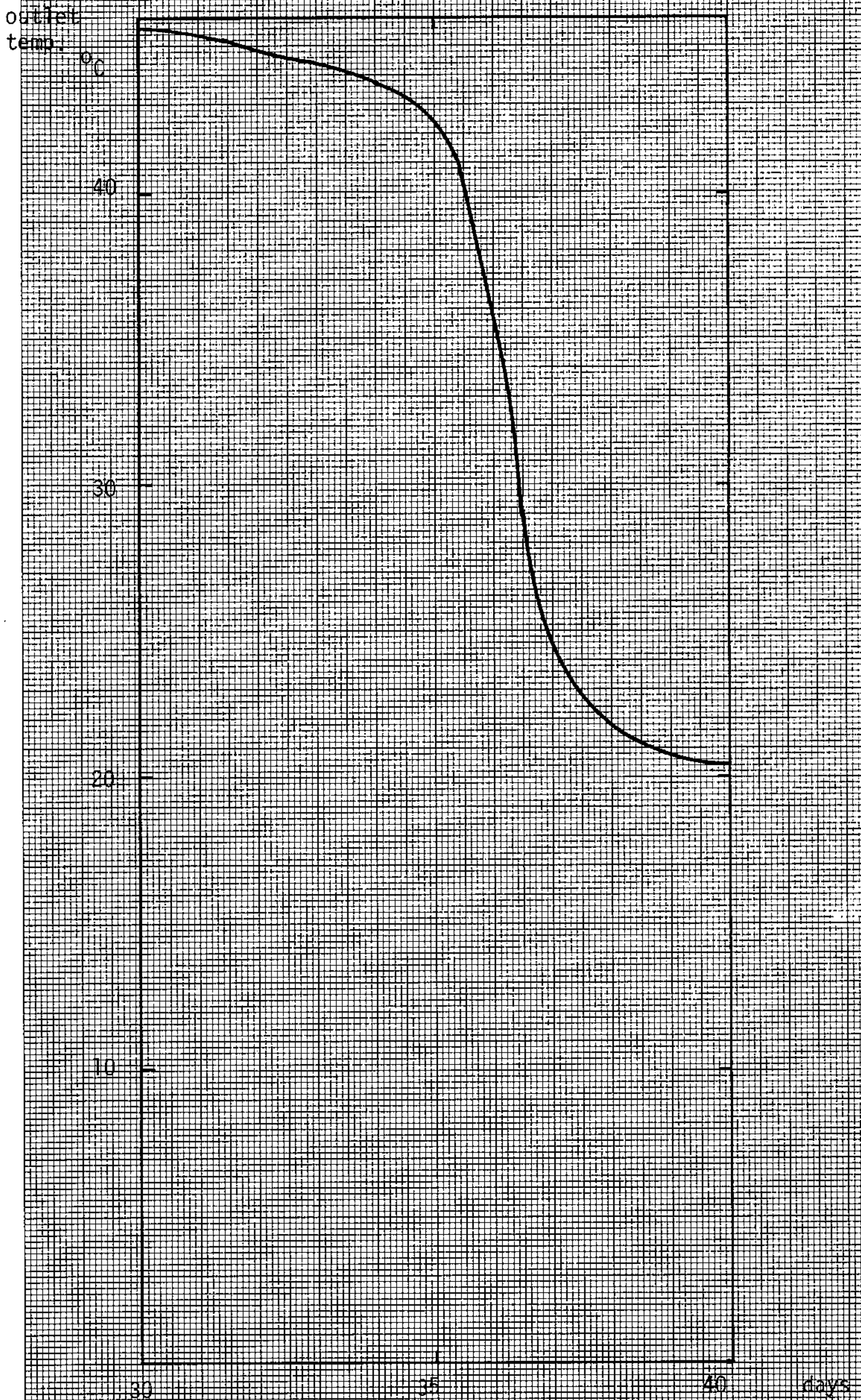
figure 37/a



Water tank
SST

Outlet water temperature during production

figure 37/b

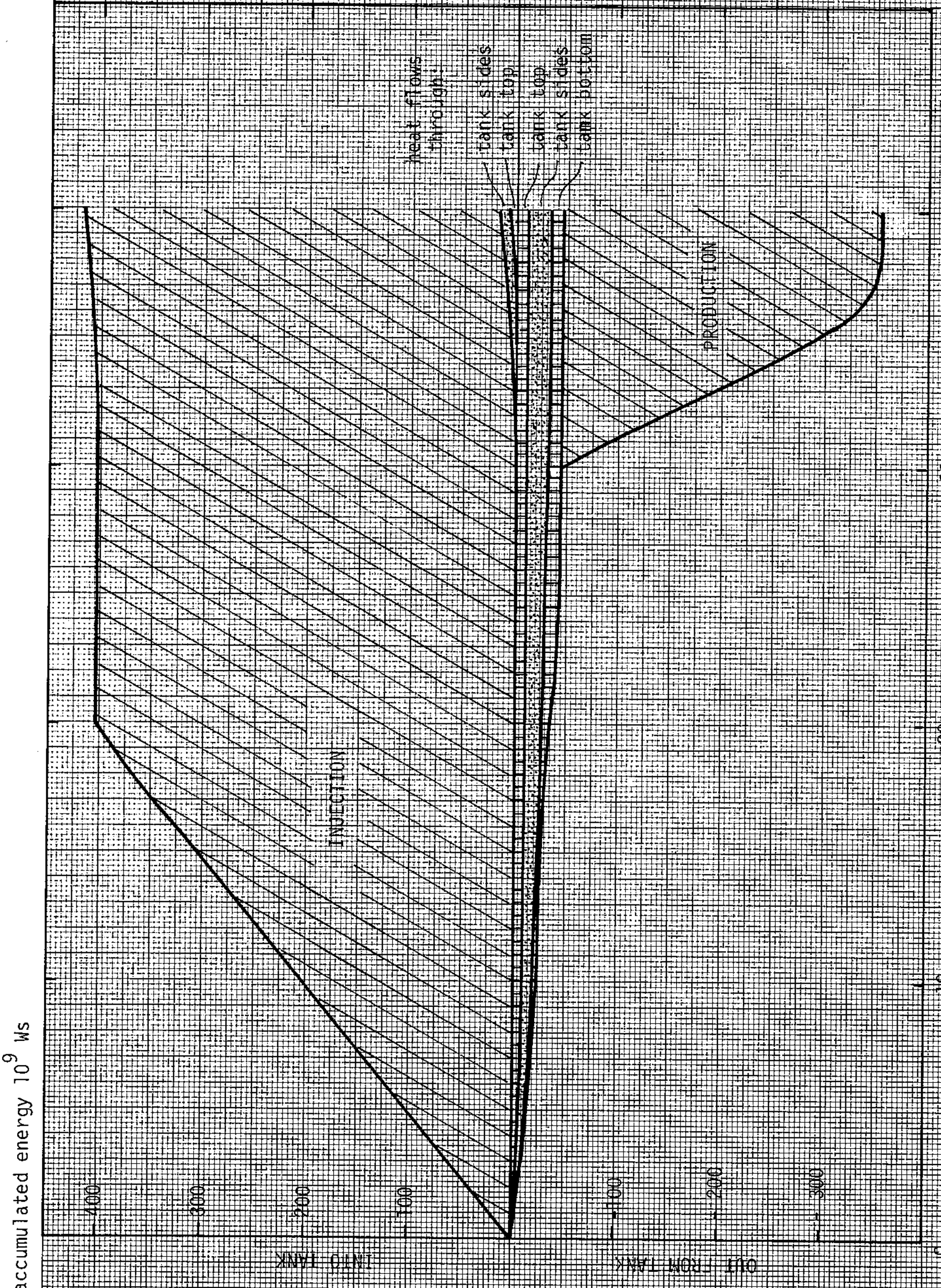


Water tank SST

ENERGY BALANCE

Accumulated heat flows into and out of tank

figure 38



FABRICATION SUISSE

A.5.2. NTACT-1 (ref. A-3)

The input parameters used for the NTACT model, and the output results of the test case are as follows (note that 5 cycles were run):

NTACT2 SIMULATION RESULTS - CYCLE 1 INJECTION			
STORAGE TEMP - START		15.000	DEG. C
	END	33.557	DEG. C
STORAGE HEAT INJECTION		253335.06	MJ
STORAGE HEAT LOSS -	TANK TOP	614.90	MJ
	TANK WALLS	4766.84	MJ
	TANK FLOOR	17109.37	MJ

NTACT2 SIMULATION RESULTS - CYCLE 1 STORAGE			
STORAGE TEMP - START		33.557	DEG. C
	END	32.742	DEG. C
STORAGE HEAT LOSS -	TANK TOP	445.99	MJ
	TANK WALLS	2739.92	MJ
	TANK FLOOR	6922.92	MJ

NTACT2 SIMULATION RESULTS - CYCLE 1 PRODUCTION			
STORAGE TEMP - START		32.742	DEG. C
	END	22.496	DEG. C
STORAGE HEAT PRODUCTION		125049.31	MJ
STORAGE HEAT LOSS -	TANK TOP	314.05	MJ
	TANK WALLS	1339.05	MJ
	TANK FLOOR	692.67	MJ

IEA Test - Computer Printout of Energy Balance - Cycle 1 - NTACT

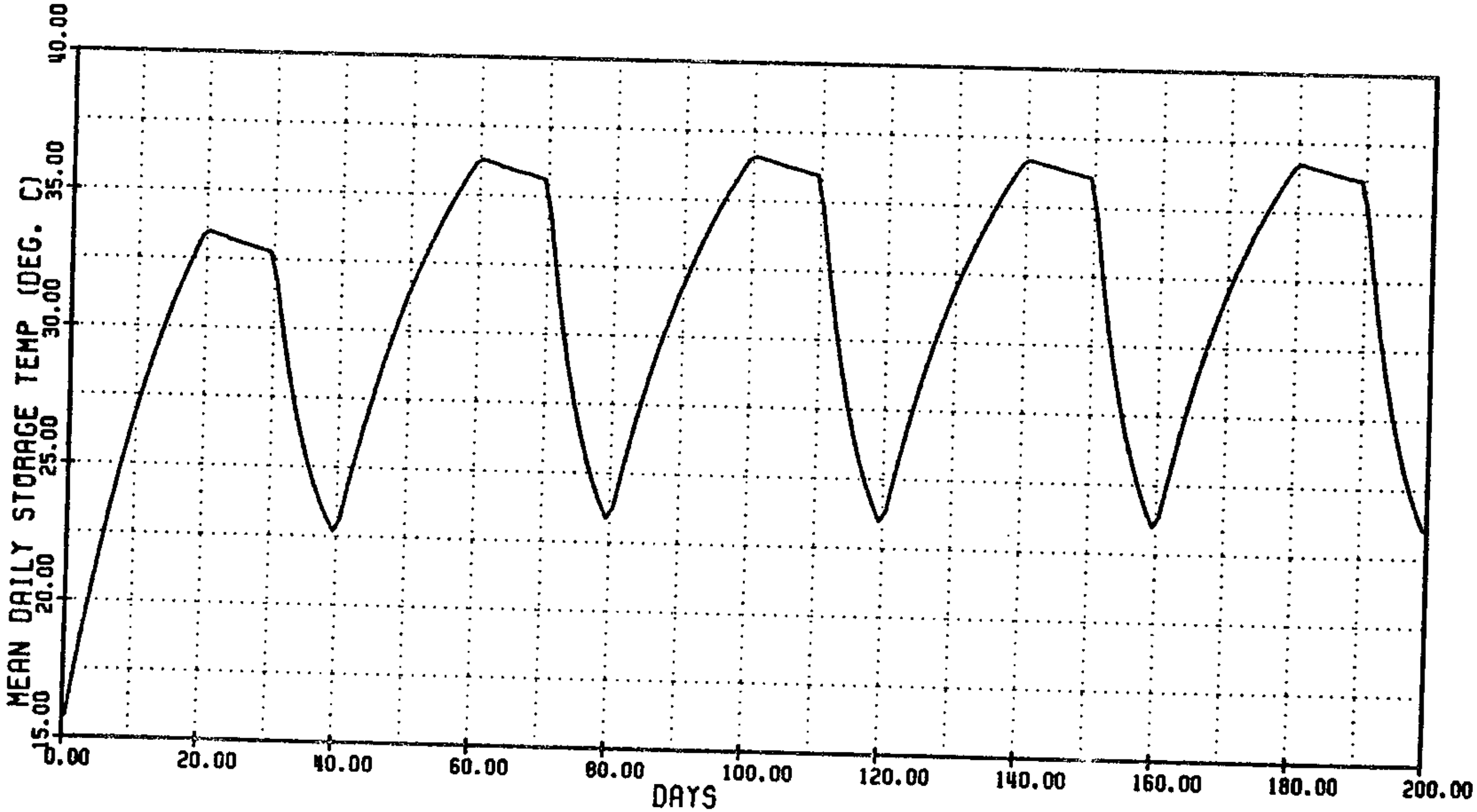


Figure 39: NTACT/Mean daily storage temperature (5 cycles have been run)

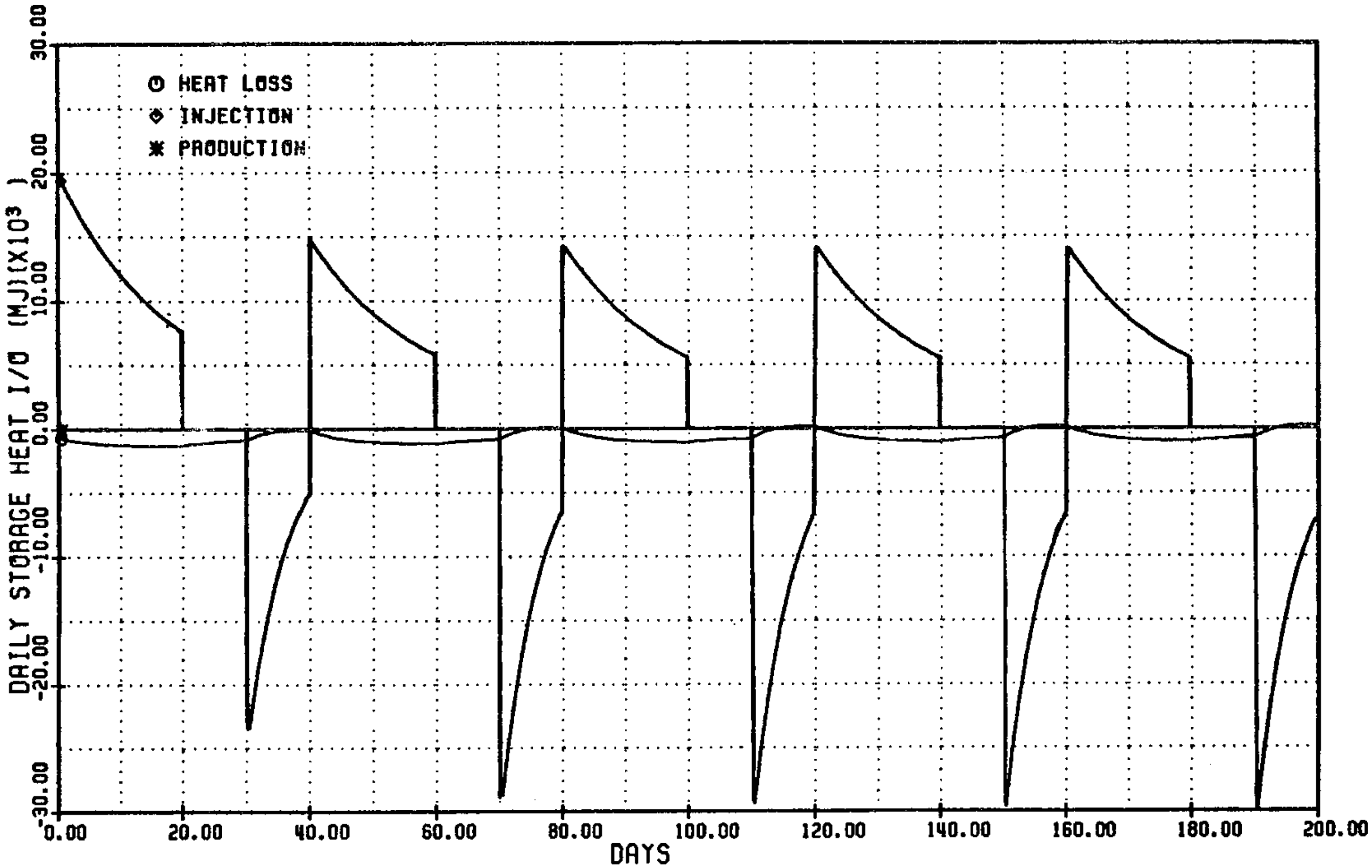


Figure 40: NTACT/Daily storage heat input/output

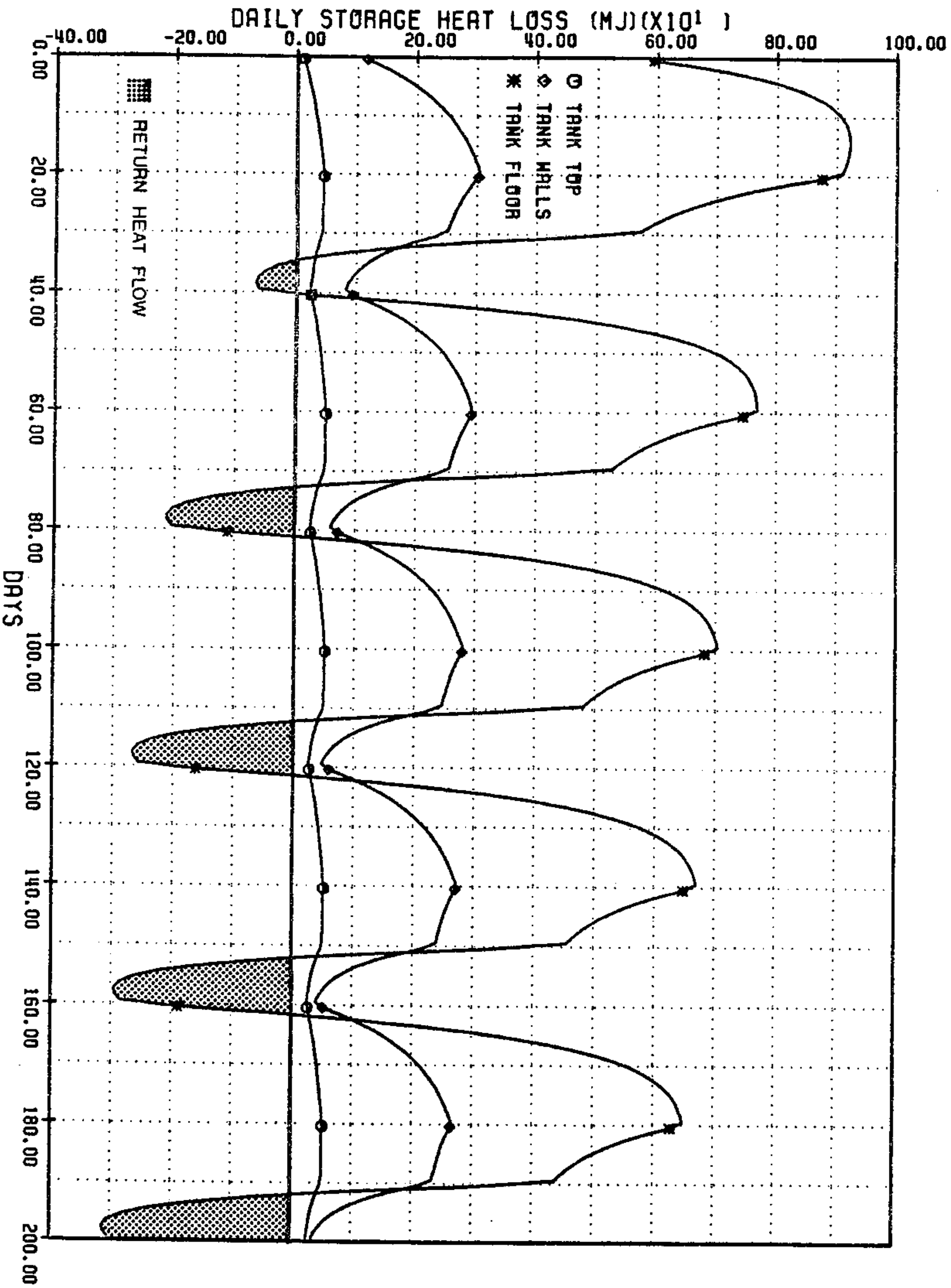


Figure 41: NTACT/Daily storage heat loss

A.5.3. COMPARISON OF TEST CASE RESULTS

Table 15 summarizes the heat flow results found by each model at the end of each period (injection, storage, production), and Table 16 indicates the computing requirements of each program.

Figures 42 to 45 show the temperature fields as computed by LUND-SST. The average storage temperature as given by NTACT is also indicated for comparison.

Figure 47 represents the evolution of the storage mean temperature computed by each model. For LUND-SST this is an average value over the 20 segments assumed, whereas for NTACT the tank is assumed to be fully mixed.

Great discrepancies can be found between the results, with no obvious explanation, except that the systems simulated by each model were quite different:

- stratified (SST) or not (NTACT)
- concrete walls accounted for (SST) or not (NTACT)
- bottom insulation (NTACT) or not (SST)

The test case being hypothetical, no relevant conclusions could be taken out of the test case results.

However, the test case has allowed Lead Country 1c to get a precise idea of the capabilities of the models, as concerns Task VII needs, but the problem of the models validation remained.

Table 15: WATER TANK STORAGE MODELS/RESULTS OF TEST CASE (Energy in MJ)

	NTACT		LUND-SST	
Heat injected during injection period	253'335		403'600	
Heat losses during injection and storage periods				
Top	1'061		11'200	
Walls	7'507		20'500	
Floor	24'032		14'100	
Total	32'600		45'800	
Heat losses during production				
Top	314		- 5'800	
Walls	1'399		- 10'300	
Floor	693		- 50	
Total	2'346	(losses)	- 16'150	(gains)
Heat production	125'049		310'900	

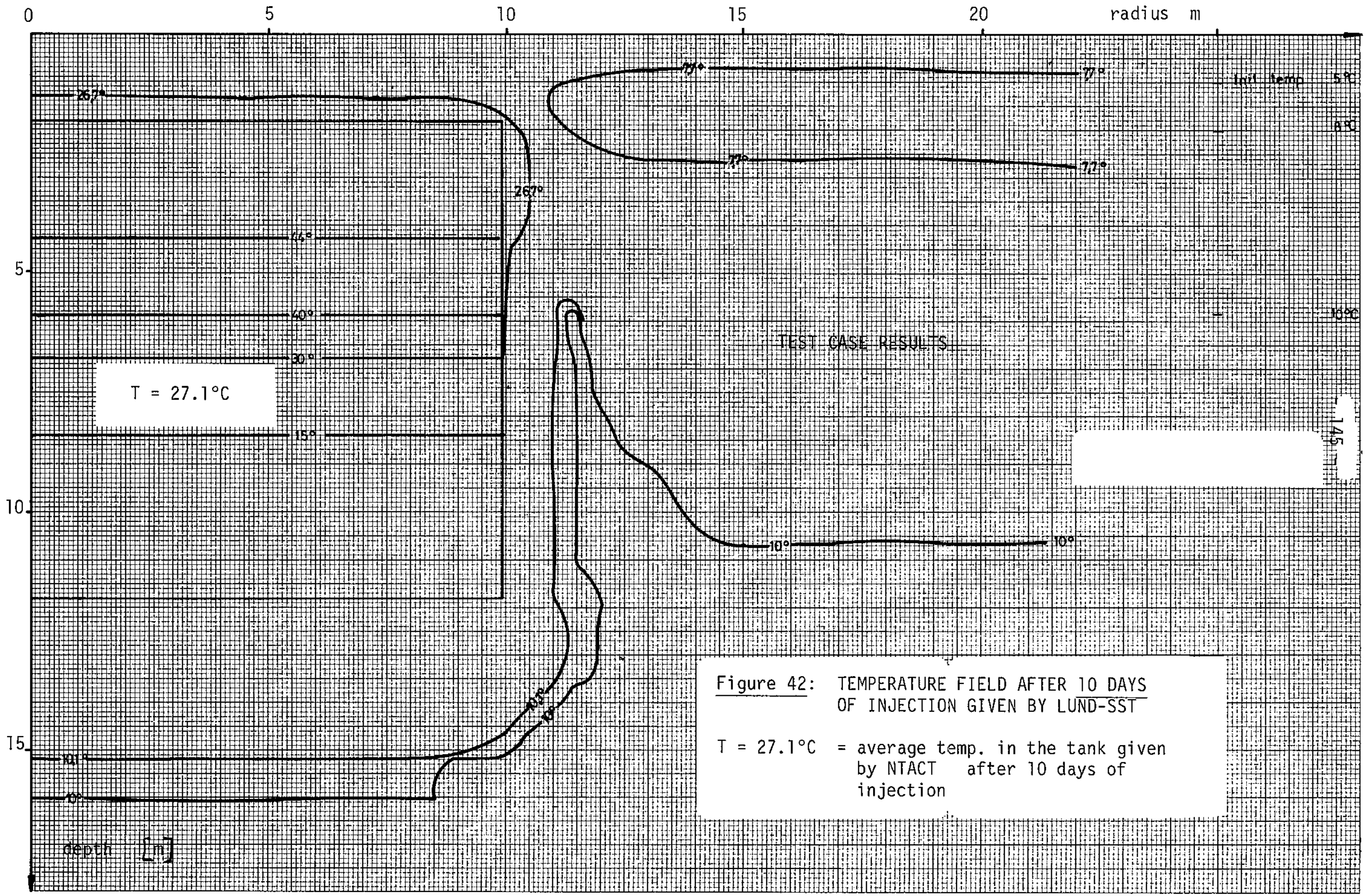


Figure 42: TEMPERATURE FIELD AFTER 10 DAYS OF INJECTION GIVEN BY LUND-SST

T = 27.1°C = average temp. in the tank given by NTACT after 10 days of injection

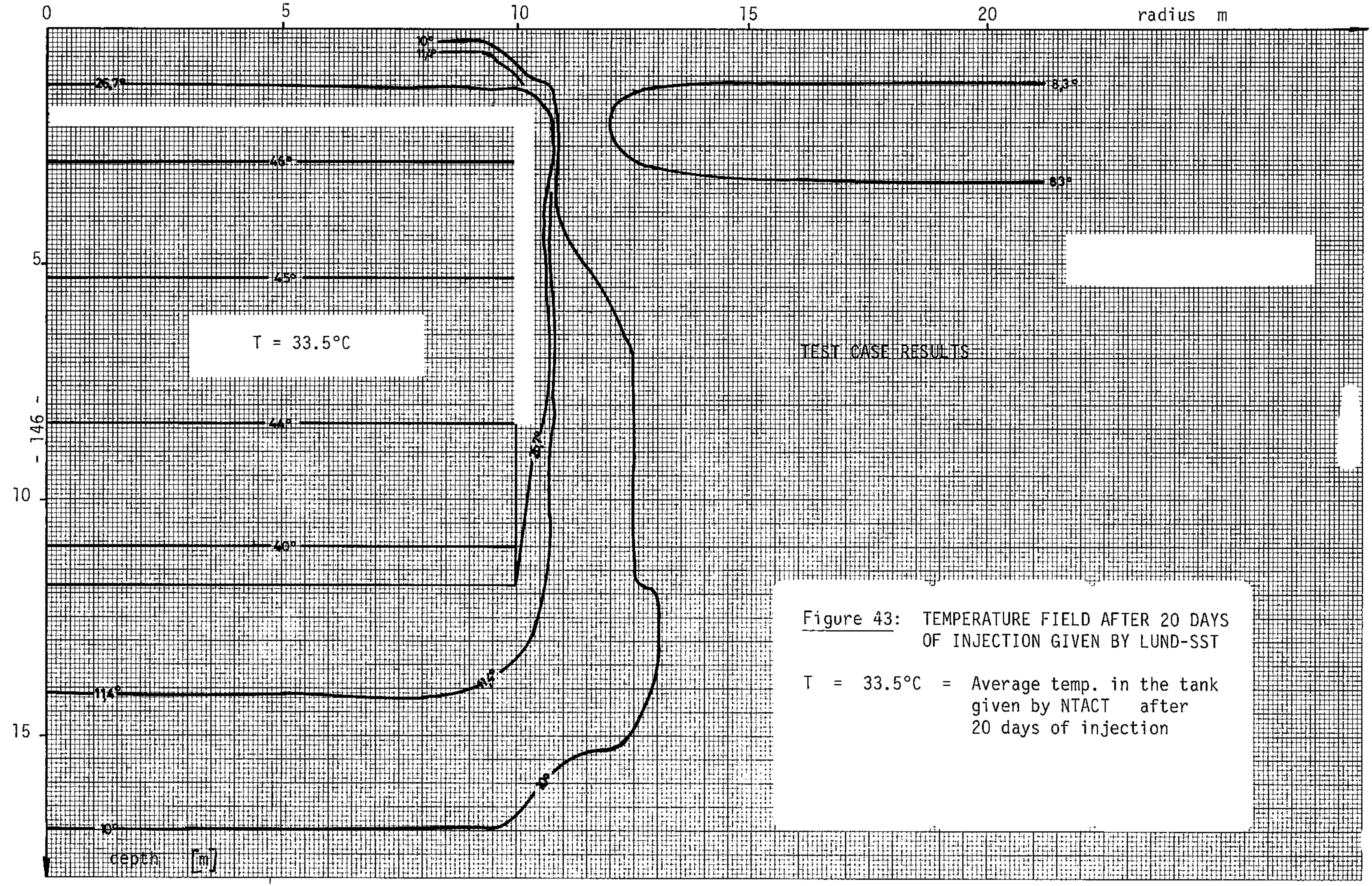


Figure 43: TEMPERATURE FIELD AFTER 20 DAYS OF INJECTION GIVEN BY LUND-SST

T = 33.5°C = Average temp. in the tank given by NTACT after 20 days of injection

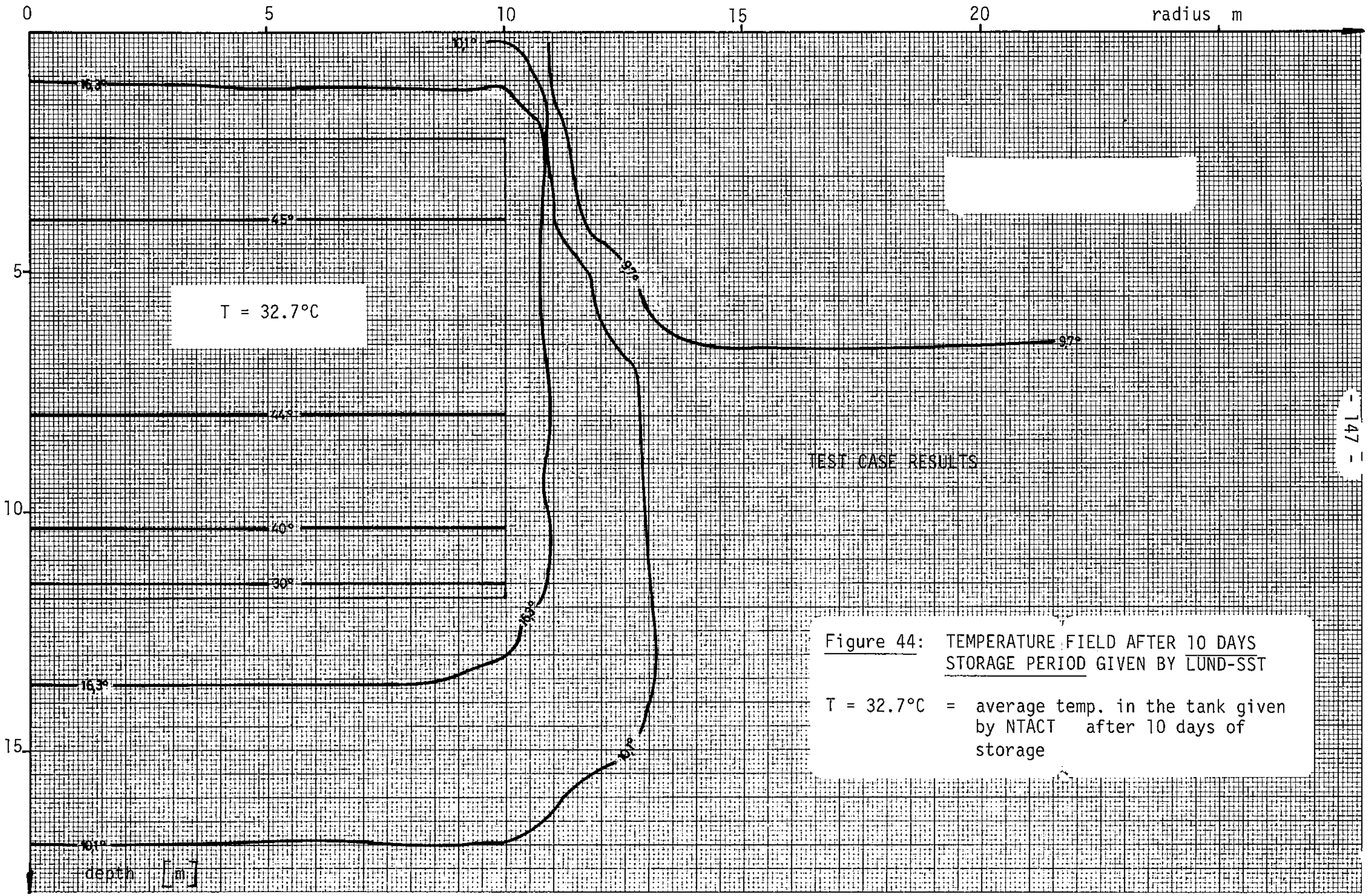


Figure 44: TEMPERATURE FIELD AFTER 10 DAYS STORAGE PERIOD GIVEN BY LUND-SST

T = 32.7°C = average temp. in the tank given by NTACT after 10 days of storage

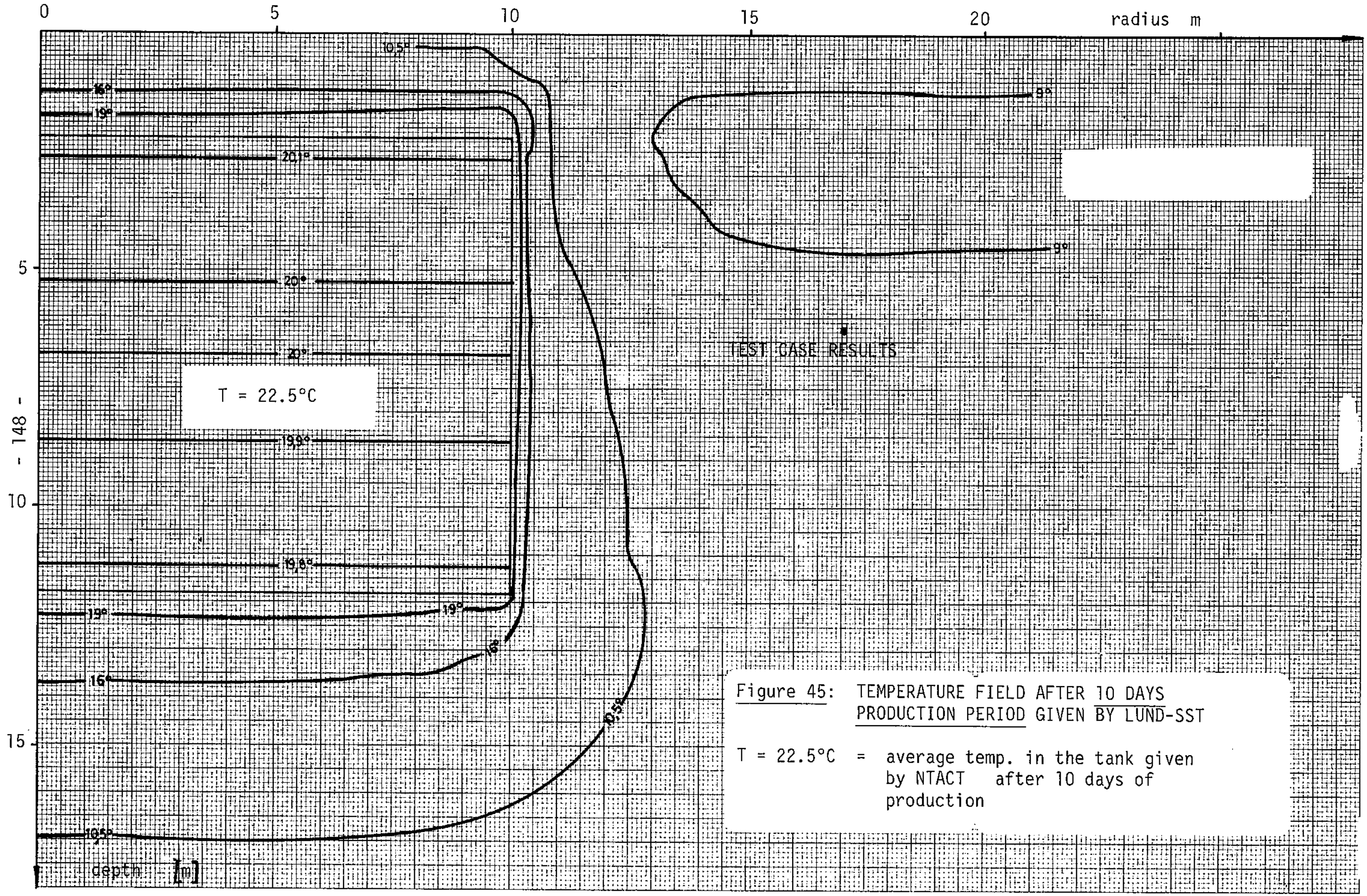


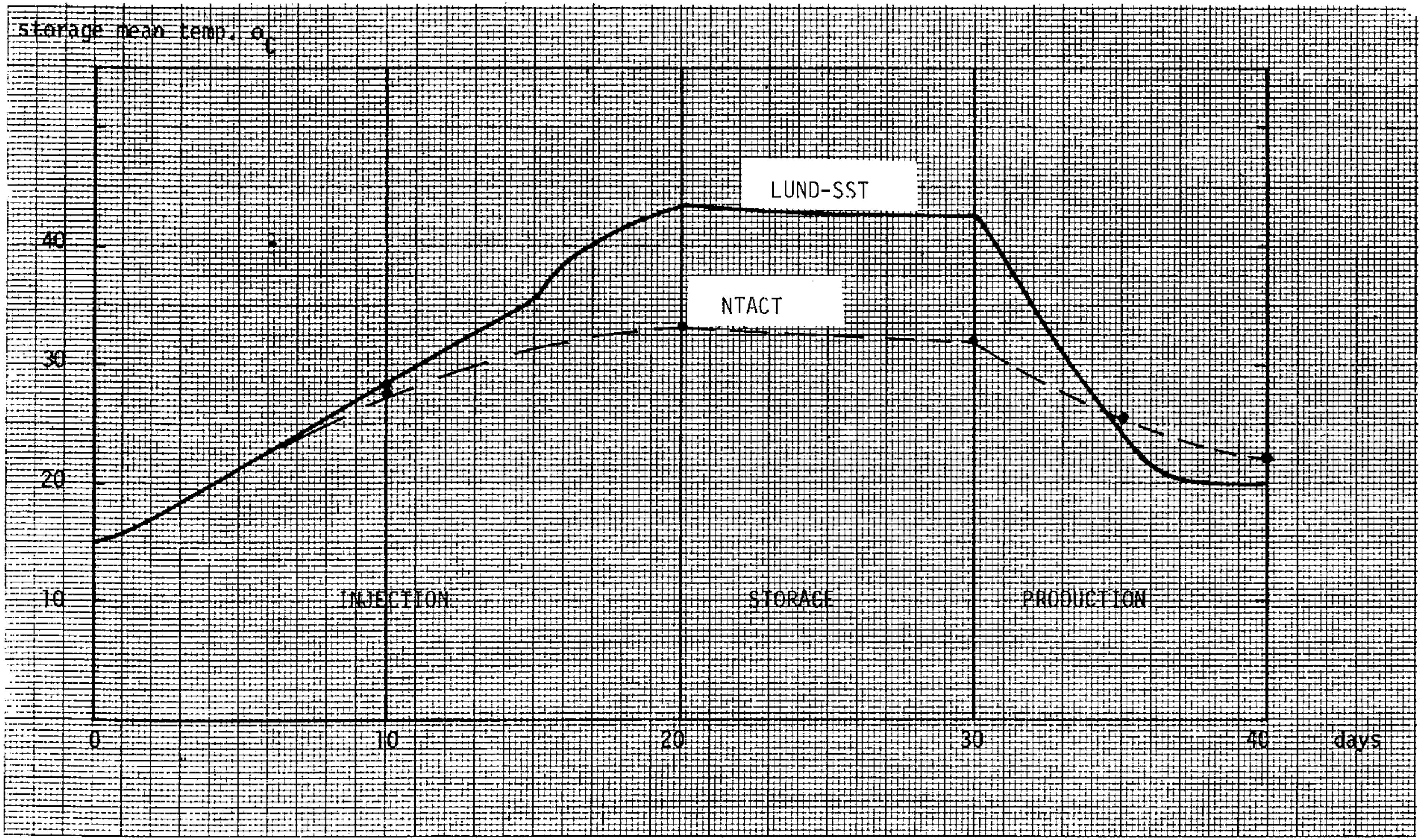
Figure 45: TEMPERATURE FIELD AFTER 10 DAYS PRODUCTION PERIOD GIVEN BY LUND-SST

T = 22.5°C = average temp. in the tank given by NTACT after 10 days of production

Figure 46: WATER TANK MODELS

Comparison of test case results

Evolution of the storage mean temperature



	NTACT	LUND
Computer	IBM ?	UNIVAC 1100/80
Memory size	250 K bytes	200 K bytes
CPU time	1 second for a year, daily time step	5 seconds for a year, hourly time step

Table 16: WATER TANK STORAGE MODEL - COMPUTING REQUIREMENTS

Appendix 6: TEST CASE RESULTS FOR EARTH STORAGE MODELS

In order to have a common reference base between models, a test case has been proposed to be run by each model.

The original test case and its conception is described in Appendix 4 of this report.

As the original test case has been generated without any model confirmation, the loading period has been found to be too short to allow a significant heat withdrawal.

A modified test case has thus also been run by the Swedish team, and we have run this modified test with the LT-TPD-I model.

Only 3 countries have sent results for the prescribed test case. These are: the Netherlands, Sweden and the United Kingdom.

The SPIPE model from Switzerland, and the GROCS model from the USA cannot handle the test without important modifications.

We did not receive results from EC (ADES-Store), but modifications to account for an upper insulation.

Therefore, the comparison will concern LT-TPD-I (original and modified version), LUND-DST, and TUBE.

A.6.1. ORIGINAL TEST CASE

The injection period lasts 20 days, the storage period 10 days, and the production period 10 days.

From the 3 countries that have run the test case, we received the code listing and the output listings of their runs.

From the Netherlands and Sweden, we received a description of the results, which is partially reproduced in the following pages.

It is important to note that only the DST model could handle the proposed test case. The LT-TPD-I and TUBE models have to simplify some conditions, such as variable air temperature, heterogenous soil properties, extension of insulation.

The LT-TPD-I model has been run with constant heat exchanger efficiencies for the injection and production periods: this might affect the heat injection and withdrawal rates.

The timesteps chosen for the run were also quite different between the models:

- 1 day for LT-TPD-I: this masks the fact that heat cannot be injected at the end of a day as the prescribed inlet temperature is too low (30°C) compared with the inlet temperature at noon (60°C)

- 200 s for the local process for the Duct Storage Model, and 3.5 hours for the global process

- 1 hour for TUBE

A.6.2. LT-TPD-I (ref. B-2)

Test runs with the LT-TPD-I model for an earth storage have been carried out with the prescribed input data, with the following remarks:

1. The heat exchanger: the rate of heat exchange for the given configuration has been calculated on the TPD-one-pipe-model

   Results:

   During heat input the average rate of heat exchange is 6500 W/K, and during heat output the rate of heat exchange is 4375 W/K.

   Remark: the heat resistance of the pipe wall is assumed to be zero.

2. The insulation: the insulation layer is thought to be extended over the whole top surface.

3. The ground:

   thermal conductivity: $\lambda_1 = \lambda_2 = \lambda_3 = 2.0$ W/mK

   initial soil temperature: T = 10°C at all depths.

4. Boundary conditions on the top.
   The air temperature is constant during the day.

The heat output was supposed to be zero if the temperature in the storage reservoir was below the inlet temperature.

A.6.3. LUND-DST (ref. B-7)

A cylindrical region, which contains 61 vertical pipes for the heat carrier fluid, is used. The duct storage model is used.

The program can handle the specified case without modifications. The insulation layer is represented by two cell layers at the top of the storage. The three soil strata are accounted for. the temperature at the ground surface above a surface resistance varies sinusoidally.

The total temperature field in the soil is represented by three parts: a global solution, a steady-flux solution, and local solutions around the pipes. The mesh of the global solution contains 18 x 26 cells. The smallest cell has the dimension 0.66 x 0.3 m2. The storage region is divided into three sections. There is a local solution and a balance for the convective heat flow in the pipes for each section. The local solution uses 13 cells. The radial width of the smallest cell is 0.025 m.

The total water flow through the pipes during injection periods and during extraction, as well as the inlet temperatures are as prescribed. The water flow pattern in the pipes of the storage region is not specified. We have assumed the following: the water is injected at the top and flows downwards to the bottom during injection and extraction of heat. The heat exchange during the return in an inner pipe is not considered. the three sections divide the storage into three horizontal layers. So there is a falling fluid temperature from top to bottom during injection.

The timestep of the global solution is 3.5 hours, and the timestep for the local solutions is 200 seconds. The computation required 21 seconds in total and 13 seconds of CPU-time on a UNIVAC 1100/80.

A.6.4. COMPARISON OF RESULTS

The comparison will be based on energy balances, temperature profiles, outlet temperature for 2 days, and mean storage temperature (see figures in the following pages).

In mean values, the 3 models gave comparable results. The losses calculated by the TUBE program appear to be very low compared with the other models (Table 17).

The vertical temperature profiles after 40 days confirm this remark (Figure 48).

The LUND model gives more precise indications about the local process, due to the short timestep used: it detects the fact that heat is withdrawn after the 15th day, at the end of the day (Figure 49).

The LT-TPD-I original version gives nearly the same results as the modified version: the simulation period seems too short to see the effect of the assumption of continuous upper insulation in the original version.

LT-TPD-I and LUND models compared well, even with the longer timestep taken for LT-TPD-I run and the constant heat exchange coefficient (Figure 50).

One should notice that even with few heat losses, the TUBE model leads to a "correct" mean temperature. Thus one could not presume that the model gives reliable results.

Table 17: EARTH STORAGE MODELS - COMPARISON OF RESULTS FOR THE ORIGINAL TEST CASE

injection: 20 days
storage: 10 days
production: 10 days

Days	Mwh	LUND	LT-TPD-I (original)	TUBE	LT-TPD-I (mod.version)
0	Injected Heat	31.97	29.19	25.14	29.09
↓	Extracted Heat	1.16	0		0
	Heat loss bottom	0.77	-		-
20	" " side	2.06	-		-
	" " top	0.07	-		-
	Total	2.90	3.56	0.3	3.55
	Injected Heat	0	0	0.04	0
21	Heat loss bottom	0	0	0	0
↓	" " side	0.59	-		-
	" " top	0.61	-		-
30	Total	2.7	1.93	0.32	1.92
31	Injected Heat	1.47	0	0.76	0
↓	Extracted Heat	0	0.25	0	0.25
40	Heat loss bottom	0.41	-	-	-
	" " side	1.14	-	-	-
	" " top	0.06	-	-	-
	Total	1.61	1.33	0.32	1.33
0 to 40	Total losses	7.21	6.82	0.95	6.80
	Remaining heat in storage	25.69		24.94	

Figure 47: Earth storage models - Comparison of results for the original test case

Vertical temperature profile at 9.5 m from the storage axis
(nearest pipe at 0.9 m from profile)

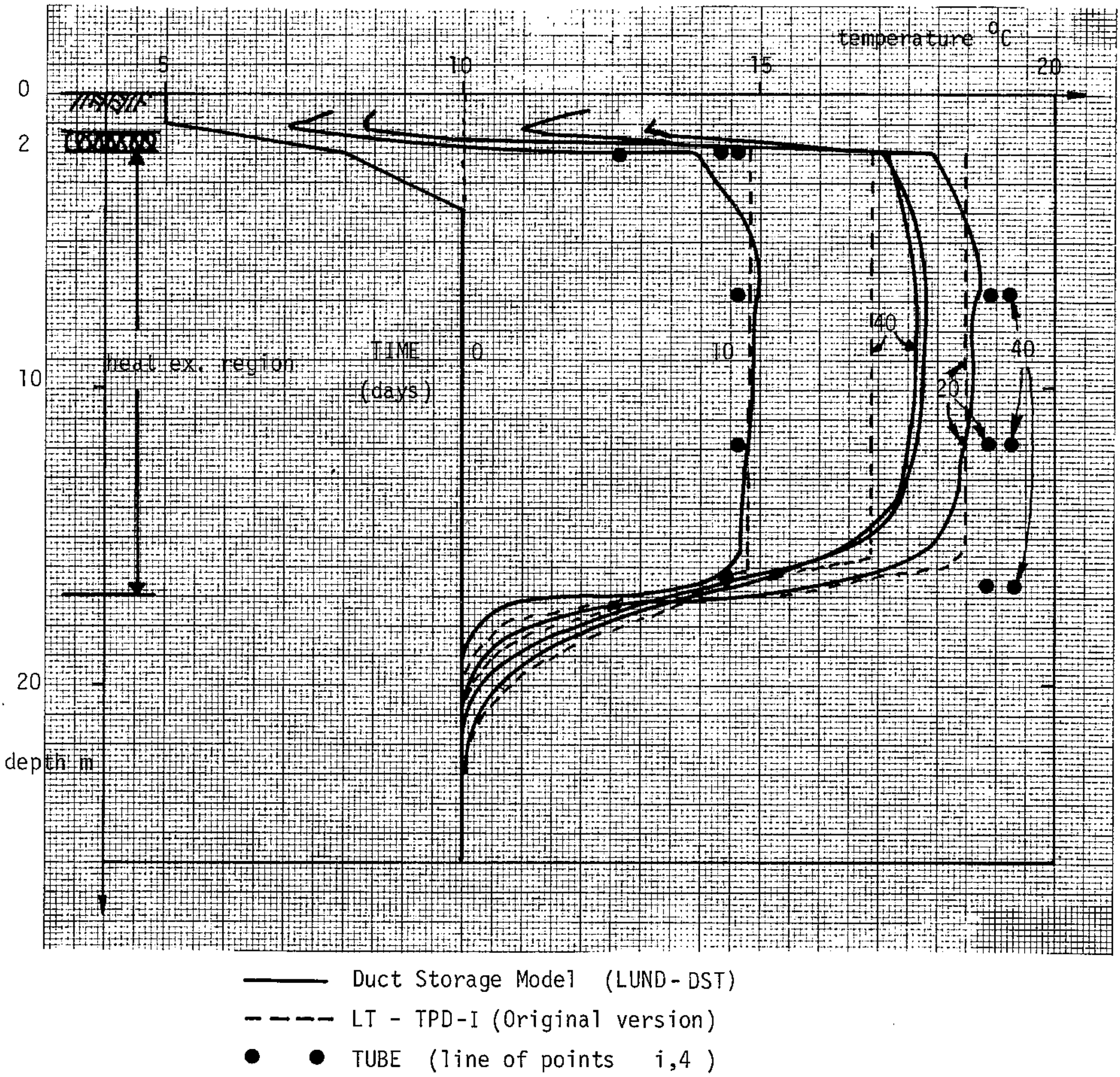
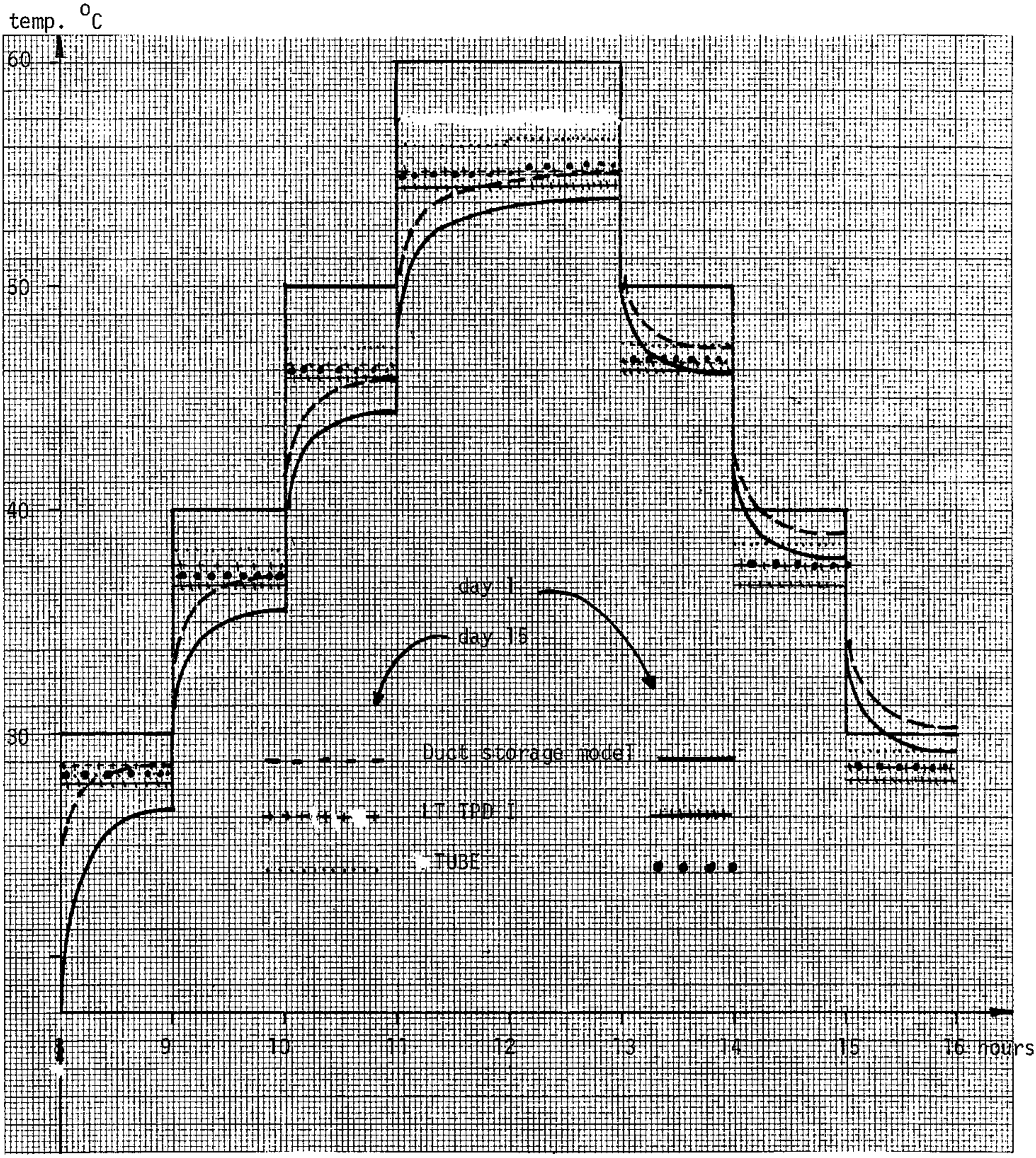


Figure 48: Earth storage models - Comparison of results for the original test case

Inlet and outlet temperature during the 1st and the 15th day

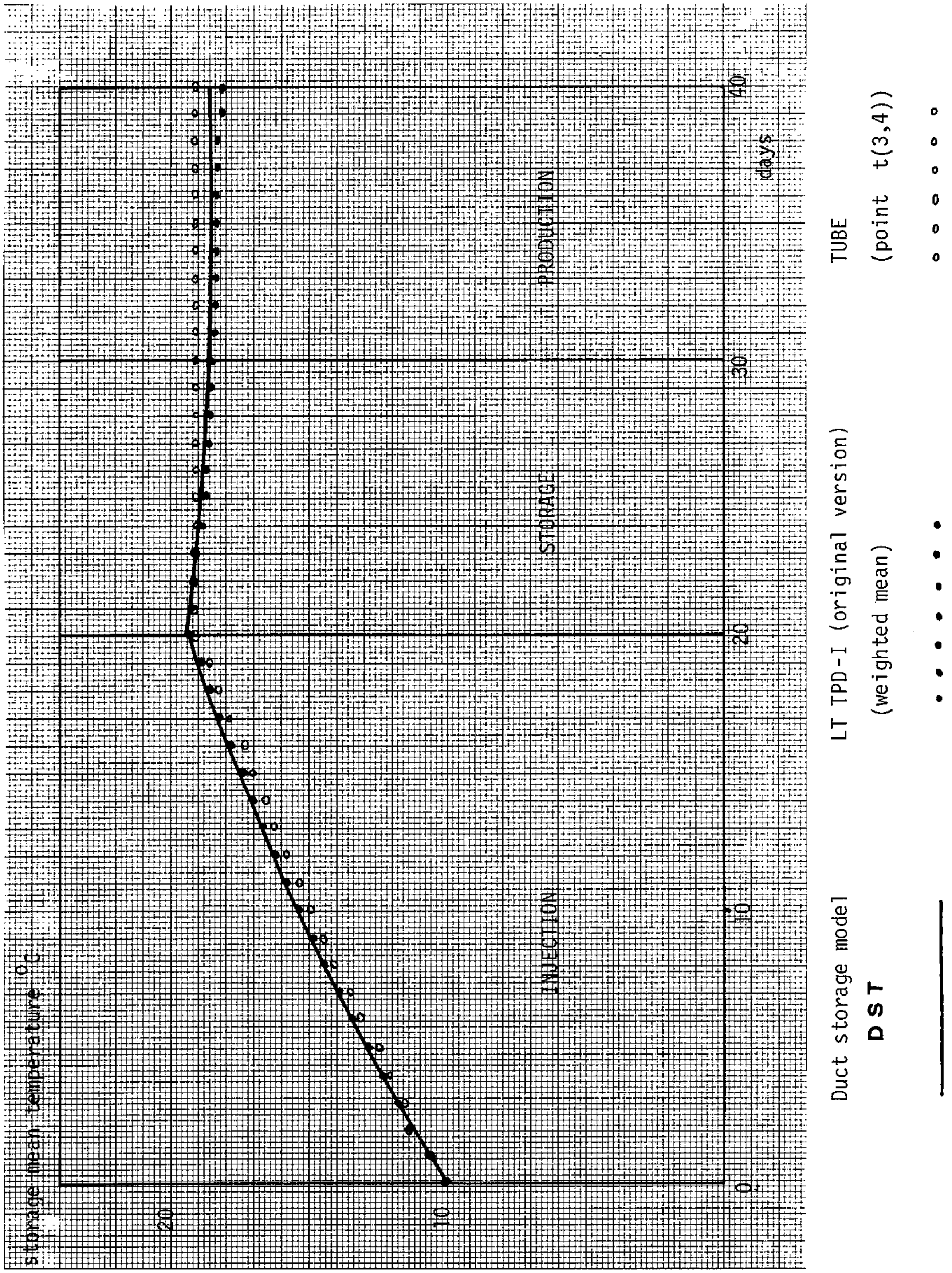


Note : time steps

- Duct storage model : 200 s
- LT TPD-I : 1 day with constant α
- TUBE : 1 hour

Figure 49: Earth storage models - Comparison of test case results

Computed mean temperature of the heat exchanger region



A.6.5. MODIFIED TEST CASE

As proposed by the Swedish team, the simulation period is multiplied now by three:

90 days of injection

30 days of storage

30 days of production

All other conditions remain unchanged.

This modified test case has been run the the LUND model in Sweden, LT-TPD-I (original and modified version) on our computer.

The results (Table 17 and Figure 51) show that LT-TPD-I seems to underestimate the injected heat and overestimates the extracted heat: this could be due to the assumption of constant heat exchange factor, and to the too large timestep used for the local process calculation (one day).

Table 18: EARTH STORAGE MODELS - COMPARISON OF RESULTS FOR A MODIFIED TEST CASE

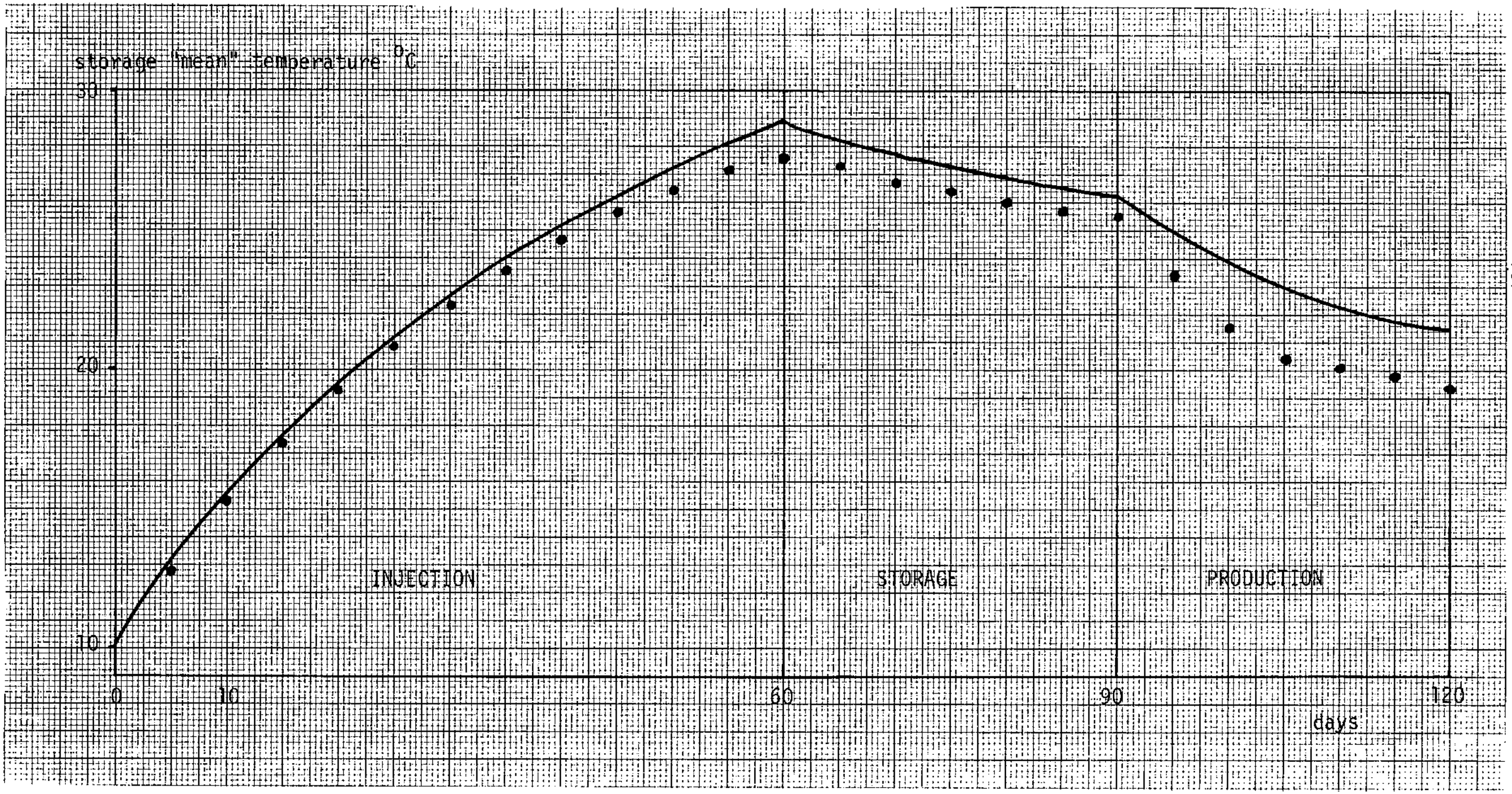
injection: 60 days
storage: 30 days
production: 30 days

Days	Mwh	LUND DST	LT-TPD-I (original)	LT-TPD-I (modified)
0 to 90	Injected heat	77.25	64.46	64.41
	Extracted heat	6.03	0	0
	Total heat losses	23.08	21.90	21.91
91 to 120	Injected heat		0	0
	Extracted heat	9.94	14.20	14.28
	Total heat losses	4.69	3.25	3.23
	Total losses	27.77	25.15	25.14

Figure 50: Earth storage models - Comparison of modified test case results

Duct storage model

LT TPD-I (original and modified version)



A.6.6. COMPUTATIONAL EFFORTS FOR THE ORIGINAL TEST CASE

The following table indicates the required memory size and CPU time for the original test case run, when this information has been made available to us.

	LUND-DST	LT-TPD-I	TUBE
Computer	UNIVAC 1100/80	?	?
Memory size for test case run	50/60 K	2/3 K	2/3 K
CPU time for the original test case run	13 s	3.6 s	
CPU per iteration (global solution)	0.047	0.095	

Table 19: EARTH STORAGE MODELS - COMPUTING REQUIREMENTS

A.6.7. CONCLUSION OF THE TEST CASE RUNS

Although few models have run the test case, it becomes interesting to note that the simple model LT-TPD-I compares well with the more complex one DST from Lund,
and that the TUBE model gives "approximate" results compared with the other models.

The test case has been found not to be significant enough to allow a clear decision to be made at this stage.

However, it has been constructed in order to get a more precise idea of what the models could handle, and of their performances.

Appendix 7: TEST CASE RESULTS FOR AQUIFER STORAGE MODELS

Four models have run the test case (CFEST, PT, SFM, and LUND-AST), and the LBL-Charts have also been used by the Lawrence Berkeley Laboratory.

Very detailed results have been provided by the modellers concerning these test cases and they can be found under References C-5, C-7, C-8, and C-9. A study of the discrepancies between PT and CFEST has also been done by the Pacific Northwest Laboratory (reference C-9).

A.7.1. ORIGINAL TEST CASE

The proposed test case was not a real case with measured data. The aim was to have a check point for the simple tools LUND-AST and LBL-Charts by comparing their results with the reference output given by complete models such as PT, CFEST or SHAFT 79.

The test case data was found not to be precise enough, so that different interpretations of the data have been done by the modellers.

Moreover, some data was missing for the complete models, such as the porosity, the storage coefficient, the dispersion lengths of the aquifer layer.

Due to the extent of work accomplished by the modellers for this IEA test case, a detailed description of the test case results will not be presented, but a summary of the major assumptions used by each modelling team and a comparison of some important results will be commented.

A.7.2. CFEST (ref. C-7)

The problem was interpreted as being vertically uniform and exhibiting steady-state flow during the injection and recovery cycles.

A two-dimensional horizontal analysis was performed with a one-dimensional vertical heat conduction solution within the bedrock and caprock assumed impervious.

Buoyancy effects within the aquifer were thus not taken into account, although the analysis pointed out that in the proposed case these effects may influence results.

Values of flow rate and injection temperature were taken as 1 m3/h per meter of aquifer thickness (total 10 m3/h) and 45°C respectively.

Longitudinal and transverse dispersivities of 1.5 m and 0.15 m were assumed in the aquifer, with a porosity of 20%.

The evolution of the temperatures in the store during injection, storage and recovery, and of the outlet temperature during production was provided (see comparison of results).

A.7.3. PT (CCC) (ref. C-8)

The main assumptions chosen for the simulation were justified in detail, and can be summarized by the following points:

- Tilting of the thermal front due to buoyancy flow was expected to be small and negligible for the test case using the tilting criteria developed under reference C-10. This was confirmed using two two-dimensional radial meshes, one with five layers, and the other with one layer, to represent the aquifer layer.

- Using a three-dimensional mesh, doublet effects were found to be significant during the injection period, but the recovery factor and production temperatures were almost not affected by doublet effects. A one well radially symmetrical two-dimensional model was thus found adequate for the proposed case.

- Despite an order of magnitude difference between the permeabilities of the caprock and bedrock the extent of the temperature increase above and below the aquifer was found to be very similar. The heat flow in these confining layers was thus conduction dominated.

- Little errors were made in assuming the problem to be symmetrical about the midplane of the aquifer.

- Daily temperature and flowrate variations were found to be unnecessary and could be replaced with constant average values taken as 45° C and 10 m3/h respectively. Other numerical studies were conducted concerning the mesh dependence, and the number of layers representing the aquifer.

- The porosity of the cap and bedrocks was assumed to be 40%, and the porosity of the aquifer 20%. A mixed specific heat for cap and bedrock was then derived, and differed from the one taken by the CFEST team. A storage coefficient of 10^{-4} (1/m) was assumed for all layers.

The evolution of the temperature in the domain during injection, storage, and production, for different conditions, and of the outlet temperature during production was provided (see comparison of results).

A.7.4. SFM (ref. C-8)

This simplified model, which is very similar to LUND-AST, was found to be applicable for the proposed case (no buoyancy effect, minor doublet effect, cap and bedrock almost impermeable).

The results were compared with PT runs and agreed well.

A.7.5. LUND-AST (ref. C-5)

The limits of validity of this simplified model were checked:

- the buoyancy effects (tilting criteria) were found to be negligible
- the doublet effect (thermal radius criteria) was found to have minor influence
- the bedrock and caprock permeabilities were found to be very small compared with that in the aquifer

An average injection temperature of 45°C was used.

Two cases were studied: one with an injection flow rate of 1.5 m3/h, and one with an injection flow rate of 5 m3/h. Only the second case will be considered in the comparison.

A.7.6. LBL-CHARTS (ref. C-8)

The two graphical characterization schemes were also used by the PT team, since they were adapted to the proposed test case.

A.7.7. COMPARISON OF THE TEST CASE RESULTS

Although different interpretations of the input data for the problem have been made (namely the LUND team took a flow rate of 5 m3/h while the other teams took 10 m3/h), a comparison can be achieved, mainly because SFM and AST are nearly the same models.

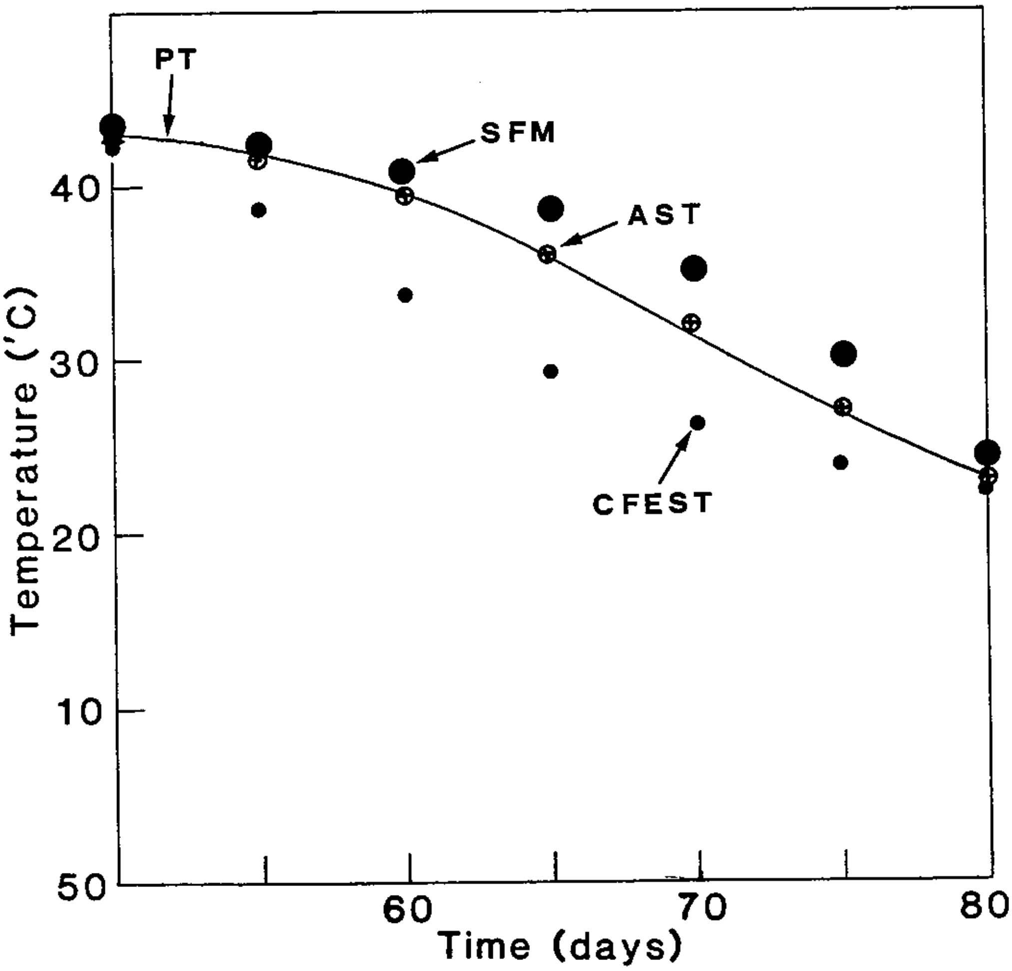
A.7.7.1. Production temperature versus time

The following figure represents the production temperature versus time found by the four models: PT, SFM, AST, and CFEST. Discrepancies can be found between all models. The differences between CFEST and PT could be explained by different assumptions concerning missing input data and the horizontal analysis performed by the CFEST team.

The SFM and AST curves have a shape similar to the PT curves, while these simplified models seem to overestimate the production temperature. This could mainly be due to the assumption of impermeable confining layers.

Figure 51: Aquifer storage models - Production temperature versus time

Comparison between models



Note : Assumed flow rate

10 m^3/h for PT, SFM, CFEST

5 m^3/h for AST

A.7.7.2. Energy recovery factor: e

Several definitions can be considered to define a recovery factor. In this report, we shall consider the following one:

$$e = \frac{\text{extracted energy}}{\text{injected energy}}$$ with a reference temperature

taken equal to the initial temperature in the domain (11°C).

The following table gives the value e found for the proposed test case by each model:

CFEST (horizontal 2D)	PT (radial 2D)	SFM (radial 2D)	AST (radial 2D)	LBL 1	LBL 2
0.600	0.704	0.749	0.702	0.745	0.753

Table 20: AQUIFER STORAGE MODELS - COMPARISON OF PREDICTED ENERGY RECOVERY FACTORS

Note:
- flow rate assumed: 10 m3/h except AST 5m3/h
- LBL 1: graphical method based on SFM simulations buoyancy effects can be neglected
- LBL 2: graphical method based on PT simulations buoyancy effects are accounted for

Except that the CFEST result can be explained as above, the reported values are very close to each other. We must note that SFM and AST are essentially the same models and the graphical methods LBL 1 and LBL 2 are derived from SFM and PT. Thus, the agreement must not be too surprising since the simplified models are applied within their limits of validity.

A.7.7.3. Computational efforts

Another point of interest is the core and computer time required to achieve the test case simulation since the models are to be used as subroutines of MINSUN and TRNSYS.

The computers, the mesh chosen, the timesteps being different, and the level of information given by the output (plots or not...) being also variable between models and methods, one should consider this information as indicative.

The following table presents the available information for "standard conditions" (average mesh):

	CFEST	PT	SFM	AST	LBL 1*	LBL 2*
Computer	PDP-11/70	?	?	UNIVAC 1100/80	---	---
Core needed	32K (16bit)	?	?	?	few K (?)	
Computer time	675 mn	?	?	6s	1s (?)	

Table 21: AQUIFER STORAGE MODELS - COMPUTING REQUIREMENTS

*: the graphical methods are not available as a "code". It could consist of tables of values or regression curves. The given figures are estimations.

LIST OF THE IEA TASK VII REPORTS

1. Tools for Analyzing Central Solar Heating Plants with Seasonal Storage,
Verne G. Chant, Ronald C. Biggs,
Subtask I(a) - June 1983 - Document CENSOL 1
Distribution: Technical Information Office
Solar Energy Program
Building R-92
National Research Council
Ottawa, Ontario K1A 0R6, Canada

2. The MINSUN Simulation and Optimization Program - Application and User's Guide,
prepared by Subtask I(a) participants from Canada and Sweden - Document CENSOL 2
Distribution: see Report N° 1

3. Basic Performance, Cost, and Operation of Solar Collectors for Heating Plants
with Seasonal Storage,
Charles A. Bankston
Subtask I(b) - May 1983
Distribution: National Technical Information Service
5285 Port Royal Road
Springfield, Va. 22161, USA

4. Heat Storage Models/Evalu ation and Selection,
Jean-Christophe Hadorn, Pierre Chuard,
Subtask I(c) - June 1983
Distribution: EDMZ
3000 Berne, Switzerland

5. Cost Data and Cost Equations for Heat Storage Concepts,
Jean-Christophe Hadorn, Pierre Chuard,
Subtask I(c) - June 1983
Distribution: EDMZ
3000 Berne, Switzerland

6. Heat Storage Systems: Concepts, Engineering Data, and Compilation of Projects,
Pierre Chuard, Jean-Christophe Hadorn,
Subtask I(c) - June 1983
Distribution: EDMZ
3000 BERNE, Switzerland

7. Basic Design Data for the Heat Distribution System,
Thomas Bruce, Lennart Lindeberg,
Subtask I(d) - October 1982 - Document D22:1982, ISBN 91-540-3819-7
Distribution: Svensk Byggtjänst
Box 7853
S - 10399 Stockholm, Sweden

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 simulation models for seasonal sensible heat storage. The aim is to evaluate and select computer programs which would be suitable for the needs of the IEA Task VII, dealing with Central Solar Heating Plants with Seasonal Storage (CSHPSS).

The report gathers general information about existing heat storage models among the ten participating countries, describes in detail some available models for different families of seasonal storage, and presents the evaluation and the final selection of models to be considered as common tools in the optimization and design of CSHPSS.

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