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IEA DHC|CHP

International Energy Agency
IEA Implementing Agreement on District Heating and Cooling, including the integration of CHP

STRATEGIES TO MANAGE HEAT LOSSES - TECHNIQUE AND ECONOMY

International Energy Agency

Program of Research, Development and

Demonstration on District Heating

Strategies to Manage Heat Losses
- Technique and Economy -

by

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Preface and Acknowledgements

Introduction
The International Energy Agency (IEA) was established in 1974 in order to strengthen the co-operation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climate-destabilising carbon dioxide.

The IEA's *World Energy Outlook*[1] "Reference Scenario" 2004 projects that, in the absence of new government policies or accelerated deployment of new technologies, world primary energy demand will rise by 59% by 2030, with 85% of that increase from the use of coal, oil and natural gas. However, these trends are not unalterable. The *World Energy Outlook* "Alternative Policy Scenario" shows that more vigorous government action and accelerated deployment of new technologies could steer the world onto a markedly different energy path, where world energy demand would be 10% lower and carbon-dioxide emissions 16% lower.

DHC makes a difference
One of the key technologies that can make a difference is District Heating and Cooling.
DHC is an integrative technology that **can** make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.

The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating **and** cooling.
The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling carbon-intensive electrically-based airconditioning, rapidly growing in many countries, can be displaced.

As an element of the International Energy Agency Programme, the participating countries undertake co-operative actions in energy research, development and demonstration.

One of the programmes that has run for more than 25 years is the Implementing Agreement 'District Heating and Cooling including the integration of Combined Heat and Power'.

Annex VII
In May 2002 Annex VII started.

Following is a list of the recent research projects (annexes) undertaken by the District Heating & Cooling Implementing Agreement. Ten countries participated from Europe, North America and Asia: Canada, Denmark, Finland, Germany, Korea, The Netherlands, Norway, Sweden, United Kingdom, United States.

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[1] The annual *World Energy Outlook* presents long-term projections for supply and demand of oil, gas, coal, renewable energy sources, nuclear power and electricity. It also assesses energy-related carbon dioxide emissions and policies designed to reduce them. The annual World Energy Outlook has long been recognized as the authoritative source for global long-term energy market analysis. This flagship publication from the IEA is produced by the agency's Economic Analysis Division with input from other internal and external energy experts as required. For more information see http://www.worldenergyoutlook.org/.

Project title	**Company**	
A comparison of distributed CHP/DH with large-scale CHP/DH	**Parsons Brinckerhoff Ltd** Formerly PB Power Ltd – Energy **Project leader:** **Paul Woods**	8DHC-05.01
Two-step decision and optimisation model for centralised or decentralised thermal storage in DH&C	SP Swedish National Testing and Research Institute **Project Leader:** **John Rune Nielsen**	8DHC-05.02
Improvement of operational temperature differences in district heating systems	ZW Energiteknik **Project leader:** **Heimo Zinko**	8DHC-05.03
How Cellular gases influence insulation properties of district heating pipes and the competitiveness of district energy	Danish Technological Institute **Project leader:** **Henning D. Smidt**	8DHC-05.04
Biofouling and microbiologically influenced corrosion in district heating networks	Danish Technological Institute **Project Leader:** **Bo Højris Olesen**	8DHC-05.05
Dynamic Heat Storage Optimization and Demand Side Management	Fraunhofer Institut Umwelt Sicherheit Energietechnik Umsicht **Projectleader:** **Michael Wigbels**	8DHC-05.06
Strategies to manage Heat Losses – Technique and Economy	MVV Energie AG Technology and Innovationsmanagement **Project leader:** **Frieder Schmitt**	8DHC-05.07

Benefits of membership
Membership of this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

- DHC is already a mature industry
- DHC is well established but refurbishment is a key issue
- DHC is not well established.

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organisations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include the cross-fertilisation of ideas which has resulted not only in shared knowledge but also opportunities for further collaboration.

New member countries are very welcome – please simply contact us (see below) to discuss.

Information
General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website www.iea-dhc.org or from:

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The work on this task has been monitored by the IEA-Experts Group "Heat losses of DH-networks" with Dr.-Ing. Frieder Schmitt from MVV Energie AG, Mannheim, Germany as project leader and chairman of the Experts Group.

The members of the Experts Group have been:

- Sten Tore Bakken, Norway
- Ture Nordenswan, Sweden
- Velli-Pekka Sirola, Finland
- Mogens H. Nielsen, Denmark
- Paul Ramsak, The Netherlands
- Neville Martin, United Kingdom
- Manfred Klöpsch, Germany
- Heinz-Werner Hoffmann, Germany

The chairman wants to thank everybody who has contributed and made it possible to carry through this work – especially every individual of the Experts Group for making a good effort and showing a positive will to cooperate.

Summary

Heating utilities should review their concepts for insulating their district-heating lines at regular intervals. Not only should the volume of investment costs be taken into consideration, but also the expected operating expenditures need to be included when conducting required cost-efficiency analyses. After all, heat losses and thus the selected insulation concept substantially influence accruing operating costs. When calculating operating expenditures, heating utilities should regularly review whether the general technical and/or economic setting has/have changed compared to the last computation process. Redetermining them on a five-year basis should be deemed sufficient.

Detailed cost-efficiency calculations should be made in consideration of the deteriorating insulation quality of the pipelines as a result of the ageing PUR foam. If such ageing process is not taken into account, the actual heat losses may be underestimated by up to 20%. Excellent insulation qualities stand for the distinguishing feature of twin pipes being a special range of preinsulated plastic jacket pipelines. By contrast, the method of laying preinsulated plastic jacket pipelines on top of one another does not have a substantial impact on the occurrence of heat losses.

Most heat losses occur on pipes of small nominal diameters. Even though Insulation Series 1 is today still considered the standard series – in particular in Germany –, there are very well application cases in which insulation of a higher quality proves to be more cost-efficient. Higher-quality insulation is recommended for projects marked by low-cost pipeline construction, in case of high heating costs, and a high temperature difference between the medium and its surroundings. The related marginal costs were calculated for typical application cases to determine when a higher or lower insulation series will lead to cost benefits. As a minor deviation from the calculated optimal insulation costs only results in relatively low additional costs, it is recommended to change over to the next higher insulation series prior to reaching the relevant level of marginal costs, since it is expected that heating costs will rise in the future due to an ever-increasing shortage of resources. For instance, changing over to the next higher insulation series may be implemented when the relevant marginal costs are underrun by approx. 10% to 20%.

Apart from upgrading the insulation series, the application of enhanced insulation materials marked by lower heat conductivity may help improve insulation efficiency. However, when opting for this approach, it is indispensable that the saved heat loss costs exceed the higher material expenditures.

The closing discussion focuses on how heat suppliers normally deal with heat losses. For the purpose of assessing the state of their own grids, heating utilities are recommended to regularly compare themselves with other district-heating networks on the basis of benchmarks. To provide for – to the extent possible – realistic comparisons of district-heating grids on the basis of statistical data or benchmarks from other enterprises, further ratios, i.e. not just the usual loss factor, which reflect the supply setting as comprehensive as possible should be taken into account, as well. The last chapter revolves around outlining and evaluating measures aiming at reducing heat losses occurring within installed district-heating networks.

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1 General

The heat losses occurring on pipelines determine the operating costs for distributing district-heating services. Although heat losses cannot be prevented, it is yet possible to substantially influence them by applying – more or less costly – heat insulation options. The economic weight inherent in this interrelationship may be clarified by an example: The reduction of annual heat losses occurring within a large-scale district-heating network from 12% down to 11% would result in cost savings of approx. € 200,000 p.a. (Mannheim).

The high complexity of heat loss-related problems becomes apparent when facing the installation of a new heat supply grid or when extending (i.e. increasing the density of) an existing network. In case of new grids, the interrelationships can be recognized easily, as the applied technology is based upon preinsulated plastic jacket pipelines; moreover, the financial setting can be clearly specified, as well.
By contrast, the analysis of existing district-heating networks stands for a task which is substantially more complex. Over long distances, such grids hold pipelines which do no longer meet modern requirements in terms of heat insulation. Additionally, old pipelines were insulated in keeping with economic standards (energy prices, cost of capital) which have undergone radical changes in the meantime. Against that backdrop, old heat insulation methods – even if they are still in a technically perfect state – do often no longer comply with modern requirements.
When extending or increasing the density of existing district-heating grids, an optimized heat insulation concept becomes all the more decisive, the greater the length of the district-heating projected for extension.

In keeping with the economic significance of heat losses, a heating utility should regularly and at particular intervals review the technical and economic setting which forms the basis for calculating the cost-efficiency of the heat insulation concept applied in its day-to-day operation. The results so obtained need to be integrated into the construction of new pipelines.

The present report addresses planning engineers responsible for the insulation concepts of district-heating networks. Both real-life experience collected from implemented insulation projects and international benchmarks are placed at their disposal to enable them to perform their complex tasks. This report is subdivided in three parts each revolving around a specific aspect related to heat losses:

Part A focuses on the calculation of heat losses of various types of preinsulated plastic jacket pipelines. The results take into consideration the increase of heat losses due to ageing in relation to the average useful life.

Part B concentrates on the economic optimization of heat insulation. The total insulation costs are evaluated in consideration of the installation costs on the basis of dynamic cost-efficiency analyses. With the aid of model calculations, various technical insulation concepts are developed by taking into account changing economic settings.

Part C revolves around the practical problems of heat supply services. First, the differences between the (idealized) physical processing and real-life application are outlined. Then, problems inherent in benchmarks are dealt with to finally summarize the obtained results in form of recommendations. Additionally, possibilities for reducing heat losses are explained, as well.

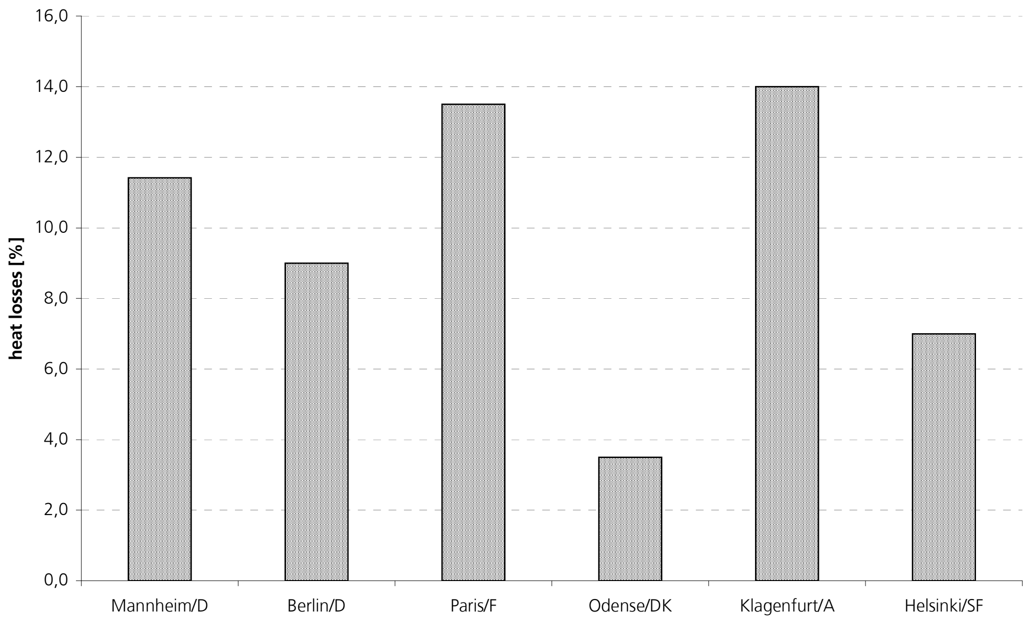
The structure of each of the above-mentioned three parts contains a final section summarizing the prime results obtained. This structuring should help readers to speedily select the sections they are most interested in.

2 Introduction

In general, network losses are defined as the difference between the heat fed into the network and the transfer of useful heat (sold heat quantity). For comparison purposes, network losses are related to the heat fed into the network, and expressed in percent (heat loss coefficient). Usually, network losses range between 6% and 17% [12].

Even though it holds various inaccuracies, that definition – thanks to its simple calculatory basis – is widely accepted, today. For instance, water losses, which in the majority of cases are eventually heat losses, are not taken into account, etc. Therefore, in some places, the percentage defined above is also called 'thermal distribution efficiency' (e.g. in Finland).

Fig. 2-1: Heat losses of European district-heating networks

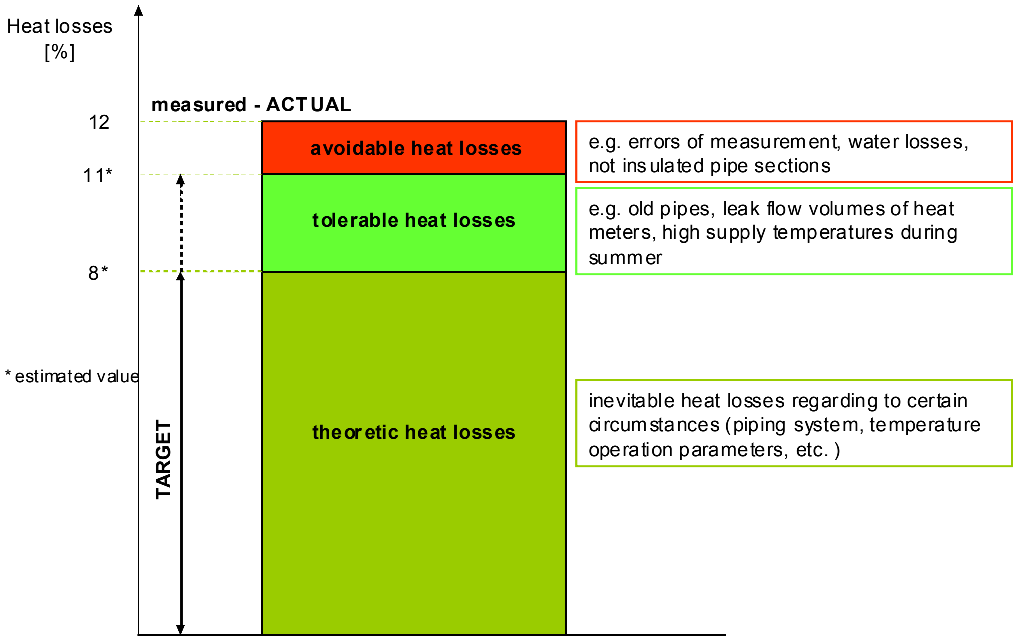


Associations of the district-heating industry publish heat losses in their statistics. Figure 2-1 depicts an international comparison of six major European cities.
Unfortunately, it is not possible to simply compare the heat losses of various companies with each other, as the definition does not take into consideration major impacts, in particular

- the structure of the grid (heat density of the service area),
- the operating temperatures, and
- the load utilization period.

What does the situation of an operator of a district-heating system look like who strives for eliminating all avoidable losses occurring within his network? He can avail himself of the actual heat losses in form of the results obtained within the framework of heat measurements. He can now compare these values in two ways: Either with the results established on the basis of detailed engineering inspections of the system (preferably heat loss calculations) or with the figures of other enterprises (statistics), also see Figure 2-2. The comparative values, which are designated 'theoretic heat losses' in Figure 2-2, stand, so to speak, for the optimal heat losses of the grid.

Fig. 2-2: Diagram for the determination of avoidable heat losses



Generally speaking, the optimal heat losses cannot be realized, as e.g. grids are composed of outdated sections showing suboptimal insulation, because of operating temperatures reaching suboptimal levels at times etc. These factors reflect the heat losses indicated in Figure 2-2 which the operator is compelled to tolerate.

Reducing the heat losses measured within the system by the ‘theoretic heat losses’ and the ‘tolerable heat losses’ results in such heat losses which should be reduced by means of specific measures.

Part A, the ensuing section of the present report, describes the heat loss calculations for currently accepted technologies applied for laying preinsulated pipes. These methods account for approx. 90% of the construction volume of district-heating pipelines. The results of these calculations are made available in form of diagrams. Additionally, all contributing factors for the calculations and the formulas are explained, so that interested readers are given the opportunity to recompute all calculations themselves.

The model cases forming the basis for the relevant cost-efficiency calculations were specified so as to cover the general supply setting which is usually met today. This way, readers can transfer the statements of the present report to their individual network situation to accuracy sufficient for strategic analysis without conducting in-depth calculations.

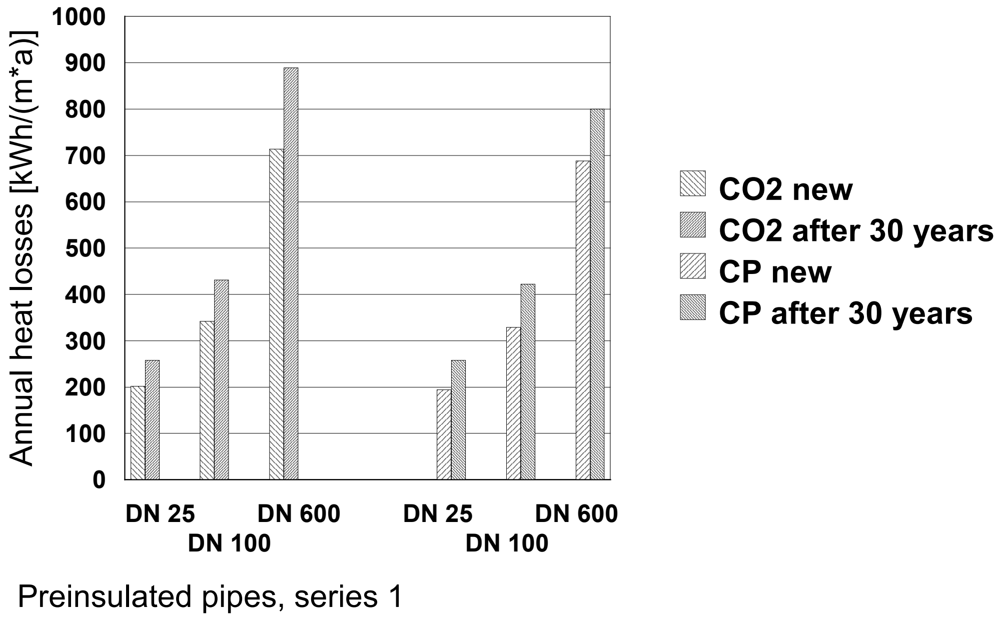
Part A: Heat losses of District-Heating Pipelines (Physical Calculation)

3 Heat losses of Preinsulated Plastic Jacket Pipelines

Already the calculation of heat losses on new district-heating pipelines stands for a complex problem which may only be resolved, if certain simplifications are made. For instance, the impact of the insulating effect of the surrounding soil can only be specified in an approximate fashion; moreover, the operating temperatures, too, which are marked by interaction with the climatic conditions, can be taken into consideration only in form of mean values.

Another complex factor results from the ageing process of the pipelines. Due to diffusion processes penetrating the plastic walls, the composition of the cell gas contained in the PUR foam changes in the course of the pipe's average useful life. The propellant cyclopentane (CP) or CO_2 escapes and is replaced by air. In consequence, the heat conductivity of the foam increases and thus also the heat loss of the pipelines, see Figure 3-1.

Fig. 3-1: Annual heat losses of new district-heating pipelines compared to district-heating pipelines of a average useful life of 30 years



While, in the past, the optimization of insulation systems was calculated only on the basis of constant insulation properties, engineers can today avail themselves of calculation procedures taking into account the ageing behavior of the foam. The present report provides for an in-depth analysis of the increase in heat conductivity of the foam over the years and takes this development into detailed consideration within the context of optimization efforts (Section 3.2).

3.1 Heat Losses of New Preinsulated Plastic Jacket Pipelines

Various formulas applied to calculate heat losses of buried district-heating pipes may be found in many publications. The present report bases its calculations on the algorithms established by Jarfelt [1], see Appendix 3.

The calculation takes into account a variety of parameters which may be summarized and subdivided into the categories to follow:

- heat conductivity of the insulation,
- operating data of the district-heating system and climatic data,
- properties of the soil,
- geometric data, and
- pipe arrangement.

Further special influences, e.g. laying method and type of residential area, are dealt with in Sections 3.3 and 4.3.

These impacts are listed in Table 3-1 and discussed separately in the sections to follow.

Table 3-1: Major factors influencing heat losses

	Category	Parameter	Impact on heat losses
1	Insulating material	Heat conductivity	high
2	Operating data, climate	Supply pipe temperature Return pipe temperature Ambient air temperature Climate and/or utilization period of temperature (supply pipe, return pipe)	high high high high
3	Soil	Heat conductivity (water content)	high
4	Geometry	Pipe geometry: Diameter, thickness of insulation layer Pipeline geometry: Laying depth, pipe distance	high low
5	Pipe arrangement	Twin pipes Pipes on top of one another	high low

3.1.1 Heat Conductivity of PUR Foam

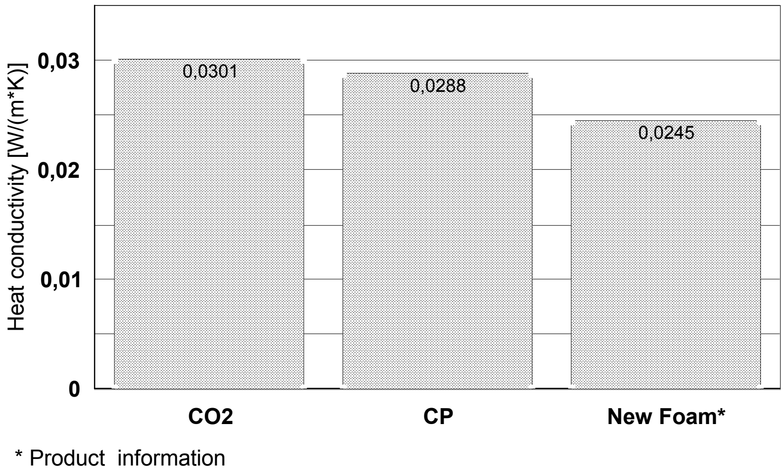
Preinsulated plastic jacket pipelines are supplied in keeping with standard EN 253 and composed of polyurethane (PUR) foam of a heat conductivity value of

$$\lambda_{CP} = 0.0288 \text{ W/(m·K)}$$ with propellant cyclopentane (CP), or

$$\lambda_{CO2} = 0.0301 \text{ W/(m·K)}$$ with propellant CO_2.

Today, heating utilities mostly order pipe material which was manufactured in combination with CP as propellant and which offers better insulation properties. Increasingly, especially fine-pored foams which have been developed over the preceding years and offer a substantially better conductivity than conventional CP foams have been entering the market. Figure 3-2 depicts the conductivity of new conventional PUR foams.

Fig.3- 2: Heat conductivity of conventional PUR foams



Depending on the relevant source, the data on the heat conductivity of the foams differ from each other substantially. Not only are there deviations between the data released by the relevant manufacturers and the data established by testing institutes, but also between the data published by various testing institutes. Within the framework of the present report, the values as specified by Jarfelt, Chalmers University of Göteborg, will be used for conventional foams containing CP, CO_2 as well as CFC 11 as propellants (until about 1990, preinsulated plastic jacket pipelines were foamed in combination with CFC 11 exclusively), see Appendix 1. These data have been proved in the course of practical testing. As regards the new fine-pored foam, the data published by the manufacturer Star Pipe are taken into consideration. Values established over long testing periods and, in particular, taking into account the ageing process are not yet available for this type of foam. (These heat conductivity values are consistent with the calculations set forth in Appendices 1 and 2.)

3.1.2 Operating Temperatures and Utilization Period

On the one hand, the level of heat losses is defined by the operating temperatures of the district-heating system and the temperature of the ambient air. On the other hand, when assessing annual losses, the duration over which these temperatures are maintained plays a major part (utilization period). Both impacts may be considered in form of a combined factor here.

Operating temperatures: Heat losses crop up due to the circumstance that heat flows from the supply and return pipes to the cold ambient air. Primarily the individual resistance of the heat insulation and the surrounding soil try to prevent this heat flow. (At the same time, there is also a heat transfer from the supply to the return pipeline, see calculation model in Appendix 1.) These heat losses increase, the greater the supply and return pipe temperature and the lower the ambient temperature. The calculation model applied here uses the discrepancy between the arithmetic mean of the supply and return pipe temperature and the ambient temperature as driving temperature difference, hence

$$\Delta T = (T_1 + T_2) / 2 - T_0$$

with

T_1 = supply pipe temperature [°C]
T_2 = return pipe temperature [°C]
T_0 = ambient air temperature [°C]

According to the law of heat transfer, the heat loss flow is *proportional to the driving temperature difference.*

Utilization period: The climatic fluctuations of the surroundings are compensated by adjusting the operating temperatures (and the mass flow which may be neglected here), i.e. in case of longer-lasting cold periods, it is necessary to maintain increased operating temperatures for longer terms, variable operation mode provided. Consequently, the energy loss increases *proportional to the period of time*.

For the cost-efficiency analysis, heat losses are taken into consideration on a one-year basis. Now, the computation of a time-weighed mean value composed of supply pipe, return pipe and ambient temperature leads – for physical reasons – to the conclusion that the energy loss of a district-heating network has to be proportional to the driving temperature difference calculated on the basis of these mean values.

$$Q_{N,a} \sim \Delta T_m$$

$Q_{N,a}$ = annual quantity of heat loss occurring within a network [MWh/a]
$\Delta T_m = (T_{1m} + T_{2m}) / 2 - T_{0m}$ [K]

As to the computation of heat losses, this interrelation offers the great advantage that heat loss calculations need to be made only for a single parameter, namely the *annual mean driving temperature difference* ΔT_m, and not for several separate parameters (operating temperatures and climate).

The parameter ΔT_m may be of valuable help when it comes down to interpreting statistical data. It should be referred to whenever heat losses should be compared between networks which are operated at differing operating temperatures. This parameter should also be considered whenever heat losses of networks located in different climatic zones should be analyzed in relation with each other. The following concrete example should help explain how to use the parameter ΔT_m:

For the parameter-based heat loss calculations of the present report a standard case is assumed which defines a mean supply pipe temperature of 92.1°C, a mean return pipe temperature of 55.5°C and a mean ambient temperature of 10°C. This calculation basis results in a ΔT_m value of 63.8 K (Mannheim, Germany).

As to Denmark, Finland and Sweden, the ΔT_m values are calculated on the basis of available data [3, 4, 5]. Table 3-2 depicts the annual mean temperatures collected from the available documentation and lists the relevant calculated value for ΔT_m.

Table 3-2: Annual mean temperatures in four countries

No.	Country	Annual mean temperature [°C]			ΔT_m [K]	Documentation
		Supply pipe	Return pipe	Ambient air		
1	Denmark	78	41.6	8	51.8	[10]
2	Germany	89.1	55.5	10	62.3	[4]
3	Finland	87.5	55	5	66.3	[7]
4	Sweden	85	48	5	61.5	[9]
5	Mannheim (mean value)	92.1	55.5	10	63.8	

In keeping with the above statement, that heat losses have to be proportional to the parameter ΔT_m, Table 2 suggests the conclusion that an identical district-heating system, which records an annual heat loss of 100 MW in Germany, has to face heat losses in the amount of 100 · 61.5/63.8 = 96.4 MW due to the lower operating temperatures in Sweden and the less favorable North European climate.

If the lowest value of ΔT_m is considered to be equal to 100% for Denmark, the highest value for Finland totals 128% etc. Figure 3-3 shows the values of ΔT_m in relation to the value calculated for Denmark. Hence, the conclusion to follow may be drawn from this diagram: An identical district-heating network which is operated under standard German conditions instead of Danish conditions (i.e. operating parameters and climatic conditions typical of Denmark) shows higher heat losses than in Denmark (+ 20.3%). As to the other countries indicated above, relevant relations apply.

Fig. 3-3: Influence of operating temperatures and climatic conditions on the volume of heat losses

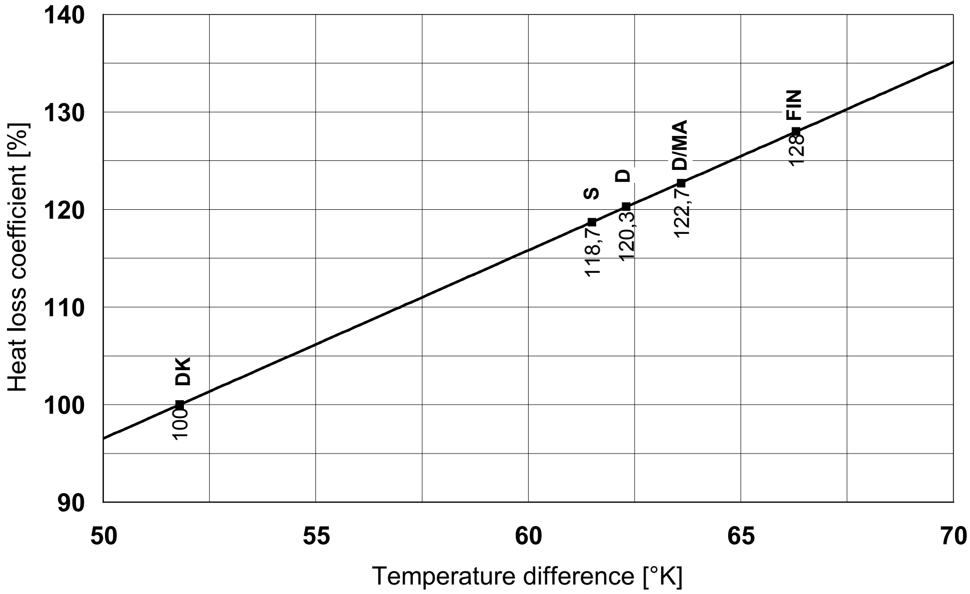
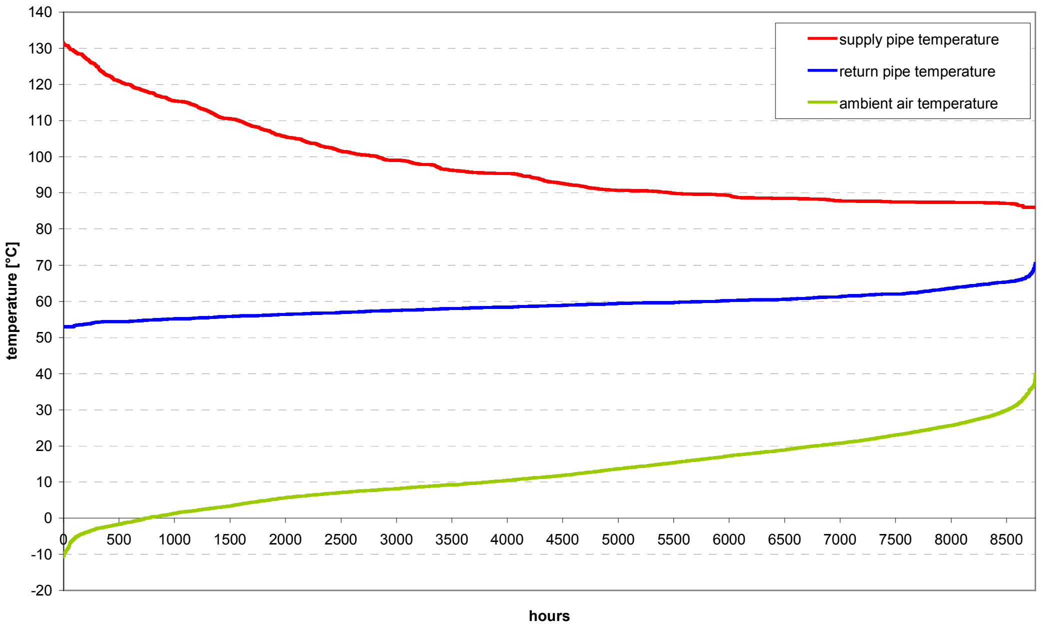


Figure 3-3 depicts an additional entry for Germany (city of Mannheim) which represents a mean value established over several years.

As may be gathered from Figure 3-4, substantial deviations may occur in a specific year. The diagram displays the hourly values of the temperatures recorded during the 2002/2003 heating period. These values form the basis for calculating a mean supply temperature of 97.7°C and a mean return temperature of 58.9°C. The inclusion of an ambient temperature of 10°C leads to a ΔT_m value of 65.8 K. In that heating period, ΔT_m exceeded the annual mean value by 2 K (being equal to an increase of 3.1%).

Fig. 3-4: District-heating supply and return pipe temperatures as well as ambient air temperature in the 2002/2003 Mannheim heating period



3.1.3 Heat Conductivity of Soil

In the end, the energy loss occurring on district-heating pipes is released into the atmosphere via the soil. Within the transmission chain, the covering soil and its heat transfer resistance contribute to the pipe's heat insulation. Depending on the relevant situation, the soil's contribution to the overall heat insulation effect may range between approx. 5% and 35%. In this context, the heat conductivity coefficient of the soil plays the major part.

The heat conductivity coefficient of soil may range between

0.5 W/(m·K) = dry sand and
2.5 W/(m·K) = wet clay soil.

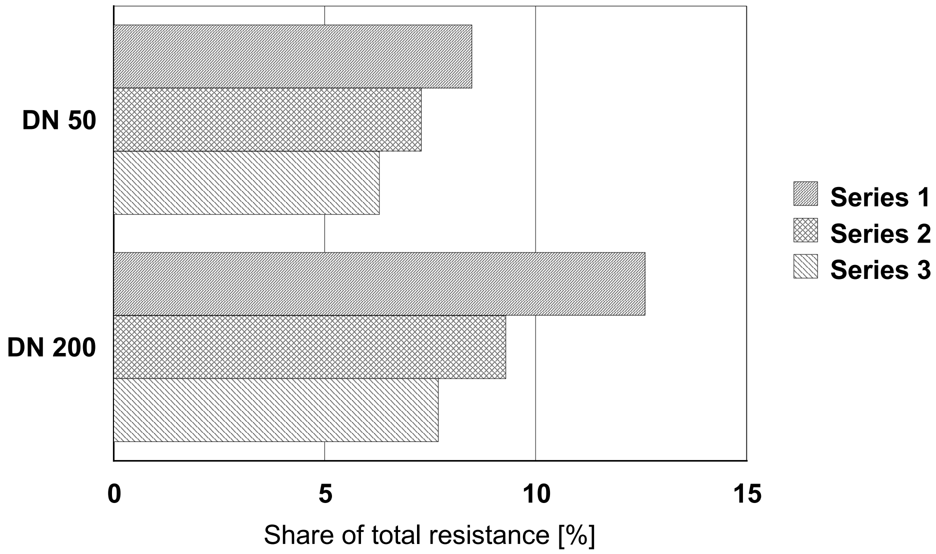
A mean value usually applied to calculate the heat conductivity coefficient of sand-bedded pipes is equal to 1.5 W/(m·K).

District-heating pipes are installed within both traffic areas and green spaces. From the point of view of thermal engineering and within the framework of the accuracy possible for the calculations made here, there is only a slight difference between these installation cases (see Appendix 2). Hence, it is not necessary to make a distinction between these two cases when conducting calculations here.

The total resistance of heat transfer is mainly composed of the resistance of the insulation and the resistance of the soil; compared to these two factors, the remaining resistance components are of no practical significance. So, how is the total resistance split between the factors heat insulation and soil?

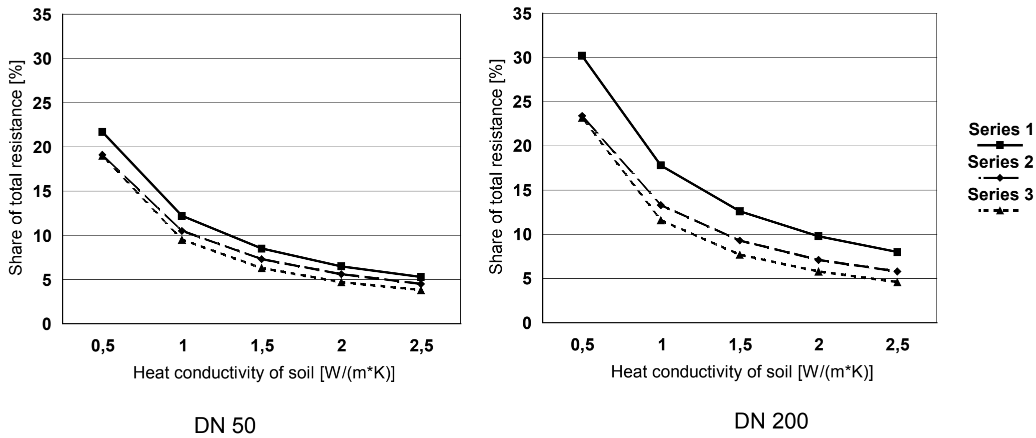
The PUR foam always offers the greatest share in the overall insulation effect. The share the soil contributes is on small-sized pipelines smaller than on large-scale pipes. Figure 3-5 depicts the insulation share of the soil in case of a small-scale DN 50 pipe and a large-sized DN 200 pipe. For a tube of a nominal diameter of 50 and Insulation Series 1, the soil's contribution rate totals 8.5%; for a pipe of a nominal diameter of 200, it is equal to approx. 12.5%. On pipes of Insulation Series 2 and 3 which offer improved insulation, the share is smaller, see Figure 3-5. (For larger-scale pipelines between DN 150 and DN 600, the share is approximately the same; it only starts increasing on greater diameters.)

Fig. 3-5: Share of soil in total insulation effect (coverage H = 0.8 m; λ_E = 1.5 W/(m·K))



When varying the heat conductivity within the possible range, i.e. between 0.5 and 2.5 W/(m·K), it is possible to recognize the influence the resistance of the soil can exert. Figure 3-6 shows for a small-sized DN 50 pipe and a large-scale DN 200 pipe the shares of the soil's resistance in relation to the total resistance. For instance, the left diagram, standing for DN 50 pipes of Insulation Series 1, shows that in case of normal soil conditions (with λ_E = 1.5 W/(m·K)) the soil accounts for a share of 8% in the heat insulation of the pipeline. In the event of very wet clay soil, this share decreases down to a maximum of 5%. By contrast, in very dry sand (with λ_E = 0.5 W/(m·K)) the share may increase up to more than 20%. The diagram on the right displays the calculations for a DN 200 pipe; however, the depicted relations only apply to the pipe range between DN 150 and DN 600.

Fig. 3-6: Influence of the soil's heat conductivity on insulation effect (coverage H = 0.8 m)



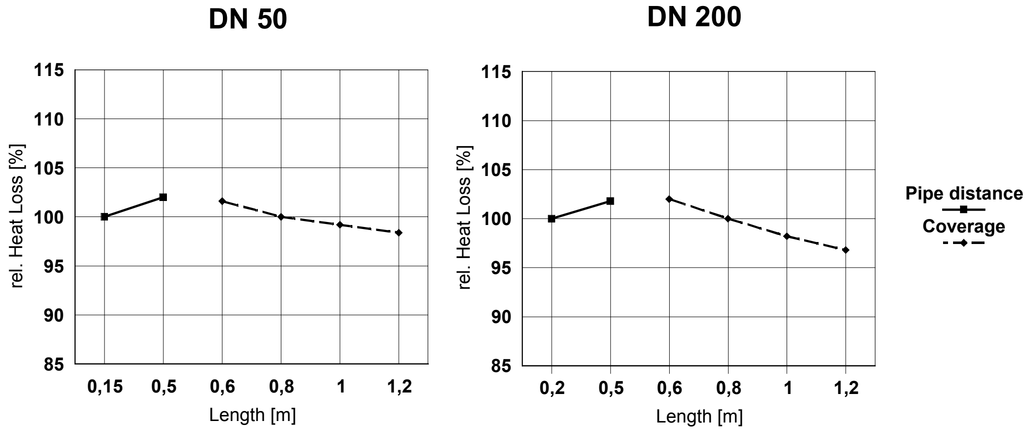
In the Nordic countries there is often installed a drainage pipeline parallel to the district-heating pipeline. According to Fig. 3-6 it can be seen, that this may have a very positive effect on heat losses. But in other countries (i.e. Germany) laying of drainage pipelines is not allowed due to environmental reasons.

3.1.4 Pipe and Pipeline Geometry

Apart from the dimensions of the pipes, both the coverage of the pipeline and the pipe distance also serve as geometric data relevant to calculate heat losses. The coverage – so to speak – represents a layer of a certain thickness which the heat loss flow has to overcome by way of transfer. By contrast, the pipe distance is material to the heat flow from the supply pipe to the return pipe.

Both parameters have a substantially smaller influence than the variables discussed in Sections 3.1.1 to 3.1.3. Figure 3-7 depicts how heat losses change on a small-sized DN 50 pipe and a large-scale DN 200 pipe, in case the pipe distance is increased and the coverage is varied. The baseline case is defined as follows: Insulation Series 1; pipe distance of 0.15 m (DN 50) and 0.2 m (DN 200), respectively; and coverage of 0.8 m.

Fig 3-7: Change of heat losses depending on pipe distance and thickness of coverage (Insulation Series 1; λ_{PUR} = 0.0288 W/(m·K); λ_E = 1.5 W/(m·K))



3.2 Change of Heat Losses in Relation to Average Useful Life (Ageing)

As plastic materials are not fully impermeable for gases, an exchange of the gas contained in the cells of the PUR-based insulating materials takes place in the course of their average useful life. The cyclopentane (or carbon dioxide) originally absorbed during the production process escapes from the insulating material and is replaced by air. For further information, please refer to Appendix 1. Diffusion does not necessarily occur solely via the pipe jacket. In pipelines composed of a medium-transporting pipe made of plastic, diffusion also takes place towards the high-temperature water.

When producing PUR foam, the material's cells are filled with a gas of low heat conductivity, nowadays with cyclopentane. If, over the years, this gas is gradually replaced by air whose heat conductivity is greater, the heat conductivity of the PUR foam increases. In the present report, the change of heat conductivity was calculated in relation to its average useful life in consideration of the parameters to follow:

Cell gas:	Cyclopentane (CP) and carbon dioxide (CO_2)
Thickness of insulating layer:	Insulation Series 1, 2, 3
Diameter:	DN 25, 50, 80, 100, 150, 200, 300, 400, 600, 800
Type of pipe:	Preinsulated jacket pipeline and twin pipe

The results of these calculations are set forth in Appendix 1. The diagrams reflect the increase in heat conductivity over a period under consideration of 50 years.

3.2.1 Change of Heat Conductivity of PUR Foam

Here, in the main part of the present report, the period under consideration is limited to 30 years, as it is usual for a average useful life as per standard EN 253 and useful for the cost-efficiency analyses conducted in Section 4 below.

Figure 3-8 depicts the increase of heat conductivity in the course of a 30-year average useful life of pipes. On small-sized pipes of a nominal diameter of DN 25, the cell gas exchange takes place quickly and is virtually completed after a period of 20 years. By contrast, on large-scale pipes of nominal diameters of DN 300 and DN 600, the gas exchange is much slower – due to the rather thick walls of the preinsulated pipes – and, even after thirty years, still has by far not reached the state of equilibrium of the completed exchange of gas, see diagram. Besides the cell gas CP, which is preferred today thanks to its more favorable heat conductivity properties, the standard EN 253 also provides for the application of CO_2 as cell gas. Not only is the heat conductivity coefficient of CO_2 higher than that of CP, it is also marked by less favorable diffusion properties. Figure 3-9 illustrates anew the ageing process of CP foam already depicted in Figure 3-8 – here, however, on a larger scale – and contrasts this process with the ageing of CO_2-blown foam for the same pipe geometry (thin lines). The graphs show that the exchange of gas takes place much faster in CO_2-blown foams than in CP-blown foams.

Fig. 3-8: Increase of heat conductivity of PUR foam (for: Cell gas CP; Insulation Series 1)

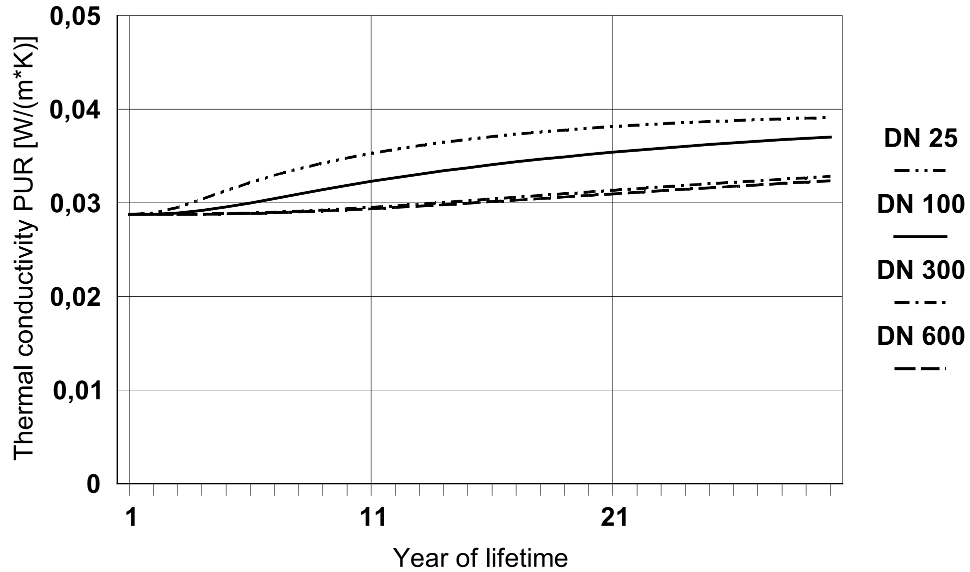


Fig 3-9: Increase of heat conductivity of PUR foam (for: Propellants CP, CO_2 and CFC-11; Insulation Series 1)

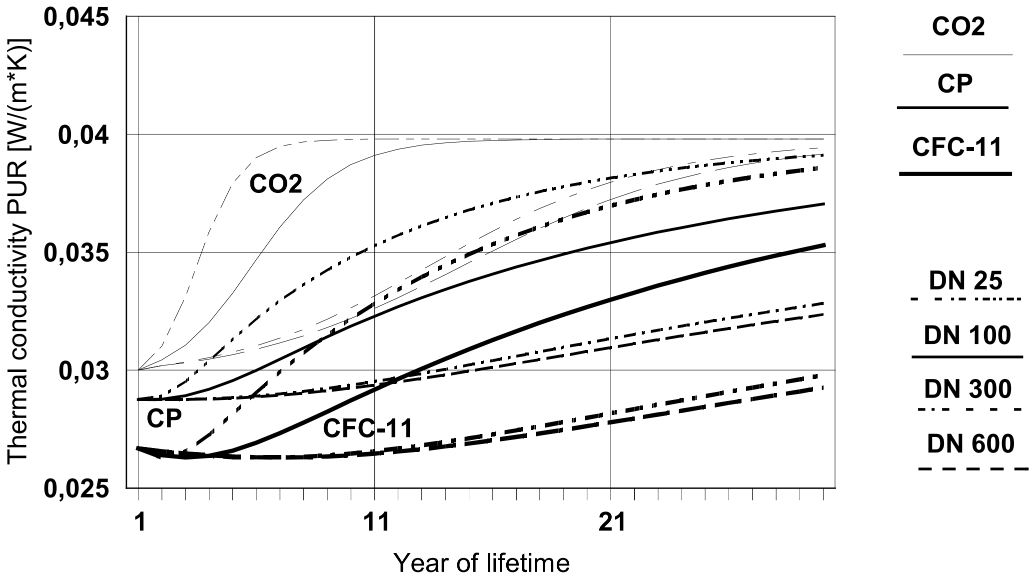


Figure 3-9 also depicts the ageing process of the foam which was formerly widely used and produced in conjunction with CFC 11 as propellant to provide for a comparison with modern PUR foams.

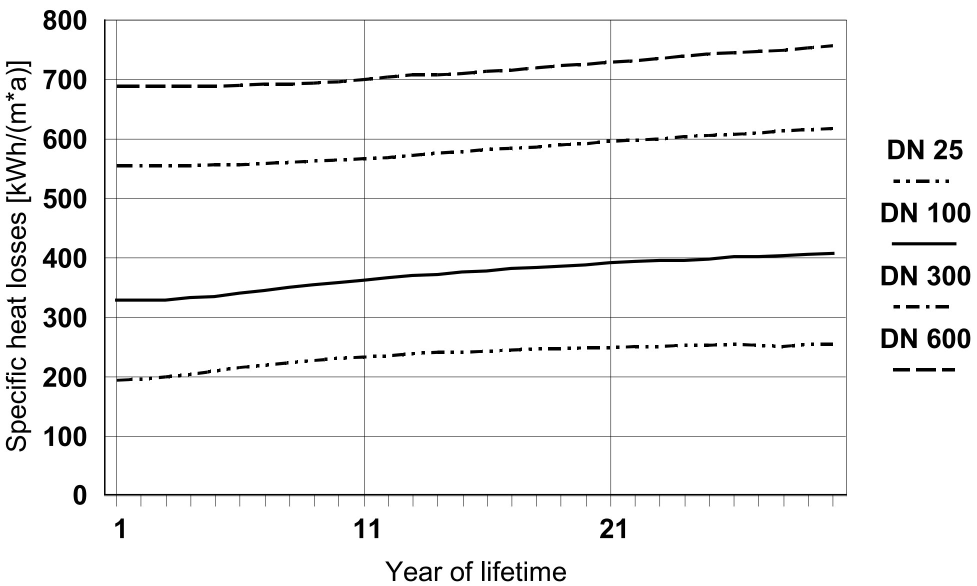
For some of the gases most of the transport resistance is in the foam, while the casing contributes more to the resistance for others. For CP the main part of the transport resistance is attributable to the foam, while for CO_2, Nitrogen and Oxygen the resistance of the casing dominates (see also Appendix 1).

To date, solely manufacturer's information is available for new foams; moreover, it is not known whether studies on the ageing behavior of this new foam have so far been conducted. Yet, in order to evaluate the utilization potential of this foam, its properties are assumed or assessed as follows: The heat conductivity of the new foam is presumed to comply with the manufacturer's data, namely 0.0245 W/(m·K). This foam is blown in conjunction with CP. As soon as the CP has been completely replaced by air, the foam should show the same heat conductivity as conventional CP foam. If the same time period is assumed for the exchange of gas (calculation model for the diffusion resistance within the jacketed pipe), it is possible to assess the ageing of new foam as depicted in Figure A5-1 (Appendix 5). The diagram reflects a conservative estimate.

3.2.2 Change of Specific Heat Loss Due to Ageing

When calculating the heat loss of a pipeline of a length of one meter in consideration of the heat conductivity changing over the years and in relation to time, the heat loss has to increase in the course of time, as well. Figure 3-10 shows the volume of specific heat losses for pipes of the same nominal diameters as specified in the preceding figures in each year of the 30-year average useful life*. (An additional diagram displaying a time span of 50 years has been attached hereto in Appendix 5, Figure A5-2. In particular, that diagram depicts the behavior of large-scale pipelines over an even longer period of time.)

Fig. 3-10: Specific heat losses in the course of average useful life (for: Cell gas CP; Insulation Series 1; ΔT_m = 63.8 K; H = 0.8 m; λ_E = 1.5 W/(m·K)



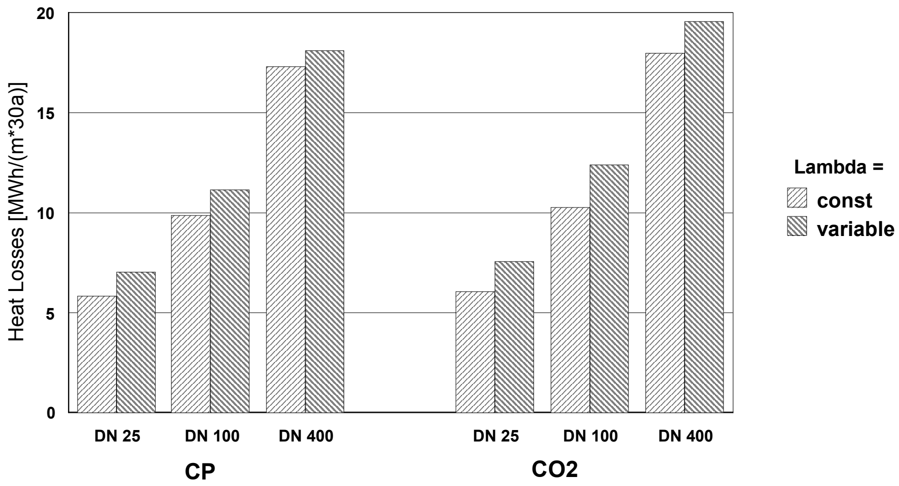
However, when taking a close look at Figure 3-10, it also becomes transparent, that small-sized pipes play a substantial part in the assessment of heat losses; for further details, please refer to Section 6.2.2.3.

In the past, cost-efficiency analyses on heat losses were mostly conducted on the basis of a constant value for the heat conductivity of the PUR foam (new material). Consequently, actual losses were considered at too low. Figure 3-11 illustrates in form of a bar chart the magnitude of

* Here, the losses are displayed as annual heat losses for each meter of the pipe network. The heat loss per pipeline meter can be obtained by dividing it by 8,760 h/a.

the error resulting therefrom. This procedure tends to underestimate the heat losses of small-sized pipes much more than the heat losses expected to occur on large-scale tubes.

Fig. 3-11: Accumulated heat loss after 30 years of average useful life (for: Cell gas CP; Insulation Series 1; $\Delta T = 63.8$ K; $H = 0.8$ m; $\lambda_E = 1.5$ W/(m·K)



3.3 Special Laying Methods

Apart from the standard pipe installation method – i.e. pipes are laid side by side –, pipes are today also installed on top of one another or so-called twin pipes are selected for installation. In the sections to follow, the heat losses of these two special laying methods will be calculated and compared with the standard pipe installation methods. As regards the particularities of flexible pipeline systems and the diffusion barriers as promulgated by manufacturers, only some qualitative remarks may be made here.
Special embodiments of pipelines, such as asymmetric cross sections of supply and return pipe will not be treated in this study. This contains pipelines where the supply pipe has a increased insulation thickness or the return pipe is carried out with a larger dimension. This special pipe design is according to experience valid for pipes with larger dimensions. Here this case can not be considered in general. Corresponding calculations should be carried out for specific applications.

3.3.1 Laying Pipes on Top of One Another (Piggy-back Laying)

As heat losses are transferred from the pipes via the covering soil to the ambient air, it is of relevance for the determination of the level of heat losses whether the supply pipe is arranged above or below the return pipe. If the supply pipe is laid below the return pipe, heat losses need to be lower.

Within the framework of the present report, the heat losses occurring in case of piggy-back pipe installation were calculated for both arrangement cases (supply pipe above or below return pipe). The results of these FEM calculations have been attached hereto as Appendix 2.

Calculations were made for two laying depths, i.e. for coverage of 0.65 m and 0.45 m. The laying depth of 0.65 m is considered the standard depth in case of vertical pipe arrangement. This depth is comparable to the depth of 0.8 m applied when pipes are arranged next to each other. For, when arranging pipes next to each other, the service connection is established by way of a 45° branch lifting the lines to a higher level (coverage of 0.65 m). The piggy-back pipe installation method does not require any branching to a higher level, i.e. the pipes can be guided horizontally to the service connection.

The results are interesting from two points of view:
What are the effects of resulting from the arrangement of the supply pipe (above or below), and how much do the heat losses of the vertical pipe guidance differ from those of the conventional horizontal pipe arrangement?

Arranging the supply pipe below the return pipe hardly leads to considerably lower heat losses compared to an arrangement where the supply pipe is laid above the return pipe, see Figure 3-12. The deviations are less than 1%, see Appendix 2.

Fig. 3-12: Heat losses in case of piggy-back pipe laying
Supply pipe above or below return pipe

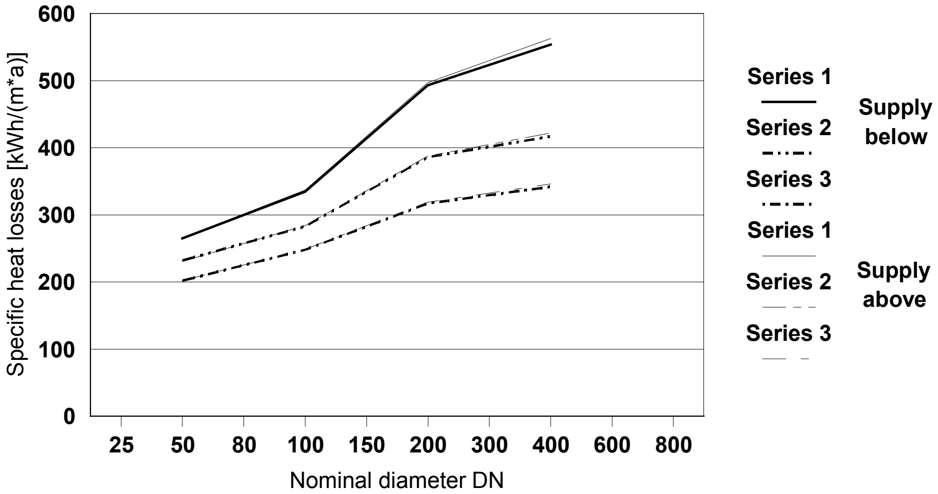
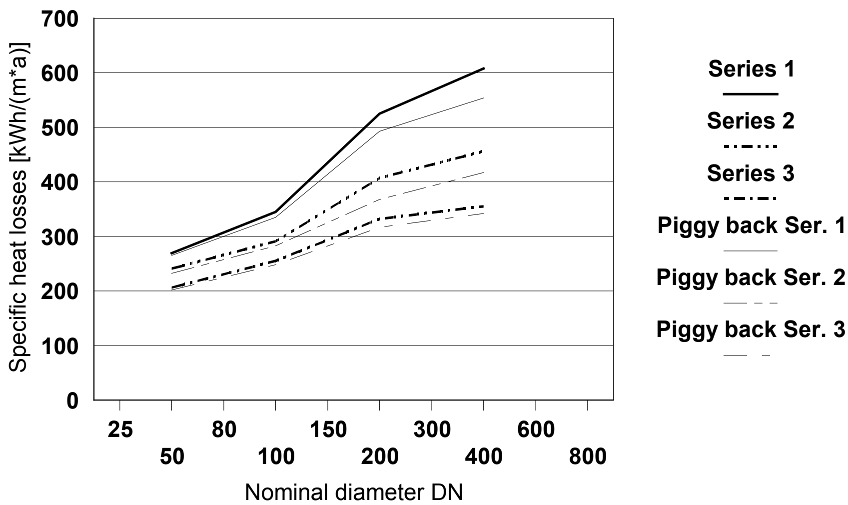


Figure 3-13 depicts the comparison of heat losses of the piggy-back pipe arrangement and the standard (horizontal) pipe arrangement. The diagram reflects for the piggy-back pipe arrangement the more favorable values, in case the supply pipe is arranged below the return pipe. The result shows that for small-sized pipes up to DN 150 the heat losses occurring in case of piggy-back laying are only slightly more favorable than the losses occurring on horizontally arranged pipes (approx. 3%). Increasing benefits do not become transparent until pipes of a nominal diameter exceeding DN 200 are installed; on DN 400 pipes, for instance, benefits total approx. 10%, see Figure 3-13.

Fig. 3-13: Comparison of heat losses
Pipes laid side by side
Pipes laid on top of one another
(supply pipe below return pipe)



3.3.2 *Twin Pipes*

Compared to single pipes, twin pipes show considerably lower heat losses. Here again, the heat losses of twin pipes were calculated on the basis of the heat conductivity of PUR foam and Jarfelt's equations, see Appendix 1 and Appendix 3. The following dimensions of twin pipes were used in these calculations:

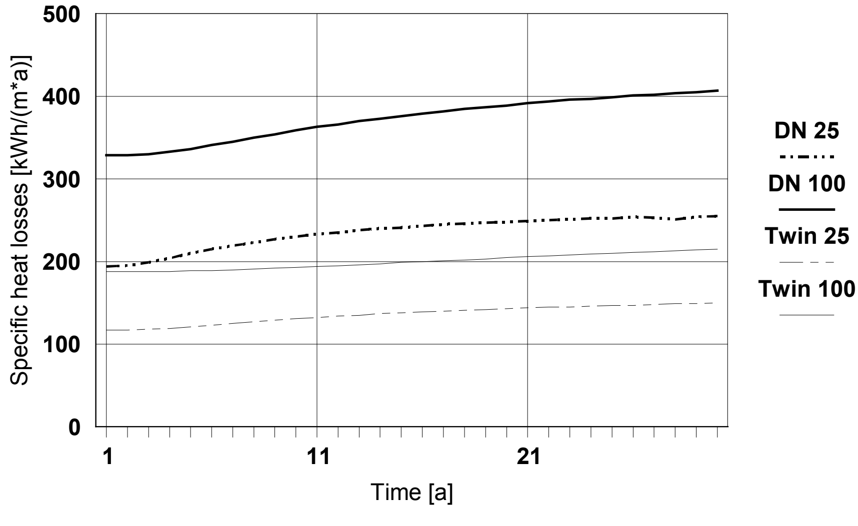
Table 3-3: Dimensions of twin pipes

DN	D_{ST} [m]	D_A [m]
25	0.0337	0.1400
50	0.0603	0.2000
80	0.0889	0.2500
100	0.1143	0.3150
150	0.1683	0.4500

The results are mirrored in form of the heat losses displayed in Figure 3-14 (DN 25 and DN 100). The diagram also reveals how much better twin pipes are compared to single pipes. When taking a look at the heat losses accumulated over a average useful life of thirty years, the heat losses of twin pipes only reach 54% of the heat losses of single pipes.

The very low heat losses of twin pipes are contrasted by the disadvantage that a heat exchange process takes place via the metal pipe links between the supply pipe and return pipe. However, there are substantial differences between the individual types of twin pipes, as both the form and the number of pipe links vary considerably from manufacturer to manufacturer. To the extent it is possible to specify these factors, it is necessary to determine the dimensions and the frequency of pipe links on the installed twin pipes, first.

Fig. 3-14: Heat losses of twin pipes and single pipes (for: Cell gas CP; new pipe; ΔT = 63.8 K; H = 0.8 m; λ_E = 1.5 W/(m·K))



Roughly speaking, it may be concluded that the magnitude of heat transfer taking place between supply line and return line via a pipe link ranges between 10 W and 20 W. This heat transfer, however, is of relevance only in case of smaller-scale pipes; on pipes of a nominal diameter exceeding DN 50, this heat exchange may be deemed insignificant compared to the transported heat quantity. As the distance which the high-temperature water covers through smallest-scale pipes to reach the customer is but a short one, the exchange of heat between the supply line and the return pipe may be neglected in good approximation here.

3.3.3 Flexible Systems and Diffusion Barriers

For the installation of smallest-scale pipes, flexible systems with medium-transporting metal or plastic pipes are used, as well. In part, these pipes are also available in form of tubes equipped with reinforced insulation layers the thickness of which meeting the requirements of Insulation Series 2 and 3. The PUR foam and the polyethylene (PE) of the jacketed pipes of these systems often differ from the materials used for preinsulated plastic jacket pipelines. There is a broad spectrum of variants inside the market which can not be treated here in detail.

In some countries, e.g. Germany, flexible systems don't play a deciding role with respect to the total amount of heat losses of a district-heating network as they are used for house service connections which are usually short, see also chapter 6, Fig. 6-3. In other countries, such as Denmark, heat losses of house service connections could be significant due to the fact, that even many one family houses in scattered settlements are supplied with district heat.

For flexible systems in terms of quality, it may be stated that these differences to preinsulated pipes mainly result in increased diffusion and thus in an accelerated exchange of cell gas. At present, it is, however, not possible to make exact statements, as these interrelationships have so far not been the subject matter of sufficient studies [14].

A similar state of uncertainty also marks the durability of diffusion barriers of preinsulated pipes. Although manufacturers highlight the low-level heat losses of these systems, it is yet questionable whether these barriers can prove longevity and reliability, today. Initial studies give rise to doubts in this respect [14]. Apparently, a longitudinal transport of gas by diffusion and a substantial exchange of gas takes place via the faces within the foam (pipe ends, sleeves).

In consequence, to the extent such smallest-scale pipes need to be incorporated into an insulation concept, engineers are today still required to rely on the product information furnished by manufacturers. As experience shows, some caution should be exercised in this context.

3.4 Interim Results of Heat Loss Calculations

As a kind of sensitivity analysis the synopsis to follow provides for an overview of the magnitude the impacts discussed in Section 3.1 have on heat losses. For such purpose, the relations to be compared are incorporated in a joint diagram, even though there is no direct interrelationship between them. The relevant parameters are varied within the range possible in practical application. The parameters to follow are juxtaposed:

- Insulating effect of soil,
- insulating effect of conventional PUR foams,
- insulation effect of soil coverage and
- influence of pipe distance, as well as
- influence of temperature difference ΔT_m,

whereby the values indicated in Table 3-4 are assigned to the parameters used in the calculations.

Table 3-4: Parameters for heat loss calculations

No.	Parameter	Unit	Step				
			-2	**-1**	**0** **Basic case**	**1**	**2**
1	λ_{Soil}	W/(m·K)	0.5 (dry sand)	1	1.5	2	2.5 (wet clay)
2	λ_{Foam}	W/(m·K)	0.024 (New foam)	0.0288 (CP)	0.0301 (CO_2)	-	-
3	Coverage	m	-	0.6	0.8	1	1.2
4	Pipe distance	m	-	-	0.15 to DN 150 0.2 as from DN 200	-	0.5
5	Temperature difference ΔT_m	K	51.8 (DK)	61.5 (S)	63.8 (Mannheim, D)	66.3 (FIN)	-

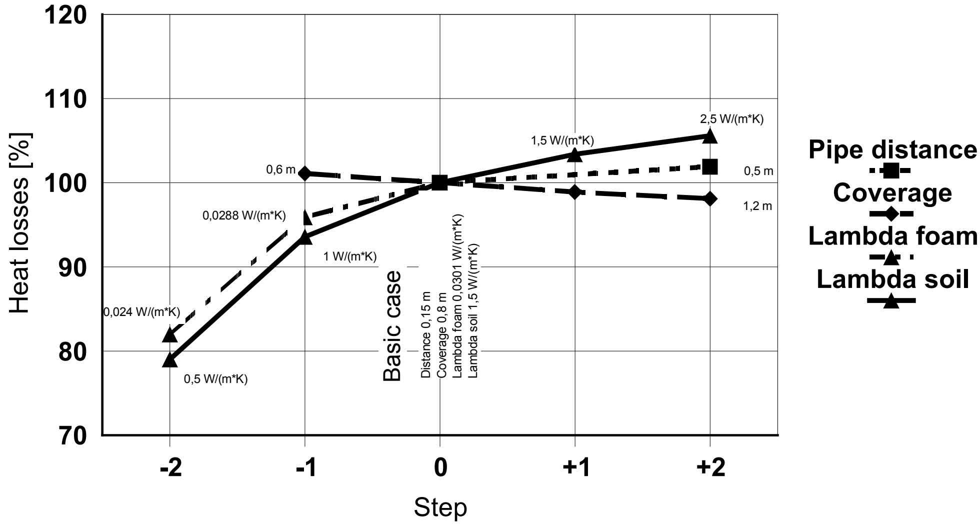
Figure 3-15 depicts the results of the heat loss calculations for both a small-sized DN 50 pipe as well as a large-scale DN 200 pipe. The abscissa is graduated in steps. Each step is assigned the value indicated in Table 3-4. For each graph the parameter concerned is varied while all the other parameters equal the basic value. The graph for the temperature difference ΔT_m is incorporated only in the lower diagram, as it would not be recognizable in the upper diagram where it would coincide with other graphs. It would have the same run in the upper diagram.

Another important finding of Section 3.2 substantiates the statement that the ageing of the PUR foam needs to be taken into account when intending to reliably determine heat losses. In the course of a thirty-year average useful life of a pipeline, heat losses increase up to a maximum value. On smallest-scale pipes, this limit is reached after a period of only 10 years, on DN 80 pipes after 30 years, and on largest-scale pipelines the increase attains just one third of the possible value even after a average useful life of 30 years.

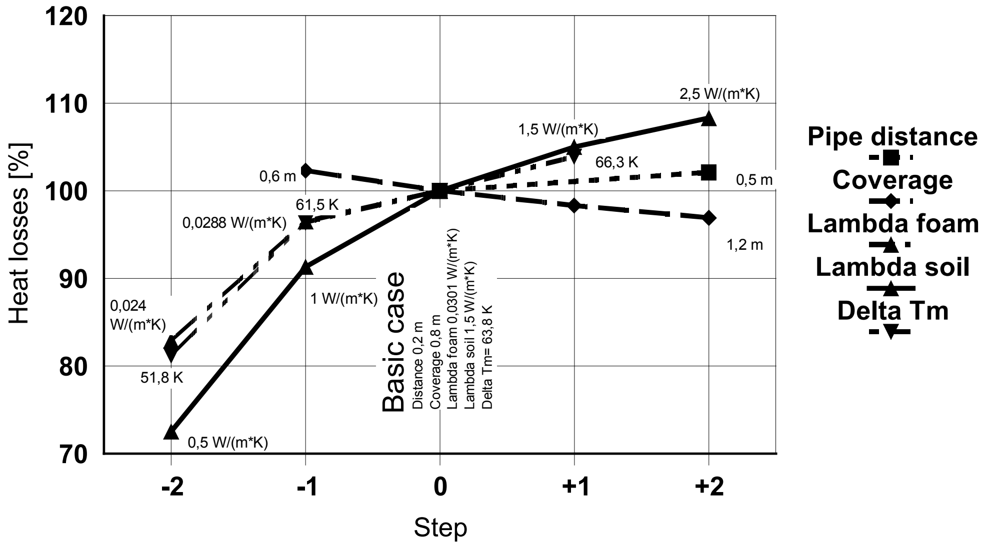
Simplified assumptions on heat losses which are only based on the insulation properties of new pipe materials and, additionally, on constant insulation behavior underestimate the actual values by approx. 20% for small-sized pipes, and still by approx. 5% for DN 400 pipes. This error applies to the cell gas CP; as regards CO_2-blown pipes, this error is even greater.

Fig. 3-15: Comparison of impacts on heat losses (Insulation Series 1)

DN 50



DN 200



The two special laying methods – piggy-back and twin pipe laying – reveal substantial differences in terms of heat losses. The method of laying pipes on top of one another shows, compared to the standard installation technique (laying pipes next to each other), only insignificantly diverging heat losses on small-scale pipes. For pipes of a nominal diameter of DN 200 and greater, the piggy-back pipe arrangement is more beneficial; arranging the supply pipe below the return pipe only offers a minor additional advantage.

In comparison with single pipes, twin pipes hold excellent insulating properties. Figure 3-16 summarizes the heat losses – under identical conditions – of the various pipelines examined here. The figure displays for the standard installation method (side-by-side laying of the pipes) the losses occurring on the three conventional insulation series and contrasts these heat losses with the piggy-back pipe-laying technology. The graph describing the insulation properties of the twin pipes is placed even far below the graph of Insulation Series 3, see Figure 3-16.

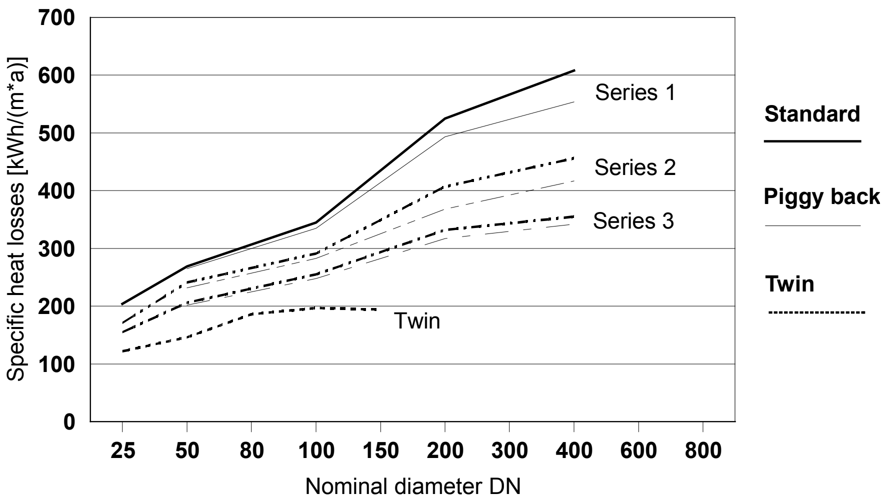


Fig. 3-16: Comparison of heat losses of various district-heating pipelines (for: λ_{PUR}=0.03 W/(m·K); new pipes; ΔT = 63.8 K; H = 0.65 m; λ_E = 1.5 W/(m·K))

Part B: Cost-Efficiency of Heat Insulation

4 Economic Insulation Thickness

Preinsulated plastic jacket pipelines are available in three types, each offering a different insulation thickness, namely the standard Insulation Series 1 or the reinforced forms of Insulation Series 2 and 3. Moreover, PUR foams offering various insulating properties are applied throughout the marketplace (CP, CO_2 and New foam). The efforts aiming at optimizing the insulation thickness of preinsulated plastic jacket pipelines have for their objective to determine under what conditions which type of pipes causes the least costs.

The costs to be analyzed here are comprised of two components: The heat loss costs and the investment costs for heat insulation. The heat loss costs may be determined relatively easily, as they are the product of the occurring heat losses (see Part A) and the heat costs.

In many cases, the investments for heat insulation are not explicitly available. On the one hand, the pipe material of the higher insulation series is more expensive, on the other hand, a higher insulation series also accounts for higher installation costs due to its greater dimensions.

In this context, the foremost aim is not an optimization of the insulation thickness accurate to the millimeter; rather the insulation thickness is subject to specified delivery standards. In consequence, the selection of the economic insulation thickness boils down to the question whether the next higher insulation series is more cost-efficient or not. Within the framework of that comparison, it is sufficient to focus solely on the *additional costs* cropping up for the higher insulation series, i.e. the difference of the installation costs of both variants.

The parameters incorporated in the cost-efficiency analyses result, on the one hand, from economic factors and, on the other hand, from technical impacts.

4.1 Cost-Efficiency Analyses

The long average useful life of district-heating pipelines and the ever-changing general economic setting call for a dynamic cost calculation over the lifetime of the pipes. The costs and benefits of the heat insulation system form the matter of consideration. The costs crop up at the point of time of installation of the pipes. The benefits of the (improved) heat insulation, however, come to the fore year by year in the course of the average useful life of the pipes.

The evaluation of the benefits needs to take into account that

1. the benefits are the more inconsiderable, the later they start taking effect, and
2. the volume of heat losses increases in the course of time, since – as past experience shows – increasing energy prices need to be expected also in the future.

In additional consideration of the fact that the volume of heat losses increases over the years due to the ageing process, this flow of money is translated into the relevant cash equivalent (reflecting the point of time of investment) here, to provide for a comparison of the analyzed variants.

The price increase and the cash equivalent are determined on the basis of the formulas applied for compound interest calculation.

Interest payment/price increase:

$$z = a \cdot q^n$$

with

$$q = 1 + \frac{p_K}{100}$$

p_K = rate of interest [%]
n = average useful life [a]
a = cash equivalent

The cost-efficiency analyses are conducted in such a way that a standard case is defined and analyzed step by step to determine how the result changes, if one of the parameters takes a diverging value. The standard case is based on the situation currently prevailing in Germany.

4.1.1 Economic Parameters

The cost-efficiency analyses takes into account three factors, i.e. the long-term interest rate, average useful life, and heat costs. A separate inflation markdown is not applied, because of the presently low rate of inflation. If need be, the inflation effect may be incorporated by reducing the long-term interest rate.

Long-term interest rate: The value as determined by the internal cost accounting department of the company is regarded as the applicable long-term interest rate. Within the framework of the present report, the standard value is deemed to be

$$p = 7\% \text{ p.a.}$$

Comparative calculations are also conducted on the basis of p = 5% p.a.

Average useful life: The dynamic calculations are conducted for a study term of 30 years, i.e.

$$n = 30 \text{ a}$$

That value is in keeping with the usual approach for the average useful life of district-heating pipelines [standard EN 253].

Heat costs: The heat losses are evaluated in relation to the heat costs. A value of

$$C = € 20 \text{ per MWh}$$

is considered the standard amount which constitutes the mean value of base and peak load energy. Costs of € 10/MWh which crop up for industrial waste-heat are considered low, while costs in the amount of € 30/MWh which apply to e.g. heat-only plants are regarded as high. Costs to the tune of € 40/MWh may be deemed an extremely high value, in case energy prices develop in an unfavorable fashion.

Within the framework of the calculations, the generation costs are increased by a constant percentage of

$$p_E = 2\% \text{ p.a.}$$

over the study period. Additional comparisons are made on the basis of growth rates of 4% and 6% p.a.

4.1.2 Technical Parameters

Of all technical parameters which need to be varied within the framework of cost-efficiency calculations, the installation costs, which need to be taken into consideration as well, cause some problems. Additionally, it is necessary to vary the temperature-related influences via ΔT_m (see Section 3.1.2); further, the heat conductivity of the various PUR foams needs to be taken into account. Geometric impacts such as coverage layer (i.e. its height) and the pipe distance are not examined here, as their influence may be neglected (see Part A). Nor is the heat conductivity of the soil varied within the framework of the cost-efficiency calculations. Rather, a constant value of $\lambda_E = 1.5$ W/(m·K) is incorporated in the analyses.

For the purpose of the present report, the installation costs for district-heating pipelines had to be determined in form of a continuous function in relation to the nominal diameter. It was necessary to establish these functions for several countries, as the objective is the provision of an international comparison.

The determination of the cost functions required for the present report constitutes a task in itself which, consequently, has been attached hereto in form of an independent part, see Appendix 4. The cost functions for the standard method of laying preinsulated plastic jacket pipes as determined there are depicted in Figure 4-1. The installation costs ascertainable in the countries included in the present report may be subdivided into *three categories*:

High installation costs:	e.g. Germany
Medium installation costs:	e.g. Denmark and Sweden
Low installation costs:	e.g. Finland

In the sections to follow the economic interrelationships are outlined for these three categories to which the above-mentioned countries were allocated. *Each reader is requested to select himself/herself the category which, depending on the relevant installation costs, is the most appropriate for him/her*. For instance, if a German supply utility faces very low installation costs in an analyzed case (installation of a new pipeline grid within a development area), it should assign the appropriate lower cost category, i.e. either the group formed by Denmark and Sweden or the group composed of Finland.

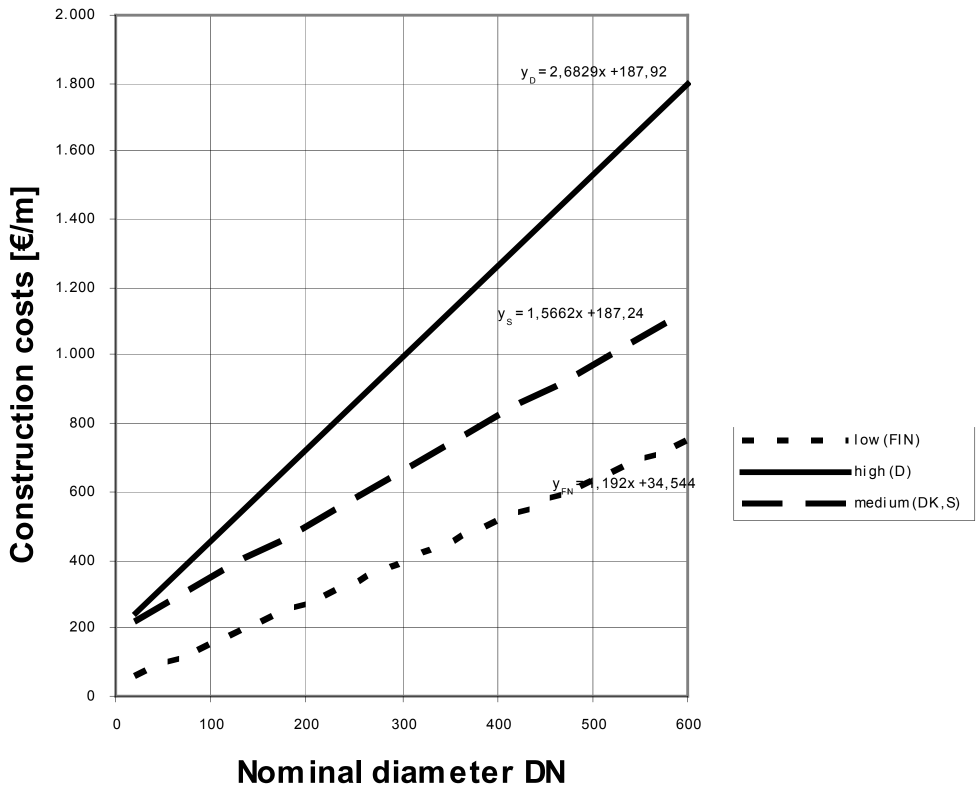


Fig. 4-1: International comparison of installation costs for district-heating pipelines

The installation costs for both twin pipes and single pipes in case of piggy-back laying are not restated here; if need be, they may be gathered from Appendix 4 which also depicts a breakdown of installation costs by components, namely material, installation and excavation work.

The values which may be gathered from Figure 4-1 were taken as representative installation costs cropping up in the analyzed countries. Lower prices for raw materials which were not – as it is usual in most cases – CP-blown but CO_2-blown or higher prices for New foam were integrated in the cost-efficiency calculations with the aid of adjustment factors.

All temperature-related impacts are fully accounted for in parameter ΔT_m. The standard value applied throughout the cost calculations amounts to

$$\Delta T_m = 63.8 \text{ K}$$

Apart from the German situation, this value also reflects the conditions in Sweden and Finland with sufficient accuracy. Variation calculations were made for ΔT_m = 51.8 K (Denmark).

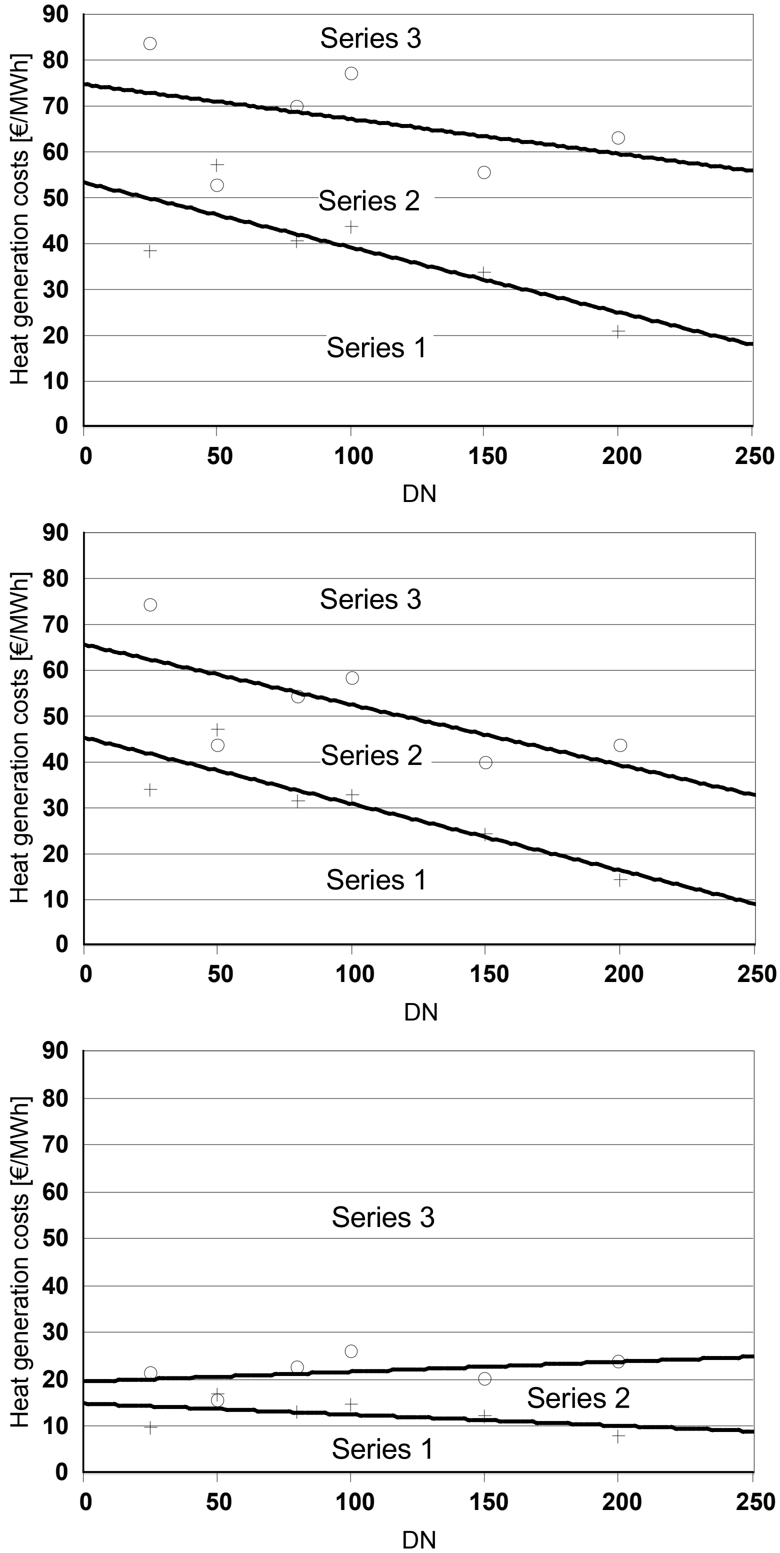
4.2 Optimal Insulation Series

The prime question posed when selecting the heat insulation technology for a pipeline is: When do the savings from losses avoided thanks to improved insulation exceed the increased installation costs? Against that backdrop, the initial calculations concentrate on specifying such heat costs at which a changeover to the next higher insulation series is useful and on the impact of the installation costs on such changeover. The first step analyses the influence of the installation costs, see Section 4.2.1; thereafter, the impact of the temperature is examined, see Section 4.2.2.

4.2.1 Influence of Installation Costs

For specified installation costs, several variation calculations were conducted for a standard case (ΔT_m=63.8 K; long-term interest rate 7% p.a.; heat costs + 2% p.a.) to determine such heat costs at which the overall costs (investments plus cash equivalent of heat loss costs) of Insulation Series 1 respectively 2 are equal to Insulation Series 2 respectively 3. These variation calculations were made for high, medium and low installation costs; the results may be gathered from Figure 4-2. (The leaps depicted in the findings result from the fact that preinsulated plastic jacket pipelines are made of medium-transporting and jacketed pipes whose graduations are subject to standards. Despite these leaps, the trends can be clearly recognized.)

Fig. 4-2: Economic insulation series as function of heat costs in relation to different installation costs
Top: High installation costs
Centre: Medium installation costs
Bottom: Low installation costs



The applicability of this illustration should be discussed with reference to the top diagram as follows: In combination with low heat costs (i.e. less than € 40/MWh), a pipeline of a nominal diameter of DN 80 which meets Insulation Series 1 specifications is selected. Improved heat insulation characterizing Insulation Series 2 saves energy and thus heat loss costs. The higher the heat costs need to be assumed, the higher the savings. On the basis of a specific heat generation price (here) of € 41/MWh, the costs for an Insulation Series 1 installation are equal to the expenses for an Insulation Series 2 arrangement (overall cost compensation composed of increased installation costs and saved heat loss costs). In case heat costs continue to rise, it will be more cost-efficient to opt for an Insulation Series 2 pipeline. By analogy, in case of a changeover from Insulation Series 2 to 3, the costs will be considerably higher. This way, Figure 4-2 describes the ranges within the individual insulation series can be applied in a more cost-efficient manner. The top diagram applies to cases involving high installation costs (mean value for Germany), the diagram in the centre reflects medium installation costs (mean value for Denmark and Sweden) and the bottom diagram stands for low installation expenditures (mean value for Finland). In the end, a supply utility should position itself in keeping with its installation costs and not with its geographic location.

Comparison of these three diagrams reveals that already very low heat costs increase the cost-efficiency of a heat insulation system of a higher quality, in case of very low installation costs.

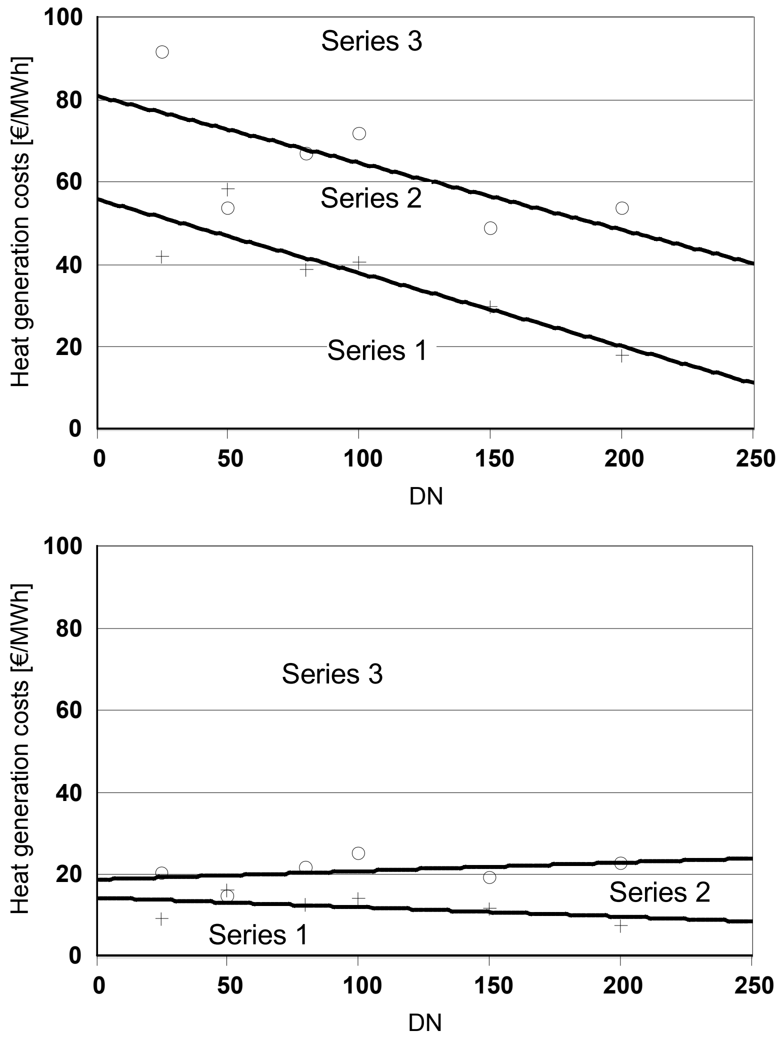
Fig. 4-2 bottom shows also that Finish practice is reasonable for small diameters only to use pipes with insulation series 3. Insulation series 1 and 2 are normally not installed.

4.2.2 Influence of ΔT_m

Figure 4-2 applied to an annual mean temperature difference of 63.8 K (see Section 3.1.2), reflecting the standard conditions in Germany and Sweden. Due to lower operating temperatures, a mean value of ΔT_m = 51.8 K holds true for Denmark. For the purpose of examining the influence of ΔT_m on the areas of application of the insulation series, the variation calculations for the centre diagram in Figure 4-2 *(level of installation costs as applicable in Denmark and Sweden)* were repeated on the basis of ΔT_m = 51.8 K. The top diagram of Figure 4-3 reflects the results of these variation calculations. Since the heat losses are lower in this constellation (19%), the installation of pipes offering better insulating properties does not prove more cost-efficient until higher heat costs crop up.

As to the situation in Finland, tendencies are contrary. The higher value of ΔT_m = 66.3 K is characteristic of Finland; the recalculation of the bottom diagram of Figure 4-2 shows that changeover to pipe materials offering better insulating properties proves to be cost-efficient as soon as lower heat costs are faced, see Figure 4-3, bottom.

Fig. 4-3: Economic insulation series for lower ΔT_m
Top: ΔT_m = 51.8 K (Denmark)
Bottom: ΔT_m = 66.3 K (Finland)



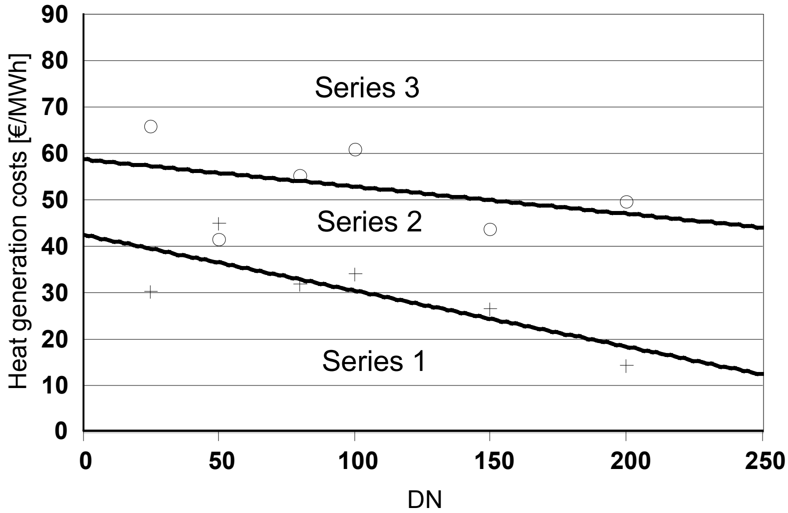
4.2.3 Influence of Interest Rate and Increasing Heat costs

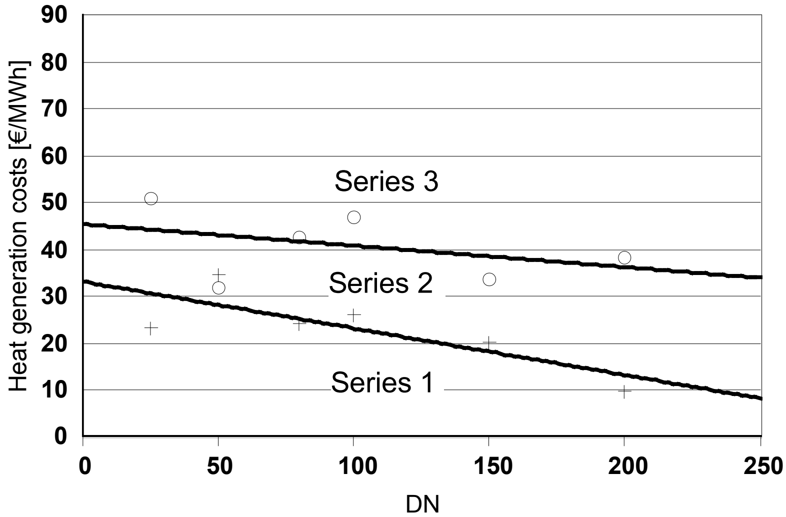
The higher the interest rate, the lower the cash equivalent resulting from saved energy quantities realized due to improved heat insulation, and the less favorable become better insulation systems. The standard value for the calculatory interest rate used for the cost-efficiency analyses conducted here is equal to

$$p_K = 7\% \text{ p.a.}$$

On the basis of the assumption that the long-term interest rate will continue to decrease in the future, the top diagram of Figure 4-2 was recalculated in consideration of the parameter $p_K = 5\%$ p.a. The result is depicted in Figure 4-4.

Fig. 4-4: Cost-efficiency of insulation series in relation to changing interest rates and increasing heat costs
Top: p_K = 5% p.a. and p_E = 2% p.a.
Bottom: p_K = 5% p.a. and p_E = 4% p.a.





Unlike the interest rate, an increase in heat costs results in a contrary influence on the result. The saved energy has to be revalued (to a higher level) each year. In consequence, the cash equivalent increases as well. In this context, calculations were made in which the increase of heat costs of 2% as reflected in Figure 4-2 was replaced by a 4% rise. The result is comparable to the one displayed in Figure 4-4, i.e. a decrease of the interest rate by 2% affects the result in the same manner as an increase of the energy price by 2%.

Another calculation was conducted on the basis of an interest rate of p_K = 5% p.a. and an increase of heat costs of 4% p.a. The result is displayed in Figure 4-4, bottom. Improved heat insulation proves to be cost-efficient as soon as lower heat costs are faced.

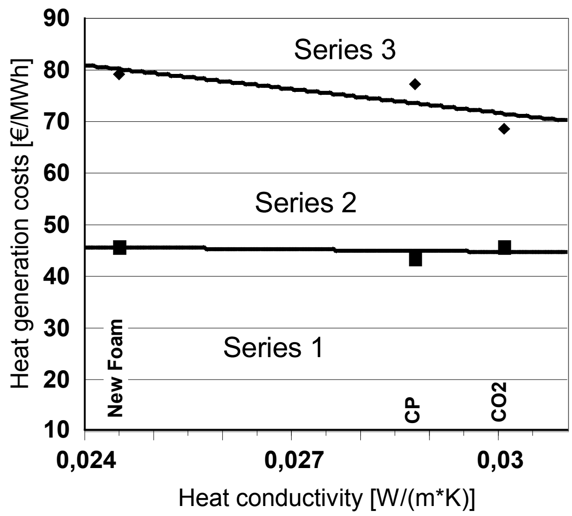
(However, the bottom diagram of Figure 4-4 may also be applied to the following cases:

1. p_K = 3% p.a. and p_E = 2% p.a. or
2. p_K = 7% p.a. and p_E = 6% p.a.)

4.2.4 *Insulating Properties of PUR Foams*

Today, three types of preinsulated plastic jacket pipelines are available on the market. Their distinctive feature is the relevant heat conductivity of the integrated PUR foam. To examine the extent to which the insulating effect of the foam affects the areas of application of the insulation series, the application limits of the insulation series were determined for the three foam types in an exemplary fashion for the nominal diameter DN 100. Figure 4-5 shows the results on the heat conductivity of the new PUR foam. For the calculations, it was assumed that pipe material containing CO_2 foam is 5% less expensive and pipe material holding new foam is 8 % more expensive than CP-blown foam. The higher the heat losses occurring on the pipe, the more recommendable is a changeover to a higher heat insulation technology.

Fig. 4-5: Areas of application of insulation series for various foams as exemplified by a DN 100 pipe; high installation costs



Apart from the useful application limits for the three insulation series, the question of the most cost-efficient foam quality is also of interest to a supply utility. For this purpose, exemplary comparative calculations were conducted for pipes of a nominal diameter of DN 100. These computations were based on the information provided by manufacturers stating that CO_2-foamed pipe material is 5% less expensive and that tubes with new foam are 8% more expensive than CP-foamed pipes.

In consideration of a general setting defined by

heat costs = € 20/MWh,
high installation costs and
material costs = 20% of total investments,

the investments and the cash equivalent of the heat losses occurring on CP- and CO_2-foamed material amount to

	CP	CO_2
Investments	€ 456,000	€ 451,440
Cash equivalent of losses	€ 118,053	€ 131,447
	€ 574,053	€ 582,887

for a DN 100 pipeline of a length of 1,000 m over a thirty-year average useful life.

The pipe material containing CP-foam proves to be more cost-efficient. All in all, the CO_2-blown material – in addition to the actual price advantage of 5% – has to be another 5% less expensive to reach the same cost level as CP-blown tubes.

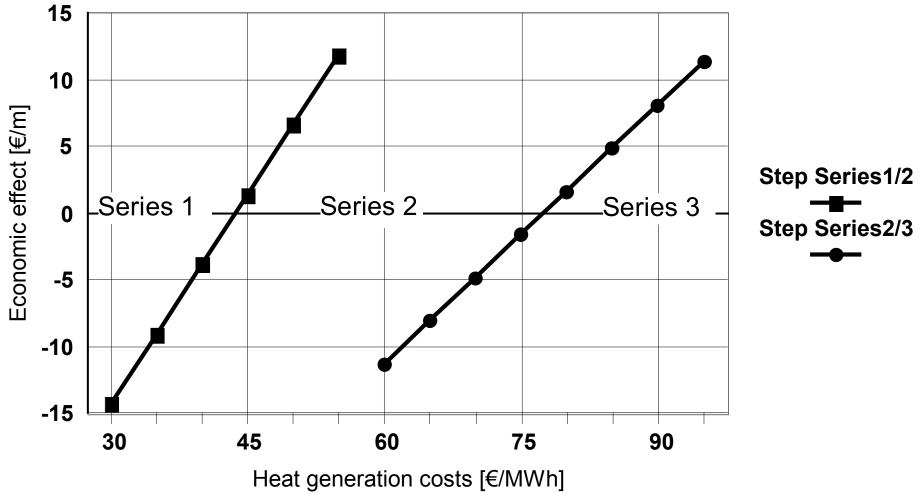
As regards the comparison of CP and New foam, the results to follow apply to a DN 100 pipe meeting the same conditions. Both foam types entail almost the same total cost volume.

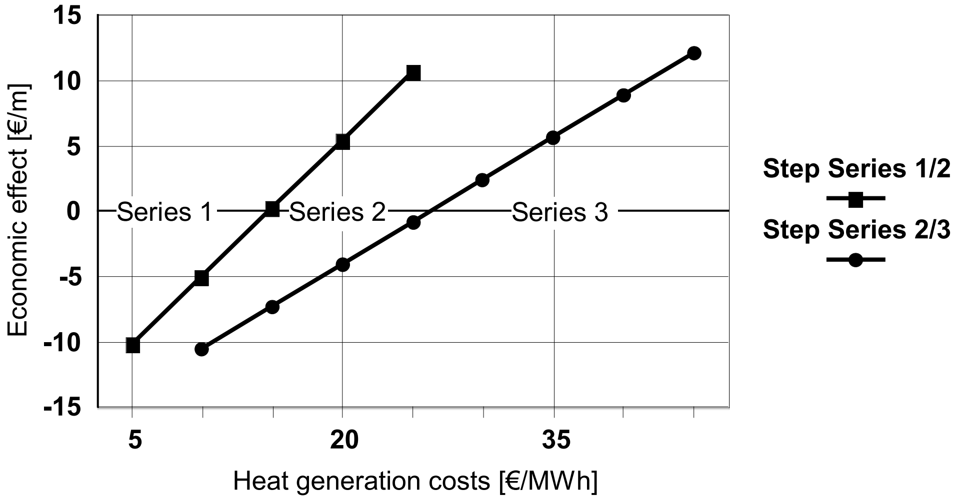
	CP	New Foam
Investments	€ 456,000	€ 463,296
Cash equivalent of losses	€ 118,053	€ 108,845
	€ 574,053	€ 572,141

4.2.5 Suboptimal Heat Insulation

Often, district-heating grids which have grown over decades hold pipelines whose heat insulation was optimized in keeping with formerly applicable and nowadays outdated specifications. Improving the heat-insulating properties of pipelines and thereby exceeding the calculatory optimum – so to speak, an investment for the future – stands for another case of suboptimal insulation. In both cases, it is interesting to determine the volume of additional costs caused by suboptimal insulation.

Fig. 4-6: Cost situation in case of suboptimal heat insulation
Top: High installation costs (Germany)
Bottom: Low installation costs (Finland)





Total costs of heat losses in 30 years 97 €/m (cash equivalent), Series 2

The economic effects were calculated in an exemplary fashion for a CP-foamed pipeline of a nominal diameter of DN 100, see Figure 4-6. Here, the results are discussed on the basis of the top diagram, namely the graph designated 'Step Series 1/2'. This graph shows that in case of heat costs in the amount of € 43/MWh, the expenditures for Insulation Series 1 are equal to those of Insulation Series 2. If, already in case of heat costs of less than € 43/MWh, Insulation Series 2 is selected instead of Insulation Series 1, the economic result is negative. In the event of heat costs exceeding € 43/MWh, the improved insulation has a positive effect. The ordinate concretely shows the result, i.e. the amount for 1 m of pipeline. For instance, if, in consideration of heat costs of € 35/MWh, the pipeline meets the Insulation Series 2 instead of the Insulation Series 1 specifications, the additional costs for each meter of pipeline amount to € 9. This value stands for the total of the increased investments and the saved heat costs (as cash equivalent).

The additional costs of € 9/m should be considered in relation to the installation costs of (here) € 456 per meter and the cash equivalent of the heat loss costs of € 97/(m·30a). The results reveal that the economic advantages and disadvantages of suboptimal insulation are relatively insignificant.

Analogous interrelationships apply to a changeover from Insulation Series 2 to Insulation Series 3, represented by the right graph depicted in the diagram. The bottom diagram of Figure 4-6 displays the same interrelation, in case the installation costs for pipelines are very low (on Finland level). It becomes transparent that improved insulation is beneficial as soon as very low heat costs are met and that the area of application of Insulation Series 2 becomes largely restricted.

In view of these results obtained on the basis of the two situations outlined above, the conclusions to follow may be drawn:

1. The disadvantage of suboptimal heat insulation due to increased heat costs is not very great.

2. Opting for pipelines of a higher insulation series only causes minor additional costs; however, in view of future energy price increases and the economic objectives, i.e. energy conservation and environmental protection, they offer advantages.

3. With regard to the calculatory optimum of heat insulation, changeover to the next higher insulation series appears to be useful as soon as heat costs are slightly lower than the relevant marginal costs. Taking precautions for the future by way of a changeover is very well deemed justified, if the marginal costs are underrun by 10% to 20%.

4.3 Comparison of Costs for Insulation Strategies

The results of the optimization measures were transferred to a model grid to evaluate the economic effects of the various determinants. A network actually installed by MVV Energie served as model grid. The network was constructed within a municipal suburb to supply a new residential area of detached family houses, see site plan in Figure 4-7. In this context, only the length of the pipes and their dimensions as listed below are of relevance.

Fig. 4-7: Site plan of model grid

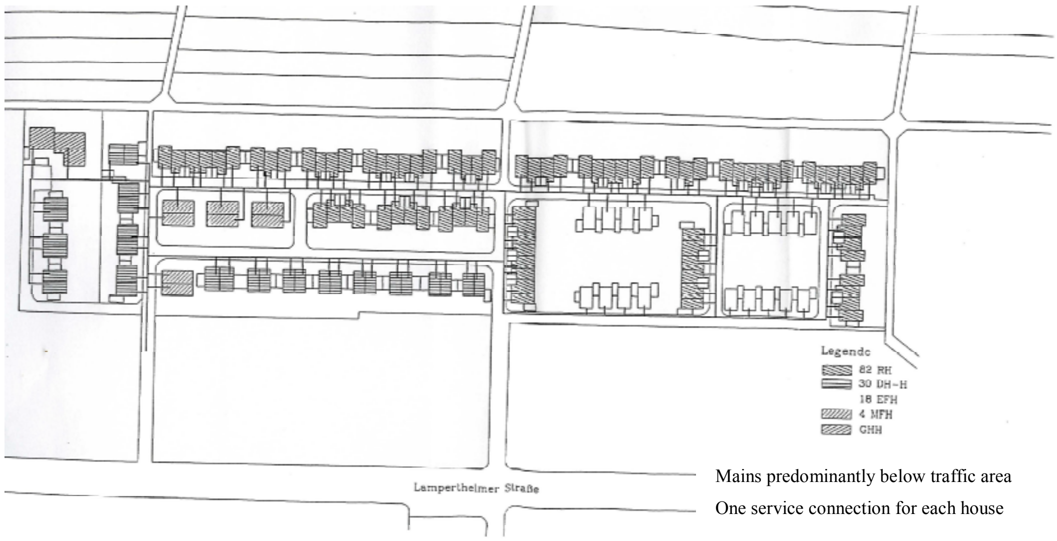


Table 4-1: Nominal diameter and length of model grid

DN	Length of grid [m]
25	790
32	72
50	246
65	126
80	174
100	45
	1,453

Within the framework of comparative calculations, it was assumed that this model grid was operated in technically differing variants (i.e. with CP-foam, New foam, twin pipes, etc.) and under various operating conditions (climate, temperatures). For these variants, the investments and the cash equivalents of the heat losses were calculated for a thirty-year average useful life. The respective totals of investments and heat loss costs were compared with each other.[2]

Calculations were made for the following five technical variants:

CP foam
CO_2 foam
New foam
Twin pipes
Piggy-back laying (supply line below return line)

In terms of operating conditions, reference was made to the standard conditions already applied before, see Table 4-2.

[2] This optimization approach aims at determining the recommended economic insulation thickness of a pipeline of a specific nominal diameter in consideration of fixed operating temperatures. As a rule, the network design concept is defined within the framework of a superior optimization process, in particular the temperature mode which is, after all, material to the design of the pipes.

Table 4-2: Parameters of cost comparison

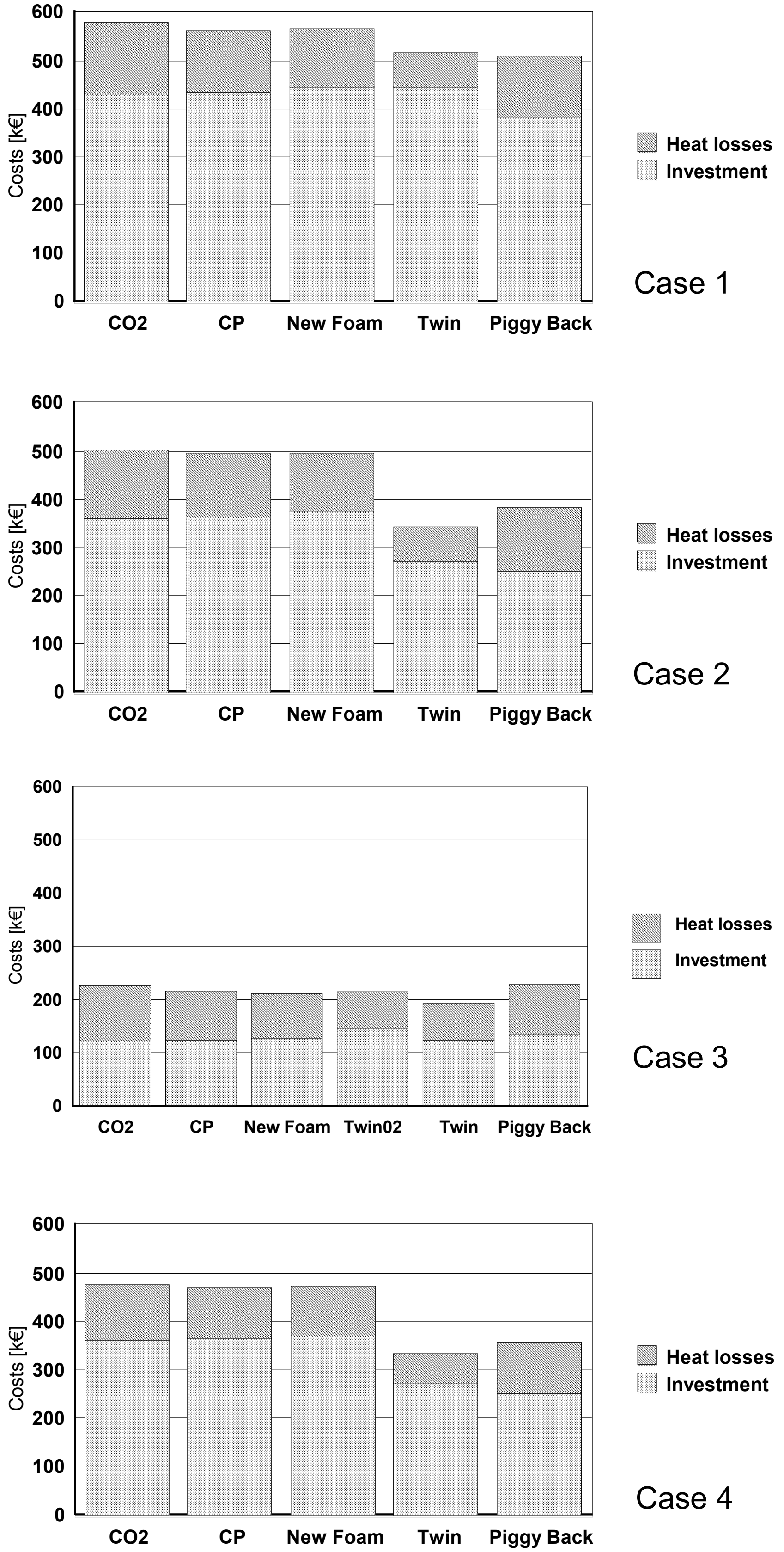
	Parameter	Code	Gerneral settting
Case 1	High installation costs ΔT = 63.8 K Insulation Series 1	Germany	Average useful life: 30 a Energy price: € 20/MWh Interest rate: 7% p.a. Heat costs: +2% p.a.
Case 2	Medium installation costs ΔT = 63.8 K Insulation Series 1	Sweden	
Case 3	Low installation costs ΔT = 63.8 K Insulation Series 3	Finland	
Case 4	Medium installation costs ΔT = 51.8 K Insulation Series 1	Denmark	

Hence, the costs were calculated:

- for the optimal insulation variant (as per Section 4.2)
- in consideration of the relevant installation costs of the respective technical variant
- in consideration of the heat losses increasing due to ageing
- as dynamic cost-efficiency analysis (compound interest) and in consideration of increasing heat costs.

The results are displayed in the four diagrams contained in Figure 4-8. The three top diagrams apply to a temperature difference of ΔT_m = 63.8 K, i.e. to the standard situations in Germany and, in an approximate fashion, also to Finland and Sweden; they differ from each other by the level of installation costs. For the Finish standard case there are shown 2 columns for Twin pipe laying. Column “Twin02” bases on construction costs from the Finish 2002 statistical report. Due to statistical variance these given values don’t correspond to long term experiences (see also Appendix 4).
The bottom diagram applies to ΔT_m = 51.8 K and reflects the situation in Denmark. As regards the costs for heat losses, the excellent insulating properties of twin pipes stand out. The fact that the heat loss costs depicted in the two bottom diagrams are lower than on top is, in case 3, due to the selection of Insulation Series 3 pipes (optimum), and, in case 4 (Denmark), due to lower operating temperatures and thus a lower ΔT_m value.

Fig. 4-8: Comparison of costs for five insulation strategies
Case 1: Standard case Germany
Case 2: Standard case Sweden
Case 3: Standard case Finland
Case 4: Standard case Denmark



4.4 Premature Renewal of Pipelines Due to Insufficient Heat Insulation

In connection with damaged as well as extremely old pipelines, the question always arises whether it is more cost-efficient to replace or maintain a poorly insulated or an almost uninsulated pipe. With the aid of Figure 4-8, the answer to this question may be given for a wide area of application.

Figure 4-8 depicts both the investments and the total heat loss costs as cash equivalent over a period of thirty years. Usually, supply utilities write off the value of their pipes on the basis of the straight-line method of depreciation over a specific period. In case a pipeline is replaced prematurely, it is necessary to depreciate a *pro rata temporis* share in the investments. As to heat losses, it should be taken into account that the value of the losses has to be discounted (geometric series), i.e. the value of future heat savings is lower than in case of equal instilment depreciation. If, nevertheless, a (pessimistic) linear time distribution is assumed, it becomes transparent that there is hardly a case in which premature replacement is justified from the economic standpoint. The investments always exceed the value of the relevant heat losses – and in many cases to a substantial extent. In consequence, in cases 1, 2 and 4 of Figure 4-8, the additional expenditures accruing for premature replacement could never be compensated by savings resulting from avoided heat losses.

Exceptions are conceivable for case 3 (Finland) where very low installation costs need to be taken into account. In case 3, the investments are approximately equal to the value of heat losses; in derogation of the other cases, case 3 applies to Insulation Series 2. If the replacement of an Insulation Series 1 pipeline were assessed (the value of the heat losses for Insulation Series 1 may be gathered from the diagrams displaying the other cases), the threshold of cost-efficiency could be reached. Only in this case would a detailed analysis be useful.

4.5 Interim Result

Generally speaking, all impacts increasing the volume or costs of the heat losses suggest improved heat insulation. Therefore, a higher temperature difference between supply and return pipe and the environment (see Section 4.2.2) also fosters increased insulation.

For the most part, heat losses occur on small-sized pipelines. Consequently, special focus should be placed on these networks in terms of improved heat insulation. The increase in savings of a better insulation method is the higher, the higher the heat costs. The cost-efficiency of improved heat insulation is often reached on large-scale pipes as soon as lower heat costs are faced (compared to those of small-sized pipes). In many areas of application, the insulation of pipes as per standard Insulation Series 1 today proves to be more cost-efficient than improved insulation. Primarily, high installation costs, lower operating temperatures, lower heat costs and high interest rates account for the selection of lower-level insulation.

In view of the current heat prices and high or medium installation costs (Germany, Denmark, and Sweden), heat insulation as per Insulation Series 1 stands for the most cost-efficient option, today. Only if the additional installation costs for improved insulation are on a low level is the application of Insulation Series 2 or, as the case may be, 3 useful. However, the additional costs cropping up due to the fact that a pipeline is not realized in keeping with the calculated most cost-efficient insulation, but with the next higher insulation series are relatively low (see Section 4.2.5).

4.5.1 Critical Evaluation of Calculations

Both the heat loss computations as well as the dynamic cost calculations were made on the basis of a couple of simplified assumptions which are resummarized in this section to give the reader a better understanding of the accuracy of the results. First of all, it should be pointed out that there is no problem in completely determining the impacts of temperature on the heat losses of district-heating networks which, at first sight, seem to be complex. If they are determined in consistent consideration of the temperature difference as defined in Section 3.1.2, it is possible to take into account both the impact of the design and/or operating temperatures as well as the influence of the climatic zone.

However, the requirement of adhering to specific mean values sets limits to the accuracy of the loss calculations. On the one hand, the calculations were conducted only in consideration of a mean heat conductivity coefficient fixed for the soil. On the other hand, the tolerances of the material, e.g. eccentricity of the pipes and the exact density of the PUR foam, were not taken into account, either. As regards the calculation of the impact of the ageing process, reference should be made to the circumstance that the exact diffusion coefficients are not known and that the calculation model holds some uncertainties, as well.

The results of the cost-efficiency calculations suffer from the uncertainties inherent in the forecasts for the future development of the interest rate and the future increase of energy prices. Finally, they cover a time horizon of 30 years. Experience gathered in connection with such estimates has often shown that, in the end, the actual development did not meet predictions; in most cases, the actual developments proved to be less favorable than expected.

In consideration of these reservations, the results contained herein should be regarded as trend statements which, in any particular case, need to be verified by way of exact studies. All in all, the presented results are confirmed by published national and international study results.

4.5.2 Recommendations for New Pipelines

Of the PUR foams today available on the market the CP foam (and, in the future, possibly also the new foam) seems to hold the best cost-efficiency potential. With their slightly lower material prices, the CO_2-foamed pipes do not really offer an advantage. Thanks to their excellent thermal properties, twin pipes stand for an especially beneficial option.

The calculations revealed that a minor deviation from the calculatory heat insulation optimum does not entail major cost disadvantages (total of investment and loss costs). Consequently, in consideration of the experience with increasing energy prices in the past, a forward-looking planning approach is recommended which provides for a changeover to the next higher insulation series even before reaching the cost-efficiency threshold (as soon as the marginal costs are underrun by 10% to 20%).

Part C: Heat Losses Within Installed Supply Grids

Against the backdrop of the economic significance which heat losses have for the operation of a district-heating network, it is important for the supply utility to evaluate the heat losses of its grid with regard to possible savings potentials. In keeping with Figure 2-2 of Section 2, the supply utility, in the end, has to find an answer to the question whether the operation of its district-heating system entails so-called ‘avoidable heat losses’ whose elimination would result in tapping relevant savings potentials.

The first step taken to answer this question consists of determining the actual volume of the heat losses of the relevant district-heating network. Thereafter, comparative or target values are determined. By comparing the determined actual volumes with the relevant target quantities, it is possible to establish whether avoidable heat losses occur on the district-heating network or not.

First, the present section concentrates on determining the actual state. Then, two methods are described with the aid of which it is possible to calculate relevant values for the comparison of target and actual performance for the district-heating network under review. Finally, the Mannheim district-heating network serves as an example to outline possibilities to reduce heat losses. In this context, the efficiency of these possibilities is evaluated, as well.

5 Determination of Actual State

It is not possible to directly measure the heat losses of an existing district-heating network. Hence, the actual state has to be determined by balancing the heat quantities fed into the district-heating grid against the heat volume purchased by the customers. Usually, to specify heat losses, the difference between fed and sold heat quantity is put in relation to the fed thermal energy and expressed in percent as depicted in the following equation:

$$\text{percentage of heat losses} = \left(1 - \frac{\text{sold heat quantity}}{\text{fed heat quantity}*}\right) \cdot 100\%$$

The percentage of heat losses or the distribution efficiency* quantifies the efficiency of thermal distribution. However, high network efficiency (i.e. a low percentage of heat losses) does not necessarily mean that absolute heat losses are low, as well. Moreover, it has to be taken into account that the relevant heat demand of the customers supplied with district-heating services has a major impact on the distribution efficiency [15].

As the heat losses of existing district-heating grids may only be determined by balancing measured values against each other, the applied measurement technology as well as the method of reading heat meters on the premises of the customers play a major part. The sections to follow focus on these aspects.

5.1 Accuracy of Heat Metering

In terms of its overall measurement inaccuracy, the applied measurement technology has to comply with the relevant legal requirements as operative at any given point of time. However, depending on the applied measurement method, measurement errors may vary within permissible limits.

The type of heat meters predominantly installed at MVV Energie on the premises of small customers (households, commercial firms) are single-flow impeller-type heat meters. As regards the attainable measurement inaccuracy, the design of in-house installations as well as the regulation and control equipment for substations play, apart from the design of the measurement equipment and optimal sensor pairing, a substantial role.

MVV Energie's practical experience shows that almost 100% of the currently installed novel single-flow impeller-type heat meters used for low-performance metering operate within set gauging error tolerances, even after a useful life of more than 5 years (standard calibration period). Hence, it is possible to draw the conclusion that in the course of a useful life of five years the measurement inaccuracy of the single-flow impeller-type heat meters installed within the Mannheim district-heating system lies, as a rule, within a range of ±5%. A large number of heat supply measurements carried out within the district-heating network as well as preventive and qualified maintenance provided, it may be assumed that the systematic and non-systematic measurement inaccuracy occurring under real-life conditions during the 5-year useful life are, in all probability, distributed in an almost symmetric fashion around ±0% as quantity-weighed sum.

In the Nordic countries there are experiences that heat meters installed at small customers show a negative error on measurement during the 5-year useful life. This would have the effect that the value of the balanced percentage of heat losses will exceed the real value.

On the premises of industrial customers and for measuring the input of thermal energy fed into the district-heating grid, heat meters of various measurement methods are used. In keeping with MVV Energie's experience, the following average total measurement inaccuracy may be allocated to the various types of heat meters:

* As it is usual, the energy quantity fed into the system via pump energy is not taken into consideration. It normally totals approx. 1% of the sold heat volume.

- Heat meter with hydrometric vane-type water meter, approx. ±4%
- heat meter with ultrasonic water meter (low performance) (q_p = 15 – 60 m³/h), approx. ±4%
- heat meter with ultrasonic water meter (high performance) (q_p > 60 m³/h), approx. ±1.8%
- heat meter with throttling equipment, approx. ±2%.

As there is normally a rather small number of thermal input points on a district-heating network and, at the same time, major heat quantities are measured, the measurement inaccuracy of the heat meters installed there may have a significant influence on the balanced heat losses of a district-heating grid. In consequence, qualified dimensioning and maintenance of the metering equipment used to measure thermal input are indispensable in this context.

5.2 Point of Time of Meter Reading

The method of heat meter reading, too, influences the balance of fed and sold thermal energy which is always put in relation to a specified study period:

- Monthly reading,
- annual reading,
- fixed-date reading with remote readout, and
- calculation of the sold heat quantity on the basis of the input mass flow and the specified temperature difference.

In particular in connection with annual manual heat meter reading, it is not always possible to provide for an exact allocation of sold and fed heat quantities within the same review period. In order to ensure an efficient deployment of personnel charged with reading heat meters, heat meters are – to the extent possible – read at 12-month intervals; however, reading takes place all over the year. In extreme cases, this periodically alternating heat meter reading method leads to the result that the consumption of a customer is, statistically speaking, allocated to the ‘wrong’ baseline year in terms of thermal input.
In general, fixed-date reading with remote readout may help avoid this problem, here. However, it is necessary to verify the cost-efficiency of this reading method in each individual case.

Within the Mannheim district-heating grid, heat meters of households and small-sized commercial consumers are read all over the year. Weighing customer groups in relation to the total heat sales revealed that, on the basis of the implemented reading system, about 25% of the total sold heat quantity is statistically allocated to the ‘wrong’ baseline year.
The greatest error may occur, if a year marked by an extremely high volume of purchased heat is followed by a period marked by an extremely low quantity of purchased heat, or *vice versa*. This situation causes a fluctuation range of the balance heat losses which, in extreme cases, may total ±1.4%. However, as such extreme heat purchase fluctuations occur rather rarely in the context of two successive review periods, MVV Energie’s periodically alternating heat meter reading system normally accounts for a statistical error of only ±0.1% to ±0.2%.

6 Determination of Comparative Values

6.1 Detailed Engineering Calculations

Relevant comparative and/or target values may be obtained by way of detailed engineering calculations of the pipeline losses on the basis of the interrelationships already comprehensively outlined in Part A. In this context, the calculations need to consider the characteristics of the relevant district-heating network, namely the grid length of the respectively applied laying technology, including the specific distribution of the installed nominal diameters, the laying conditions (coverage, type of soil), the ageing process of the insulation system, as well as the real-life operation mode of the district-heating system. With the aid of this detailed, but laborious method, it is possible to quantify the volume of the so-called ‘theoretic heat costs’ and ‘tolerable heat costs’ in keeping with Figure 2-2. As to the calculation of heat losses occurring on different installation systems (district-heating pipelines in hooded channels or foamed concrete – Thermocrete), relevant calculation bases may be found in relevant technical publications [19, 20].

6.2 Comparison With Other District-Heating Grids

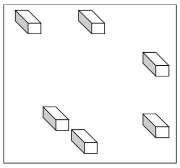
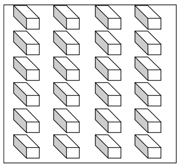
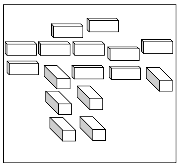
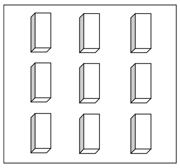
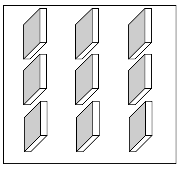
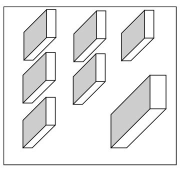
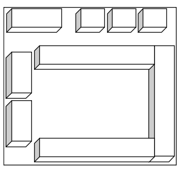
Relevant comparative and/or target values may also be obtained by way of comparison with other similar district-heating networks. This method is obviously less accurate than the detailed calculation of pipeline losses, yet it is less time-consuming.

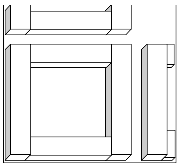
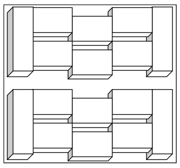
Apart from the general physical and technical setting of a distribution network, the type of populated area supplied with district-heating also influences heat losses. This aspect should be taken into account when comparing district-heating networks with each other and forms the focus of attention in the ensuing section.

6.2.1 Influence of Settlement Structure

The characterization of the settlement structure of an area supplied with district-heating services may be determined by way of classification. In this context, a settlement class is defined as a pattern of constructed forms conceived in keeping with urban development considerations with the aid of which it is possible to identify common construction and settlement forms. For an in-depth deduction and description of the calculation bases of the individual settlement classes, reference is made to [17].
The table to follow shows the individual settlement classes and offers a short description. Moreover, the table lists the characteristic percentage of heat losses of the relevant settlement class.
The calculation of heat losses was based on the coverage of the heat demand differing in each individual settlement class. Moreover, it was assumed that district-heating supply services are provided for an area of 1 km² each. The characteristic arrangement of the supplied buildings and the related heat demand call, depending on the relevant settlement class, for different pipe lengths as well as different mean nominal diameters. The heat losses indicated in Table 6-1 were calculated by putting the determined pipeline losses in relation to the required heat demand. In this context, the listed heat losses refer to the application of preinsulated plastic jacket pipelines of Insulation Series 1 (λ_{PUR}= 0.025 W/(m·K), ΔT_m= 55 K).
For a comprehensive characterization of the individual settlement classes, please see Appendix 5.

Table 6-1: Description of settlement classes [17]

Settlement class	Isometric representation	Short description	Heat losses
ST1 – Scattered settlements		ST1 is characterized by loosely scattered and irregular development, mostly small-sized buildings. This settlement class is found on the outskirts of cities and in suburban municipalities, mostly, however, in form of strung-out villages located along roads in rural areas.	23%
ST2 – Settlements of detached family houses		ST2 covers settlements of detached family houses located on the outskirts of cities and in suburban municipalities, mostly equipped with a dense, geometrically arranged development network.	11%
ST3 – Village Centers		ST3 categorizes villages in rural areas or concentrated along thoroughfares, and former village centers in cities.	9%
ST4 – Settlement of terraced houses		ST4 typifies settlements of terraced houses almost always showing close-meshed geometric development, on the outskirts of cities and in suburbs. The buildings are arranged mainly in a dense and parallel fashion.	6%
ST5 – Blocks of flats, 3-5 floors		ST5 comprises 3- to 5-storey residential buildings. A major share of the residential buildings erected after 1945 may be allocated to ST5. Depending on their age, these buildings are found mainly on the outskirts of large and medium-sized cities.	6%
ST6 – Multi-storey buildings and major linear buildings		Multi-storey buildings and major linear buildings make up a single settlement class, as they are mostly found next to each other within cities and thus form a coherent settlement structure. Typical of ST6 are large building distances, a large-meshed development network; moreover, they are located on the outskirts of cities.	3%
ST 7 – Urban peripheral settlements		ST7 categorizes urban multiple dwellings, located almost exclusively in major cities as well as in areas bordering city centers. Typical features include the spacious, central in-block open spaces and the main orientation of the apartments towards the street/road.	5%

Settlement class	Isometric representation	Short description	Heat losses
ST 8 – High-density buildings in city centers		ST8 comprises two different building types: The historical or post-war developments and the highly voluminous commercial buildings of the 1960's and 70's.	3%
ST9 – Historical/old parts of cities		ST9 comprises the medieval city centers. The confined developments with their relatively high buildings show a high density and a development network full of nooks and crannies.	4%

6.2.2 Ratios Providing For Comparability

The comparison of heat losses of district-heating grids showing a similar network structure and operation mode offers network operators the possibility to evaluate the heat losses of their district-heating systems. To find an appropriate and comparable counterpart and to verify the comparability of district-heating networks, the ratios set forth hereunder may be helpful.

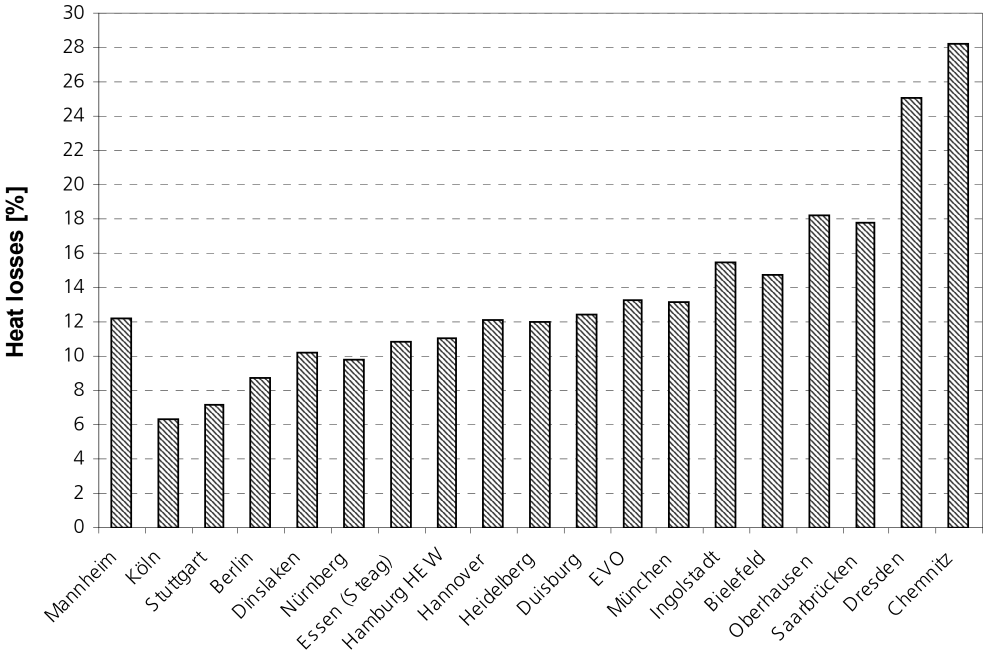
6.2.2.1 Specific Heat Losses

In order to draw conclusions on the technical conditions of the heat insulation system of a district-heating system from the values mostly indicated in percent, it is useful to put the difference of the fed and sold heat quantity in relation to the length of the pipeline. At the same time, it is possible to eliminate the influence of various pipeline lengths within the framework of the comparative analysis.

The calculation of the work-related specific heat losses expressed in MWh/($km_{Pipeline\ length}$·a) is based on the following equation:

$$\text{specific heat losses} = \frac{\text{fed heat quantity} - \text{sold heat quantity}}{\text{total pipeline length}}$$

Figure 6-1 exemplifies for various German district-heating networks the percentage of heat losses and the specific heat losses put in relation to the pipeline length. The statistics prepared by other national associations are similar to the findings depicted in the top diagram of Figure 6-1, e.g. in [9] and [10].
When analyzing Figure 6-1, it becomes transparent that the consideration of the pipeline length modifies the ranking from which a more reliable conclusion may be drawn on the condition of the heat insulation system of a district-heating grid.



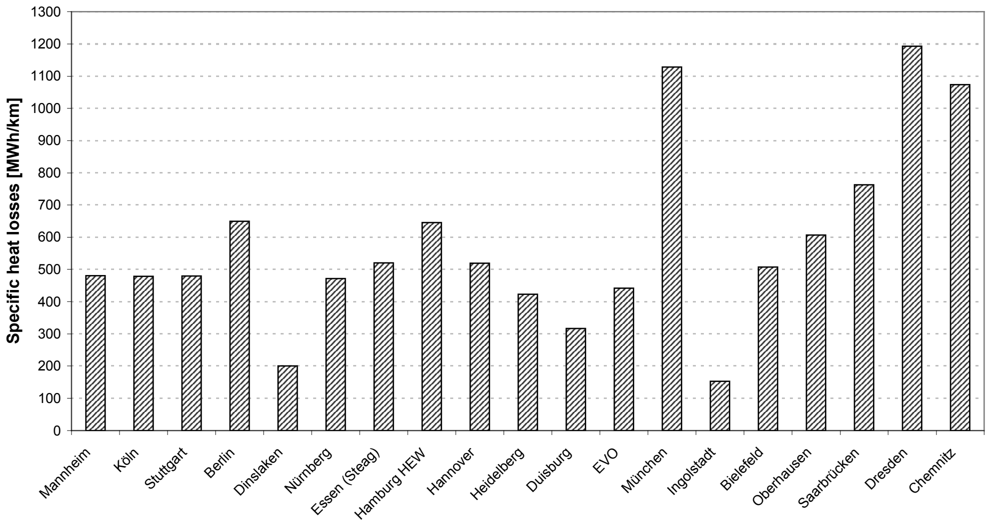


Fig. 6-1: Heat losses of district-heating networks in Germany
Top: In relation to fed heat quantity
Bottom: In relation to length of pipeline

The ratios to follow help to characterize the network structure.

6.2.2.2 Heat Density

The heat density (or density of heat demand) is expressed in $MWh/km_{\text{Pipeline length}}$ and can be determined on the basis of the formula to follow:

$$\text{heat density} = \frac{\text{sold heat quantity}}{\text{total pipeline length}}$$

To calculate heat density, the annual sold heat quantity is put in relation to the pipeline length of the district-heating network. The ratio so determined provides for a statement on the utilization of the district-heating network and thus specifies the efficiency of heat distribution.

Additionally, the number of service connections plays a major part when analyzing heat losses. The density of service connections stands for an indicator for the specific number of service connections.

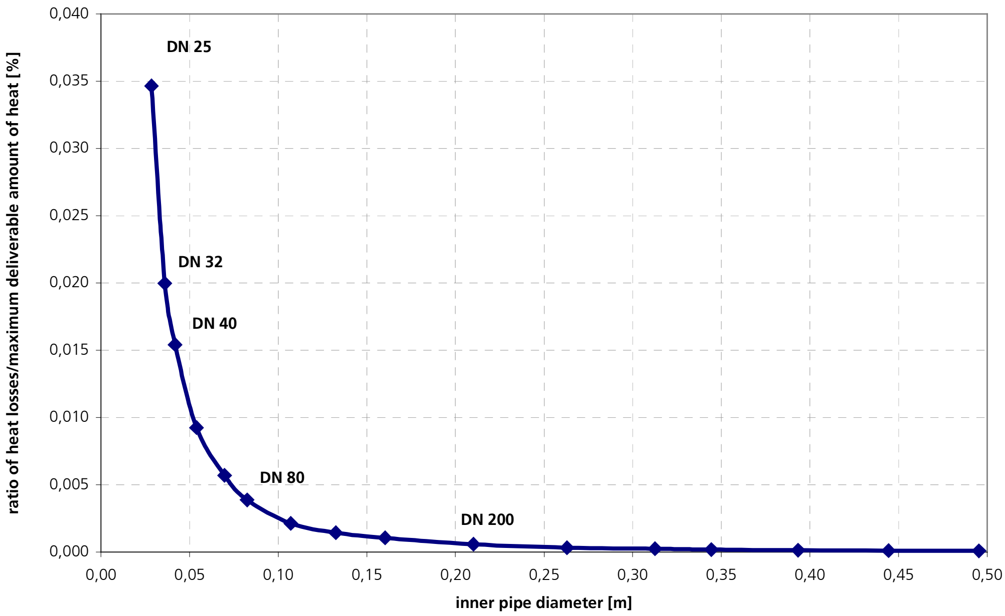
6.2.2.3 Density of Service Connections

$$\text{density of service connections} = \frac{\text{number of service connections}}{\text{total pipeline length}}$$

The density of service connections indicates the average number of consumers connected to the district-heating network per pipeline kilometer. The reciprocal value of this parameter helps specify what mean pipeline length is required to supply a customer. The density of service connections is of special relevance, as particularly pipes of smaller nominal diameters show, in relation to the transported energy quantity, higher heat losses than pipes of greater dimensions.

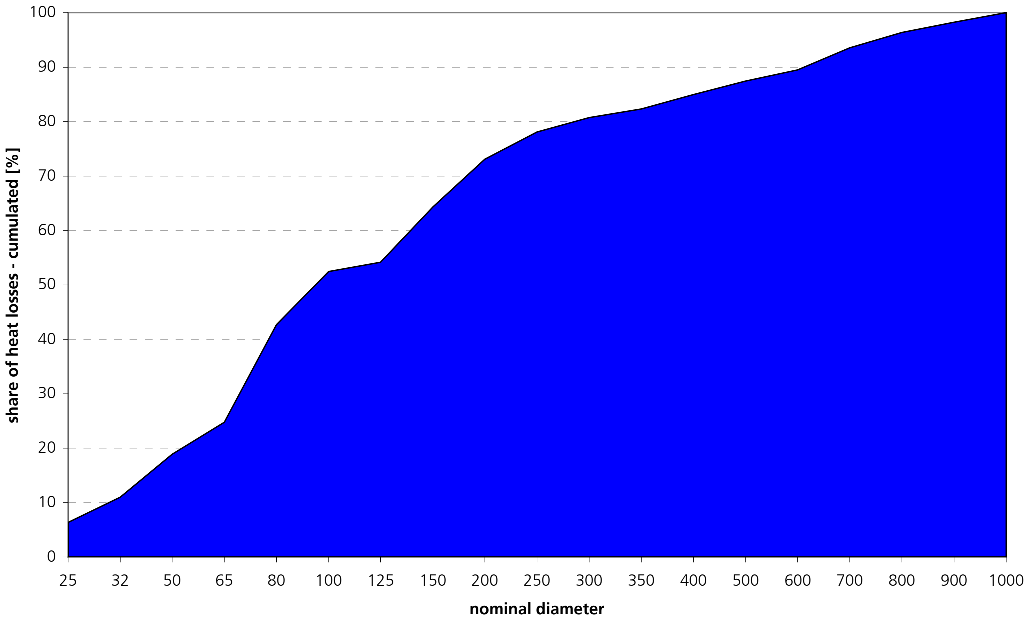
The diagram to follow depicts the relationship between specific heat losses and the maximum deliverable amount of heat for various pipeline dimensions.
The presented results were calculated for each pipeline meter composed of preinsulated plastic jacket pipes of Insulation Series 1 and containing PUR foam of a heat conductivity of $\lambda = 0.0288$ W/(m·K). Moreover, the mean driving temperature difference of $\Delta T_m = 63.8$ K as defined as standard case within the framework of this study was applied. The computation of the maximum deliverable amount of heat was made on the basis of a permissible specific pressure drop of 1 bar/km.
Similar results were obtained under other general operating conditions (Denmark) in [18].

Fig 6-2: Heat loss per pipeline meter in relation to the maximum transportable energy quantity



The impact of pipes of smaller dimensions on the overall losses becomes transparent, when incorporating the losses each nominal pipe diameter contributes to the overall losses of a district-heating network, see Figure 6-3. There it could be seen that only about 18% of the heat losses occur on pipes of up to DN 50, in spite of the large number of connected customers (Mannheim district-heating grid, mean nominal diameter: DN 150, number of connected customers: 11,764). The explanation for this is that the average length of each house service connection is short compared to the length of supply pipelines. This picture could be different in other countries, such as Denmark. In many Danish district-heating systems, the heat losses in house service connections could make up 30-40% of the total heat losses in the pipe system due to the fact, that many one family houses in scattered settlements are supplied with district heat.

Fig. 6-3: Share of heat losses of the individual nominal diameters in the overall losses of a major district-heating network – accumulated illustration



6.2.2.4 Mean Connected Heat Load

The value reflecting the mean connected heat load provides for a statement on the average heat demand of the supplied customers. If mainly major or industrial consumers are connected to the district-heating grid, the mean connected heat load will be considerably higher in comparison to district-heating networks by means of which predominantly detached houses for one or more families are supplied.

$$\text{mean connected heat load} = \frac{\sum \text{connected heat load of each customer}}{\text{number of supplied customers}}$$

6.2.2.5 Mean Nominal Diameter

The mean nominal diameter provides for a statement on the average pipe dimension installed within a district-heating network. The mean nominal diameter can be calculated as follows:

$$DN_m = \frac{\sum_i DN_i \cdot L_i}{L_{ges}}$$

6.2.3 Corrective Factors

The ratios presented in the preceding section should help network operators compare the balanced heat losses of their district-heating networks with other, similar district-heating grids.
If it is not possible to find suitable counterparts whose operation mode and network structure are similar to the ones of the grid under review, it is possible to determine the approximate target values for the heat losses of other district-heating grids by way of so-called corrective factors. The sections to follow outline the corrective factors for various operation modes and for various settlement structures.

6.2.3.1 Corrective Factor for Operating Temperatures

Here, reference should be made to the influence of the annual mean driving temperature difference ΔT_m already deduced in detail in Section 3.1.2 of Part A on the amount of heat losses. The usefulness of this ratio for the comparative evaluation of heat losses has already been described in depth there. Reference can be made to the diagram of Figure 3-3 to transfer the heat losses to district-heating networks whose structure is identical, but which are operated on different supply and return pipe temperatures and/or in different climatic zones.

6.2.3.2 Corrective Factor for Consumption Structure

When calculating approximate heat losses, the individual settlement classes can be taken into consideration by roughly subdividing the area supplied with district-heating into the relevant predominant settlement types (see Table 6-1). Then, the relevant share in the overall annual volume of sold heat is allocated to these settlement classes. However, this approach presupposes the availability of information about the settlement structure of the analyzed district-heating network as well as the share of the individual settlement class in the total volume of sold heat. Now, the percentage of heat losses of each settlement class is weighed with the shares in the total volume of sold heat. Summing up these weighed heat losses with the aid of the following equation results in a value reflecting the heat loss of the district-heating network.

$$Q_{Loss,total} = \sum_i x_i \cdot Q_{Loss,i}$$

In the above equation, x_i represents the share of the relevant settlement class in the overall volume of sold heat; $Q_{Loss,i}$ reflects the percentage of heat loss of the relevant settlement class.
On the basis of this method it is possible – to the extent the relevant data are available – to verify the indicated percentage of heat losses of district-heating networks and to compare them with each other.

The Mannheim district-heating network should serve as an example to illustrate this approach (Table 6-2).
In this specific case, the customer structure may be roughly subdivided into tariff-bound customers as well as major and bulk-rate clients. The settlement areas of the tariff-bound customers supplied with district-heating are composed of settlement classes ST1 – ST8. The settlement areas of major and bulk-rate customers may be roughly allocated to settlement class ST 6. In Mannheim, a large number of detached houses for one or more families located on the city’s outskirts was connected to the district-heating network. Against that backdrop, the relatively high heat loss of the ‘Tariff-bound customers’ consumer group can be explained.

Table 6-2: Customer structure and settlement classes of the Mannheim district-heating network

Customer group – Settlement class	Heat loss per customer group	Share in volume of sold heat
Tariff-bound customers (ST1 – ST8)	12%	50%
Major and bulk-rate customers (ST6)	3%	50%

In keeping with the equation indicated above and on the basis of the specified settlement structure for the Mannheim district-heating network, the percentage of heat losses totals approx. 8%. This result is roughly congruent with the balanced heat losses.

7 Options to Reduce Heat Losses

The section to follow focuses on evaluating alternatives as regards their potential to reduce heat losses on installed district-heating networks. The individual alternatives are exemplified on the basis of the Mannheim district-heating network.

The Mannheim district-heating network is a meshed dual-pipe high-temperature grid characterized by the specifications listed in the table below.

Table 7-1: Specifications of the Mannheim district-heating network

Operation mode:	Variable
Maximum supply temperature:	130°C
Pipeline length:	516 km
Applied laying technologies:	- 82% preinsulated plastic jacket pipelines, Insulation Series 1 - 2% hooded channel - 11% overhead/basement pipelines - 1% Thermocrete - 4% steel-jacketed pipes
Mean nominal diameter:	DN 150
Connected heat load:	2,135 MW
Number of customer substations:	11,764
of which directly operated customer substations:	6,618

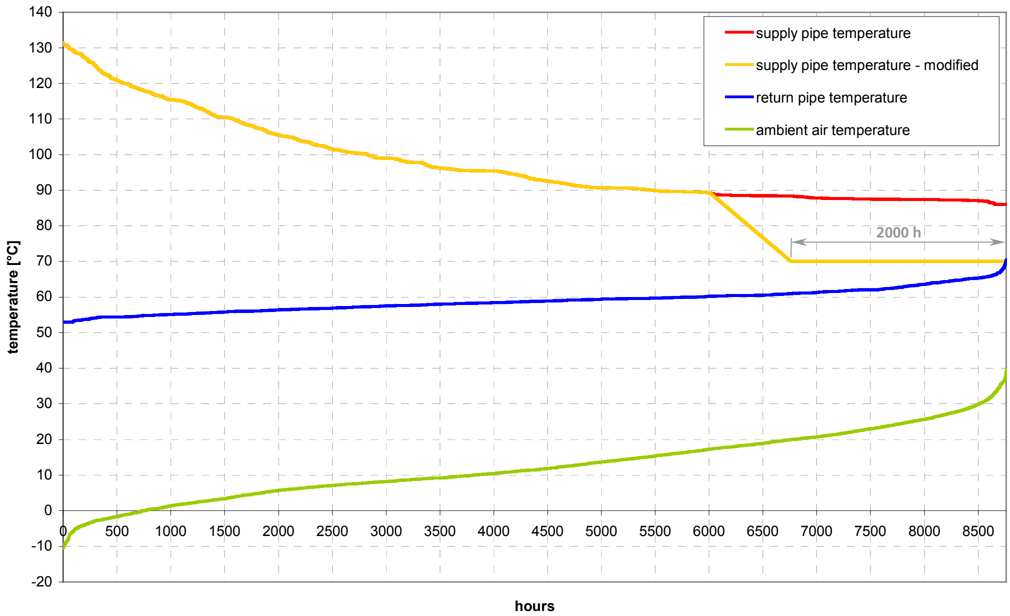
The options to reduce heat losses as presented further below aim at changing the operation mode of the district-heating network as well as implementing measures to subsequently insulate pipeline sections, in particular in shaft-type buildings.
The general possibility to increase the density of service connections to provide for a better utilization of the grid will not be analyzed in terms of heat losses here.

7.1 Decrease of Supply and Return Pipe Temperatures

The temperatures at which the high-temperature supply and return pipes are operated in the course of a year are material to the amount of heat losses. In part, district-heating networks have to be operated at higher supply pipe temperatures than it would be necessary to cover the relevant demand for heating energy. That holds true in particular for the operation mode during summer months. That is due to the district-heating-powered absorption chillers which require sufficiently high supply pipe temperatures (80°C – 90°C) in the summer. This situation also applies to the Mannheim district-heating network.

On the basis of the annual load duration graphs for the supply pipe, return pipe and outside temperatures depicted in the following figure, an attempt was made to determine to what extent the losses of district-heating grids can be reduced by lowering the supply pipe temperature during summertime. Reducing the supply line temperature in the summer months may also be realized by applying absorption chillers which are available on the market and which can be operated at lower supply pipe temperatures. In such case, the supply pipe temperature can be reduced for a period of approx. 2,000 operating hours.

Fig. 7-1: Annual load duration graphs of the Mannheim district-heating network



Additionally, an analysis was conducted to determine the contribution which the return pipe temperature can make to reduce heat losses.
The figure to follow depicts the calculation results which would be reached, in case of a theoretic decrease of the supply pipe temperature in the summer months (approx. 2,000 operating hours) and an all-year lowering of the return pipe temperature. The calculations made take into detailed consideration the type of installed systems and the relevant distribution of nominal diameters.

Table 7-2: Calculation results

Parameter	Saved heat losses
Decrease of supply pipe temperature during summer months (approx. 2,000 operating hours)	0.72 MWh/(K·km)
All-year decrease of return pipe temperature	2.67 MWh/(K·km)

In the concrete Mannheim case as analyzed here, decreasing the supply pipe temperature by 5 K during the summer months would lead to savings in the amount of € 15,000 p.a. An all-year lowering of the return pipe temperatures of the same scale would result in an annual cost-savings potential of approx. € 55,000.

The calculation results clearly show that an all-year temperature decrease, in particular of the return pipe temperature, constitutes an effective option to reduce heat losses. Appropriately dimensioned and optimally adjusted customer substations stand for the requirements for realizing return pipe temperatures at as low a level as possible.
In terms of magnitude, an all-year decrease of the supply pipe temperature would lead to the same effect as an all-year lowering of the return pipe temperature. However, due to the design of the district-heating pipelines to which a relevant heat demand is allocated, this option may only be realized within district-heating networks offering reserves with regard to the installed network hydraulics.

Moreover, it becomes transparent that an operation mode on the basis of increased supply pipe temperatures in the summertime does not substantially influence heat losses. Against that backdrop, lowering the supply pipe temperature in the summer months can only play a negligible part in reducing the heat losses occurring on existing district-heating networks.

7.2 Subsequent Insulation of Pipeline Sections in Shaft-Type Buildings

Subsequent insulation of pipelines in shaft-type buildings stands for another option to reduce heat losses on existing district-heating networks. In particular pipelines of a diameter of < DN 100 were, for cost reasons, often installed without insulation within shaft-type buildings.
For the purpose of determining the savings potential in terms of reduced heat losses, reference was made to the model of a district-heating system of a medium nominal diameter installed on the basis of the hooded channel technology as described in [20], whereby the length of non-insulated pipes was estimated to total 1.5 m/shaft.

The savings potential of approx. 4 MWh/(a·shaft) was calculated on the basis of the standard case of ΔT_m = 63.8 K assumed in this study. Depending on the heat costs and number of non-insulated pipeline sections within shaft-type buildings connected to the district-heating network, subsequent insulation of such pipes may very well prove to be a cost-efficient option to reduce heat losses within existing district-heating grids.

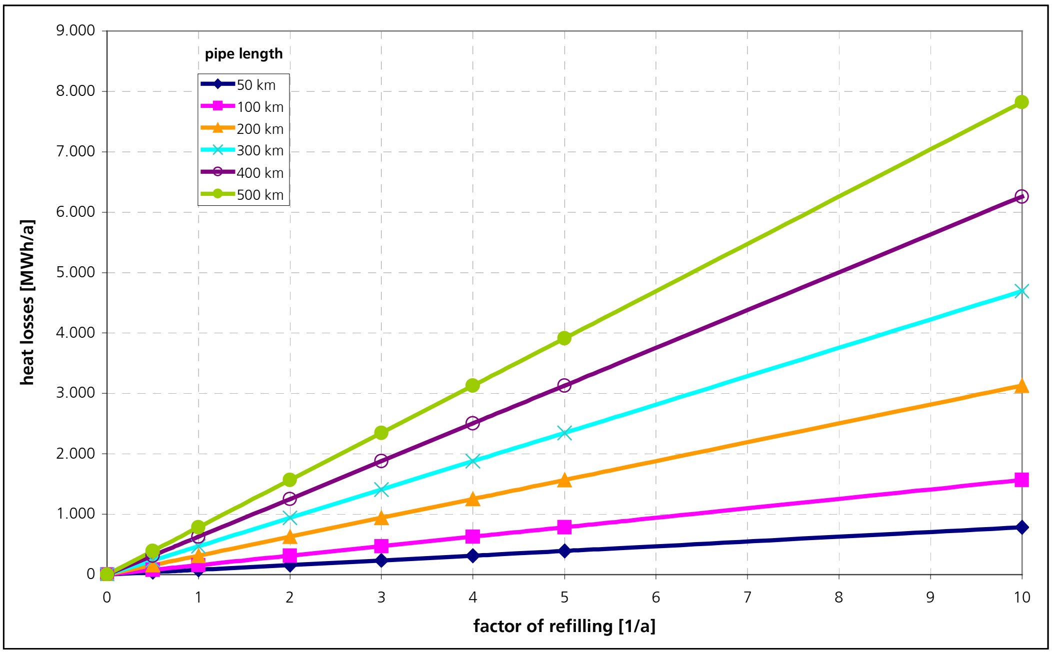
7.3 Change of Design Criteria for District-Heating Pipelines

In order to optimally dimension district-heating pipelines with regard to heat losses, two options may be adopted. On the one hand, pipes can be realized in a form meeting the requirements of a higher insulation series to reduce heat losses and thus to save operating costs. However, this option goes hand in hand with increased installation costs resulting therefrom (see cost-efficiency analyses in Part B).
On the other hand, the design principles for pipelines, in particular pipes of small nominal diameters, could be changed towards higher, permissible specific pressure drops. In this context, studies were conducted in Denmark [16]. Yet, it is necessary to consider that higher permissible pressure drops result in increasing the flow rate within the pipelines. That may lead to higher flow noise levels which, especially near substations, customers might find disturbing.

7.4 Reduction of Water Losses

Network water losses cause additional operating costs for district-heating networks. On the one hand, it is necessary to treat the heating water fed into the district-heating grid (demineralization, degasification), on the other hand, the volume of lost network water is equal to lost (i.e. not sold to customers) heat quantities, if heating water losses are caused by leaks on the supply pipes. Hence, unsold heat quantities should be regarded as heat losses.
The illustration to follow helps estimate the magnitude of heat losses resulting from water losses.

Fig. 7-2: Heat losses caused by network water losses



In this context, the annual refill factor stands for a ratio reflecting network water losses. It indicates how often the volume of the district-heating network has to be refilled in the course of a year to compensate for network water losses. As experience shows, the greater share of network water losses occurs on the supply pipe. Against that backdrop, the illustration in Figure 7-2 assumes that two thirds of the total water losses are the result of leaks along the supply pipe. Furthermore, the calculations were based on a mean nominal diameter of DN 150 to determine the network volume. The average temperature difference between supply pipe and return pipe totals 50 K. Additional heat losses due to wet thermal insulation are not considered here.

8 Summary of Part C

Due to the economic significance of heat losses, it is important to evaluate such losses occurring on existing district-heating networks.
In this context, balanced heat losses may be evaluated either on the basis of direct engineering calculations on the system or by comparing them with the values of other, similar district-heating grids. Here, it is possible to provide for comparability, by determining network-specific parameters comprehensively mirroring to the extent possible the general supply setting.

The structure of the relevant settlement area supplied with district-heating plays, with regard to heat losses, a material part and thus needs to be taken into account when evaluating heat losses.

Pipes of smaller nominal diameters show, in relation to the transported energy quantity, higher specific heat losses than pipes of greater dimensions.

Pipes with smaller diameter are mostly used for house service connections. In the case that the settlement structure of the supplied areas has a high site density the length of house service connections is generally speaking short. Therefore the contribution of these pipes to the overall heat losses of a district-heating network is small. If scattered settlements of small houses will be supplied with district heat, the heat losses of house service connections could make up 30 – 40% of the total heat losses.

To reduce heat losses, an all-year reduction of the supply pipe and/or return pipe temperature proves to be very effective.

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10 Appendices

CHALMERS

Appendix 1:

Investigation of the foam ageing process

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Report R-04:3
Work nr. 991

Introduction

As time passes the polyurethane foam ages and the insulating capacity of the foam decreases as the gas composition in the cells changes. In order to get an insulation of good performance, it is desirable to blow the foam with a gas that has low thermal conductivity and that stays in the cells of the foam for a long time. Since the 1990's cyclopentane with zero ozone depletion potential is used as blowing agent. Earlier fluorotrichloromethane (CFC-11) was used. Solely carbon dioxide blown pipes was used to achieve non-ozone depleting blowing during a short transitional period between CFC-11 and cyclopentane.

As long as there is a difference in partial pressure/concentration of the gas between the foam and its surroundings, the gas will strive to even out the difference. Hence, as time passes air will enter the foam of the district heating pipe and the blowing agent will leave the foam. Different gases are transported at different speeds through the materials of the pipe; the diffusion and permeability coefficients differ between the gases. A low value of the coefficient indicates that the transport is slow through the material and is consequently advantageous. For some of the gases most of the transport resistance is in the foam, while the casing contributes more to the resistance for others. For cyclopentane the main part of the transport resistance is attributable to the foam, while for carbon dioxide, nitrogen and oxygen the resistance of the casing dominates.

The initial cell gas content in the polyurethane foam of the pipes differs due to different polyurethane foam recipes and manufacturing methods. There might be liquid cyclopentane present in the pipes in the beginning that evaporates as cyclopentane leaves the foam. The Swedish National Testing and Research Institute (SP) has in 2004 measured the gas content at 25ºC in six different new preinsulated district heating pipes in an assignment for the Swedish District Heating Association. Liquid cyclopentane was found in two of the pipes. At use the pipes are exposed to higher temperatures. The vapour pressure of cyclopentane rises markedly with increased temperature, giving space for more cyclopentane in the cell gas. As the temperature increases the solubility of cyclopentane in the polyurethane matrix decreases and cyclopentane from the walls will be released to the cells. Condensed cyclopentane and cyclopentane from the walls adds to the cell gas.

This work package "Investigation of the foam ageing process " has been conducted at Chalmers University of Technology, Department of Building Technology and is part of the IEA-Annex VII "Strategies to manage heat losses- technique and economy" under the leadership of MVV Manheim.

Studied cases

The foam ageing process is investigated for cyclopentane, carbon dioxide and CFC-11 blown preinsulated district heating pipes of the following dimensions (see also Table 1 and Table 2):

- Single district heating pipes of steel pipe nominal diameter 25, 50, 80, 100, 150, 200, 300, 400, 600, 800 with series 1, 2 and 3 insulation.
- Twin district heating pipes of steel pipe nominal diameter 25, 50, 80, 100, 150.

Table 1. Dimensions of single pipes studied.

DN	Steel pipe outer diameter [mm]	Insulation series	Casing outer diameter [mm]	Casing wall thickness [mm]
25	33.7	1	90	3.0
		2	110	3.0
		3	125	3.0
50	60.3	1	125	3.0
		2	140	3.0
		3	160	3.0
80	88.9	1	160	3.0
		2	180	3.0
		3	200	3.2
100	114.3	1	200	3.2
		2	225	3.4
		3	250	3.5
150	168.3	1	250	3.5
		2	280	3.8
		3	315	4.1
200	219.1	1	315	4.1
		2	355	4.4
		3	400	4.7
300	323.9	1	450	5.1
		2	500	5.5
		3	560	6.0
400	406.4	1	560	6.0
		2	630	6.5
		3	710	7.1
600	610.0	1	710	7.1
		2	800	7.8
		3	900	8.6
800	813.0	1	900	8.6
		2	1000	9.4

Table 2. Dimensions of twin pipes studied.

DN	Steel pipe outer diameter [mm]	Casing outer diameter [mm]	Casing wall thickness [mm]
25	33.7	140	3.0
50	60.3	200	3.2
80	88.9	250	3.5
100	114.3	315	4.1
150	168.3	450	5.1

Calculation strategy

The foam ageing process was investigated by assuming:

- A constant contribution from radiation and heat conduction through the polymer matrix of 0.012 W/(m·K) [1].
- A varying contribution from heat conduction through the cell gas, due to diffusion of the gases. The contribution from cell gas conduction was calculated using Brokaw's method with the coefficient 0.5 [2]. The gas diffusion was modelled as if all gas transport resistance was in the casing using an effective permeability of the casing (including both foam and casing resistance) [1][3].

In Table 3 the assumed initial partial pressures in the foams are presented. Table 4 illustrates the permeability coefficients used, while Table 5 shows the thermal conductivities applied for the gases.

Table 3. Initial partial pressures at 50ºC.

Gas	Partial pressure in cyclopentane blown foam [kPa]	Partial pressure in carbon dioxide blown foam [kPa]	Partial pressure in CFC-11 blown foam [kPa]
Oxygen	0.5	0.5	0.5
Nitrogen	1	1	1
Carbon dioxide	90	140	80
Cyclopentane	50	0	0
CFC-11	0	0	60

Table 4. Permeability coefficients.

Gas	Permeability coefficient [mol/(m·s·Pa)]
Oxygen	$4.1 \cdot 10^{-17}$
Nitrogen	$5.3 \cdot 10^{-17}$
Carbon dioxide	$55 \cdot 10^{-17}$
Cyclopentane	$6.2 \cdot 10^{-17}$
CFC-11	$6.2 \cdot 10^{-17}$

Table 5. Thermal conductivities at 50ºC.

Gas	Thermal conductivity [W/(m·K)]
Air	0.0278
Carbon dioxide	0.0180
Cyclopentane	0.0145
CFC-11	0.0110

Calculation results

Figures that show the ageing of the polyurethane foam of cyclopentane, carbon dioxide and CFC-11 blown pipes are given in Appendix 1. The insulating capacity of the carbon dioxide blown foam decreases more quickly than the insulating capacity of the other foams. The average thermal conductivities over 50 years are presented in Table 6 for single pipes and in Table 7 for twin pipes.

Table 6. Average thermal conductivity over 50 years of use of the single pipes.

Pipe dimension DN	Insulation series	Thermal conductivity of cyclopentane blown [W/(m·K)]	Thermal conductivity of carbon dioxide blown [W/(m·K)]	Thermal conductivity of CFC-11 blown [W/(m·K)]
25	1	0.037	0.039	0.036
	2	0.037	0.039	0.035
	3	0.036	0.039	0.034
50	1	0.037	0.039	0.035
	2	0.036	0.039	0.034
	3	0.035	0.039	0.034
80	1	0.036	0.039	0.035
	2	0.035	0.039	0.034
	3	0.035	0.038	0.032
100	1	0.035	0.039	0.033
	2	0.034	0.038	0.032
	3	0.034	0.038	0.031
150	1	0.035	0.039	0.033
	2	0.034	0.038	0.031
	3	0.033	0.037	0.030
200	1	0.034	0.038	0.031
	2	0.032	0.037	0.030
	3	0.031	0.036	0.028
300	1	0.032	0.037	0.029
	2	0.031	0.036	0.028
	3	0.030	0.034	0.027
400	1	0.032	0.036	0.028
	2	0.030	0.034	0.027
	3	0.030	0.033	0.027
600	1	0.032	0.037	0.029
	2	0.030	0.034	0.027
	3	0.029	0.032	0.026
800	1	0.032	0.037	0.029
	2	0.030	0.033	0.027

Table 7. Average thermal conductivity over 50 years of use of the twin pipes.

DN	Thermal conductivity of cyclopentane blown [W/(m·K)]	Thermal conductivity of carbon dioxide blown [W/(m·K)]	Thermal conductivity of CFC-11 blown [W/(m·K)]
25	0.036	0.039	0.034
50	0.035	0.038	0.032
80	0.034	0.038	0.031
100	0.032	0.037	0.030
150	0.031	0.036	0.028

References

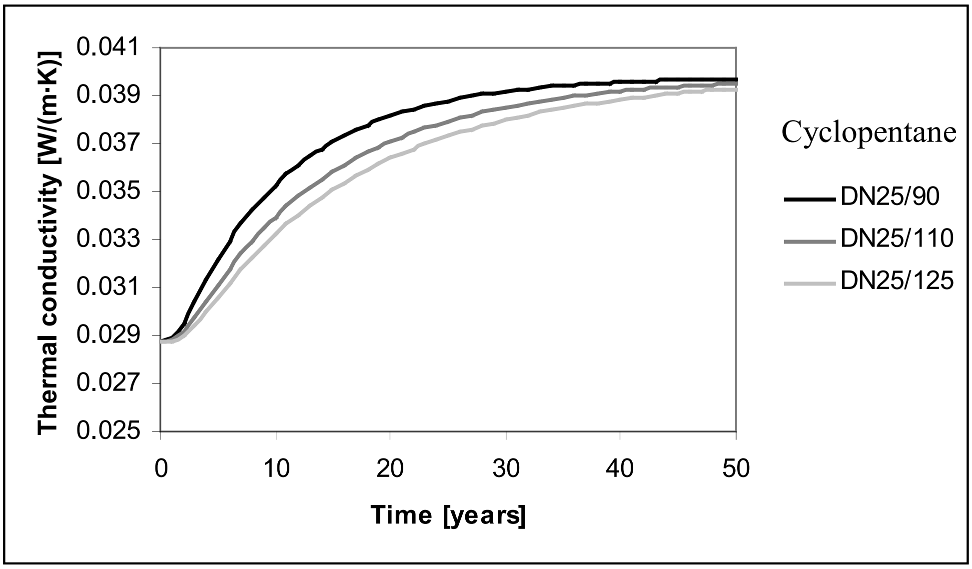
[1] Jarfelt U. (1998) Field measurements of Gas Diffusion from District Heating Pipes, Thermal Insulation Gas Diffusion Report 8, Department of Building Physics, Chalmers University of Technology; Sweden.

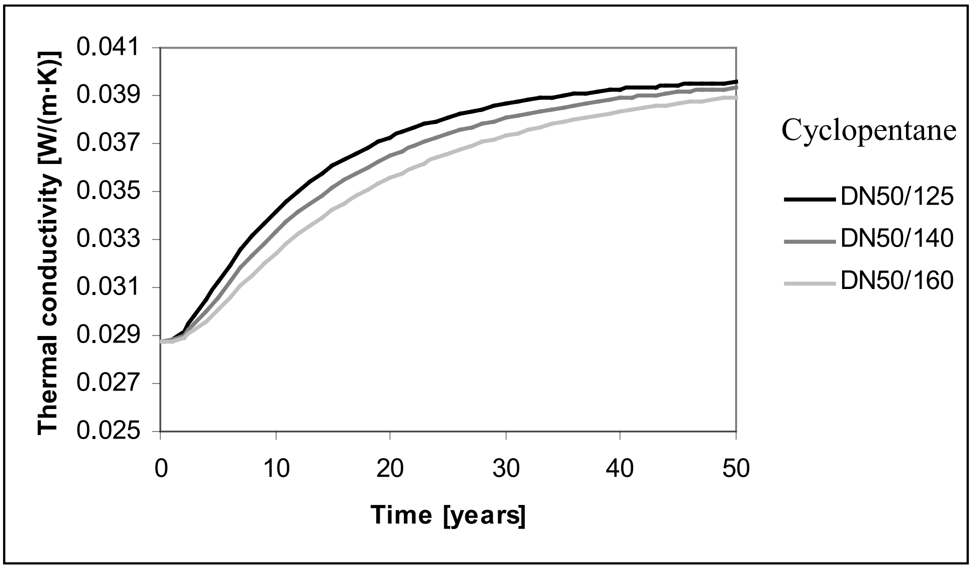
[2] Isberg J. (1988) The Thermal Conductivity of Polyurethane Foam, Doctoral thesis, Division of Building Technology, Chalmers University of Technology, Sweden.

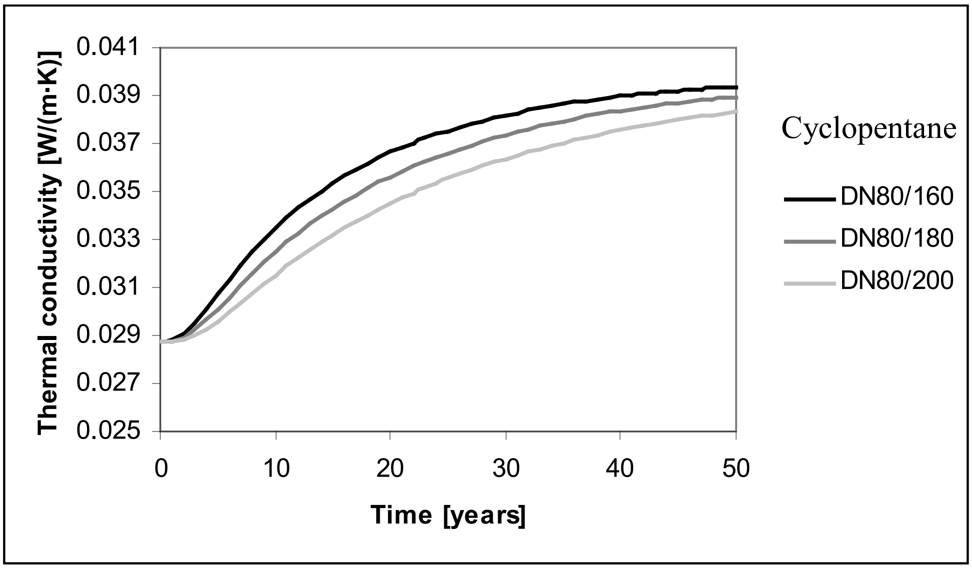
[3] Ekodim calculation programme – is it profitable to insulate more? Report 2002:69 and calculation programme available via the Swedish District Heating Association.

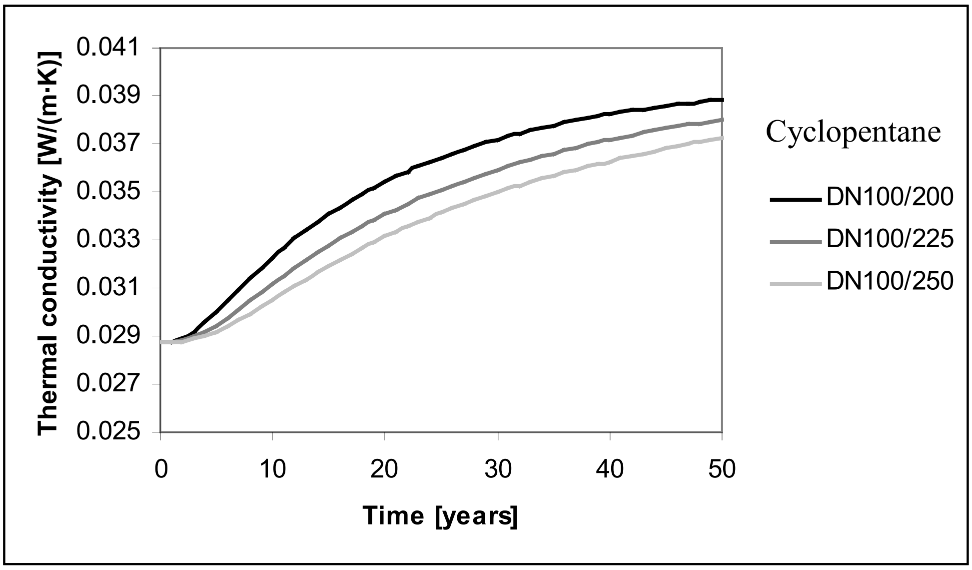
Thermal conductivity vs time for polyurethane foam of cyclopentane, carbon dioxide and CFC-11 blown pipes.

Cyclopentane blown:









Thermal conductivity [W/(m·K)]
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0.039
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0.033
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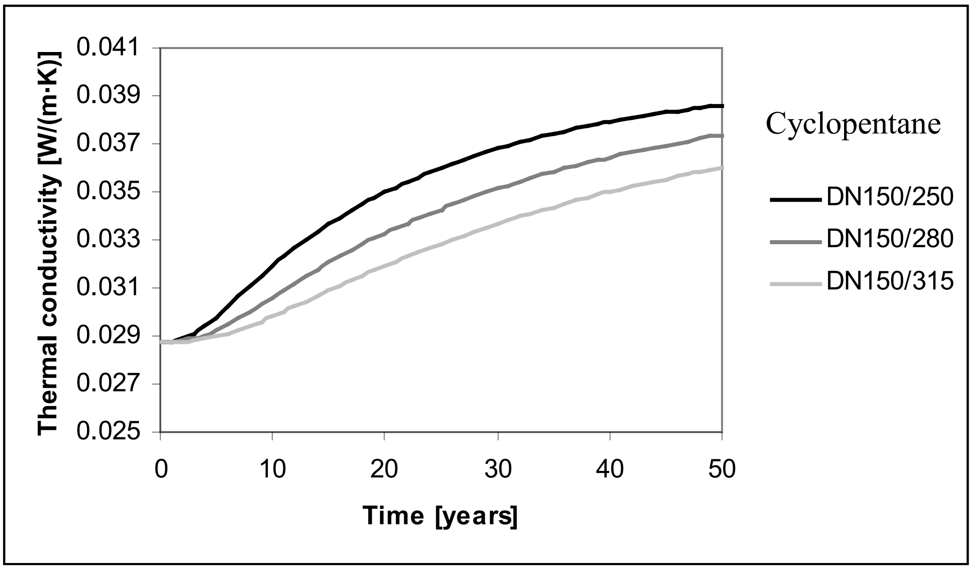
10
20
30
40
50
Time [years]
Cyclopentane
DN100/200
DN100/225
DN100/250



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40
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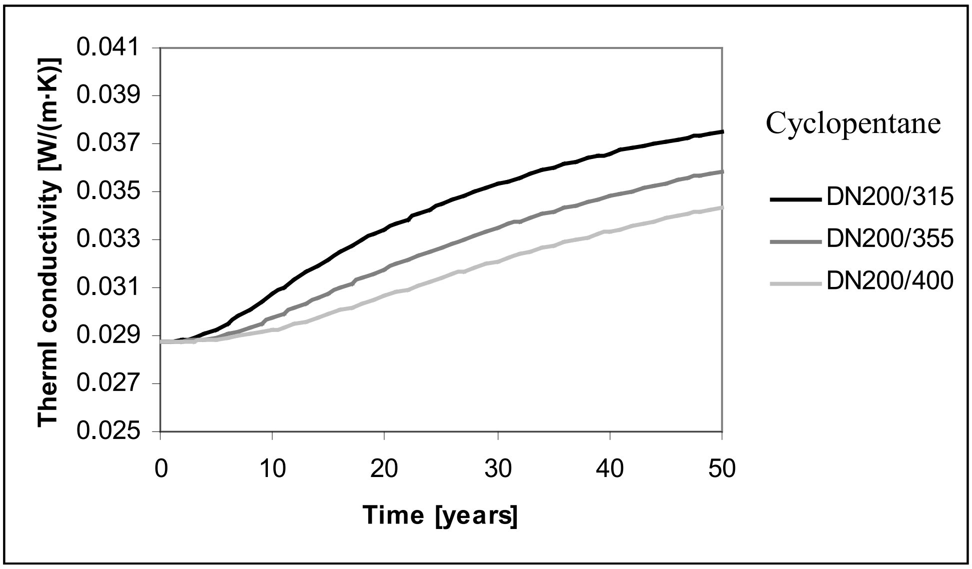
Time [years]
Cyclopentane
DN150/250
DN150/280
DN150/315



Therml conductivity [W/(m·K)]
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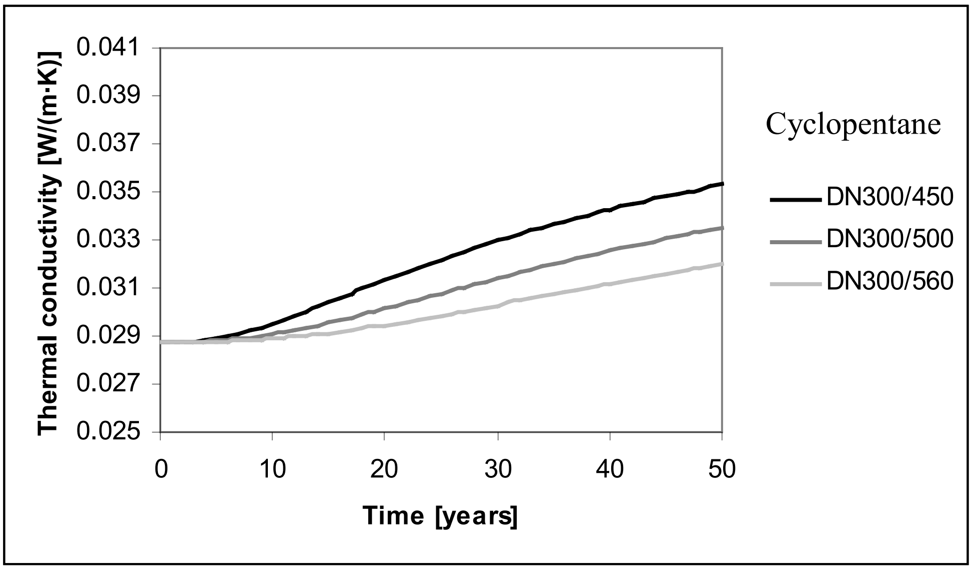
Time [years]
Cyclopentane
DN200/315
DN200/355
DN200/400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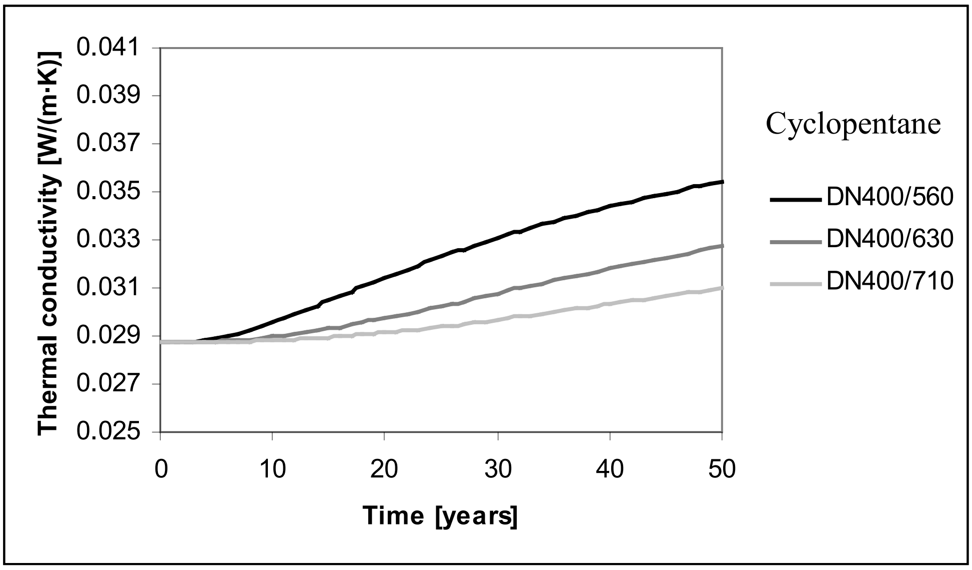
Time [years]
Cyclopentane
DN300/450
DN300/500
DN300/560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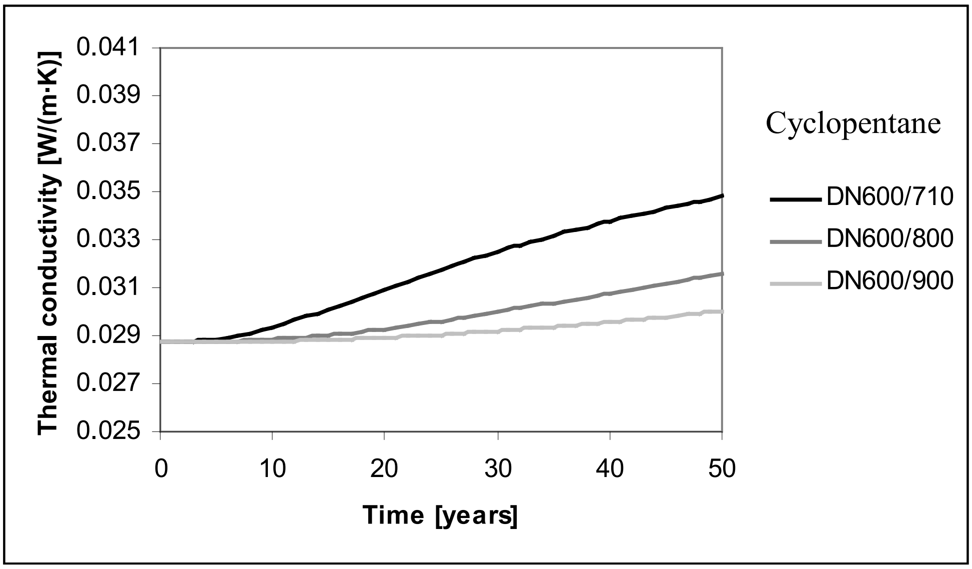
Time [years]
Cyclopentane
DN400/560
DN400/630
DN400/710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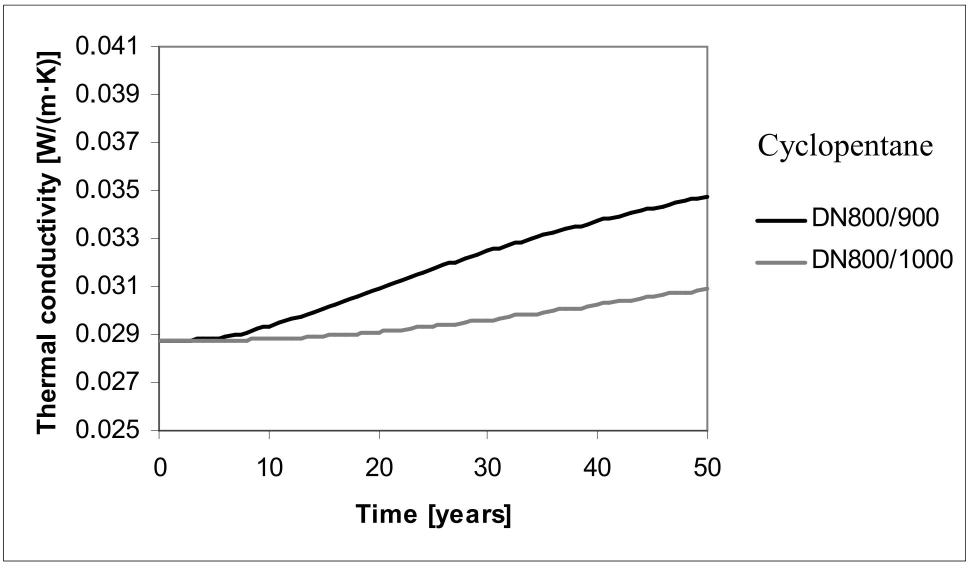
Time [years]
Cyclopentane
DN600/710
DN600/800
DN600/900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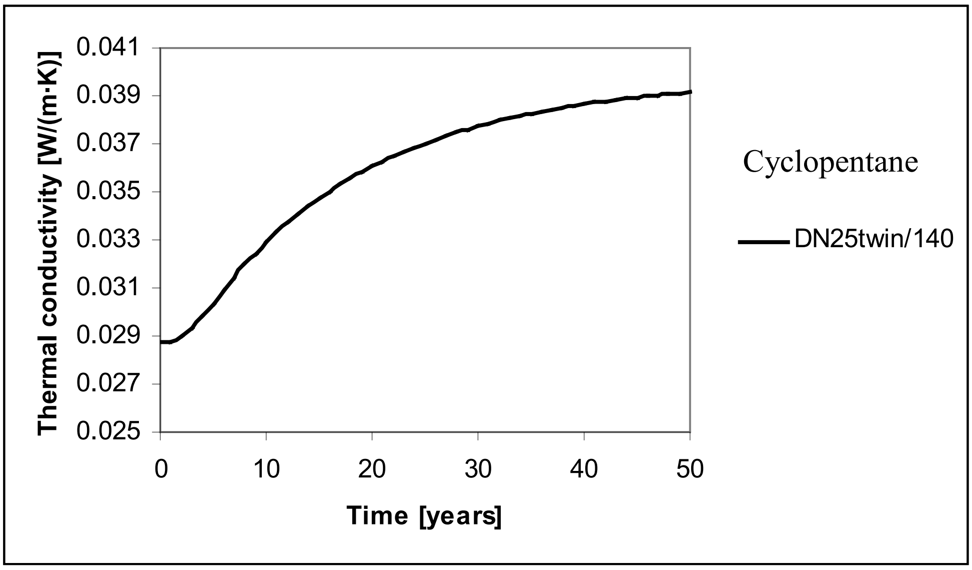
Time [years]
Cyclopentane
DN800/900
DN800/1000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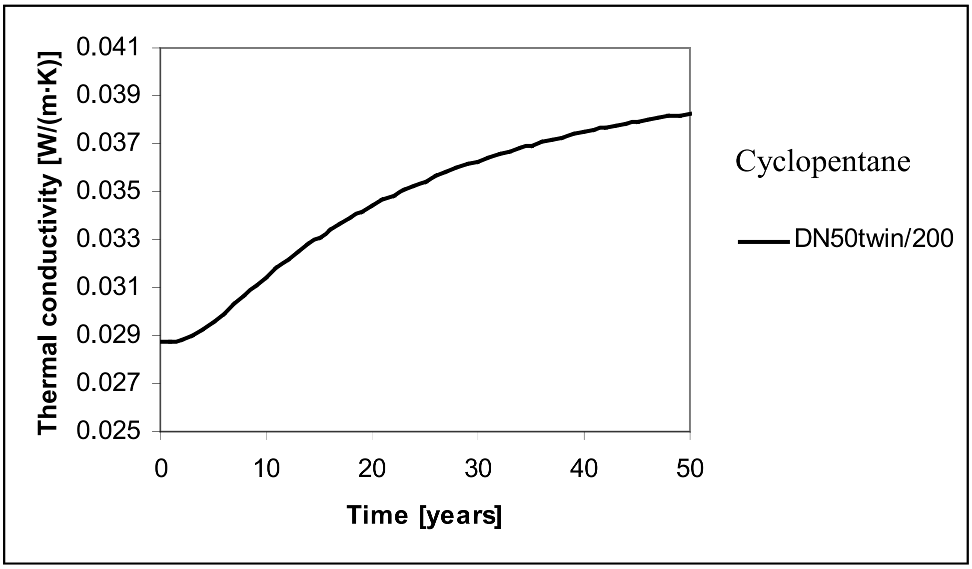
Time [years]
Cyclopentane
DN25twin/140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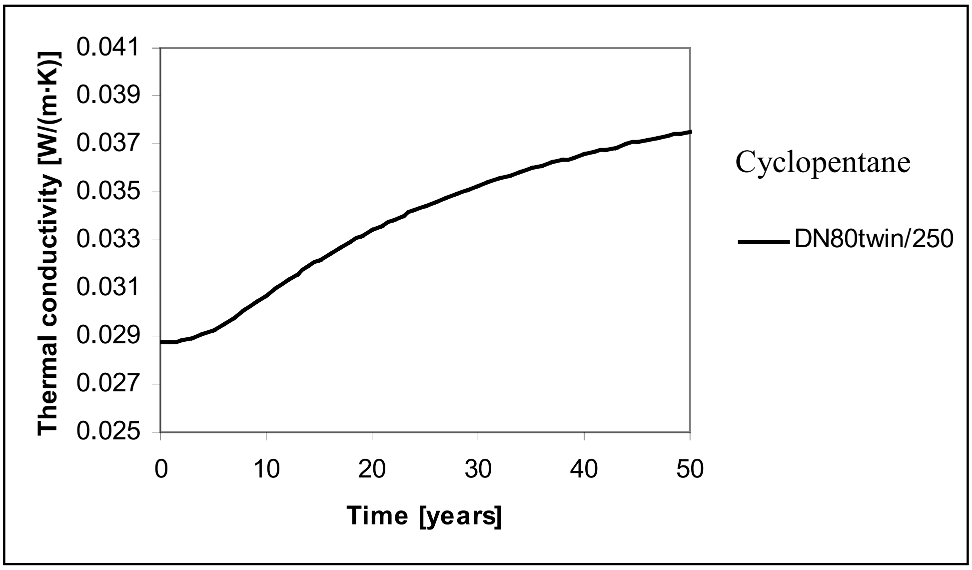
Time [years]
Cyclopentane
DN50twin/200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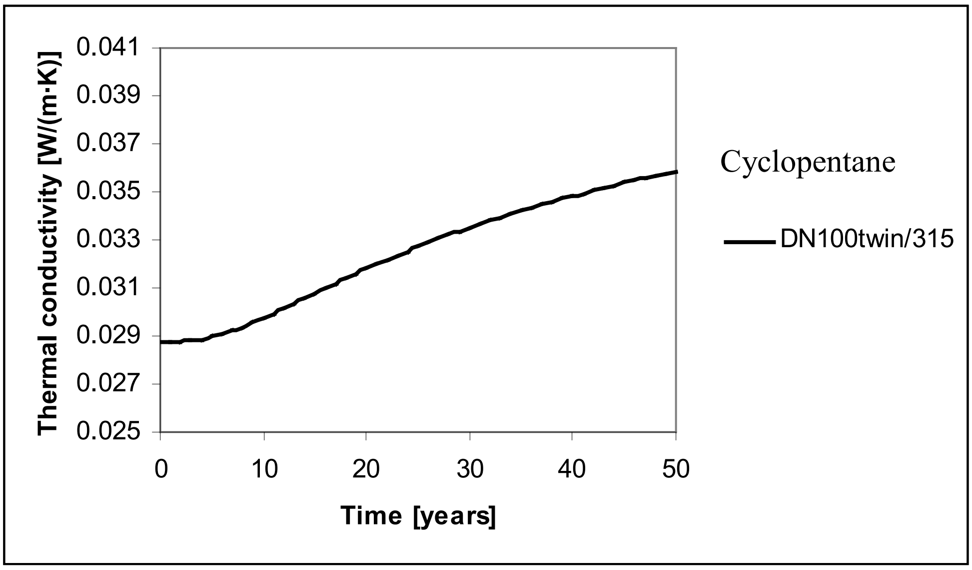
Time [years]
Cyclopentane
DN80twin/250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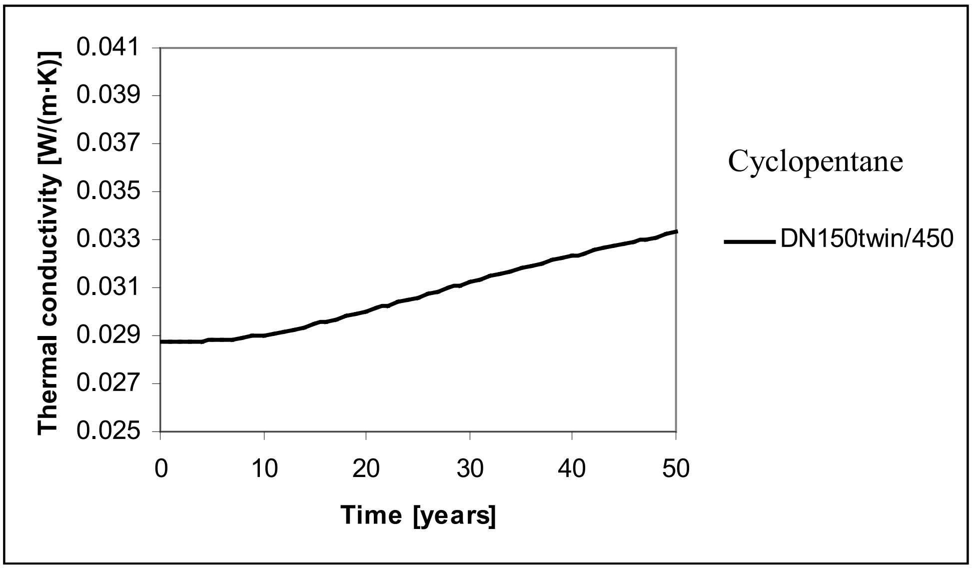
Time [years]
Cyclopentane
DN100twin/315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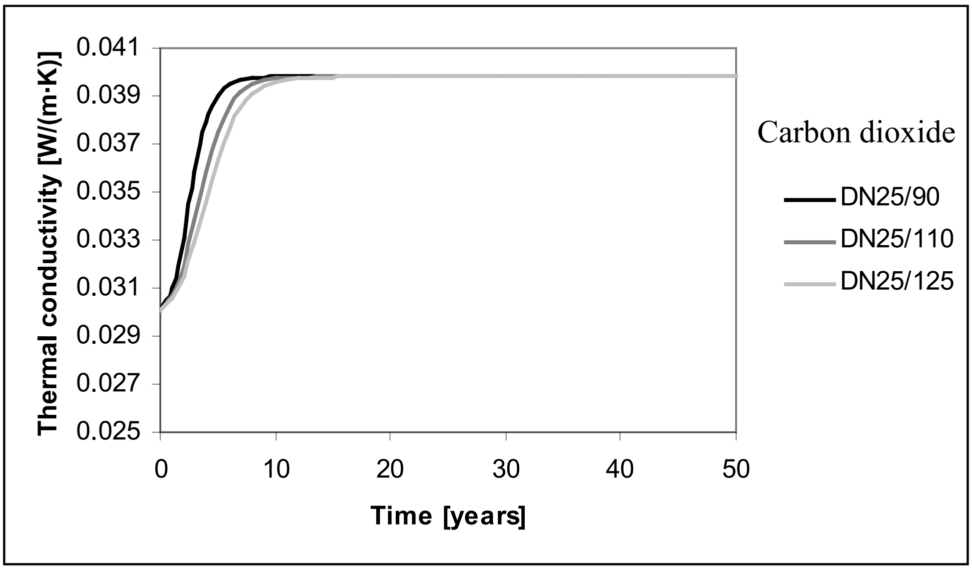
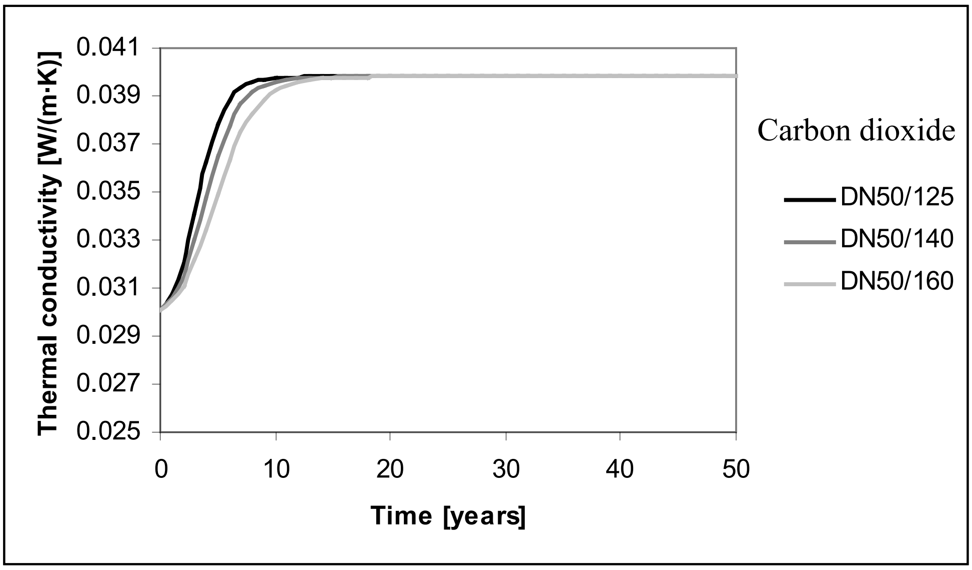
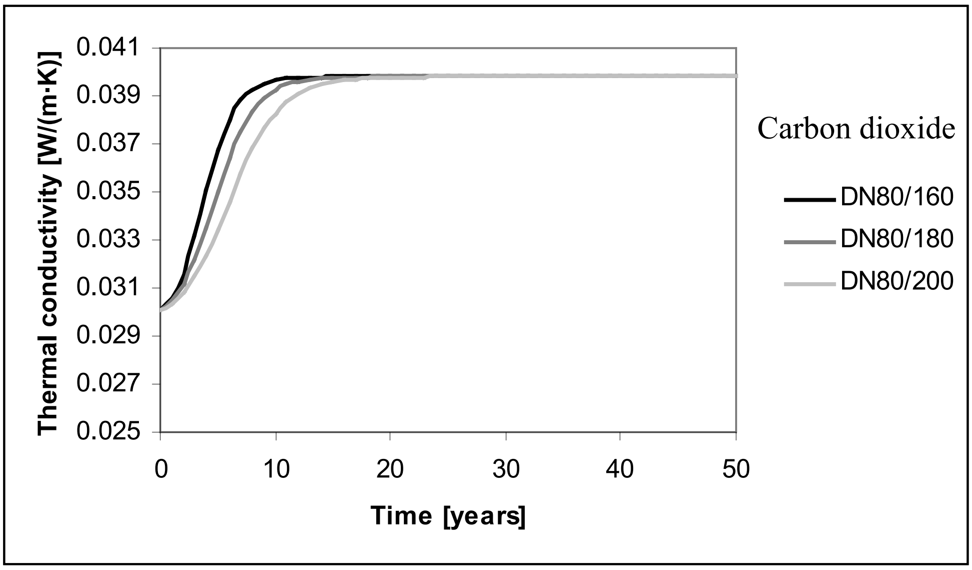
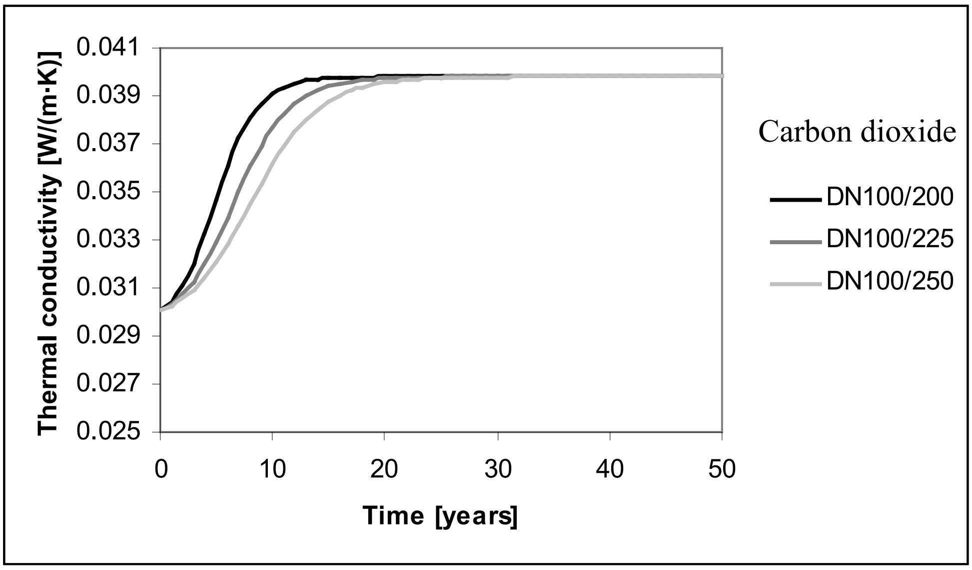
Time [years]
Cyclopentane
DN150twin/450

Carbon dioxide blown:





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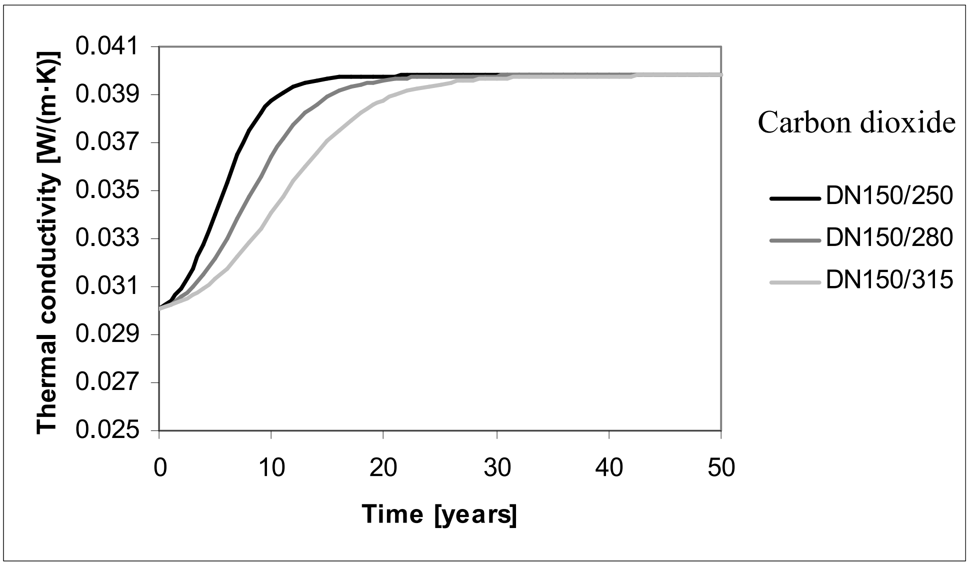
Time [years]
Carbon dioxide
DN100/200
DN100/225
DN100/250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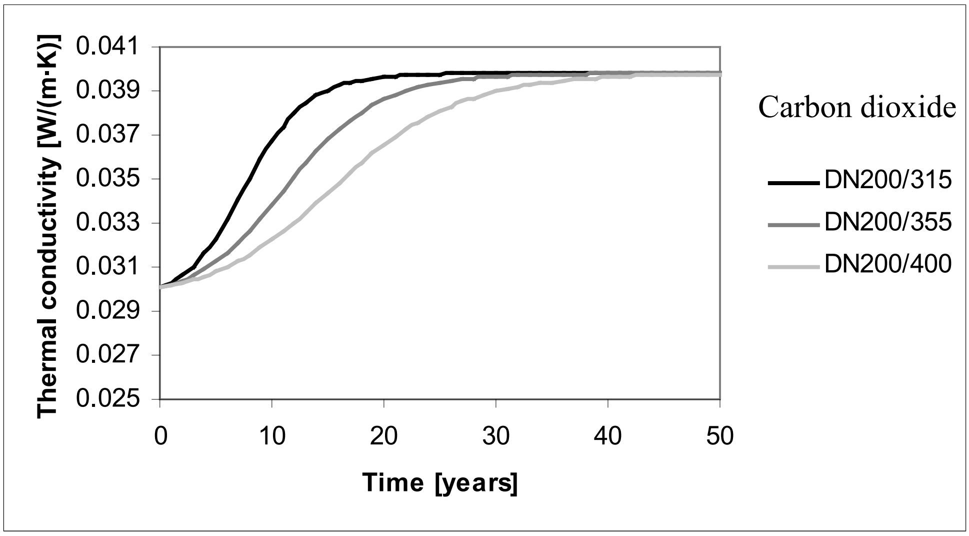
Time [years]
Carbon dioxide
DN150/250
DN150/280
DN150/315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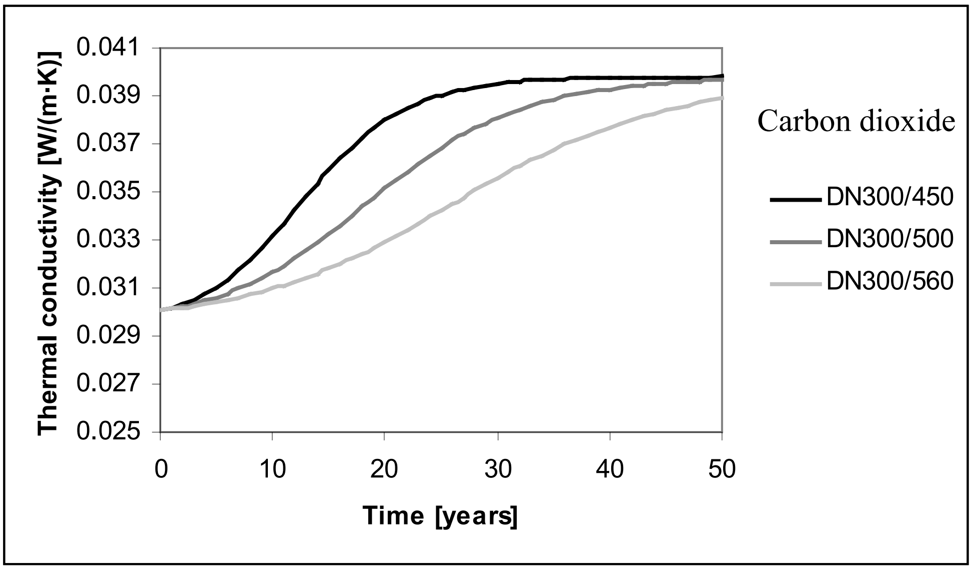
Time [years]
Carbon dioxide
DN200/315
DN200/355
DN200/400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Time [years]
Carbon dioxide
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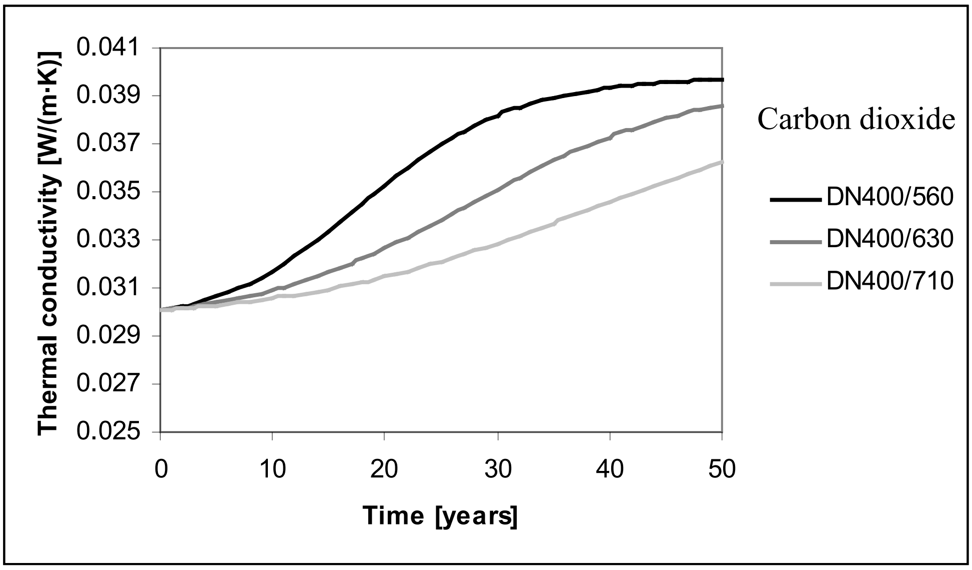
DN300/500
DN300/560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Time [years]
Carbon dioxide
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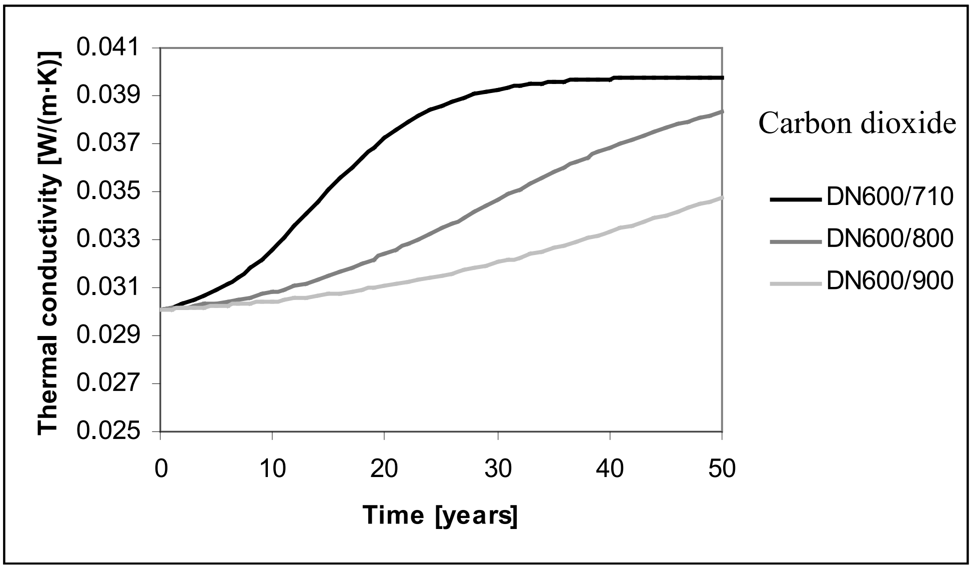
DN400/630
DN400/710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Time [years]
Carbon dioxide
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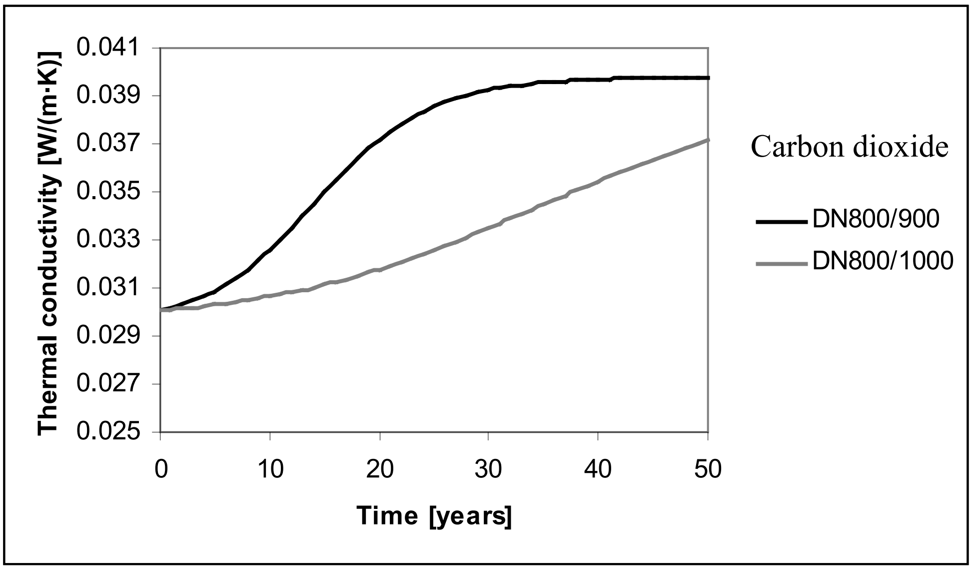
DN600/800
DN600/900



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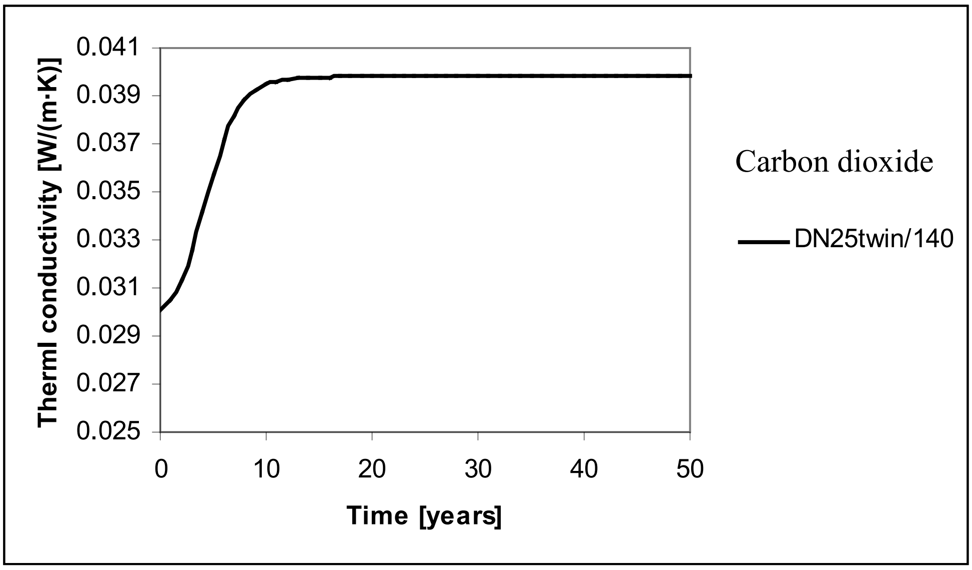
Time [years]
Carbon dioxide
DN800/900
DN800/1000



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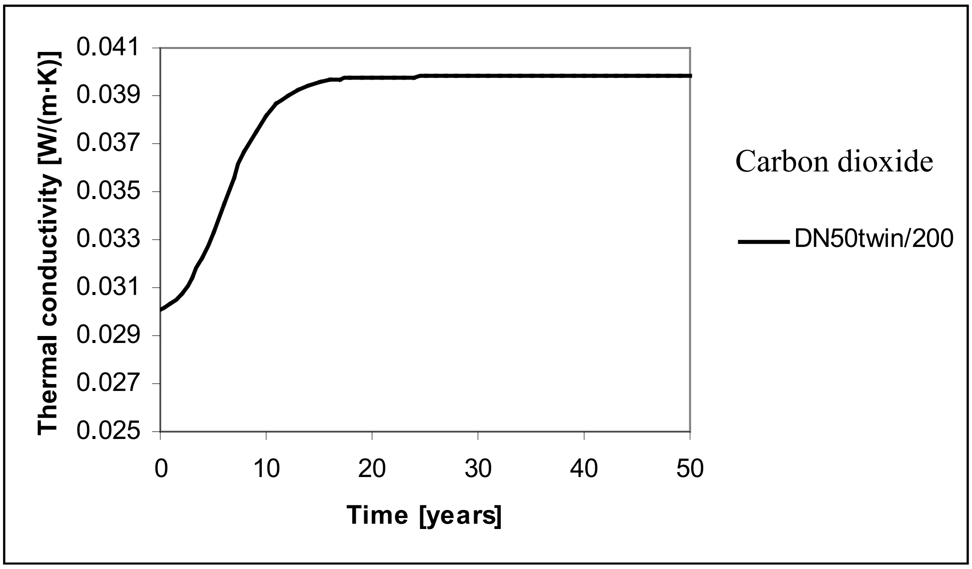
Time [years]
Carbon dioxide
DN25twin/140



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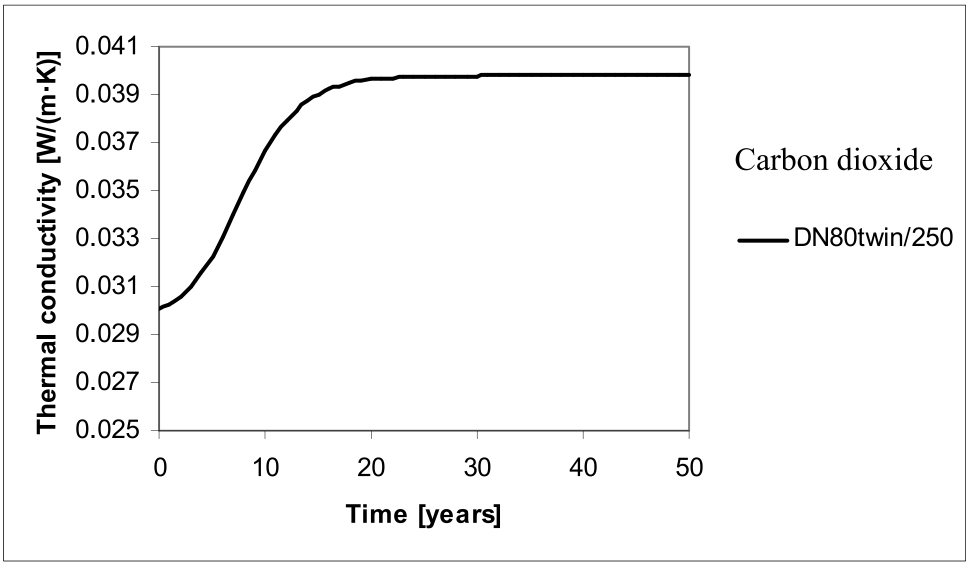
40
50
Time [years]
Carbon dioxide
DN50twin/200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Thermal conductivity [W/(m·K)]
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20
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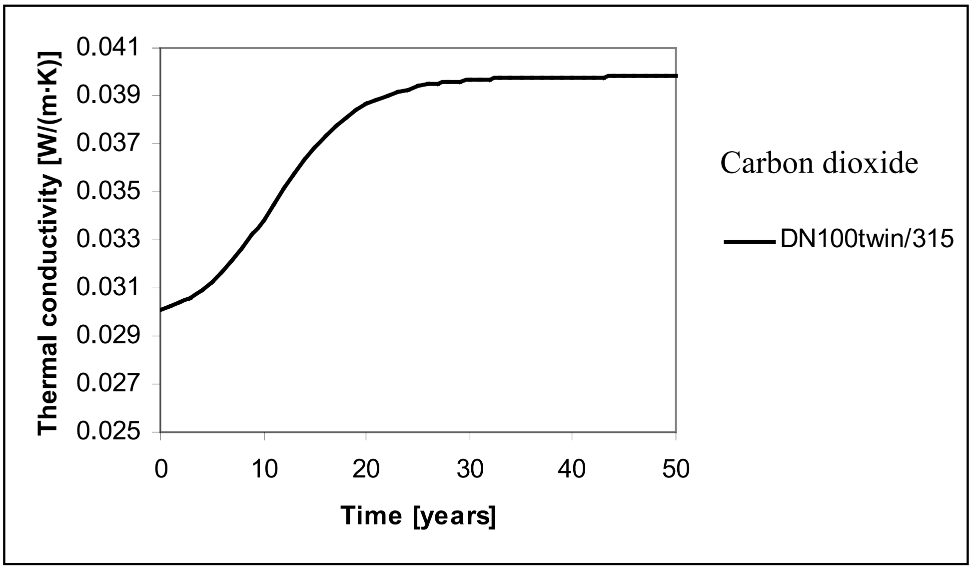
40
50
Time [years]
Carbon dioxide
DN80twin/250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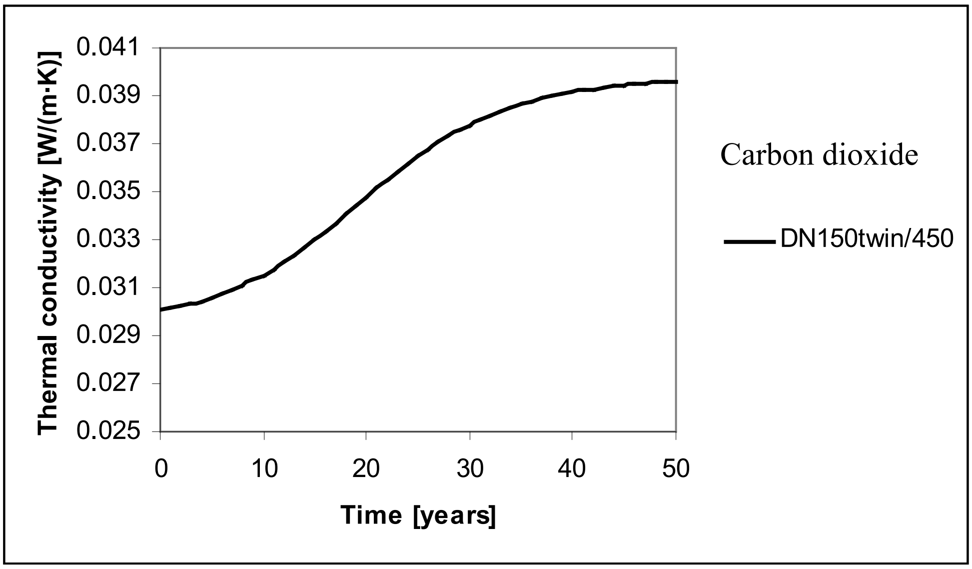
50
Time [years]
Carbon dioxide
DN100twin/315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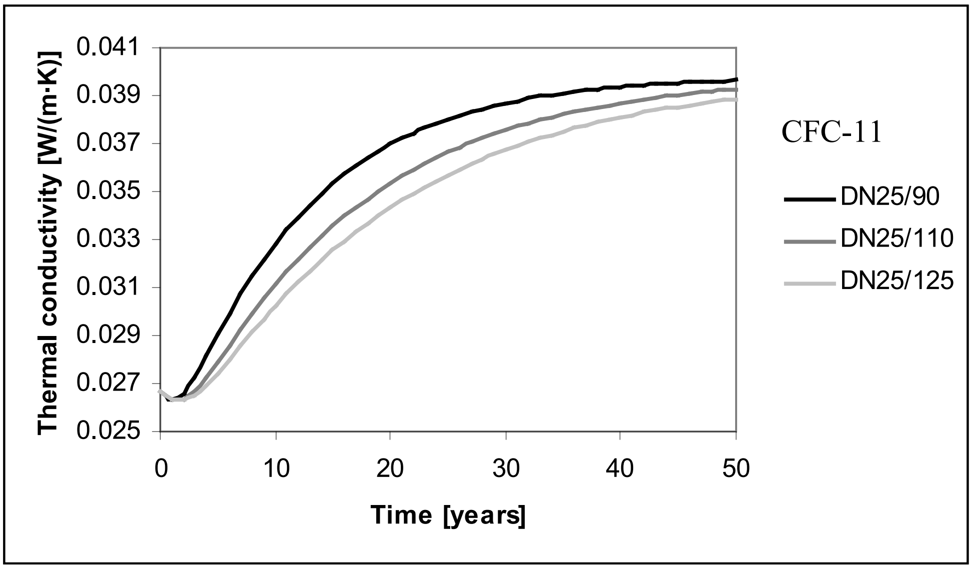
30
40
50
Time [years]
Carbon dioxide
DN150twin/450

CFC-11 blown: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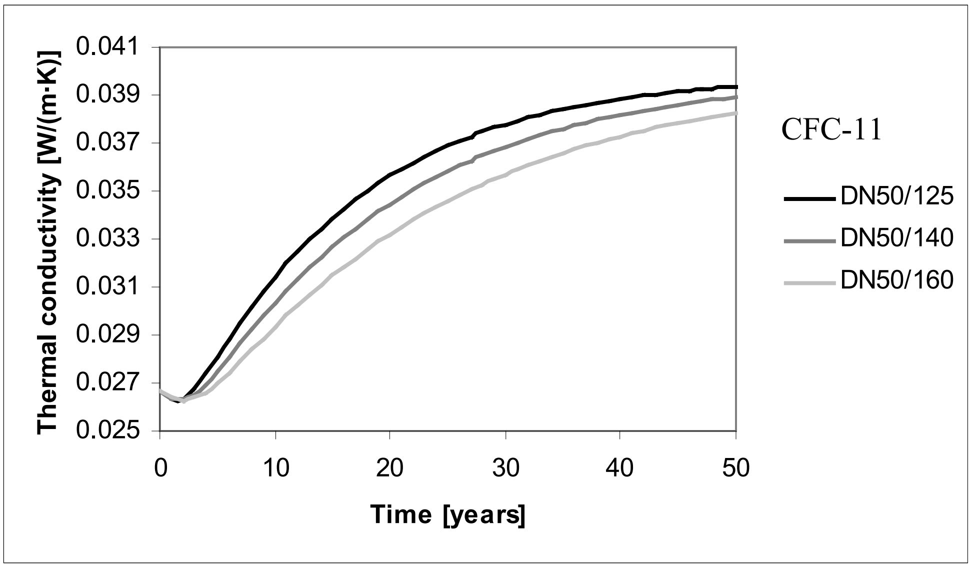
30
40
50
Time [years]
CFC-11
DN25/90
DN25/110
DN25/125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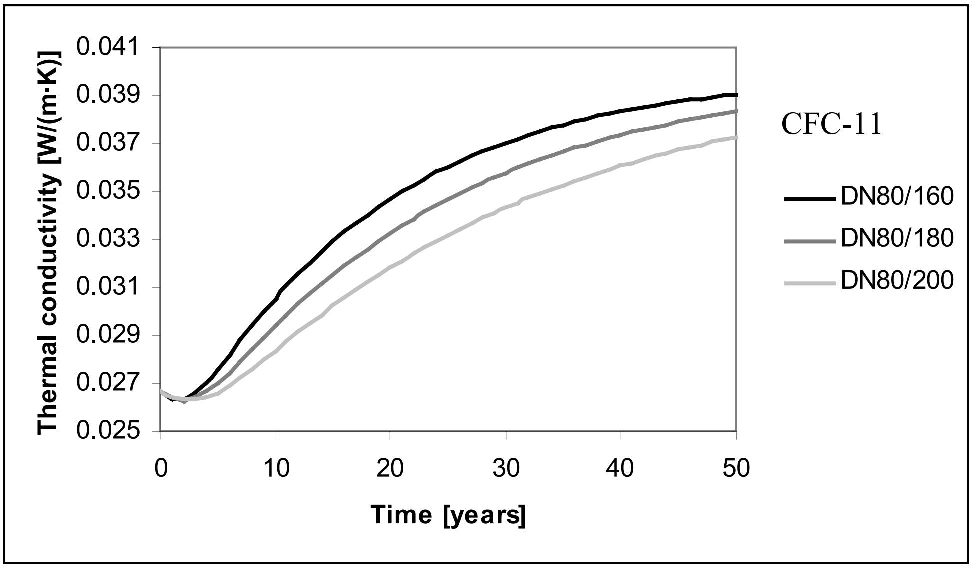
10
20
30
40
50
Time [years]
CFC-11
DN50/125
DN50/140
DN50/160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Thermal conductivity [W/(m·K)]
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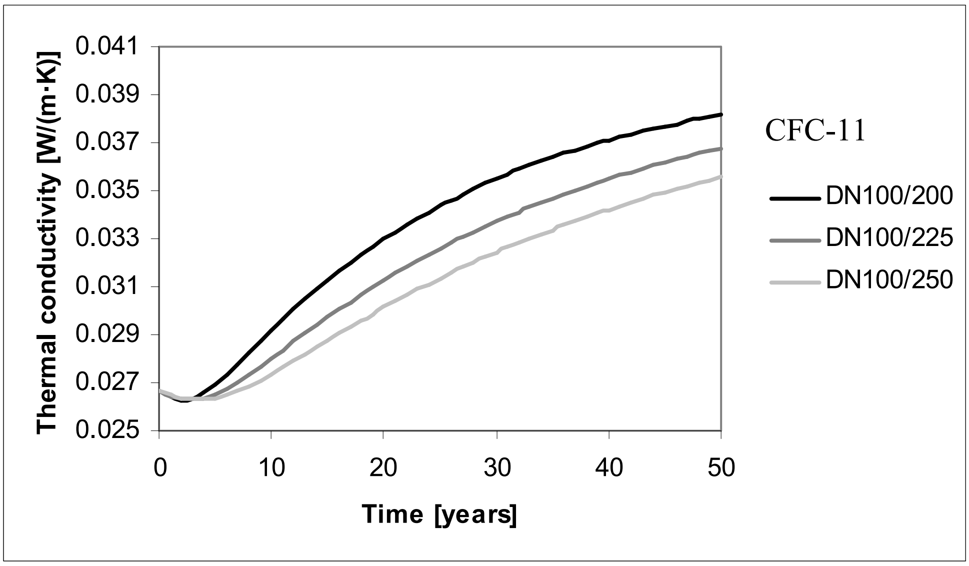
40
50
Time [years]
CFC-11
DN80/160
DN80/180
DN80/200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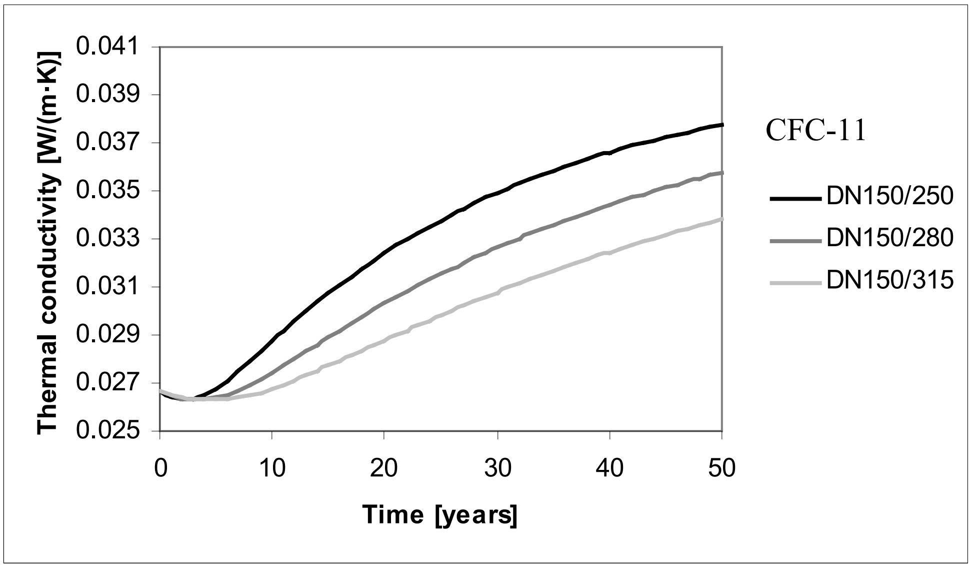
Thermal conductivity [W/(m·K)]
Time [years]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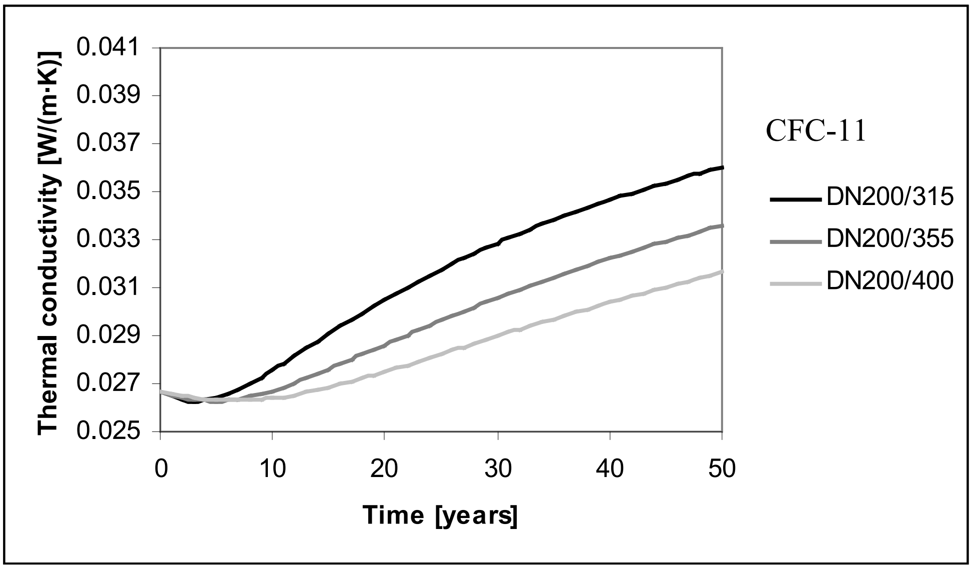
Time [years]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DN200/315
DN200/355
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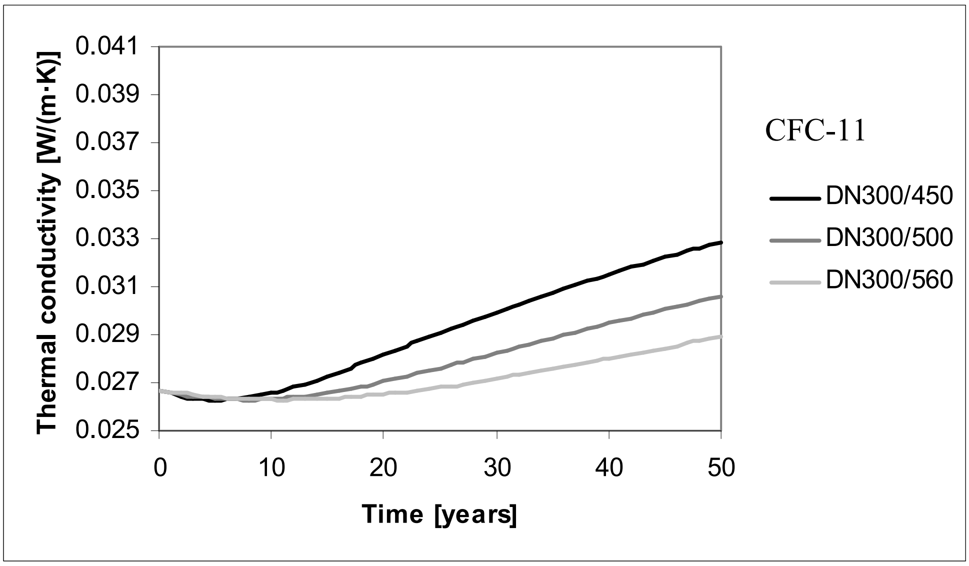
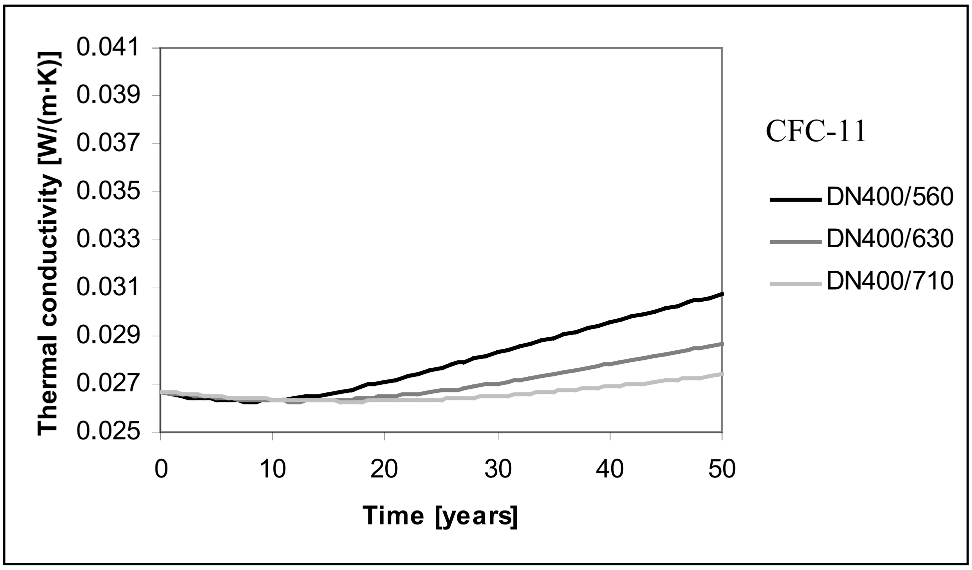
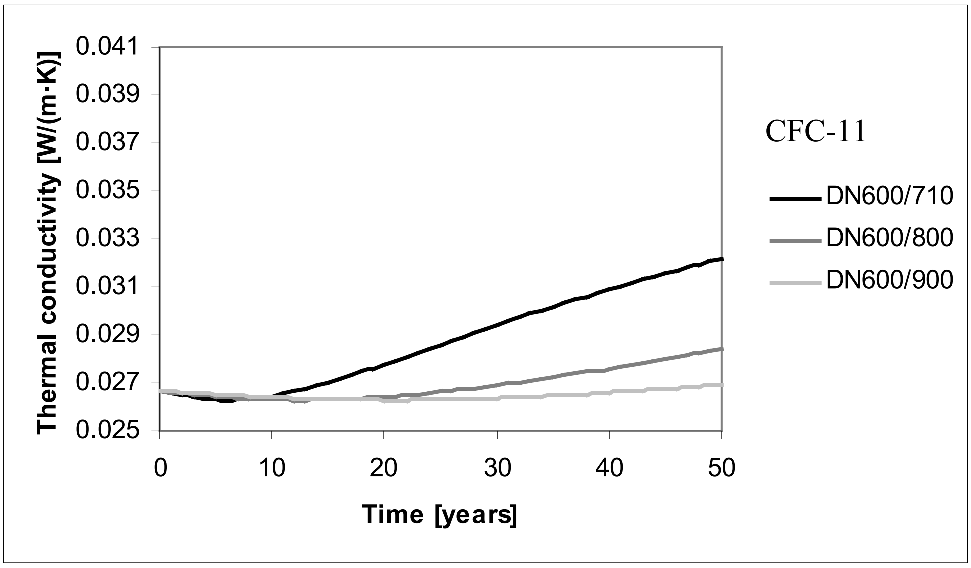
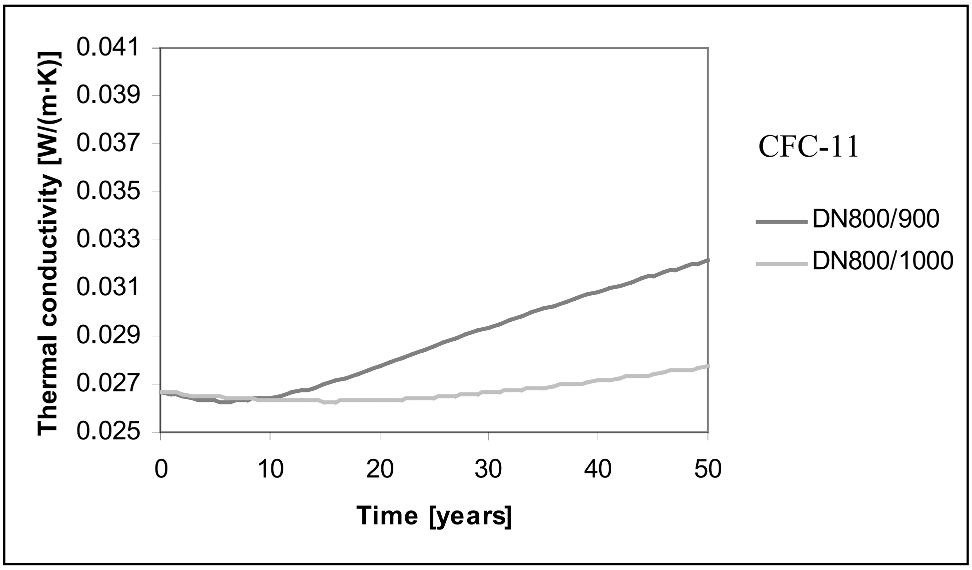
Thermal conductivity [W/(m·K)]
Time [years]

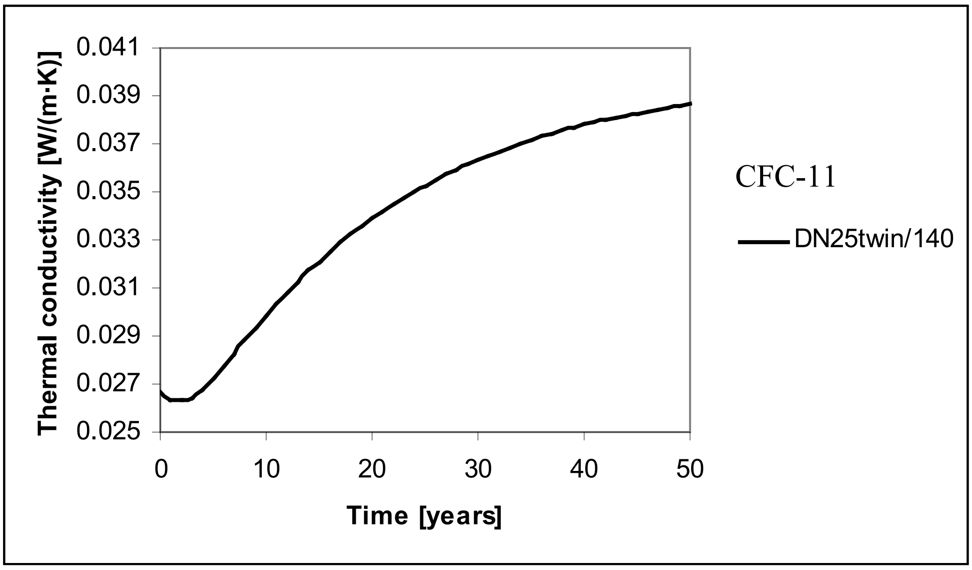

CFC-11
DN300/450
DN300/500
DN300/560
Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]


CFC-11
DN400/560
DN400/630
DN400/710
Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]

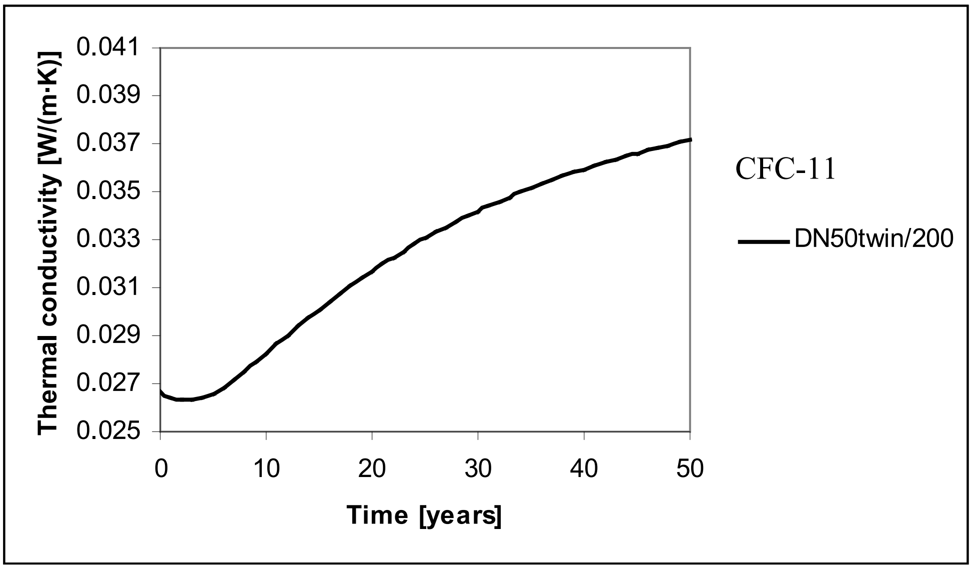

CFC-11
DN600/710
DN600/800
DN600/900
Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]



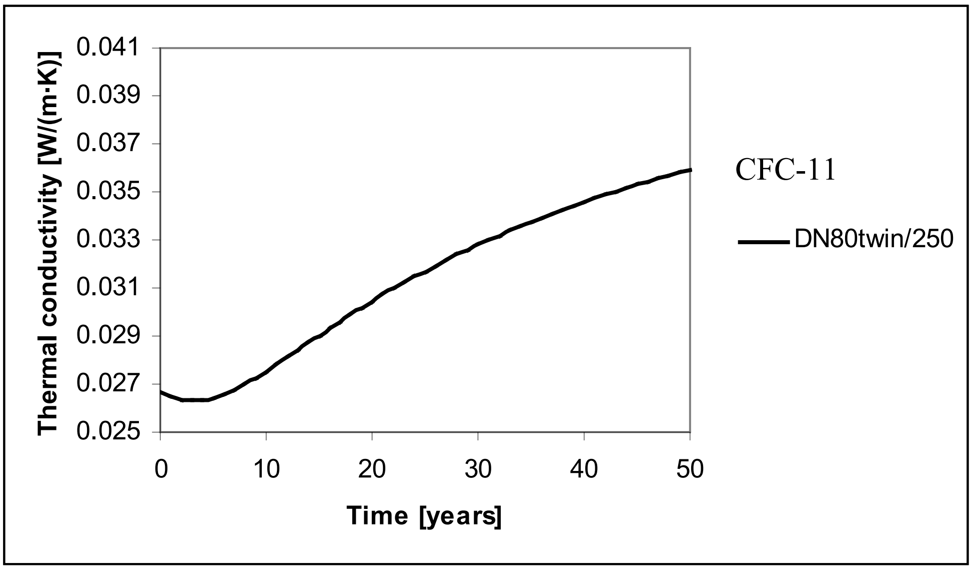
Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]
CFC-11
DN800/900
DN800/1000



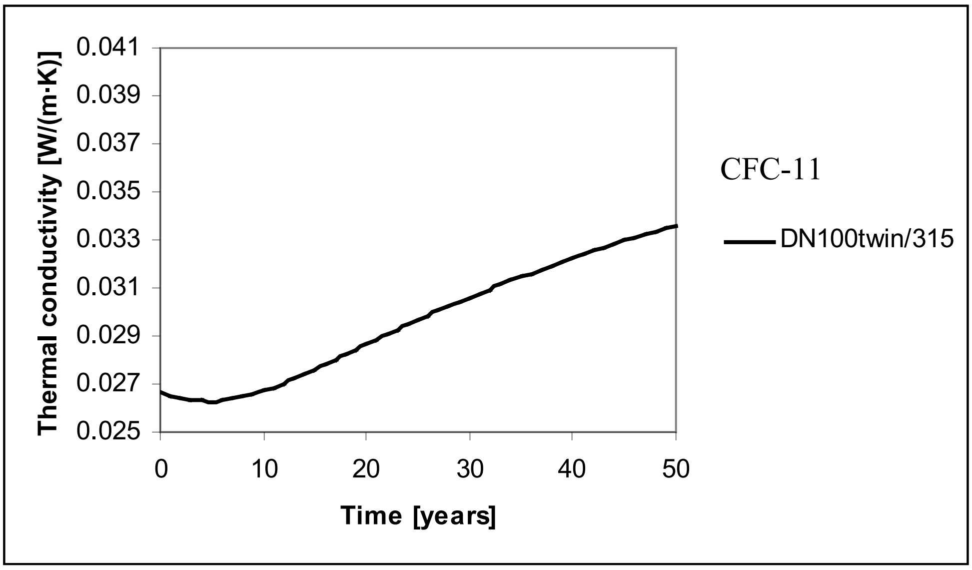
Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]
CFC-11
DN25twin/140



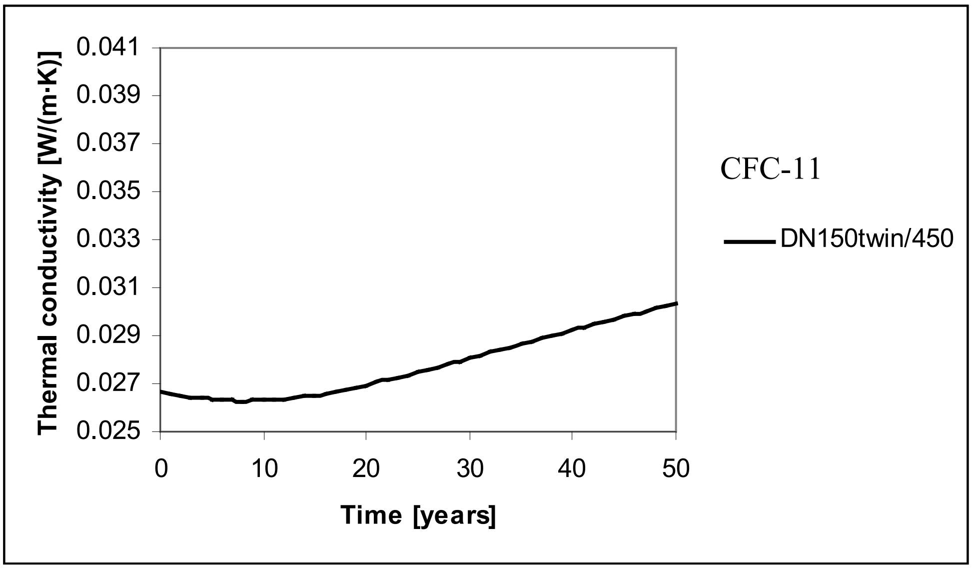
Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]
CFC-11
DN50twin/200



Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]
CFC-11
DN80twin/250



Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]
CFC-11
DN100twin/315



Thermal conductivity [W/(m·K)]
0.041
0.039
0.037
0.035
0.033
0.031
0.029
0.027
0.025
0
10
20
30
40
50
Time [years]
CFC-11
DN150twin/450

CHALMERS

Appendix 2:

Examination of heat losses resulting from piggy-back laying of preinsulated pipes

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Göteborg 2004

Report R-04:4
Work nr. 992

Introduction

This work package “Examination of heat losses from piggy-back laying of preinsulated pipes” has been conducted at Chalmers University of Technology, Department of Building Technology and is part of the IEA-Annex VII “Strategies to manage heat losses- technique and economy” under the leadership of MVV Manheim. The studied cases have been decided by MVV and the calculations have been done at Chalmers.

Studied cases

Heat losses from district heating pipes of four nominal diameters DN50, DN100, DN200 and DN400 and of insulation series 1, 2 and 3 are investigated, see Figure 1 and Table 1. Different laying arrangements are studied:

- supply pipe above or below return pipe
- cover depth: 0.45 or 0.65 m
- surface type: road (fortified - asphalt thickness 200 mm) or green area (unfortified)

as well as different system operation temperatures and climates:

- Supply pipe temperature: 130 or 90ºC (return pipe temperature always 50ºC).
- Surrounding soil temperature: 10 or 5ºC.

Thermal conductivities given in Table 2 are assumed for the materials.

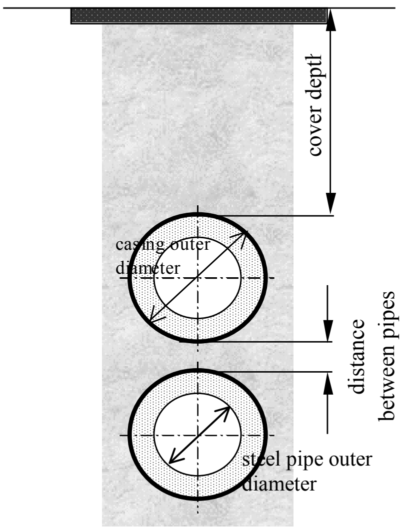


Figure 1. Geometry of pipe trench.

Table 1. Dimensions for which heat losses are studied.

DN	Steel pipe outer diameter [mm]	Insulation series	Casing outer diameter [mm]	Casing wall thickness [mm]	Distance between pipes [mm]
50	60.3	1	125	3.0	100
		2	140	3.0	100
		3	160	3.0	100
100	114.3	1	200	3.2	100
		2	225	3.4	100
		3	250	3.5	100
200	219.1	1	315	4.1	100
		2	355	4.4	100
		3	400	4.7	100
400	406.4	1	560	6.0	100
		2	630	6.5	100
		3	710	7.1	100

Table 2. Thermal conductivities for the different materials.

Material	Thermal conductivity [W/(m·K)]
Asphalt	1.8
Soil	1.5
Polyethylene casing	0.4
Polyurethane insulation	0.03

Heat loss determination / calculation strategy

The heat losses were determined numerically by applying the finite element method. The calculation software programme FEMLAB was used to solve the heat conduction equation.

Because of symmetry only half of the pipe trench needed to be studied. Soil at a depth and width of 10 m was considered. At the soil boundary no heat flow was assumed. Calculations with constant temperature soil boundary condition were performed for some of the cases. The “true” solution should lie in between the no flow and the constant temperature solution. The difference between the no flow and the constant temperature solutions was within a few steps in the first decimal of the rounded numbers.

A automatically refined net was used for most of the cases, except for the cases for which refined meshes resulted in a too large memory demand. The difference in the result depending on if the net was refined or not was tested for some cases. The first decimal in the heat loss was observed to change by roughly one step depending on if the net was refined or not.

Thus there is an uncertainty in the first decimal place of the results.

Results

If the surface is fortified (asphalted) or unfortified (green area) is of minor importance for the heat losses. The difference in heat loss for the cases is at maximum 0.3 W/m, i.e. in the vincinity of the calculation uncertainty. The heat losses can be said to be independent of surface type.

Figure 1 to Figure 16 show heat losses from the studied pipes in green areas with the supply pipe below respectively above the return pipe for the two different supply pipe temperatures, two different surrounding soil temperatures and two different cover depths.

The supply pipe arrangement, above or below the return pipe, changes the heat loss by at maximum 2.1 W/m (3%) for the studied cases. The heat loss is lower when the supply pipe is placed below the return pipe.

The heat loss increase with increased temperature of the supply pipe, lower surrounding soil temperature and shallower trench.

U-value

For a pipe network the linear thermal transmittance (Equation 1) may be used to describe the heat loss. The linear thermal transmittance for the networks are given in Table 3.

$$U = \frac{q}{\left(\frac{T_1 + T_2}{2} - T_3\right) \cdot L} \qquad (1)$$

U	linear thermal transmittance	[W/(m·K)]
q	heat loss	[W/m]
T_1	temperature of supply pipe	[K]
T_2	temperature of return pipe	[K]
T_3	temperature of surrounding soil	[K]
L	network length	[m]

Table 3. Linear thermal transmittance for the networks.

DN	Insulation series	Linear thermal transmittance [W/(m·K)] Cover depth 0.65 m, supply below return	Cover depth 0.65 m, supply above return	Cover depth 0.45 m, supply below return	Cover depth 0.45 m, supply above return
DN50	1	0.48	0.48	0.48	0.49
	2	0.42	0.42	0.42	0.42
	3	0.36	0.36	0.37	0.37
DN100	1	0.60	0.60	0.61	0.62
	2	0.51	0.51	0.51	0.52
	3	0.44	0.45	0.45	0.45
DN200	1	0.88	0.89	0.90	0.91
	2	0.69	0.70	0.70	0.71
	3	0.57	0.57	0.57	0.58
DN400	1	0.99	1.01	1.01	1.03
	2	0.75	0.76	0.76	0.77
	3	0.61	0.62	0.62	0.63

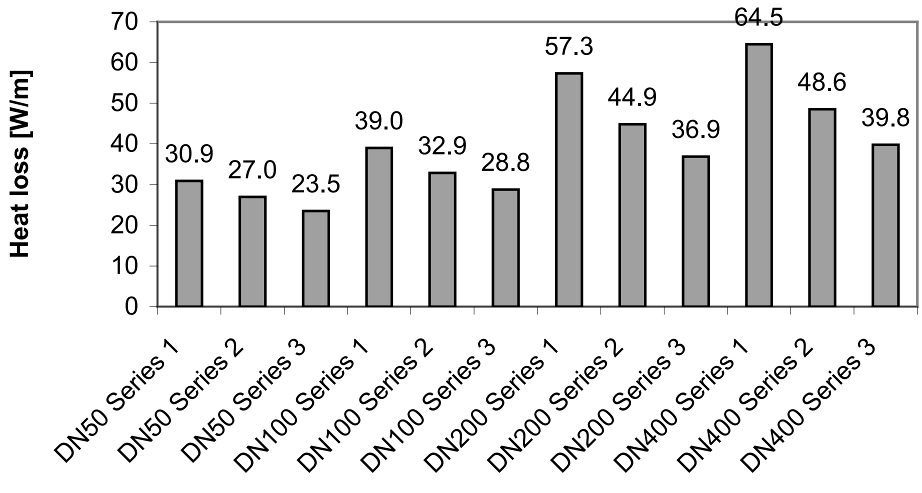


Figure 1. Heat losses with the supply below the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.65 m.

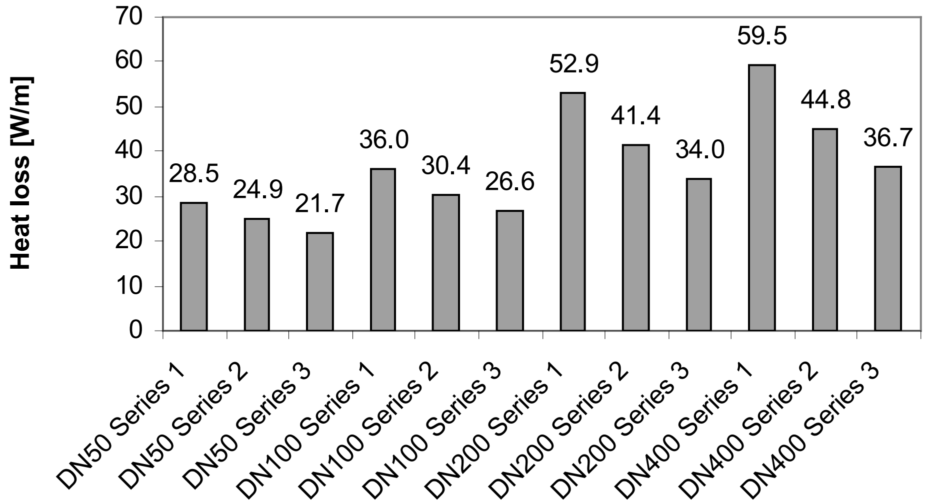


Figure 2. Heat losses with the supply below the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.65 m.

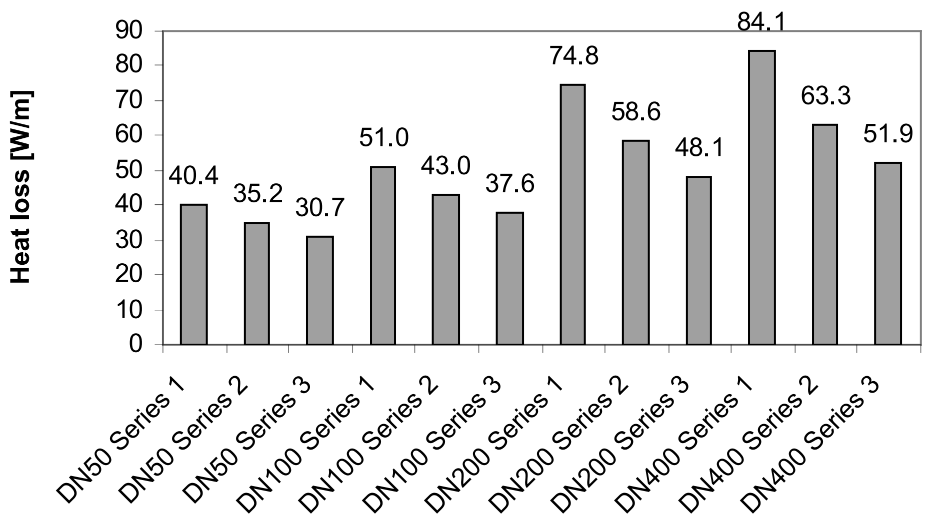


Figure 3. Heat losses with the supply below the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.65 m.

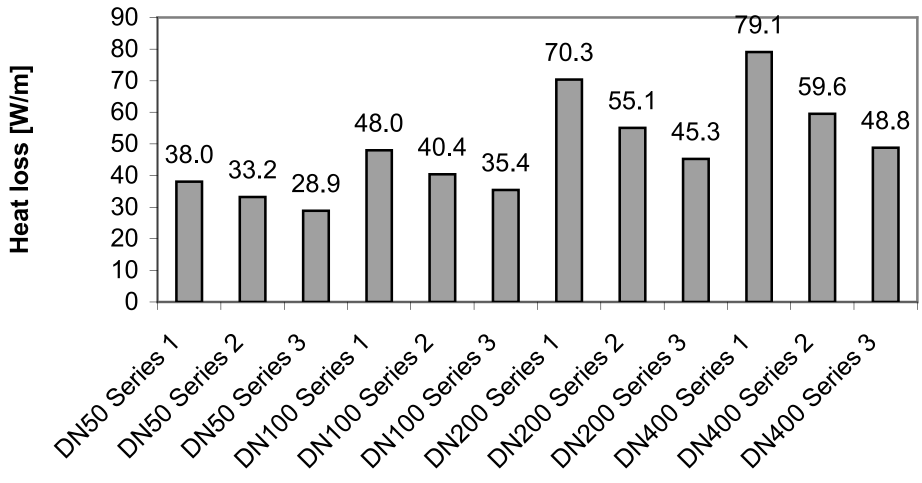


Figure 4. Heat losses with the supply below the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.65 m.

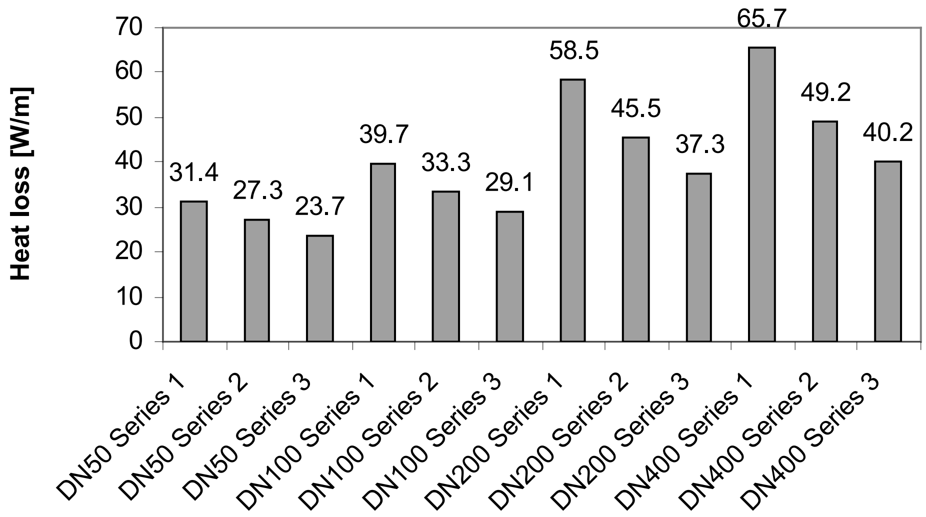


Figure 5. Heat losses with the supply below the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.45 m.

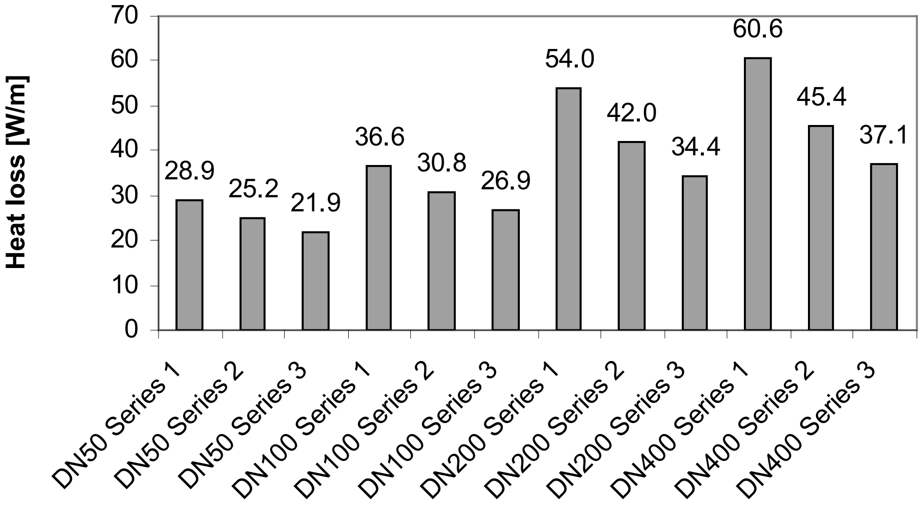


Figure 6. Heat losses with the supply below the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.45 m.

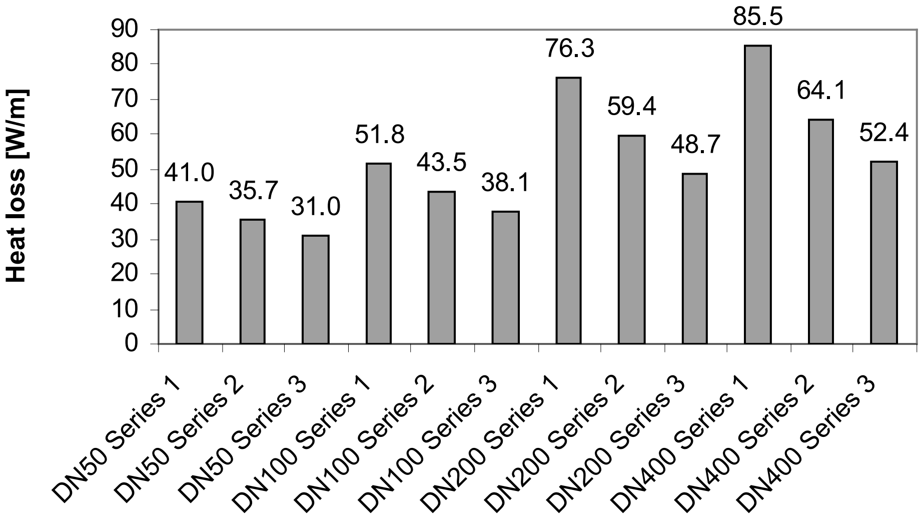


Figure 7. Heat losses with the supply below the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.45 m.

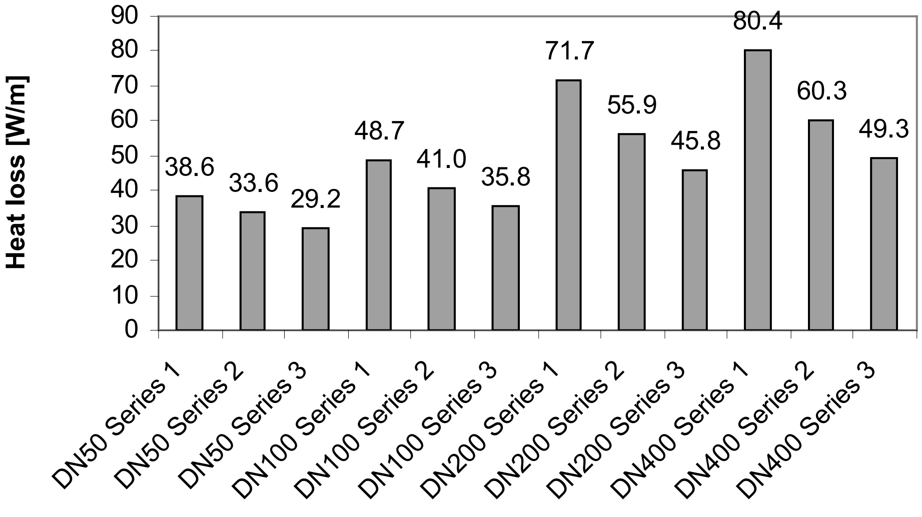


Figure 8. Heat losses with the supply below the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.45 m.

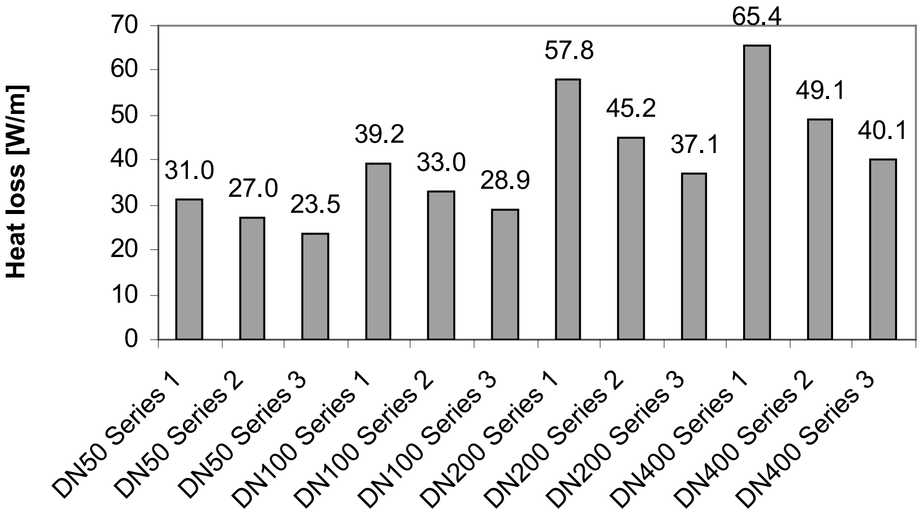


Figure 9. Heat losses with the supply above the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.65 m.

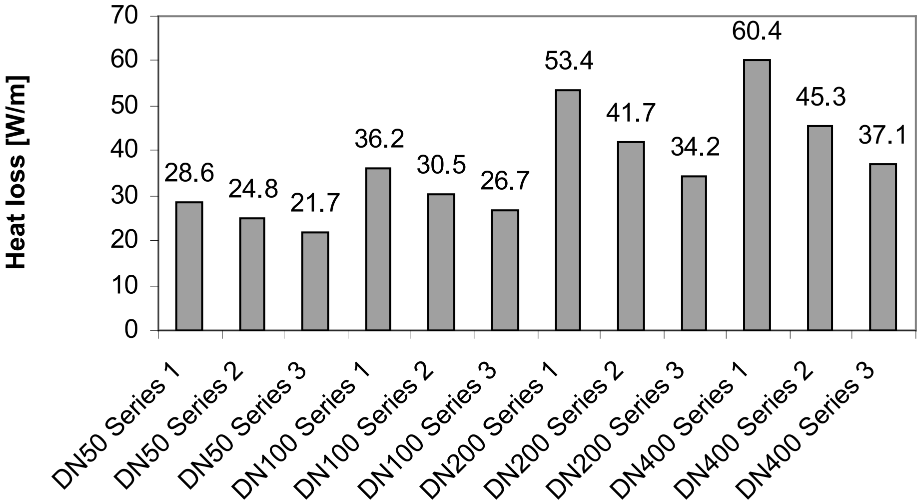


Figure 10. Heat losses with the supply above the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.65 m.

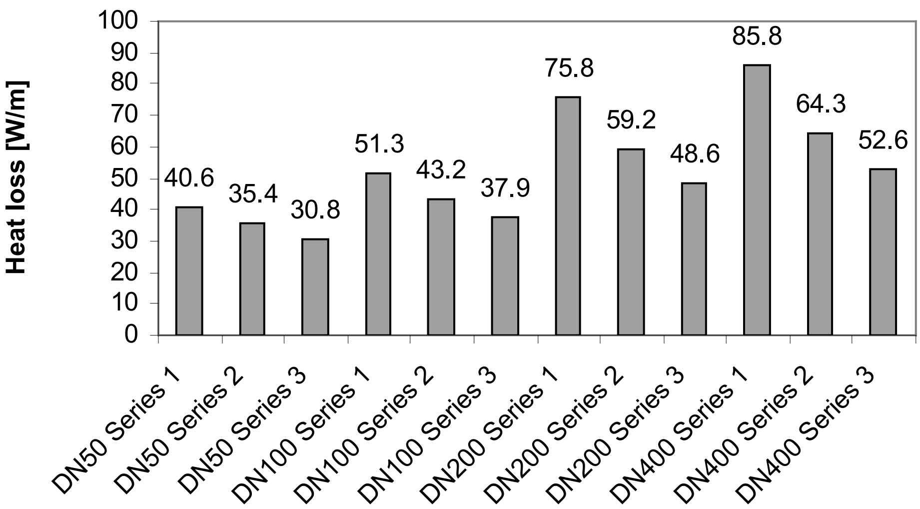


Figure 11. Heat losses with the supply above the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.65 m.

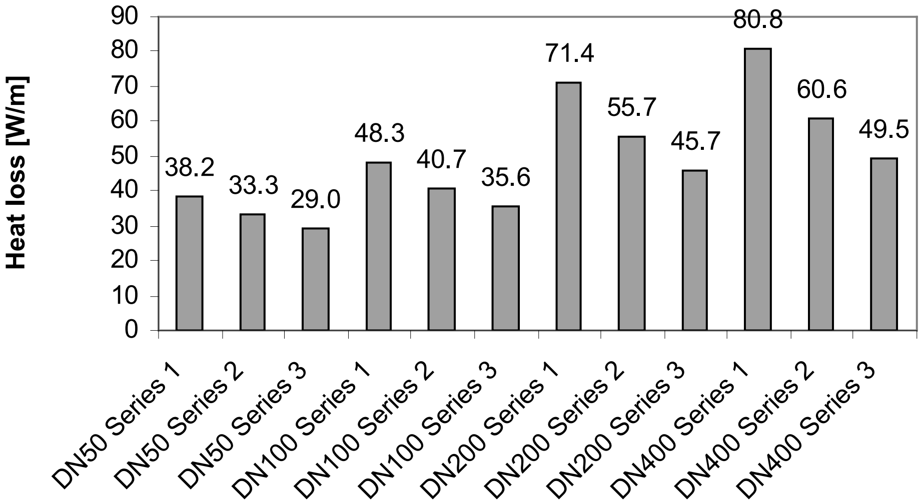


Figure 12. Heat losses with the supply above the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.65 m.

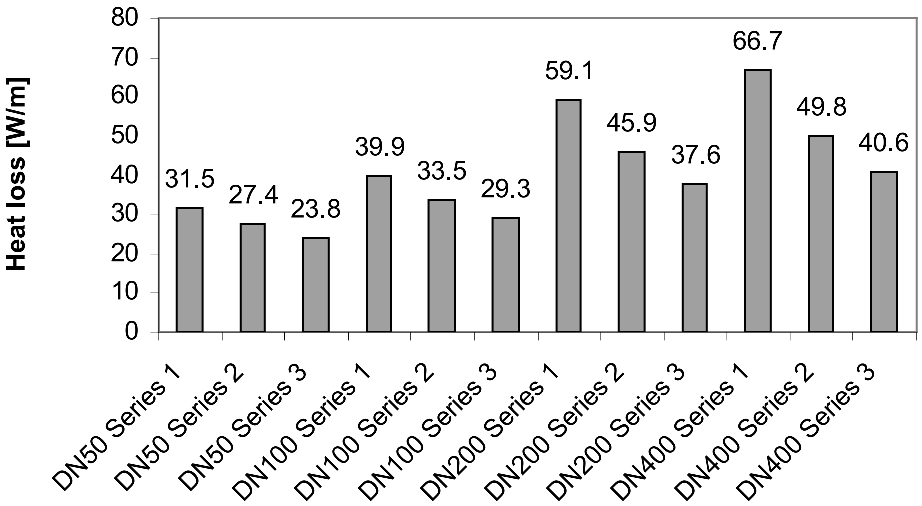


Figure 13. Heat losses with the supply above the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.45 m.

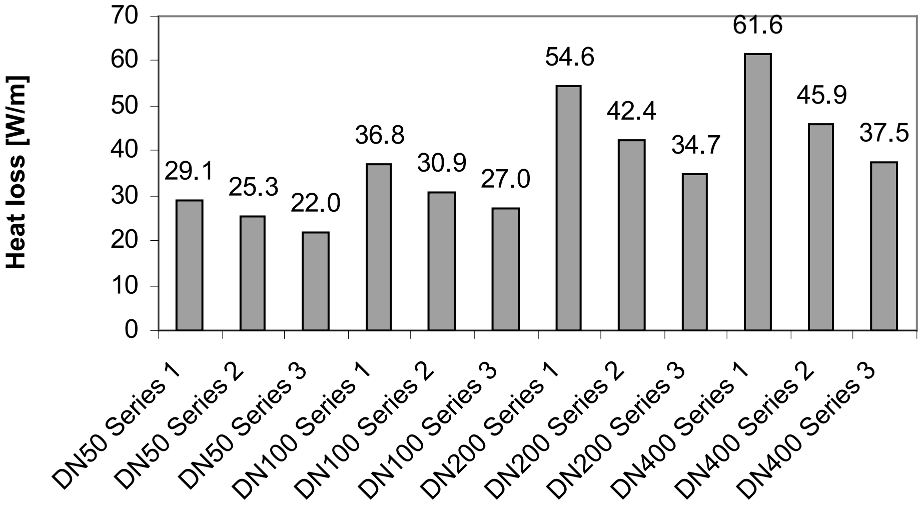


Figure 14. Heat losses with the supply above the return, a supply pipe temperature of 90ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.45 m.

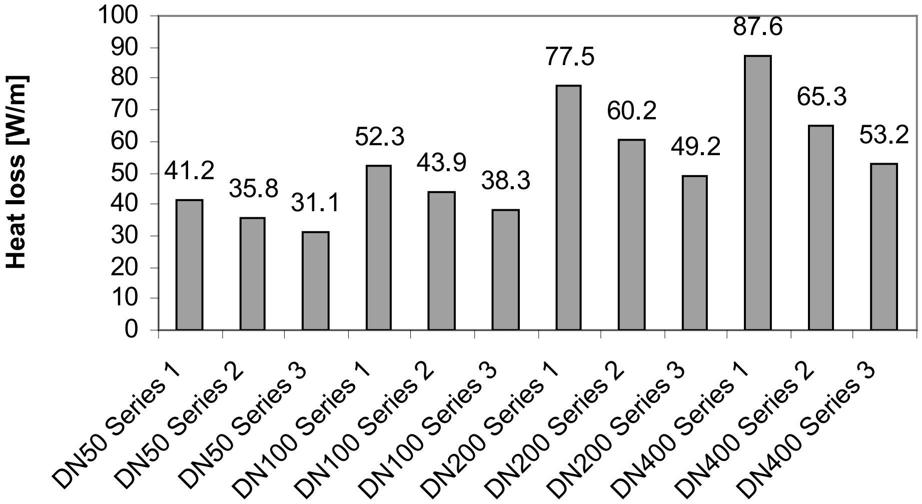


Figure 15. Heat losses with the supply above the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 5ºC and a soil coverage of 0.45 m.

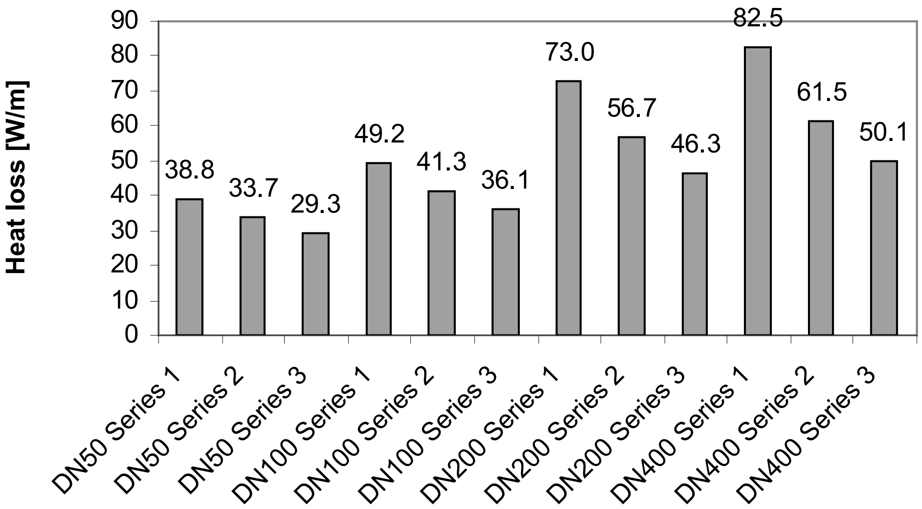


Figure 16. Heat losses with the supply above the return, a supply pipe temperature of 130ºC, a surrounding soil temperature of 10ºC and a soil coverage of 0.45 m.

Appendix 3: Formulas for calculation of heat losses

Source: Jarfelt, U.
Jämforelse mellan dubbel- och enkelrör
Ackumulerade värmeförluster och miljöbelastning under 5 aars drifttid
FOU 2002:79, Svenska Fjärrvärmeforeningens Service AB,
Stockholm, Sweden 2002

$$U_l = \frac{q_{total}}{\frac{T_1 + T_2}{2} - T_0} \qquad (W \cdot m^{-1} \cdot K^{-1})$$

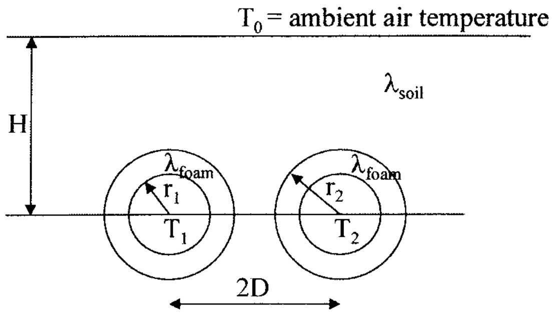
Nomenclature:

D	half of the distance between centre of pipe 1 and 2	(m)
H	distance between surface and axis of pipes	(m)
L	length of pipeline	(m)
T_0	ambient air temperature	(°C)
T_1	temperature of pipe 1	(°C)
T_2	temperature of pipe 2	(°C)
U_l	coefficient of heat transmission	$(W \cdot m^{-1} \cdot K^{-1})$
h_s	coefficient of heat loss for symmetric case	-
h_a	coefficient of heat loss for asymmetric case	-
q_{total}	heat loss of the pipeline	$(W \cdot m^{-1})$
q_s	heat loss of symmetric case	$(W \cdot m^{-1})$
q_a	heat loss of asymmetric case	$(W \cdot m^{-1})$
r_1	outer radius of the medium pipe	(m)
r_2	outer radius of the jacket pipe	(m)
β	parameter for description of insulation	-
λ_{soil}	heat conductivity of soil	$(W \cdot m^{-1} \cdot K^{-1})$
λ_{foam}	heat conductivity of PUR foam	$(W \cdot m^{-1} \cdot K^{-1})$
σ	parameter for description of insulation	-

1.1 Two single pipes side by side

Calculations of heat losses of preinsulated pipes in the soil:

Fig.A3-1: General drawing of two pipes in the ground



$$q_{total} = q_1 + q_2$$

with

$$q_1 = q_s + q_a$$

$$q_2 = q_s - q_a$$

$$q_s = \left(\frac{T_1 + T_2}{2} - T_0\right) \cdot 2\pi\lambda_{soil} \cdot h_s$$

$$q_a = \left(\frac{T_1 - T_2}{2}\right) \cdot 2\pi\lambda_{soil} \cdot h_a$$

$$h_s^{-1} = \ln\left(\frac{2H}{r_2}\right) + \beta + \ln\left(\sqrt{1 + \left(\frac{H}{D}\right)^2}\right) - \frac{\left(\frac{r_2}{2D}\right)^2 + \left(\frac{r_2}{2H}\right)^2 + \frac{r_2^2}{4\left(D^2 + H^2\right)}}{\frac{1+\beta}{1-\beta} + \left(\frac{r_2}{2D}\right)^2}$$

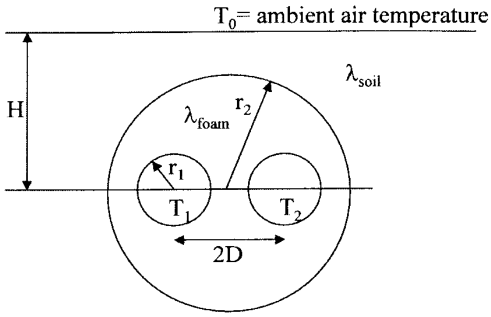
$$h_a^{-1} = \ln\left(\frac{2H}{r_2}\right) + \beta - \ln\left(\sqrt{1 + \left(\frac{H}{D}\right)^2}\right) - \frac{\left(\frac{r_2}{2D}\right)^2 + \left(\frac{r_2}{2H}\right)^2 + \frac{r_2^2}{4\left(D^2 + H^2\right)}}{\frac{1+\beta}{1-\beta} - \left(\frac{r_2}{2D}\right)^2}$$

$$\beta = \frac{\lambda_{soil}}{\lambda_{foam}} \ln\left(\frac{r_2}{r_1}\right)$$

1.2 Twin pipe

(The following formula can also be used for calculating the heat losses of a pipe assembly rotated by 90°. The Error will be in the range of 0.2%)

Fig. A3-2: General drawing of a twin pipe in the ground



$$q_{total} = q_1 + q_2$$

with

$$q_1 = q_s + q_a$$

$$q_2 = q_s - q_a$$

$$q_s = \left(\frac{T_1 + T_2}{2} - T_0\right) \cdot 2\pi\lambda_{foam} \cdot h_s$$

$$q_a = \left(\frac{T_1 - T_2}{2}\right) \cdot 2\pi\lambda_{foam} \cdot h_a$$

$$\sigma = \frac{\lambda_{foam} - \lambda_{soil}}{\lambda_{foam} + \lambda_{soil}}$$

$$\gamma = \frac{2(1-\sigma^2)}{1 - \sigma\left(\frac{r_2}{2H}\right)^2}$$

$$h_s^{-1} = \frac{2\lambda_{foam}}{\lambda_{soil}} \ln\left(\frac{2H}{r_2}\right) + \ln\left(\frac{r_2^2}{2Dr_1}\right) + \sigma \cdot \ln\left(\frac{r_2^4}{r_2^4 - D^4}\right) - \frac{\left(\frac{r_1}{2D} - \frac{\sigma 2 r_1 D^3}{r_2^4 - D^4}\right)^2}{1 + \left(\frac{r_1}{2D}\right)^2 + \sigma\left(\frac{2r_1 r_2^2 D}{r_2^4 - D^4}\right)^2}$$

$$h_a^1 = \ln\left(\frac{2D}{r_1}\right) + \sigma \ln\left(\frac{r_2^2 + D^2}{r_2^2 - D^2}\right) - \frac{\left(\frac{r_1}{2D} - \gamma\frac{Dr_1}{4H^2} + \frac{2\sigma r_1 r_2^2 D}{r_2^4 - D^4}\right)^2}{1 - \left(\frac{r_1}{2D}\right)^2 - \gamma\frac{r_1}{2H} + 2\sigma r_1^2 r_2^2 \cdot \frac{r_2^4 + D^4}{\left(r_2^4 - D^4\right)^2}} - \gamma\left(\frac{D}{2H}\right)^2$$

Appendix 4

International Comparison of Installation Costs for Preinsulated Plastic Jacket Pipelines for Various Laying Methods and Different Insulation Thickness

<u>Installation Costs for Preinsulated Plastic Jacket Pipelines</u>

for standard installation, twin pipes and piggy-back laying

1 Standard Installation

Pipe arrangement: Single pipes, laid horizontally next to each other, Insulation Series 1

1.1 Germany

The standard costs, namely the mean values, as set forth in the district-heating publication entitled *AGFW Neuartige Wärmeverteilung, B 1.2*, Figure 3.3.1/03, were taken over. These costs reflect the installation expenditures resulting from the annual specification and schedule of prices.

(The parameters are comparable to the approaches discussed in the AGFW study entitled *Pluralistische Wärmeversorgung* [2] as well as the values contained in the catalog of ratios named *EWU Kennziffernkatalog* [3]. For comparison see Figure 1.)

The mean installation costs in Germany can be calculated as follows:

$$V_D = 2.6829 \cdot N + 187.92$$

with V = Installation costs in €
N = Nominal diameter DN

applying to nominal diameters DN 20 through DN 500.

1.2 Finland

The construction costs were taken over from the Finish 2002 statistical report [4]. They apply up to DN 200 to Insulation Series 3, for DN 250 through DN 400 to Insulation Series 2, and as from DN 500 to Insulation Series 1.

For the purpose of the present study, these parameters are translated into Insulation Series 1 by dividing the prices for Insulation Series 3 by 1.21 and the ones of Insulation Series 2 by 1.1; the reason for that may also be gathered from Section 4.

Figure 2 depicts the Finish installation costs for Insulation Series 1 pipelines; a fit helps clearly mirror the cost values.

The mean Finish installation costs for pipes of Insulation Series 1 can be determined on the basis of the equation to follow:

$$V_{FIN} = 1.192 \cdot N + 34.544$$

applying to nominal diameters DN 25 through DN 600.

Fig 1: Construction costs of preinsulated pipes in Germany

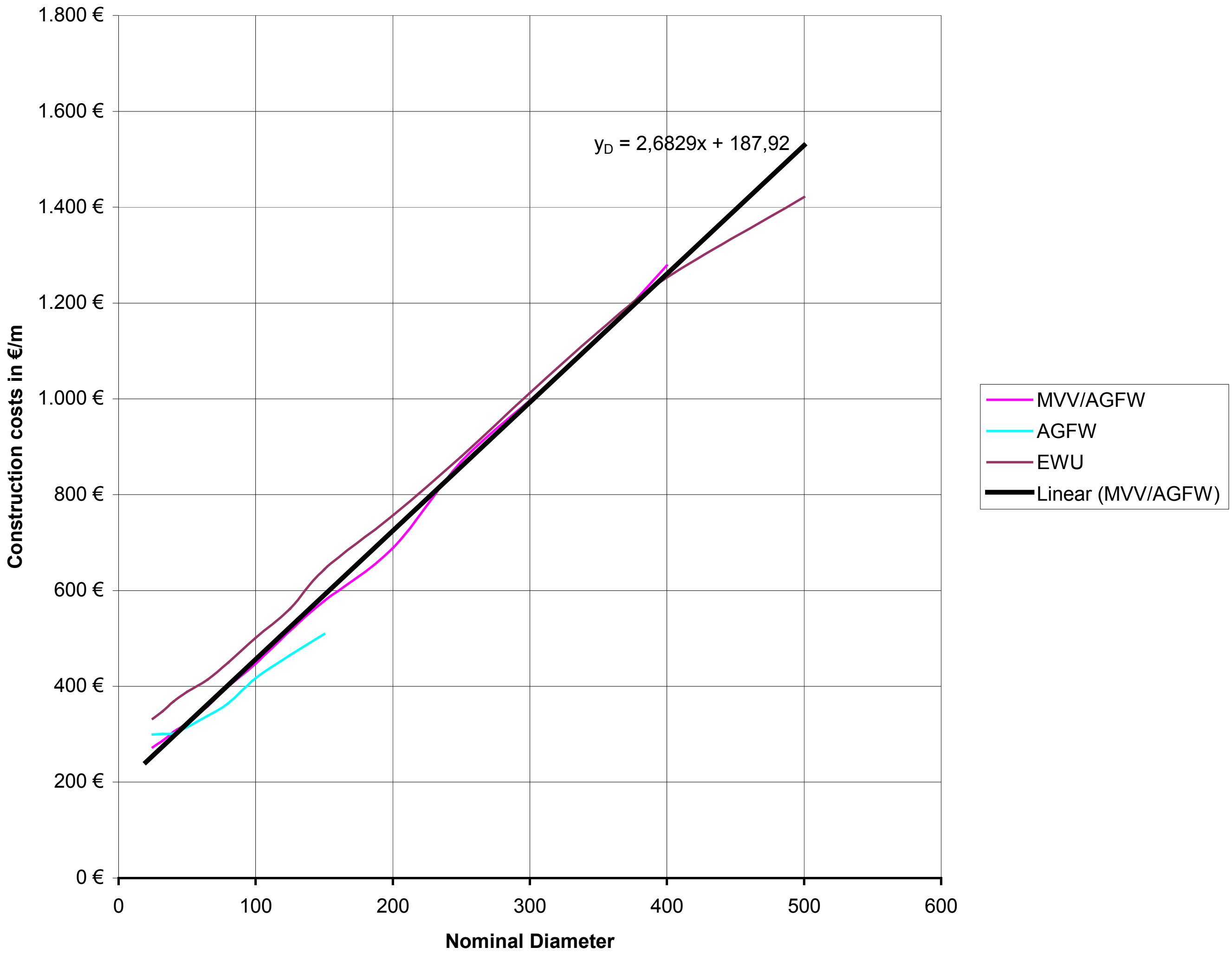
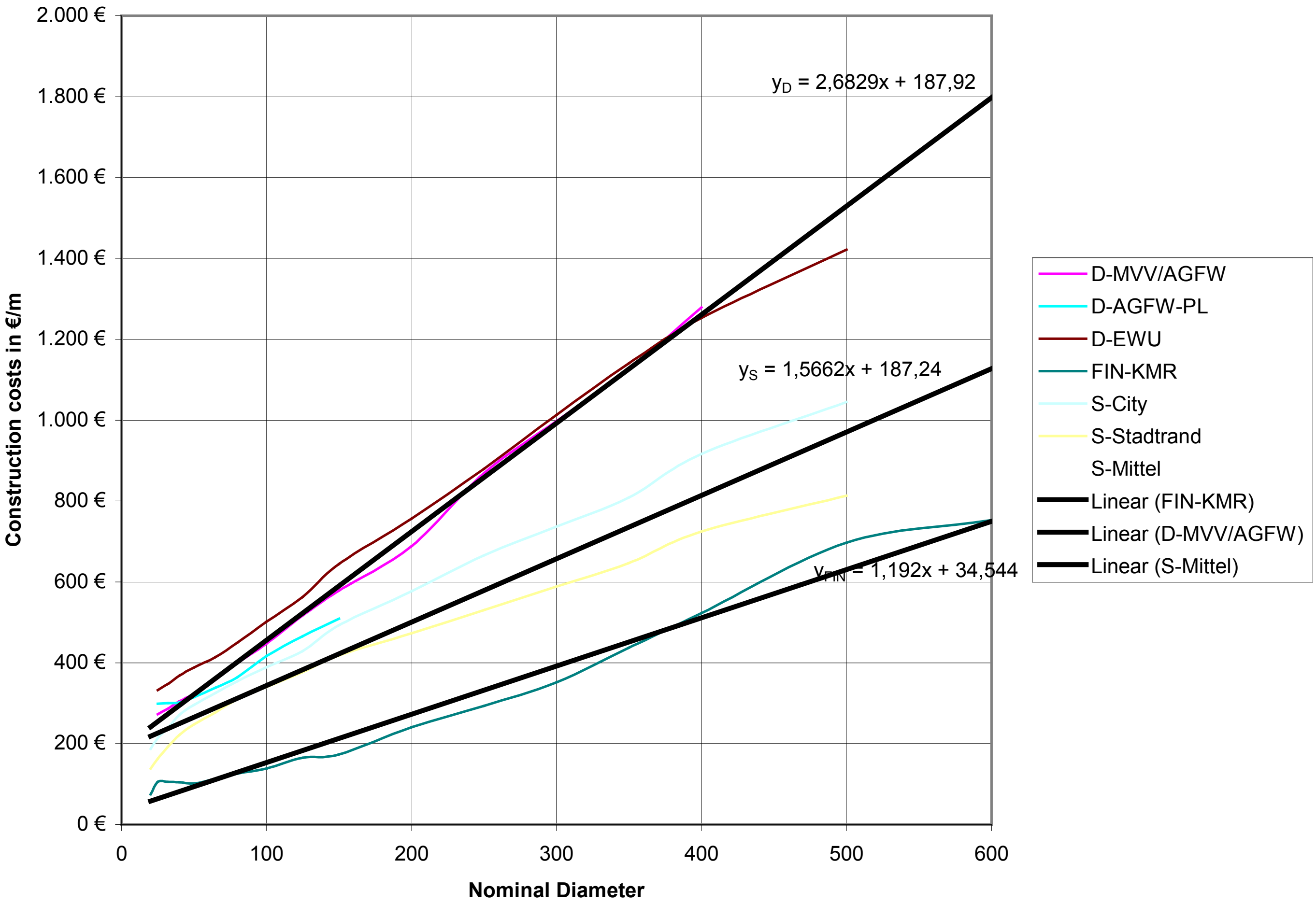


Fig. 2: Construction costs of preinsulated pipes



1.3 Sweden

The representative installation costs were taken from the FVF catalog [6]. The data apply to Insulation Series 2 pipes and were translated into Insulation Series 1 by dividing them by 1.1. The arithmetic average of the laying situations “innerstad” and “ytteromrade”, reflected by the lines designated “City” and “Outskirts” in Figure 2, represents the applicable values.

The mean Swedish construction costs for Insulation Series 1 pipelines may be specified as follows:

$$V_S = 1.5662 \cdot N + 187.24$$

applying to nominal diameters DN 25 through DN 600.

1.4 Other Countries

Compared to other countries, the installation costs in Germany are high; those in Finland are regarded as low. They differ from each other by factor three. The Swedish costs lie in between, and underrun the German expenditures by approx. factor 1.5.

The construction costs for other countries are expected to range between the German and Finish expenditures. On the basis of the comparison of costs as set forth in the 1999 Euroheat & Power Yearbook [7], the installation costs for Denmark are estimated to be approx. on the same level as the Swedish costs.

2 Twin Pipes

Twin pipes are available up to DN 200; they are available in a single insulation series only.

2.1 Germany

In Germany, twin pipes are installed only rarely. The values calculated by MVV Energie [8] are taken over as representative installation costs. Figure 3 displays the German cost volume.

The installation costs for twin pipes may be calculated as follows:

$$V_D = 1.8868 \cdot N + 227.75$$

applying to nominal diameters DN 25 through DN 150.

2.2 Finland

In Finland, small-sized pipelines up to DN 200 are predominantly realized in form of twin pipes. The Finish district-heating association maintains representative statistics on the installation costs for twin-piped grids, see Figure 3.

The Finish installation costs for twin pipes may be determined on the basis of the following equation:

$$V_{FIN} = 0.727 \cdot N + 69.103$$

applying to nominal diameters DN 25 through DN 200 [4].

Unfortunately the cost function according to fig. 3 doesn’t correspond to long term experiences due to statistical variance. Usually twin pipe installation is cheaper for small diameters than shown in 2002 statistics.

A cost function considering this is:

$$V_{Fin} = 1.24 \cdot N + 32.9$$

applying to nominal diameters DN 20 through DN 200 [8].

2.3 Sweden

Grids composed of small-sized tubes are also realized on the basis of twin pipes. The construction costs of twin pipes are also depicted in Figure 3, source [9]. The arithmetic average of the “innerstad” and “ytteromrade” loops, reflected by the lines designated “City” and “Outskirts” in Figure 3, represents the values applicable to Sweden.

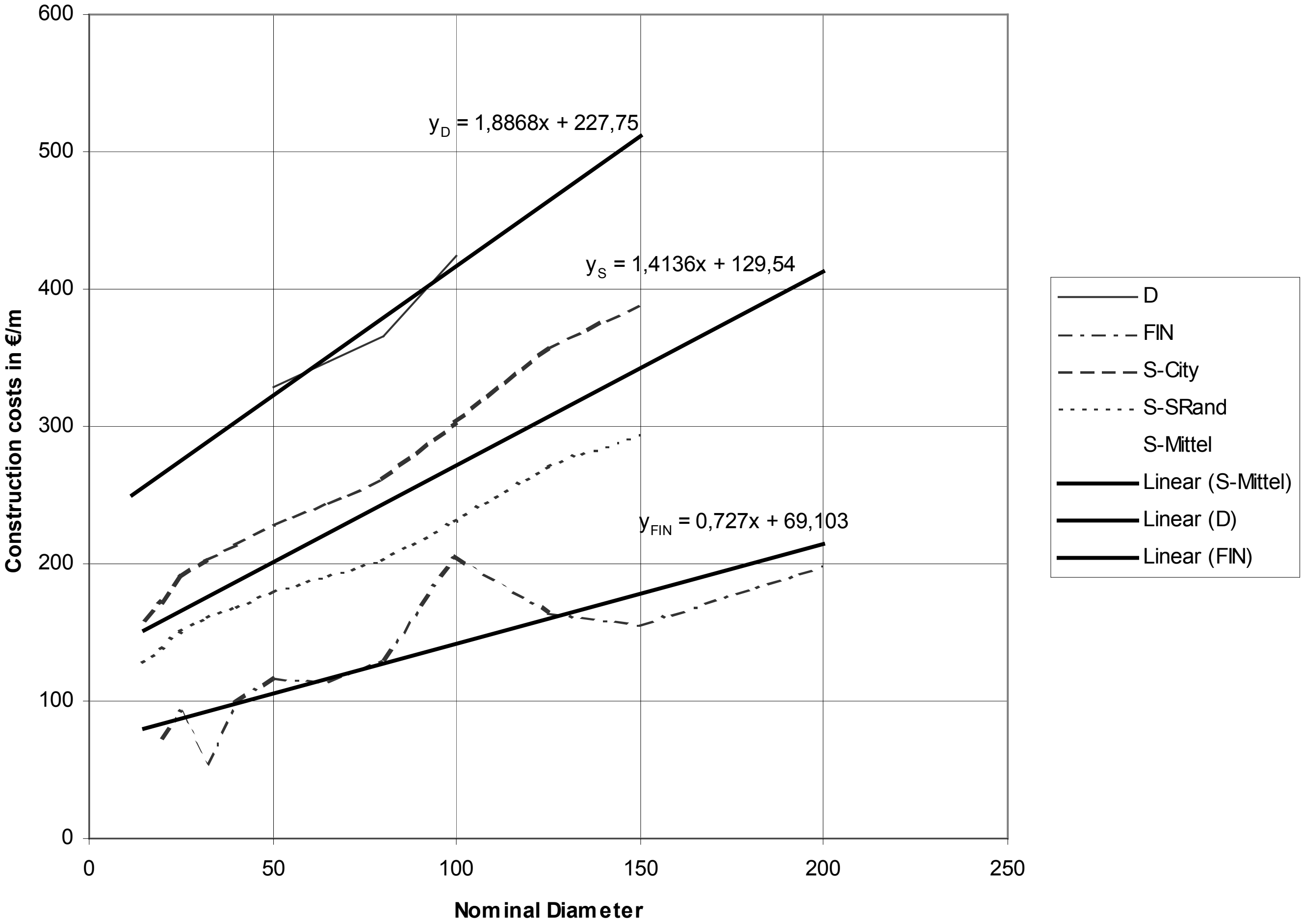
The mean installation costs for twin pipes can be calculated as follows:

$$V_S = 1.4136 \cdot N + 129.54$$

applying to nominal diameters DN 25 through DN 150.

2.4 Other Countries
The conditions described in Section 1.4 apply accordingly.

Fig. 3: Construction costs of Twin pipes



3 Piggy-Back Laying

Pipe arrangement: Single pipes laid on top of one another, Insulation Series 1

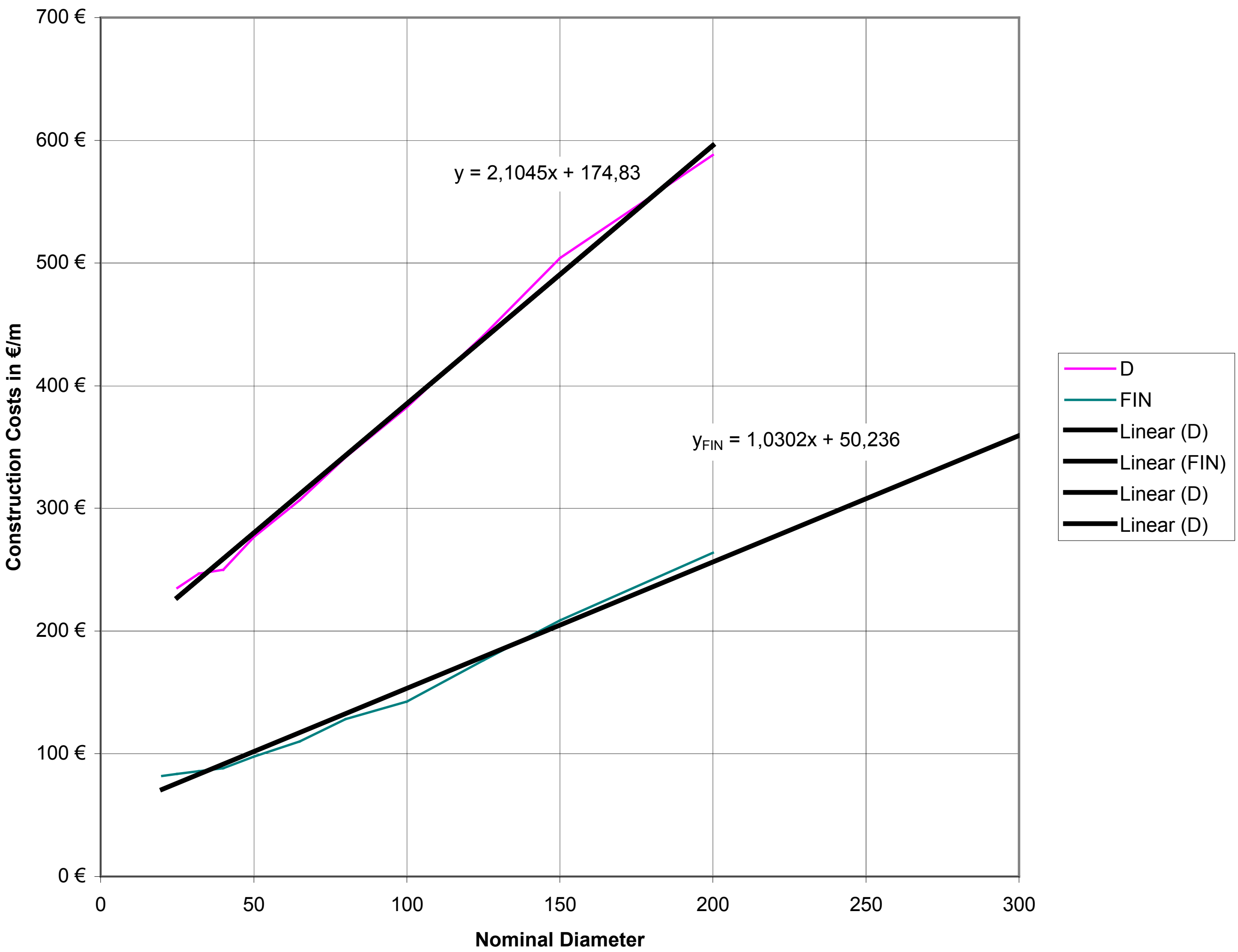
3.1 Germany
MVV Energie can look back on long-standing experience in the area of piggy-back pipe laying. Installation costs underrun the conventional pipe-laying method by 14%. Figure 4 depicts the installation costs representative for Germany.

Piggy-back pipe-laying expenditures may be calculated as follows:

$$V_D = 2.1045 \cdot N + 174.83$$

applying to nominal diameters DN 25 through DN 200.

Fig. 4: Construction costs of Piggy-back laying



3.2 Finland

Even though piggy-back pipe laying is unusual in Finland, this method was recalculated on the basis of unit prices for Finish construction projects [8].

Figure 4 also displays these installation costs.

The Finish installation costs for piggy-back pipe laying may be calculated as follows:

$$V_{FIN} = 1.0302 \cdot N + 50.236$$

applying to nominal diameters DN 25 through DN 200.

3.3 Other Countries

The relations described in Section 1.4 are suspected to apply to piggy-back pipe laying projects in other countries, as well.

4 Improved Heat Insulation

4.1 Insulation Series

Preinsulated plastic jacket pipelines are available in three insulation series, i.e. Insulation Series 1 (basic series), as well as 2 and 3. A higher insulation thickness causes both increased material expenditures as well as higher construction costs. This cost increase shows different effects on the individual nominal diameters in terms of material costs and excavation expenses. Moreover, a distinction should be made between conventional pipe arrangement, i.e. laying pipes next to each other, and piggy-back pipe laying.

Insulation Series 1 stands for the standard insulation type for preinsulated plastic jacket pipelines. The heat protection offered by this series is often considered the economically optimal solution. However, small-sized tubes are more and more often equipped with improved insulation properties. The Scandinavian focus on increased heat protection is greater than in Central European countries.

Material costs:
When regarding the material costs cropping up for Insulation Series 1 pipes as baseline value and assigning a cost index of 100% to them, the increase in material costs as indicated by manufacturers and required for Insulation Series 2 totals approx. +13.5 % [10]. This parameter represents a mean value for various components and applies to the entire range of nominal diameters.

Likewise, the additional costs accruing for Insulation Series 3 – compared to Insulation Series 2 – also total approx. 13.5 % for all nominal diameters [10].

Excavation costs:
On the one hand, excavation costs include the cost shares defined by the surface per each loop meter (tear-up and restoration of surface) and other shares defined by the volume per loop meter (excavation, delivery and integration of refill material). The costs charged by the size of the surface exert the greatest impact.

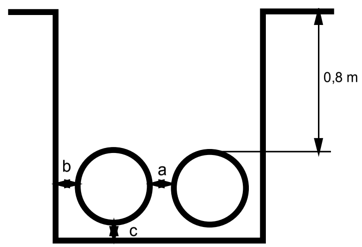
The increase in excavation costs for pipelines of a greater insulation thickness depend on

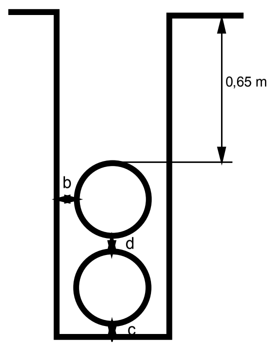
- the pipe arrangement (pipes next to each other, on top of one another), and
- the nominal diameter.

Figure 5 depicts for both pipe arrangements of nominal diameters DN 50, 200 and 400 and coverage of 0.8 m each how the excavation masses (i.e. trench, surface and volume) increase when changing over to the next higher insulation thickness.

To put it in simple terms: In case of small nominal diameters, excavation masses increase by approx. 5% to 6% when changing over to the next higher insulation series, in case of large nominal diameters by approx. 6% to 10%. The smaller value applies to the increase in trench surface, the greater value to the increase in trench volume. That holds true for both conventional pipe laying as well as piggy-back pipe laying. Increased material costs in the amount of +13.5% should be taken into account, as well. However, this cost factor should be regarded in relative terms, as the material costs only account for approx. 25% of the installation costs.

Conclusion:
For the purpose of the present study, it is estimated that a changeover from Insulation Series 1 to 2 or from Insulation Series 2 to 3 the construction costs increase by 10% in each case.





			Da	Coverage	Distance a	Distance b	Distance c	Distance d	Width	Depth	Surface/m	Volume/m	**Δ surface [%]**	**Δ volume [%]**
Horizontal	DN 50	Series 1	0.125	0.8	0.2	0.2	0.05		0.85	0.975	0.85	0.80	**100.0**	**100.0**
		Series 2	0.14	0.8	0.2	0.2	0.05		0.88	0.99	0.88	0.84	**103.5**	**104.5**
		Series 3	0.16	0.8	0.2	0.2	0.05		0.92	1.01	0.92	0.89	**108.2**	**110.5**
	DN 200	Series 1	0.315	0.8	0.2	0.2	0.05		1.23	1.165	1.23	1.28	**100.0**	**100.0**
		Series 2	0.355	0.8	0.2	0.2	0.05		1.31	1.205	1.31	1.38	**106.5**	**108.1**
		Series 3	0.4	0.8	0.2	0.2	0.05		1.4	1.25	1.40	1.50	**113.8**	**117.4**
	DN 400	Series 1	0.56	0.8	0.2	0.35	0.05		2.02	1.41	2.02	2.36	**100.0**	**100.0**
		Series 2	0.63	0.8	0.2	0.35	0.05		2.16	1.48	2.16	2.57	**106.9**	**109.2**
		Series 3	0.71	0.8	0.2	0.35	0.05		2.32	1.56	2.32	2.83	**114.9**	**120.0**
Vertical	DN 50	Series 1	0.125	0.65		0.05	0.05	0.1	0.225	1.05	0.23	0.21	**100.0**	**100.0**
		Series 2	0.14	0.65		0.05	0.05	0.1	0.24	1.08	0.24	0.23	**106.7**	**107.9**
		Series 3	0.16	0.65		0.05	0.05	0.1	0.26	1.12	0.26	0.25	**115.6**	**118.6**
	DN 200	Series 1	0.315	0.65		0.05	0.05	0.1	0.415	1.43	0.42	0.44	**100.0**	**100.0**
		Series 2	0.355	0.65		0.05	0.05	0.1	0.455	1.51	0.46	0.49	**109.6**	**111.8**
		Series 3	0.4	0.65		0.05	0.05	0.1	0.5	1.6	0.50	0.55	**120.5**	**125.4**
	DN 400	Series 1	0.56	0.65		0.05	0.05	0.1	0.66	1.92	0.66	0.77	**100.0**	**100.0**
		Series 2	0.63	0.65		0.05	0.05	0.1	0.73	2.06	0.73	0.88	**110.6**	**113.7**
		Series 3	0.71	0.65		0.05	0.05	0.1	0.81	2.22	0.81	1.01	**122.7**	**129.9**

Fig. 5: Increase of excavation masses in case of changeover by 1 or 2 insulation series

4.2 New Foam

The specifications for preinsulated plastic jacket pipelines assume the application of two PUR foam systems. Their heat conductivity amounts to

$\lambda = 0.0301$ W/(m·K) for CO_2 as propellant, and
$\lambda = 0.0288$ W/(m·K) for CP as propellant.

Recently, an improved PUR foam of finer cell structure was introduced on the market. This new foam is also CP-blown and offers a heat conductivity of

$\lambda = 0.0245$ W/(m·K) (manufacturer's data).

As other manufacturers have also announced improvements on their foams, this fine-pored foam has been included in the present study. The graphs of the heat conductivity of the three foam systems are displayed in Figure 6.

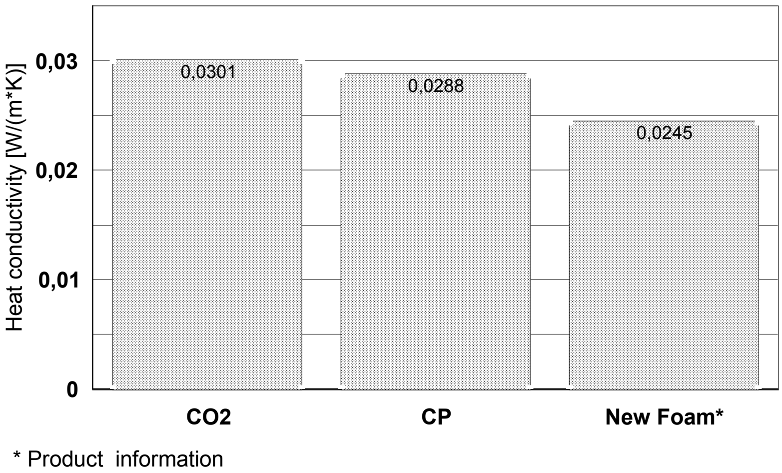


Fig. 6: Heat conductivity of PUR foams

The heat transfer of an individual preinsulated plastic jacket pipeline reduces by approx. 10% in case of a changeover from CO_2 to CP and by another 6% when changing over to the new foam. (Results obtained from heat loss calculations based on DN 100 pipes, Insulation Series 1.)

When comparing the efficiency of heat insulation following improvement of a pipe's insulation thickness by equipping it with Insulation Series 2 instead of Insulation Series 1 and applying new foam, the heat losses of a pipe decrease by approx. 18% in the first case and by 6% in the second case.

The price for pipeline material containing new foam instead of conventional CP-blown foam is approx. 8% more expensive [10].

Possibly, the ageing behavior of new foam is slightly more favorable than conventional CP-blown foam, as the cell gas can diffuse through a greater number of cell membranes more slowly in such a case. However, test results on this phenomenon have not been published, yet. Therefore, this impact is not taken into account in the present study.

On the basis of the strategic approach adopted within the framework of the present study, it is assumed that pipes insulated with new foam involve construction costs which are approx. 2% higher (8% for material in connection with Figure 9, material share of 20%).

4.3 Plastic Medium Pipes und Diffusion Barriers

For the purpose of the present study, plastic medium pipes are taken into consideration as jacketed pipes and treated as preinsulated plastic jacket pipelines within the framework of thermal calculations.

The effects of blocking foils to prevent diffusion are not taken into account here, either,

- as there are no solutions tried and tested over several years (steam and cell gases) and the developments of the manufacturers are not in full swing, yet; and
- as laboratory tests have revealed substantial defects occurring on available solutions (longitudinal tightness, mechanical stability).

5 Components of Installation Costs

In Sections 1 though 4, installation costs were used as sums only. In order to make cost influences transparent, at least a differentiation of excavation costs and pipe installation costs is indispensable; usually, a further breakdown of these costs is made.

Figure 7 shows how installation costs vary from place to place. This figure contains the installation costs for different German cities and for a specific pipeline network (length of 510 m and nominal diameters of DN 100/80/65) [11].

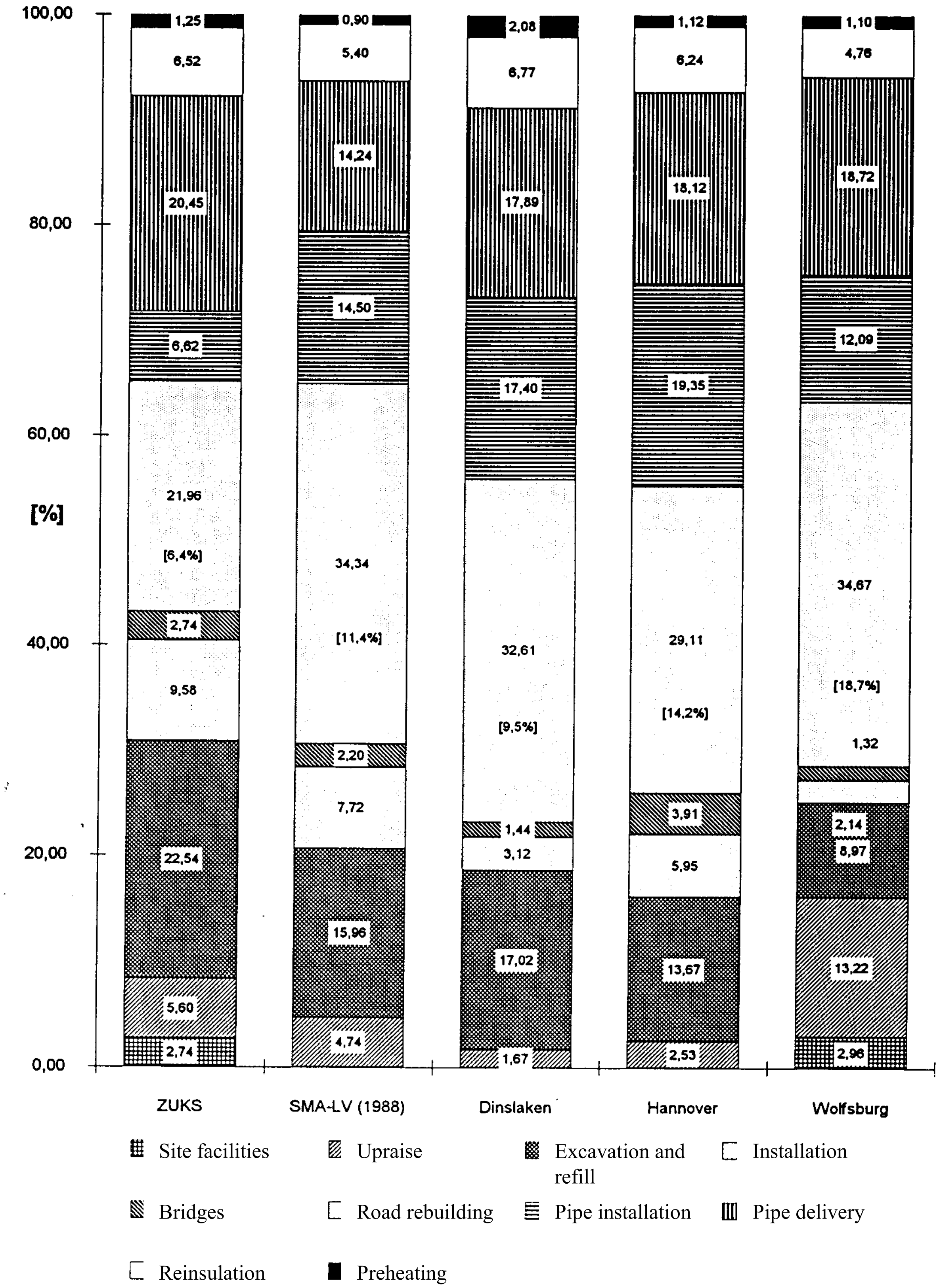
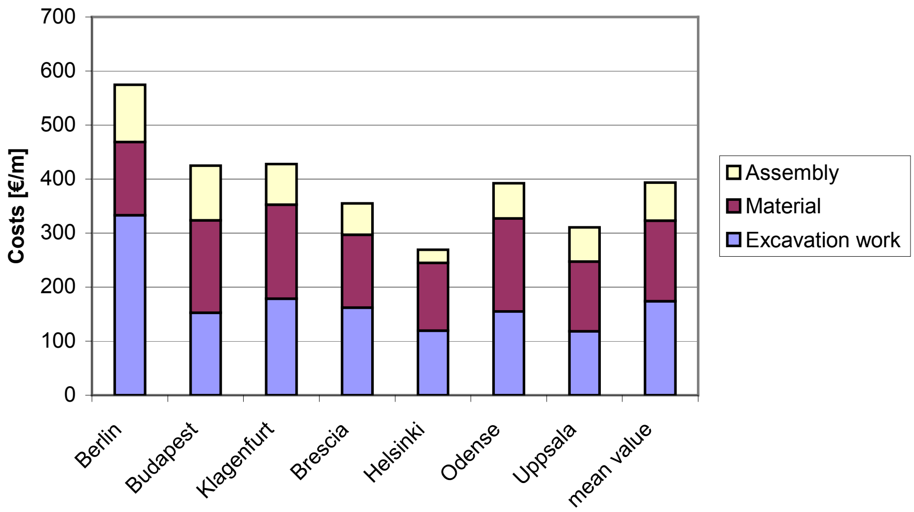


Fig. 7: Total installation expenditures for different German cities

On an international scale, these cost relations are very similar. Euroheat & Power presented a cost comparison [7] which is reflected for 7 major European cities here. Figure 8 displays how the installation costs for a DN 200 preinsulated plastic jacket pipeline vary in these cities. Figure 8a depicts the absolute installation costs in €/loop meter and Figure 8b shows the percentages of excavation work, material and installation in the overall expenses. The assembly costs encompass pipe laying, welding and reinsulation work.

Figure 8a proved the assumption that material costs are almost the same in these countries. Excavation costs are particularly high in Berlin (which is also true for Paris); at first sight, this circumstance suggests in Figure 8 b that the share of material costs is relatively low.



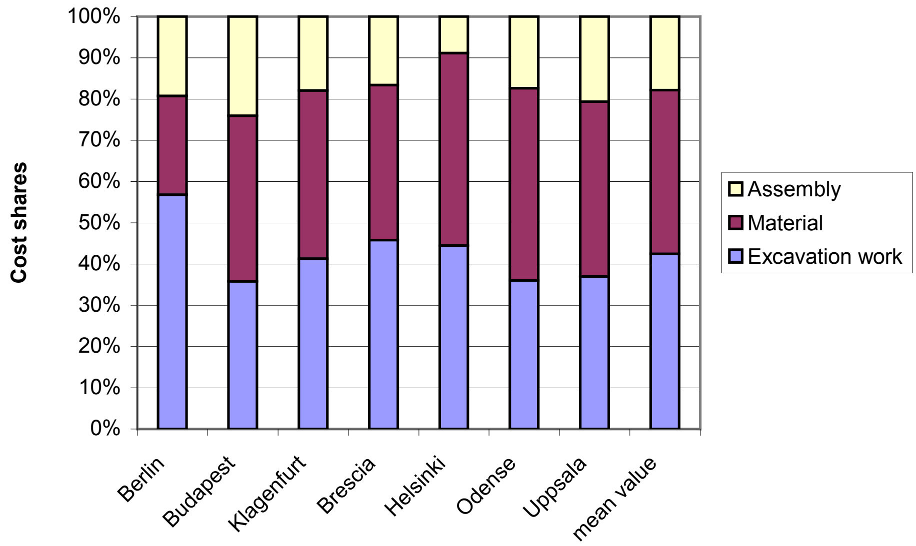


Fig. 8: Installation costs for a DN 200 preinsulated plastic jacket pipeline
a) Installation costs in €/loop meter
b) Cost shares of assembly, material and excavation work

The present study assumes a simplified and uniform structure of the installation costs for all nominal diameters. The relation of excavation costs to pipe installation costs is 58:42, see Figure 9. When further breaking down the costs for street and road construction, tear-up and restoration of surface account for a share of 35%, and excavation, integration and refill for 23% in the overall costs. The pipeline installation costs may be broken down into material costs of 20% and assembly expenses (laying, incl. welding and reinsulation) of 22%.

When comparing this breakdown with the available statistical material, it comes very close to the conditions met in Sweden [6] and Germany [11]. By contrast, the share of material costs is greater in the cities depicted in Figure 8b.

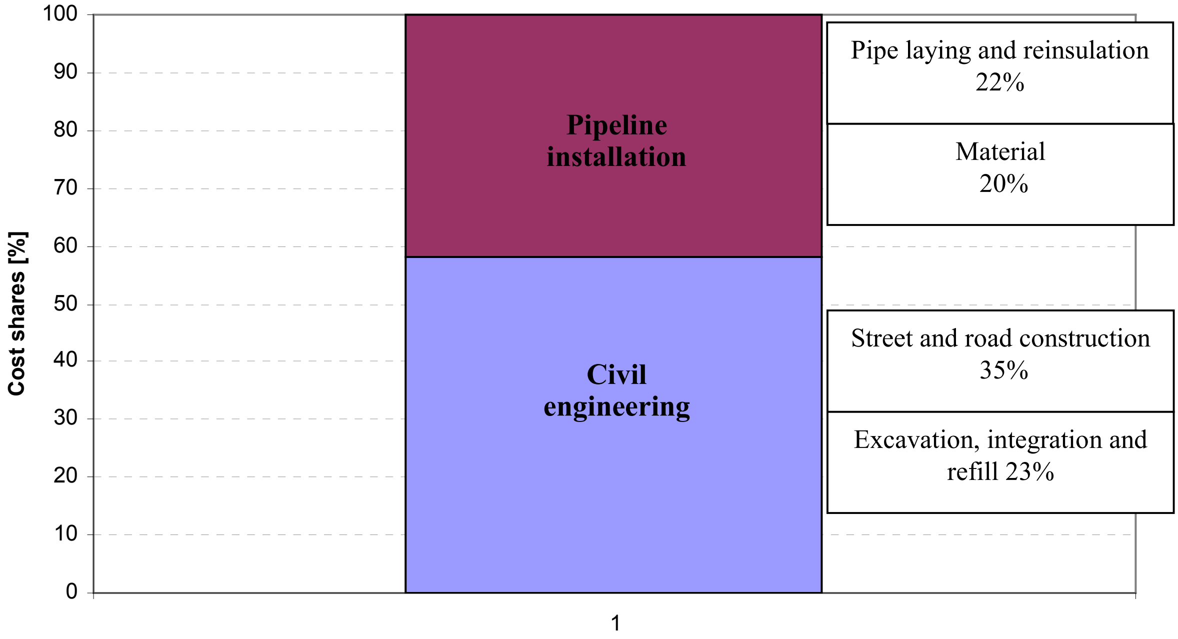


Fig. 9: Breakdown of total installation costs

6 Sources for the Installation Costs of Preinsulated Plastic Jacket Pipelines

[1] Herstellkosten
MVV-Richtwerte, abgeglichen mit AGFW
MVV intern

[2] AGFW-Studie
Pluralistische Wärmeversorgung
AGFW 2002, Kapitel 03

[3] EWU
Kennziffernkatalog
1999

[4] Finnish District Heating Association
DH Pipe Construction Costs 2002
Statistics 2002

[5] Fa. Lögstör, persönliche Mitteilung v. 6.4.2004

[6] Fjärrvärme Föreningen
Kulvertkostnadskatalog 1997
FVF 1997:10 Stockholm

[7] Euroheat & Power
Construction costs comparison of preinsulated bonded district heating pipes
Yearbook 1999

[8] IEA District Heating and Cooling
New ways of installing district heating pipes
Novem, Sittard 1999:T 3.2

[9] FVF/Chalmers
EkoDim-Software, Schweden 2003
Baukosten der Twinrohrverlegung: Halmstad

[10] Fa. Isotec/Star Pipe, persönliche Mitteilung v. 3.3.2004

[11] Hoffmann, H.-W.
Neuartige Verlegetechniken für das Kunststoff-Verbundmantelrohr-System
MVV-SMA Stadtwerke Mannheim 1995

7 Schedules

Basic data and schedules referring to Figures 1 through 4.

Table 1: Standard preinsulated plastic jacket pipelines
Table 2: Twin pipes
Table 3: Piggy-back pipe laying

Table 1: Installation costs for preinsulated plastic jacket pipelines (PJP), single pipes, Insulation Series 1

DN	[1] DM	D [1] in €	[2] DM	[2] in €	[3] DM	[3] in €	R 3-1 [4] in €	FIN Series 1 [4] in €	i [6] SKR	R 2 [6]i in €	R1 [6]i in €	y [6] SKR	R 2 [6]y in €	R 1 [6]y in €	S S mean [6iy]	FIN	S [6]i	S [6]y
20							91 €	75 €										
25	533	273 €	585	299 €	650	332 €	128 €	106 €	1,900	206 €	187 €	1,400	152 €	138 €	163 €	2.58	1.46	1.97
32	560	286 €		301 €	680	348 €	128 €	105 €	2,170	235 €	214 €	1,650	179 €	163 €	188 €		1.34	1.76
40		305 €	590	302 €	720	368 €	127 €	105 €	2,430	263 €	240 €	1,950	211 €	192 €	216 €			
50	633	324 €	616	315 €	760	389 €	123 €	102 €	2,750	298 €	271 €	2,250	244 €	222 €	246 €	3.18	1.19	1.46
65	701	358 €	662	338 €	810	414 €	137 €	113 €	3,000	325 €	296 €	2,513	272 €	248 €	272 €	3.17	1.21	1.45
80	781	399 €	713	365 €	880	450 €	153 €	126 €	3,300	358 €	325 €	2,813	305 €	277 €	301 €	3.16	1.23	1.44
100	875	447 €	815	417 €	980	501 €	167 €	138 €	3,600	390 €	355 €	3,150	342 €	310 €	333 €	3.24	1.26	1.44
125	1,010	516 €	910	465 €	1,100	562 €	200 €	165 €	3,950	428 €	389 €	3,450	374 €	340 €	365 €	3.12	1.33	1.52
150	1,131	578 €	996	509 €	1,260	644 €	210 €	174 €	4,350	472 €	429 €	3,825	415 €	377 €	403 €	3.33	1.35	1.53
200	1,346	688 €			1,480	757 €	291 €	240 €	5,000	542 €	493 €	4,238	459 €	418 €	455 €	2.86	1.40	1.65
250	1,700	869 €			1,720	879 €	323 €	294 €	5,850	634 €	577 €	4,800	520 €	473 €	525 €	2.96	1.51	1.84
300	1,950	997 €			1,980	1,012 €	387 €	352 €	6,750	732 €	665 €	5,378	583 €	530 €	598 €	2.83	1.50	1.88
350	2,200	1,125 €			2,230	1,140 €	481 €	437 €		811 €	737 €		648 €	589 €	663 €	2.57		
400	2,500	1,278 €			2,450	1,253 €	575 €	523 €	8,200	889 €	808 €	6,563	712 €	647 €	728 €	2.45	1.58	1.98
500					2,780	1,421 €	697 €	697 €	9,300	1,008 €	917 €	7,350	797 €	724 €	821 €			
600							753 €	753 €	10,600	1,149 €	1,045 €	8,250	894 €	813 €	929 €			
															Comparative factor f. Germany [1]	2.95	1.36	1.66

Costs in €, incl. planning, normal city area

[1] Germany, MVV/AGFW: PJP, Series 1, as per 2003
[2] Germany, AGFW Cogeneration study, Pluralistische Wärmeversorgung, as per 2002
[3] Germany, EWU, Kennziffernkatalog 1999, PJP, lower limit
[4] Finland, LLY statistics, 2002, PJP, up to DN 200 Series 3, up to 400 Series 2, as from 500 Series 1 (design costs are not included, approx. 5-10%)
[6]i Sweden, FVF statistics, 1997, PJP, city center, Series 2
[6]y Sweden, FVF statistics, 1997, PJP, outskirts, Series 2
[8] IEA, New Ways of Installing DH Pipes, 1999, PJP and twin pipes, D and FIN
[9] Sweden, FVF - EkoDim 2003, PJP and twin pipes, PJP, city, Series 2

Table 2: Installation costs for preinsulated plastic jacket pipelines (PJP), twin pipes

		D	**FIN**					**S**			
DN	[8] D in $	[8] in €	[5] in €	[9i] SKR	[9i] in €	[9y]	[9y] in €	Mean	FIN	S City	S Outskirts
15				1,461	158 €	1,189	129 €	144 €			
20			73 €	1,579	171 €	1,273	138 €	155 €			
25			92 €	1,756	190 €	1,400	152 €	171 €			
32			54 €	1,874	203 €	1,484	161 €	182 €			
40			98 €		215 €		169 €	190 €			
50	399	329 €	117 €	2,110	229 €	1,654	179 €	204 €	2.81	1.44	1.84
65		348 €	115 €	2,258	245 €	1,760	191 €	218 €			
80	444	366 €	130 €	2,405	261 €	1,866	202 €	232 €	2.82	1.40	1.81
100	515	425 €	206 €	2,789	302 €	2,140	232 €	267 €	2.06	1.40	1.83
125			165 €	3,290	357 €	2,500	271 €	314 €			
150			156 €	3,585	389 €	2,712	294 €	341 €			
200			199 €								
									2.56	1.42	1.83
									Comparative factor f. Germany [1]		

Costs in €, incl. planning, normal city area

[5] Finland, LLY statistics, 2002, PJP-twin pipes (design costs are not included, approx. 5-10%)
[8] IEA, New Ways of Installing DH Pipes, 1999, PJP and Twin pipes, D and FIN
[9i] Sweden, FVF - EkoDim 2003, twin pipes, city center
[9y] Sweden, FVF - EkoDim 2003, twin pipes, outskirts

Table 3: Installation costs for preinsulated plastic jacket pipelines (PJP), piggy-back pipe laying

		D		**FIN**	
DN	[8] D in DM	[8] in €	[8] in US$	[8] in €	FIN
20			99.15	82 €	
25	460	235 €	101.35	84 €	
32	483	247 €	103,81	86 €	
40		250 €	106.86	88 €	
50	541	277 €	118.36	98 €	2.83
65	600	307 €	133.37	110 €	2.79
80	668	342 €	155.57	128 €	
100	748	382 €	172.87	143 €	2.68
125	863	441 €	213.78	176 €	
150	986	504 €	253.18	209 €	
200	1,150	588 €	319.58	264 €	
250					
300					
					2.77
					Comparative factor f. Germany [1]

Costs in € , incl. planning, normal city area

[5] Finland, LLY statistics, 2002, PJP-twin pipes
[8] IEA, New Ways of Installing DH Pipes, 1999, twin pipes, FIN

Appendix 5: Miscellaneous

Fig. A5-1: Estimation of the ageing behavior of new foam

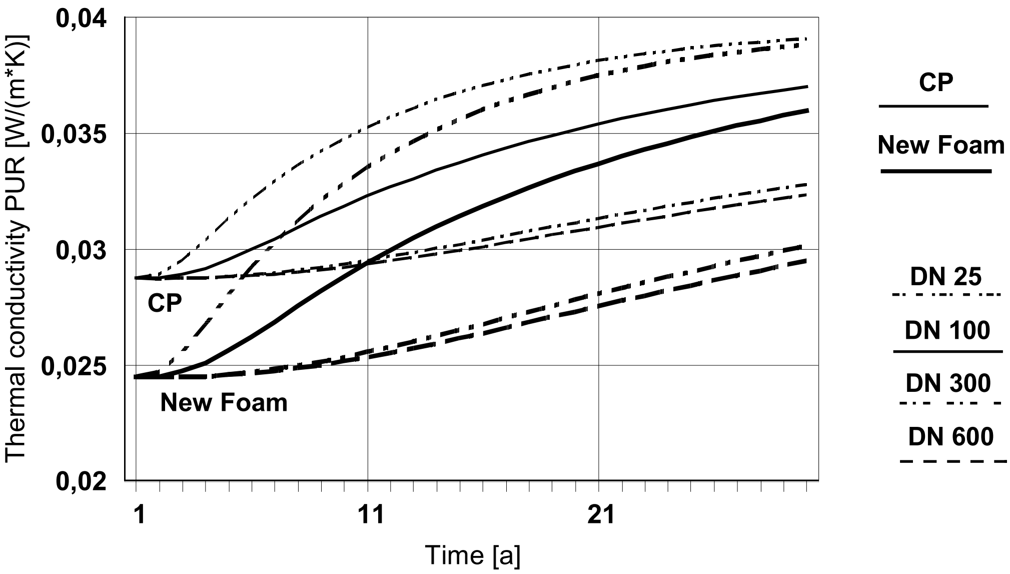


Fig. A5-2: Specific heat losses over a period of 50 years (for: Cell gas CP; Insulation Series 1; ΔT = 63.8 K; H = 0.8 m; λ_E = 1.5 W/(m·K)

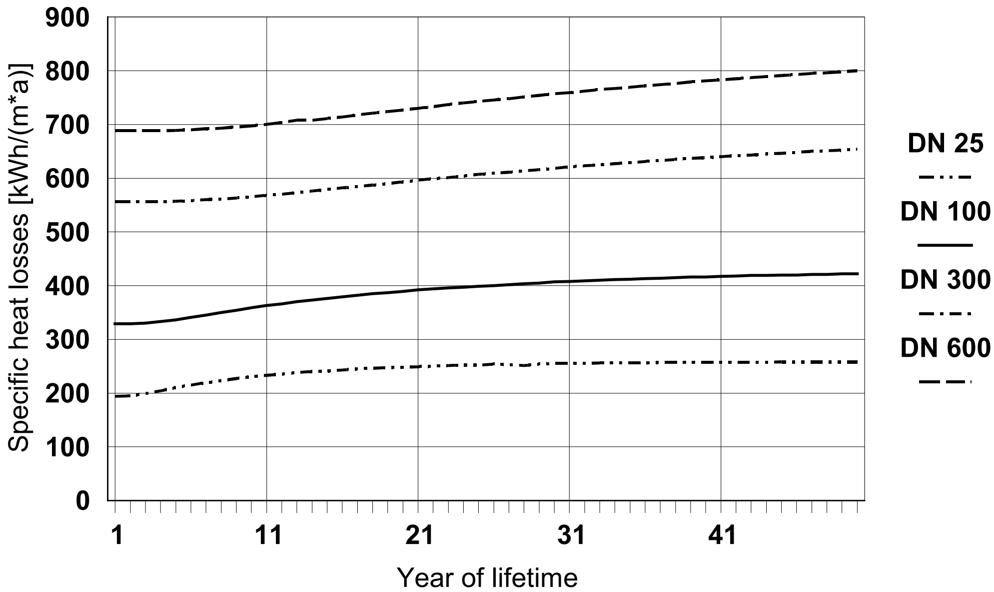
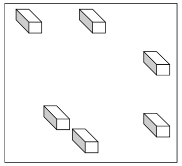
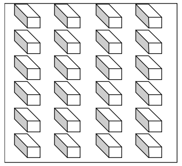
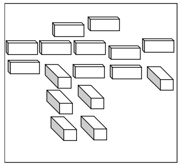
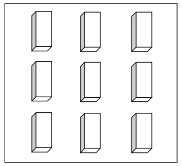
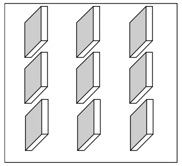
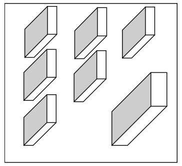
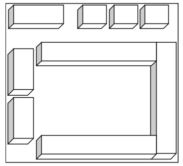
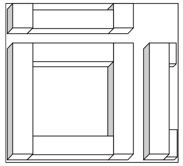
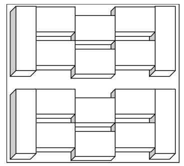


Fig. A5-3: Characterization of settlement structure by settlement classes [H.P. Winkens; Untersuchung einer zum Heizöl alternativen Energiebedarfsdeckung (Versorgungskonzept) für den Rhein-Neckar-Raum; Forschungsbericht BMFT-ET-5286-A Energieforschung, 1984]

Settlement class	**ST1**	**ST2**	**ST3**	**ST4**	**ST5**	**ST6**	**ST7**	**ST8**	**ST9**
Isometric representation									
Annual heat demand [MWh/a·km²]	8,763	43,434	42,362	45,688	64,904	104,359	93,573	196,684	168,454
Pipeline length [m/km²]	10,000	15,879	13,451	10,522	11,842	6,255	15,174	19,085	18,314
Mean diameter [mm]	43	60	60	60	64	71	70	81	79
Total of heat losses, supply pipe and return pipe [MWh/a·km²]	1,999	4,851	3,930	2,628	3,742	2,698	5,066	6,387	7,299
Percentage of heat losses in annual heat demand [%]	23	11	9	6	6	3	5	3	4

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