International Energy Agency

IEA District Heating and Cooling

Programme of Research, Development and Demonstration on District Heating and Cooling

FATIGUE ANALYSIS OF DISTRICT HEATING SYSTEMS

Published by

Novem

Acting as operating agent for
the IEA District Heating and Cooling project

1999: T4

International Energy Agency

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Fatigue Analysis of District Heating Systems

July 1999

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Date 1999-07-12

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Preface

The IEA was established in 1974 within the framework of the OECD to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the 21 IEA participating countries to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

As an element of the International Energy Programme, the participating countries undertake co-operative activities in energy RD&D.

District heating is seen by the IEA as a means by which countries may reduce their dependence on oil and improve their energy efficiency. It involves the increased use of indigenous or abundant fuels, the utilisation of waste energy and combined heat and power production.

With the same objectives district cooling is gaining increased acceptance. The positive environmental effects of improved energy efficiency will give an additional and very strong impulse to increase district heating and district cooling activities.

IEA's programme of Research, Development and Demonstration on district heating was established in 1983 at a meeting in Stockholm. In the first phase (Annex I) 10 countries took part in the programme: Belgium, Canada, Denmark, Germany, Finland, Italy, The Netherlands, Norway, Sweden and the USA. Later Annexes II, III and IV were prepared.

This project has been worked out under Annex V and 9 countries have participated: Canada, Denmark, Finland, Germany, Republic of Korea, The Netherlands, Norway, Sweden and United Kingdom.

The annex in question comprises the following technical areas:

- Cost effective district heating networks
- Optimal operation, operational availability and maintenance in district heating systems
- Optimisation of district heating operating temperatures and appraisal of the benefits of low temperature district heating
- District heating and cooling in future buildings
- Combined heating and cooling, balancing the production and demand in CHP
- Fatigue analysis of district heating systems
- Handbook on plastic pipe systems

NOVEM, Netherlands Agency for Energy and the Environment has been acting as the operating agent for Annex V.

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Acknowledgements

The temperature measurements described in this report are based on the goodwill and help from Korea District Heating Corporation, Seoul, Korea. Contact person: Mr. Lee, Hoon. In this connection we would like to thank this company.

In addition to this, the project was inspired by and received help from the members of the Expert Group, whom we would also like to thank:

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1. Summary and Conclusion

This project is divided in two parts:

1. A practical part with temperature measurements
2. A theoretical part dealing with design model and calculations.

Practical part

The practical part is a continuation of a project under IEA District Heating and Cooling, Annex IV: Temperature Variations in Preinsulated DH Pipes, Low Cycle Fatigue [2]. In this report temperature variations were measured at 17 district heating sites in Denmark, Germany, Korea, The Netherlands and Sweden.

For the present Annex V project the measurements were made by the Korean District Heating Corporation with the equipment used in the Annex IV project (4 units) at locations chosen by the Korean District Heating Corporation. The measurements at the four new locations lasted for one full year.

The data was sorted by the rain-flow method and matrixes of temperature variation and graphs are produced in accordance with the data processing done in the Annex IV project.

The data processing was done by Lund's Institute of Technology, Sweden.

Theoretical part

The discussion in the theoretical part is mainly based on the design model in a draft European standard [1] prepared by joint working group JWG1 under CEN/TC107/TC267. This standard uses the hot-spot method for low cycle fatigue analysis.

Based on this method a limited number of details of preinsulated bonded pipe systems are analysed. The details include:

- 90° L-bends
- Consumers connections, where the tee piece is the critical part
- Bevel welds (small changes of direction up to 5°)

Background

The development of preinsulated pipe systems for district heating has for quite some time been characterised by simplification of laying methods, thus employing cold-laying or pre-stressed systems instead of using expansion facilities like compensators and U-bends, giving more robust and cost-effective systems.

The simplified laying methods on the other hand give rise to higher stress and strain in the system, and therefore calculation methods have been developed in order that the full potential of the systems can be utilised. This development has, e.g., taken place in a technical committee, TC 107 under the European Standardisation Organisation, CEN. The result, a Draft Standard for the Design and Installation of Preinsulated Bonded Pipes for District Heating, is presently being prepared for enquiry [1].

When the stress range is larger than twice the yield stress, the system is said to be in the low cycle fatigue range. When designing according to the draft standard, it is clear that the most important limit state for preinsulated bonded pipes is low cycle fatigue. In this limit state, the temperature variations are the most decisive action.

On this background, the measuring project in Annex IV was implemented with the purpose to register the number of temperature variations (at 17 sites). In this project the measuring program was extended with 4 new sites in Korea. Furthermore, this project deals with the whole concept for calculation in the low cycle fatigue range to give a general view of the method and to give examples for fatigue analysis.

Results, practical part

In this project temperature measurements were made on 4 points numbered 18 to 21 in continuation of the 17 points in Annex IV. Point 19 is a commercial building with district cooling, the other sites are blocks with apartments as follows:

- Number 18: 208 apartments
- Number 20: 408 apartments
- Number 21: 690 apartments

All measuring points are placed in substations on the primary side, which means on the district heating side of the installation and on top and underside of the pipes.

The temperature variations are transformed to full temperature cycles with a full temperature variation at ΔT_{ref} = 110°C. The results for the 4 sites are shown in enclosure S/R 18 to 21.

The results for point 19 and 21 are in the same range as the results in Annex IV while the results for point 18 and 20 for the return pipe gives much higher values than have been seen in Annex IV. The maximum value in Annex IV was about 400 cycles for $b = 4$ (b is the slope of the SN-curve) for the return pipes by the consumer. For point 18 and 20 the corresponding values are about 730 cycles.

A new table for all the results in Annexes IV and V has been worked out, see table 1.1. There are no changes for production (main pipes), while all the new figures are found at consumers. The values from Annex IV can be seen in table 3.1.

All the values for $b = 4$ are plotted in enclosures 1A, B and C with the limit values recommended in the draft European standard [1].

Supply Production	Min.	Average	Max.
$b = 3$	17	136	365
$b = 4$	4	42	102
$b = 5$	1	18	37

Return Production	Min.	Average	Max.
$b = 3$	2	7	14
$b = 4$	0	1	1
$b = 5$	0	0	1

Supply Consumer	Min.	Average	Max.
$b = 3$	7	130	578
$b = 4$	2	51	308
$b = 5$	1	28	197

Return Consumer	Min.	Average	Max.
$b = 3$	30	788	2828
$b = 4$	4	207	728
$b = 5$	1	66	233

Table 1.1 Numbers of full temperature cycles for ΔT_{ref} = 110°C and b = 3, 4 and 5 based on results in this project and in the project in Annex IV [2].

By analysing the results from measuring on top and bottom of the pipes, it can be concluded, that there are only small differences on the supply pipe. On the return pipe there are differences, which go up to 25°C with some single values of 40°C. Especially one consumer has big differences in the summertime. The differences mean very little for the fatigue analyses, but the differences may have effect on temperature measuring in connection with operation and energy measuring systems.

The commercial building with district cooling has an average number of temperature cycles, but the level for the return temperature is in the range from 60°C to 100°C with an average of about 80°C. This level is 10-20°C higher than the other consumers.

Results theoretical part

In this project there has been developed a proposal for "design lines" for the temperature historic. The lines are shown in figure 7.2 to 7.5. The formulas for the curves are as follows:

- For all supply pipes and return pipes production:

$$n_i = 2 \cdot 10^6 \cdot \left(\frac{1}{\Delta T_i} \right)^{2.6}$$

- For return pipes at consumers:

$$n_i = 2 \cdot 10^6 \cdot \left(\frac{1}{\Delta T_i} \right)^{2.2}$$

where

n_i is number of cycles during 30 years for $\Delta T_i = 1, 2, 3 \ldots$ °C.

n_1 ($\Delta T_1 = 1$) means all cycles for $0 < \Delta T \leq 1$°C

n_2 ($\Delta T_2 = 2$) means all cycles for 1°C $< \Delta T \leq 2$°C

etc.

Example:

For $\Delta T_i = 50$°C the formula for consumer return pipes gives $n_i = 366$. This means that over 30 years 366 temperature variations can be expected in the range from 50-51°C. If the formula for supply pipes is used, we get 77 expected temperature variations instead.

Conclusions, design model

A conservative conclusion based on the results of the present project would be:

1. The present design method as suggested by the draft European standard [1] is maintained:
   - The Palmgren-Miner rule applies.
   - The number of full temperature cycles, N_{ss} is calculated from temperature history presuming a SN-curve and a refernce temperature, ΔT_{ref}
   - The stress variations are proportional to the temperature variations, $\Delta\sigma = c \cdot \Delta T$.
   - Von Mises or Tresca for multi-axial stress/strain state.
   - Same SN-curve is used for lifetime estimation.
2. Further improvement of design methods must be based on fracture mechanics and stress history.
3. Fatigue life must be characterised by temperature history, not by full temperature cycles.
4. Small temperature cycles e.g. $\Delta T <$ 40°C can be ignored.
5. Modelling of pipe-soil interaction must be improved, specially p-y diagrams in areas with road surface.
6. Stress intensification factors should be based on "hot-spot" stresses. It should be investigated if the difference between "hot-spot" stresses and the "experimental" method (Markl [14-17]) applies to other components than bends.
7. The calculation examples might suggest that a higher SN-curve could be applied for un-welded material. However, insufficient modelling of soil reactions, the transformation from multi-axial stress state to reference stress and the lack of reduction factor for electro-chemical environmental actions indicate that the designer should be cautious applying a higher limit.
8. Concerning multi-axial stress-strain state:
   A "flat" SN-curve ($b \geq 4$) is more likely to represent the true conditions rather than a "steep" SN-curve ($b \leq 3$)

Alternative conclusion

The uncertainties in the present design methods are large concerning:

1. Actions (temperature history and p-y diagrams)
2. Modelling, see chapter 8 and 9
3. Stress concentration factors
4. Choice of SN-curves including the effect of electro-chemical environment.

Alternative design approaches could be:

Temperature variations must be monitored (specially at the consumers) and controlled at a low level ($N_0 <$??). If N_0 is chosen

sufficiently low, low cycle fatigue design will be unnecessary. This approach will be possible in systems equipped with "intelligent" heat meters presently under development.

Or

For T_{design} < e.g. 90°C design is done according to company standards and low cycle fatigue design is unnecessary.
For T_{design} > e.g. 90°C cavities are established at all expansions and all tees are chosen according to DIN 2615 Reihe 4. With this approach it might also be possible to develop standardised solutions in order that low cycle fatigue design becomes unnecessary.

Or

For T_{design} < e.g. 120°C and preheating design is done according to company standards. Stress reducing measures must be taken for bends and tees.

It is presupposed that the above mentioned company standards are developed in accordance with the European standard [1] or other generally recognised methodology for piping systems taking the large axial forces in preinsulated pipes into account.

Calculation examples
In the report calculations are made on bends, tees and bevel welds. The calculations are based on the draft European standard [1].

The calculations in chapter 8 show that modelling with beam-element programmes with bi-linear soil springs is very sensitive to the placing of the springs.

A number of stress reducing measures have been examined. It is well known that increasing the bend radius reduces the stresses and thus increases the fatigue life. Increasing the wall thickness of the bend gives a moderate increase of the fatigue life in some cases.

The most consistent way to increase the fatigue life for bends is to increase the flexibility locally by creating cavities. Foam cushions can also be used, but they have their own limitatation (see clause 7.4, Bends).

The results for bends are shown in enclosure 8A.

The calculations in chapter 9 concerns tee at branch connection to consumers.

Again it is shown that minor changes in the modelling give large variations in the results.

The calculations of tees show that choosing right type of a tee can give a considerable increase in fatigue life. very high numbers of cycles. For example an extruded tee DN200/DN80 with standard pipe wall thickness and a axial stress 150 N/mm^2 in the main pipe can only allow 58 load cycles. If instead a DIN 2605 Teil 1, Reihe 4 weld-in tee is chosen, the cycles will be increased to 7469 (ΔT_{ref} = 110°C, b = 4).

The calculations confirm that problems with the fatigue life of tees always can be handled by increasing the wall thickness.

The calculations for tees are shown in enclosure 9A and B.

The calculations on bevel welds in chapter 10 show that there are no fatigue problems with respect to the calculations in the report. But bevel welds can give problems with buckling by cold laid systems where the second order effects (local buckling) can be a decisive action.

Further studies
1. At measuring sites R12, R18 and R20 fatigue failures have been recorded. However, none of these sites have had a life time of 30 years in spite of the fact that the number of full temperature cycles have been calculated to be in range normally assumed by design. For these sites it might be interesting to establish the actual stress history.

Alternatively it could be considered if the rather large number of temperature cycles can have caused micro cracking, which due to the electro-chemical environment (the pH-value of the water), causes stress crack corrosion (SCC) earlier than expected by the usual design approach.

2. Calculating the reference stress at a multi-axial stress state by using von Mises or Tresca yield criterions. The possible error thus introduced might explain the difference in the SN-curves used and the lower experimental curve established by Markl [14-17].
3. Improved modelling of the pipe-soil interaction under road surfaces and development of a methodology applicable for practical use.
4. The present study deals mainly with the lifetime of the steel pipes. However, increased stress levels in the steel will also give increased stresses in the PUR-foam. The limit state for compression and shear stresses in the PUR-foam are insufficiently well known and should be elaborated further.
5. There are still some uncertainties concerning stress concentration factors mainly due to the difference between stress concentration factors based "hot-spot stresses" and factors based experiments. However, the way the stress concentration factors are applied when modelling the pipe systems can give large differences. For example the two methods for calculating stresses in the draft European standard [1] give much different results.
6. The calculations in chapter 8 and 9 have confirmed what often has been observed when making comparative studies with different edp-programmes: Beam-element programmes with elastic-plastic soil springs are very sensitive to even small changes in the model. Minor changes in the modelling can give large differences in the calculated lifetime. It would therefore be suitable if minimum requirements for modelling were set up.
7. Further assessment of the influence of the electro-chemical environment on the fatigue life of preinsulated district heating pipes. In principle this could be done by making fatigue tests on relevant steel qualities embedded in hot district heating water. Especially it should be examined what influence the pH-value has. Only very limited research has been done in this field because the effect of corrosion on low cycle fatigue cracking cannot be accelerated.

2.Introduction

2.1 Background

Codes for piping systems under pressure normally presumes that the force controlled actions (e.g. pressure and selfweight) are the decisive actions. However, for district heating pipes it is normally the deformation controlled actions (stresses induced by temperature variations in the low cycle fatigue range), which are decisive.

The number of cycles used in the fatigue analysis were analysed based on measurements in the IEA project in Annex IV: Temperature Variation in Preinsulated DH Pipes, Low Cycle Fatigue, see reference [2] and chapter 3, Previous Work.

However, this project raised a number of questions concerning the methodology used in fatigue analysis in the low cycle range. These questions are addressed in this project.

Furthermore this project is based on design methods given in the draft European standard [1].

Purpose of the project:
The purpose of the project is:

1. To make additional measurements of temperature variations on Korean district heating systems, and to process and analyse these data according to the processing done in the Annex IV project: Temperature Variations in DH Systems [2].

2. To assess coherent values for fatigue curve stress intensification factors and number of full equivalent load cycles, and to establish user-friendly design data for fatigue analyses with the hot-spot method for Preinsulated DH systems.

Introduction
Traditionally fatigue analyses for DH systems are based on fatigue curves and stress intensification factors developed by Markl in USA in the mid fifties [14, 15, 16, 17]. These results come from test on large specimens (bends and tees), and they were made on steel types, which are not used any more. The results have been used in a large number of codes for piping design:

- ANSI B31.1, Power Piping (USA)
- The Stoomwezen Rules (The Netherlands)
- Rörledningsnormer (Sweden), etc.

The most recent development is that the so-called hot-spot method is used for fatigue analysis in contrary to the above-mentioned experimental method. The major reasons for this are that it now is possible to calculate or measure hot-spot stresses e.g. by FEM-analysis on computers or by measurement with strain gauges. Experiments on full size specimens are only used to verify the results reached by hot-spot analysis, because fatigue experiments are very expensive, and it is therefore not possible to cover all situations, which will occur in practical design.

The hot-spot method is used in:

- Off-shore design
- Eurocode 3, Design of steel structures
- The first draft from CEN/TC267, Industrial piping
- The first draft from CEN/TC54, Pressure Vessels
- Danish code of practice for DH distribution systems, DS448 [8]

In the draft European standard [1] only the hot-spot method is used.

The results of the IEA, Annex IV project Temperature Variations in DH Systems [2] have shown that the largest numbers of cycles are found in consumers connections. However, the maximum number of full

load cycles are found in the return lines and not in the supply line.

Also this project have lead to the realisation, that the number of full load cycles (the decisive figure in fatigue analysis) is not "a fixed figure" for a given system. The figure is not a characteristic of the system, because the conversion from the real measured data to the number of full action cycles depend on the shape of the fatigue curve used in the fatigue analysis (the slope constant b) and the arbitrary chosen reference temperature, ΔT_{ref}. This means that the number of full action cycles depend on material properties, which is unusual for an action.

The conclusion from the project in annex IV was:

When making fatigue analysis in DH systems it is crucial that the choice of

- fatigue curve
- stress intensification factors
- number of equivalent full load cycles (for a given ΔT_{ref})

belong together

This statement makes an assumption for this project, which deals with all elements in fatigue design (load, fatigue curve, stress factors)

2.2 Project Proposal

The project is divided in two parts:

1. A practical part with temperature measurements.
2. A theoretical part dealing with design model and calculations.

Practical part

Measurements have been made by the Korean District Heating Corp. with the equipment used in the Annex IV project (4 units) at locations chosen by the Korean District Heating Corporation. The temperatures have been measured for one year.

The data is sorted by the rain-flow method and matrixes of temperature variation and graphs are produced in accordance with the data processing done in the Annex IV project.

The data processing is done by Lunds Technical University, Sweden.

Theoretical part

The theoretical part is based on the design model in the draft European standard [1], which is based on the hot-spot method.

Based on this method a limited number of details of preinsulated bounded pipe systems are analysed. The details include:

- 90° L-bends, chapter 8
- Consumers connection, where the tee piece is the critical part, chapter 9
- Bevel welds (small changes of direction up to 5°), chapter 10.

3.Previous Works

Concerning previous work the results from the IEA report, Temperature Variations in Preinsulated DH Pipes, Low Cycle Fatigue, [2] are reported below. For other works please confer to the references in chapter 12 and the description in Annex IV report [2].

From the conclusion of the above mentioned IEA report, [2], following can be cited: A summary of the calculated number of full temperature cycles is given in the table 3.1 below for the reference temperature ΔT_{ref} = 110°C. The factor b is the slope constant of the fatigue curve in a double logarithmic diagram.

Supply Production	Min.	Average	Max.
b = 3	17	136	365
b = 4	4	42	102
b = 5	1	18	37

Return Production	Min.	Average	Max.
b = 3	2	7	14
b = 4	0	1	1
b = 5	0	0	1

Supply Consumer	Min.	Average	Max.
b = 3	7	139	578
b = 4	2	55	308
b = 5	1	31	197

Return Consumer	Min.	Average	Max
b = 3	35	429	1050
b = 4	4	111	379
b = 5	1	37	157

Table 3.1 Number of full temperature cycles for ΔT_{ref} = 110°C and b = 3, 4 and 5.

It shall be noticed that the highest values are at the consumers return pipe and the smallest at the return pipe at the production sites. The difference is significant.

The largest values of full temperature cycles calculated for b = 3 are within the range specified in the guideline in the Danish code of practice for DH pipes [8], which specify a SN-curve with b = 3.

These values in DS448 are:

- 100 - 250 full temperature cycles for large main pipelines
- 250 - 500 full temperature cycles for ordinary distribution pipelines
- 500 - 2500 full temperature cycles for house service connections

The same recommendations are used in the draft European Standard for design and installation of preinsulated bonded pipes for district heating [1], though the lower limit for house service connection are set at 1000 instead of 500.

Lower figures should only be used, if the designer has a firm knowledge of the temperature history to which the system in question will be subject. Even if such knowledge is available conservatism is advisable, because there might be suspicion that the expectations of the operating personnel are not in accordance with the realities. Furthermore it is important to be aware of systems with irregular operational conditions and future changes in operational conditions.

The information on where the largest number of full cycles occur should cause more attention to details like the fatigue life of branch connections at consumers, especially the tee where the branch is connected to the main pipe.

The operating personnel should use the results to evaluate the mode of operation and especially the impacts on the DH system from the consumers. Some temperature variations are due to energy saving measures and the systems should of course be designed to withstand these variations. However, many of the temperature curves

more than indicate that many of the large temperature variations occur due to inexpedient instrumentation or over-sized control valves at the consumers, thus causing an unnecessary wear of the system.

Finally, it must be mentioned that although the Palmgren-Miner cumulative damage rule is a generally accepted theory for fatigue analysis. There is a strong suspicion, that a temperature history with few large temperature cycles is more harmful than a temperature history with many small variations, which give the same number of full temperature cycles.

This is especially true for preinsulated bonded pipes. If for example a change of direction is designed with foam cushions in order to absorb the expansion of e.g. $\Delta T = 110°C$, it is more or less evident that the construction detail better can absorb a large number of small temperature variations than a limited number of very big variations.

When the Annex IV project originally was planned it was expected that processing of the temperature measurements would give figures for full temperature cycles, which, without any further consideration, could be used as a design basis when designing bends, tees and other district heating components in the low cycle fatigue range.

However, even though the project has added considerably to the knowledge of temperature variations it has not given the final answer, but raised a number of new questions.

The most important question is the choice of limit state for low cycle fatigue, the SN-curve. It is very important that the same SN-curve is used for calculation of the number of full temperature cycles and as limit state for the fatigue analysis, but which curve is most relevant for buried preinsulated pipes, $b = 3$, 4 or 5?

The second question is the conversion into full temperature cycles. From many of the temperature spectra it is seen that very many of the temperature cycles must be in the high cycle fatigue range and it might therefore not be correct to convert them into few cycles in the low cycle fatigue range.

A third question is the assumption that the stress differences are proportional to the temperature differences.

From the conclusion can also be noted, that

- The number of full temperature cycles depends on b.
- The large peaks have the greatest influence (especially for $b = 5$).
- The small peaks have greater influence for $b = 3$.

Draft European Standard

In the draft European standard [1] following recommendation is given:

The number of full action chosen must not be lower than the number of equivalent full action cycles stated in table 3.2:

Main pipelines	100
Distribution pipelines	250
Service connections	1000

Table 3.2 Equivalent full action cycles.

In the draft standard an SN-curve with $b = 4$ is given. This means that the values in table 3.2 refer to an SN-curve with $b = 4$. This again means that the values in table 3.2 cannot directly be compared with the values in the Danish code of practice as it refers to an SN-curve with $b = 3$. In fact due to the various SN-curves the recommendation in the draft standard is to use a higher value than the recommendation in the Danish code of practice. This can be seen in table 3.1 where the same temperature action by for instance maximum "Supply Production" gives 365 equivalent cycles for $b = 3$ and 102 equivalent cycles for $b = 4$.

The question is whether it is a good idea to operate with the equivalent cycles as a recommendation as the value depends on material properties. This question will be discussed later in this report.

4.Temperature Variations in Korean DH Systems

4.1 Description of Measuring Points

In this chapter all the measuring points will be described briefly. The description is based on a questionnaire, which has been filled in by the utility involved.

The measuring points are numbered from 18 to 21 in continuation of the 17 points in Annex IV. The supply pipes has an "S" before the number and the return pipes has an "R" before the number.

All the measuring points are placed in substations on the primary side, which means on the district heating side of the installation, and on top and underside of the pipes.

Points S18/R18:
380 apartments with indirect connection. The substation is equipped with heat exchangers for space heating and domestic hot water and no storage tank for domestic hot water.

Points S19/R19:
Commercial building with indirect connection. There are absorption chillers for district cooling, space heating and domestic hot water and no storage tank for domestic hot water.

Points S20/R20:
408 apartments with indirect connection. The substation is equipped with heat exchangers for space heating and domestic hot water and no storage tank for domestic hot water.

Points S21/R21:
690 apartments with indirect connection. The substation is equipped with heat exchangers for space heating and domestic hot water and no storage tank for domestic hot water.

In table 4.1 and 4.2 additional information about the measuring points are listed.

On the system with S18/R18 there has been one break down related to fatigue close to a weld.

On the other system there has been 4 breakdowns related to fatigue, 3 times in the neck of tees and one time close to a weld.

4.2 Measuring Programme

The measurements started at the beginning of February 1997 and ended at the end of February 1998. Table 4.3 states the start and finish dates of the measuring period together with the amount of missing days.

Mes. point no.	Type of installation	Type of consumer	Indirect installation	District cooling	Space heating	Domestic hot water	Hot water storage	Distance to production site	Pipe diameter
S18 R18	Consumer substation	Apartments (380 house-holds)	Yes	No	Yes	Yes	No	5 km	80 mm
S19 R19	Consumer substation	Commercial building	Yes	Yes	Yes	Yes	No	50 m	100 mm
S20 R20	Consumer substation	Apartments (408 house-holds)	Yes	No	Yes	Yes	No	6 km	125 mm
S21 S21	Consumer substation	Apartments (690 house-holds)	Yes	No	Yes	Yes	No	12 km	150 mm

Table 4.1 Replies from Questionnaire concerning consumer installations

Mes. point no.	No of consumers	Pipe type	Length of main pipes	Length of house connections	Max dimen-sion	Age of network	Design temp.	Design pressure
S18/R18	197 sub-stations for apartments (62.222 house holds) +46 sub-stations for office buildings =243 sub-stations all together	100% PP	> 200 mm: 109 km	<150 mm: 68 km	850 mm	1991-1993	Supply: 115°C Return: 65°C.	16 bar
S19/R19 S20/R20 S21/R21	402 substations for apartments (100.719 house holds) +397 sub-stations for office buildings =799 sub- stations all together	100% PP	>200 mm: 189 km	<150 mm: 229 km	850 mm	1990-1993	Supply: 115°C Return: 65°C	16 bar

Table 4.2 Replies from Questionnaire concerning general network. PP: Preinsulated pipes.

Location	Start date	Finish date	Number of days start-finish	Number of days recorded	Number of days missing
S18 T	5 Feb. 1997	25 Feb. 1998	385	355	30
S18 U	5 Feb. 1997	25 Feb. 1998	385	355	30
R18 T	5 Feb. 1997	25 Feb. 1998	385	347	38
R18 U	5 Feb. 1997	25 Feb. 1998	385	355	30
S19 T	1 Feb. 1997	27 Feb. 1998	391	346	45
S19 U	1 Feb. 1997	27 Feb. 1998	391	327	64
R19 T	1 Feb. 1997	27 Feb. 1998	391	346	45
R19 U	1 Feb. 1997	27 Feb. 1998	391	346	45
S20 T	5 Feb. 1997	25 Feb. 1998	385	371	14
S20 U	5 Feb. 1997	25 Feb. 1998	385	371	14
R20 T	5 Feb. 1997	25 Feb. 1998	385	371	14
R20 U	5 Feb. 1997	25 Feb. 1998	385	371	14
S21 T	11 Feb. 1997	25 Feb. 1998	379	346	33
S21 U	11 Feb. 1997	25 Feb. 1998	379	346	33
R21 T	11 Feb. 1997	25 Feb. 1998	379	346	33
R21 U	11 Feb. 1997	25 Feb. 1998	379	346	33

Table 4.3 Start and finish dates for the measuring period (S: supply, R: return, T: top, U: underside)

5.Measuring Results

The recorded data files are treated to comply with a computer code, using the Rainflow method, developed by Mats Frendahl and Igor Rychlik at the Institute of Mathematical Statistics at Lund Institute of Technology. The procedure of data treatment is equal to the one used previously in Annex IV [2].

In the following the results from the sixteen points of measurement at four different locations will be presented.

Results from each measuring point are presented in enclosures S18A to S/R21I. Enclosures are numbered in continuation of the enclosures in the Annex IV project:

S denote Supply pipe
R denote Return pipe
18 to 21 denotes the measuring sites 18 to 21
Suffixes A to I denotes the type of graph:

Suffix A:

- A graph describing the temperature as a function of the time of year, beginning on the first of February and ending simultaneously with the end of measurement at each measuring point. Missing data is represented with an empty space of which the length corresponds to the amount of missing data.
- A matrix showing the number of rainflow cycles during the period of measurement as a function of range and mean. The leftmost column states the range and the uppermost row states the mean values. To each value for range and mean are the sum of number of rain-flow cycles between two consecutive values for range and mean connected, as an example, range equals 30°C and mean equals 30°C holds the sum of number of rain-flow cycles with a range between 25°C and 30°C and a mean value between 25°C and 30°C.
- A table showing the number of days recorded and the number of full temperature cycles, calculated with a reference temperature of $\Delta T_{ref} = 110$°C and extrapolated to a presumed lifetime of 30 years for different values of the exponent b (see chapter 7).

Suffix B:
For each site the curves for supply pipe, S, and a bold line shows return pipes, R, in a single logarithmic diagram together with the curves for minimum, average and maximum shown by thin lines.

Suffix C:
The cumulative damage is also shown for supply and return pipe for each site

The curves are made up as follows: Each temperature spectrum is presupposed to act on a pipe component dimensioned to the limit with safety factor $\gamma = 1$. This means that

$$\sum \frac{n_i}{N_i} = 1$$

and the values at the ordinate axis therefore represent the accumulated contribution from ΔT starting with the lowest values.

Suffix D:
The enclosures present for each channel close-ups of the days where we have one of the highest temperature differences between top and underside of the pipes. A close-up of four hours around and during the peak is also presented. The temperature on top of the pipe is represented with a lighter shaded curve.

Suffix E:
The enclosures show two plots of the temperature difference between upper and lower side of the pipes as a function of the time of year, the upper plot presents the supply pipe and the lower the return pipe. The plots begin on the first of February and end simultaneously with the end of measurement at each measuring point. Missing data is like before represented with an empty space, of which the length corresponds to the amount of missing data.

Enclosures with suffix F to I consist of plots describing the daily variations of the temperature for different weekdays and time of year.

Suffix F: A Sunday in summertime
Suffix G: A Weekday in summertime
Suffix H: A Sunday in wintertime
Suffix I: A Weekday in wintertime

In the graphs is only the temperature on the top of the pipe plotted for readability.

Enclosure 5.1 shows a table presenting the number of rain-flow cycles during a presumed lifetime of 30 years with range in step of two degrees centigrade. The row where "Range" equals 2 contains temperature cycles with range between 0 and 2°C and so on.

Enclosure 5.2 shows a table of the number of full temperature cycles during a lifetime of 30 years, calculated with a reference temperature of ΔT_{ref} = 110°C for different values of the exponent b.

6.Evaluation of Measuring Results

A summary of the results in Annex IV is given in table 3.1 in chapter 3. According to the new measuring results (see chapter 5) with 4 new measuring points table 6.1 is worked out.

As the 4 new points all are placed at consumers, only changes in the table dealing with consumers will occur. In table 6.1 the updated results are stated together with the values for production - this as comparison.

Supply Production	Min.	Average	Max.
$b = 3$	17	136	365
$b = 4$	4	42	102
$b = 5$	1	18	37

Return Production	Min.	Average	Max.
$b = 3$	2	7	14
$b = 4$	0	1	1
$b = 5$	0	0	1

Supply Consumer	Min.	Average	Max.
$b = 3$	7	130	578
$b = 4$	2	51	308
$b = 5$	1	28	197

Return Consumer	Min.	Average	Max.
$b = 3$	30	788	2828
$b = 4$	4	207	728
$b = 5$	1	66	233

Table 6.1 Numbers of full temperature cycles for $\Delta T_{ref} = 110°C$ and $b = 3$, 4 and 5

It is noted in table 6.1 that compared with table 3.1 the values for "Supply Consumer" are reduced by 5-10% for the average values, this is a minor change. For "Return Consumer" there is a remarkable change as the average values are increased with 50-55% and the maximum values are increased with 150-300%.

The remarkable increase in the values for the return pipe is caused by two of the new measuring points (R18 and R20) where the numbers of full temperature cycles at $b = 3$ are calculated to approximately 3000 cycles where the largest value in Annex IV was approximately 1000 cycles. This means that the two measuring points with approximately 3000 cycles are very different compared with all the other points. The two points are both apartments with 280-408 households.

It is also remarkable that the third apartment (R21) has a value on the return pipe of 30 full cycles by $b = 3$. This point is one of the lowest values of all consumer points. R20 and R21 are on the same network.

The fourth measuring point is a commercial building (S19/R19) with district cooling. The values for this point by $b = 3$ is 183 on the supply pipe and 479 on the return pipe. The value for the supply pipe is 60 above the average value in table 6.1. The value for the return pipe is 25% below the average value in table 6.1.

This means that the commercial building with district cooling does not differ remarkably from the other values in table 6.1.

The general reasons for the temperature variations by the four measuring points stated by the utility are given as follows:

- Manual operation and intermittent operation may cause a large part of temperature fluctuation.
- Flow rate between primary side and secondary side may be unbalanced.
- Temperature control system may be improperly acting.
- Control valves are over-sized.

Measuring on top and underside

In this project measuring has been done on top and underside of the pipes. The various values are stated in chapter 5. The underside has more full cycles than the top. Ex-

cept for R20, the differences are below 5%. For R20 the difference is 12% for $b = 3$, 17% for $b = 4$ and 21% for $b = 5$.

Characteristics

- The temperature difference on the return side is more pronounced than the one on the supply side. This indicates that it is the conditions in the substation, which mainly give rise to a varying temperature pattern and to temperature differences between upper and lower sides of the return pipes. Considering the supply pipes, see enclosure S/R18E to 21E, there is virtually no sign of temperature differences except for S19 which is located just 50m away from a production plant which in turn is a source of temperature variations. All the other measuring points are located 5-12 km away from production plants.
- The temperature on top of the pipe is almost always higher than the one below, enclosure S/R18E to 21E.
- The temperature difference is in some cases more pronounced in summertime when the domestic hot water circuit has a greater impact on the return temperature, e.g. enclosure S/R20E.
- At a slow cool off like in enclosure S20D, with presumably no or very low flow rates, the cooler water gathers at the bottom of the pipe and the temperature will be higher on top of the pipe.
- A dynamic behaviour with fast varying temperature is characterised by inability of the top temperature to follow the temperature on the underside, enclosure R20D.
- Enclosure R21D, long transmission pipeline, 12 km from production site, with signs of temperature stratification in the return line during night-time when the demand for district heating normally is low.

Possible explanations

Conditions in the district heating central give rise to temperature differences possibly due to intermittent operation, the control system or the connection principle or a combination of these. A parallel connection principle with several divided heat exchangers i.e. several flows ending up in the same return pipe suggests a state of improper mixing in the return pipe.

Stresses

The temperature differences between top and underside cause a stress in the steel.

Presuming "worst case", that the pipe is completely restrained against bending, the temperature difference between top and bottom will induce a stress difference

$$\Delta\sigma = \pm\frac{\Delta T \cdot \alpha \cdot E}{2}$$

For the site with the largest difference (R20, see above) this means that the variation in full cycles between top and bottom will always be less than ± 6% for $b = 3$ and ± 10.5% for $b = 5$.

Considering the uncertainties in low cycle fatigue these differences are small and can be ignored.

7.Design Model for Low Cycle Fatigue

7.1 Introduction

The development of preinsulated pipe systems for district heating has for quite some time been characterised by simplification of laying methods, thus employing cold-laying or prestressed systems instead of using expansion facilities like compensators and U-bends, giving more robust and cost-effective systems.

The simplified laying methods on the other hand give rise to higher stress and strain in the system, and therefore calculation methods have been developed in order that the full potential of the systems can be utilised. This development has, e.g., taken place in a technical committee, CEN/TC 107. The result, a draft European Standard for the Design and Installation of Preinsulated Bonded Pipes for District Heating [1], is presently being prepared for enquiry.

For preinsulated, bonded, buried pipes for district heating the major actions are pressure and temperature. It has shown crucial for district heating that special standards are developed because the temperature is the decisive action, whereas other standards presently under development in CEN consider the pressure to be the decisive action without leaving possible reserves in the steel to be fully utilised.

Concerning design a cold-laid or prestressed system can be divided into three zones.

1. Fully restrained zone
2. Partly restrained zone
3. Expansion zone

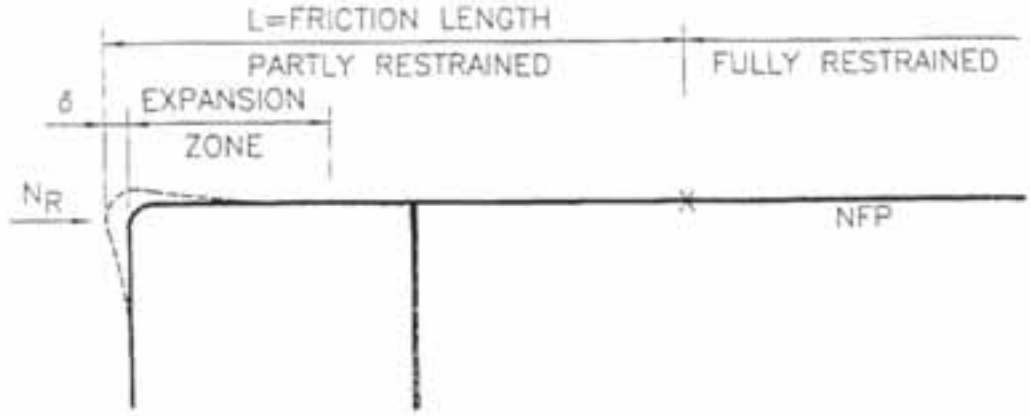

Figure 7.1 Three zones of preinsulated pipe system

The purpose of the design is, of course, to avoid failure, and this is achieved by comparing the actual stress-strain state with a number of failure modes, the so-called limit states.

In the fully restrained zone the most important limit state is local buckling. However, in case of small angular deviations or misalignments in welds low cycle fatigue can be a limit state.

In the expansion zone low cycle fatigue is the most important limit state for bends. Tees (and other local discontinuities like small angular deviations) can be found in all three zones, and for those low cycle fatigue also is the most important limit state.

The three zones refer to preinsulated pipes directly buried in the soil. However, most codes dealing with pipe systems are based on design in the low cycle fatigue range,

and therefore the following discussion applies to all types of district heating systems where the media pipe is made from mild steel.

This report deals with limit states for the steel pipes, but it must be remembered, that there are also important limit states for the PUR foam and the PE casing.

7.2 Design based on Low Cycle Fatigue

Under high cycle, low stress fatigue situations, the material deforms primarily elastically; the failure time or the number of cycles to failure under such **high cycle fatigue** has traditionally been characterised in terms of **stress range**. However, the stresses associated with **low cycle fatigue** are generally high enough to cause appreciable plastic deformation prior to failure. Under these circumstances, the fatigue life is characterised in terms of the **strain range** [3].

The classical approach in piping design is to estimate the lifetime, the number of full cycles, from an SN-curve (Wöhler curve) opposed to the more complicated methodology based on fracture mechanics.

When the design is based on fracture mechanics, which often is the case in aeroplane design and offshore structures, crack propagation is calculated based in detail models for the complete structure. The actions are simulated using statistical methods assuming different distributions for wave height and the energy transferred to the structure. In this way the "cross section forces history" is calculated, and the stress history is established for each critical construction detail by finite element methods (FEM). The lifetime is estimated by calculation of crack propagation or by SN-curves.

Analytical and experimental studies of fatigue in steel structures subject to stochastic loading show that the Palmgren-Miner rule, which normally is used in piping design, may give quite un-conservative predictions of the fatigue life [25].

The temperature variation action on district heating pipes may also be considered as a stochastic variable. However, applying fracture mechanics will complicate the design considerably, which will not be justified by subsequent savings in construction. Furthermore, designing district heating pipes in the low cycle fatigue range involve using elastic-plastic models opposed to structures designed in the high cycles range using elastic models.

In the future when suitable methodologies and computer programmes have been developed, the design of district heating might benefit from more advanced fracture mechanics, but it is most likely that these methods will be used to refine the methodologies presently used.

The more practical design approach used in district heating is reflected in the draft European standard [1] and explained in more detail in the EuHP District Heating Handbook [4]:

1. Assessment of actions (loads), see clause 7.3.
2. Choice of SN-curve.
3. A temperature history is assumed for the system.
   The number of full temperature cycles is calculated based on the chosen SN-curve and the Palmgren-Miner rule.
4. Stress analysis, see clause 7.4.
   Forces and deformations are calculated. The stresses are calculated using stress intensification factors.
5. Estimation of lifetime based on the chosen SN-curve, see clauses 7.5

The five steps above all introduce errors. The basic purpose of this project is to discuss the factors influencing on the low cycle fatigue strength mainly by literature study and to identify and discuss the uncertainties in modelling mainly by analysis.

7.3 Actions

The major actions on buried district heating pipes are:

- Maximum pressure and pressure variation.
- Maximum temperature and temperature variations.

Normally the pressure only gives small stresses compared to the temperature, and consequently the pressure variations give even smaller stress variations and are therefore often ignored.

Until recently the knowledge of the actual temperature actions on district heating systems has been limited, and therefore the IEA District Heating and Cooling Programme has carried through a study, where the temperature has been measured on supply and return pipes at utilities in 5 different countries [2].

In the present study four sites in Korea has been included, see chapter 4, 5, and 6. The measurements from these new sites support the conclusions in the previous project [2], see chapter 3.

The measurements from all 21 sites are illustrated on figure 7.2 to 7.5. The measurements have been carried out during approximately one year and by simple multiplication converted to number of cycles during 30 years. This means that observations $n < 30$ cycles do not appear on the converted curves.

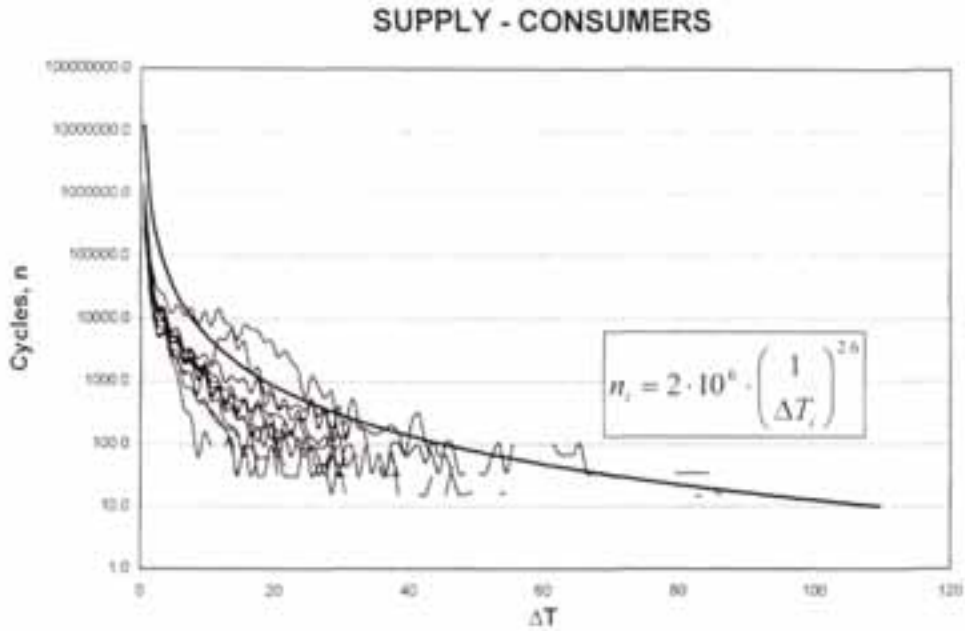

Figure 7.2 Temperature measurements from Supply - Consumers

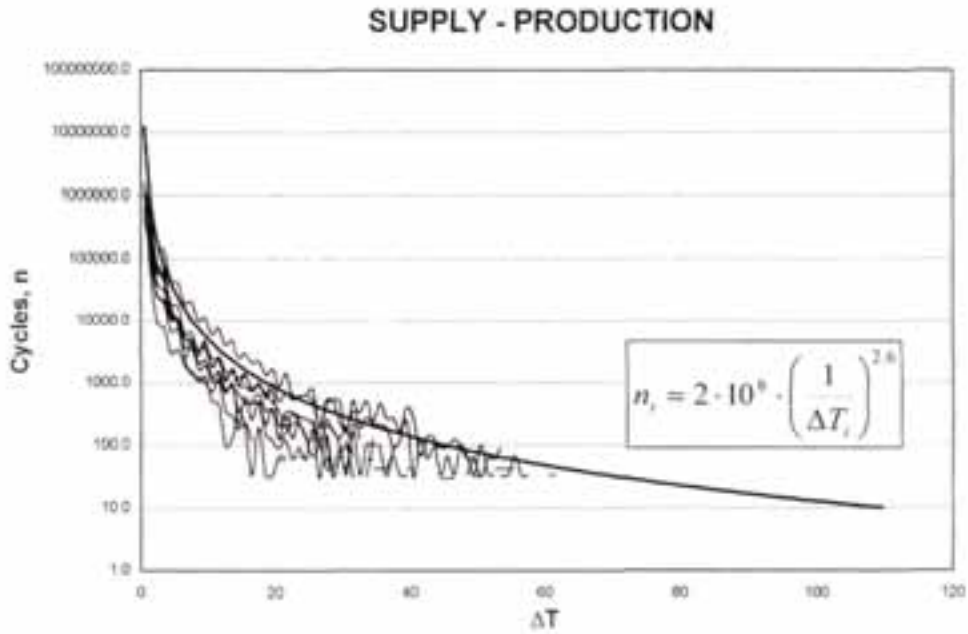

Figure 7.3 Temperature measurements from Supply - Production

Figure 7.4 Temperature measurements from Return - Consumers

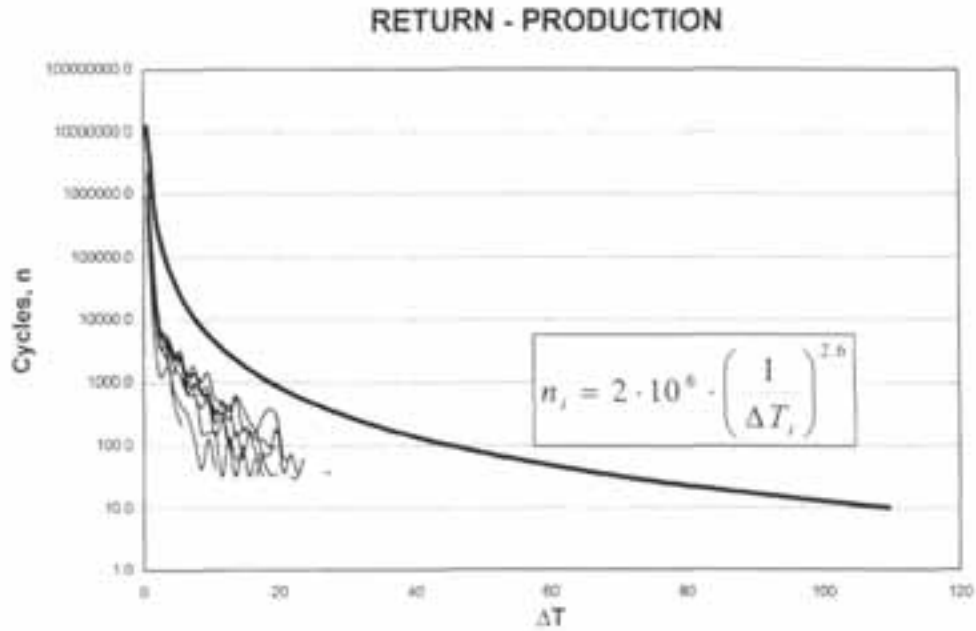

Figure 7.5 Temperature measurements from Return - Production

In each figure a "design line" is suggested for calculation of maximum number of full cycles. The "design lines" are based on data from return - consumers and supply - production. On order to simplify the design process it is suggested that the same lines is used for supply - production and consumers and return - production.

For return pipes from consumers:

$$n_i = 2 \cdot 10^6 \cdot \left(\frac{1}{\Delta T_i} \right)^{2.2}$$

For all other pipes (supply pipes to consumers and production and return pipes to production):

$$n_i = 2 \cdot 10^6 \cdot \left(\frac{1}{\Delta T_i} \right)^{2.6}$$

where n_i is number of cycles during 30 years for

ΔT_i = 1, 2, 3, ...°C i.e.
$n(i = 1)$ means all cycles for $0 < \Delta T \leq 1$°C
$n(i = 2)$ means all cycles for 1°C $< \Delta T \leq$ 2°C etc.

These lines can be used to estimate a conservative temperature history for a specific project if no further data are available. For a specific project all values up to T_{design} minus laying temperature
(e.g. $\Delta T_{max} = T_{design} - 10$°C) should be used.

For ΔT_i in discrete steps different from 1°C following expressions can be used:

For return pipes from consumers:

$$n(\text{from } \Delta T_1 \text{ to } \Delta T_2) = \frac{2 \cdot 10^6}{1.2} \left((T_1 - 0.5)^{-1.2} - (T_2 + 0.5)^{-1.2} \right)$$

For all other pipes:

$$n(\text{from } \Delta T_1 \text{ to } \Delta T_2) = \frac{2 \cdot 10^6}{1.6} \left((T_1 - 0.5)^{-1.6} - (T_2 + 0.5)^{-1.6} \right)$$

For a new district heating pipeline the temperature history can be estimated in a number of ways:

1. If the pipeline is an extension of an existing system, the temperature history can be established by measuring the temperature variations for one year. It must be noted, however, that the most serious temperature variations are generated by the consumers, and this approach can therefore only be used, if the consumers connected to the new pipeline in consumption pattern and type (and automation) of installation comply with the existing consumers.

2. The temperature history (n_i, ΔT_i) can be estimated by analysis of production and consumption pattern and type (and automation) of installation and by comparison to other similar systems. However, this approach also suffers from shortcomings. The preceding IEA project [2] and experience show that there quite often is considerable difference in the expected and the measured temperature history. Therefore this approach in many cases will lead to an underestimation of the number of cycles, n_i.

3. The temperature variations in the systems can be monitored continuously and the calculated number of full cycles compared to the design value. Also this methodology suffers from the shortcoming, that that the maximum values are expected at the return lines from the consumers. However, the present development towards heat meters interacting, both with the production plant and the consumer installation will enable such an algorithm to be build

into the heat meter.

4. The temperature variations can be considered as a stochastic variable. The design temperature history is then chosen based on statistical analysis of measurements, e.g. by calculating the 90% fractile and applying a partial safety factor.

   However, the available statistical material is still limited and do not justify a further complication of the design methodologies, and therefore it is suggested for the time being that the "design-lines" are used.

   It must be noted that the "design-lines" are extrapolated to temperature differences larger than those measured during one year. This is justified by the argument that higher values of ΔT ($< T_{design}$) will occur if the measuring period is sufficiently long.

   The extrapolated values of (ΔT, n) are dominating when calculating the number of full cycles, and therefore the approach must be expected to be conservative. However, it does not give results, which differs considerably from present practice.

Based on a known temperature history the stress-strain history can be calculated using a suitable model of the construction detail in question. This approach requires extensive analysis for each construction detail (bends, tees, etc.) and is therefore too comprehensive for practical use. Therefore the number of full temperature cycles is used in most cases as well as in the draft European standard [1].

The number of full temperature cycles, N_{tr} is calculated assuming:

1. Variations in stresses are proportional temperature variations, $\Delta\sigma = c \cdot \Delta T$.
2. The Palmgren-Miner rule $\sum \frac{n_i}{N_i} \leq 1$

   (or $\leq 1/\gamma$ with partial safety factor)
3. A relevant SN-curve
4. A reference temperature

Re. 1: Variations in stresses are proportional temperature variations,
$\Delta\sigma = c \cdot \Delta T$

In order to assess this question the relation between $\Delta\sigma$ and ΔT was calculated with a FEM beam-element model with following data:

1. L-loop with 168.4/4 mm steel pipe and 250 mm PE casing
2. Short leg 10 m, long leg > the friction length
3. Soil cover 0.875 m. The pipes are embedded in sand $\varphi = 35°$. No road surface.

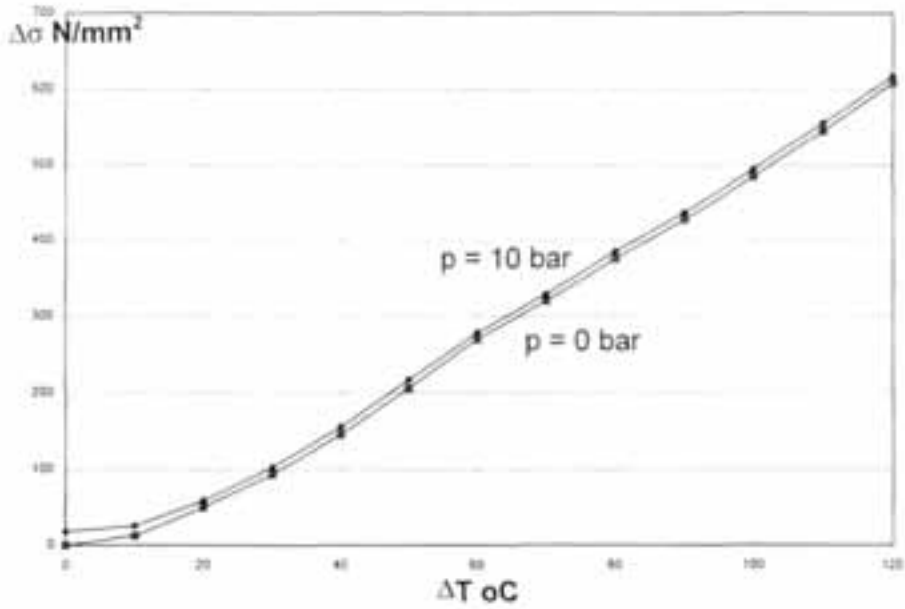

Figure 7.6 Relationship between $\Delta\sigma$ and ΔT

The relationship between $\Delta\sigma$ and ΔT on figure 7.6 is applied to temperature histories measured in the previous IEA project [2]. This approach gives numbers of full stress cycles, which are from 2 to 10 times smaller than the number of full temperature cycles depending on which temperature history is used.

It is seen that using the relationship between ΔT and $\Delta\sigma$ in figure 7.6 gives a reduction in number of full cycles depending on which temperature history is used presuming that the curve is repeated for each change in movement.

However, for pipes buried in sand the majority of the elastic-plastic soil springs will be in the plastic range thus approaching a linear model where the variation in stresses will be proportional to the variation in temperature.

The conclusion must be that it must be presumed that $\Delta\sigma = c \cdot \Delta T$ unless the relation $\Delta\sigma = f(\Delta T)$ is established in each case based on rather complicated modelling.

Re. 2: The Palmgren-Miner rule

$\sum \frac{n_i}{N_i} \leq 1$ (or $\leq 1/\gamma$ with partial safety factor)

The Palmgren-Miner rule expresses that relative damage of n_i cycles with the stress range $\Delta\sigma(\Delta T_i)$ is $\frac{n_i}{N_i}$, where N_i is the number of cycles causing failure with the stress range $S = \Delta\sigma(\Delta T_i)$ calculated from a relevant SN-curve.

The fatigue life depends on both the mean stress level and the order in which the stress blocks of different amplitude are imposed. The Palmgren-Miner rule does not take all these factors into account. This can only be done by design based on fracture mechanics.

When a temperature history has been assumed and applying the Palmgren-Miner rule **the number of full temperature cycles** is calculated from (see [2]):

$$N_0 = \frac{1}{(\Delta T_{ref})^8} \sum n_i \cdot (\Delta T_i)^8 .$$

where

n_i is the number of cycles at ΔT_i – the temperature history

ΔT_{ref} is a reference temperature chosen by the designer, normally the design temperature - 10°C

b is slope of the chosen SN-curve, see clause 7.4.

It is seen that N_0 is **not** constant, which is characteristic for a given system. The fatigue life of a system can only be unambiguously characterised by the temperature history.

According to present practice [1] and [8] the number of full temperature cycles has been specified presuming that an SN-curve specified elsewhere in the same standard is used.

A more correct approach will be to specify a temperature history. Following this the designer can calculate the stress-strain history or use the more simple approach calculating the number of full temperature cycles.

For design purposes the "design-lines" have been calculated in table 7.1 and 7.2. For practical reasons the number of cycles have been summed for ΔT in intervals of 5°C. For analysis the average values for ΔT should be used e.g. for $1 \leq \Delta T \leq 5$°C ΔT = 3°C should be used.

ΔT °C From	ΔT °C To	n Other pipes	n Return consumers
1	5	3707571	3613511
6	10	52680	116304
11	15	13467	37028
16	20	5617	17714
21	25	2935	10239
26	30	1749	6612
31	35	1137	4594
36	40	786	3363
41	45	569	2559
46	50	427	2007
51	55	330	1613
56	60	261	1323
61	65	210	1102
66	70	172	931
71	75	143	797
76	80	121	689
81	85	103	600
86	90	88	528
91	95	76	467
96	100	67	417
101	105	58	373
106	110	52	336
111	115	46	304
116	120	41	277
121	125	37	253
126	130	33	231

Table 7.1 "Design-lines"

Presuming that ΔT_{ref} is chosen = T_{design} - 10°C and b = 4 (c.f. the European standard) values for design purpose can be taken from table 7.2. Once again it must be emphasised that the same value for ΔT_{ref} must be chosen when calculating the stress range.

T_{design} °C	100	105	110	115	120	125	130	135	140
ΔT_{ref} = T_{design} - 10° °C	90	95	100	105	110	115	120	125	130
N_0, Return Consumers	3288	3069	2891	2718	2574	2434	2316	2200	2098
N_0, All other pipes	637	578	537	492	460	425	399	371	349

Table 7.2 Values for number of full cycles (with partial safety factor γ = 1)

The calculated number of full cycles for different values of ΔT_{ref} and b are presented in table 7.3 and 7.4.

Normally a designer will choose to set $T_{design} = T_{max}$ and $\Delta T_{ref} = T_{design} - 10°C$ according to the table 7.3, but in order to demonstrate that the two "design-lines" give a more severe action for increasing values of T_{max} table 7.4, where $\Delta T_{ref} = 110°C$, has been included. This table also allows comparison with calculations in the previous IEA project [2] where $\Delta T_{ref} = 110°C$ is used in all calculations.

T_{design}	ΔT_{ref}	b	N_o Other pipes	N_o Return consumers
80	70	3	1886	7153
80	70	4	964	4475
80	70	5	675	3306
90	80	3	1484	6035
90	80	4	773	3798
90	80	5	543	2806
100	90	3	1205	5203
100	90	4	637	3288
100	90	5	449	2430
110	100	3	1002	4561
110	100	4	537	2891
110	100	5	378	2136
120	110	3	850	4052
120	**110**	**4**	**460**	**2574**
120	110	5	324	1902
130	120	3	732	3638
130	120	4	399	2316
130	120	5	282	1711

Table 7.3 N_o for $\Delta T_{ref} = T_{design} - 10°C$

T_{design}	ΔT_{ref}	b	N_o Other pipes	N_o Return consumers
80	110	3	486	1843
80	110	4	158	734
80	110	5	70	345
90	110	3	571	2322
90	110	4	216	1063
90	110	5	111	571
100	110	3	660	2850
100	110	4	286	1473
100	110	5	164	891
110	110	3	753	3427
110	110	4	367	1975
110	110	5	235	1327
120	110	3	850	4052
120	**110**	**4**	**460**	**2574**
120	110	5	324	1902
130	110	3	951	4723
130	110	4	565	3280
130	110	5	435	2643

Table 7.4 N_o for $\Delta T_{ref} = 110°C$

Presuming the Palmgren-Miner rule table 7.5 (Other pipes) and table 7.6 (Return consumers) demonstrates the influence - the damage - for each step of ΔT.

For $b = 4$ and 5 it is seen that temperature variations up to 45°C contribute less than 10% to the cumulative damage. The same observations can be made for different temperature histories studying the enclosures marked "C" in the previous IEA project [2].

This means that temperature variation due to normal production operation, e.g. variation in supply temperature summer and winter or daily variations due to heat storage, do not contribute significantly to the damage effect i.e. the reduction of lifetime of the steel pipes.

The influence of small temperature variations on other components e.g. welded casing joints remains to be examined.

ΔT °C From	ΔT °C To	n Other pipes	$b = 3$	$b = 4$	$b = 5$
1	5	3707571	8%	0%	0%
6	10	52680	10%	1%	0%
11	15	13467	12%	1%	0%
16	20	5617	15%	2%	0%
21	25	2935	18%	3%	1%
26	30	1749	21%	4%	1%
31	35	1137	24%	6%	2%
36	40	786	27%	8%	2%
41	45	569	31%	10%	4%
46	50	427	35%	13%	5%
51	55	330	39%	16%	7%
56	60	261	43%	20%	10%
61	65	210	47%	24%	13%
66	70	172	51%	28%	16%
71	75	143	56%	33%	20%
76	80	121	60%	38%	25%
81	85	103	65%	44%	31%
86	90	88	69%	51%	38%
91	95	76	74%	57%	45%
96	100	67	79%	65%	54%
101	105	58	84%	73%	64%
106	110	52	89%	81%	75%
111	115	46	95%	90%	87%
116	120	41	100%	100%	100%
121	125	37	100%	100%	100%
126	130	33	100%	100%	100%

Table 7.5 Cumulative damage effect for "Other pipes"

ΔT °C From	ΔT °C To	n Return Consumers	b = 3	b = 4	b = 5
1	5	3613511	2%	0%	0%
6	10	116304	2%	0%	0%
11	15	37028	4%	0%	0%
16	20	17714	5%	1%	0%
21	25	10239	7%	1%	0%
26	30	6612	10%	2%	1%
31	35	4594	12%	3%	1%
36	40	3363	15%	5%	2%
41	45	2559	19%	7%	2%
46	50	2007	22%	9%	4%
51	55	1613	26%	11%	5%
56	60	1323	30%	15%	7%
61	65	1102	34%	18%	10%
66	70	931	39%	22%	13%
71	75	797	44%	27%	17%
76	80	689	49%	32%	22%
81	85	600	55%	38%	27%
86	90	528	60%	45%	34%
91	95	467	66%	52%	41%
96	100	417	73%	60%	50%
101	105	373	79%	69%	60%
106	110	336	86%	78%	72%
111	115	304	93%	89%	85%
116	120	277	100%	100%	100%
121	125	253	100%	100%	100%
126	130	231	100%	100%	100%

Table 7.6 Cumulative damage effect for "Return consumers"

7.4 Stress Analysis

With today's aids modelling typically involves following steps:

1. Forces and deformations are calculated by FEM-methods, normally a beam-element model, where the steel is assumed to be linear elastic and the soil is assumed to be elastic-plastic.

2. The stresses are calculated by the usual formulas. Local stress concentrations are handled by multiplying the stresses with stress concentration factors. The methodology can either be based on hot-spot stresses or experimental methods.

   Locally stresses will exceed the plastic limit, and further analysis in these points should in fact be based on strains rather than stresses. However, for practical reasons the analysis is done on "formal stresses" above the plastic limit. This is why stresses as high as $\sigma \cong 1000$ N/mm^2 can occur. This formal stress should be understood as a strain $\varepsilon = \sigma/E \cong 0{,}5\%$.

3. Calculation of a reference stress for multi-axial stress states.

Re. 1: Modelling
The typical methodology involving a beam-element model (FEM) with elastic-plastic soil springs is described in chapter 8. When the actions are defined the results from different FEM-models should be unambiguous. However, comparative calculations show that there often are even considerable differences in the results.

This difference can be due to erroneous use of the FEM-model (often present as a "black box" computer programme) or in particular differences in the way the reactions of the soil are modelled.

In chapter 8 it is shown that a beam-element programme is very sensitive to the distance at which the elastic-plastic are placed. In chapter 9 it is shown that the fatigue life of tees at consumers connections varies very much depending on how the main pipe next to the tee is modelled.

The decisive factors are the friction coefficient between PE casing and the soil for axial movement and the reaction of the soil to lateral movement of the pipes.

The friction coefficient is often fixed to 0,4 - 0,45 but can vary in the range 0,2 - 0,6.

The soil reaction to the lateral movement of the pipes is typically modelled with bilinear elastic-plastic discrete soil springs. For pipes in areas without road surface it is expected that this approach gives reasonable results. Many tests indicate the reactions are reduced after the initial start-up movements of the pipes. However, in areas with stiff road surface it is most likely that the soil reaction is underestimated. Only limited tests or calculations exist for the assessment of soil reactions under road surface. In the German draft AGFW, Richtlinien, FW401 [23] graphs based on FEM-analysis are available. These graphs should be verified by comparison to available test. Expecting reasonable agreement this approach could be modified for practical use.

This large uncertainty in the estimation of decisive actions will, in other types of structures, typically be handled e.g. by applying partial safety factors. However, due to the functioning of the pipe-soil interaction of buried district heating pipes, and the most important limit state being low cycle fatigue the design must be done with partial safety factor $\gamma = 1$, the serviceability limit state.

Re. 2: Stress concentration factors
The code B31.1, Power Piping [27] is based on the experiments made by Markl [16]. The stress concentration factors in this code must therefore be used with the belonging SN-curves.

In more recent codes (the draft European standard [1], DS448 [8] and EC3 [26]) the stress analysis is based on hot-spot stresses. The stress concentration factors are calculated by FEM-methods or measured with strain gauges. Hot-spot stresses must as well be estimated with belonging SN-curves, it is important that hot-spot and experimental methods are not mixed.

However, the difference in stresses calculated by the two methods (a factor 2) might only apply to bends.

Tees:
In a cold laid system the general stress level will be so high that the local weakening from a branch connection necessarily will require a local reinforcement. This is best is done by using a tee with increased wall thickness. An increased wall thickness gives a considerable reduction of stresses and it eliminates the weak link in the chain.

The practical methods for calculation of stress intensification factors (e.g. the formulas in the draft European standard [1]) are only "rules of thumb" and they only give an estimate of the stresses. More exact determination of stresses can only be done by costly experiments or by FEM.

The location of maximum stresses is normally not known when the practical method is used. However, in most cases the

maximum stresses are in or close to the saddle point (point B [19]). The stress picture here is very complicated, the base material has undergone complex deformation during production (extruded and weld-in tees) or there is a weld (welded tees).

Bends:
For bends the situation is quite different. The only practical ways to reduce stresses in a bend is to increase the bend radius or to establish a cavity. Besides from this stresses cannot be reduced in a cost-effective way.

Foam cushions can be used, but they have their own limitations:

1. The available deformation parameters are often measured by an uni-axial test. In practice the stress state in the cushions will be multi-axial, and the stiffness of the cushions will be larger.

2. The cushions might follow the pipes at small movements, but there is a considerable risk that soil will clog up cavities between cushion and pipe at large movements.

3. Due to degrading from moisture, bacterial action, mechanical action etc. it is optimistic to expect that the cushions have the expected properties for 30 years.

4. Fully compressed cushions will increase the effective diameter of the casing pipe thus increasing the soil reaction even further.

5. The foam cushions acts as insulation material thus heating the PE casing and impairing the lifetime of casing and joints.

6. For larger diameters fully compressed cushions mean that the pipe will be ovalized and the ovalizing bending stresses will be higher than if there had been no cushions, because the support from the surrounding soil will be concentrated at one point (at 3 o'clock). This will affect not only the steel pipe but also the PUR.

Further the stresses in bends can be reduced by establishment of cavities where the pipes move perpendicular to the pipe axis is used for large pipe diameters, but should not be used for smaller diameters for economical reasons.

For these reasons it is important that the "right" limit state is established for bends, and it will of course be beneficial for district heating if further studies and experience show that a higher limit state can be used for bends.

Small angular deviations:
Small angular deviations (bevel welds) are discussed in chapter 10.

The stress concentration factor proposed in the draft European standard [1] presupposes that the angular deviations are limited according to following table:

Maximum temperature difference	Maximum angular deviation
90 K	2°
100 K	1°
110 K	0,5°
> 110 K	0°

An installation tolerance of ± 0,25° on the above-mentioned deviations is accepted.

If the angular deviations in the table are exceeded there will be a risk of local buckling resulting in an increase of the stress concentration factor. These factors could be established by FEM-analysis taking second order effects into account or by experiments. However, this material is not available.

Re. 3: Reference stress, multi-axial stress-strain state.
In practice the stress-strain state is almost always multi-axial, and therefore a proper transformation to a reference stress must be

chosen when comparing to the limit state curve, where only a reference stress range, S, is represented.

A number of approaches are used:

- Largest tensile main stress
- Largest tensile stress perpendicular to a defect (e.g. a weld seam)
- Von Mises or Tresca yield criterion
- Cumulative Damage Assessment (CDA) i.e. the effect of all stress components is added.

There is very limited literature or experiments on this question. Suresh [4] concludes based on a short discussion: The von Mises stress or strain criterion appears to have found the widest appeal.

However, the von Mises criterion describes the stress-strain relation when yield starts in one point, and possibly not the condition when alternating yield takes place in a point, line or area.

The slope constants and levels of different SN-curves might also give an indication that this transformation is not sufficiently accounted for.

In EC3 [26] the slope of the base curve is $b = 3$.

In AD S2 [22] the average slope of the base curve is $b = 2.6$ in the range relevant for district heating. However, mainly due to the reduction factor for yield $b = 4$ for the limit state curve.

The experiments made by Markl [16] in the 1950'es on pipe components like bends and tee includes reductions for yield. These experiments resulted in a limit state curve with $b = 5$, which is used in B31.1, Power Piping [27].

Calculation examples with stresses in the range typical for district heating pipes show that the reference stress only vary very little when it is calculated according to the different theories. In the draft European standard [1] it is therefore suggested to allow the choice between von Mises or Tresca, because these two theories are commonly used in piping design.

7.5 Limit State (SN-curve)

The basis for the **SN-curve** is normally established by uni-axial fatigue testing of polished test bars (AD S2 [22]), by uni-axial fatigue testing on specimens with welding defects (EC3 [26], International Welding Institute) or by fatigue testing on complete components (Markl [16]). In the high cycle fatigue range the testing is done by stress (elastic) cycling and in the low cycle range by strain (plastic) cycling.

Historically the basis SN curve is expressed as [4], [5], [33]:

$$\varepsilon_a = \frac{\sigma'_f}{E} \cdot (2N)^b + \varepsilon'_f \cdot (2N)^c$$

where

σ'_f is the fatigue strength coefficient
ε'_f is the ductility coefficient
b is the fatigue strength exponent
c is the fatigue ductility exponent
$2N$ is the number of **half** cycles or reversals
N is the number of full cycles
ε_a is the strain **amplitude**

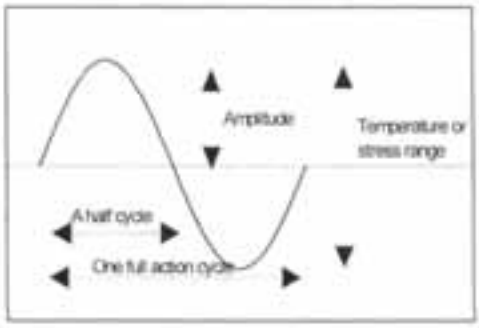

Figure 7.7 Action cycle

Using figures for mild carbon steel [5] and introducing the stress range

$$S = \frac{2 \cdot \varepsilon_a}{E}$$

the expression above is converted into

$$S = 1120 \cdot \left(\frac{1}{N}\right)^{\frac{1}{9.62}} + 82000 \cdot \left(\frac{1}{N}\right)^{\frac{1}{2.33}} \text{ N/mm}^2$$

The first link represents elastic cycling, the second plastic cycling. The numbers used

are obtained by regression analysis of results from endurance tests thus representing average values (valid for half failure life). For practical use a safety coefficient must be applied taking into account the variation of the test results or an upper fractile is used, typically 90%.

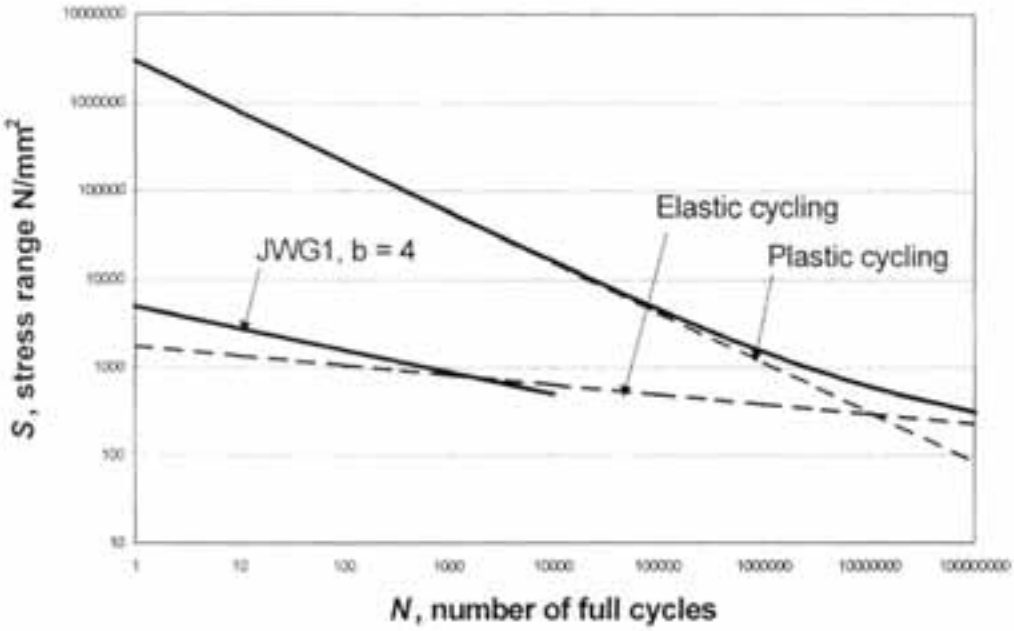

Figure 7.8 SN-curves

The base SN-curve must be reduced by a number of coefficients:

- Surface condition
- Temperature
- Welding detail
- Reduction for yield
- Reduction for electro-chemical environment?
- Corrosion fatigue
- Creep fatigue
- Electro-chemical impacts (external and internal)

Thus the conclusion can be an SN-curve like the one proposed in the draft European standard [1] a straight line in a double logarithmic diagram with the slope constant $b = 4$ (The JWG1 curve in figure 7.8):

$$N = \left(\frac{5000}{S}\right)^4 \quad \text{or} \quad S = 5000 \cdot N^{-1/4} \text{ N/mm}^2$$

N is the number of full cycles giving failure with the stress range S in N/mm^2.

The proposed limit state for low cycle fatigue is in principle derived from the German AD-Merkblatt S2, Berechnung auf Wechselbeanspruchung - Fatigue Analysis [22].

However, the AD S2 [22] is an extensive generalised document. Calculation of stress range, when the number of load cycles is known requires more calculations than is justified by the uncertainties in low cycle fatigue analysis. Furthermore, calculation of load cycles, when the stress range is known requires iterations. Therefore the JWG1 curve has been established from AD S2 [22] by using values typical for district heating followed by "best curve-fit".

A consistent reference to AD S2 [22] would give a very high limit state for unwelded details. During the development of

the draft standard this was extensively discussed.

It has been insisted that high curve for un-welded details (bends and some kinds of tees) could be used directly. On the other hand it has been opposed that it is necessary to look at the complete "design package", and that single elements of this "package" should not be changed without considering the complete system safety illustrated in the figure below:

ACTIONS	→	DESIGN MODEL	→	LIMIT STATES

Whether the high limit state for un-welded details can be used must be justified by analysis and comparison to practical experience.

The calculation examples in chapter 8 and 9 seem to indicate that a curve for un-welded material can be used for bends. However, this presupposes that realistic models are used for soil actions specially when the pipes are placed in streets with rigid surface. It is more doubtful whether an SN-curve for un-welded material can be used for tee due to the more complicated strain-picture.

An SN-curve for un-welded material derived from AD S2 in the same way as the SN-curve above can be expressed as:

$$N = \left(\frac{15800}{S}\right)^{3.2} \text{ or}$$

$$S = 15800 \cdot N^{-1/3.2} \text{ N/mm}^2$$

i.e. b=3.2.

For practical reasons it is not convenient to have two SN-curves with different values of b (b = 3.2 and 4), because the number of full cycles, No, is a function of b.

According to the Markl-curve (b = 5) large stress variations are more decisive to the lifetime compared to SN-curves with b < 5. This is in line with a suspicion that the effect of large variations is underestimated in normal design.

For the time being it is estimated that b = 4 is a reasonable figure, which should be used for possible curves for welded and un-welded details.

In AD S2 the limit state for fatigue is based on stress cycling tests on polished rods in the high cycle fatigue range and on strain cycling in the low cycle range. This gives an upper theoretical limit for fatigue analysis.

In order to reach to a limit state which can be applied in practical cases a number of reduction factors are applied:

1. Correction factor for taking into account the notch effect caused by surface roughness
2. Correction factor for taking into account the influence of variable wall thickness
3. Temperature influence factor
4. Correction factor for taking into account the influence of the mean stress level
5. Correction factor for taking into account the mean stress level in the case of welded, stress-relieved components
6. Load cycle reduction factor for taking into account the medium of the pressure vessel
7. Enlargement factor for mechanical stresses beyond yield
8. Enlargement factor for thermal stresses beyond yield

All these factors are applied by multiplication (or division):

$$S = S_a \;\; k_1 \;\; k_2 \; ....$$

On the figure 7.9 the AD S2 base curve for welded material is shown together with reduced curves relevant for district heating.

f_{t*} is the temperature influence reduction factor, it is seen to be close to 1.

k_e is the enlargement factor for mechanical stress beyond yield. This is the largest of the factors applied.

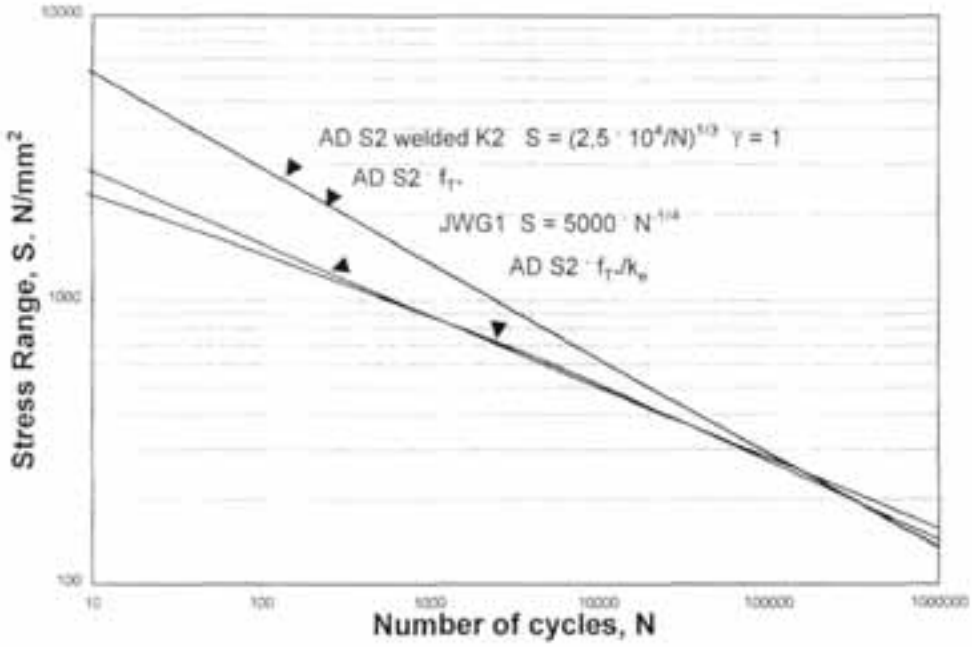

Figure 7.9 SN-curves

Applying the reduction factors by multiplication means that the effect of each factor is expected to be independent of each other.

This presumption can be questioned. Specially the influence of the electro-chemical environment has lately been pointed out as a factor which possibly can cause a fatigue life time lower than expected.
It is evident that local corrosion (pitting) will impair the fatigue life, but the mere presence of water, the pH-value, oxygen and hydrogen content have a direct effect also.

The electro-chemical environment can cause micro-cracking (SCC), which initiates fatigue cracks much earlier than expected, when the steel is subject to variable temperature stresses.

According to Suresh [4] the presence of water within a fatigue crack in steels adversely affects its growth rates. Furthermore the frequency of the temperature actions affects the fatigue life. Low frequencies increase the time for environmental interactions per stress cycle, and in this connection the temperature variations in district heating pipes are in the very low frequency range.

According to an article "Stress-Corrosion Cracking in Pipelines" [31] high pH cracking occur when the environment typically has a pH of near 9. Further it is stated that elastic stresses or strains are too small to rupture the protective iron oxide film. So, plastic strains are needed.
Both conditions are present in district heating pipes. However, it is not clear whether the conditions apply to internal condition in water filled pipes.

For the measuring site S/R12 [2] it has been reported that leaks has occurred close to weld seams in the return pipe in the connecting pipeline between main line and consumer. In the previous IEA project R12 had a temperature history giving the highest number of cycles, but presuming a proper design the number was not excessive for a 30 years lifetime.

However, the failure occurred after 8 years, and examinations of the cracks said that they were caused by stress corrosion cracking (SCC). This could give an indication that the combination of environment and the cyclic temperature actions severely have effected the lifetime of the pipe.

At the measuring sites S/R18 and 20 low cycle fatigue cracking have also been reported.
Whereas it is justified to use a simplified SN-curve for design purposes, additional calculations have been made in order to verify, that the simplified curve also can be used for the studies in the present project.

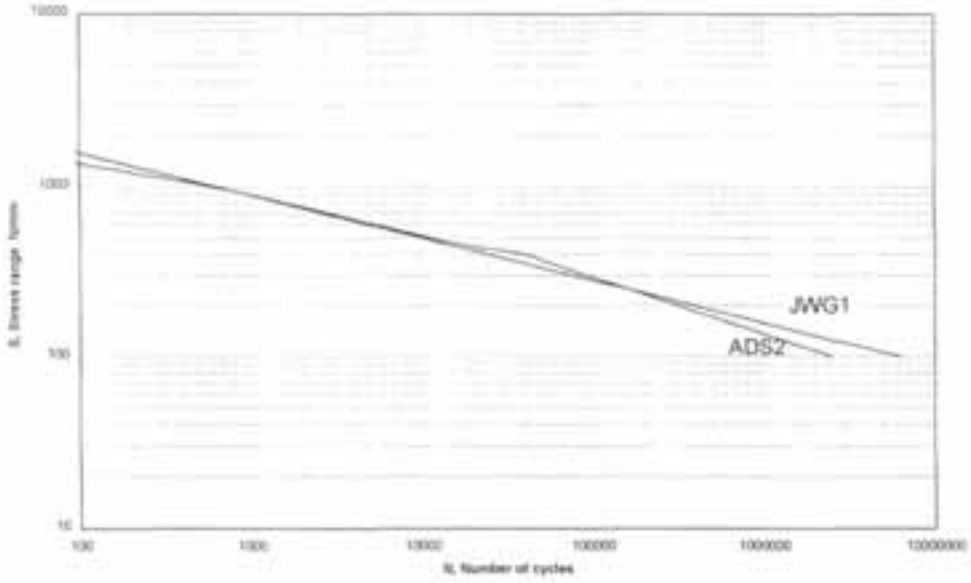

Figure 7.10

In figure 7.10 the AD S2-curve is compared to the "best curve-fit" JWG1-curve.

It is immediately intelligible the difference between the two curves is small. Due to the statistical nature of fatigue curves minor differences can be ignored, and therefore the user-friendlier JWG1 curve should be used for practical design purposes. The JWG1 curve is used for the calculations in chapter 8, 9 and 10.

Other design criterions

The present project deals mainly with the design criterion for the steel pipes. However, when the full capacity of the steel is utilised it must be remembered that other design criterion must be assessed with same accuracy.

1. The limit state for compressive stresses in the PUR foam should possibly be graduated according to pipe diameter. Experimental work [36] shows that for small diameters the pipe "cuts" through the PUR foam after tensile failure has occurred on the backside of the pipe. For medium size pipes the failure mechanism is compression failure as normally presumed. For large pipes the failure mechanism is shear failure at the top and bottom of the pipe due to the ovalisation of the pipe [24].
2. The commonly used methods for calculating the soil reactions when the pipes move perpendicular to the pipe axis are believed to give reasonable results in areas without road surfacing. Some experiments [35] indicate that the results are correct for first time movements, but the following movements give lower values. In areas with road surface, on the other hand, the reactions from the soil are often believed to be highly underestimated. It is very important that this question is assessed before higher stresses in steel and PUR are utilised.
3. In the computer models foam cushions perform very nicely. But does the foam cushions have the presumed properties in nature - especially over time? See clause 7.4 under bends.

Calculation of lifetime

The lifetime or the maximum number of full cycles is estimated using the same SN-curve and compared to the number of full temperature cycles calculated under clause 7.4 above.

From the discussion above it is clear, that it is crucial that the same SN-curve is used for calculation of the number of full temperature cycles and for the estimation of life time.

If the stress range, S, from the stress analysis gives a maximum number of full cycles, N_f, and N_0 is the number of full temperature cycles, then $\frac{N_0}{N_f} \leq \frac{1}{\gamma}$, where γ is a partial safety factor, normally $\gamma = 5 - 10$.

8. Calculation Examples, Bends

The purpose of the calculation examples is to give examples of lifetime evaluation under well-defined presumptions e.i. the methodology in the draft European standard [1] as discussed in chapter 7. Examples are also given concerning the sensitivity to variation of some of the parameters.

In clause 8.1 the methodology of modelling bends is discussed, and the sensitivity to placing of the elastic-plastic soil springs is examined. In clause 8.2 a number of stress reducing measures are examined.

8.1 Modelling of bends

An L-bend of preinsulated bonded pipe has been examined. The pipe is laid in compressed sand without expansion cushions.

For simplicity, the stiffness of the PUR foam is neglected. The bedding constant of PUR is of the same magnitude as the bedding constant of the soil. However, the elasticity of the PUR only has effect in the elastic range of the elastic-plastic model.

Initial calculations were made for DN150 and DN600 pipes without pre-stressing with pipe data according to table 8.1:

Nominal diameter of steel pipe, DN, mm	150	600
Outer diameter of steel pipe, d_o, mm	168.3	610.0
Pipe wall thickness, t_s, mm	4.0	7.1
Casing diameter, D_c, mm	250	800
Bend radius, R, mm	390	1219
Soil cover, m	1	1
Modulus of elasticity, E	2.07E5 N/mm^2	
Coefficient of thermal expansion, α	1.2E-5 K^{-1}	

Table 8.1 Pipe data

As shown in figure 8.1 the short leg is fixed at a length of 10 m. The length of the long leg is adjusted to exceed the friction length.

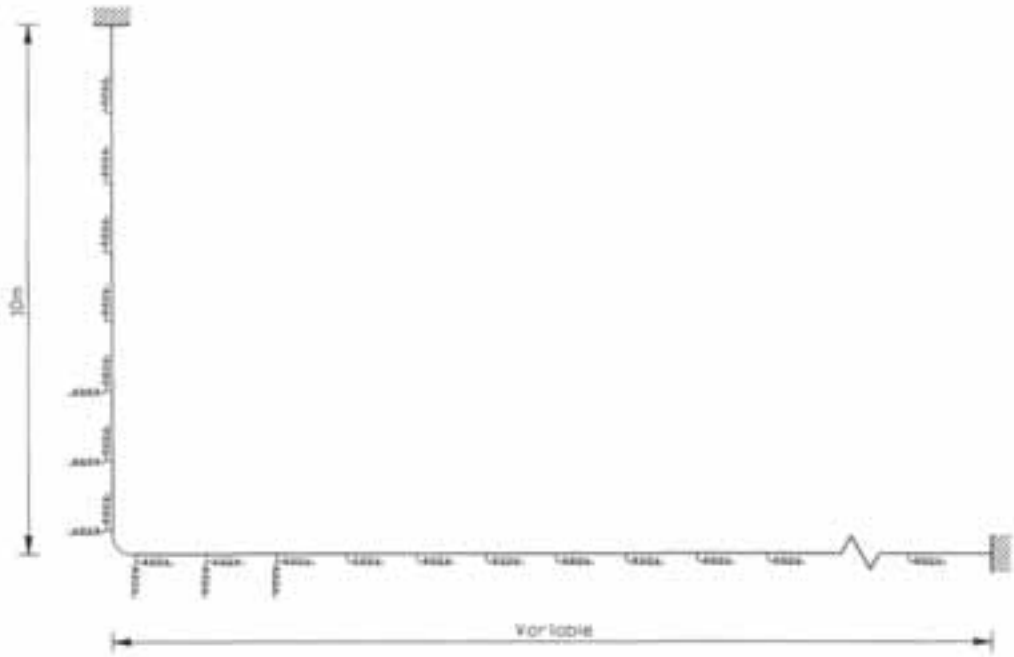

Figure 8.1 Beam-element model of L-bend.

The pipe-soil interaction is modelled using discrete elastic-plastic soil springs both axial and perpendicular to the pipe as shown in figure 8.1.

The relation between lateral pipe displacement and soil restraint is derived according to the draft European standard [1] sub-clause A2.3.3.

The friction force is calculated according to sub-clause A2.3.2. The friction is applied as springs that acts in the opposite direction of the pipe movement in the partly restraint parts of the L-bend.

Following values are used in the calculations:

Effective density of soil, γ	18 kN/m³
Friction angle of soil, φ	35°
Friction coefficient between soil and PE casing, μ	0.4

Table 8.2 Soil data

Normally the friction coefficient is evaluated at $\mu = 0.4 \pm 0.2$, the lower value $\mu = 0.2$ covers long-term effects (creep and tunnelling effect) and the higher value $\mu = 0.6$ covers e.g. increased friction by commissioning of pipes. The average value $\mu = 0.4$ is considered to be a reasonable estimate for fatigue analysis.

The pipe soil interaction is modelled as shown in figure 8.2 and figure 8.3.
The relation between lateral pipe displacement and soil restraint is modelled using a bilinear force-deformation relationship, while the relation between axial pipe displacement and pipe to soil friction is modelled using a plastic force-deformation relationship.

In axial direction only very small displacements are needed before the plastic range is reached. The axial displacement of most of the pipe is of larger magnitude, thus it would not affect the result much if a bilinear function was used for axial friction. Calculations show that the effect of using a bilinear function is less than 1 %.

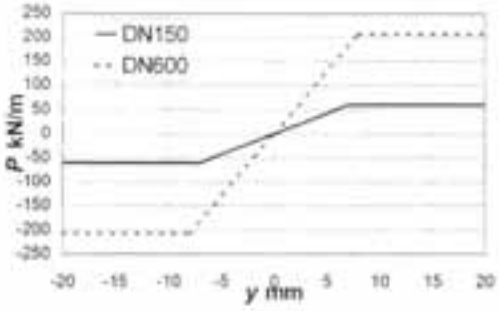

Figure 8.2 Lateral soil reaction

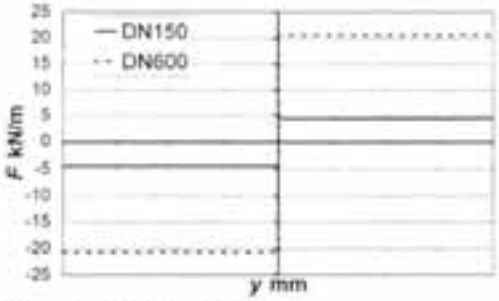

Figure 8.3 Soil friction

The forces and moments in the symmetry line of the bend are found using RAMBØLL's beam-element program "RØR".

The stress range, S, is calculated as the maximum von Mises reference stress for each degree along the perimeter using hot spot values for the stress intensification factors according to draft European standard, sub-clause A3.7.2, method 2 [1].

The stress range is converted to the equivalent number of full load cycles using the SN-curve in the draft European standard, sub-clause A3.8.1 [1], see figure 7.8.

8.1.1 Spring Intervals

The perpendicular and axial soil springs in the expansion zone were first applied with intervals of 1 m.

The stress ranges, S, are calculated for heating in the range from 0 to 120°C. Internal pressure is neglected, as it does not contribute to the stress range for fatigue

analysis. The result can be seen in figure 8.4 and figure 8.5.

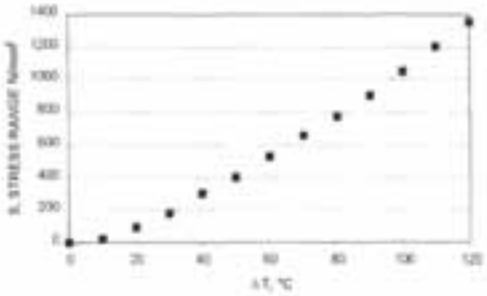

Figure 8.4 Stress range, DN150.

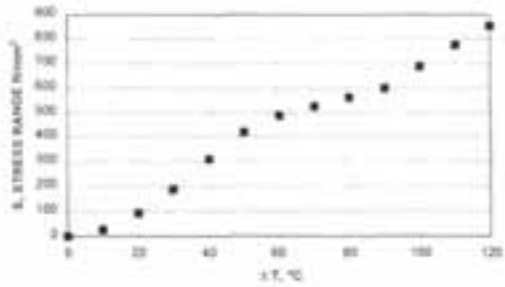

Figure 8.5 Stress range, DN600.

For DN150 there is an almost linear relationship between ΔT and S in the temperature range above 30°C.

For DN600 the relationship between ΔT and S does not become linear until temperatures above 90°C.

The non-linear curve was assumed to result from the discrete soil springs, and the "stepwise" soil resistance they provide. The point on the curve where the tangent starts to decrease (ΔT = 50°C), corresponds to the ΔT where the first perpendicular spring next to the bend acting on the short leg is fully activated.

In order to investigate this phenomena further, two more calculations were made with springs applied with intervals of 0.5 and 0.25 m, see figure 8.6.

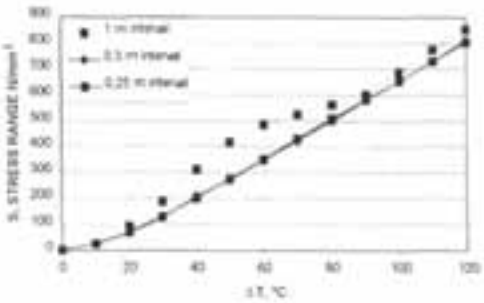

Figure 8.6 Stress range for springs applied with different intervals, DN600.

It is seen that the shape of the curves are highly influenced by the size of the spring intervals, and the curves for intervals of 0.5 and 0.25 m becomes linear above 30°C.

It is also seen that the difference between spring intervals of 0.25 m and 0.5 m is quite negligible, and using an evenly distributed soil resistance force could therefore be expected only to result in a minor improvement of the accuracy of the results.

Reducing the spring intervals also gives a lower stress level. Especially in the temperature range from 20 to 90°C the difference is pronounced.

Normally springs placed at intervals of L are considered sufficient where L is calculated from

$$\frac{1}{L} = \beta = \sqrt[4]{\frac{k}{4 \cdot E \cdot I}}$$

where

k is the line bedding constant

$$k \approx 2.7 \cdot \frac{p_u}{y_u} \quad \text{(force/length}^2\text{)}$$

However, these calculations show, that the beam-element model is very sensitive to variations in the intervals. It is concluded, that in this particular case, the maximum spring interval close to the bend is 0.5 m.

Figure 8.7 and figure 8.8 show the number of load cycles that corresponds to the calculated stress range for the two dimensions.

The calculation with 0.5 m spring intervals is used for DN600.

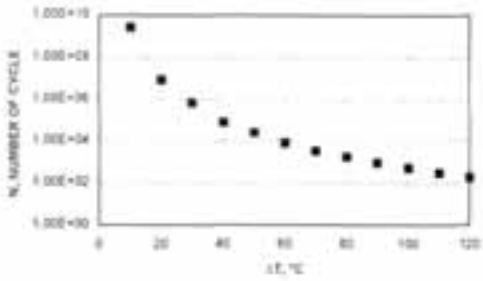

Figure 8.7 Number of load cycles, DN150.

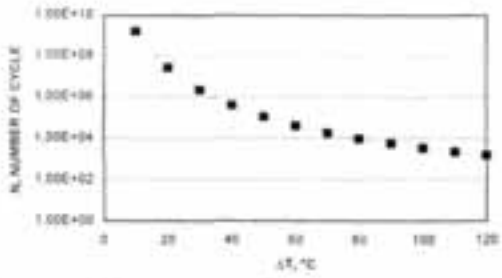

Figure 8.8 Number of load cycles, DN600.

The number of full load cycles for ΔT = 110°C is 295 for DN150 and 2212 for DN600. With a partial safety factor γ_{fat} = 5 to 10 depending on project class the fatigue life will be satisfactory for the DN600 pipe in most cases, whereas stress reducing measures must be taken for the DN150 pipe.

Stress reducing measures are more commonly applied to the larger dimensions. In the present example the DN600 pipe gives higher values of N_f because of the more favourable ratio of Z/D_c (relative burial depth).

8.1.2 Effect of Soil Cover

In order to investigate the effect of soil cover an additional calculation on the DN600 pipe was made with 2 m soil cover.

Figure 8.9 and figure 8.10 illustrates the differences in pipe-soil interaction with 1 and 2 m soil cover:

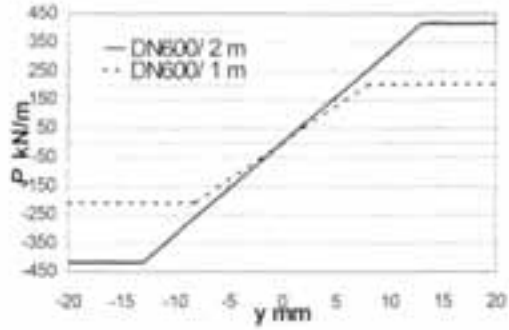

Figure 8.9 Lateral soil reaction with different soil cover.

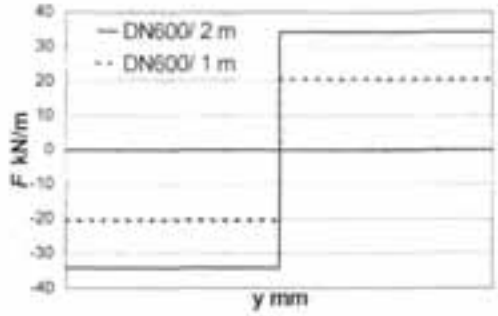

Figure 8.10 Soil friction, F, with different soil covers.

Figure 8.11 compares the results for 1 m and 2 m soil cover.

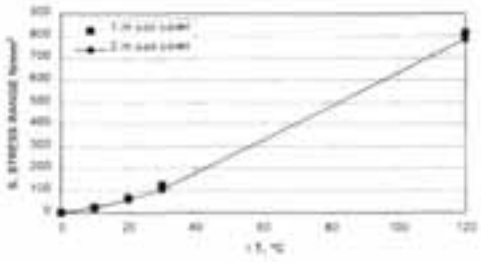

Figure 8.11 Stress range with different soil covers, DN600.

While an increased friction force causes a smaller expansion and therefore reduces stresses, the increased soil reaction increases the stress level, and it is seen that these two effects almost neutralise each other for the dimension examined.

8.2 Stress Reducing Measures

Stress reducing measures are analysed by comparison of following alternatives:

- standard wall thickness for bends
- increased wall thickness for bends
- foam cushions
- cavities
- preheating

The alternatives are examined for following standard pipe dimensions and soil data are shown in table 8.3.

Nominal diameter	DN80	DN150	DN600
Diameter of steel pipe, d_o, mm	88.9	168.3	610.0
Pipe wall thickness t_n, mm	3.2	4.2	7.1
Casing diameter, D_c, mm	160	250	800
Bend radius, R, mm	205	390	1525
Ultimate soil resistance, Pu, kN/m	49.7	69.4	203
y^* (see below) mm	7	7	8
Friction, F, kN/m	2.99	4.93	20.65
Spring interval near bend, m	1	1	0.5
Soil cover to top of pipe, m	1	1	1

Table 8.3 Pipe and soil data

y^* is the lateral movement in the point where bilinear force-deformation relationship changes from elastic to plastic deformation (design value). See EuHP District Heating Handbook, figure 5.3 [3].

The same beam element model as shown in figure 8.1 is used, but the location of the soil springs for the DN150 pipe close to the bend are changed. In figure 8.1 the first spring was applied one meter away from the point of intersection of the two legs of the L-bend, but now springs are also applied to the endpoints of the bend. This is also the case for the DN80 pipe.

For the DN600 pipe the radius of the bend exceeds 1 m and therefore the first spring in the previous calculations applied to the endpoints of the bend.

This is assumed to result in a more realistic model, but a better solution would be to apply springs directly to the curvature of the bend.

The radius of the DN600 pipe is changed compared to the previous calculations.

When examining the effects of stress reducing measures only the stress range at the reference temperature 110°C and the number of load cycles that induces fatigue failure, N_f, are calculated, see enclosure 8A.

In enclosure 8A N_f is shown with a graphical presentation of the geometry.

8.2.1 Standard Wall Thickness

The results of the calculations for the standard layout divert insignificantly from the previous results in spite of the changes made to the model. The tendency that the fatigue life deteriorates with decreasing dimension is confirmed by the result for the DN80 pipe.

The conclusions concerning the fatigue life made earlier are unchanged, and the calculations with the DN80 pipe show that stress reducing measures are necessary for the smaller dimensions.

8.2.2 Increased Wall Thickness

The wall thickness of the bend for DN80 and DN150 are increased in accordance with DIN 2605 Teil 1, Reihe 4, while it is Reihe 3 only for DN600.

The wall thickness is shown in table 8.4. For all dimensions it is an increase of the wall thickness of about 75%. The rest of the L-bend has standard wall thickness.

Diameter of steel pipe, d_o, mm	80	150	600
Bend wall thickness, t_n, mm	5.6	7.1	12.5

Table 8.4 Increased wall thickness of bends

It is shown that increasing the wall thickness of the bend causes an increase in the fatigue life. Even though the relative increase of the wall thickness is the same for all dimensions, there is a clear tendency that the effect is more pronounced for the smaller dimensions. This is suitable, as it is the smaller dimensions, which are having the biggest problems achieving a satisfactory fatigue life. If it is sufficient to increase the wall thickness depends on the actual number of load cycles and the safety factor, but N_f is still critically low in many cases.

When using a bend with increased wall thickness, the bend becomes stronger, but it also becomes more flexibile, which causes the forces and moments on the bend to increase.

It is generally believed that this positive and negative effect compensate each other, but the calculations indicates that this is not the case when the wall thickness is increased 1 series according to DIN 2605, e.g. from Reihe 3 to Reihe 4.

An additional calculation (not documented in the report) shows that increasing the wall thickness one more series causes larger stresses, and therefore a shorter fatigue life. The point with the largest stress then moves from the bend to the straight part next to the bend.

8.2.3 Foam Cushions

The foam cushions are applied to a length of 2 m at both ends of the bend. In the model this is done by changing the properties of the relevant soil springs, see table 8.5.

The foam cushions are 40 mm thick and has a stiffness of 100 kN/m^2 by 50 % compression. To absorb the rather large movements it is necessary to use more than one layer.

Diameter of steel pipe, d_o, mm	88.9	168.3	610
Thickness of foam cushions, mm	2x 40	3x 40	4x 40
y' (see table 8.3) m	47	67	88
Ultimate soil resistance, Pu, kN/m	35.6	52.5	119

Table 8.5 Soil spring properties with foam cushions

The effect of the foam cushions varies much with the dimension. While the improvement of the fatigue life for the two largest dimensions is about the same as observed in the previous subsection, the improvement for the DN80 pipe is quite limited.

It is important to ensure that the cushions are not fully compressed, because this will result in increasing stresses, due to the larger cross sectional area of the pipe and the cushion. In practice not more than 50 % compression is accepted.

Because of the large axial movements from the long leg of the L-bend, it is therefore necessary to apply a number of layers, up to 4 layers for the DN600 pipe.

The use of foam cushions has many inconvenient side effects, see clause 7.4, bends. Therefore foam cushions are not a practical alternative when dealing with movements that requires more than one layer.

8.2.4 Cavities

Creating cavities around the pipes where they move lateral give a more flexible system, and thus it is the normal way to reduce stresses in non-restrained pipe systems. Cavities are typically made by

making a duct of concrete or corrugate steel elements.

A cavity is modelled by removing all soil springs inside the cavity and replacing the springs at the inlets to the cavity with lateral steering guides.

The length of the cavity must obviously vary with pipe dimension. In this case the length of the cavity was adjusted in order to reach a specified fatigue life, N_f, the approach normally used in design.

As point of reference a length of 2 meters is set for the DN80 pipe. This results in a value of N_f of nearly 4000, compared to 140 for the standard wall thickness.

To achieve the same magnitude of N_f in round numbers the lengths of the cavity was determined (by iteration) to respectively 3 and 6 meters for the DN150 and the DN600 pipe.

This shows that even a relatively small cavity is a very efficient way of reducing stresses in the bend. The only disadvantage is that it is quite costly.

8.2.5 Preheating

The effect of preheating with $\Delta T = 55°C$ is investigated.

With preheating, the stress range is calculated as twice the range corresponding to $\Delta T = 55°C$.

Due to the non linear ΔT –S curve below 30°C, the stress range is reduced compared to the range calculated from a $\Delta T_{ref} = 110°C$.

The use of preheating only causes N_f to increase moderately. The increase is about 100 % for the smallest dimension, but an increase of about 100 % is in fact just a minor increase. It corresponds to a 15 % reduction of the stress range only.

Furthermore, the presupposed S-ΔT relationship is too optimistic for fatigue analysis, see clause 7.3. For varying temperature it cannot be expected that each cycle will start from (0,0) in the S, ΔT diagram, the relationship is more likely to be linear.

Therefore it can be concluded that preheating only has very little - if any - influence on the fatigue life.

8.2.6 Increasing Bend Radius

It is well known that increasing bend radius improves the fatigue life, so this has not been examined further.

9.Calculation Examples, Tees

Similar to bends a number of calculations have been made in order to evaluate the lifetime of tees at consumers connections with different configurations and different types of tees.

In clause 9.1 the principles of the modelling are outlined and the sensitivity of the model to one specific effect is examined.

In clause 9.2 a number of stress reducing measures are examined.

9.1 Modelling of Tees

Branches at consumers' connections are of particular interest, as they are subject to the largest number of temperature variations, especially the return pipe.

For the preliminary modelling a branch is considered where the run pipe of the tee is fixed in the axial direction. The branch is located in the partly restrained part of the main pipe, which means, that the axial stress of the main pipe is moderate. The axial stress from heating in the main pipe is modelled by applying an axial force.

The beam-element model is shown in figure 9.1. The full line represents a layout used as reference in clause 9.2. The dotted line shows the variation of the geometry called "fly leg".

In the reference layout a standard prefabricated preinsulated tee is used where the branch connects to the main pipe in an angle of 45° as shown.

The pipe-soil interaction is modelled as described in clause 8.1 with the same soil data.

The section forces and moments at the branch and run pipe of the tee are found using RAMBØLL's beam-element program "RØR".

The stress range, S, is calculated as the maximum von Mises reference stress. Stress intensification factors according to DS448 [8] and the draft European standard [1] are used.

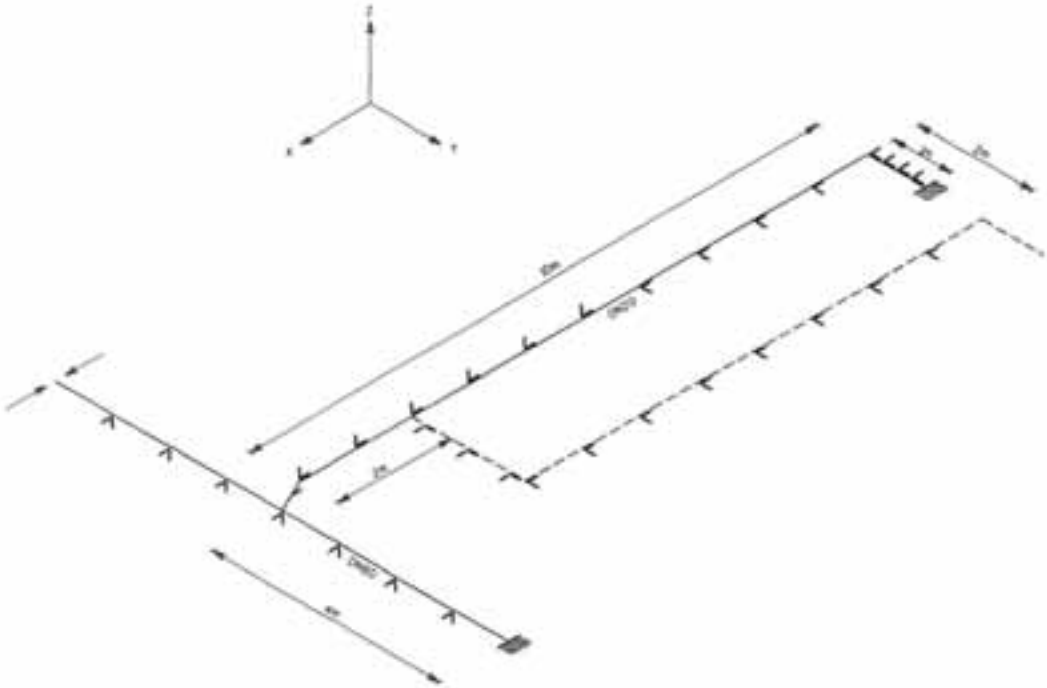

Figure 9.1 Beam-element model of a consumer branch connection

The stress range is converted to the equivalent number of full load cycles using the SN-curve in the draft European standard [1].

The method of calculation is covered in the EuHP District Heating Handbook [3] subclause 6.7.5, and a detailed example of calculation can be seen in clause 8.4 in the handbook.

9.1.1 Quality of Model

Initial calculations were made on a DN80 main pipe with a DN20 branch pipe with no pre-stressing with the geometric data in table 9.1.

The material data are the same as used for bends, chapter 8.

	Main pipe	Branch
Nominal diameter of steel pipe, d_n, mm	80	20
Outer diameter of steel pipe d_o, mm	88.9	26.9
Wall thickness t_n, mm	3.2	2.0
Casing diameter D_o, mm	160	90
Bend radius R mm	-	57.5
Soil cover Z, m	1	0.825

Table 9.1 Pipe data

Preliminary it is examined if it has any effect on the results if the length of the main pipe is varied between 4, 8 and 16 m.

In figure 9.2 and 9.3 it is seen that the length of the main pipe has a significant influence on the result.

The stress range increases with decreasing length of the main pipe. The branch affects the main pipe with a torsional moment. With a longer main pipe, the resistance against torsion becomes smaller and the stresses in the tee decreases.

This indicates that the consumer branch connection cannot be considered isolated from the rest of the system, but it doesn't seem reasonable that the branch is affected of the geometry of the main pipe far away from the branch.

Similar to the soil resistance against axial movement of the pipe, the soil also provides resistance against torsion. This effect is normally not included in the modelling, but these calculations indicate that it should be included, and doing so the model would presumably be much less sensitive to the geometry of the main pipe far away from the branch.

To construct a realistic model of the soil frictional moment based on theoretical considerations is however quite difficult, as we are dealing with very small angular movements of the main pipe (considerably less than 1°). A way to assess this effect would be to perform a series of practical experiments.

The effect is omitted in the following calculations. This means that the calculated stress level as seen will depend on the specific geometry of the pipe system near the tee, and it is therefore not possible to carry out general calculations that are valid in all situations.

In the draft European standard subclause A3.6.2 flexibility factors are included for the connection branch and main pipe.

These factor should be used with caution, especially if the torsional resistance of the main pipe is not dealt with in detail.

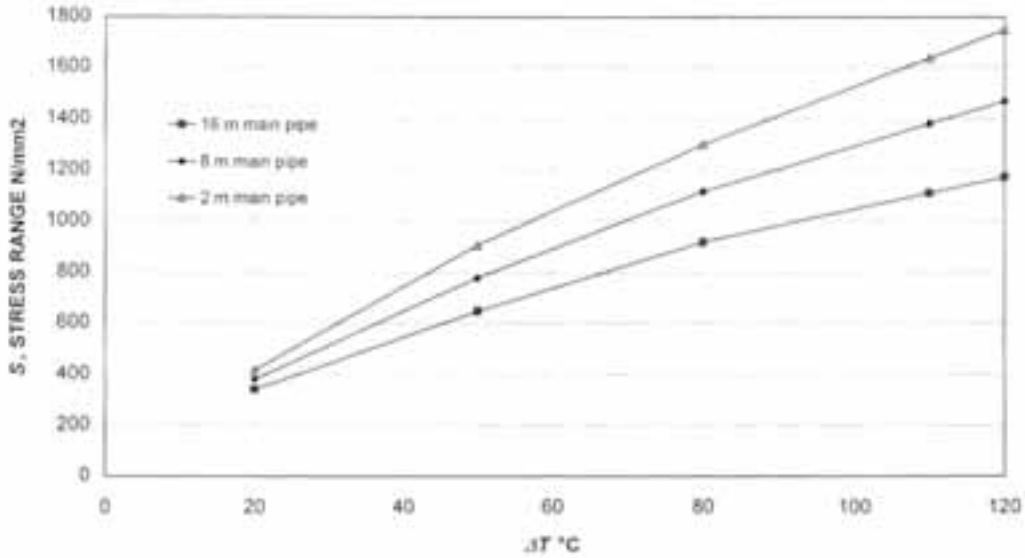

Figure 9.2 Stress range for tee 80/20 with varying length of main pipe

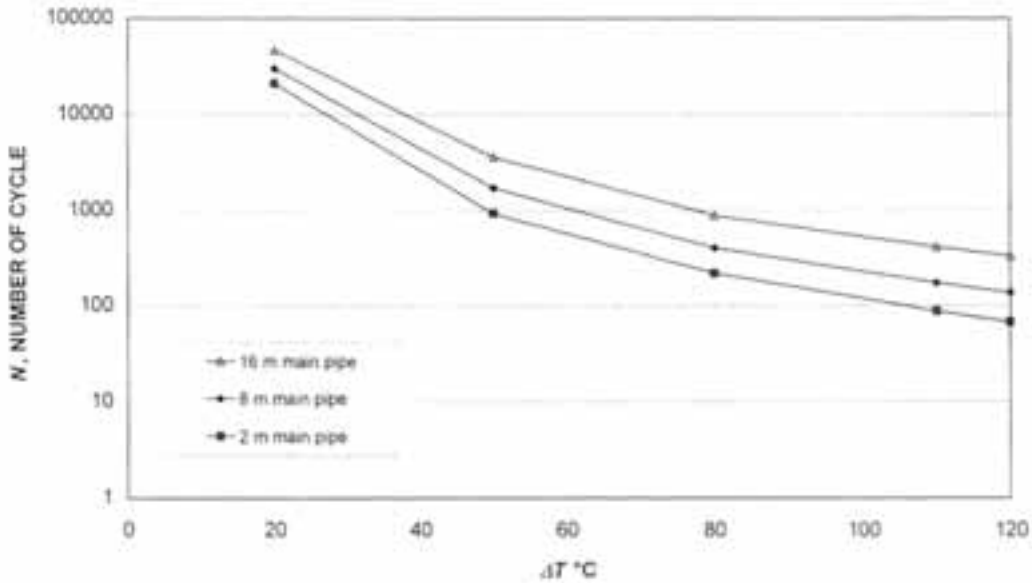

Figure 9.3 Maximum number of load cycles for tee 80/20 with varying length of main pipe

9.2 Stress Reducing Measures

Following layouts of the branch connection has been examined:

- Reference layout (figure 9.6)
- Branch with "fly leg" (figure 9.7)
- Vertical branch (figure 9.8)
- Branch with fixpoint (figure 9.9)
- Horizontal branch (figure 9.10)
- Reference layout with foam cushions on main pipe (figure 9.11)

For each layout different types of tees have been applied, see figure 9.5.

The problem concerning the stiffness of the main pipe, cf. subclause 9.1.1 is dealt with

here by using typical values for the distance L_3, see figure 9.4, table 9.4 and 9.5.

Doing so, the calculations can be used to compare different layouts of the branch, although the absolute stress level is subject to some uncertainty.

The calculations are performed with an axial stress of

- 150 N/mm^2 corresponding to a position in the partly restrained part of the main pipe,
- 200 N/mm^2 and
- 300 N/mm^2 corresponding to a position in the fully restrained part of the main pipe.

9.2.1 Pipe Dimensions and Geometry

The calculations are performed with a DN200/DN80, a DN100/DN100 and a DN450/DN450 tee. The first one is a typical branch connection to a large consumer, while the two others are typical branches in distribution pipe systems.

Pipe data are shown in table 9.3, geometry in table 9.5 and the beam-element model in figure 9.4.

The support of the main pipe at one end is fixed in horizontal and vertical direction. The support is free to move in axial direction for application of the axial force.

Main pipe / branch		DN/DN	80/20	200/80	100/100	450/450
Nominal diameter	Main pipe	mm	80	200	100	450
of steel pipe, DN	Branch	mm	20	80	100	450
Outer diameter	Main pipe	mm	88.9	219.1	114.3	457.0
of steel pipe, d_o	Branch	mm	26.9	88.9	114.3	457.0
Pipe wall	Main pipe	mm	3.2	4.5	3.6	6.3
thickness, t_n	Branch	mm	2.0	3.2	3.6	6.3
Casing diameter,	Main pipe	mm	160	315	200	630
D_c	Branch	mm	90	160	200	630
Bend radius, R	Branch	mm	57.5	205	270	1122

Table 9.3 Pipe data

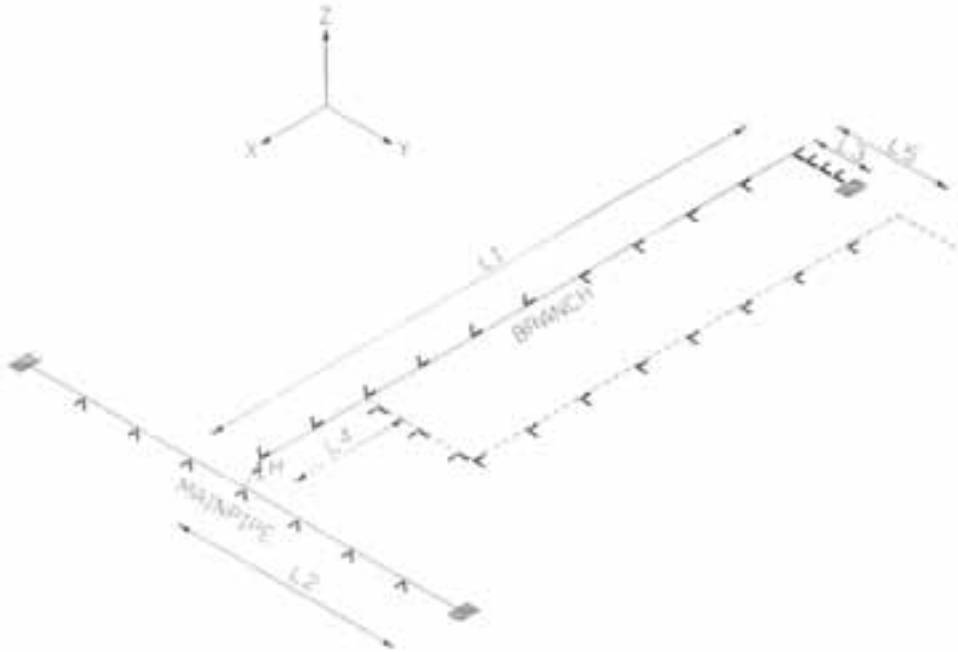

Figure 9.4 Beam-element model

The values of L_1 in table 9.5 are estimates based on experience.

To determine a realistic value for L_2 two district heating pipe system in Copenhagen, Denmark and in Pundang, Korea are analysed to determine the average distance from tee to tee or tee to bend. The results are shown in table 9.4.

The registration shows similar conditions in the two investigated areas and almost the same average distance between tees or between tees and bends.

The average nominal pipe dimensions in both places are very close to the DN200/DN80 branch connection and L_2 is therefore set to half the average distance between tees or between tees and bends for this dimension (~25 m).

This value is also used for the dimensions DN100/DN100 and DN450/DN450.
For the smallest dimension L_2 is set to 10 m, as this is considered a realistic value for a residential area.

L_3 is set in accordance with the minimum distance between a bend and an anchor recommended in a typical supplier's catalogue.

L_4 and L_5 are set in accordance with a standard preinsulated bend from the same supplier.

Place	Copenhagen Tårnby Denmark	Pundang Sujih Korea
Number of investigated tees	80	51
Max. nominal pipe dimension	500 mm	700 mm
Min. nominal pipe dimension	40 mm	25 mm
Average nominal dimension of main pipe	231 mm	199 mm
Average nominal dimension of branch	71 mm	98 mm
Average distance from tee to tee or bend	53 m	50 m

Table 9.4 Distances from tee to tee or bend

Main pipe/branch	DN/DN	80/20	200/80	100/100	450/450
L_1	m	10	30	30	30
L_2	m	10	25	25	25
L_3	m	1	2	2.5	6
L_4	m	2	2	2	2
L_5	m	2	2	2	2
H	m	0.175	0.2875	0.250	0.680

Table 9.5 Geometric data

9.2.2 Tees

The calculations include three different types of tees with variations in wall thickness. The different stress intensification factors can bee seen in the draft European standard, subclause A3.7.5 [1].

These stress intensification factors are mainly based on finite element modelling (FEM) in the research project [19].

The results from these FEM-calculations are converted into practical rules-of-thumb, which should be used with caution. The proposed methodology refers all stresses to the same point on the tee (the saddle point on the side of the tee). For most load cases the maximum stresses will occur in this point.

However, for in-plane bending with a high moment in the branch (e.g. where the main pipe has large axial movement) the highest stresses will occur in the top point. Recent calculations seam to indicate that stress intensification factors used for this load case are too small.

Extruded tee
is made by forging a collar onto the run pipe by pulling a ball through a hole which is smaller than the diameter of the ball. The collar is then welded onto a transitional piece with increased wall thickness.

The calculation is made on an extruded tee with standard pipe wall thickness of both branch and main pipe.

Welded tee
also sometimes designated a fabricated tee. It is made by welding the branch pipe directly to the run pipe. Welded tee without reinforcement have not been considered, as it is considerably weaker than the extruded tee, and it is seen that the use of an extruded tee without reinforcement results in an unacceptably low number of N_f. Instead calculations are made with a welded tee with reinforcement plate around the run pipe. The wall thickness of the reinforcement plate is the same as that of the run pipe, and it is modelled by increasing the wall thickness of the run pipe locally.

Weld-in tee
is normally made by forging, and the formulas are applicable for dimensions according to ISO 3419 or DIN 2615. Again a DIN 2615 Teil 1, Reihe 4 weld-in tee where the wall thickness of both the branch and the main pipe are increased is chosen.

Extruded tee with increased wall thickness
A calculation where the wall thickness of both the branch and the main pipe are increased is also made. They are increased to the same values as a DIN 2615 Teil 1, Reihe 4 weld-in tee to facilitate comparison.

Welded tee with increased wall thickness
A calculation where the wall thickness of both the branch and the main pipe are increased, according to a DIN 2615 Teil 1, Reihe 4 weld-in tee is made.

Main pipe/branch		DN/DN	80/20	200/80	100/100	450/450
Normal wall-thickness	Main pipe	mm	3.2	4.5	3.6	6.3
	Branch	mm	2.0	3.2	3.6	6.3
Reinforcement plate	Main pipe	mm	6.4	9.0	7.2	12.6
	Branch	mm	2.0	3.2	3.6	6.3
DIN 2615 Reihe 4	Main pipe	mm	5.6	8.0	6.3	14.2
	Branch	mm	3.2	5.6	6.3	14.2

Table 9.6 Wall thickness of tees

	Extruded tee with standard pipe wall thickness
	Welded tee with reinforcement plate
	DIN 2615 Teil 1, Reihe 4 weld-in tee
	Extruded tee with increased wall thickness
	Welded tee with increased wall thickness

Figure 9.5 Symbols used for the different types of tees

9.2.3 Soil Mechanics

The modelling of the pipe-soil interaction is the same as in chapter 8.
The soil cover (measured from centre of the main pipe) is set at 1 m for the three smallest dimensions, and the soil cover of the branch is determined by the geometry of a standard preinsulated tee. The use of 1 m soil cover for the large dimension (DN450) would result in an unrealistic low soil cover of the branch, and it is therefore increased to 2 m.

The soil data are presented in table 9.7.

Main pipe/branch		DN/DN	80/20	200/80	100/100	450/450
Main pipe	Z	m	1	1	1	2
	P_u	kN/m	45.4	68.5	51.3	274.1
	y'	mm	7	7	7	15
With foam-cushions	P_u	kN/m	28.8	45.4	-	-
	y'	mm	27	27	-	-
Branch	Z	m	0.825	0.713	0.750	1.320
	P_u	kN/m	24.3	28	34.6	158.4
	y'	mm	6	5	6	10
	F	kN/m	1.27	1.99	2.63	15.09

Table 9.7 Soil data

9.3 Evaluation of Results

The results are presented in enclosure 9A (150-200 N/mm^2) and 9B (300 N/mm^2), which show N_f in connection with a graphical presentation of the geometry.

In the IEA project [2] a maximum number of full temperature cycles was calculated to 379 (extrapolated to a period of 30 years) based on measurements in the return pipe of a consumer branch connection (ΔT_{ref} = 110°C, b = 4).

In the present project the maximum measured values are No = 728 (R18) and No = 678 (R20) (ΔT_{ref} = 110°C, b = 4).

According to the draft European standard the partial safety factor γ = 5-10 depending on project class. As consumers connection typically will be in the lowest class (project class A) the lower limit for the design value of full load cycles will be $5 \cdot 728 = 3640$ cycles.

It should be noticed that the value of 728 is from one particular project, and it is possible, that a higher number could be measured elsewhere, but this value is considered the most realistic for the time being.

9.3.1 Reference Layout

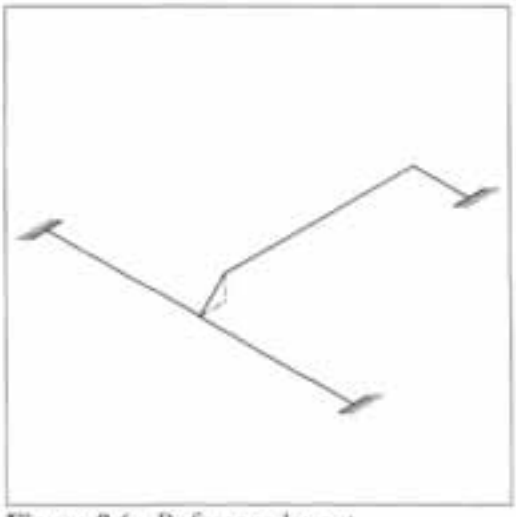

Figure 9.6 Reference layout

With the reference layout calculations on all the dimensions and the five different tees (see figure 9.5) has been carried out with a normal stress of 150 N/mm^2 and 300 N/mm^2 in the main pipe. For two of the tees calculation has also been made with a normal stress of 200 N/mm^2.

The calculations with the extruded tee with normal wall thickness again show too low N_f for all dimensions to be acceptable for practical use. The fatigue life deteriorates with increasing dimension and N_f reaches values as low as 23 (150 N/mm^2) and 7 (300 N/mm^2) for the DN450/DN450 tee.

The use of a welded tee with reinforcement plate to some extent improves the fatigue life, but N_f is still too low. The improvement is largest for tees where branch and main pipe are of same dimension. In fact, the reinforcement plate halves the normal stress in the main pipe, and it seems reasonable that the tees with the largest branches relative to the main pipes is most sensitive to the magnitude of the normal stress.

The last three tees differs in type but the increased wall thickness of both the main pipe and the branch is the same, therefore the calculations with these can be used to illustrate the effect of the different stress intensification factors used in connection with the different types of tees.

It is seen that the fatigue life is highly dependent of the chosen type of tee.
The DIN 2615 Teil 1, Reihe 4 weld-in tee is seen to cause a pronounced improvement, and the fatigue life would in most cases be satisfactory for the pipe in the partly restrained part of the main pipe (150 N/mm^2). With the pipe in the fully restrained part (300 N/mm^2) N_f is unacceptably low for many cases, therefore a larger wall thickness is required.

Using an extruded tee with increased wall thickness also improves the fatigue life, but the improvement is significantly smaller than with the weld-in tee. The fatigue life

(with 150 N/mm²) would never the less still be satisfactory in many cases.

The welded tee with increased wall thickness results in a much smaller improvement than the other two, and it does not seem to be a useful alternative.

It is seen that the relative effect of using a DIN 2615 Teil 1, Reihe 4 weld-in tee compared to an extruded Tee with normal wall thickness is largest for the DN450/DN450 dimension.

This is due to the fact that the normal wall thickness of the DN450/DN450 tee only relates to Reihe 2, where it is Reihe 3 for the others (except the DN200 main pipe that is also Reihe 2). This means that the relative increase of the wall thickness is largest for the DN450/DN450 tee.

9.3.2 Fly Leg

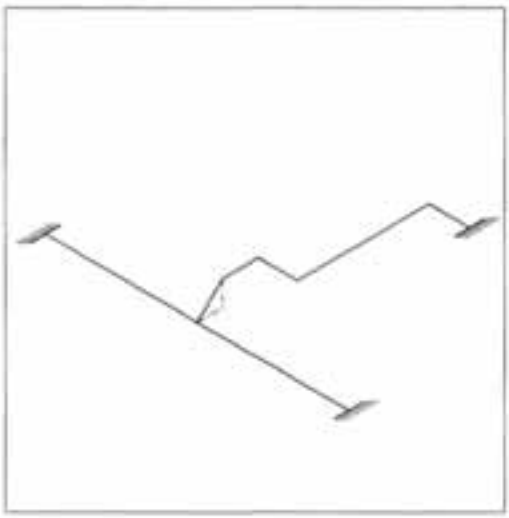

Figure 9.7 Layout with "fly leg"

The calculations with the "fly leg" are made with dimensions DN80/DN20 and DN200/DN80 and with three different tees: Extruded tee with normal wall thickness, welded tee with reinforcement plate and DIN 2615 Teil 1, Reihe 4 weld-in tee.

As seen earlier the "fly leg" is a very effective way of increasing N_f.

The weld-in tee results in values of N_f which are acceptable for practical use even if an exceptionally high number of temperature variations are expected to occur.

With the low axial stress and the largest dimension this is also the case for the welded tee with reinforcement plates. In the other cases the evaluation of the fatigue life is more dependent of the expected number of load cycles and the safety factor.

The reason why the relative difference between the two dimensions is reversed compared to the calculation with the reference geometry is of course that L_1 differs while L_4 is kept the same for the two dimensions, se table 9.5.

9.3.3 Vertical Branch

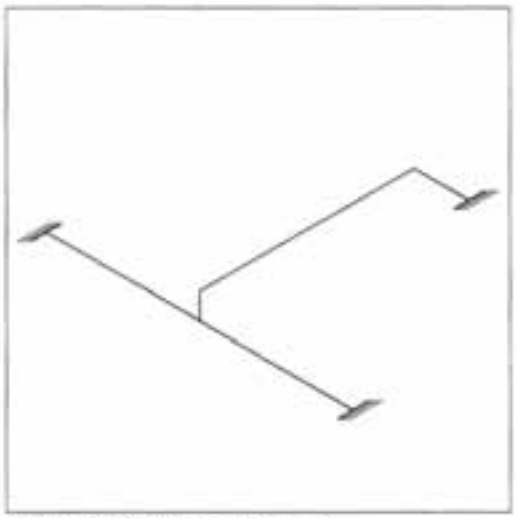

Figure 9.8 Vertical branch

The calculations with the vertical branch are made with the dimensions DN80/DN20 and DN200/DN80 and with two different tees: Extruded tee with normal wall thickness and DIN 2615 Teil 1, Reihe 4 weld-in tee.

This geometry has an unfortunate effect on the fatigue life. The deterioration is especially pronounced for the large dimension as N_f i.e. with the low axial stress decreases from 58 to 10 by increasing the angle from 45° to 90° (extruded tee, normal wall thickness). Also with the weld-in tee, N_f is lowered significantly to a value that could be critical especially for the large dimension.

The 90° bend next to the tee is more flexible than the 45° bend. This bend and the bend next to the consumer absorb the axial movement of the branch. Making it more flexible causes more movement to go towards the tee instead of towards the consumer, and this contributes to the intensification of the stress level.

Even though it is on slender grounds, these calculations strongly suggests that the 45° bend is to be preferred instead of the 90° bend.

9.3.4 Branch with Fixpoint

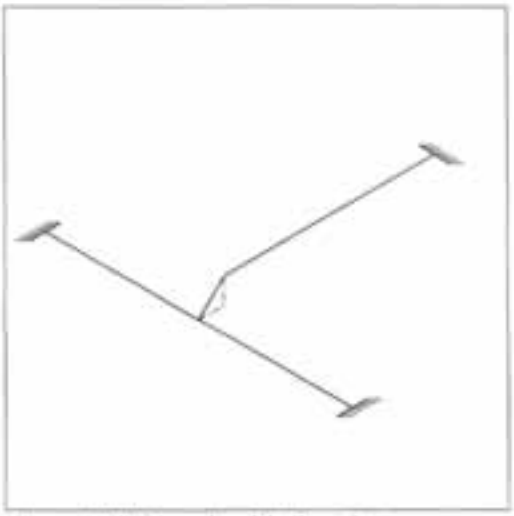

Figure 9.9 Branch with fixpoint

Calculations with this geometry are made for the same dimensions and types of tees as in the previous example.

For the large dimension the length of the branch is set to 30 m. For the small dimension the length is set to 10 m.

It is seen that this geometry, as expected, is crucial for the fatigue life of the DN200/DN80 tee. Even with a DIN 2615 Teil 1, Reihe 4 weld-in tee the fatigue life is unsatisfactory for most practical use.

Typically it is recommended that the length of the branch does not exceed 12 meters.

The fatigue life is also shortened considerably for the small dimension. In spite the fact that the geometry is in compliance with the suppliers recommendations, the use of a DIN 2615 Teil 1, Reihe 4 weld-in tee only just results in a safety against fatigue failure that would be accepted in some cases.

In fact, this geometry results in the lowest N_f of all the geometries considered. A geometry where the only possible expansion is towards the tee cannot on this basis be recommended.

9.3.5 Horizontal Branch

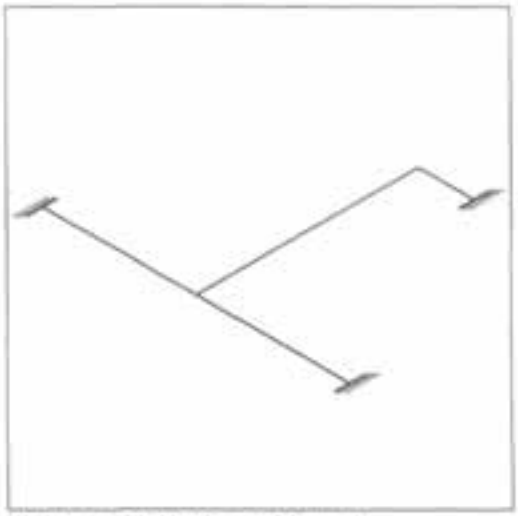

Figure 9.10 Horizontal branch

Calculations for this geometry are only carried out with the smallest dimension and with two different tees: Extruded tee with normal wall thickness and DIN 2615 Teil 1, Reihe 4 weld-in tee.

Except for the "fly leg" calculations this is the geometry where the highest values of N_f are attained.

With this geometry, there is no bend next to the tee, which means that most of the movement goes towards the bend next to the consumer. Furthermore, there is no bending moment on the branch of the tee, which is a part of the reason why the stress level is so low. Instead there is a large normal force on the branch, but this seems to be less critical for the "hot spot" than the bending moments.

It has been considered whether the calculations for this geometry result in the actual maximum stress.

The methodology assumes that the maximum stresses from internal forces occur in the vicinity of the saddle point of the tee, and if this specific geometry result in a different "hot spot" this is not taken into account.

Even if the results are correct and the fatigue life with this geometry is favourable, there is one obvious practical problem connecting to both the supply and the return pipe in this manner unless the supply and return pipes are placed under and above each other.

9.3.6 Foam Cushions on Main Pipe

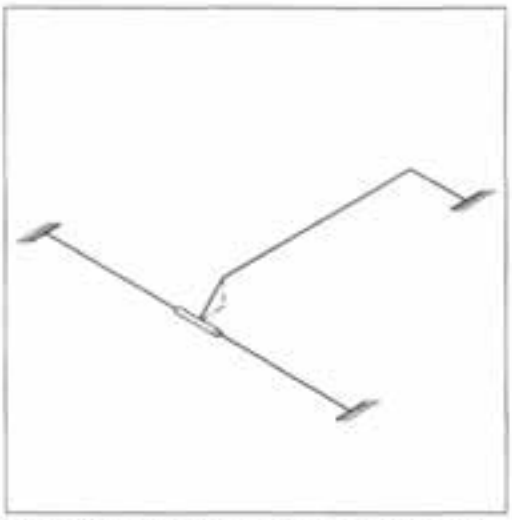

Figure 9.11 Foam cushions on main pipe

Calculations with foam cushions are only carried out with the extruded tee with normal wall thickness and with the dimensions DN80/DN20 and DN200/DN80.

In this example the cushions are applied to the main pipe (over a length of 2 meters).

It is seen that the effect of the cushions depends of the dimension. For the small dimension N_f is increased from 165 to 309 and from 75 to 124 for the low and the high axial stress respectively, but N_f is practically unchanged for the large dimension in both cases.

In fact N_f is slightly decreased which is due to the discrete soil springs that in this case are applied with an interval of 3 meters.

The cushions have the unfortunate effect that the neutral point of the branch moves 3 meters towards the bend next to the consumer. This means that the tee must absorb the movement of three more meters of the branch and this effect overrules the positive effect of the cushions.

It is possible that some positive effect could have been observed if the cushions had been applied to a longer part of the DN200 pipe. But the calculation indicates that the effect probably will be limited with main pipes in larger dimensions, which are very rigid compared to the smaller ones, where a clear effect has been seen.

Regarding the limitations in use of foam cushions see clause 7.4. The limitation mentioned for bends also applies to tees.

10. Bevel Welds

To determine the maximum number of full equivalent load cycles for pipes with small angular deviations (bevel welds) three different approaches to this problem have been compared, namely:

1. The Danish code of practice, DS 448, [8]
2. The draft European standard, [1]
3. A theoretical method, based on the formulas for an infinite beam on elastic foundation, [34].

10.1 The Danish Code of Practice

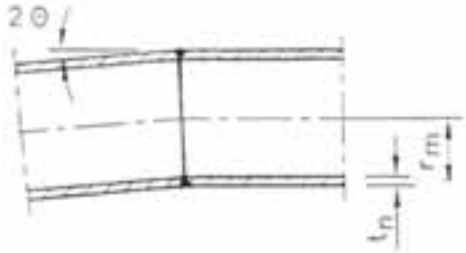

Figure 10.1 Bevel weld

In the Danish code of practice, DS448 the stress intensification factors for axial stresses from normal forces is given by:

$$k_{a2} = k \cdot k_f$$

where

$$k = 0.9 \cdot \left(\frac{t_n \cdot (1 + \cot\theta)}{2r_m} \right)^{-\frac{1}{2}} \quad (k \geq 1)$$

r_m is the mean radius of service pipe
t_n is the wall thickness
2θ is the bevel angle

$$k_f = 1 + 2 \cdot \frac{\sin\theta}{\beta \cdot d_0} \text{ for buried angles}$$

where

$$\beta = \sqrt[4]{\frac{K}{4EI}}$$

K is the modulus of soil (N/m^2)
$K = D_k \cdot \alpha_0$

where

D_k is the outer diameter of casing
α_0 is the secant gradient to the force/deflection diagram of the lateral movement of the pipe in the soil.

The gradient can be calculated by

$$\alpha_0 = 2.0 \cdot \frac{p_u}{y_u}$$

where

p_u and y_u are calculated corresponding to the current material and geometry.

Stress from bending moments is ignored in stress range analysis (but is included in the stress intensification factor).

The design fatigue figure (limit state) for axial stress is

$$n_{fat,d} = \frac{1.51 \cdot 10^{12}}{\sigma_{zr}^{3}} \quad (b = 3)$$

The load carrying capacity is determined using the Palmgren-Miner rule,

$$\Sigma \frac{n_{f,i}}{n_{fat,d,i}} \leq \eta$$

where $\eta = 0.15$ for normal safety class.

10.2 Draft European Standard

Stress intensification factors are for axial stress from normal forces and bending moment:

$$i_{at} = i_{ac} = 1 + 1.65 \sqrt{\frac{d_0}{t_n}} \cdot \tan\theta$$

where

d_0 is the outside diameter of service pipe
t_n is the nominal wall thickness
2θ is the bevel angle

i_{at} and i_{ac} must not be valued lower than the value for butt welds, which is

$$i_{al} = i_{ac} = 0.9 + 2.7 \cdot \frac{d_{max} - d_{min}}{2t_n}$$

where

d_{max} is the maximum mean diameter of pipe

d_{min} is the minimum mean diameter of pipe

If $d_{max} - d_{min} > 2.0$ mm, then 2.0 mm is used.

The stress concentration factor proposed in the draft European standard [1] presupposes that the angular deviations are limited according to following table:

Maximum temperature difference	Maximum angular deviation
90 K	2°
100 K	1°
110 K	0,5°
> 110 K	0°

Table 10.1 Maximum angular deviation

An installation tolerance of ± 0,25° on the above-mentioned deviations is accepted.

For deviations larger than stated in table 10.1 local buckling can occur due to large axial compressive forces. This effect is not included in any of the three design methods.

The design fatigue figure (limit state) for axial stress is

$$N = \left(\frac{5000}{S}\right)^4$$

For project class B, the safety factor is 6.67 (γ_{fat}), and the load carrying capacity is determined by

$$\Sigma \frac{n_i}{N_i} \leq \frac{1}{6.67} = 0.15$$

i.e. the same safety level as for DS448.

10.3 Theoretical Method

In a small angular bend, the normal force in the pipe causes a force in the direction of the bisector. The size of this force is

$$P = 2 \cdot N \cdot \sin\theta$$

where

θ is half the deviation

N is the normal force in the pipe

A pipe with a small angular bend can be calculated as a straight beam on elastic foundation if this force is applied.

The formula for the maximum bending moment is (Roark & Young: Formulas for stress and strain [34]):

$$M_{max} = \frac{P}{4\beta}$$

where

$$\beta = \sqrt[4]{\frac{K}{4EI}}$$

K is the foundation modulus (as for DS448)

The maximum axial stress from bending moments is found from

$$S_b = \frac{M}{W} = \frac{N \cdot \sin\theta}{\beta \cdot d_0^2 \cdot t \cdot \frac{\pi}{4}}$$

The total axial stress is

$$S_A = S_N + S_b = N \cdot \left(1 + \frac{\sin\theta}{\beta \cdot d_0^2 \cdot t \cdot \frac{\pi}{4}}\right)$$

10.4 Examples

The differences between the 3 methods are illustrated in the following examples.

Two pipes (DN150/250 mm and 400/520 mm) with bevels between 1 and 5 degrees have been calculated according to the 3 methods.

For all 3 methods, input data are identical:

Diameter casing, mm	250	250
Diameter of pipe, mm	168.3	406.4
Thickness of pipe, mm	4.0	6.3
E-steel, N/mm^2	2.10E+5	2.10E+5
Depth of pipeline, m	1.0	1.0
Sand, angle of friction	36 deg.	36 deg.
Sand, modulus of compression (K), MN/m^2	3.9	10.76
ΔT	90°C	90°C

Table 10.2 Input data for model

For simplicity, no internal pressure has been applied. This means that the actual load carrying capacity for a pipeline will be smaller than in these examples, but the differences between the methods will be the same.

The results are illustrated on figure 10.2 and 10.3. The curves Roak/DS and Roak/EN show the results from the theoretical methods with limit states from DS448 and EN (the draft European standard) respectively.

Comments on the calculations and methods

- DS 448:

  The influence of the soil stiffness is included in this method.

  The SN-curve includes a butt weld.

- Draft European standard:

  The stiffness of the soil has no influence.

  The SN-curve includes the effect of a butt weld.

- Theoretical:

  The effect of butt weld is not included.

10.5 Conclusion

As seen on figure 10.2 and 10.3, the calculations according to the draft European standard leads to a substantial higher load carrying capacity than the formulas from DS 448 and the theoretical method.

It shall be noted that the values for the draft European standard have been calculated for angles up to 5 degrees for comparison. This exceeds the proposed limits for the maximum angular deviation of 2 degree at $\Delta T = 90$ K.

The formulas in the draft European standard and the DS448-formulas include the effects of the butt weld, which always will be present in a small angular bend. If this effect is added in the theoretical method, the differences will be even higher.

The formulas from DS 448 give for most angles a higher load carrying capacity than the theoretical method.

None of the 3 calculation methods indicates that there should be any fatigue problems with small angular deviations in the range of 0-2 degrees if local buckling is avoided.

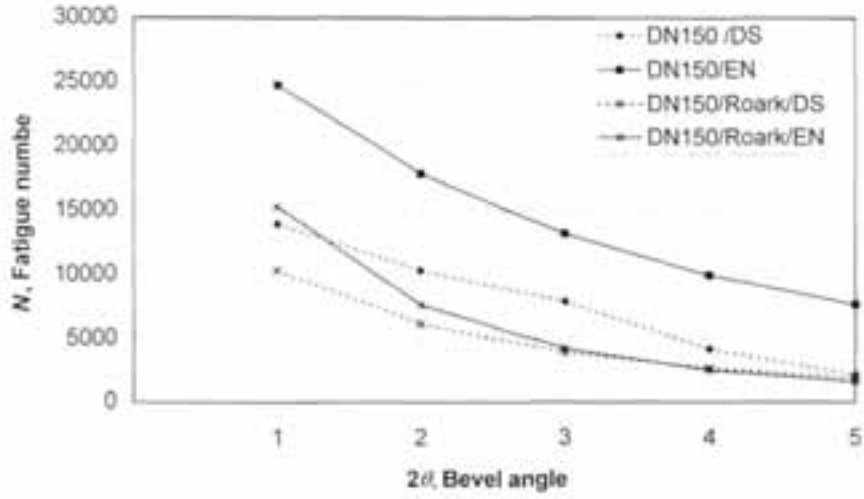

Figure 10.2 Load carrying capacities for DN150 / 250 mm pipe

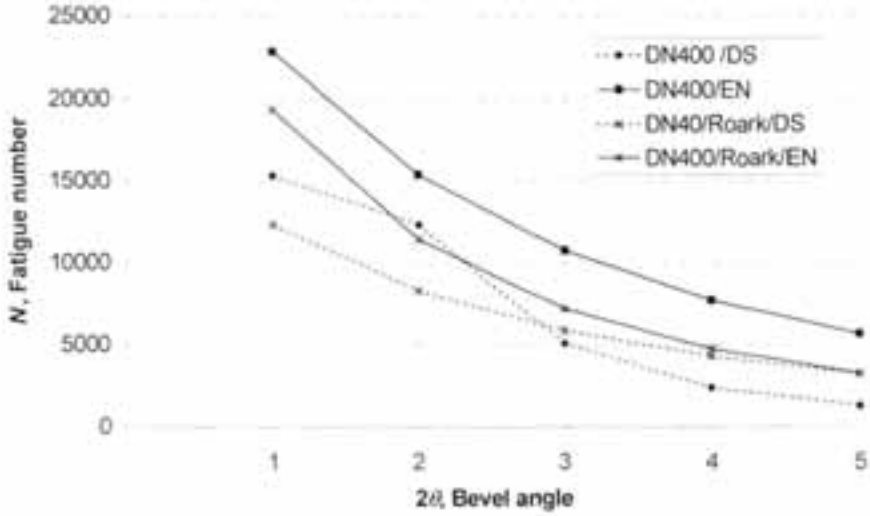

Figure 10.3 Load carrying capacities for DN 400 / 520 mm pipe

11. Symbols and Definitions

11.1 Symbols

b	exponent, slope constant in fatigue curve
c	constant
D_c	outer diameter casing
d_o	outer diameter steel pipe
E	modulus of elasticity
F	axial friction force
k_I	stress intensity factor
n	number of stress variation
n_i	number of stress variations with the temperature range, ΔT_i
N	number of full cycles
N_f	number of cycles to failure
N_i	number of full cycles with amplitude ΔT_i
N_{ti}	number of full temperature cycles with amplitude ΔT_{ref}
p_u	ultimate soil resistance
P	line bedding constant
S	stress range
S_{max}	maximum stress range
R	bend radius
t_o	wall thickness steel pipe
T	temperature
T_{max}	maximum temperature
Z	depth of burial to middle pipe
ΔT	temperature range
ΔT_{ref}	reference temperature
α	coefficient of thermal expansion
ε	strain
γ	partial safety factor, effective density of soil
μ	friction coefficient soil/PE
φ	friction angle of soil
σ	normal stress
$\Delta\sigma$	stress amplitude

11.2 Definitions

Action/load
Action is a set of concentrated or distributed forces acting on the pipe system (force-controlled action), or the cause of imposed deformation in the system (deformation-controlled action).

Action/load cycle
An action cycle is an impact at a given stress range. An action cycle comprises a full action course (which is twice the action amplitude calculated from an average value).

CEN
Comité Européen de Normalisation, The European Committee for Standardisation.

Design temperature
The maximum temperature used for the design of the pipe system.

Deformation-controlled action
Action caused by enforced deformation or movement, e.g. thermal expansion.

Fatigue strength
The stress range of constant magnitude (constant amplitudes of cyclic stresses and strains) which, under the given circumstances, induces fatigue failure.

Force-controlled action
Action which maintain its size irrespectively of the deformation of the structure, e.g. pressure and weight.

High cycle fatigue
When the stress amplitude is less than twice the yield stress the problem is referred to as high cycle fatigue. The number of cycles will typically be above 10^5. In high cycle fatigue cracking will occur due to stress failure.

JWG1
Joint working group under the technical committees CEN/TC107 "Preinsulated bonded pipes for district heating" and CEN/TC267 "Industrial pipes and pipelines".

Low cycle fatigue
When the formal stress range is more than twice the yield stress the problem is referred to as low cycle fatigue. There will be yield during each full cycle and cracking will occur due to strain failure.

Stress range
The difference between maximum stress and minimum stress for one single load cycle (the stress being computed with preceding sign).

Temperature history
Belonging values of cycles, n_i, with temperature differences ΔT_i typically sorted according to increasing ΔT_i.

Temperature range
The absolute value of the difference between the two extremes of temperature occurring during a cycle.

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ENCLOSURES

Chapter 1, Summary and Conclusion:

1A	Number of full cycles, Production
1B	Number of full cycles, Distribution
1C	Number of full cycles, Consumer

Chapter 4, Temperature Variations in Korean DH Systems
Chapter 5, Measuring Results

Supply pipe:

S18A	S18, Top of the pipe
	S18, Underside of the pipe
S18B	S18, Number of cycles, logarithmic diagram
S18C	S18, Sum, Cumulative Damage
S18D	S18, Wednesday 30/7-1997

Return Pipe:

R18A	R18, Top of the pipe
	R18, Underside of the pipe
R18B	R18, Number of cycles, logarithmic diagram
R18C	R18, Sum, Cumulative Damage
R18D	R18, Friday 10/10-1997

Supply and Return Pipe:

S/R18E	S18, R18, Difference top-underside
S/R18F	S18, Sunday 10/8-1997
	R18, Sunday 10/8-1997
S/R18G	S18, Monday 11/8-1997
	R18, Monday 11/8-1997
S/R18H	S18, Sunday 7/12-1997
	R18, Sunday 7/12-1997
S/R18I	S18, Monday 8/12-1997
	R18, Monday 8/12-1997

Supply pipe:

S19A	S19, Top of the pipe
	S19, Underside of the pipe
S19B	S19, Number of cycles, logarithmic diagram
S19C	S19, Sum, Cumulative Damage
S19D	S19, Wednesday 11/6-1997

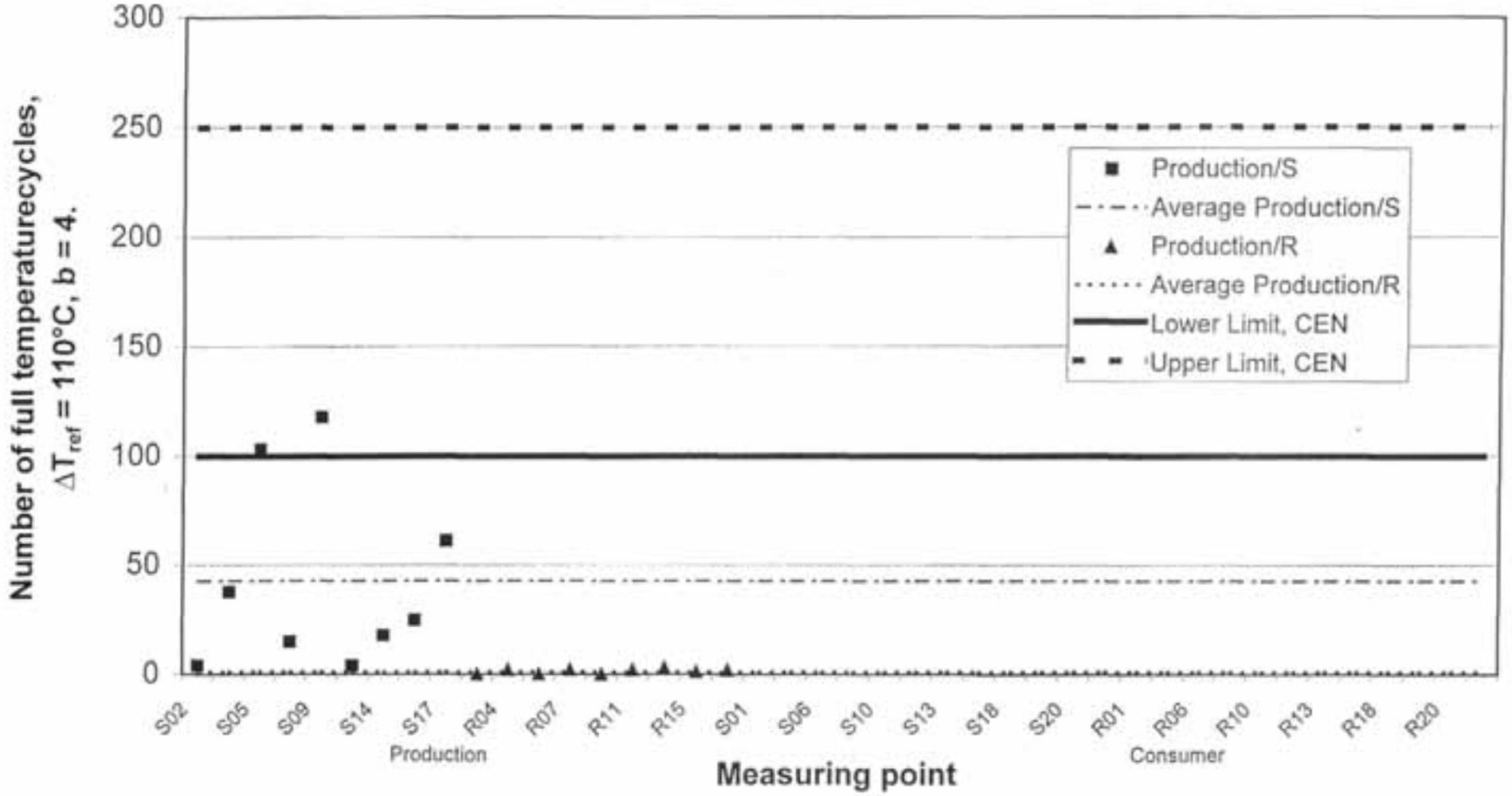
Return Pipe:

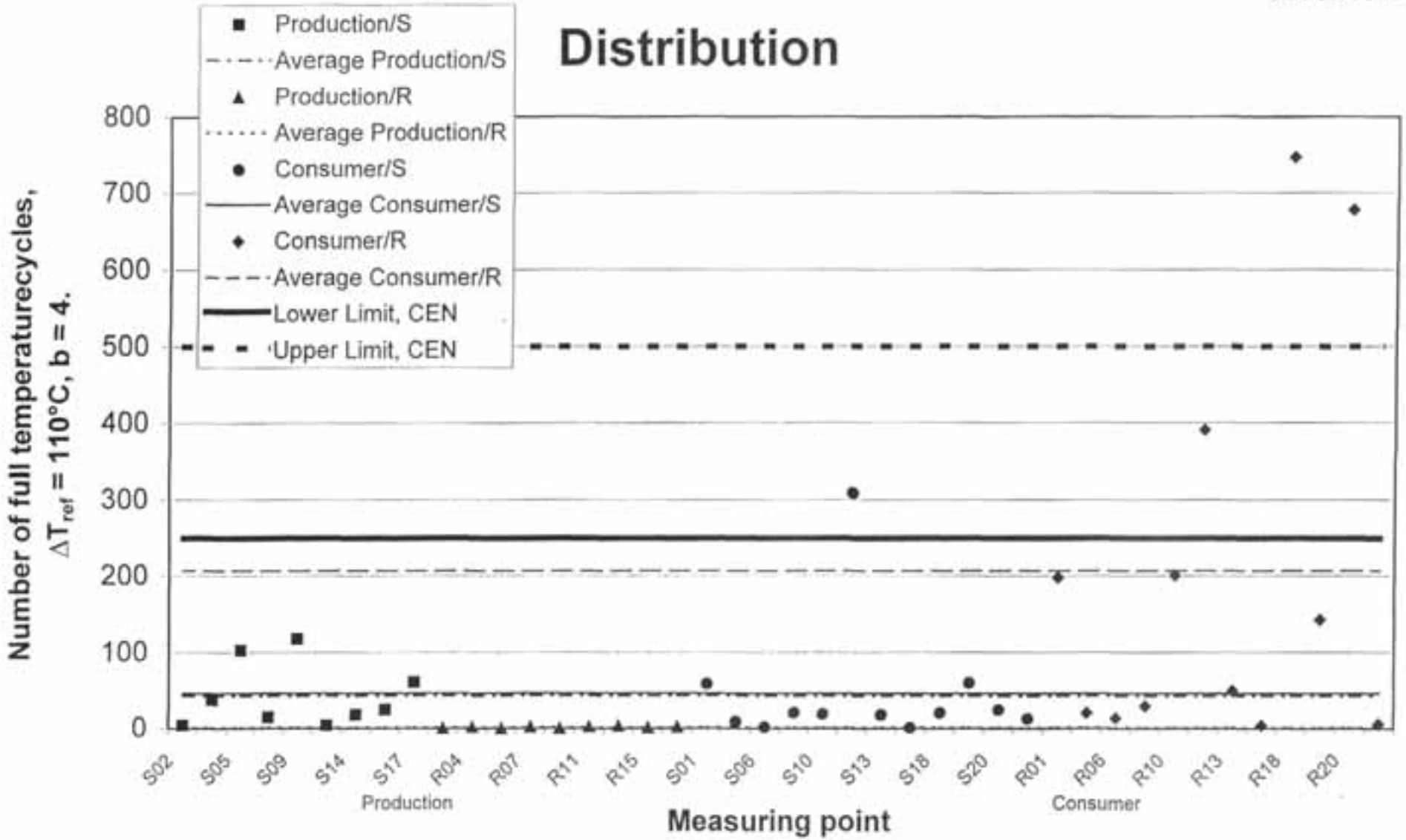
R19A	R19, Top of the pipe
	R19, Underside of the pipe
R19B	R19, Number of cycles, logarithmic diagram
R19C	R19, Sum, Cumulative Damage
R19D	R19, Sunday 13/6-1997

Supply and Return Pipe:

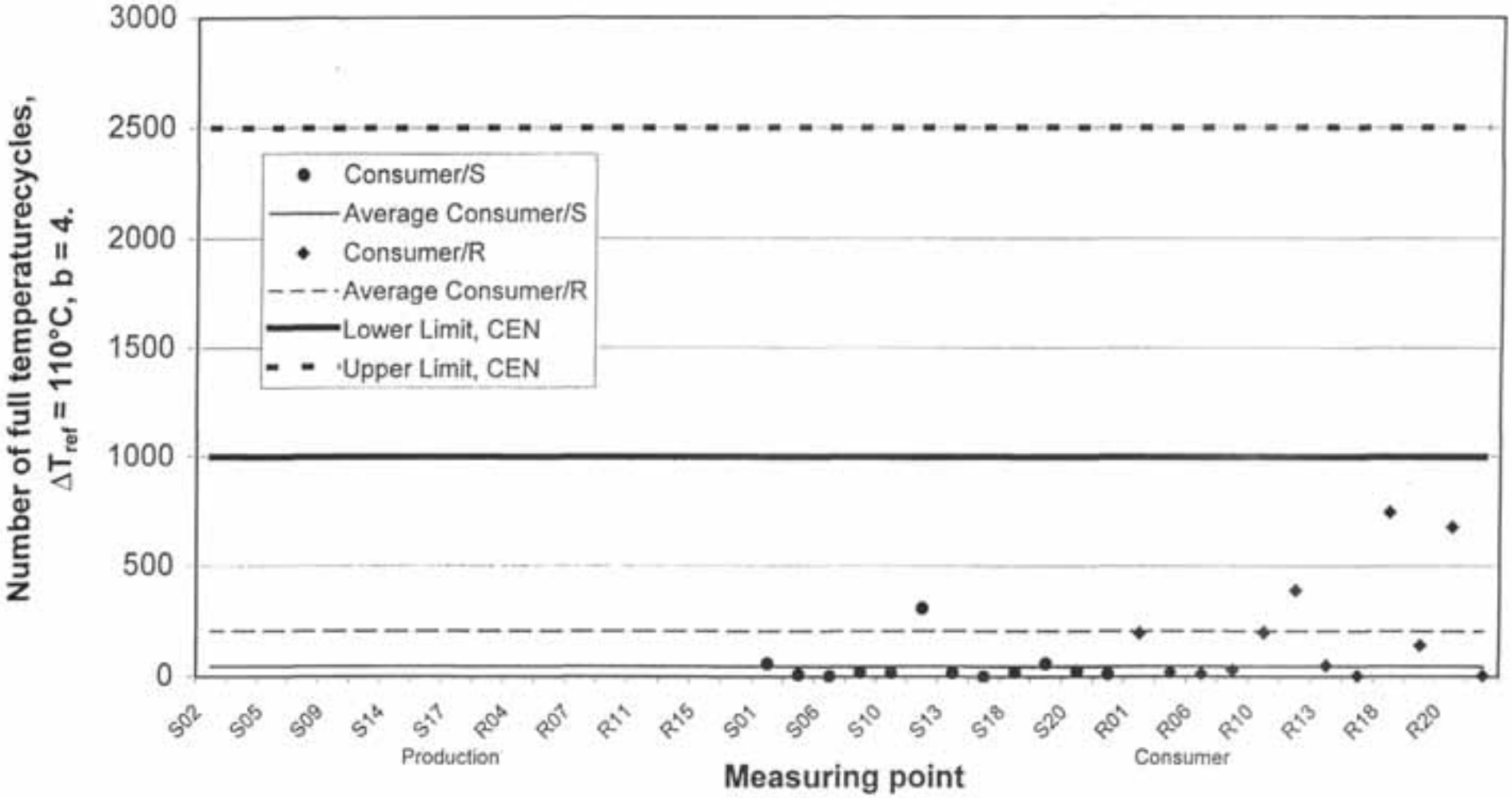
S/R19E	S19, R19, Difference top-underside
S/R19F	S19, Sunday 10/8-1997
	R19, Sunday 10/8-1997
S/R19G	S19, Monday 11/8-1997
	R19, Monday 11/8-1997
S/R19H	S19, Sunday 7/12-1997
	R19, Sunday 7/12-1997
S/R19I	S19, Monday 8/12-1997
	R19, Monday 8/12-1997

Production

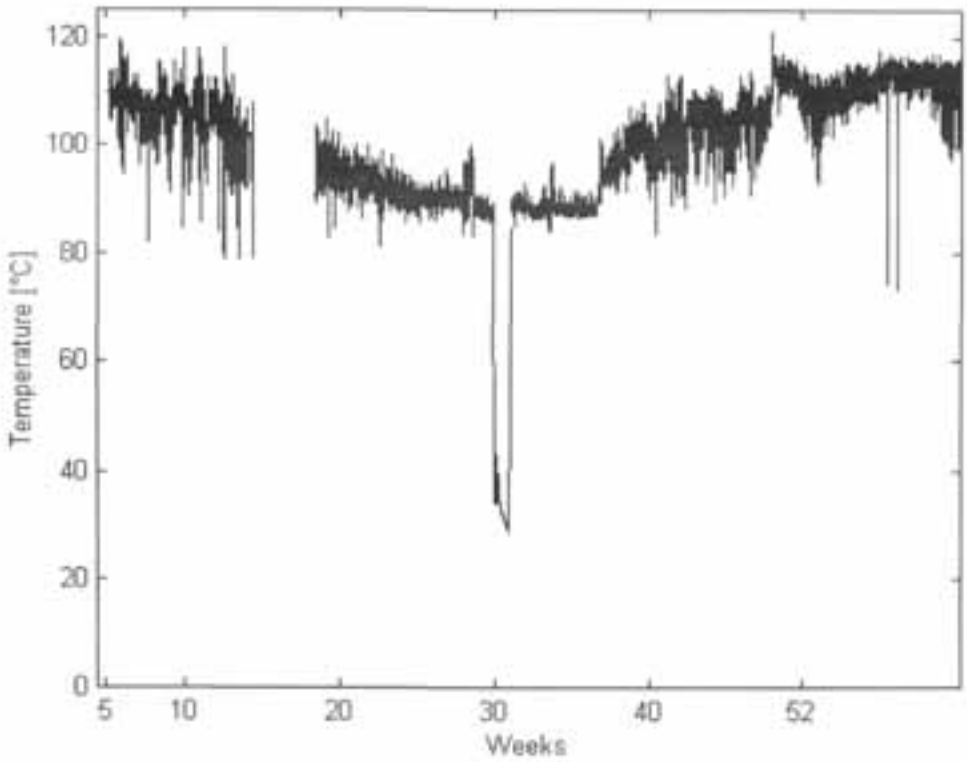

Number of full temperaturecycles, ΔT_{ref} = 110°C, b = 4.
300
250
200
150
100
50
0
Production/S
Average Production/S
Production/R
Average Production/R
Lower Limit, CEN
Upper Limit, CEN
S02
S05
S09
S14
S17
R04
R07
R11
R15
S01
S06
S10
S13
S18
S20
R01
R06
R10
R13
R18
R20
Production
Consumer
Measuring point


Distribution
Production/S
Average Production/S
Production/R
Average Production/R
Consumer/S
Average Consumer/S
Consumer/R
Average Consumer/R
Lower Limit, CEN
Upper Limit, CEN
Number of full temperaturecycles, ΔT_ref = 110°C, b = 4.
800
700
600
500
400
300
200
100
0
S02
S05
S09
S14
S17
R04
R07
R11
R15
S01
S06
S10
S13
S18
S20
R01
R06
R10
R13
R18
R20
Production
Consumer
Measuring point

Consumer


3000
2500
2000
1500
1000
500
0
Number of full temperaturecycles, ΔT_{ref} = 110°C, b = 4.
Consumer/S
Average Consumer/S
Consumer/R
Average Consumer/R
Lower Limit, CEN
Upper Limit, CEN
S02
S05
S09
S14
S17
R04
R07
R11
R15
S01
S06
S10
S13
S18
S20
R01
R06
R10
R13
R18
R20
Production
Consumer
Measuring point

S18, Top of the pipe



Range **Mean**

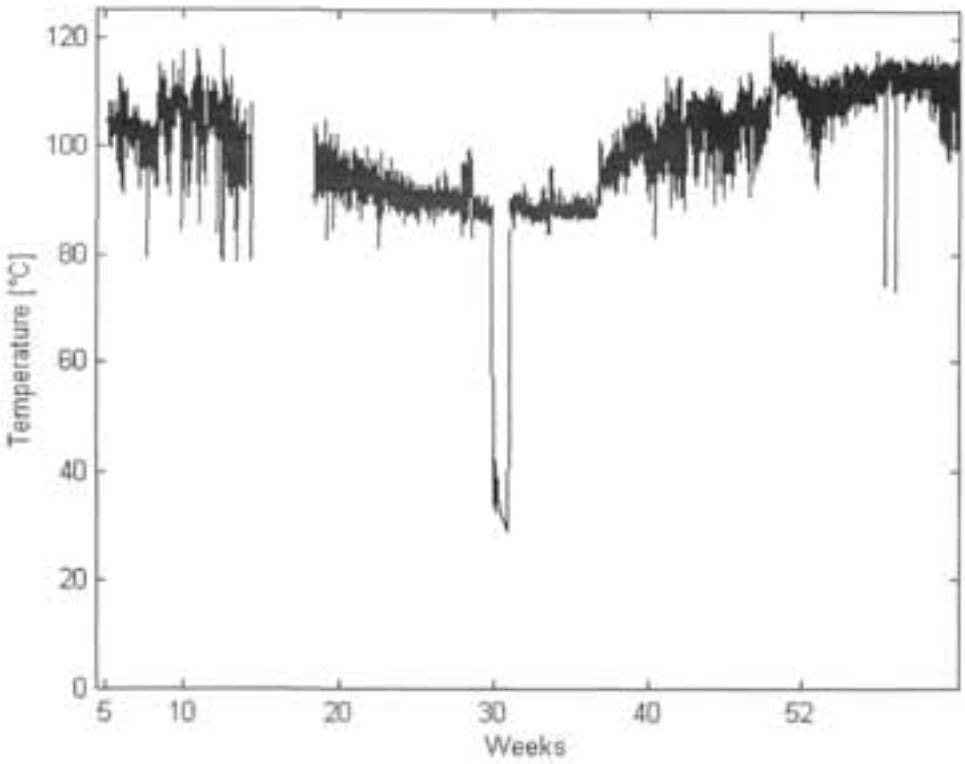
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	14	78	8	12	-	-	-	3	-	-	-	14	1386	1423	36135	1747	2815	2684	85
10	-	-	-	1	-	-	-	-	-	-	-	-	-	16	36	68	82	84	71	1
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	19	27	19	3	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	5	13	7	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	9	3	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	1	1	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-

Measuring period: 354,57 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	43,4
4	20,5
5	14,1

S18, Underside of the pipe



Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	19	59	9	5	-	1	1	-	-	-	-	16	1477	1503	1454	2402	2385	2469	66
10	-	-	-	1	-	-	-	-	-	-	-	-	1	16	39	76	87	71	69	1
15	-	-	-	-	-	-	-	-	-	-	-	-	-	1	4	22	28	15	3	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	5	15	6	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	9	1	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	1	1	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-

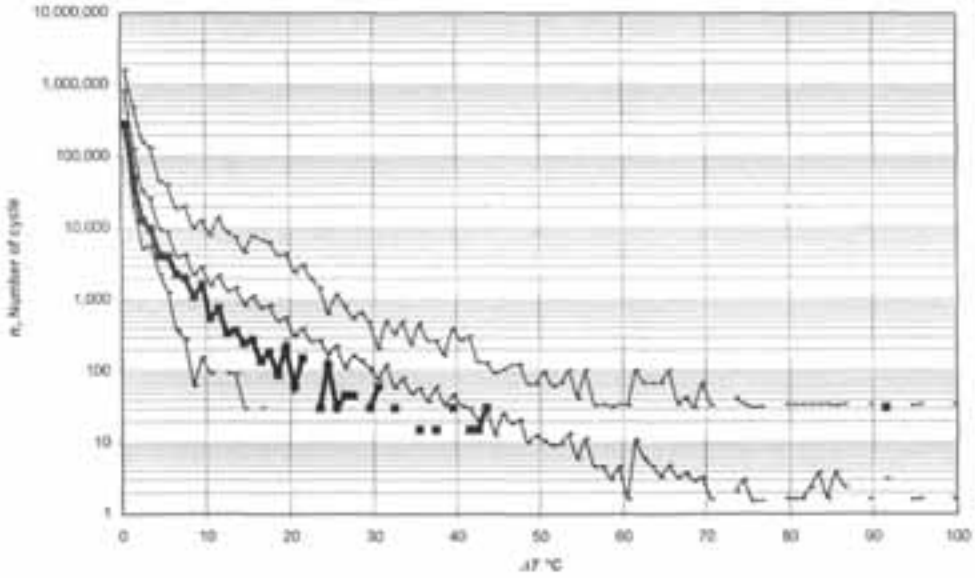
Measuring period: 354,57 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	43,1
4	20,5
5	14,1

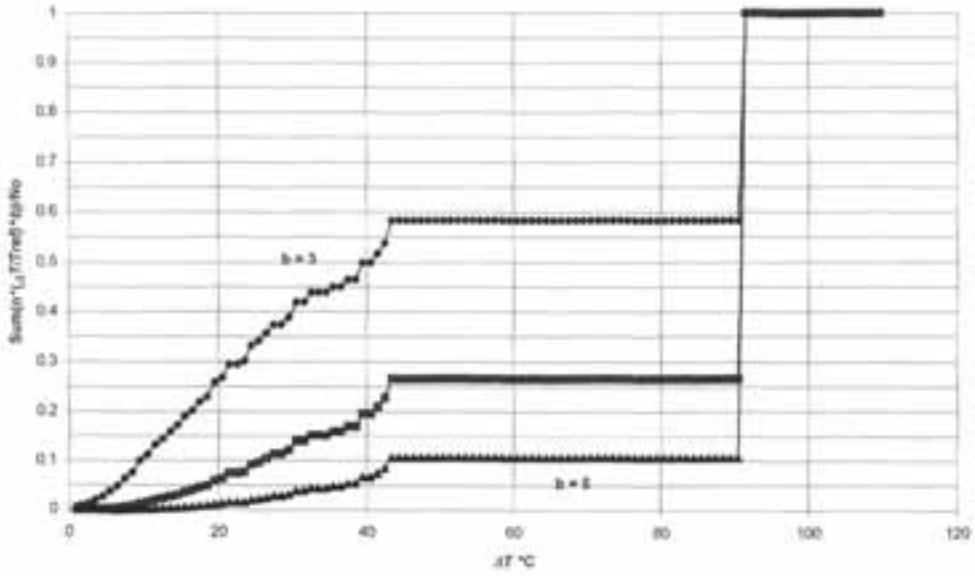
S18

Enclosure S18 B



S18

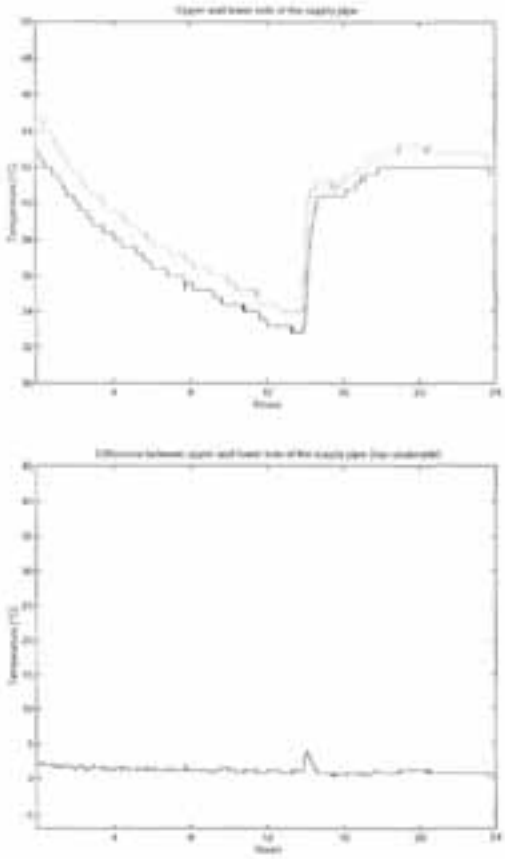
Enclosure S18 C



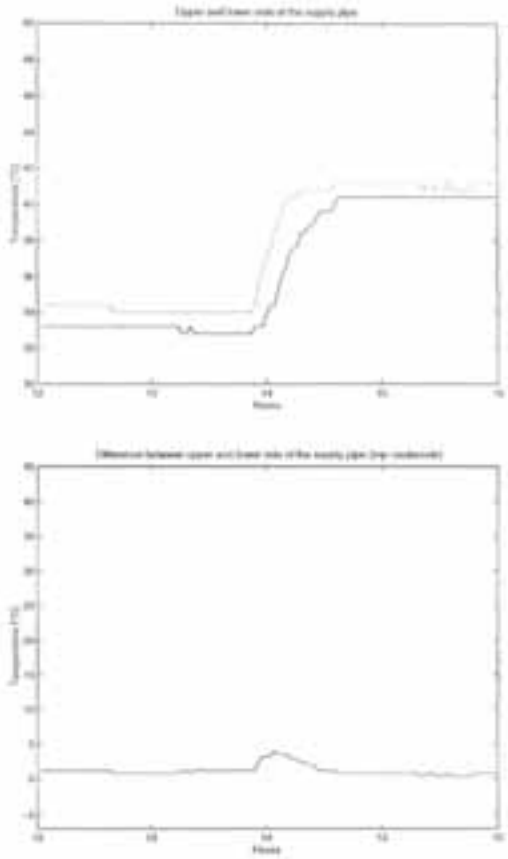
Enclosure S18 D

S18, Wednesday 30/7-1997

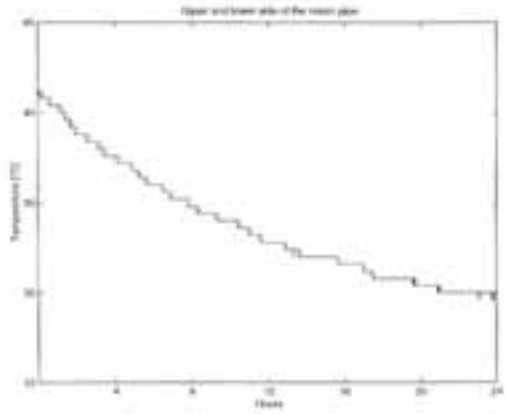
The day of the peak.
Below: Difference (top – underside)



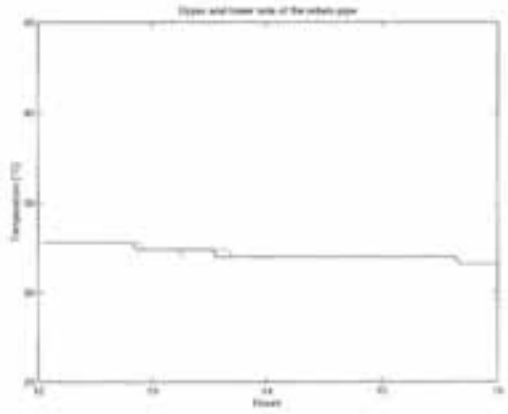
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Return temperatures for comparison.

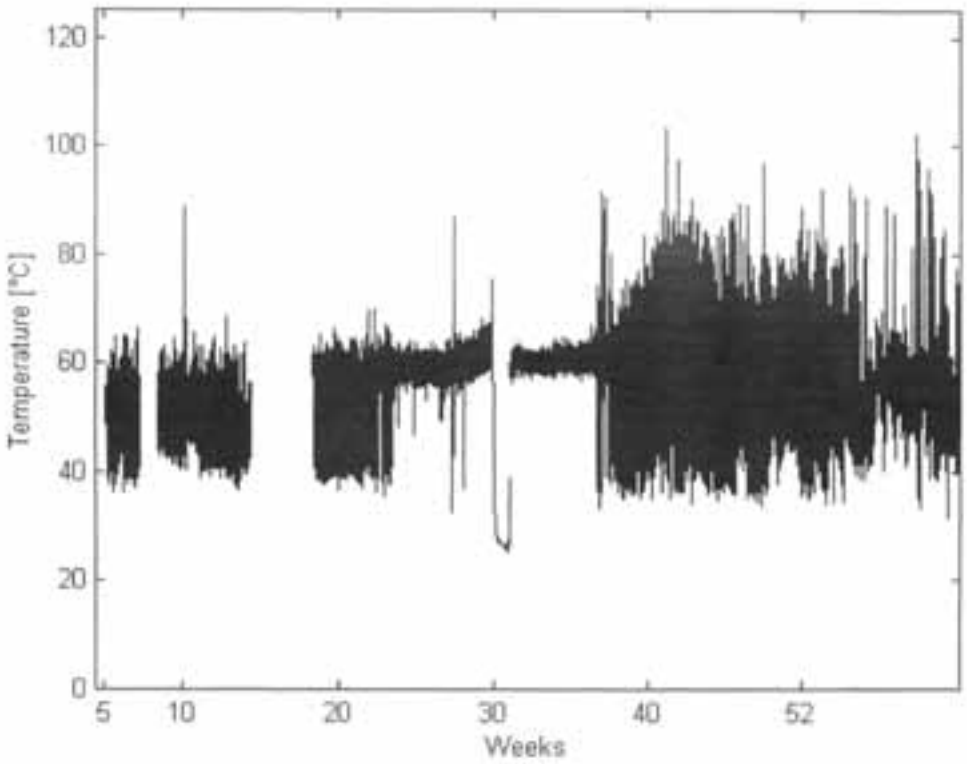


Close-up of comparable return temperatures.



The lighter shaded curves belong to the temperature on top of the pipe.

R18, Top of the pipe



Range **Mean**

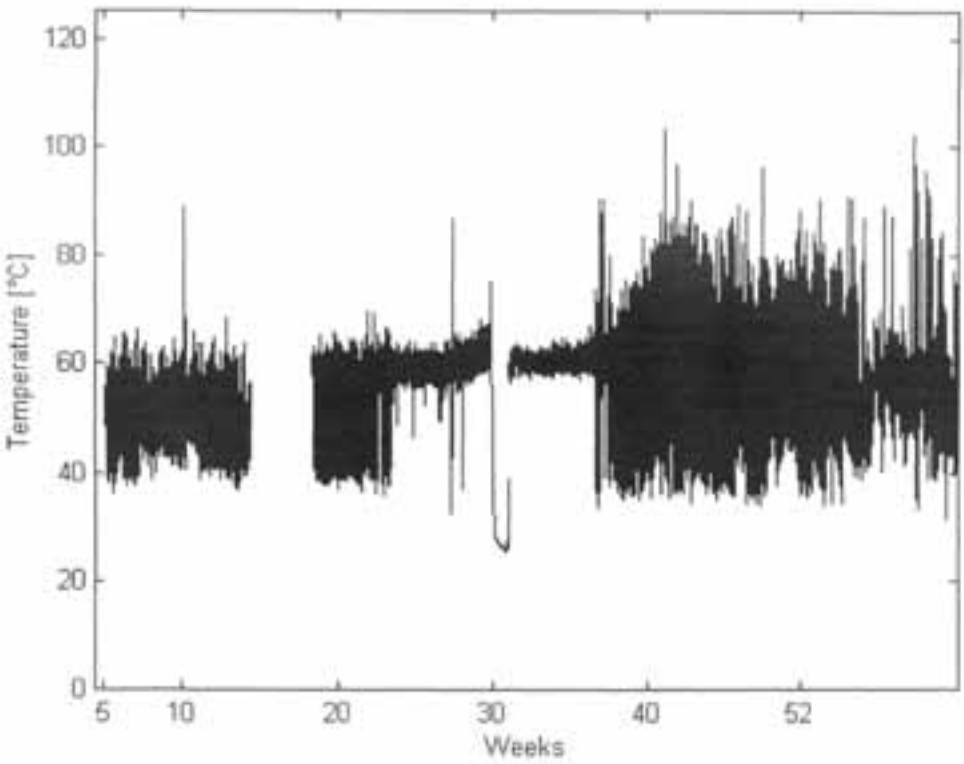
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	103	12	111	1598	5794	6451	9205	9177	357	149	77	68	33	4	3	10	-	-	-
10	-	-	1	11	402	2518	1975	1111	805	165	155	72	21	9	-	1	-	-	-	-
15	-	-	-	-	118	1026	1343	763	399	128	102	33	21	9	6	-	-	-	-	-
20	-	-	-	-	8	468	1115	974	303	131	56	11	8	5	3	-	-	-	-	-
25	-	-	-	-	-	174	753	849	171	91	25	2	1	1	-	-	-	-	-	-
30	-	-	-	-	-	16	400	650	195	53	11	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	-	103	315	136	21	-	1	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	17	134	81	7	1	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	1	42	45	3	-	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	1	6	16	4	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	1	9	3	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	1	3	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 346,72 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	2952,9
4	747,2
5	216,8

R18, Underside of the pipe



Range **Mean**

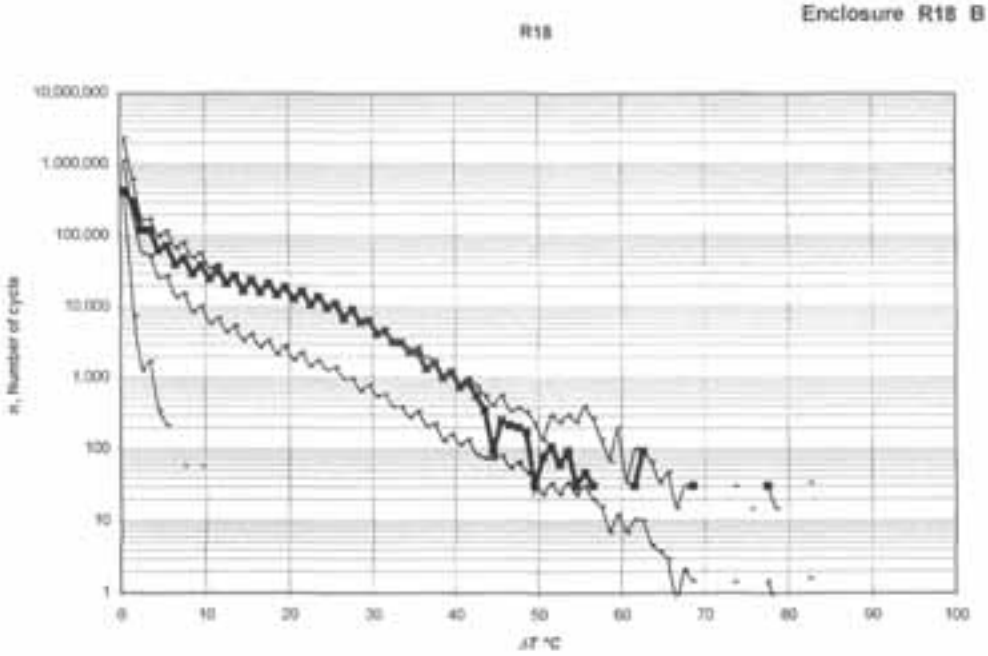
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	113	12	113	1519	5983	6886	9124	9327	381	140	71	63	37	5	3	11	-	-	-
10	-	-	1	8	400	2592	2174	1121	818	169	150	64	23	9	-	-	-	-	-	-
15	-	-	-	-	103	1009	1401	794	383	128	111	36	21	8	7	-	-	-	-	-
20	-	-	-	-	7	467	1114	972	298	142	63	10	6	4	2	-	-	-	-	-
25	-	-	-	-	-	156	737	873	169	86	23	2	1	1	-	-	-	-	-	-
30	-	-	-	-	-	16	386	618	181	46	8	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	-	94	306	143	18	-	1	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	13	147	76	6	1	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	33	42	3	-	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	1	5	19	4	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	1	9	1	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	1	3	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 354,57 days

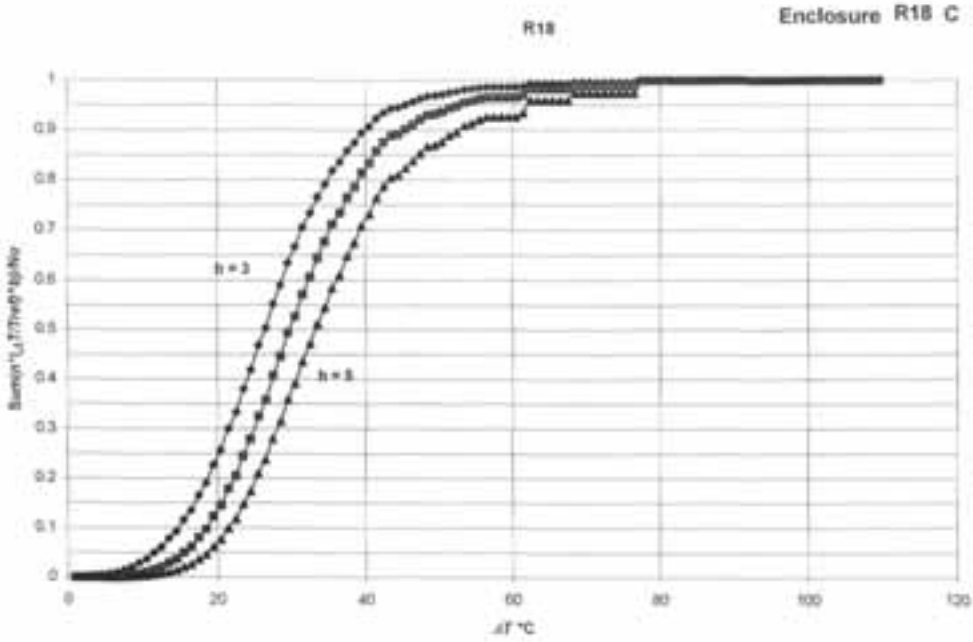
DTref 110 °C

b	Nr. of full cycles in 30 years
3	2815,2
4	706,1
5	203,2

Enclosure R18 B

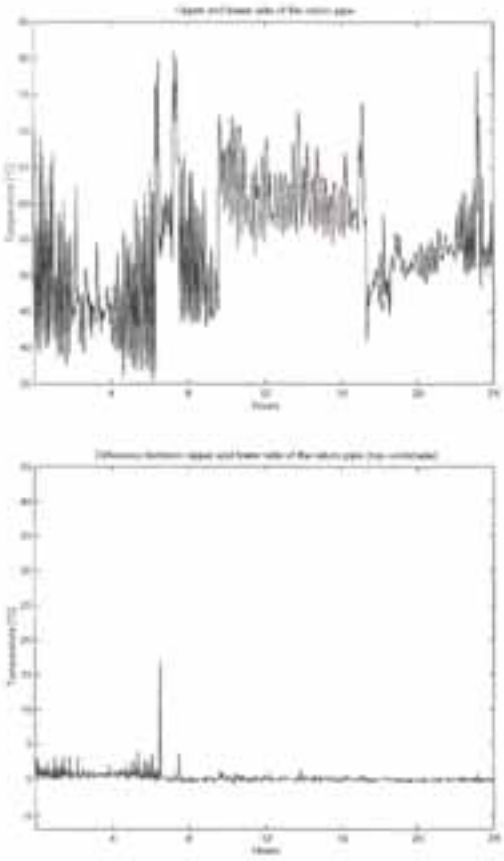


Enclosure R18 C

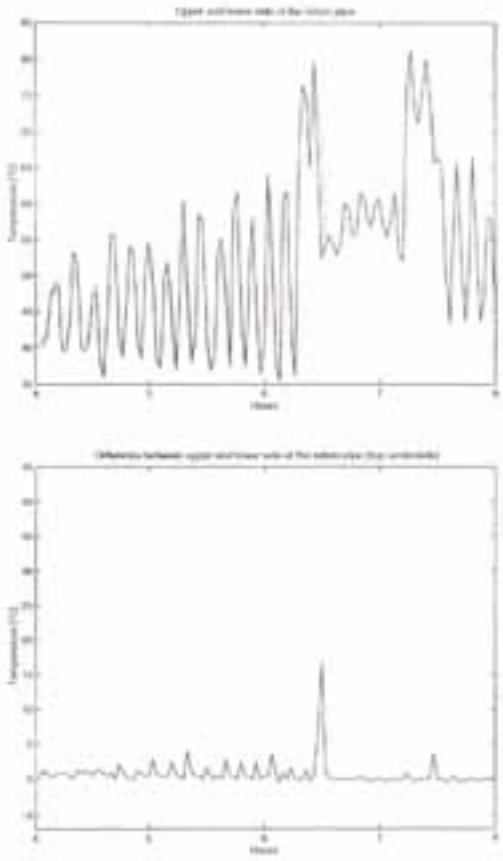


R18, Friday 10/10-1997

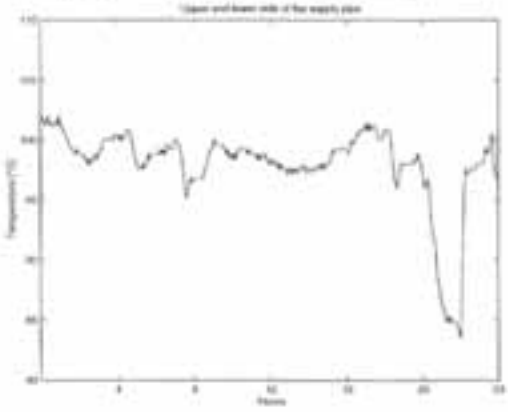
The day of the peak.
Below: Difference (top – underside)



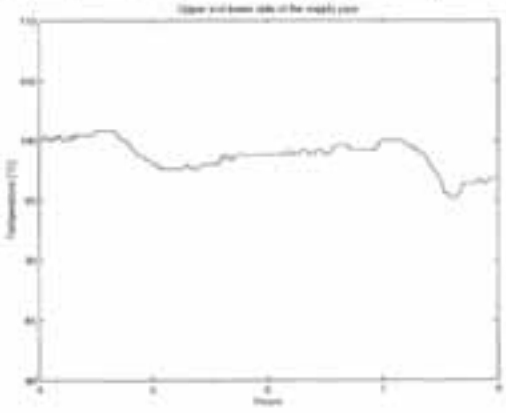
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Supply temperatures for comparison.

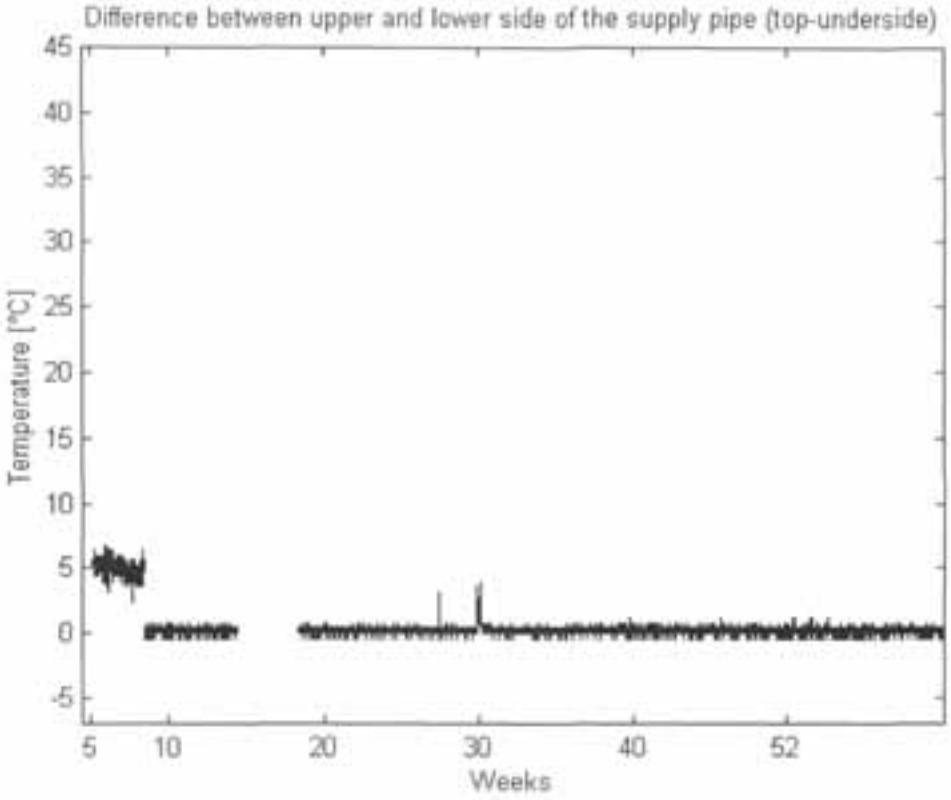


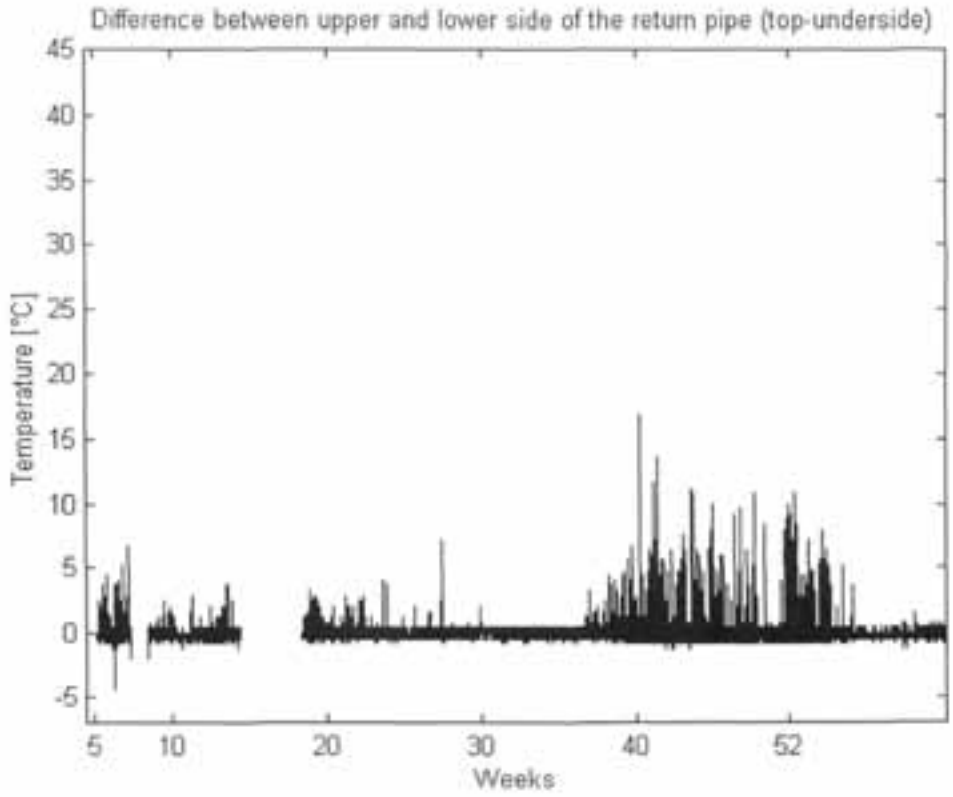
Close-up of comparable supply temperatures.



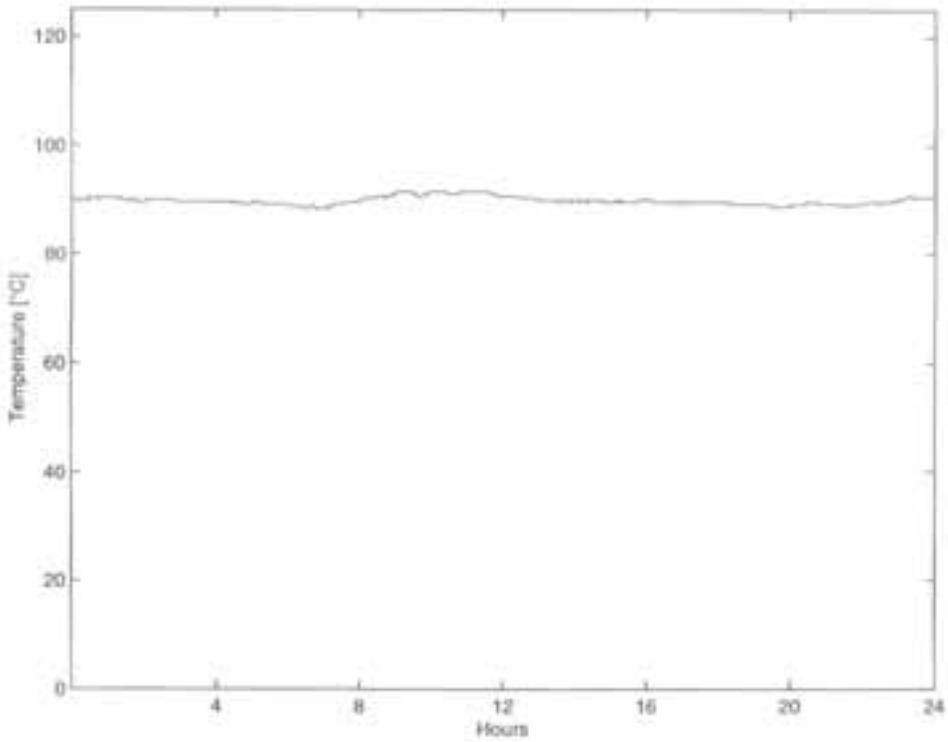
The lighter shaded curves belong to the temperature on top of the pipe.

S18, R18

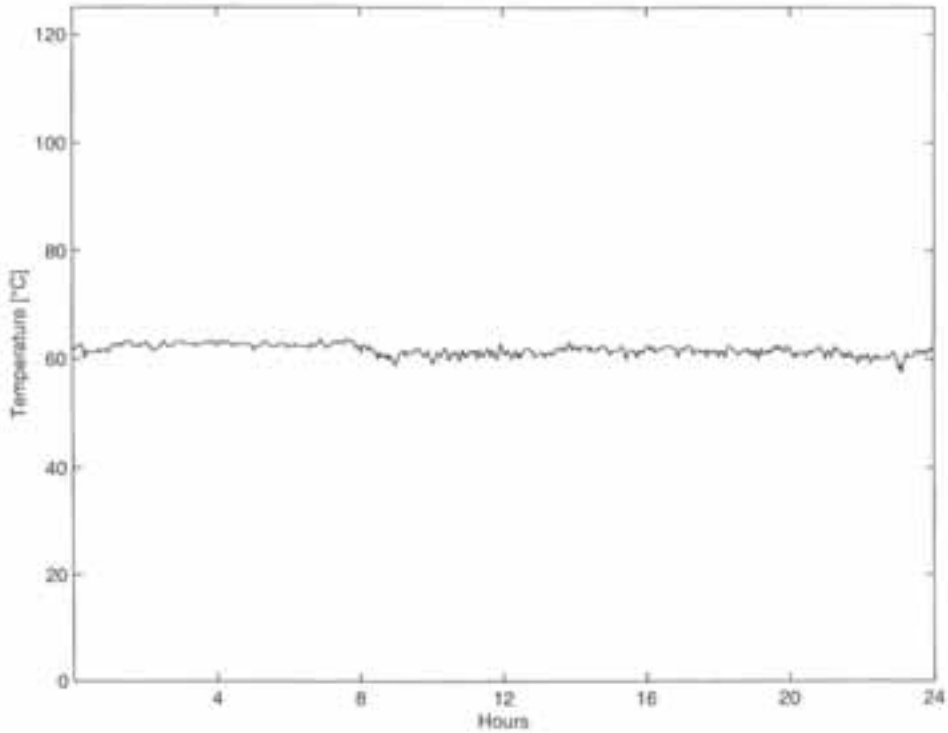

Difference between upper and lower side of the supply pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks


Difference between upper and lower side of the return pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks

S18, Sunday 10/8-1997

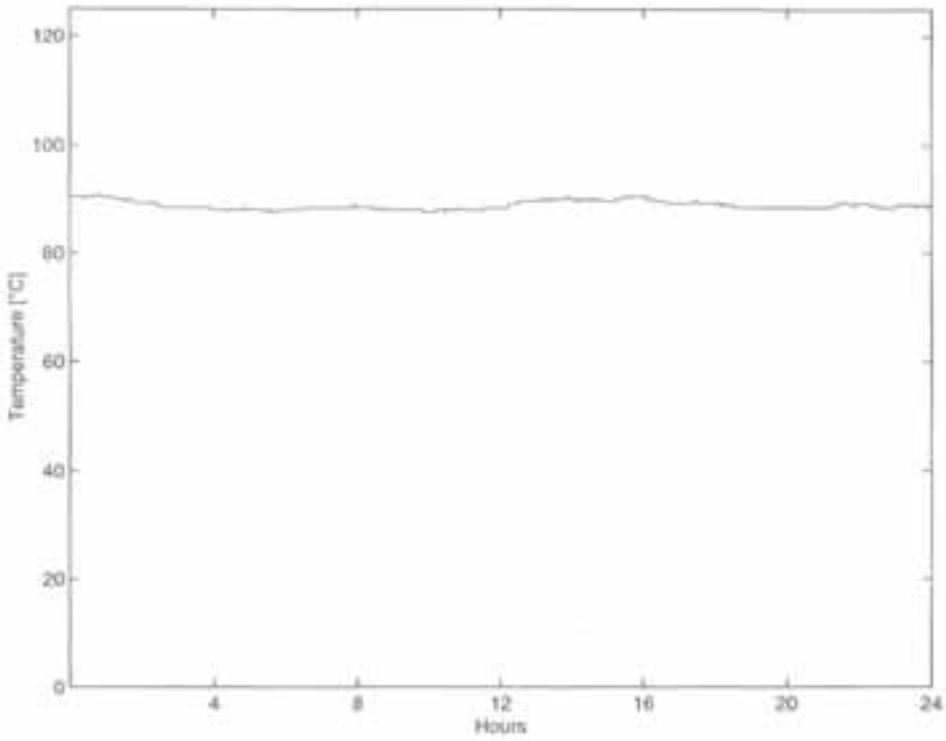


R18, Sunday 10/8-1997

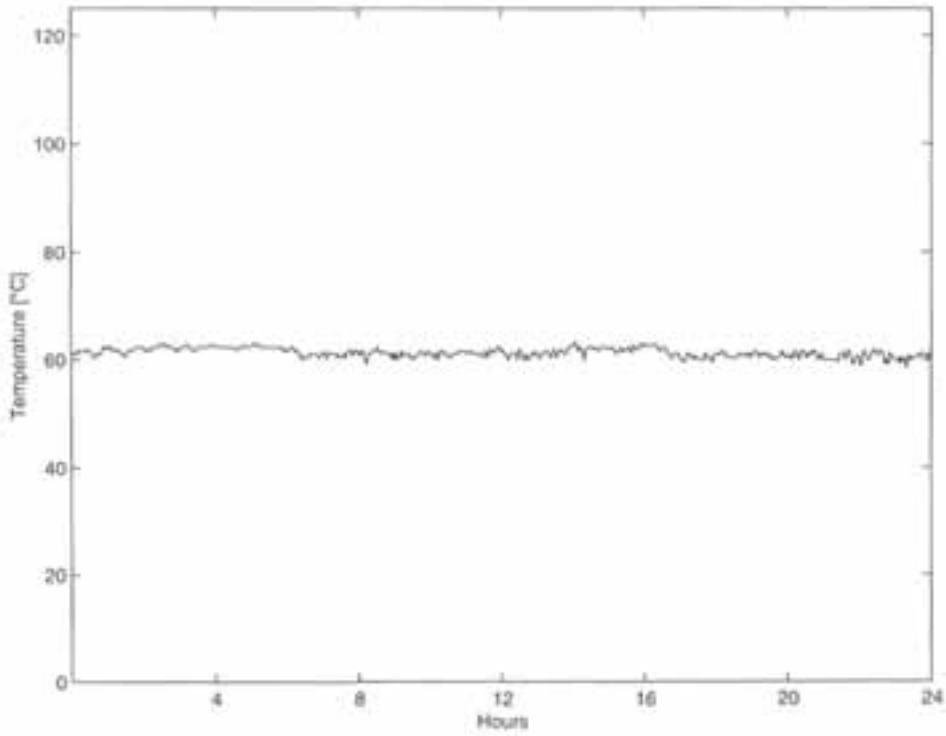


Enclosure S/R18 G

S18, Monday 11/8-1997

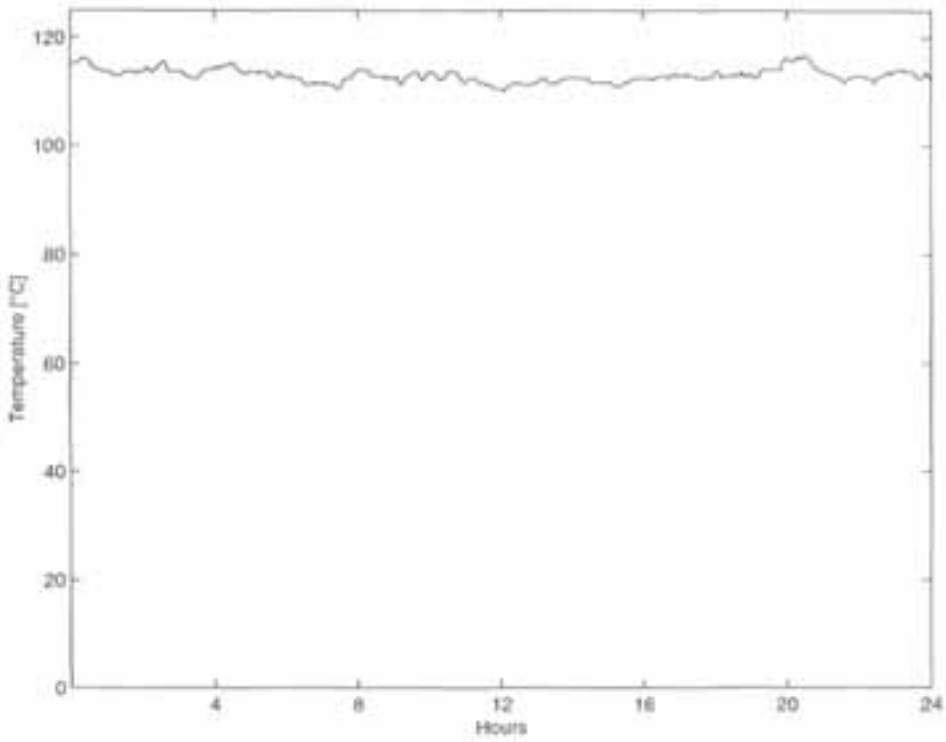


R18, Monday 11/8-1997

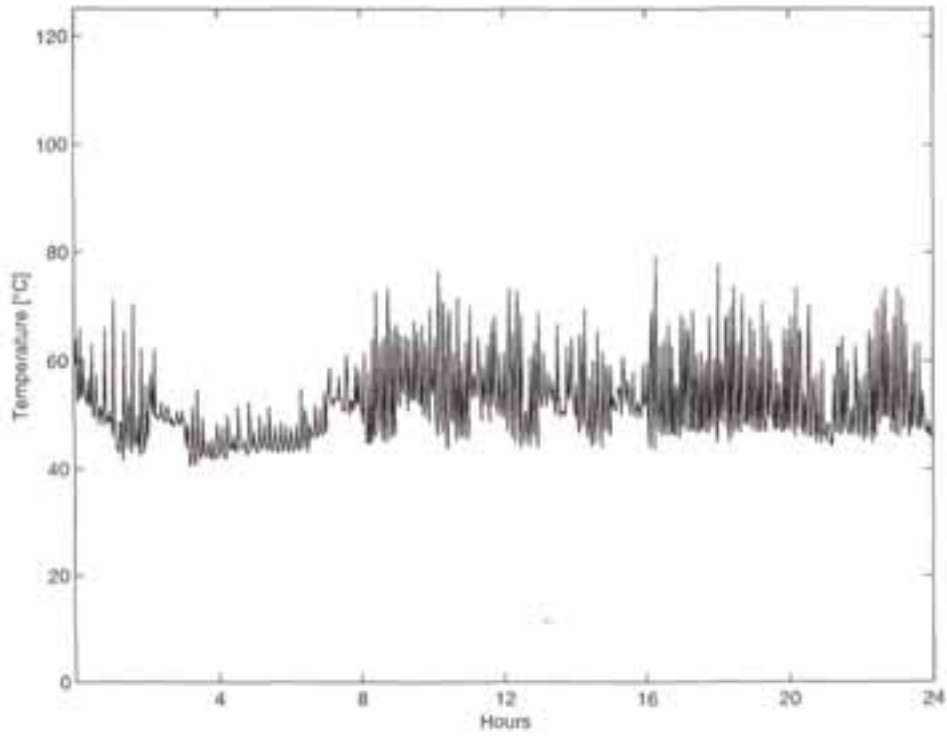


Enclosure S/R18 H

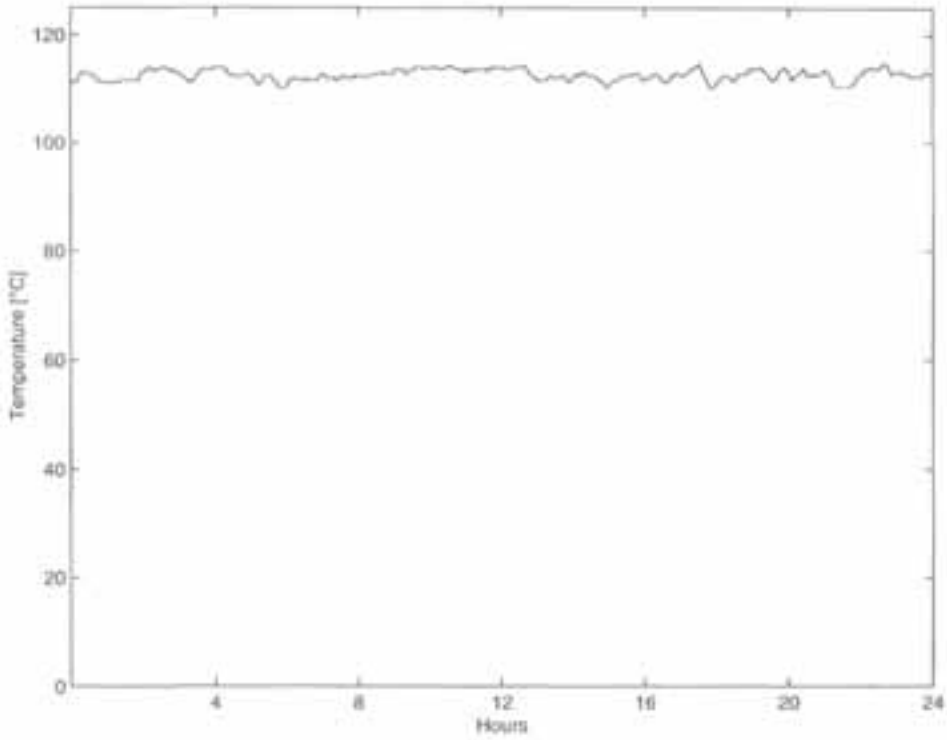
S18, Sunday 7/12-1997



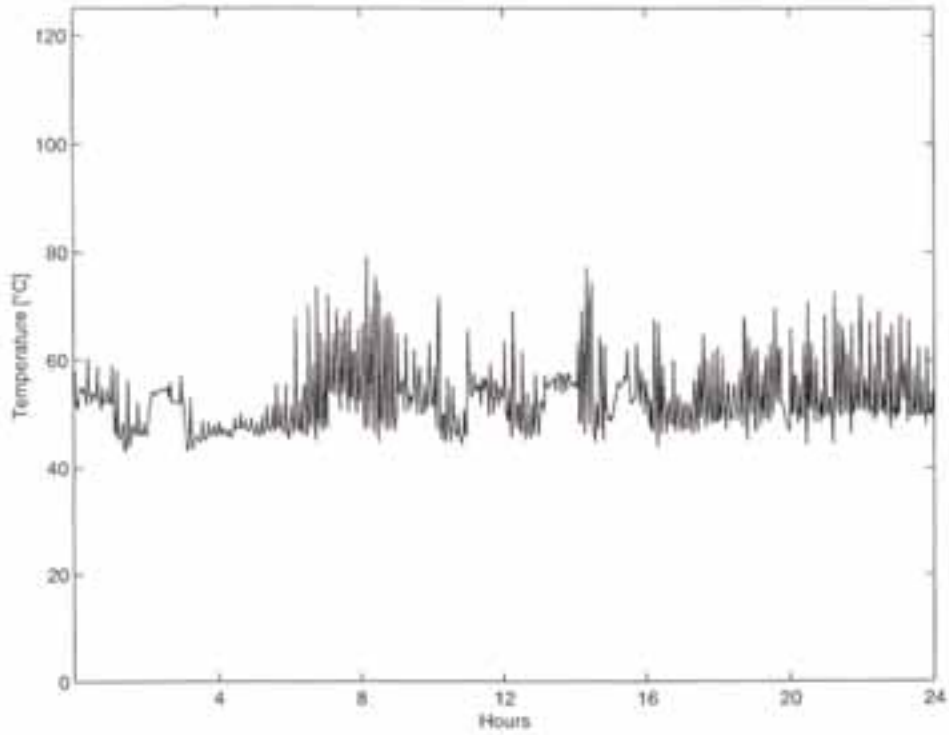
R18, Sunday 7/12-1997



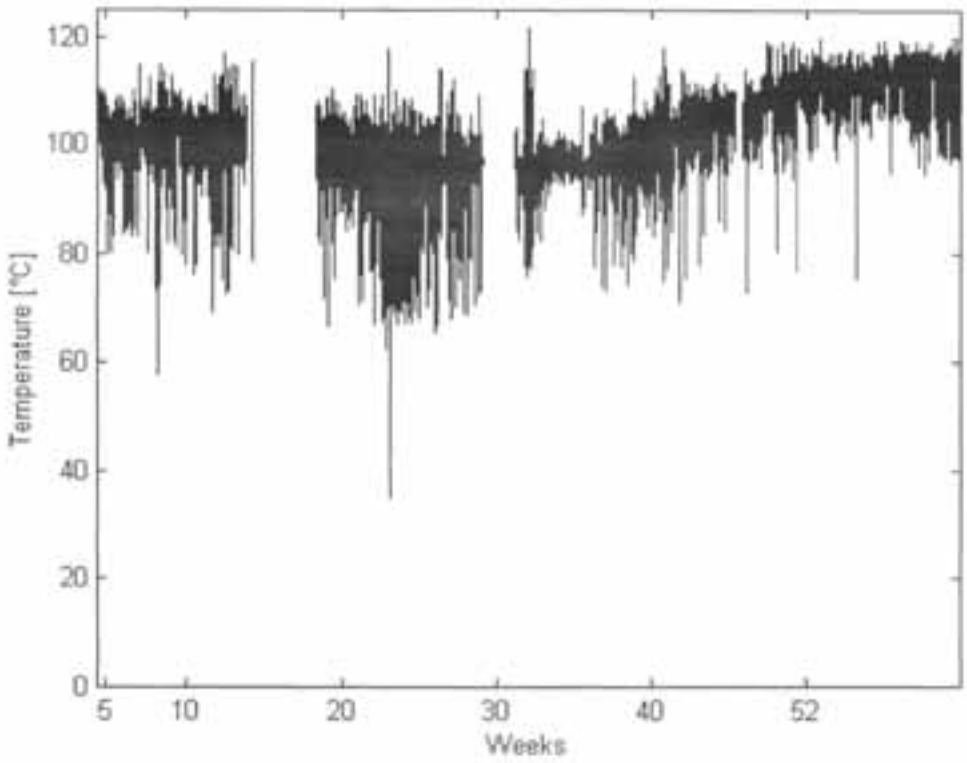
S18, Monday 8/12-1997



R18, Monday 8/12-1997



S19, Top of the pipe



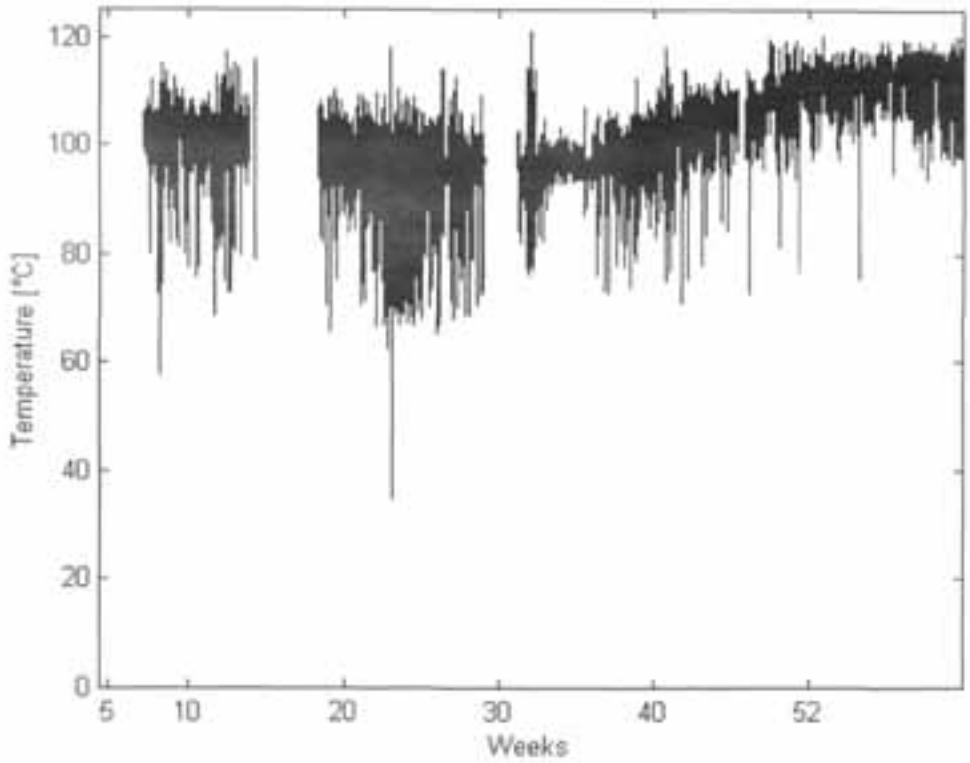
Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	8	-	3	-	-	-	3	6	7	30	32	481	4638	5699	3153	4085	1234
10	-	-	-	-	-	-	-	-	-	-	1	7	8	8	70	118	212	70	82	3
15	-	-	-	-	-	-	-	-	-	-	-	1	-	8	24	49	76	32	33	-
20	-	-	-	-	-	-	-	-	-	-	-	-	1	10	34	34	21	23	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	1	4	19	24	3	11	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	1	8	22	15	1	1	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	1	11	11	4	-	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	9	9	4	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	6	4	3	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	1	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 346,16 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	180,9
4	59,7
5	25,2

S19, Underside of the pipe



Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	7	-	4	-	-	-	3	6	4	31	34	471	4307	4369	2679	3805	1283
10	-	-	-	-	-	-	-	-	-	-	1	8	7	7	65	117	203	69	83	3
15	-	-	-	-	-	-	-	-	-	-	-	-	1	7	23	47	70	29	35	-
20	-	-	-	-	-	-	-	-	-	-	-	-	1	9	28	34	19	25	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	6	14	21	3	11	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	2	8	22	13	1	1	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	1	12	11	3	-	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	11	7	4	1	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	6	4	2	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	2	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

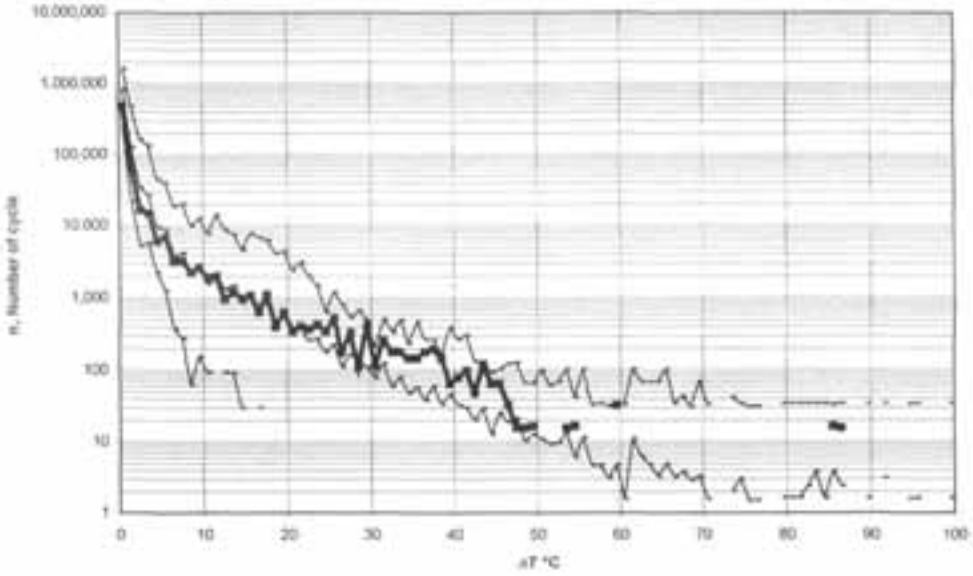
Measuring period: 327,44 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	189,0
4	63,0
5	26,7

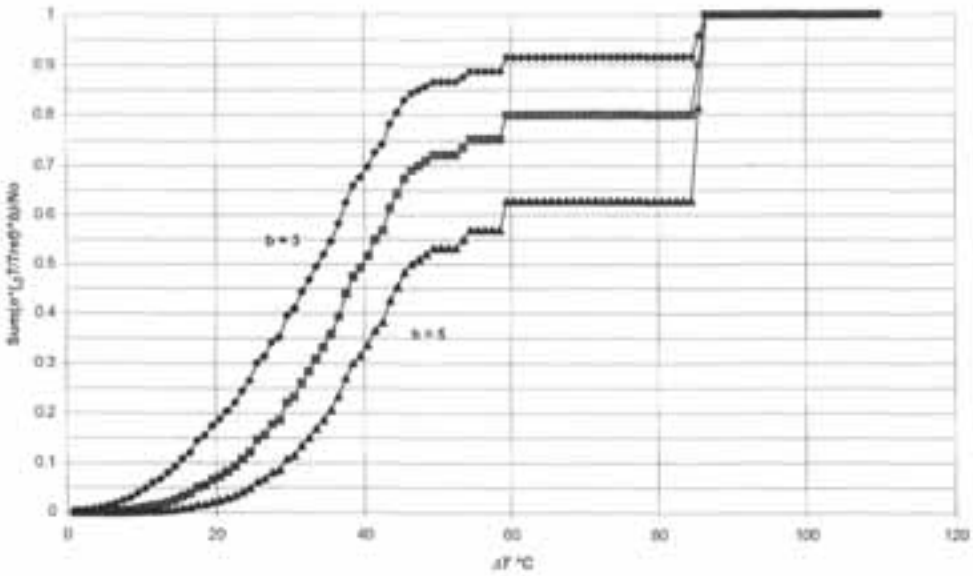
S19

Enclosure S19 B



S19

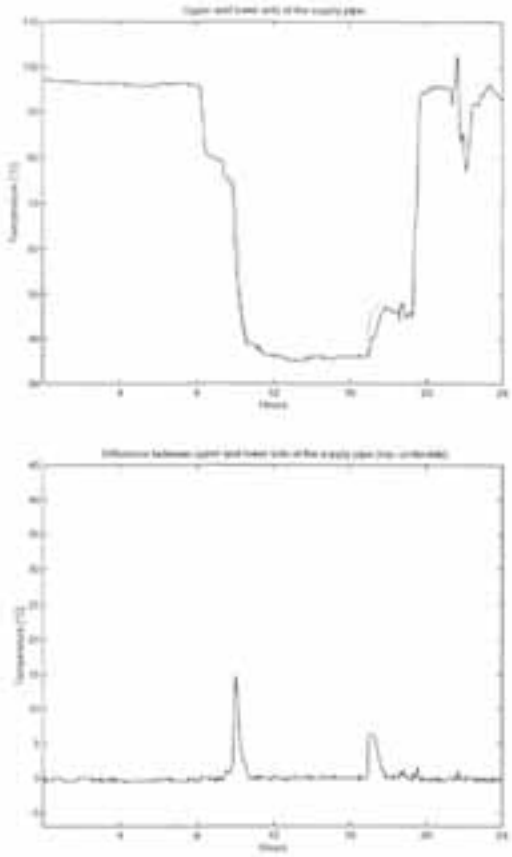
Enclosure S19 C



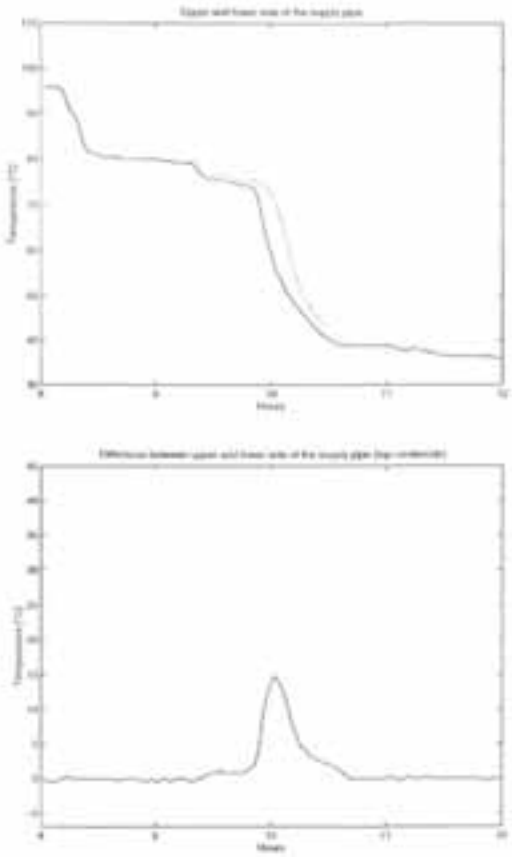
Enclosure S19 D

S19, Wednesday 11/6-1997

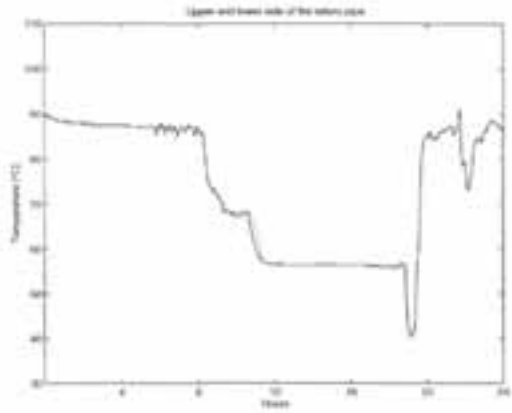
The day of the peak.
Below: Difference (top – underside)



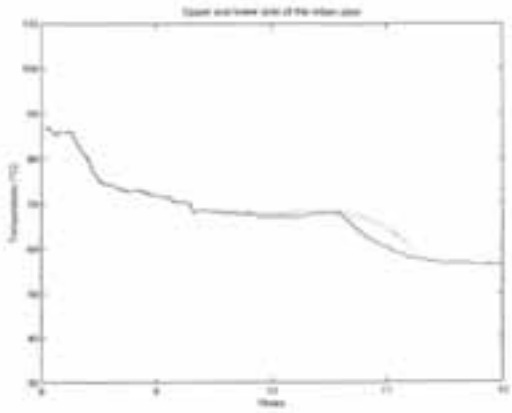
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Return temperatures for comparison.

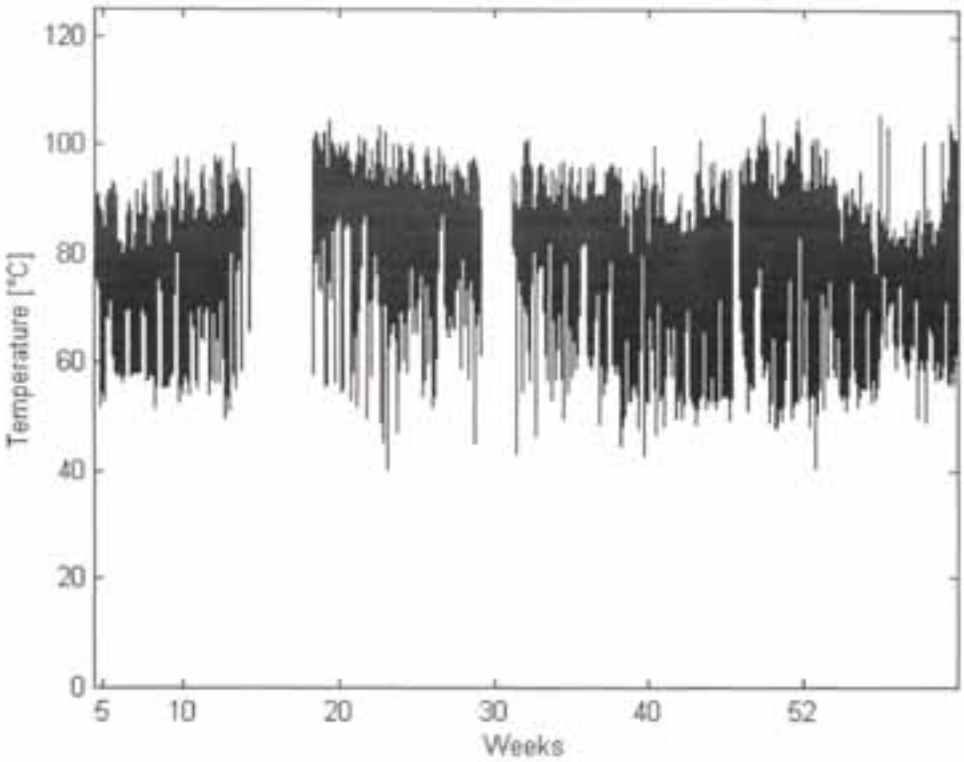


Close-up of comparable return temperatures.



The lighter shaded curves belong to the temperature on top of the pipe.

R19, Top of the pipe



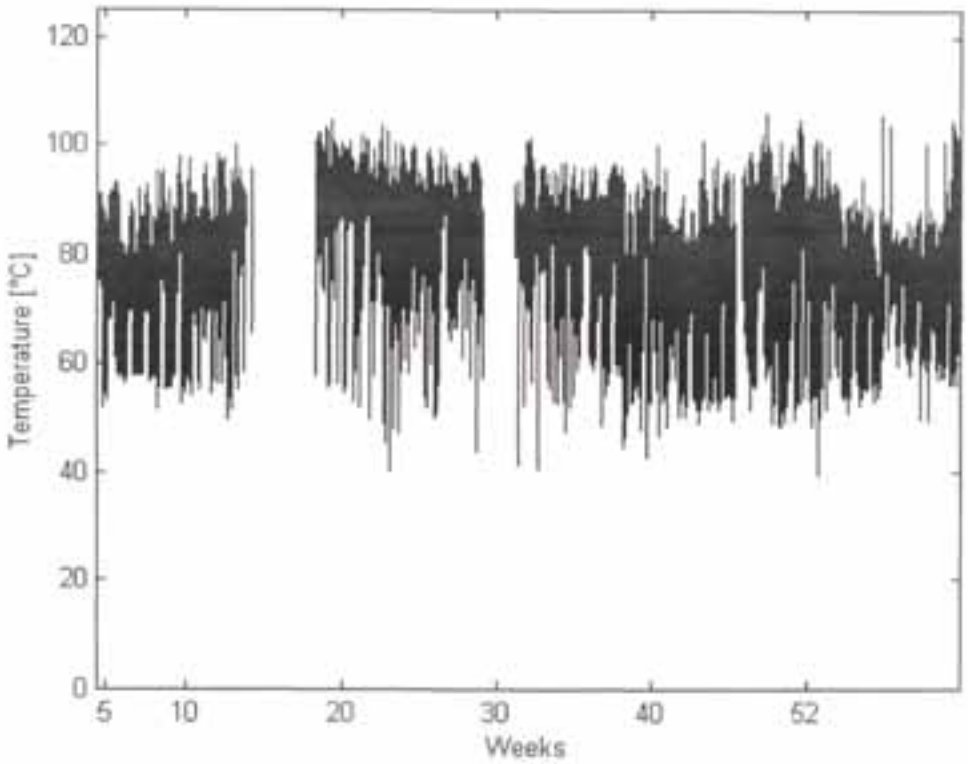
Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	-	-	15	313	1682	2716	1540	3263	6753	6762	5926	2952	612	28	-	-	-
10	-	-	-	-	-	-	2	45	225	143	394	1370	2007	1707	696	89	-	-	-	-
15	-	-	-	-	-	-	-	2	31	25	49	123	167	102	45	1	-	-	-	-
20	-	-	-	-	-	-	-	-	2	9	29	63	55	30	12	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	9	12	21	28	13	1	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	10	57	15	16	4	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-	-	6	19	12	7	2	-	-	-	-	-	-
40	-	-	-	-	-	-	-	-	-	4	28	24	5	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	1	15	15	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	8	12	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	1	5	6	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	3	1	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 346,16 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	474,2
4	143,4
5	53,3

R19, Underside of the pipe



Range **Mean**

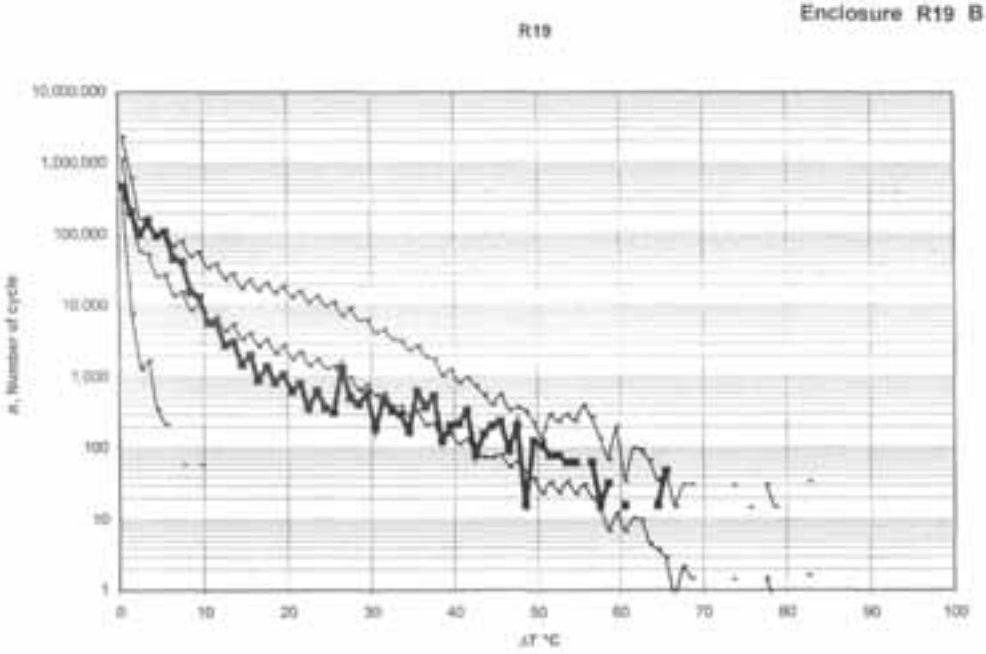
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	-	1	12	302	1616	2824	1701	3534	6711	6117	5560	2974	648	49	-	-	-
10	-	-	-	-	-	-	5	45	221	169	587	1798	2213	1681	736	71	-	-	-	-
15	-	-	-	-	-	-	-	2	26	25	65	157	195	124	53	-	-	-	-	-
20	-	-	-	-	-	-	-	-	4	9	30	61	48	30	12	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	10	14	25	29	13	2	-	-	-	-	-
30	-	-	-	-	-	-	-	-	-	39	25	11	18	4	-	-	-	-	-	-
35	-	-	-	-	-	-	-	-	-	5	22	12	5	3	-	-	-	-	-	-
40	-	-	-	-	-	-	-	-	-	5	25	22	5	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	1	18	12	1	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	1	10	12	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	2	4	7	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	2	1	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 346,16 days

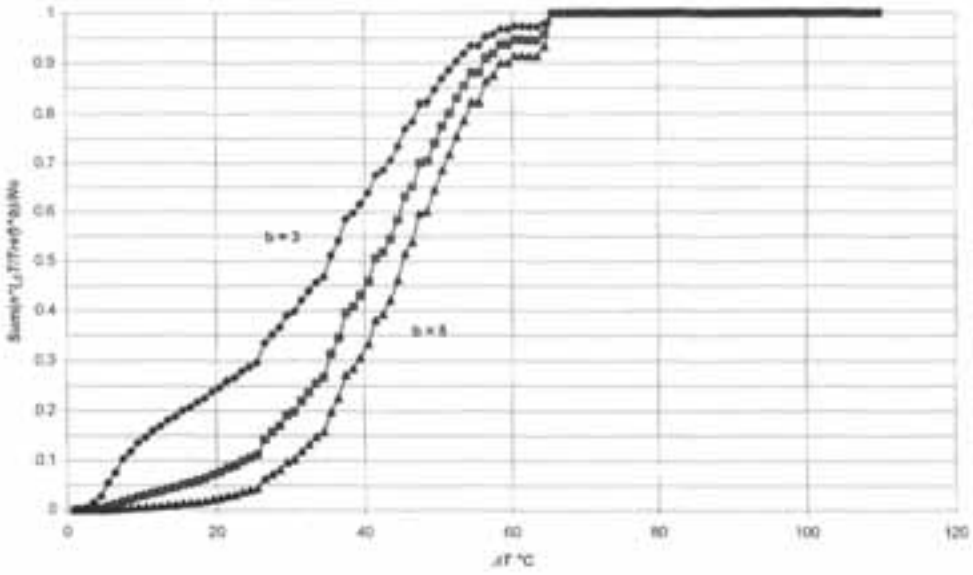
DTref 110 °C

b	Nr. of full cycles in 30 years
3	494,6
4	149,1
5	56,0

Enclosure R19 B



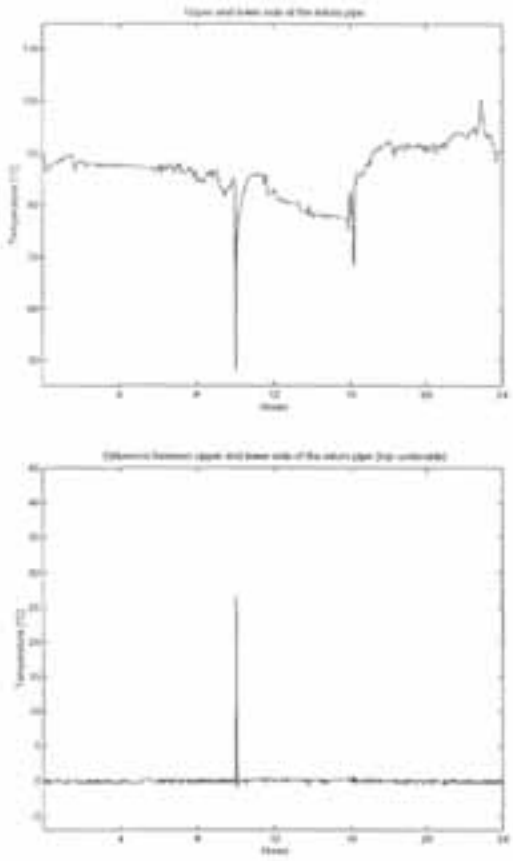
Enclosure R19 C



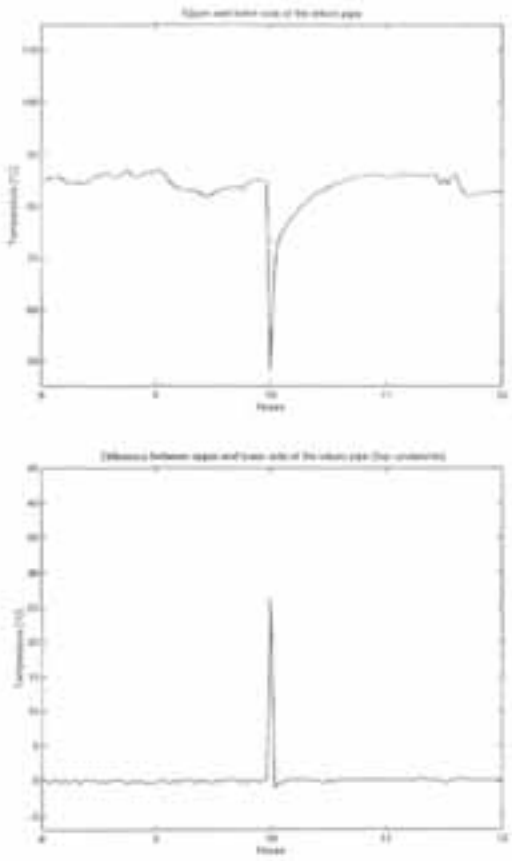
Enclosure R19 D

R19, Sunday 13/6-1997

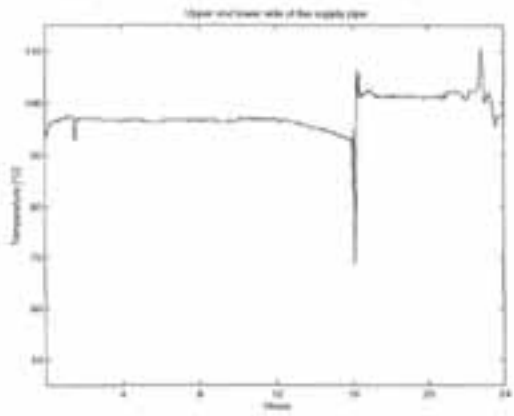
The day of the peak.
Below: Difference (top – underside)



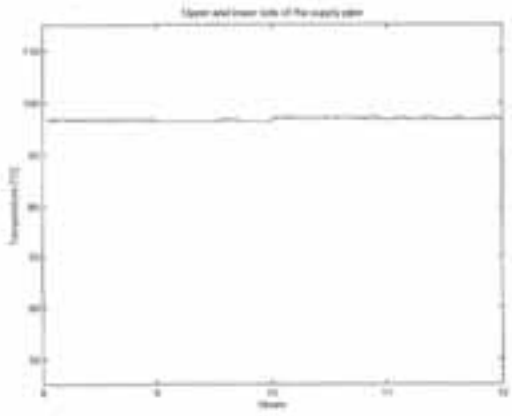
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Supply temperatures for comparison.

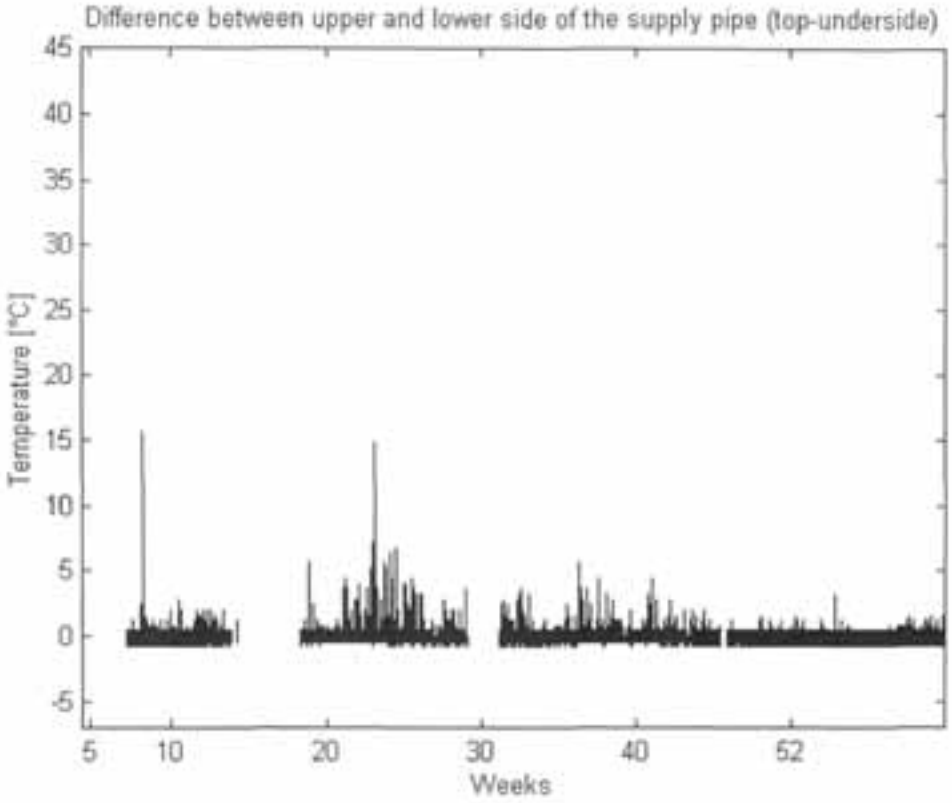


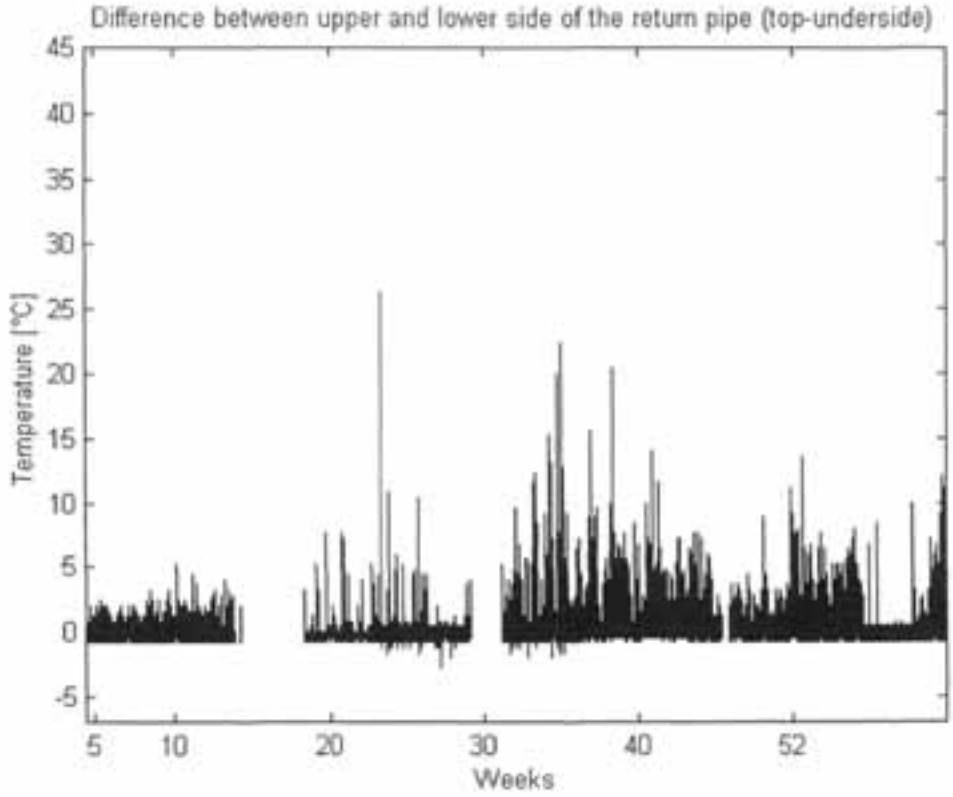
Close-up of comparable supply temperatures.



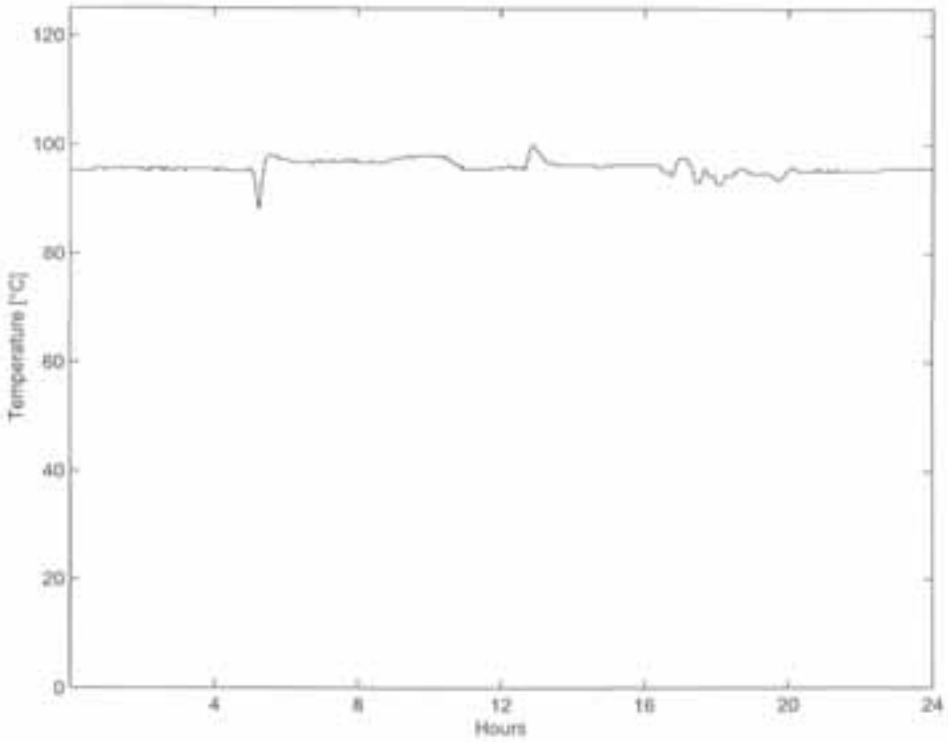
The lighter shaded curves belong to the temperature on top of the pipe.

S19, R19

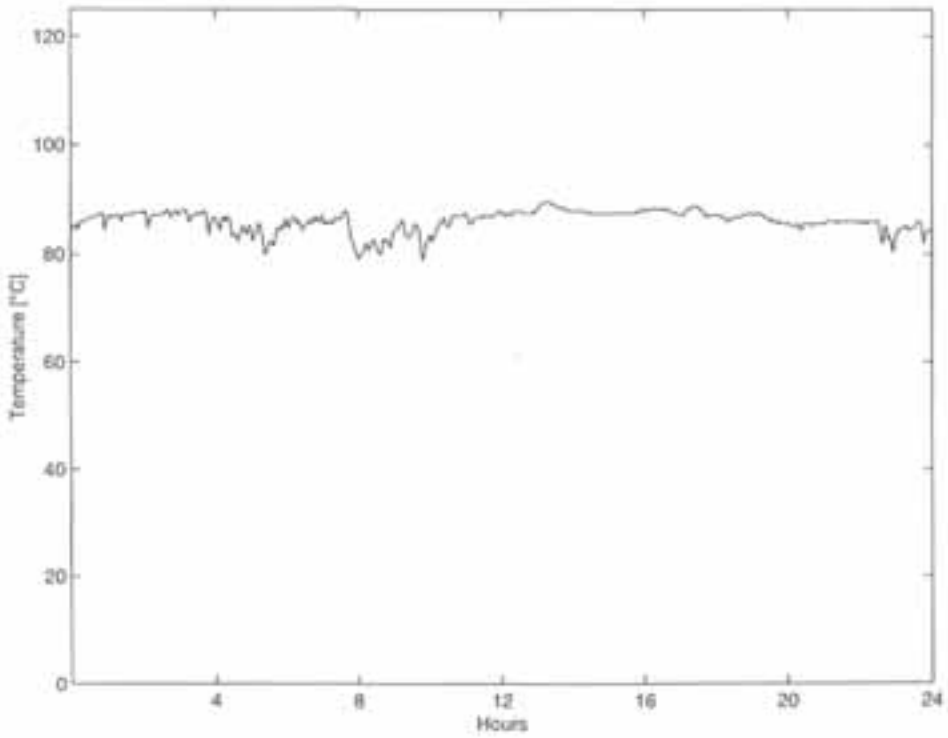

Difference between upper and lower side of the supply pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks


Difference between upper and lower side of the return pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks

S19, Sunday 10/8-1997

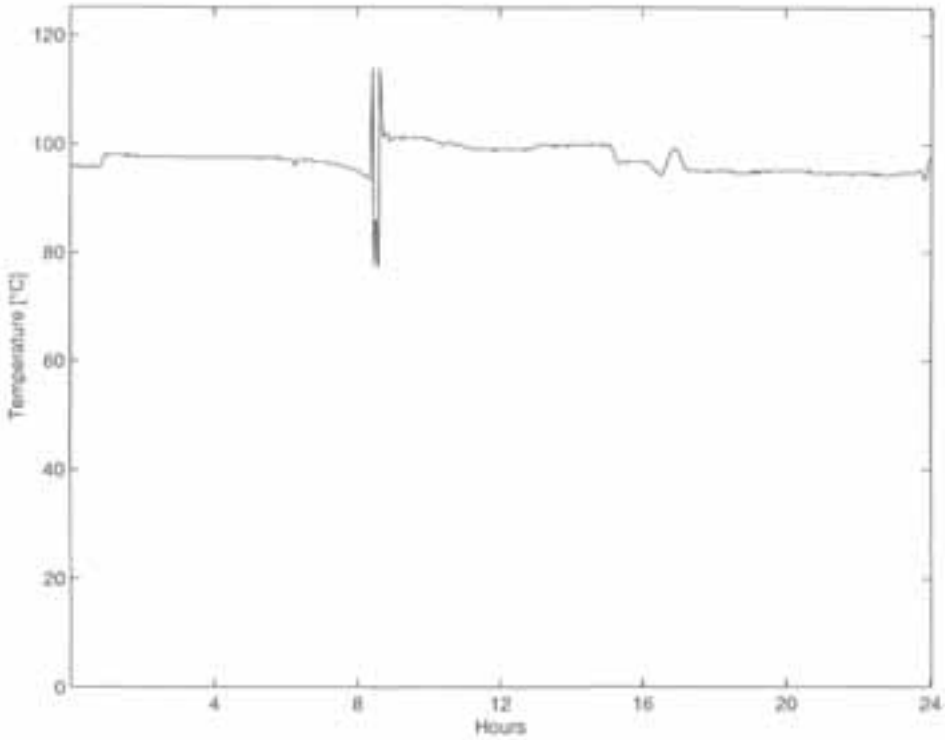


R19, Sunday 10/8-1997

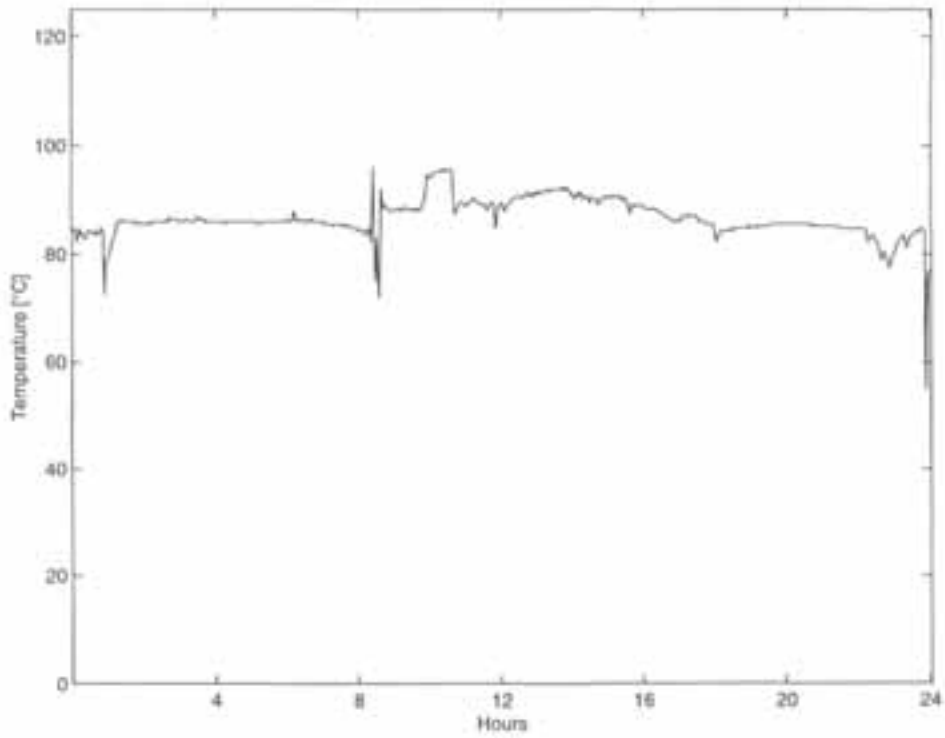


Enclosure S/R19 G

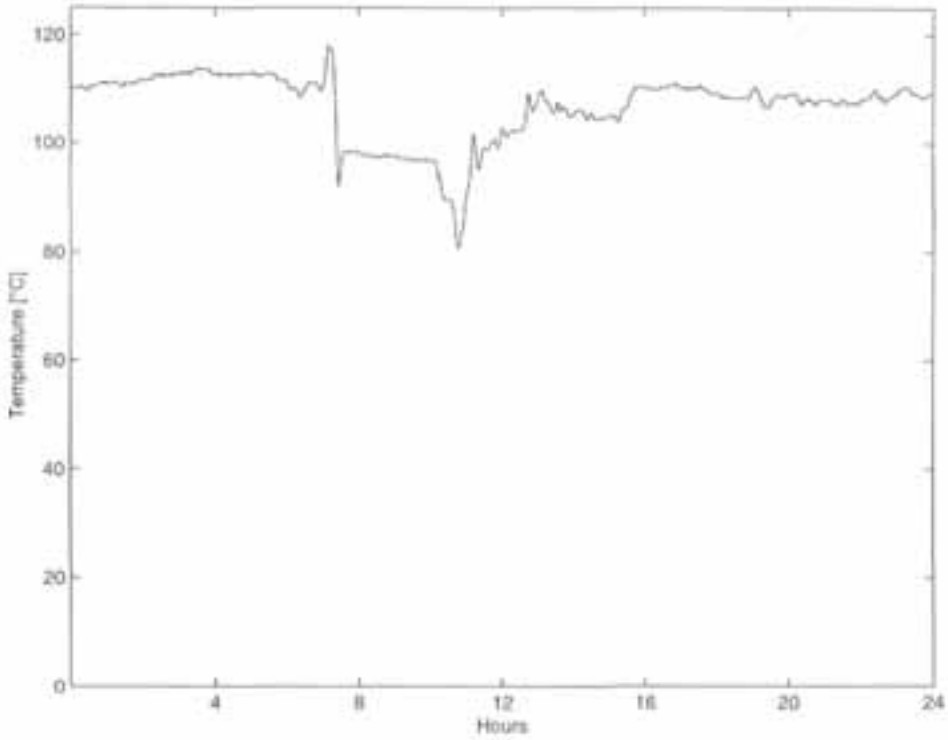
S19, Monday 11/8-1997



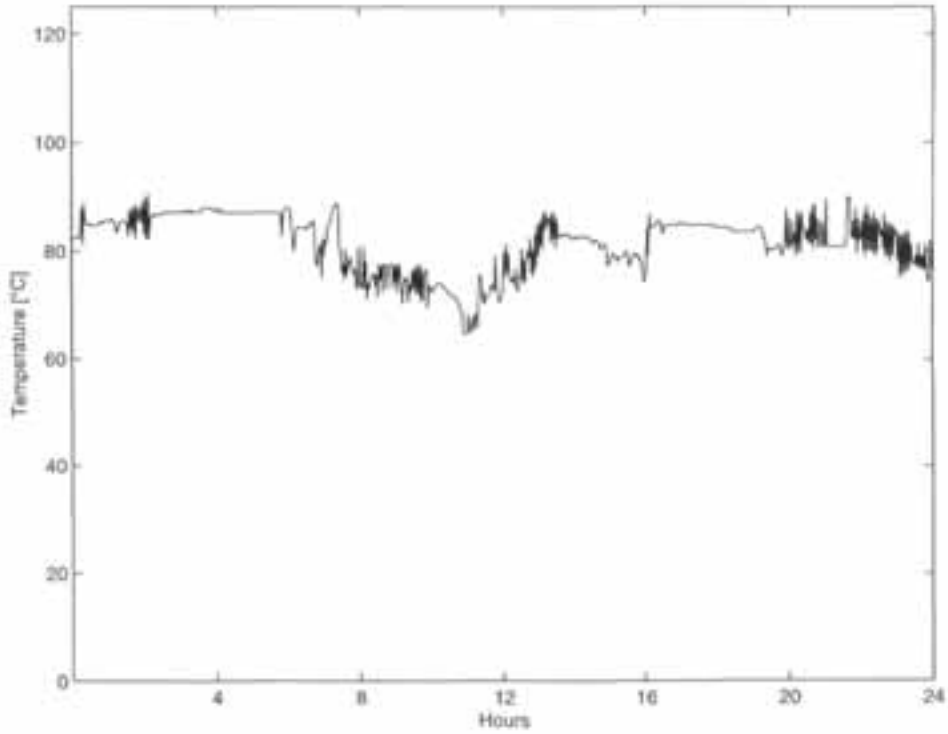
R19, Monday 11/8-1997



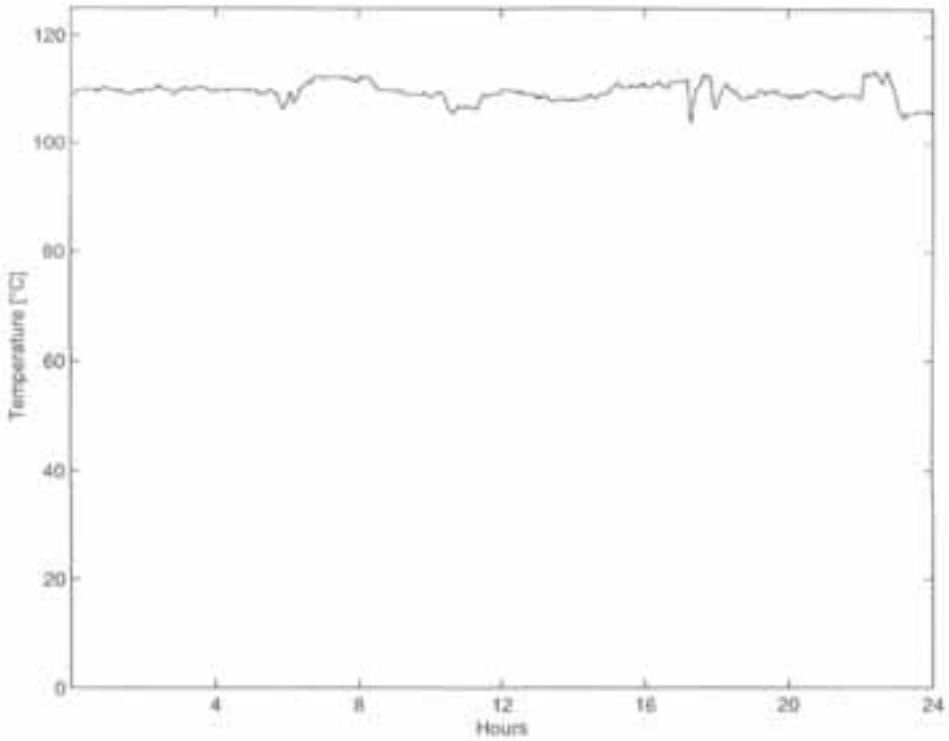
S19, Sunday 7/12-1997



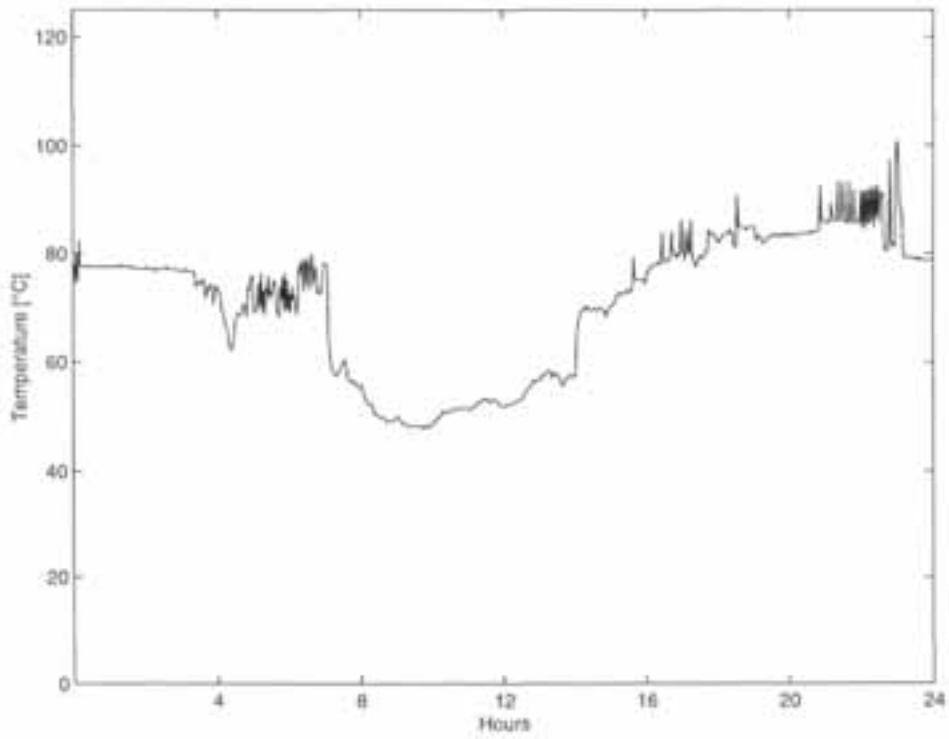
R19, Sunday 7/12-1997



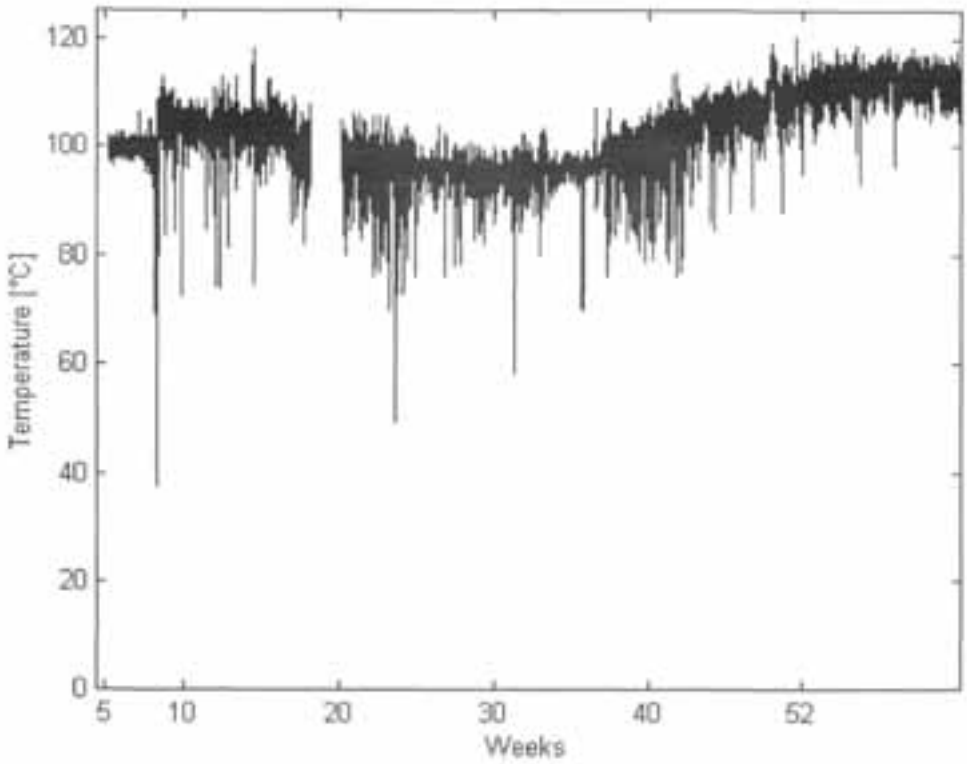
S19, Monday 8/12-1997



R19, Monday 8/12-1997



S20, Top of the pipe



Range **Mean**

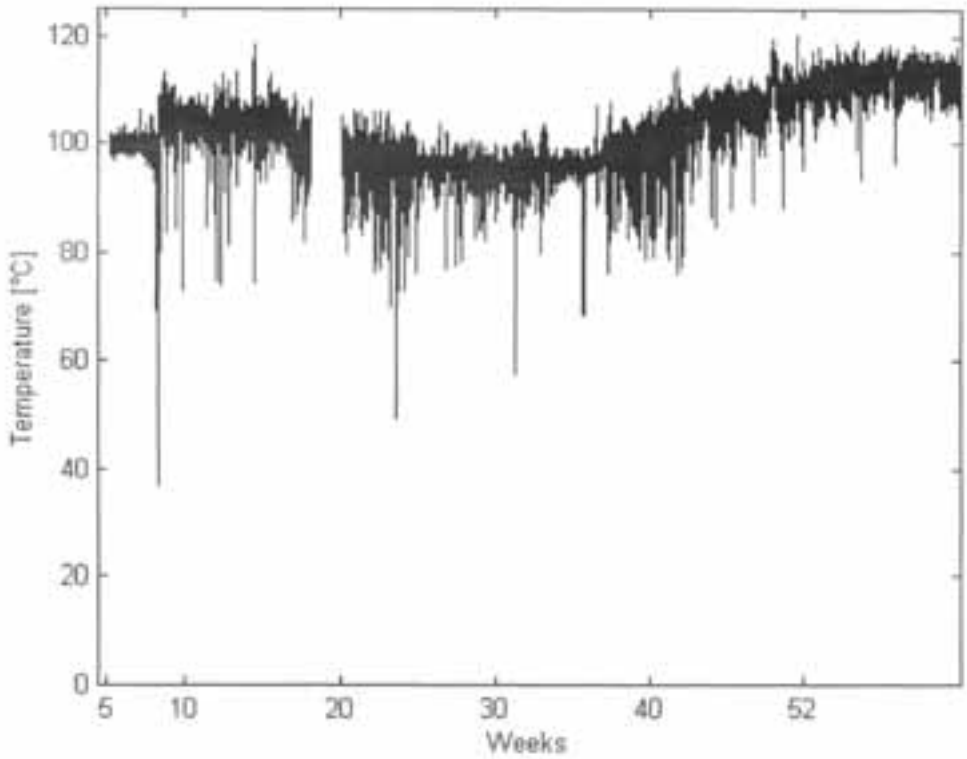
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	1	-	-	3	9	2	1	4	3	4	22	2087	6820	6356	3996	4819	533
10	-	-	-	-	-	-	-	-	-	-	-	-	-	1	62	70	153	73	92	-
15	-	-	-	-	-	-	-	1	-	-	-	-	-	4	24	36	35	15	15	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	2	26	13	4	5	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	3	13	8	3	2	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	5	11	4	-	1	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	1	1	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	1	4	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 370,84 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	69,1
4	25,3
5	13,0

S20, Underside of the pipe



Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	1	-	-	3	7	2	1	4	3	4	27	1906	6113	5186	3464	4059	693
10	-	-	-	-	-	-	-	-	-	-	-	-	-	1	60	70	152	72	101	1
15	-	-	-	-	-	-	-	1	-	-	-	-	-	4	24	36	37	13	14	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	2	25	13	4	5	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	3	12	7	4	3	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	4	12	4	-	-	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	1	1	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	2	3	1	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

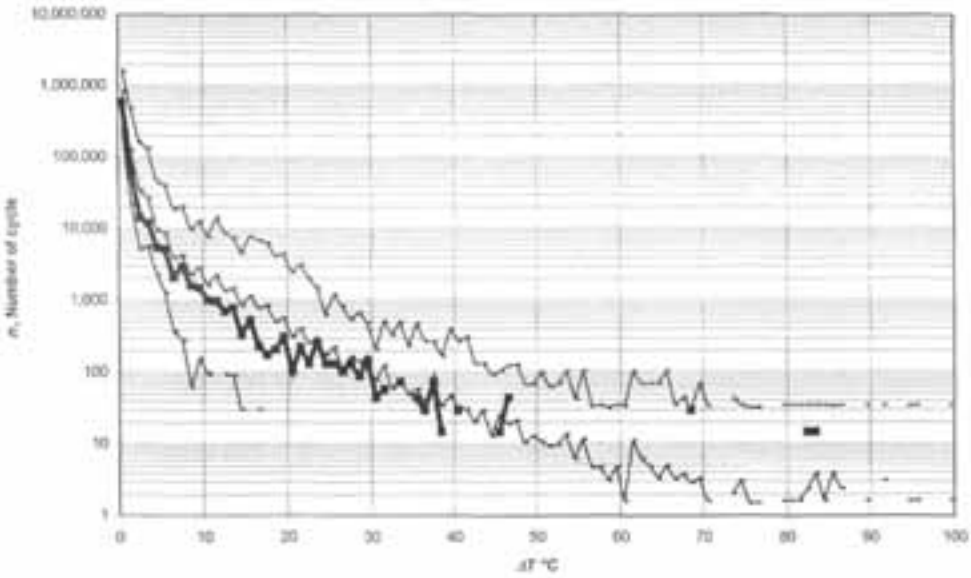
Measuring period: 370,84 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	70,4
4	26,0
5	13,4

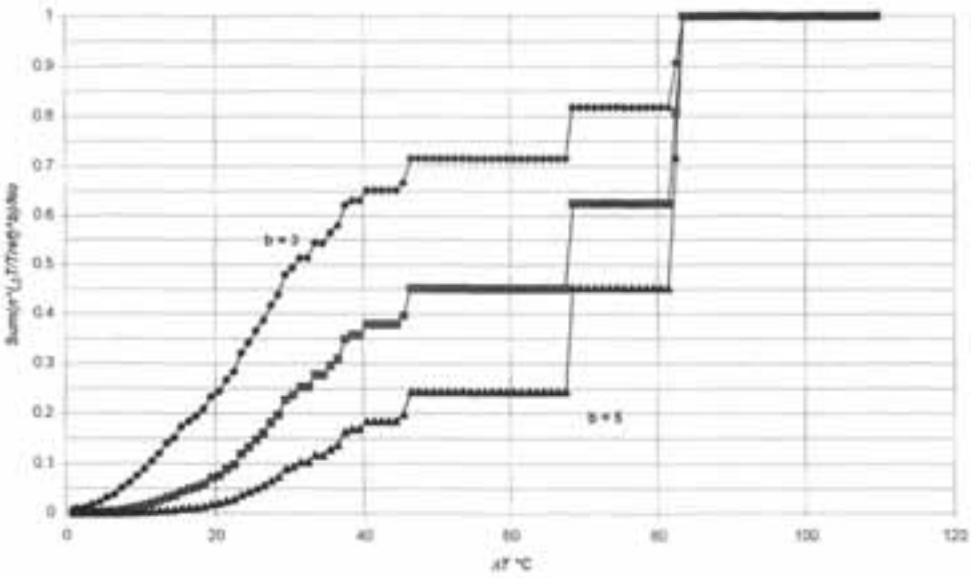
S20

Enclosure S20 B



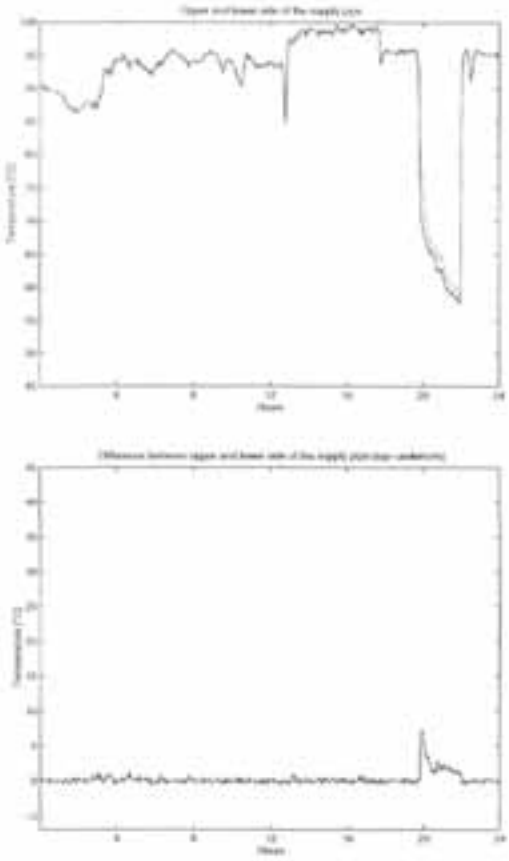
S20

Enclosure S20 C

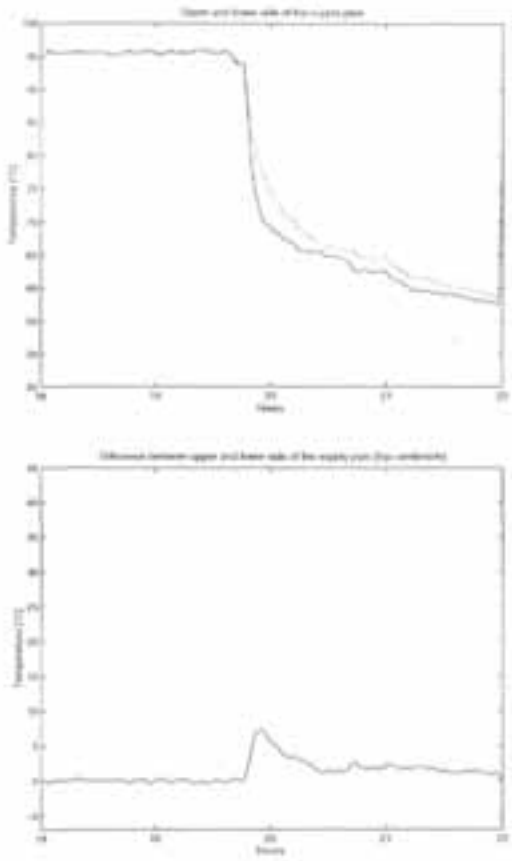


S20, Thursday 7/8-1997

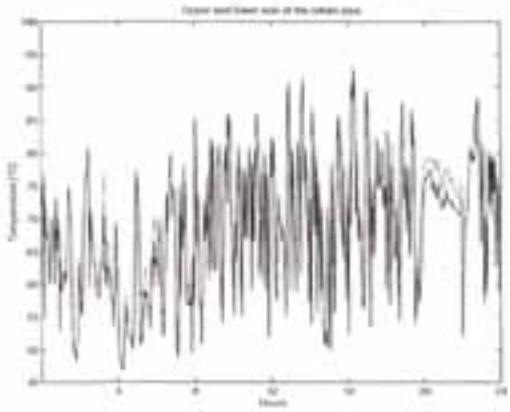
The day of the peak.
Below: Difference (top – underside)



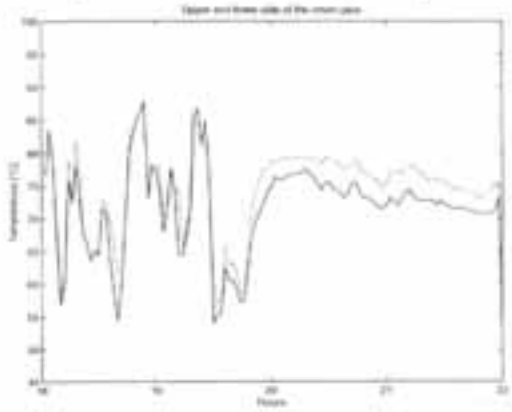
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Return temperatures for comparison.

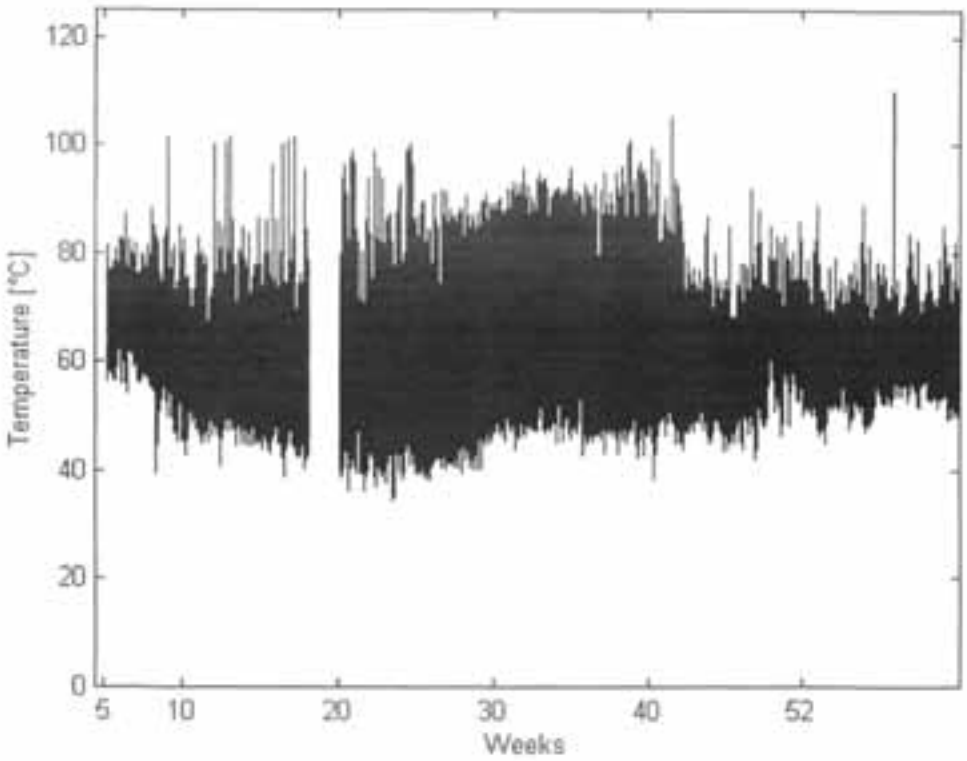


Close-up of comparable return temperatures.



The lighter shaded curves belong to the temperature on top of the pipe.

R20, Top of the pipe



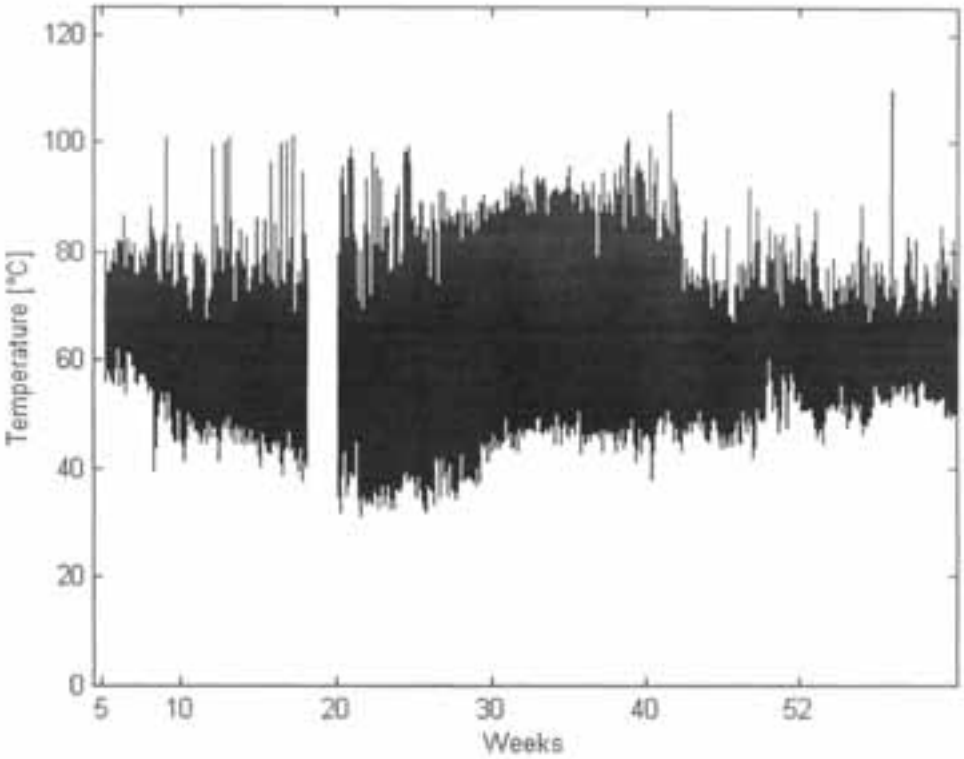
Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	1	127	1646	7474	12379	8164	4408	2237	833	379	96	59	8	15	5	-	-
10	-	-	-	-	5	152	1910	4149	3240	1671	953	443	121	29	28	7	1	-	-	-
15	-	-	-	-	-	41	607	1654	1208	698	370	129	24	6	7	-	-	-	-	-
20	-	-	-	-	-	5	156	848	662	466	260	77	4	2	1	-	-	-	-	-
25	-	-	-	-	-	2	36	335	433	344	260	41	2	-	-	-	-	-	-	-
30	-	-	-	-	-	-	12	145	286	260	177	21	2	-	-	-	-	-	-	-
35	-	-	-	-	-	-	4	48	177	224	104	4	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	1	6	66	134	47	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	2	34	61	16	1	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	1	21	21	9	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	13	4	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	5	6	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	4	3	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 370,84 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	2564,3
4	678,2
5	212,2

R20, Underside of the pipe



Range **Mean**

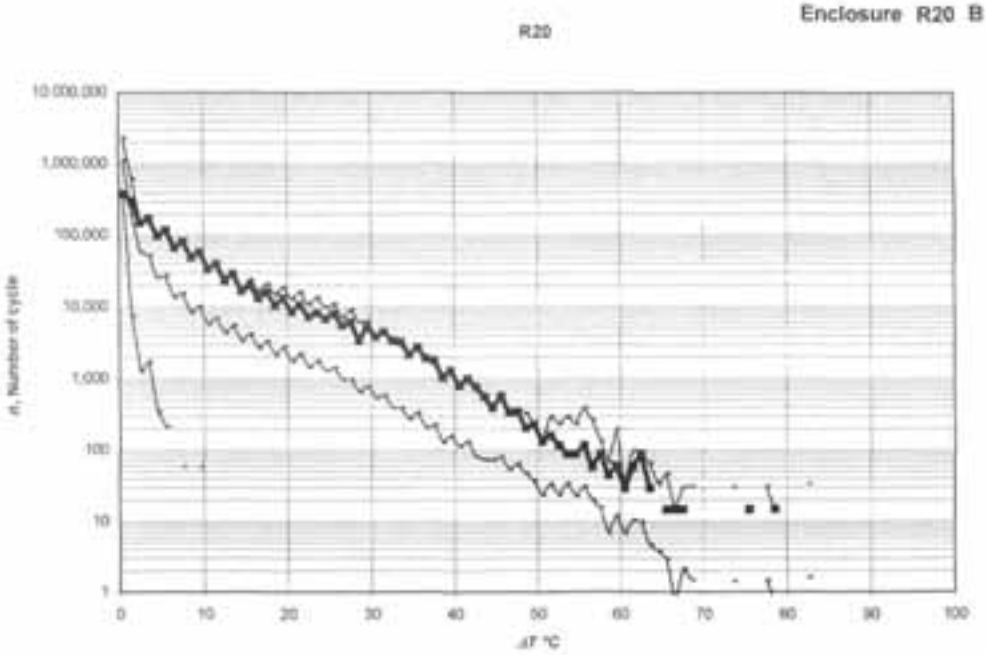
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	7	192	1945	8083	12736	7925	4246	1943	658	276	96	53	7	14	5	-	-
10	-	-	-	1	31	271	2160	4224	3079	1612	830	325	90	27	29	4	1	-	-	-
15	-	-	-	1	6	85	741	1705	1208	657	326	108	22	4	7	-	-	-	-	-
20	-	-	-	-	-	32	234	860	648	453	201	35	2	1	1	-	-	-	-	-
25	-	-	-	-	-	12	81	356	427	343	172	20	2	-	-	-	-	-	-	-
30	-	-	-	-	-	3	65	157	301	333	150	11	1	-	-	-	-	-	-	-
35	-	-	-	-	-	-	29	80	171	254	73	1	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	10	48	75	163	43	1	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	1	15	31	63	16	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	13	21	27	3	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	3	9	9	2	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	4	6	4	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	2	3	2	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	3	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 370,84 days

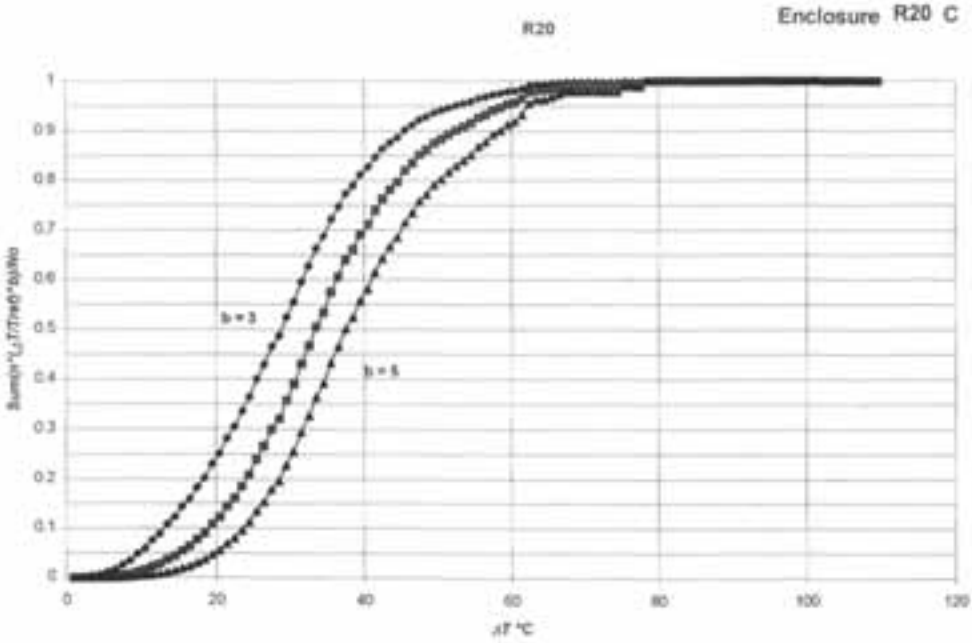
DTref 110 °C

b	Nr. of full cycles in 30 years
3	2865,3
4	790,3
5	257,1

Enclosure R20 B

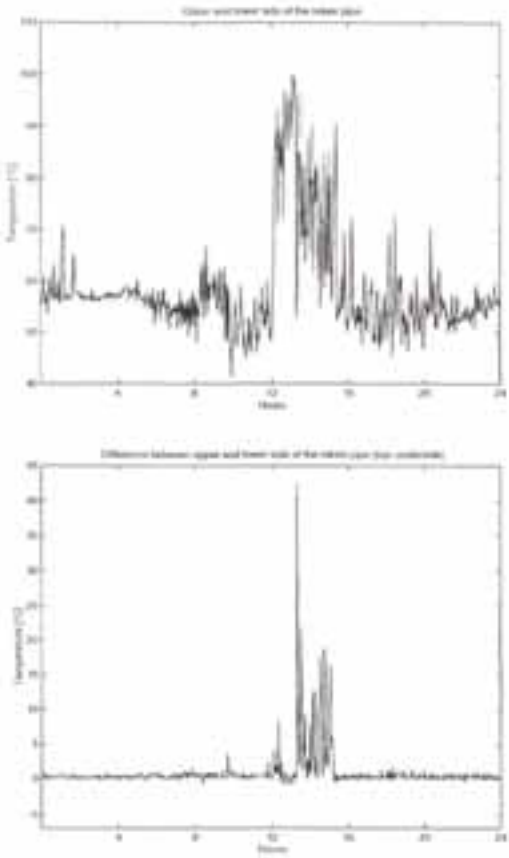


Enclosure R20 C

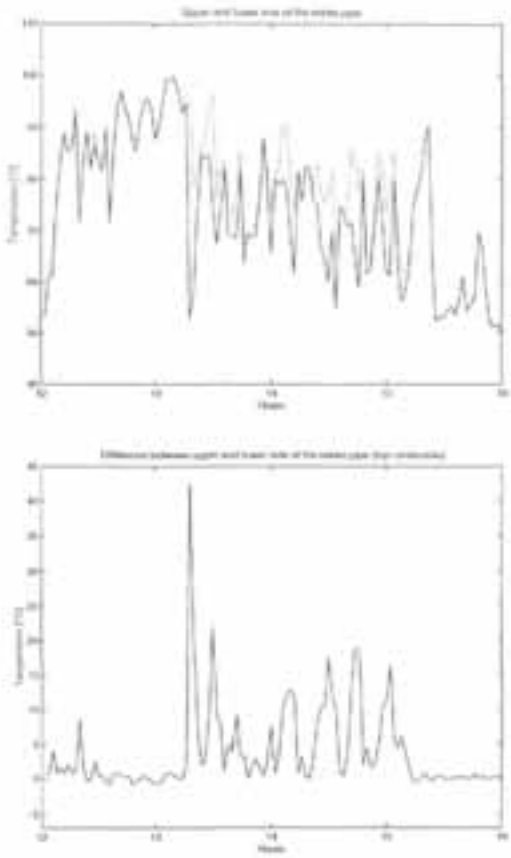


R20, Friday 25/4-1997

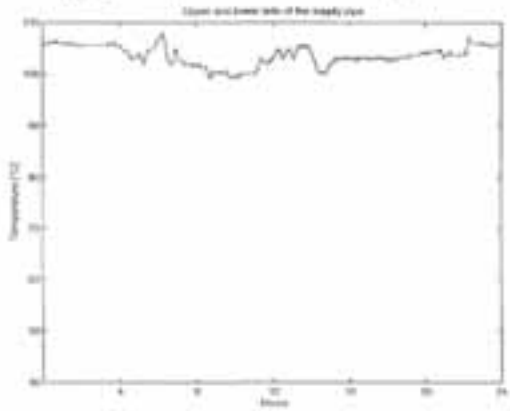
The day of the peak.
Below: Difference (top – underside)



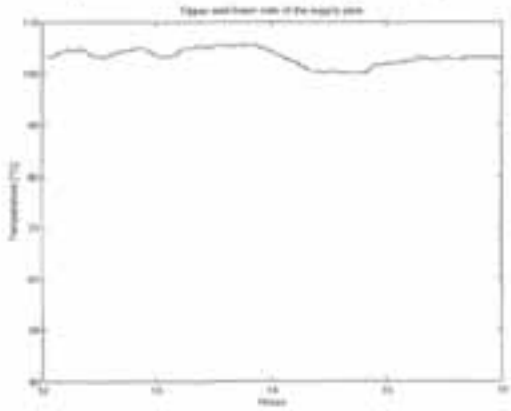
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Supply temperatures for comparison.

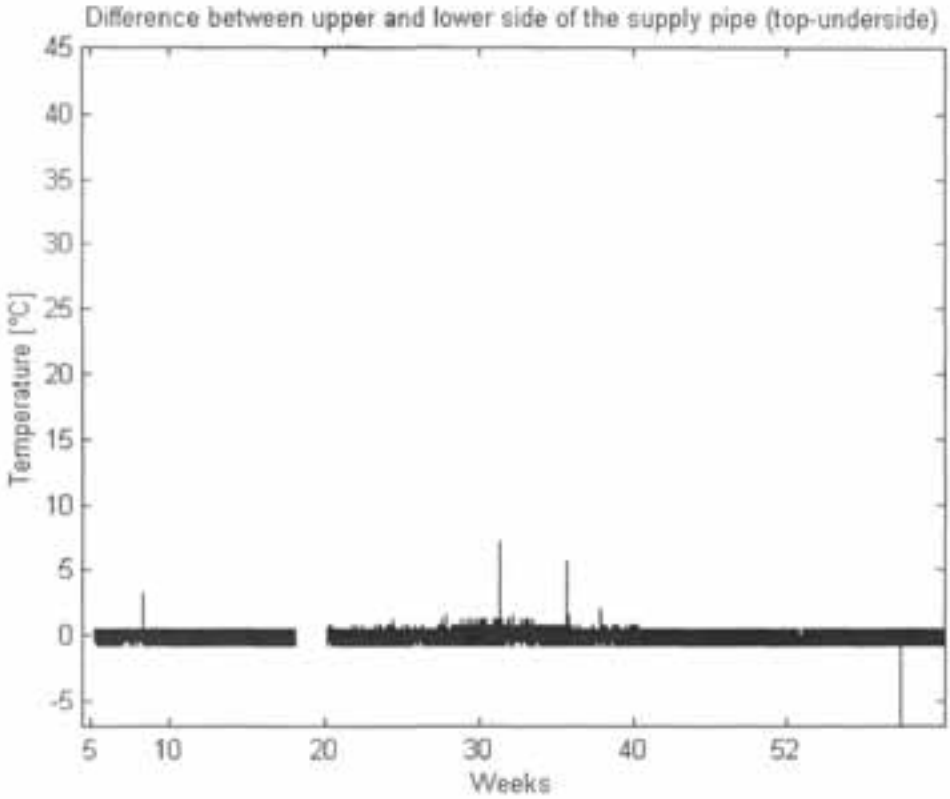


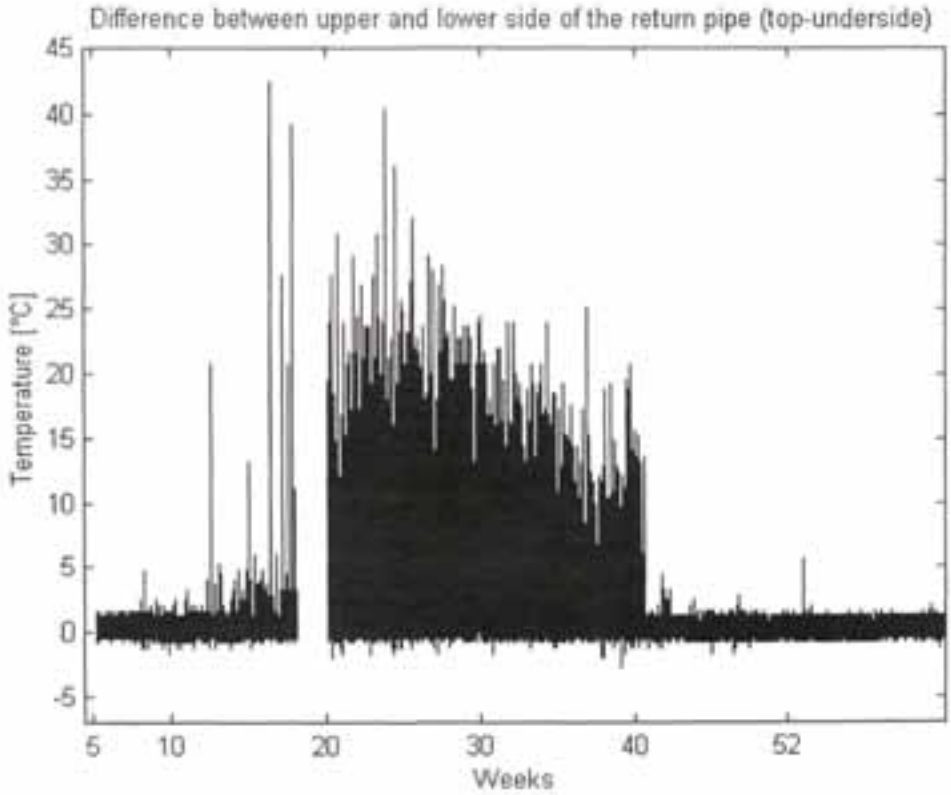
Close-up of comparable supply temperatures.



The lighter shaded curves belong to the temperature on top of the pipe.

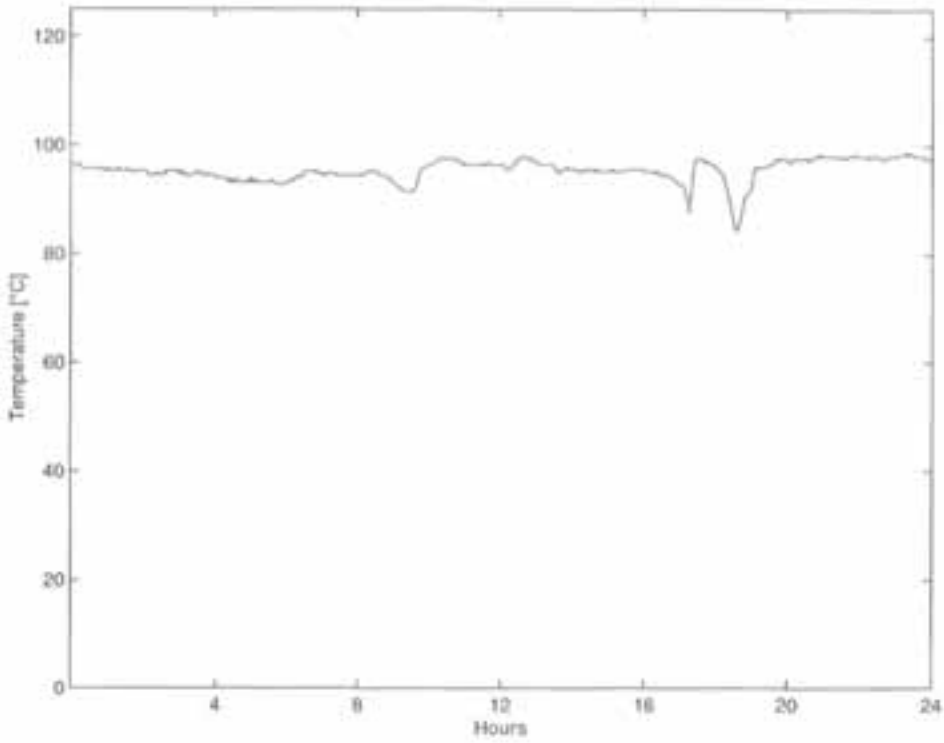
S20, R20


Difference between upper and lower side of the supply pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks

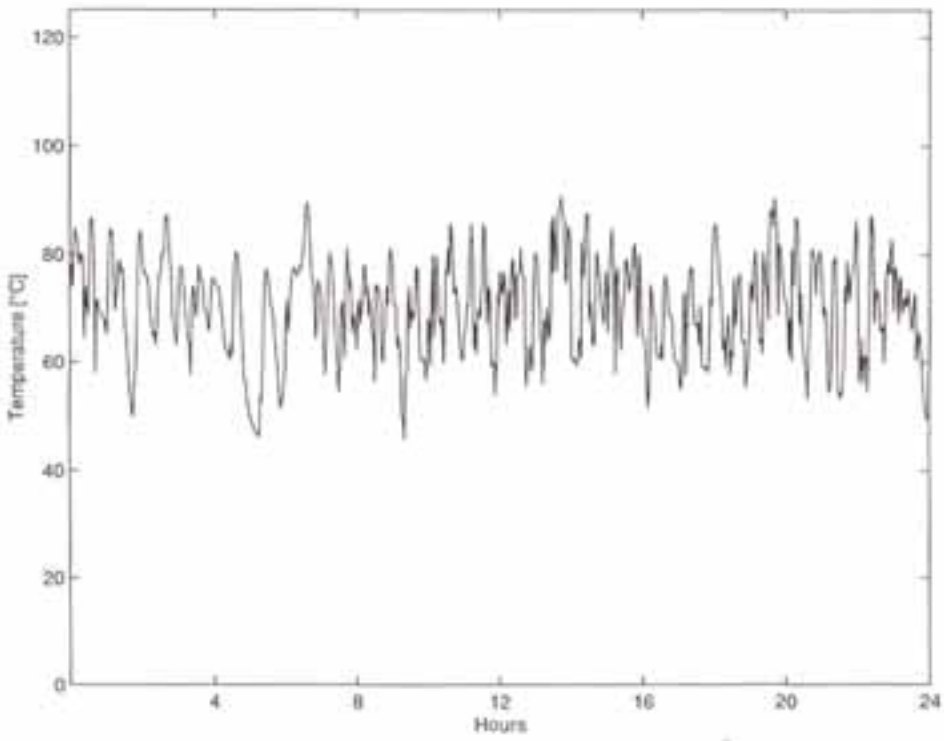

Difference between upper and lower side of the return pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks

Enclosure S/R20 F

S20, Sunday 10/8-1997

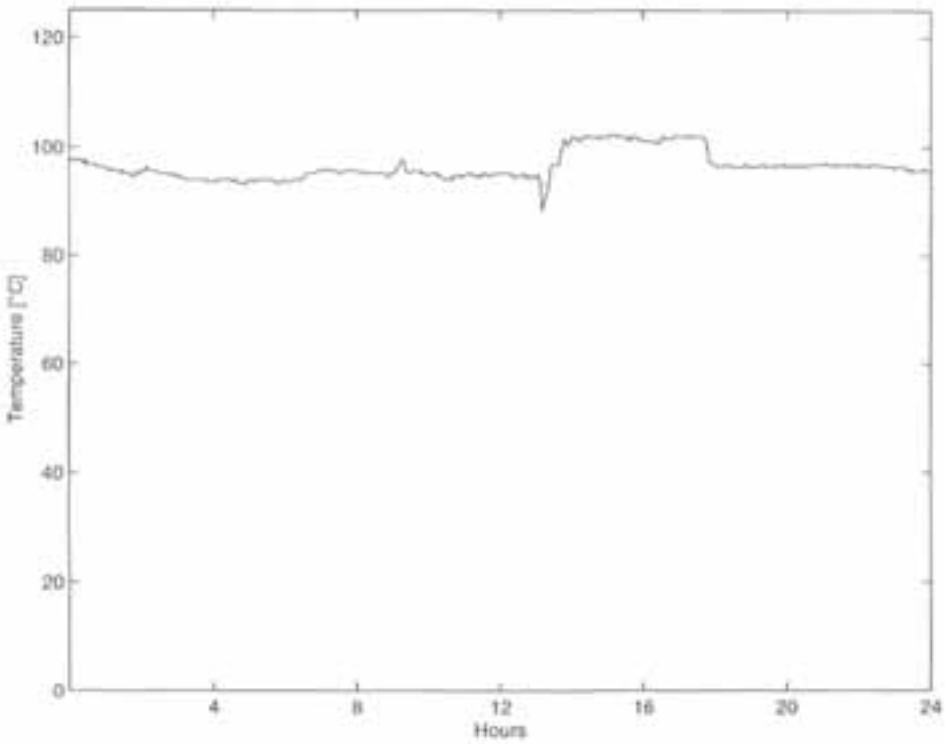


R20, Sunday 10/8-1997

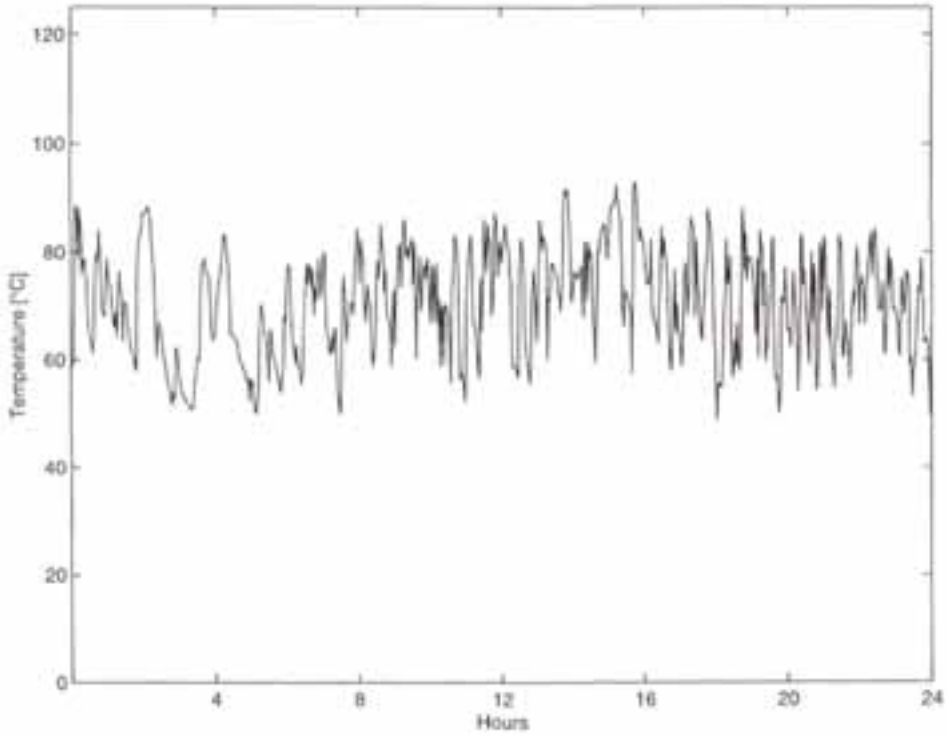


Enclosure S/R20 G

S20, Monday 11/8-1997

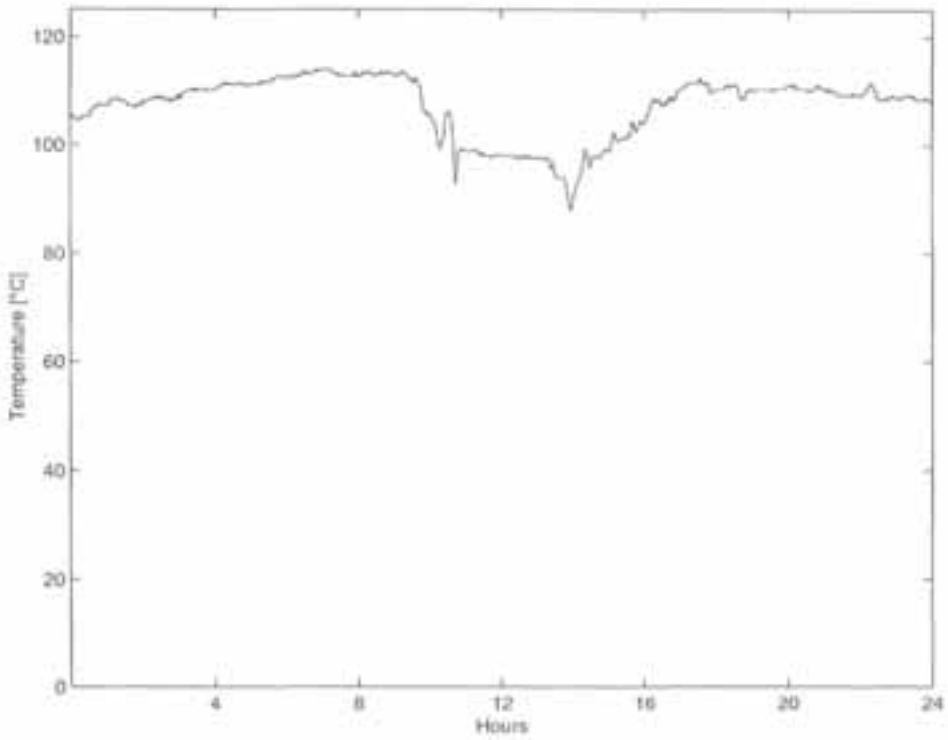


R20, Monday 11/8-1997

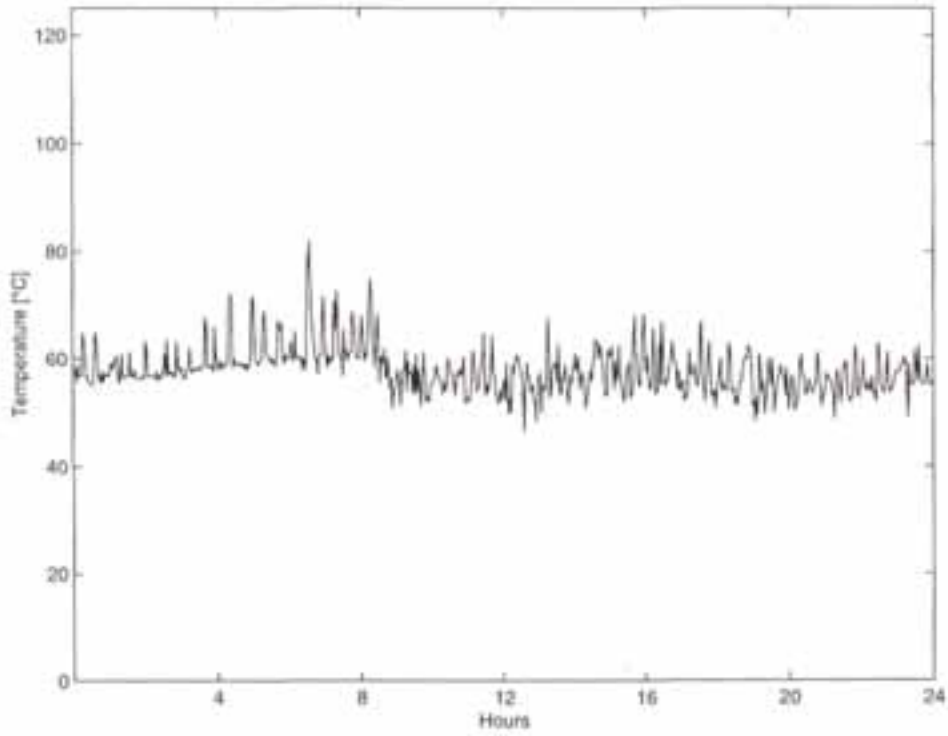


Enclosure S/R20 H

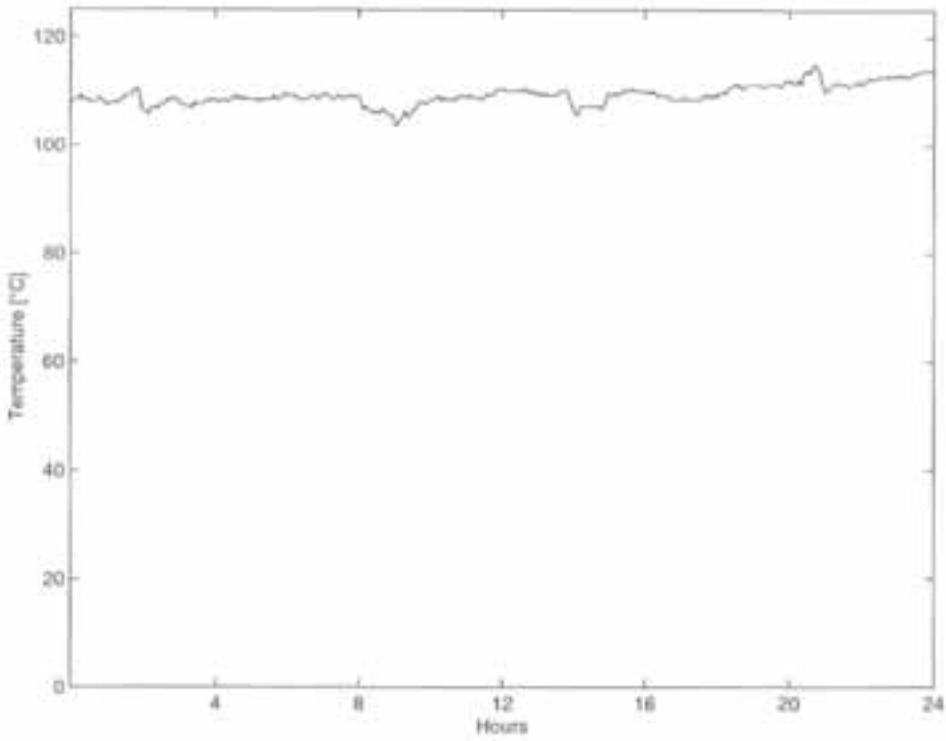
S20, Sunday 7/12-1997



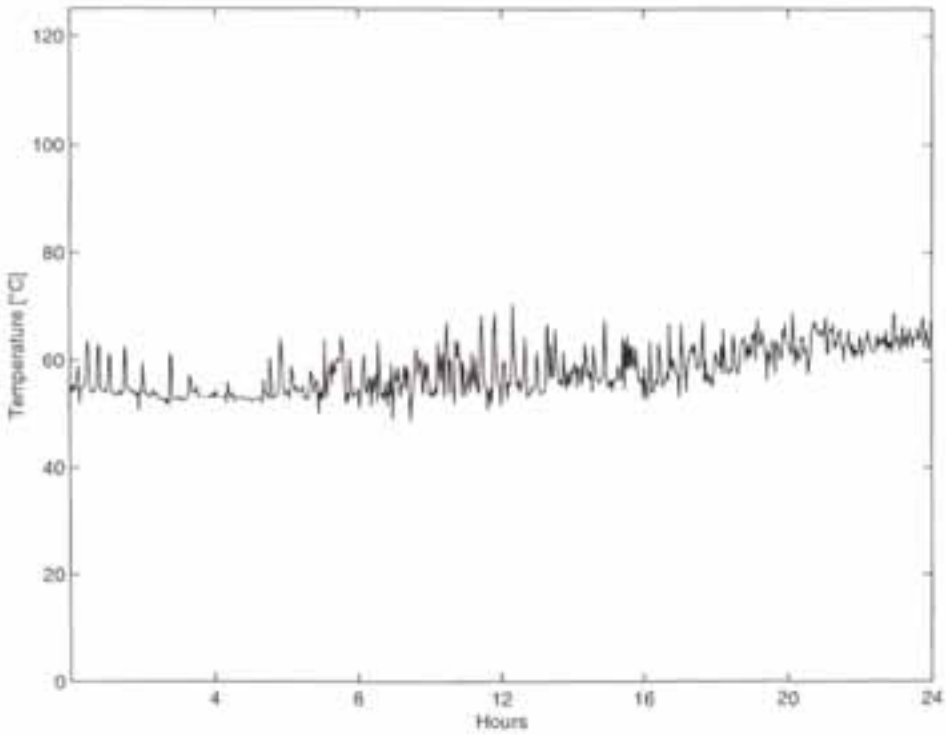
R20, Sunday 7/12-1997



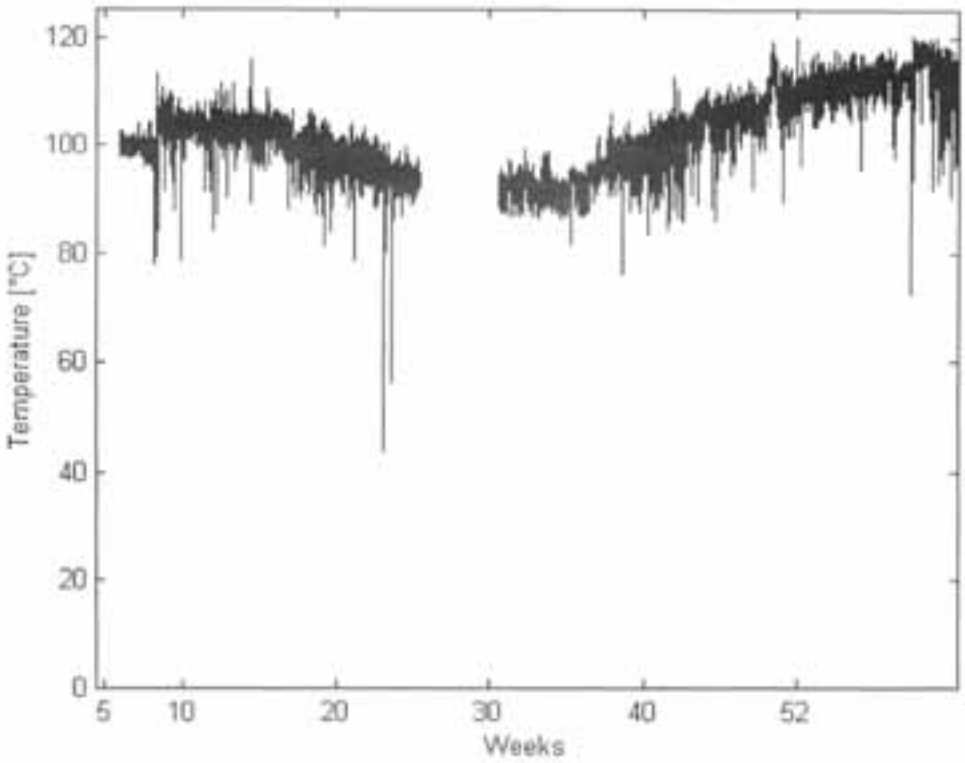
S20, Monday 8/12-1997



R20, Monday 8/12-1997



S21, Top of the pipe



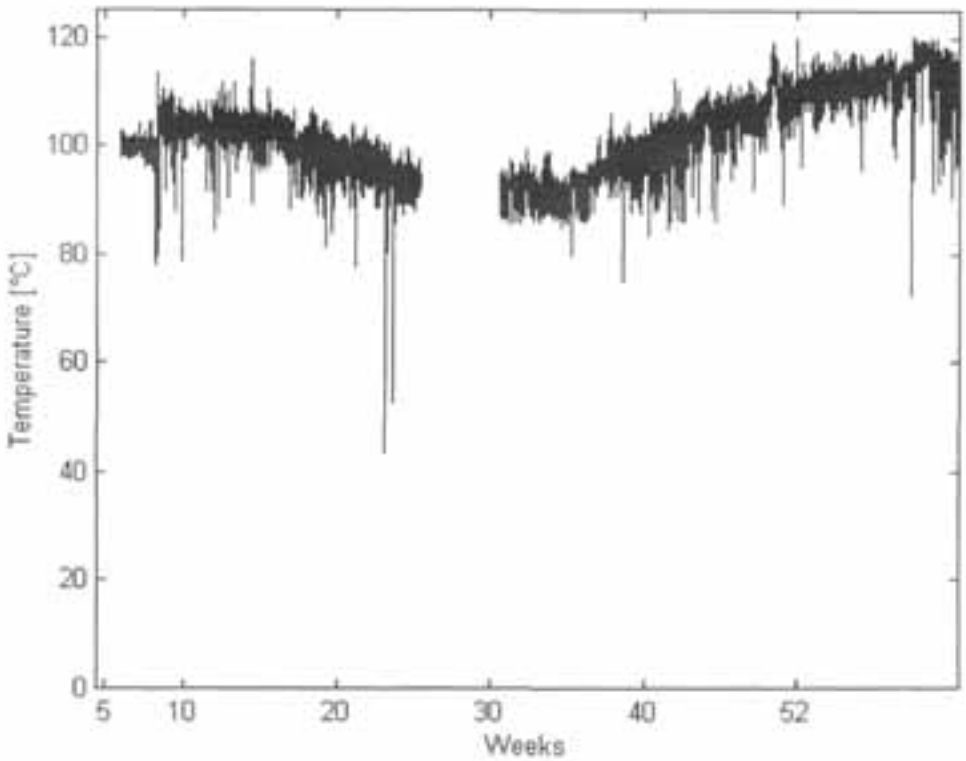
Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	-	1	3	-	-	-	1	3	-	4	22	1235	1434	2417	1425	1558	493
10	-	-	-	-	-	-	-	-	-	-	-	-	1	1	58	57	91	39	60	1
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	38	15	10	9	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	1	3	14	5	6	1	-
25	-	-	-	-	-	-	-	-	-	-	-	-	1	-	4	9	1	4	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	2	2	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 345,92 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	37,2
4	13,2
5	6,8

S21, Underside of the pipe



Range	Mean																			
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	-	-	-	-	5	9	1	4	1	-	3	2	15	116	2156	1918	3099	1669	1830	577
10	-	-	-	-	-	-	-	-	1	-	-	-	1	5	52	57	91	40	61	1
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11	38	16	10	10	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	2	2	14	5	6	1	-
25	-	-	-	-	-	-	-	-	-	-	-	-	1	-	3	9	1	4	-	-
30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	2	2	-	-
35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

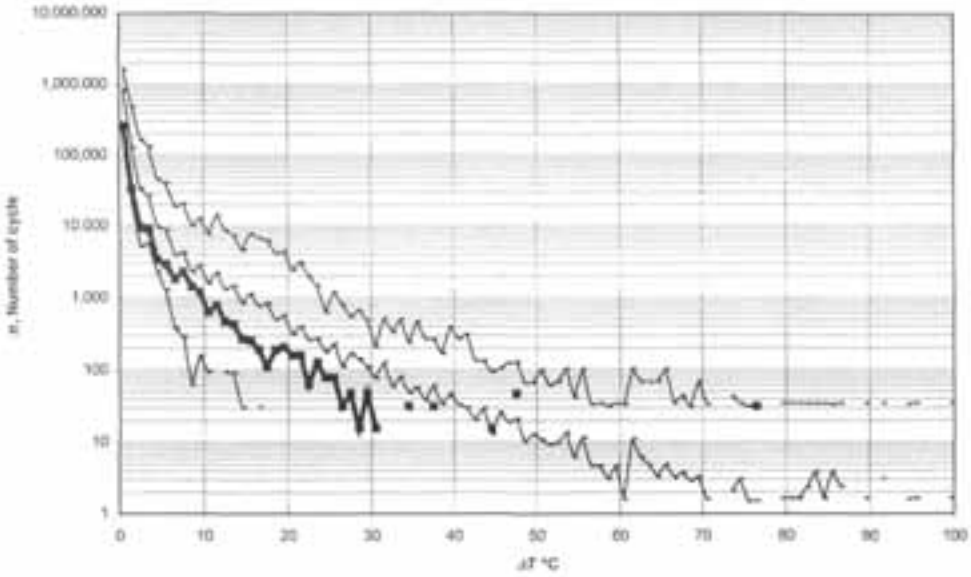
Measuring period: 345,92 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	38,5
4	13,8
5	7,1

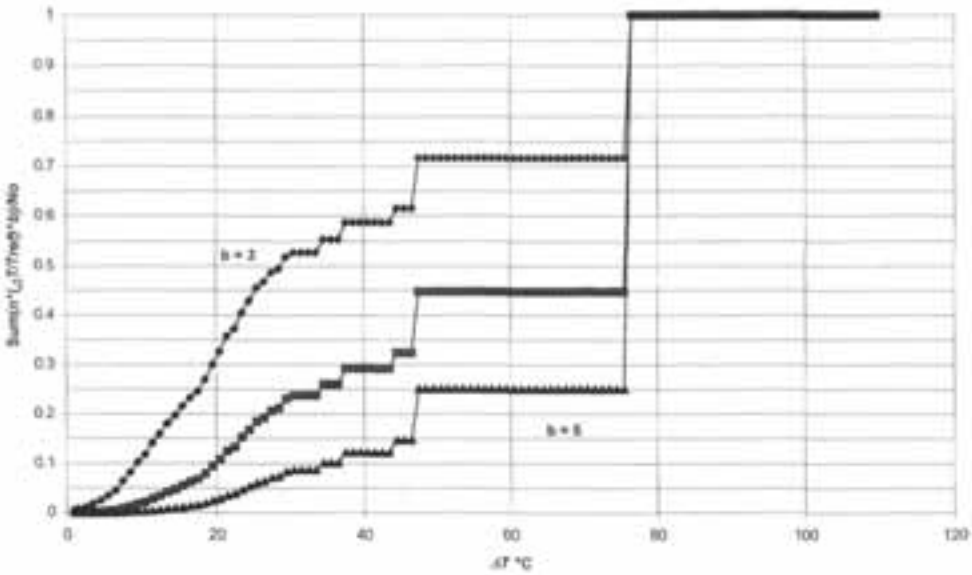
S21

Enclosure S21 B



S21

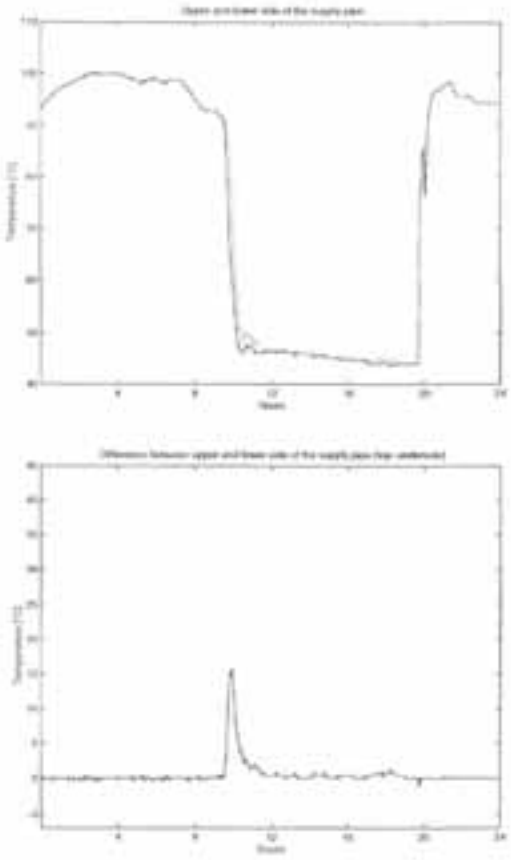
Enclosure S21 C



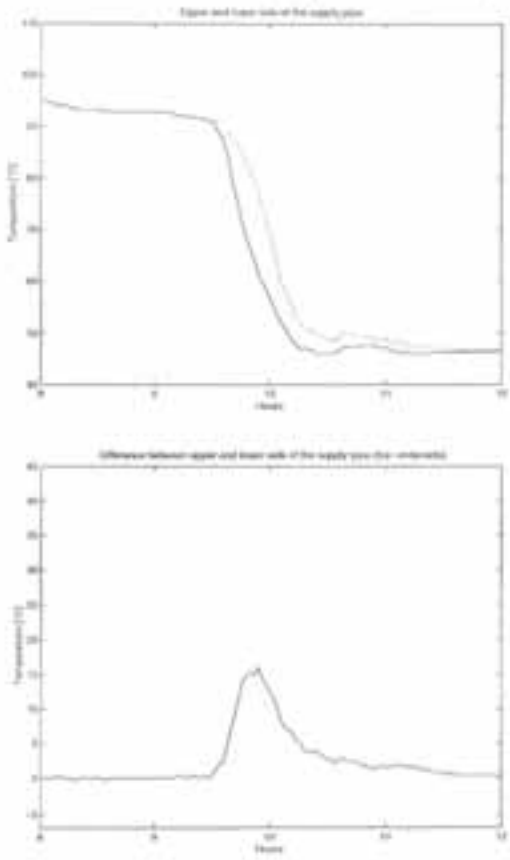
Enclosure S21 D

S21, Wednesday 11/6-1997

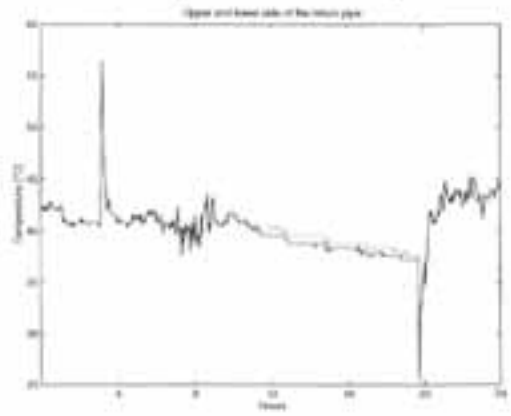
The day of the peak.
Below: Difference (top – underside)



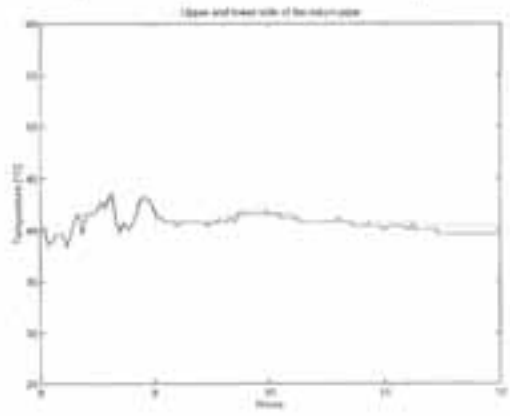
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Return temperatures for comparison.

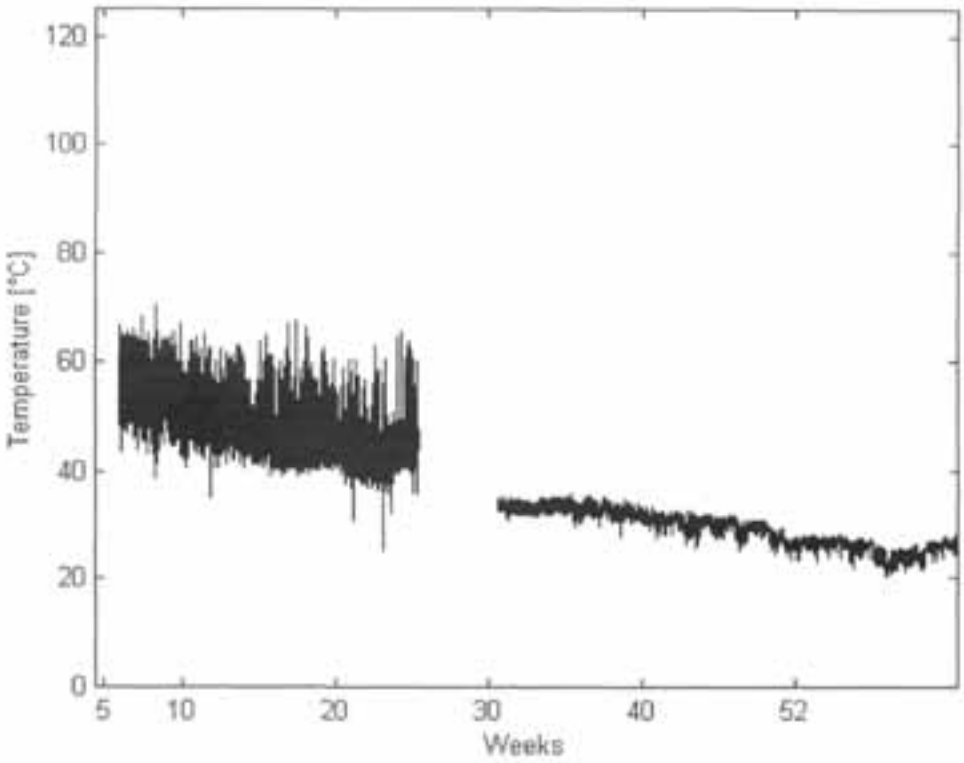


Close-up of comparable return temperatures.



The lighter shaded curves belong to the temperature on top of the pipe.

R21, Top of the pipe



Range **Mean**

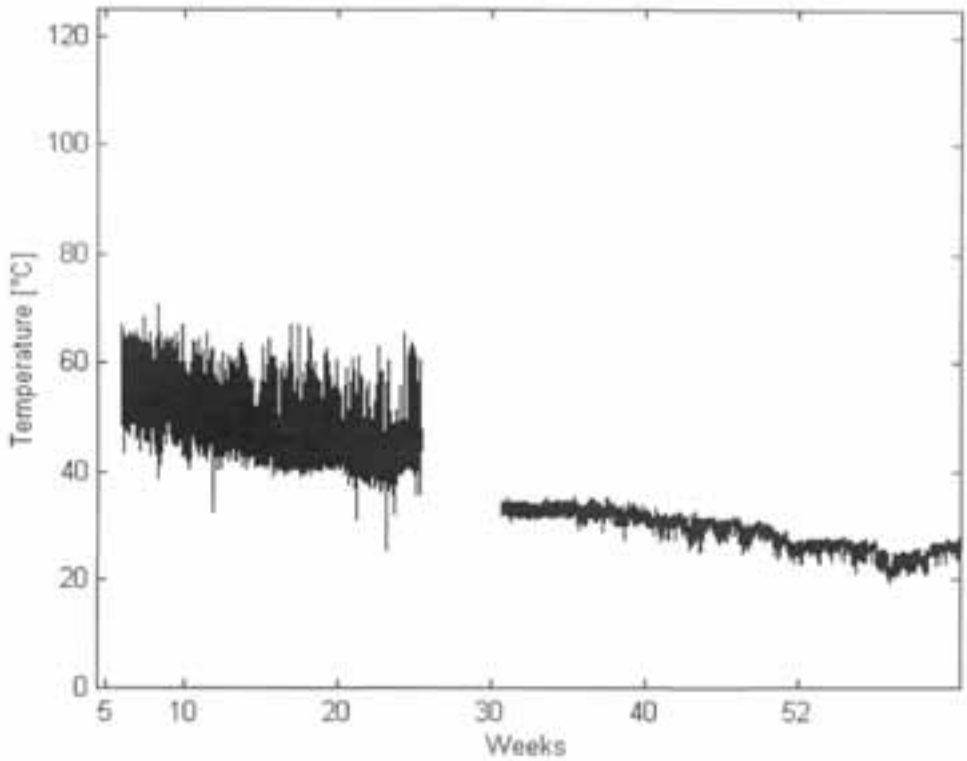
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	2308	7523	9113	231	7616	5485	2519	1570	789	1	-	-	-	-	-	-	-	-	-	-
10	2	5	6	-	68	54	70	77	12	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	10	18	9	7	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	31	36	8	-	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	5	20	2	-	-	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	1	4	-	-	-	-	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	1	2	-	-	-	-	-	-	-	-	-	-	-	-	-
40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 345,9 days

DTref 110 °C

b	Nr. of full cycles in 30 years
3	30,4
4	5,5
5	1,2

R21, Underside of the pipe



Range **Mean**

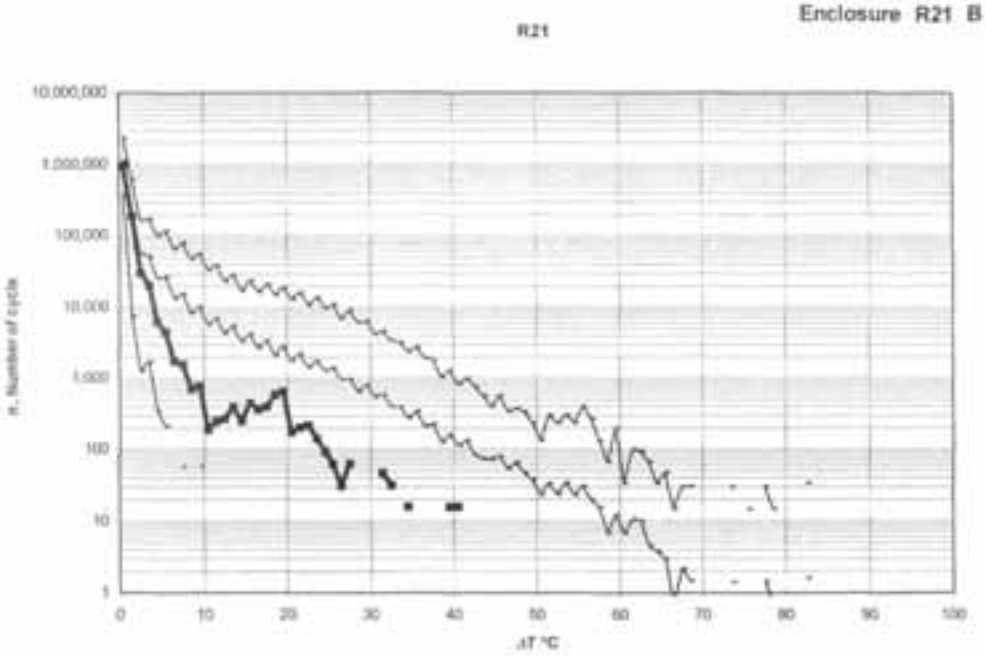
0	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120
5	3398	8754	9591	191	7590	5525	2532	1579	829	9	-	-	-	-	-	-	-	-	-	-
10	2	6	3	-	66	68	71	68	17	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	9	17	9	7	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	1	31	38	9	-	-	-	-	-	-	-	-	-	-	-	-
25	-	-	-	-	-	6	18	2	-	-	-	-	-	-	-	-	-	-	-	-
30	-	-	-	-	-	1	4	-	-	-	-	-	-	-	-	-	-	-	-	-
35	-	-	-	-	-	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-
40	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
60	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Measuring period: 345,92 days

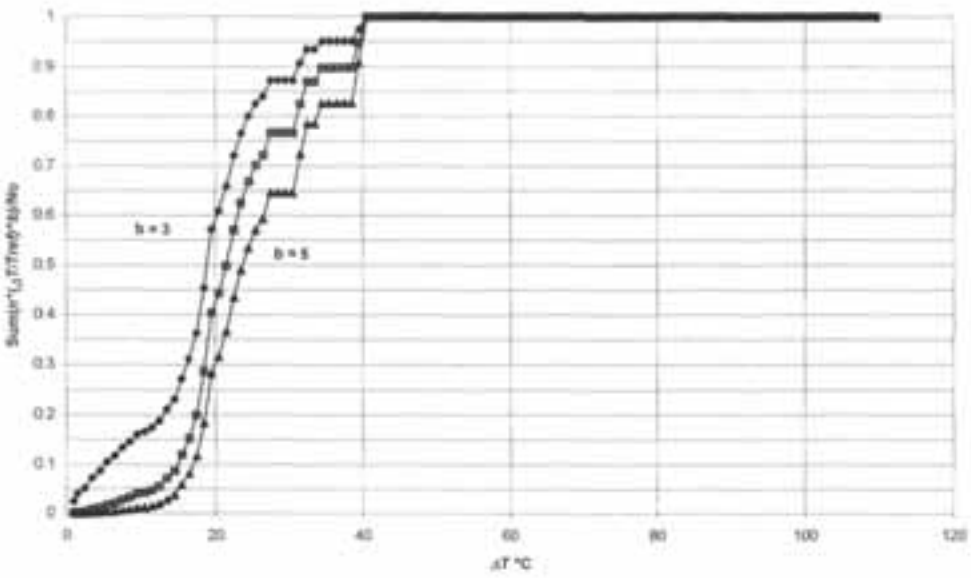
DTref 110 °C

b	Nr. of full cycles in 30 years
3	30,9
4	5,6
5	1,2

Enclosure R21 B



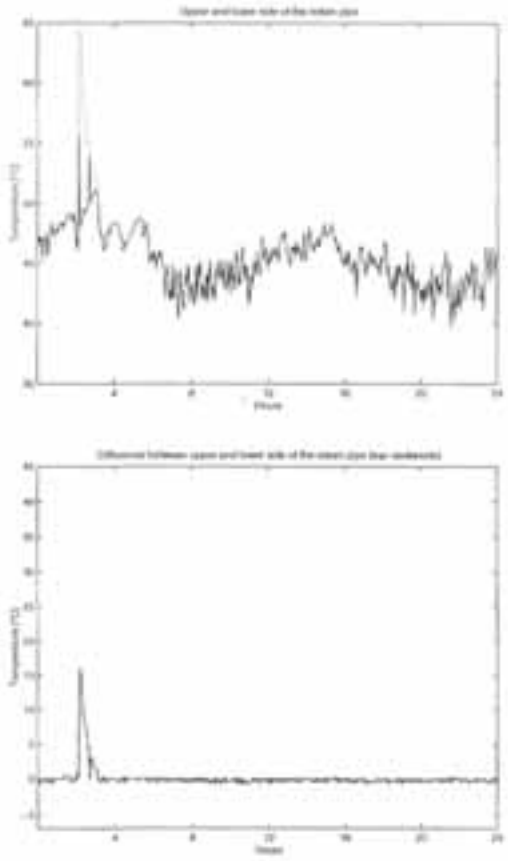
Enclosure R21 C



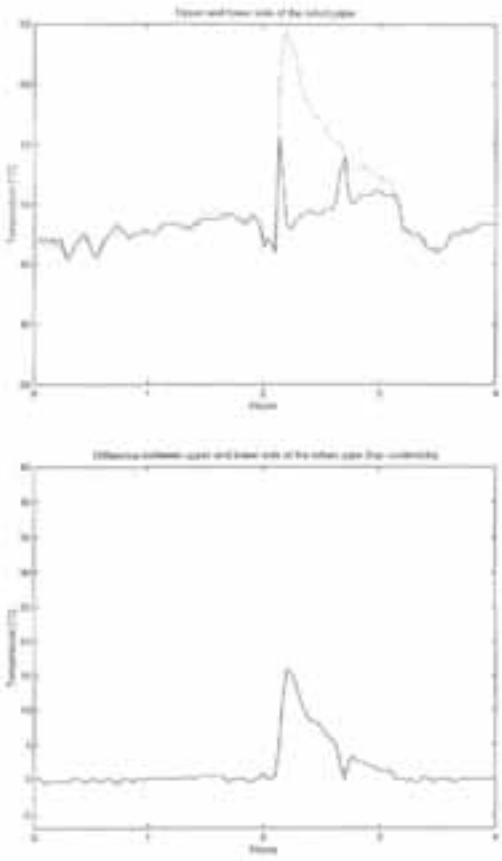
Enclosure R21 D

R21, Wednesday 18/6-1997

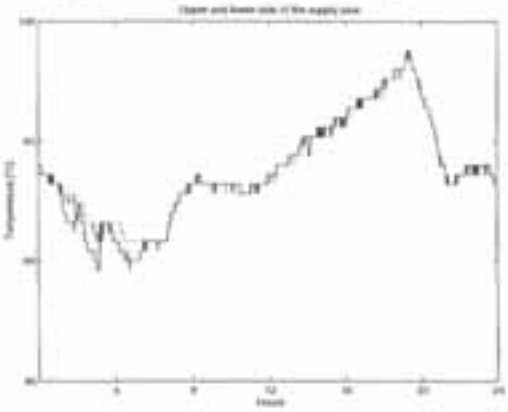
The day of the peak.
Below: Difference (top – underside)



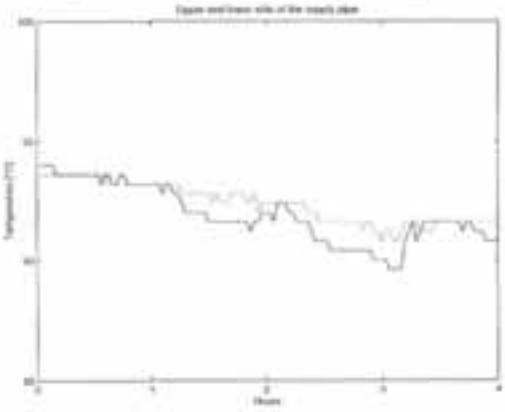
Close-up, 4 hours around the peak.
Below: Difference (top – underside)



Supply temperatures for comparison.

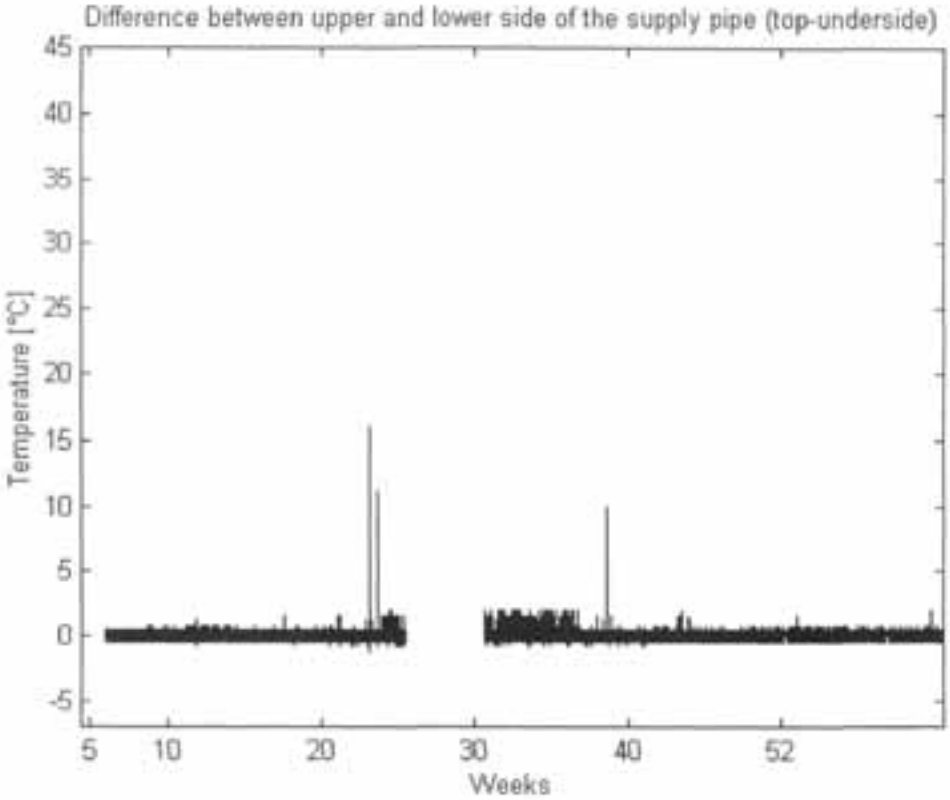


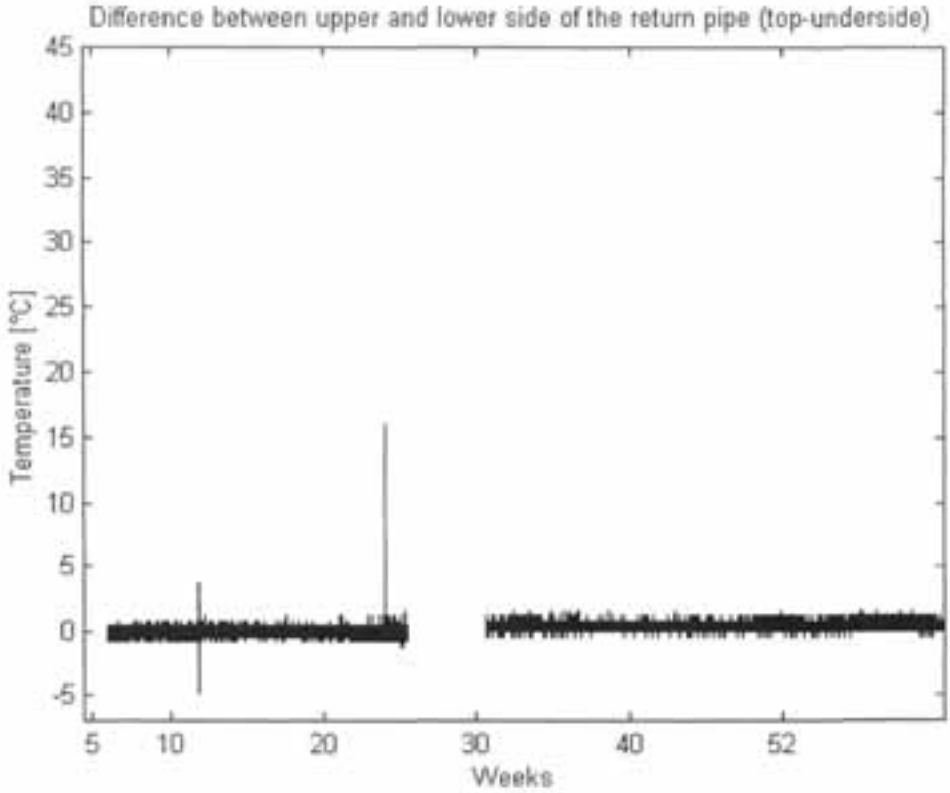
Close-up of comparable supply temperatures.



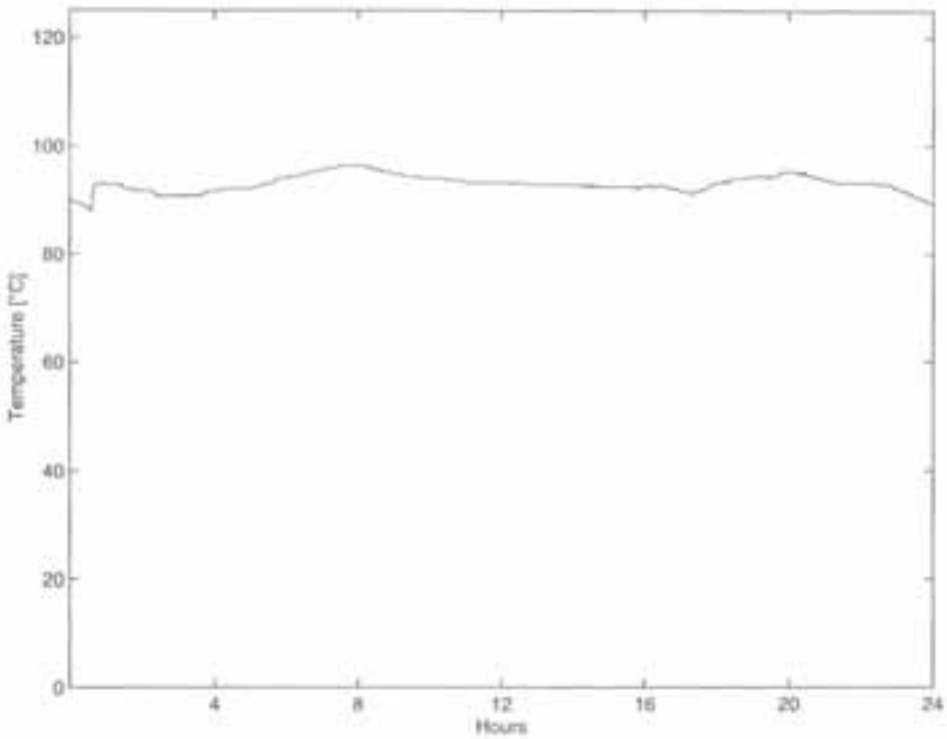
The lighter shaded curves belong to the temperature on top of the pipe.

S21, R21

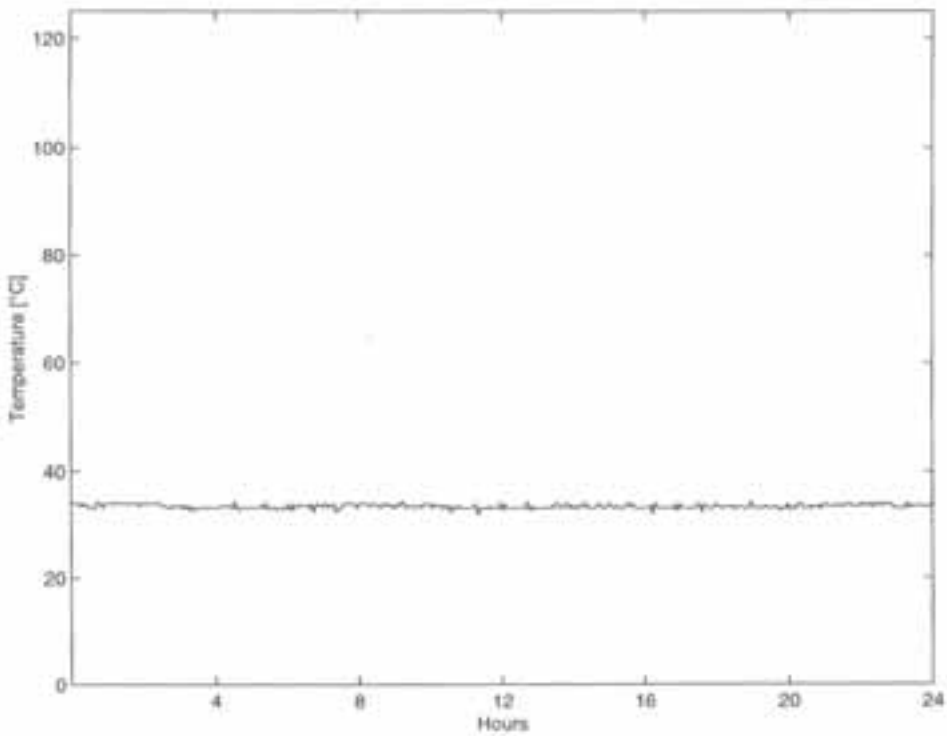

Difference between upper and lower side of the supply pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks


Difference between upper and lower side of the return pipe (top-underside)
Temperature [°C]
45
40
35
30
25
20
15
10
5
0
-5
5
10
20
30
40
52
Weeks

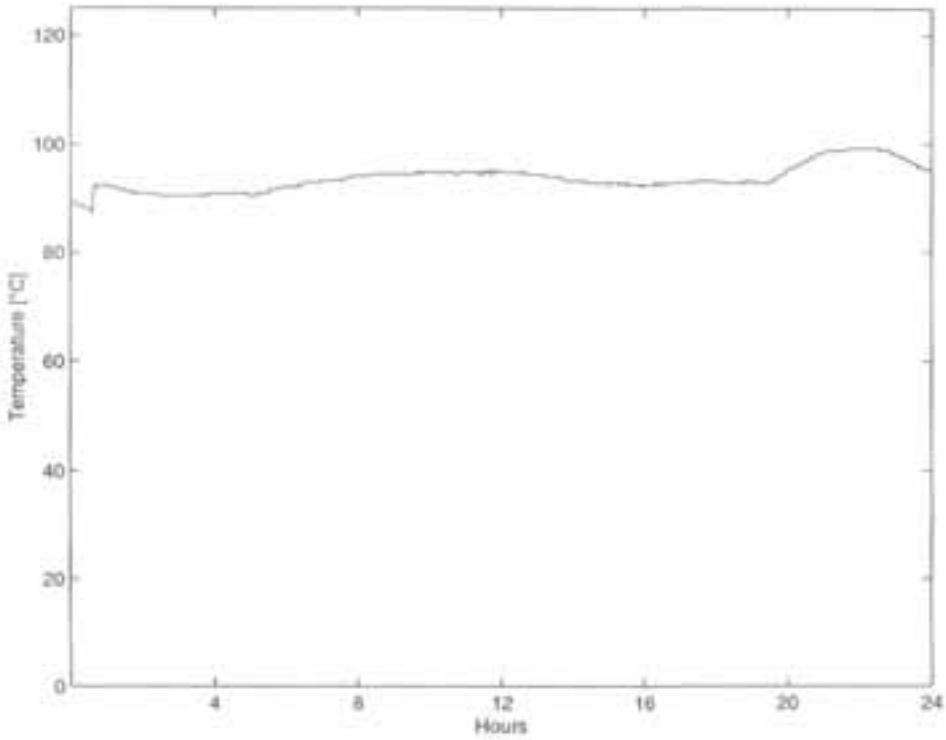
S21, Sunday 10/8-1997



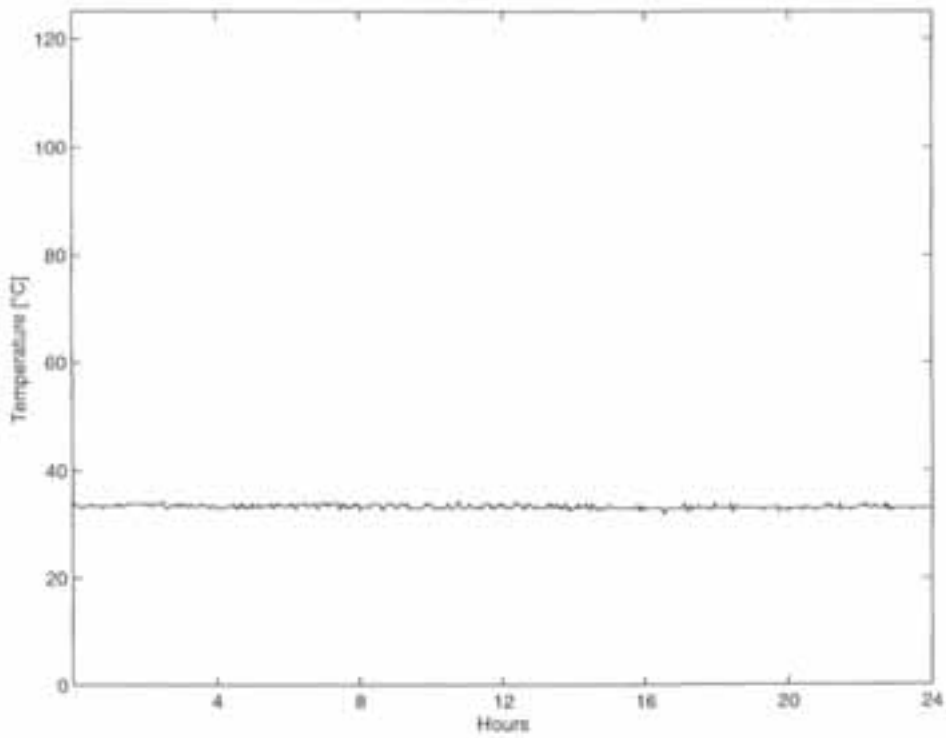
R21, Sunday 10/8-1997



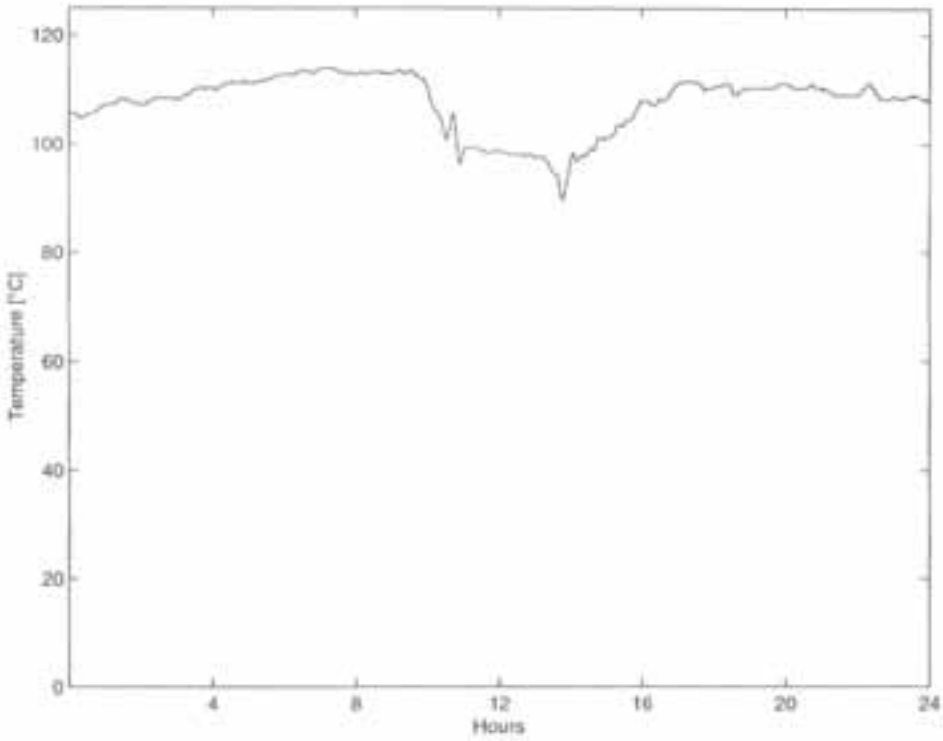
S21, Monday 11/8-1997



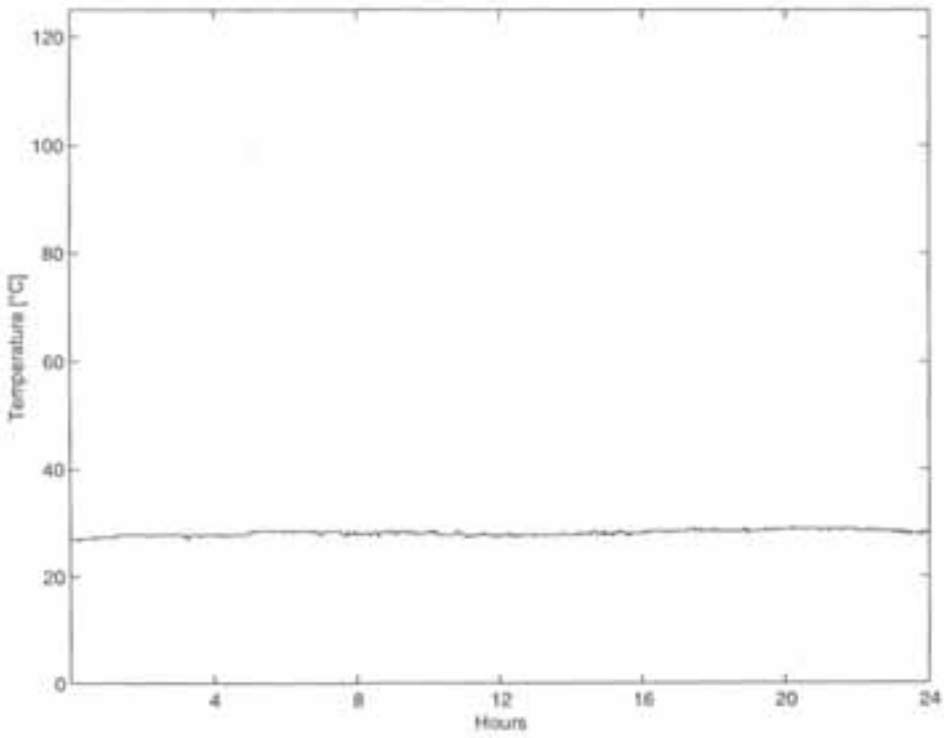
R21, Monday 11/8-1997



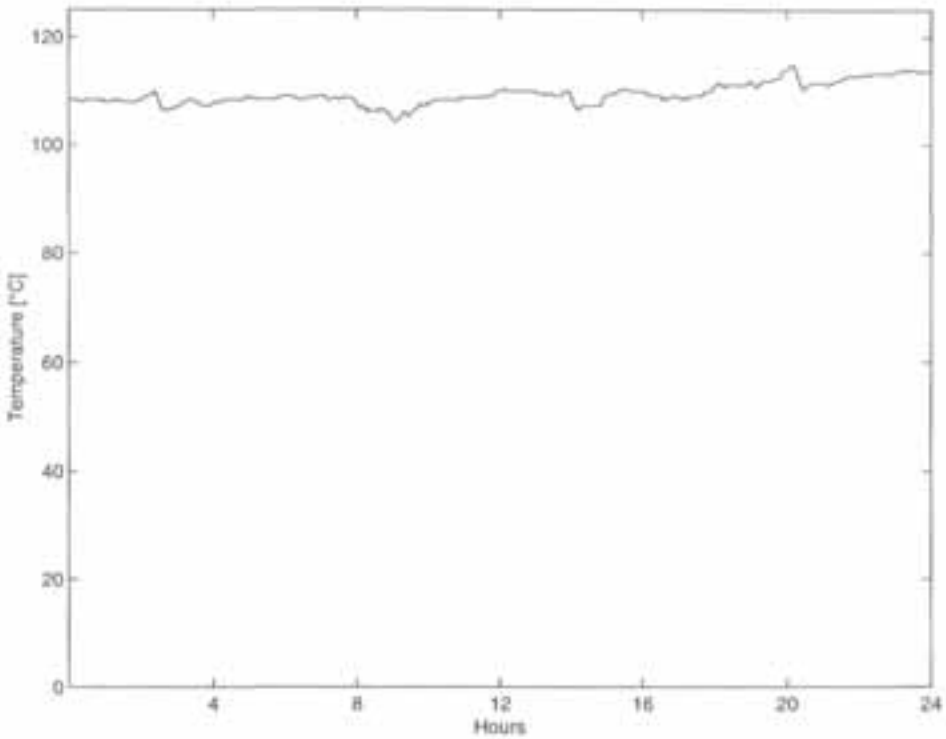
S21, Sunday 7/12-1997



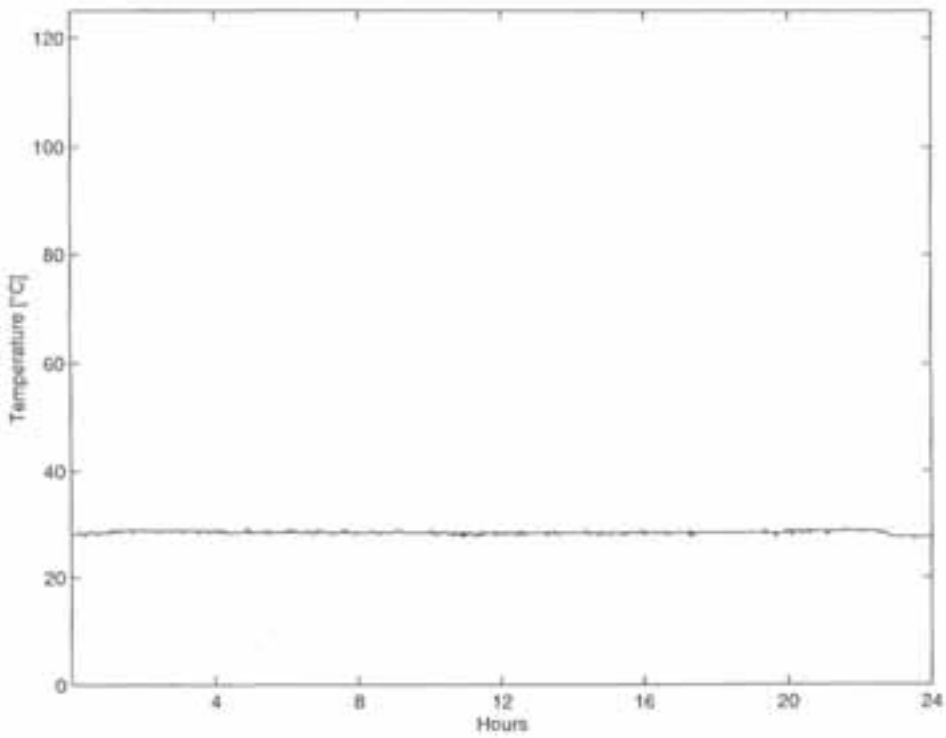
R21, Sunday 7/12-1997



S21, Monday 8/12-1997



R21, Monday 8/12-1997



Enclosure 5.1

Range **Measuring point**

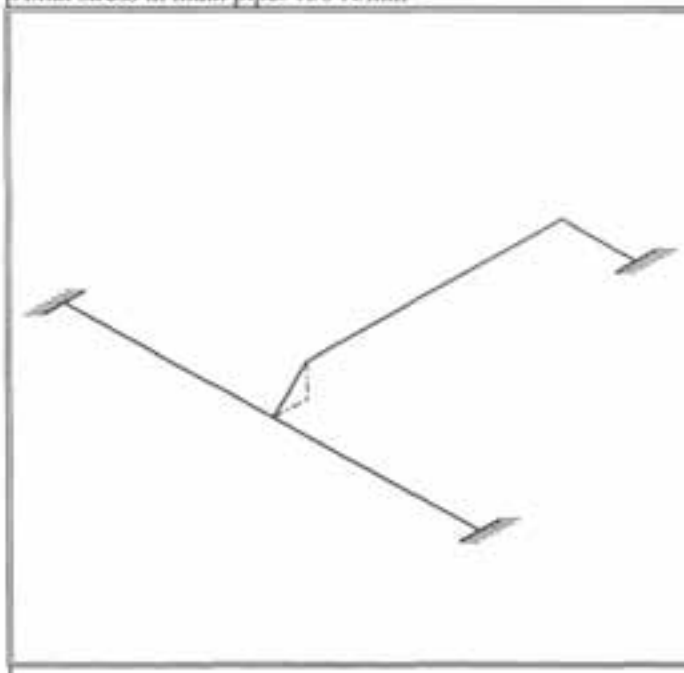
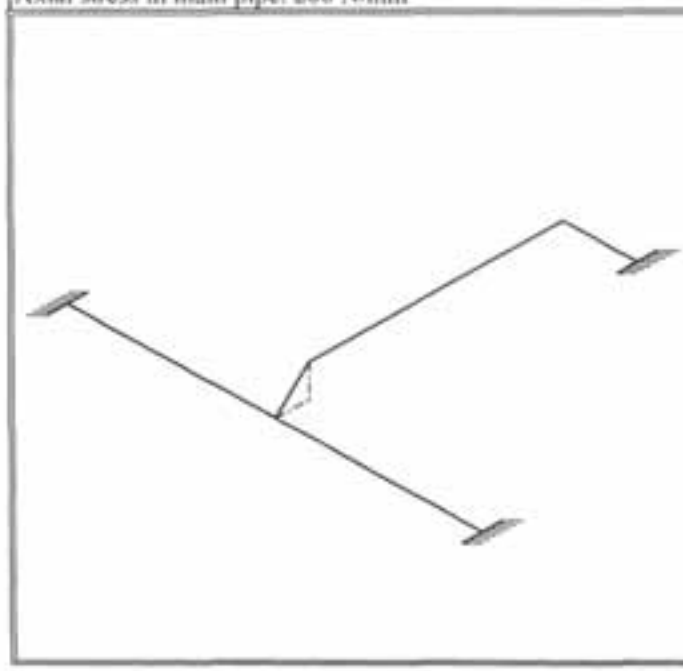
	S18	S18	R18	R18	S19	S19	R19	R19	S20	S20	R20	R20	S21	S21	R21	R21
	Top	Under	Top	Under	Top	Under	Top	Under	Top	Under	Top	Under	Top	Under	Top	Under
2	327230	339676	720950	732469	575749	531220	681212	680390	696582	601887	692595	704318	250771	338329	1120398	1207323
4	23038	22568	240821	247090	31380	31000	252778	236633	26043	26634	325245	324595	17980	19278	49572	52389
6	8091	8215	133103	137921	13349	12975	202735	208334	10600	10807	218119	218385	6363	6363	10794	10953
8	4385	4293	86316	89497	6042	7123	79019	96037	5197	5049	148966	148848	4210	4083	3166	3545
10	2718	2749	66397	68891	4808	5117	25526	31475	3041	3159	107391	105915	2532	2754	1519	1456
12	1235	1390	56947	57935	3964	3879	10312	12621	2096	1860	72136	73907	1298	1551	475	412
14	803	818	48547	48331	2088	2241	5884	5915	1417	1594	51643	52529	950	855	633	696
16	556	494	40487	41259	2024	2140	3258	3764	856	886	36525	38673	506	538	728	665
18	278	371	37244	37646	1803	1706	2088	2499	443	384	28966	29675	317	285	728	791
20	309	309	33878	33662	1076	1003	2024	1803	502	531	24065	23858	380	412	1203	1266
22	247	185	29246	29091	791	736	1329	1550	325	325	19754	19459	317	317	412	348
24	31	31	24860	24212	822	769	981	1012	443	354	16004	15502	190	190	348	380
26	154	154	21185	20753	854	869	696	664	236	295	15443	14705	127	190	158	158
28	93	93	16615	15626	506	502	1866	1803	236	236	10453	12844	127	32	95	95
30	31	31	12847	12322	506	535	1012	981	236	236	7913	9060	63	63	-	-
32	62	62	8647	9018	348	401	633	696	89	118	8533	8327	-	32	32	63
34	31	31	6701	6053	348	368	696	569	89	59	5965	7382	-	-	63	-
36	31	-	4632	4694	285	301	728	854	30	59	4547	5256	32	32	-	32
38	-	31	3057	2872	348	401	981	854	118	89	3159	4222	32	32	-	-
40	31	31	2162	2224	221	201	348	316	-	30	1860	2805	-	-	-	32
42	-	31	1668	1544	190	167	506	601	30	30	1860	1772	-	-	32	-
44	62	31	1019	803	158	167	285	190	-	-	1270	1388	-	-	-	-
46	-	-	371	309	127	134	411	474	30	-	827	1122	32	-	-	-
48	-	-	401	432	32	67	285	316	30	59	620	768	32	63	-	-
50	-	-	185	216	32	33	127	158	-	-	325	561	-	-	-	-
52	-	-	216	154	-	-	190	190	-	-	266	325	-	-	-	-
54	-	-	154	154	32	-	127	158	-	-	148	266	-	-	-	-
56	-	-	62	93	-	33	63	63	-	-	236	177	-	-	-	-
58	-	-	62	-	-	-	95	63	-	-	118	177	-	-	-	-
60	-	-	-	-	32	33	32	32	-	-	59	148	-	-	-	-
62	-	-	-	62	-	-	-	32	-	-	59	118	-	-	-	-
64	-	-	124	62	-	-	-	-	-	-	148	89	-	-	-	-
66	-	-	-	-	-	-	63	63	-	-	-	30	-	-	-	-
68	-	-	-	-	-	-	-	-	-	-	-	59	-	-	-	-
70	-	-	31	31	-	-	-	-	30	30	-	-	-	-	-	-
72	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
74	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
76	-	-	-	-	-	-	-	-	-	-	30	-	-	-	-	-
78	-	-	31	31	-	-	-	-	-	-	-	-	32	32	-	-
80	-	-	-	-	-	-	-	-	-	-	-	30	-	-	-	-
82	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
84	-	-	-	-	-	-	-	-	30	30	-	-	-	-	-	-
86	-	-	-	-	-	33	-	-	-	-	-	-	-	-	-	-
88	-	-	-	-	32	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
92	31	31	-	-	-	-	-	-	-	-	-	-	-	-	-	-
94	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
98	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
102	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
104	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
106	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
108	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
110	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
112	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
114	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
116	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
118	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

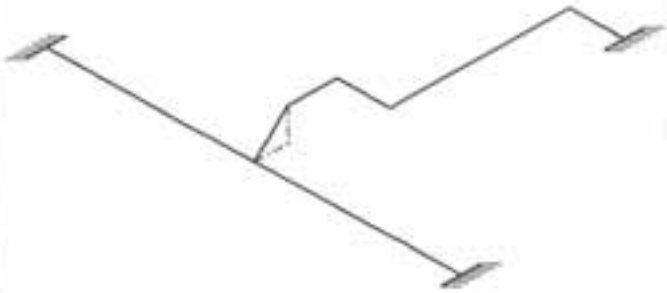
Enclosure 5.2

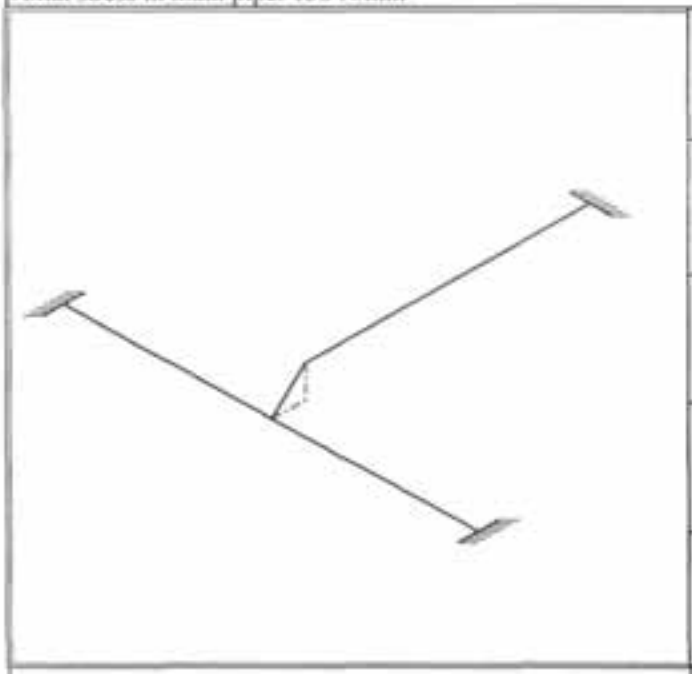
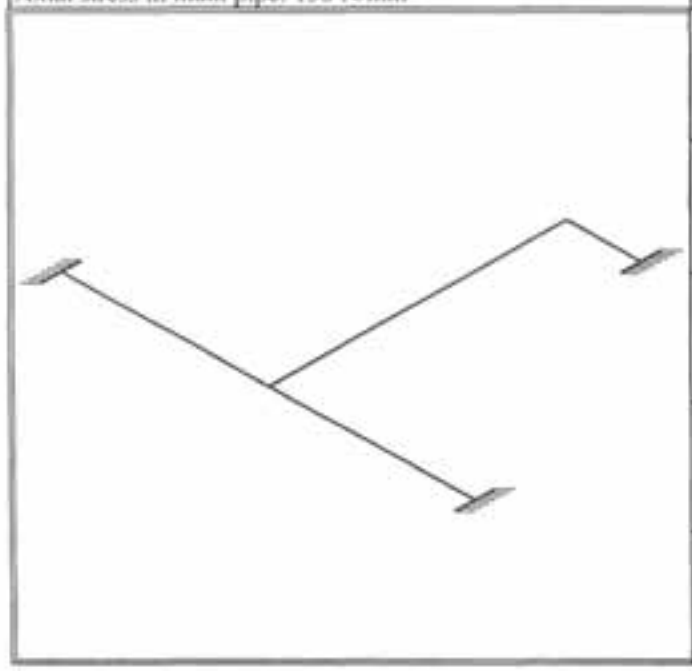
Location:	b	Measuring period days	Nr. of full cycles in 30 years DTref=110 °C
S18 Top	3,0	354,6	43,4
S18 Top	4,0	354,6	20,5
S18 Top	5,0	354,6	14,1
S18 Under	3,0	354,6	43,1
S18 Under	4,0	354,6	20,5
S18 Under	5,0	354,6	14,1
R18 Top	3,0	346,7	2952,9
R18 Top	4,0	346,7	747,2
R18 Top	5,0	346,7	216,8
R18 Under	3,0	354,6	2815,2
R18 Under	4,0	354,6	706,1
R18 Under	5,0	354,6	203,2
S19 Top	3,0	346,2	180,9
S19 Top	4,0	346,2	59,7
S19 Top	5,0	346,2	25,2
S19 Under	3,0	327,4	189,0
S19 Under	4,0	327,4	63,0
S19 Under	5,0	327,4	26,7
R19 Top	3,0	346,2	474,2
R19 Top	4,0	346,2	143,4
R19 Top	5,0	346,2	53,3
R19 Under	3,0	346,2	494,6
R19 Under	4,0	346,2	149,1
R19 Under	5,0	346,2	56,0
S20 Top	3,0	370,8	69,1
S20 Top	4,0	370,8	25,3
S20 Top	5,0	370,8	13,0
S20 Under	3,0	370,8	70,4
S20 Under	4,0	370,8	26,0
S20 Under	5,0	370,8	13,4
R20 Top	3,0	370,8	2564,3
R20 Top	4,0	370,8	678,2
R20 Top	5,0	370,8	212,2
R20 Under	3,0	370,8	2865,3
R20 Under	4,0	370,8	790,3
R20 Under	5,0	370,8	257,1
S21 Top	3,0	345,9	37,2
S21 Top	4,0	345,9	13,2
S21 Top	5,0	345,9	6,8
S21 Under	3,0	345,9	38,5
S21 Under	4,0	345,9	13,8
S21 Under	5,0	345,9	7,1
R21 Top	3,0	345,9	30,4
R21 Top	4,0	345,9	5,5
R21 Top	5,0	345,9	1,2
R21 Under	3,0	345,9	30,9
R21 Under	4,0	345,9	5,6
R21 Under	5,0	345,9	1,2

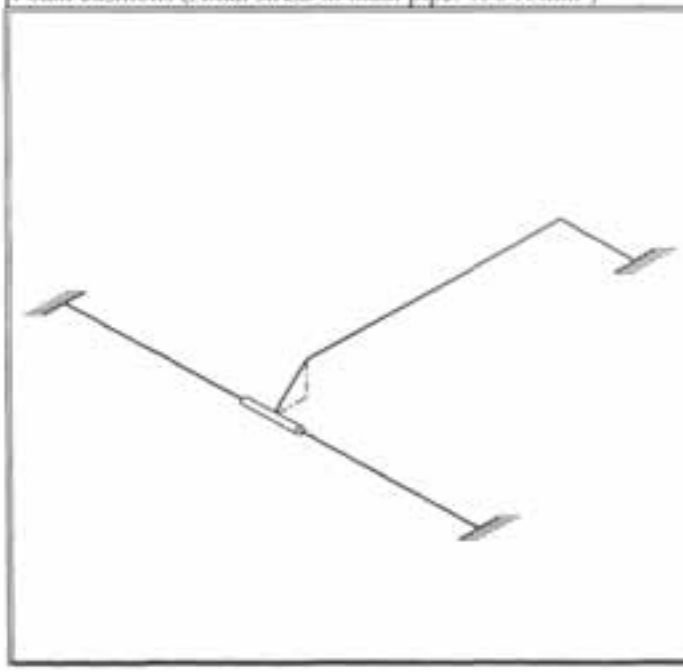
	Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C		
Normal wall thickness in bend	DN80	DN150	DN600
	**140**	**196**	**1961**
	-	-	-
	-	-	-
Increased wall thickness in bend			
	**925**	**710**	**3440**
	-	-	-
	-	-	-
With foam cushions (Normal wall thickness in bend)			
	**393**	**704**	**2755**
	-	-	-
	-	-	-

With concrete duct (Normal wall thickness in bend)	Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C		
	DN80	DN150	DN600
	**3956**	**3587**	**4534**
	L = 2 m.	**L = 3 m.**	**L = 6 m.**
	-	-	-

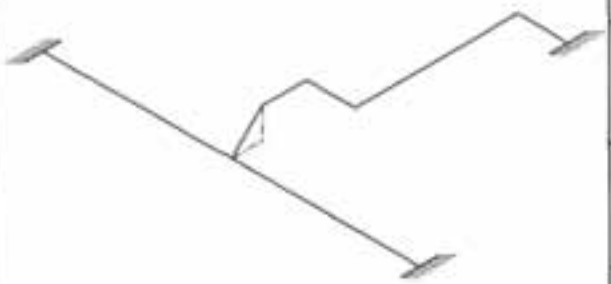
Axial stress in main pipe: 150 N/mm²		Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**165**	**58**	**88**	**23**
		**306**	**141**	**673**	**110**
		**14356**	**7469**	**5183**	**6782**
		**2832**	**1719**	**2394**	**3043**
		**646**	**392**	**529**	**674**
Axial stress in main pipe: 200 N/mm²					
		**122**	**43**	**55**	**15**
		-	-	-	-
		**9344**	**4992**	**2983**	**3939**
		-	-	-	-
		-	-	-	-

Axial stress in main pipe: 150 N/mm²		Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**3062**	**6510**	-	-
		6988	**24898**	-	-
		**154773**	**348926**	-	-
		-	-	-	-
		-	-	-	-
Axial stress in main pipe: 150 N/mm²					
		**58**	**10**	-	-
		-	-	-	-
		**6023**	**1776**	-	-
		-	-	-	-
		-	-	-	-

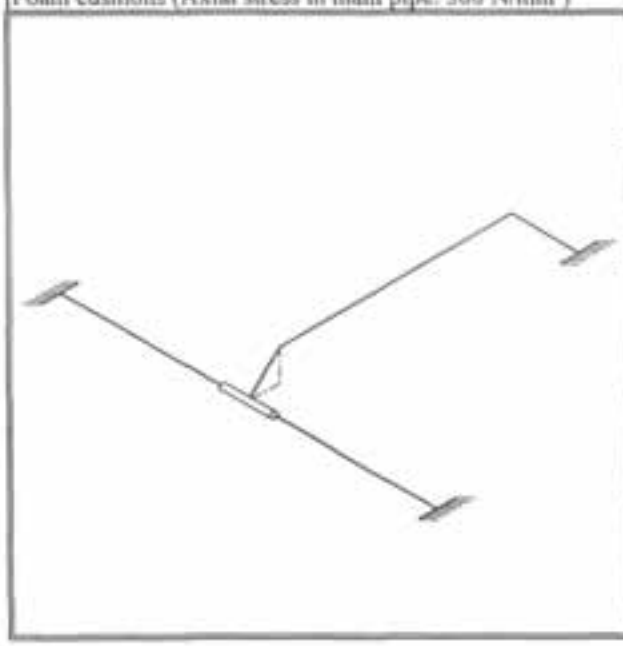
Axial stress in main pipe: 150 N/mm²		Number of load cycles to induce fatigue failure, ΔT_{mf}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**25**	**4**	-	-
		-	-	-	-
		**2718**	**688**	-	-
		-	-	-	-
		-	-	-	-
Axial stress in main pipe: 150 N/mm²					
		**1829**	-	-	-
		-	-	-	-
		**93267**	-	-	-
		-	-	-	-
		-	-	-	-

Foam cushions (Axial stress in main pipe: 150 N/mm²)		Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**309**	**52**	-	-
		-	-	-	-
		-	-	-	-
		-	-	-	-
		-	-	-	-

Axial stress in main pipe: 300 N/mm²		Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**75**	**25**	**25**	**7**
		**155**	**70**	**140**	**25**
		**4840**	**2560**	**1290**	**1650**
		**1200**	**720**	**640**	**800**
		**270**	**160**	**140**	**675**

Axial stress in main pipe: 300 N/mm²		Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**685**	**710**	-	-
		**1570**	**2560**	-	-
		**25700**	**32900**	-	-
		-	-	-	-
		-	-	-	-
Axial stress in main pipe: 300 N/mm²					
		**30**	**5**	-	-
		-	-	-	-
		**2460**	**830**	-	-
		-	-	-	-
		-	-	-	-

Axial stress in main pipe: 300 N/mm²		Number of load cycles to induce fatigue failure, ΔT_{nif}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**15**	**3**	-	-
		-	-	-	-
		**1285**	**370**	-	-
		-	-	-	-
		-	-	-	-
Axial stress in main pipe: 300 N/mm²					
		**480**	-	-	-
		-	-	-	-
		**18400**	-	-	-
		-	-	-	-
		-	-	-	-

Foam cushions (Axial stress in main pipe: 300 N/mm²)		Number of load cycles to induce fatigue failure, ΔT_{ref}=110°C			
		DN80/ DN20	DN200/ DN80	DN100/ DN100	DN450/ DN450
		**125**	**25**	-	-
		-	-	-	-
		-	-	-	-
		-	-	-	-
		-	-	-	-

IEA District Heating and Cooling

FATIGUE ANALYSIS OF DISTRICT HEATING SYSTEMS

Published by
Netherlands Agency for Energy and the Environment

Mailing address: P.O.Box 17, 6130 AA Sittard, the Netherlands
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1999: T4

ISBN-90-5748-007-7