IEA DHC | CHP

HOW CELLULAR GASES INFLUENCE INSULATION PROPERTIES OF DISTRICT HEATING PIPES AND THE COMPETITIVENESS OF DISTRICT ENERGY

How cellular gases influence
the insulation properties of district heating pipes
and the competitiveness of district energy

General Preface Annex VII

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, 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, the 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 air conditioning, 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 have 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, and the 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-, Sicherheits-, Energietechnik UMSICHT Project leader: 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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Introduction to the project "How cellulare gases influence the insulation properties of district heating pipes and the competitiveness of district energy".

This report describes the results of the project "How cellulare gases influence the insulation properties of district heating pipes and the competitiveness of district energy". The report has been carried out in co-operation with a project group comprising Lappeenranta University of Technology (LUT) in Finland, Ingenierbüro Kraaz in Germany and the Industry and Energy Division of the Danish Technology Institute (DTI) in Denmark. DTI has acted as project secretary, administrator and manager. Participants in the project group were Juha-Pekka Lemponen from LUT, Michael Kraaz from Ingenierbüro Kraaz and Henning D. Smidt from DTI.

At the outset of the project, the IEA member countries showed considerable interest in Annex VII. This resulted in the appointment of an expert group monitoring the project member. The members of the expert group were:

- – Veli-Pekka Sirola (Finland)
- – Torsten Göhler (German)
- – Thomas Bronnum (Denmark)

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Summary

Content
The report deals with a number of different methods to determine the composition of cellular gas in the foam, as experiments have been made over time with both crushing and compression as extraction for the liberation of the cellular gasses. The section ends with an indication of the reproducibility of measurements carried out on three types of PUR-foam with high, low, and no content of cyclopentane.

It is shown how the thermal conductivity of new foam may be calculated based on density, cell size, and composition of the cellular gas of the foam. Two methods are shown to calculate the insulation property of the foam over time. Based on reports and pre-insulated pipes that have been excavated, the thermal conductivity of the PUR-foam of the pipes produced with CFC PUR-foam in the mid 1980'ies is determined. Finally, the thermal conductivity and composition of cellular gasses for pre-insulated pipes produced with traditional PUR-foam and with micro-cellular PUR foam is shown. Over the next few years the latter mentioned foams are expected to be the dominant types of foam.

A program to calculate the heat loss has been developed. The programme can calculate the value of heat loss in a CFC pre-pipe system produced in 1985. Calculation is made for the years 2005 to 2035. The results may be compared with the calculated values of the transmission loss over a 30-year period from a similar new system produced with traditional or micro-cellular PUR-foam. The thermal conductivity of these types of foam is calculated to being 0.028 and 0.025 W/(m K).

A questionnaire survey has been made in the countries associated with Euroheat & Power. The survey resulted in answers from 25 plants in six countries. The answers were relatively similar and indicate the tendencies.

The section on vacuum insulation deals with the basic properties of energy transmission in materials. The properties of a series of panels on the market are then checked both with regard to type of foam, density of membranes, size, and their application. This is followed by a section on technology used to acquire the vacuum necessary to obtain the insulating property. The section ends with general experiences from the use of vacuum. The next section deals with requirements made to insulated underground pipes aimed for district heating. Finally there is a discussion dealing with the technical and physical barriers to the production and application of open-cellular foam intended for vacuum. Density of barrier material, mechanical properties, and technical lifetime are also described.

Findings
The project has resulted in several laboratories initiating measurements of the content of cellular gas when crushing foam. This method is considered best suited for the purpose. So far results have only been available from one single laboratory. Both as regards competition and comparison of results from different laboratories, this has not been satisfactory. Therefore the project is essential as regards to improving the standard among the laboratories that measure the basic properties of the insulation property of foam on a short and a long term. This can be beneficial in connection with estimating the future heat loss of the district heating system and the development of types of foam with improved insulating properties. The industry producing refrigerators and freezers may also benefit from this.

Estimation and comparison of heat loss from three types of PUR-foams show that

- During the first 30 years the heat loss of traditional foam will be approximately 10% higher than that of CFC-blown pipes in use from year 20 to year 50. This means that the environmental effect from a traditional blown pipe will be approximately 10% higher that that of an old CFC blown pipe.
- The micro-cellular foam will reduce the heat loss with approximately 10% compared to traditionally blown pre-insulated pipes. Compared to old CFC-blown pipes that have been used for 20 years, the level of heat loss from small dimensions will be the same as the level of old CFC-blown pipes and as regards big dimensions, the heat loss will be smallest in micro cellular foam.
- After 30 years of use the heat loss of traditionally blown pipes is approximately 5% higher than that of old CFC-blown pipes. However, the heat loss in micro cellular foam is

approximately 6% lower than that of traditionally blown foam. This is slightly better than the heat loss in old CFC-blown pipes that have been used for 20 years.

From the questionnaire survey it is obvious that the users prefer a low thermal conductivity to additional insulation thickness and that the preferred insulation gas in PUR-foam is cyclopentane. Everybody give high priority to long term insulation properties. Only a few plants have compared heat loss from CFC-blown pipes with that of cyclopentane-blown pipes.

Vacuum insulation is used in a number of applications including equipment for temperature controlled transportation, domestic and commercial refrigeration as well as insulation in building and construction. They are preferably applied in any system where reduced volume of insulation material, better temperature control, reduced shipping volume, and weight or increased energy efficiency is required.

The possibilities and restrictions in using this technology in the industry of pre-insulated district heating pipes may take place where costs are not a critical factor or where space is limited. Vacuum insulation of district heating systems is established in steel in steel systems that are secured from penetration of hydrogen in connection with welding of the steel pipes.

If open-cellular PUR-foam is used, vacuum can only be established in layers of a thickness up to approximately 4 cm due to the size of cells. Thermal conductivity of approximately 0.010 W/(m K) may be obtained. To ensure a continuous vacuum the PUR-foam must be heated so that it can emit gasses while a continuous vacuum is established. The PUR-foam offers sufficient compression strength for normal pipe systems whereas the shearing strength is limited.

With the present technologies it is difficult to create sufficient density in flexible barrier materials if the temperature is considerably above room temperature. This means that the insulation property decreases with time and the technical lifetime is reduced. Furthermore, barrier materials often result in edging phenomena that reduce the insulation property of products based on vacuum technology.

In consideration of these limitations it may be possible to produce small dimensioned flexible pipe systems that are insulated with PUR-foam cups or rings that are vacuum insulated. A thermal conductivity of approximately 0,010 W/(m K) of the final product is not realistic due to edging phenomena and diffusion of the flexible barrier.

Conclusions:
CFC-blown pipes will still after 20 years in use have a 10 % lower heat loss than pre-insulated pipes with traditional blown PUR-foam. This will be the case also for the coming 30 years period. This means that the phasing out of CFC has reduced the competitiveness and probably the spread of district heating to new areas. Also the environmental impact has contributed to a reduction of the competitiveness of district heating due to the phasing out CFC, as e.g. the pollution with carbon dioxide and sulphur dioxide has increased by 10%.

The new micro cellular PUR-foam that is foreseen to penetrate the market within a few years, will change this situation and bring the competitiveness and environmental impact of district heating back to the level is was before CFC was phased out. This is very positive, especially if carbon dioxide quotes, increasing energy prices, new duties and increasing VAT will bring new burdens on district heating.

The answers in the questionnaire show that the users have priority for cyclopentane for carbon dioxide in PUR-foams, that the long-term insulations properties are important and that comparison between heat-loss form CFC-blown pipes and cyclopentane pipes are seldom made.

The use of vacuum insulation technology based on PUR-foam is useful for shells or rings with a thickness op to 4 cm. To keep the low pressure the PUR-foam shall be sealed in an extremely tight but flexible barrier material. This means vacuum technology is useful where no or limit shear strength is required. Due to the high temperature in the district heating systems, the diffusion rate thru the barrier material is accelerated and the lifetime concerning low thermal conductivity of the product reduced.

Introduction

District heating takes up a significant part in the heat supply market of private households and industries e.g. in Denmark, Finland and Poland more than 50%, in Sweden more than 40 %, and in Germany 17 % (EuroHeat and Power). Further, in all parts of Europe the demand for district cooling and cooling pipes grows constantly within the area of air conditioning and process cooling. In some parts of Europe (Eastern Europe, Austria and Italy) the whole district heating market grows above average. In 27 European countries from Greece to Finland and from Portugal to the Ukraine district heating is distributed to over 100 million customers, app. 23% of the entire population in these countries.

Annual sales of heat alone bring an income of approximately 10.7 billion Euro to the district heating distributors in the European Union. The accession of Poland, Hungary and the Czech Republic to the European Union would add about a further 3.1 billion Euro to this figure. (Euroheat & Power 2004)

It is fact that during the transmission of warmth or cold there are substantial losses in the pipelines. It is estimated that approx. 10-18 % are lost, and examples up to 40% are seen. The specific technical and climatic conditions of each country are to be taken into consideration. In some countries of Eastern Europe the aged lines and systems lose up to 50 % of the energy.
The need to reduce the loss of energy increases from year to year. It must be underlined that these plants and/or nets are planned for a life span of approx. 30 years (assumed life span). The life span of main supply lines is sometimes planned for 50 years.
In view of the reduction in the conventional energy reserves and rising prices on oil and natural gas a decrease in heat loss could expand the energy reserves and improve the environment e.g. by the reduction on the carbon dioxide output.

Phasing out CFC
During the last 10 years the CFC gases have of environmental reasons been phased out and replaced by other types of gases with less influence on the environment. Especially the Ozone Depletion Potential of the well insulating CFC gases has been in focus, and governmental requirement forced the industries for phasing out this type of gases. This was the basic reason for the change in the industry and for the development of new products with more environmentally friendly insulation gases.

The table below shows the critical parameters for blowing agents that have been, are or can be used in polyurethane foam in district heating pipes.

The district heating pipe producers brought new products on the marked and these products have now been in use for a number of years. In the new products the CFC gas R11 was replaced by cyclopentane and carbon dioxide. As these gases have higher thermal conductivity than R11 the initial insulation properties for the cellular plastic insulation material in the district heating pipes increased by app. 10 %. Additionally, it was for physical reasons not possible to implement as much of the new physical cellular gases in the foam as was the case for the old ones. This means that a reservoir of the well insulating gas in the foams are reduced .

Finally, the diffusion rate of the new cellular gases was higher than R11. The consequence is that the heat conductivity increases faster in the new products than in the old ones. In cellular plastic containing cyclopentane increases by up to 30% relative in the course of the lifetime of the pipe are foreseen for some products. Measurements have demonstrated that this is due to the diffusion of carbon dioxide out of the cellular plastic and atmospheric air in the foam. The increase is highest for the small dimensions.

This alone means that new piping systems must have thicker insulation so the heat loss does not increase, as this would mean cost increase.

In some piping systems, carbon dioxide is used as insulation gas. This cellular gas diffuses quickly and is replaced by atmospheric air; that makes the heat loss of the piping system increase sharply. Calculation models show an increase of app. 40%. In spite of this, carbon dioxide is still used as cellular gas in certain piping systems giving rise to increased costs for the entire lifetime of the piping system.

New foam systems

Outside the EU other cellular gases of HCFC type such as 141b are used and new gases are on their way, e.g. 365 mfc, which are of the HFC type. The long-term insulation properties of this cellular gas should be investigated before the gas becomes available in the market, so the users can calculate the expected heat loss of the piping system in comparison with the traditional preinsulated piping systems. The advantage for the pipe producers using these gases is that the explosion risk is low compared with cyclopentane, but the price compared to the benefit is at for the moment too high.

In these years a new generation with minor cells is on the market. This type of foam is being implemented in the production of preinsulated pipes. The minor cells offer the advantage that the radiation of the heat decreases. (In practice it seems that the initial thermal conductivity of the foam is decreased by app. 10 - 20 %).

Experiments are still going on with better types of polyurethane for pre-insulated pipes for district energy, and optimisation of raw materials and processes are estimated to reduce the heat loss of the piping system by several percentages. A significant reduction in the heat loss of the piping system can therefore take place by using this technology.

Taxation

The heat loss of piping systems has gained increased focus as the energy price has increased and as energy to a greater extent has become a taxation objective. The heat loss of the piping system amounts to 5 - 40% depending on the type of cellular gas, thickness of insulation, casing pipe dimension, etc. Therefore the heat loss in certain systems is a significant economic factor.

For these reasons, a study should be carried out of how the heat loss of the piping system will develop in the future, depending on the pipe dimension, insulation thickness and physical cellular gas.

The aim of this work is to get a calculation model for replacement of the old CF blown pipes with traditional cyclopentane blown foam and the new type of foam with minor cells.

Vacuum technology

In other industries, experiments are carried out to replace cellular gases with vacuum. In addition, PUR foam systems intended for vacuum are marketed. This implies that the traditional production technology of pre-insulated pipes can be used. When using vacuum and applicable foam systems, the calculation shows that the heat loss can be reduced by up to 75% compared to existing products. This makes it possible to use smaller pipe dimensions and to further develop district energy in new areas.

But a number of conditions have not been investigated, e.g. the mechanical properties and the lifetime. Especially these two properties separate the foam systems used for pipes in district heating and cooling from other applications. In addition, it should be clarified how the vacuum has to be maintained as it is currently not believed to be possible to keep a constant vacuum in the insulation without periodic maintenance.

Vacuum-insulated pipes may in the future take over further areas of application in the area of district heating as well as in the "cooling transport" via pipelines. They obtain the same insulating efficiency as conventional insulating materials with an insulation efficiency which is 2-3 times higher. This characteristic can be kept up for decades.

"Normal" insulated pipes which are pre-insulated conventionally with PUR-foam in the factory show an insulation thickness of 2 to 20 cm - depending on the pipe diameter. The use of vacuum insulation gives the technical designer a much greater variety of planning, e.g. in transmission heat over much longer distances. The improved thermal insulation can also merge remote power stations or cities into one unit. The bringing together of power and warmth could thus be used in central areas.

The reduced size of the insulation may also be advantageous in laying pipelines in a limited space. So maybe new uses are being found, which up to now have not appeared to anyone. Vacuum insulations have already been used in district heating in the steel casing tube (steel into steel pipe /steel pipe jacket). But compared to traditional preinsulated pipes the manufacturing costs are substantially higher. Thus the uses are limited to special cases.

Blowing agent	CFC R11	HCFC 141b	Cyclo-pentane	Carbon-dioxide	HFC 365mfc
ODP	1,0	0,11	0	0	0
GWP $_{100\ yr}$	4000	630	11	1,0	840
Lifetime [Years]	45	9,2	-	-	-
λ_{gas} [mW/(m K)] 25°C	8,7	9,7	12,0	16,6	10,6
Boiling point [°C]	23,7	32,1	49	-	40
Flam. Limit [°C]	None	None	-37	None	-25
Flam. Limit [% Vol.]	None	7,4-15,5	1,5-8,7	None	3,5-13,0
Formula	CCl_3F	CH_3CFCl_2	C_5H_{10}	CO_2	$CF_3CH_2CF_2CH_3$
Molar weight [g/mol]	127	107	70	44	97
CAS no.	75694	1717-00-6	287-92-3	124389	406-58-6

Table 1: The table shows environmental influence and physical properties of insulation gases used in PUR-foam in district heating pipes.

ODP - Ozone Depletion Potential - is a measure of the chemical's relative effect upon the ozone layer compared to CFC-11. It is related to the amount of chlorine in the compound and the atmospheric lifetime of the compound molecules.
GWP - Global Warming Potential - is a similar measure, but Carbon Dioxide (CO_2) is the reference compound. Values are in '000's for 100 year time horizon
Lifetime is the amount of time after a substance enters the atmospheric air, that it takes for natural processes to remove it from the atmosphere (*Sources: ALTOFINA; US Department of Energy: Energy Efficiency and Renewable Energy*

Cell Gas Analysis Methods In Rigid Cellulare Foams

Grinder/Gas Chromatography Method

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S-412 96 Göteborg, Sweden.

Experimental Procedure
A sample cylinder (diameter = 20 mm, length = 60 mm) is cut from the foam with a thin-walled metal pipe with a sharpened end. The sample is then placed in the grinder and the system is flushed with dinitrogen oxide for 10 minutes in order to remove all oxygen and nitrogen in the gas phase surrounding the sample. (dinitrogen oxide is not used in foams and doesn't interfere with the other gaseous components in GC analysis).
The cell gases are released from the foam sample by grinding in special sampling equipment (Figure 1). The grinding is carried out by pressing the cylindrical sample towards a rapidly rotating edge at the end of the pipe. The edge is lathe steel attached to a shaft on bearings. A simple electric drill with variable speed does the rotation. (The sample is attached to the metal piston by small wooden sticks allowing the entire sample to be ground without destroying the rotating edge).
The gas released during the grinding process is collected in an all-glass syringe, permitting the total gas volume to be determined.
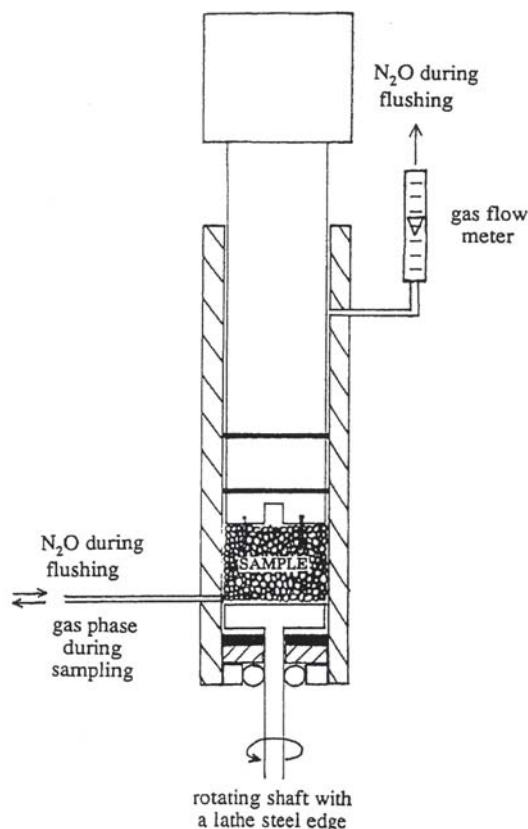
Figure 1: Grinding machine.

The chromatographic analysis is performed as soon as all the gas is collected and thoroughly mixed.

Gas Chromatography and Results

Two columns were used in the gas chromatograph for the separation of compounds with different molecular weights, as shown in Figure 2. Helium was used as a carrier gas in the gas chromatograph (25 ml/min).
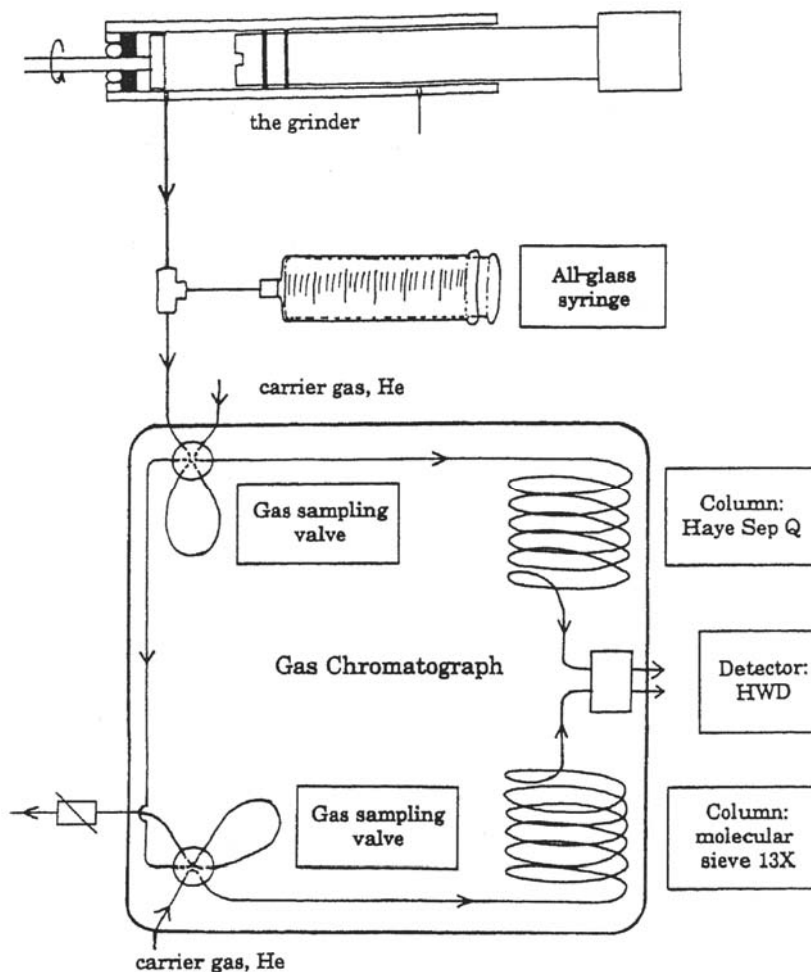
Figure 2: The gas chromatograph and sampling equipment (grinder and syringe) used for analysing the gas phase in polyurethane foams.

A packed molecular sieve column (molecular sieve 13 X, 170 cm × 1/8´´) was used for the separation of oxygen and nitrogen. About 0.05 vol. % oxygen or nitrogen can be detected in a 290 μl gas sample.

A packed porous polymer column (HayeSep Q 190 cm × 1/8´´) was used for the separation of all compounds except oxygen and nitrogen. At a temperature of 180 °C all halocarbons and hydrocarbons of interest are eluted.

Unknown peaks in the gas chromatographic analysis can be initially identified from a relationship that exists between the boiling point and retention time on this type GC columns, for compounds with similar chemical structure. This identification must always be confirmed by other methods (GC/Mass Spectroscopy (MS), reference gases). Figure 3. shows the total ion chromatogram from the separation of 19 halocarbons and hydrocarbons.

0. air
1. difluoromethane (HFC32)
2. 1,1,1,2-tetrafluoroethane (HFC134a)
3. 1,1-difluoroethane (HFC152a)
4. chlorodifluoromethane (HCFC22)
5. propane
6. dichlorodifluoromethane (CFC12)
7. 2-chloro-1,1,1,2-tetrafluoroethane (HCFC124)
8. 1-chloro-1,1-difluoroethane (HCFC142b)
9. 1,2-dichloro-1,1,2,2-tetrafluoroethane (CFC114)
10. butane
11. 2,2-dichloro-1,1,1-trifluoroethane (HCFC123)

12. trichlorofluoromethane (CFC11)
13. 1,1-dichloro-1-fluoroethane (HCFC141b)
14. 2-chloropropane
15. pentane
16. 1,1,2-trichloro-1,2,2-trifluoroethane (CFC113)
17. cyclopentane
18. hexane
19. 1,1,1-trichloroethane

Figure 3: Chromatographic separation of 19 halocarbons and hydrocarbons. The total ion GC/MS chromatogram is shown.

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Foam Compressing Device / Gas Chromatography

Thesis name: Thermal Conductivity Ageing of Rigid Closed Cell Polyurethane Foams
(Ph.D. thesis).
Author: du Cauze de Nazelle
Year: 1995
ISBN: 90-9007962-9
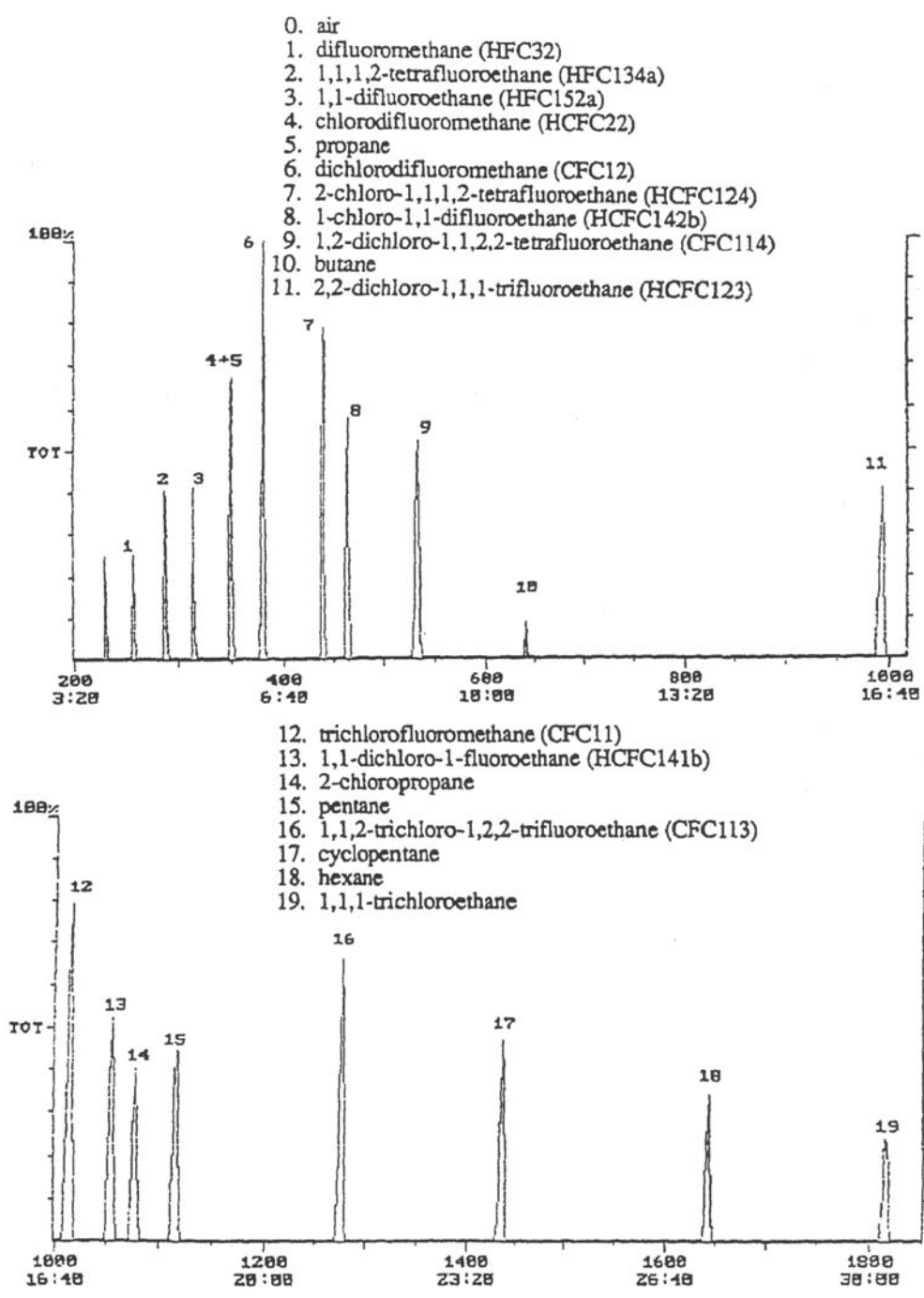Delft University of Technology, The Netherlands.

Experimental Procedure
Foam cylindrical samples of about 9 mm diameter and typical lengths between 12 and 16 mm were cut out. The lengths were chosen primarily as a function of the foam density, corresponding to 40 kg/m^3 and 30 kg/m^3.
A foam sample was first destroyed by screwing an axis that pushes a metal plug against the foam sample (Figure 4). When a thirty fold compression is reached, corresponding approximately to the cell-void-to-polymer volume ratio, the resulting half millimeter thick foam disc is ground by rotating the axis.
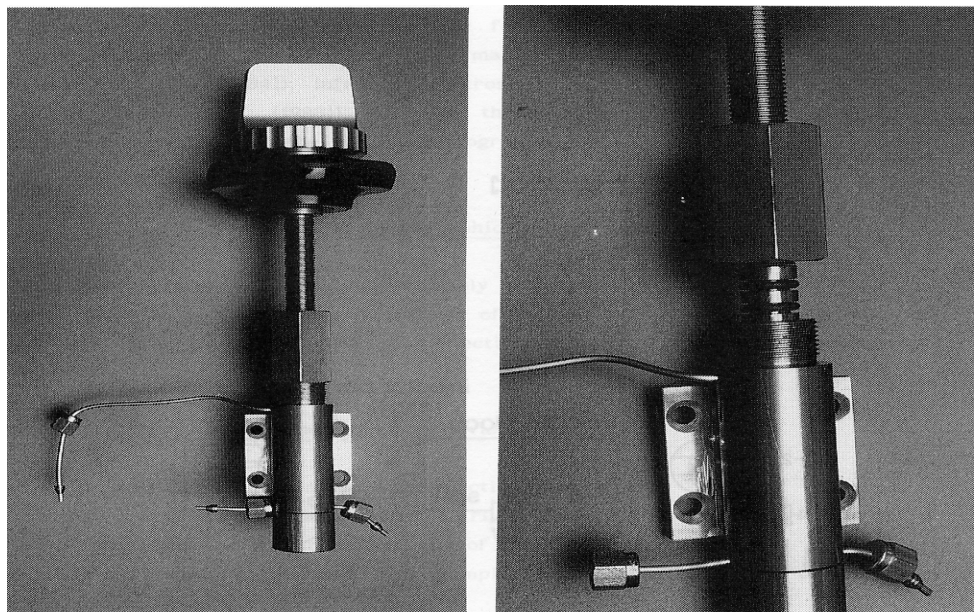
Figure 4: The crushing device designed to grind the foam samples and collect the cellular gas for further gas chromatographic analysis.

This device pulverizes the foam cylindrical sample, breaking all the cells and releasing the gases into the gas chromatograph sample loop.

Gas Chromatograph
The gas chromatograph is a Hewlett Packard 5890A, mounted with the Hewlett Packard micro thermal conductivity detector and the Hewlett Packard 3393A integrator. Two columns in series are used: first, a dummy fused silica capillary column in order to create a restriction which facilitates a constant pressure control and thus allows a more accurate adjustment of the split ratio. The second column is a capillary Porous Layer Open Tubular fused silica megabore column, type GS-Q of J & W Scientific; its length is 15 meters and its diameter 0.53 millimeter. The main operating specifications of the gas chromatograph are listed in Table 1.

Carrier gas	Helium (He), 2,8 ml/min through GC Ref. Flow: 25 ml/min, Make-up: 6ml/min, Split ratio 1:35.
Column	In series, fused silica capillary and GS-Q Plot of J&W Scientific. 15 m long.
Oven Temperature	$T_{initial}$ = 70 °C, 1 min. dT/dt = 50 °C. T_{final} = 230 °C
Detector	μ-Thermal conductivity. $T_{injection}$ = 200 °C

Table 2: Operating conditions of Delft gas chromatographic set-up.

Comments
- ➤ The sampling method described above is similar to the Grinding technique that is used by M. Svanström and O. Ramäns. However the Grinding method eliminates the risk that an increased amount of blowing agents may dissolve in the solid polymer at high compression pressures of du Cauze de Nazelle.

- ➤ One of the possibilities to prepare gas samples that was mentioned in the same thesis is based on the following procedure:
  The prepared foam sample was first put into a plastic bag connected to a bottle of compressed helium, so that a permanent helium flow was ensuring a constant helium atmosphere surrounding the foam panel. Then a 500 μl gas sampling syringe, directly stuck into the foam cells at a given thickness abscissa, was used to collect the gas sample to be analysed. However, this experimental procedure led to a poor repeatability of the obtained gas pressure measurements caused probably by:

- ❀ Variable quantities of helium surrounding the foam panel sucked out in the syringe when taking out the gasses from the cells.
- ❀ Gas losses and air contamination when bringing the filled gas sampling syringe from the helium bag to the gas chromatograph injection port.

Gasbag / Gas Chromatography Technique
Paper name: Cell Gas Analysis in Plastic Foams
International Workshop on Long Term Thermal Performance of Cellular Plastics 1989
C. Wan, F. Tyler, N. Nienhuis, & R. Bell
Society of the Plastics Industry of Canada
Don Mills, Ontario, Canada,

Experimental Procedure
A series of one-inch (2.54 cm) cubes were cut from the same board of commercial phenolic foam. The cube dimensions were selected because of the relatively high surface area-to-volume ratio, which serves to minimize the total testing period in diffusion/aging experiments.

A number of these cubes were placed in a sealable bag. The bag was evacuated and then partially charged with helium, which is the carrier gas in the GC analyzer. An internal standard (CFC-12) was added to the bag with a gastight syringe through a rubber septum. The foam cubes in the bag were carefully crushed using a hydraulic press. A gas sample extracted and injected into the GC, and the cell gas components (e.g. halocarbons, air, and carbon dioxide) determined quantitatively. The conditions for GC analysis are shown in the Table 2 below.

Examination of precision and accuracy of the Gasbag/GC technique was made using X-ray fluorescence and pyrolysis methods for determining halocarbons quantities, for comparison.

Results
Using the areas for the pertinent (relevant) GC peaks, the relative response factors with respect to the internal standard, and weight of internal standard, the actual weights of air, carbon dioxide, and CFC-114 in the sample bag before and after crushing the cubes were calculated. Based on analysis of 45 cubes, the relative standard deviations for %air, %CO_2, and %CFC-114 were 7.0 %, 8.3 %, and 2.7 %, respectively.

Oven Temperature	120 °C
Injector Temperature	180 °C
Thermal Conductivity Detector Temperature	185 °C
Carrier gas	Helium (He)
Column	6′ × 1/8′′ stainless steel column packed with 80/100 chromosorb 102

Table3: Gas chromatography conditions.

Chemical Analysis Method

Paper name: The Use of Pentanes as Blowing Agent in Rigid Polyurethane Foam
Journal of Cellular Plastics Volume 31 – November 1995
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Excerpt from page 586 of the publication:
High-density foams were prepared in high pressure resistant aluminium bottles of 2.6 litres capacity. In order to check the total amount of blowing agent present in freshly made foams, foam samples were stirred in tetrahydrofuran for at least 24 hours. The extract was analyzed by gas chromatography. The experimental results agreed within 10 % with the amount that was actually added from the formulation. These data were used as input for the predictions.

Comments
The above experiment was done to determine the partial pressure of cyclopentane in high-density (80 kg/m^3) foams. It is not named as a method for determining the cell gas composition, however it might be related in a way to the subject.

Slide Hammer Method / Mass Spectrometric Analysis
Paper name: Thermal Conductivity and Life of Polymer Foams
Journal of Cellular Plastics, January 1967
Francis J. Norton
General Electric Research and Development Center, Schenectady, New York.

Experimental Procedure
➢ A panel of polyetherol type of urethane was formed with General Tire and rubber materials R100 and R201 with no added catalysts.
➢ A pounder was made by welding a ¾" (1.9 cm) thick steel bottom into about 1⅜" (3.5 cm) diameter steel tube.
➢ A piece of foam cylinder 1" high, 1⅛" (2,85 cm) diameter was put into the tube, and on top of the pounder.
➢ Then, a cold rolled steel bar stock, 1⅛" (2,85 cm) diameter and 1½" (3.8 cm) high, was put on top of the foam.
➢ A glass top and stopcock with taper joint was waxed to the top of the 15" (38 cm) high cylinder.
➢ The assembly was quickly evacuated to about 5 micron Hg (0.533 Pa). Very little R11 (Refrigerant 11, CFCl$_3$) was lost in this process.
➢ The bottom of the tube was cooled in liquid nitrogen to render the foam brittle.
➢ By shaking vigorously up and down, the rather heavy weight pounded the foam to a powder, opening all the gas bubbles. This took intermittent pounding over 15 minutes.
➢ The cell was then warmed to 25 °C in a stream of water and stood 1½ hour.

Gas Sampling
The gas evolved was sampled and liquid air non-condensable determined. All the liquid air condensable (LAC) was taken into a 1-liter bulb with a liquid air appendage for transfer. This was

warmed so the whole amount of LAC could mix for 15 minute in the spherical bulb before sampling was attempted. It is difficult to get a good sample of CO_2 and R11 together unless this mixing method is used. Segregation can easily occur leading to very large errors. The total amount of gas in the bubbles was thus measured, and analyzed for R11, N_2, O_2, CO_2 and argon.
A portion of the residual powdered foam was completely pyrolyzed in a quartz tube and the mixture, a large amount of CO_2 resulting from pyrolysis, with the R11 was again analyzed as before, with precautions against segregation.

The results of the analysis are given in Table 3 for sample 4C, which was left in air 55 days and for sample 1A, which stood in an evacuated tube since 20.1.1960 for 56 days. Gas from this evacuated tube was removed occasionally for analysis.

		SAMPLE 4C STOOD IN AIR 25 °C 55 DAYS	SAMPLE 1A SEALED IN EVACUATED TUBE 25 °C 56 DAYS
Composition of gas in foam bubbles % by volume	R-11 CO_2 N_2 O_2	55.0 0.5 32.0 12.5	96 1 2 1
Pressure in bubbles [atm]	R-11 CO_2 N_2 O_2	0.56 0.005 0.32 0.125	0.57 0.005 0.01 0.005
atm Total		1.01	0.59
Fraction of final pressure	N_2 O_2	0.41 0.60	— —
Composition of liquid air non-condensed	N_2 O_2	72 % 28 %	68 % 32 %
R-11 by weight in bubble On and in solid polymer (Mass Spectrum)		9.1 % 5.0 % 14.1 %	9.6 % 4.1 % 13.7 %
Total R-11 % by weight		14.05 %	13.05 %

Table 4: Results of analysis.

Slide Hammer Method / Gas Chromatography Analysis
Paper name: Accelerated Aging of Rigid Polyurethane Foam
European Journal of Cellular Plastics, October 1980
D. A. Brandreth & H. G. Ingersoll
Petrochemicals Department, Freon® Products Laboratory
E. I. Du Pont Nemours & Co., Inc.
Wilmington, Delaware 19898

Sample Cutting and Preparation
Carefully machined stainless steel sample cutters with 0.010-inch (0.254 mm) walls were fabricated and used with a drill press to obtain cylinders with minimal damage to peripheral cells. Two of these cutters, 1-inch (2.54 cm) and 1.37-inch (3.8 cm) diameter, are shown in Figure 5.

Plugs for analysis are normally taken from a void-free area near the center of the test sample. The cutter is rotated at about 475 rpm and is advanced at about 1 inch/sec (2.54 cm/sec). Slow cutting causes excessive heating. The foam is blown from the cutter using air at 0.5 psi (3.45 kPa).

((Foam samples smaller than 1⅜ inch (3.5 cm) diameter were tried in order to reduce aging time. At 0.4-cm diameter the gas loss from cutting surface cells was undesirably large and in general results from samples with these smaller diameters tended to be erratic. Consequently, use of samples smaller than 1-inch (2.54 cm) was abandoned.))

Experimental Procedure

Brief Explanation:
➢ A weighted sample is loaded into a steel cylinder equipped with a slide hammer, Figure 6.
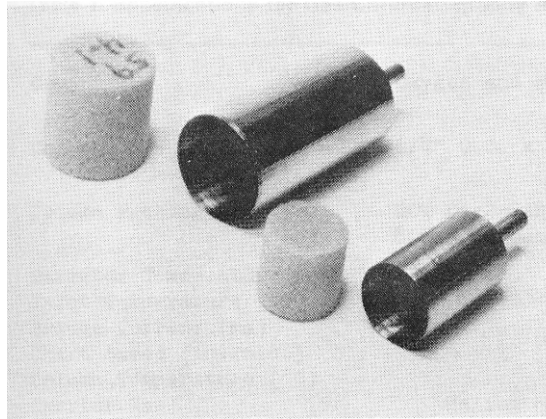
Figure 5: Steel cutters for foam plugs with typical plugs.
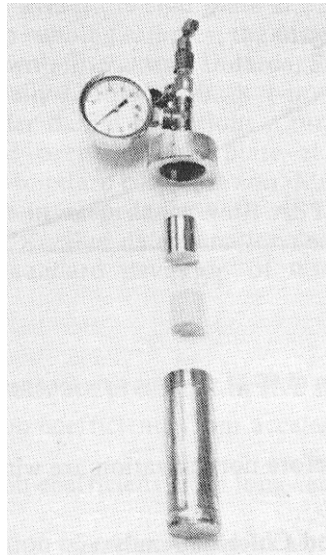
Figure 6: Sampler tube assembly

➢ The cylinder is evacuated and filled with propane as a reference gas.
➢ Next the sample is frozen with liquid nitrogen and pounded with the sliding hammer to release all the cell gas.
➢ After allowing for three days for mixing by diffusion, the gas is analyzed by gas chromatography and the powder analyzed for fluorine to determine the FC-11 (Flourocarbon-11) blowing agent retained by polymer.
➢ ((Knowing the volume and weight of the foam, the sample tube volume, and the cell gas composition, the fractional saturation of the foam with nitrogen and oxygen and the FC-11 concentration in the foam based on polymer weight can be calculated.))

Detailed Explanation:
➢ A weighted sample is loaded into the sampler tube assembly.
➢ The sampler tube is cupped and tightened one-eighth turn past hand-tight to compress the "O"-ring.
➢ The sampler tube is evacuated for one minute, vacuum (pressure) noted, and re-pressured to 760 mm Hg (101.33 kPa) with research-grade propane.
➢ The sampler tube is then removed from the vacuum bench and placed in liquid nitrogen.

❊ The level of liquid nitrogen should be about ½ inch (1.27 cm) above the top of the foam plug contained within the tube. The tube must extend into the air enough to prevent the frost line from getting near the "O"-ring; otherwise a serious leak can result.

➢ After 25 minutes, the tube is removed from the liquid nitrogen and shaken vigorously for one minute.

➢ Pressure is noted again after which the sample is allowed to come to room temperature and the pressure is recorded.

❀ The purpose of noting pressure during freezing and shaking is to follow the course of the foam crushing and to detect leaks. Normally, the pressure or vacuum does not change after the initial shaking cycle until the sample is warmed. An increase in sample tube pressure after the initial shaking suggests a leak. Calculated fractional saturations of the foam with oxygen and nitrogen larger than 1.10 are considered to indicate that an error or leak occurred.

➢ The sample is allowed for three days for mixing by diffusion.

❀ Since part of the gas sample is condensed by liquid nitrogen, it is necessary to get complete mixing before analysis. Using the slide hammer to mix the gases after the tube had warmed up tended to carry the polymer powder up into the connecting tube and gauge. The best procedure is to allow the sample to mix by diffusion for at least three days before analysis. ((Possibly a shorter time would suffice' but this was not established)).

➢ After chromatographic analysis, the polymer powder is removed from the sampler tube and examined for un-smashed fragments.

❀ If unbroken material is found, the analysis must be repeated using more severe pounding conditions. If the powder from first trials of technique appears to be uniformly fine, microscopic examination should be carried out to see that unbroken cells are not present. Samples longer than 1⅜ inch (3.5 cm) inches are difficult to smash.

Gas Chromatography Analysis

A Hewlett-Packard 700 gas chromatograph with thermal conductivity detector and a Hewlett-Packard 3370A integrator was used. Conditions used for the various gases are given in Table 4. Areas under the individual peaks are measured with the integrator and calibrated with a known sample of each five gases daily. ((Calculated volume percent concentrations are normalized so that the total equals 100. Usually the sums before normalization are within 100 ± 0.5 %.))

Fluorine and Chlorine Analysis

The powdered polymer is analyzed chemically for fluorine by a Du Pont method in which the powder is burned in a Wickbold oxyhydrogen torch. The resulting hydrofluoric content is collected in water buffered and determined potentiometrically. Fluorine concentration is calculated from a calibrated graph.

Determination of FC-11 content by chlorine analysis was also tried, but was abandoned because the results exhibited more scatter and because foams have chlorine-containing fire retardants.

Compounds	Oxygen and Nitrogen	Carbon dioxide, Propane, Fluorocarbon 11
Column	¼" (0.635 cm) Outer diameter × 6-meter copper	¼" (0.635 cm) Outer diameter × 4-meter stainless steel
Column Packing	20 % Di-2-Ethylehexyl sebacate/ 80 % Chromosorb W, 30/60 mesh	13 X Molecular sieve, 60/80 mesh
Detector Temperature [°C]	200	200
Inlet Temperature [°C]	200	200
Bridge Current [mA]	200	200
Chart Speed [in/min],	0.5, [1.27 cm/min]	0.5
Column Temperature [°C]	50	80
Carrier Gas	Helium at 60 ml/min	Same
Sample Size	5 cc at 15" Hg absolute	Same

Table5: Specifications for gas chromatography analysis.

The experimental method used here is similar to that of Norton, although important differences are noted. In this method all gases are determined on the same sample, whereas Norton used two different samples — one for FC-11 and the other for N_2 and O_2.

❀ ((Norton sealed a foam plug under vacuum and monitored the FC-11 effusion from the plug into the chamber over time using *mass spectrometry* to detect the FC-11.
❀ For N_2 and O_2 he used a separate series of plugs, which was aged in the air. The individual plugs were analyzed at intervals using a *crushing method* similar to that used here to release the cell gases.))

Hypodermic Syringe/Infrared Spectroscopy + Chemical Analysis
Paper name: Problems in Predicting the Thermal Properties of Faced Polyurethane Foams
Thermal Insulation Performance ASTM STP 718. D. L. McElory and R. P. Tye. Eds., American Society for Testing and Materials. 1980. pp. 412-428
Mark Bomberg

Comments
❀ The determination of the average cell gas composition is included as an appendix attached to the paper. The analysis was carried out by A. Desaulniers and R. Ironside, Analytical Section, Division of Chemistry, National Research Council of Canada (Lab. No. 16650, 19 Jan. 1978). The report is named "Analytical Report of Polyurethane Rigid Foam Board".
❀ It was mentioned in the paper that: requirements regarding sampling techniques to determine the cell gas content are not included (in the paper).

Experimental Procedure
The polyurethane rigid foam board was sampled by cutting "cores" through its thickness with No. 13 cork borer. These cylinders measured about 22 mm in diameter and 23 mm in length. Their weight was about 0.220 g.
To identify the captive blowing agent, a large hypodermic syringe was filled with "cores" and the needle was inserted into an evacuated infrared gas cell through a septum; the "cores" were crushed by driving home the piston of the syringe. The infrared spectrum of the gas so obtained established that it was trichloromonofluoromethane, Cl_3CF (Freon 11).
One or two of the cylinders just described were burned in the Parr oxygen bomb in 35 atm of oxygen, the combustion products being absorbed in 10 ml of 0.2-N sodium carbonate solution. The chlorine was determined in the absorbent by titrating with N/10 silver nitrate solution after acidification with nitric acid.
The total chlorine content of three specimens tried was 8.8, 9.4, and 10.0 percent by weight.
In order to correct this total chlorine value for any compounds in the non-void body of the plastic, a few "cores" were ground finely in a mechanical pulverizer and the fine powder so obtained was degassed in vacuum for 30 min. Microscopic examination confirmed that no intact cells had survived the grinding process.
Two specimens of this powder were then treated as described above and gave the following values: 4.6 and 4.7 percent weight/weight chlorine.
The corrected values for the chlorine in the cell volume, namely 4.2, 4.8, and 5.4 percent weight/weight, were calculated to Cl_3CF to give Freon 11 contents of the specimen of 5.4, 6.2, and 7.0 percent by weight.

Measurement of cell gases, experimental set up

Introduction
There are several different methods, which have been used for the analysis of the cell gases in polyurethane foams. The sampling methods vary, but gas chromatography has generally been used for the analysis. There is an example also, where mass spectrometry has been used for gas analysis. In one method the gas sample has been taken out by a syringe. In the recent studies a method where a sample is crushed in a gas tight cylinder and the gas sample is analyzed in a gas chromatography has been used. During this project an experimental set up for analysing the cell gases was built up and tested in the technical university of Lappeenranta, Finland. The grinder/gas chromatography method was similar to that described by M. Svanström and O. Ramnäs in 1997.

Sampling

A sample cylinder (diameter 20mm, length 50 mm) was cut from the foam using a rotating sharp edged metal cylinder. The edge must be well sharpened to minimize the risk of destroying the cells on the surface of the sample. The sample is then put inside the grinder cylinder which is sealed and then flushed with helium, which is used as a carrier gas in the gas chromatography. Helium is chosen because it doesn't exist in polyurethanes and it also doesn't show in the gas chromatography. The cell gases from the sample are released by grinding with a steel blade.
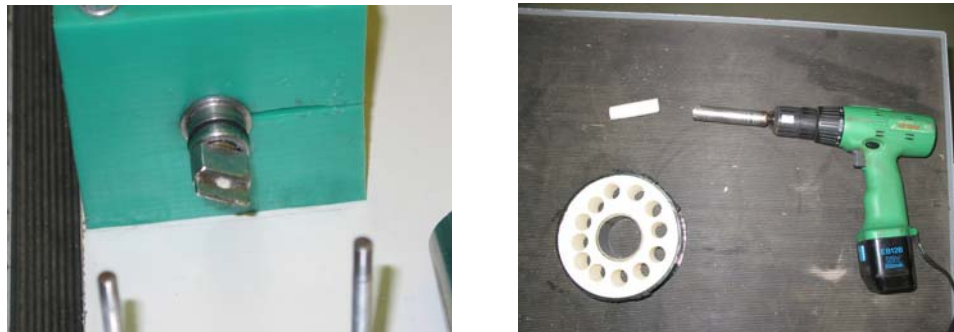

Figure 7: The blade (left) and the sample cutting apparatus (right)

The grinding itself is done by pushing the sample against the rotating blade with a plastic piston. The piston end has two small holes for two wooden sticks to hold the sample still and prevent it from rotating with the piston. A common electric drill is used to rotating the blade. The cell gases are released from the sample and collected in a glass syringe where the volume of the released gas can be determined. The sample gas is mixed by pushing and pulling the grinding piston a couple of times.

On the sample line between the grinder and syringe there is a mechanical filter which prevents the crushed polyurethane particles from entering the syringe. Gas sample from the syringe is then taken out through a rubber sealed outlet by a small needle and taken to the gas chromatography.

Gas chromatography analysis

The gas chromatography analysis was done with a Hewlett-Packard 5890 gas chromatography. The column used was HP-Plot Q which uses helium as carrier gas.
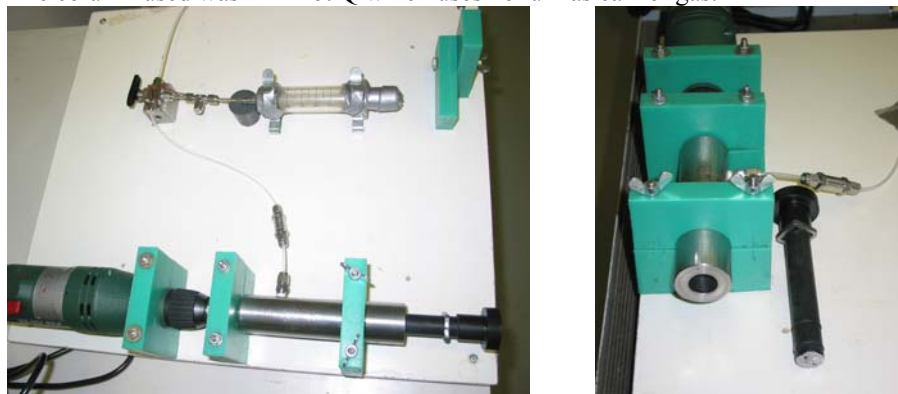
Figure 8: The grinding apparatus and sample collecting syringe (left). The grinder piston pulled out from the cylinder (right).

Results

Several tests were done for polyurethane samples taken from different district heating elements. The components of the cell gases could be seen in the gas chromatography analysis, although already in the beginning it seemed obvious that there was some leaking in the system because there was quite a high concentration of atmospheric air in the results. The most critical point for the air entering the sampling procedure is when the sample is taken out of the syringe with the needle and transported to the gas chromatography. The grinding system was detected and there was no leaks found. Here is presented the test results for three different foam types. It was known in advance that foam nr 1 contained no cyclopentane, foam nr 2 had low concentration of cyclopentane and foam nr3 had high concentration of cyclopentane.
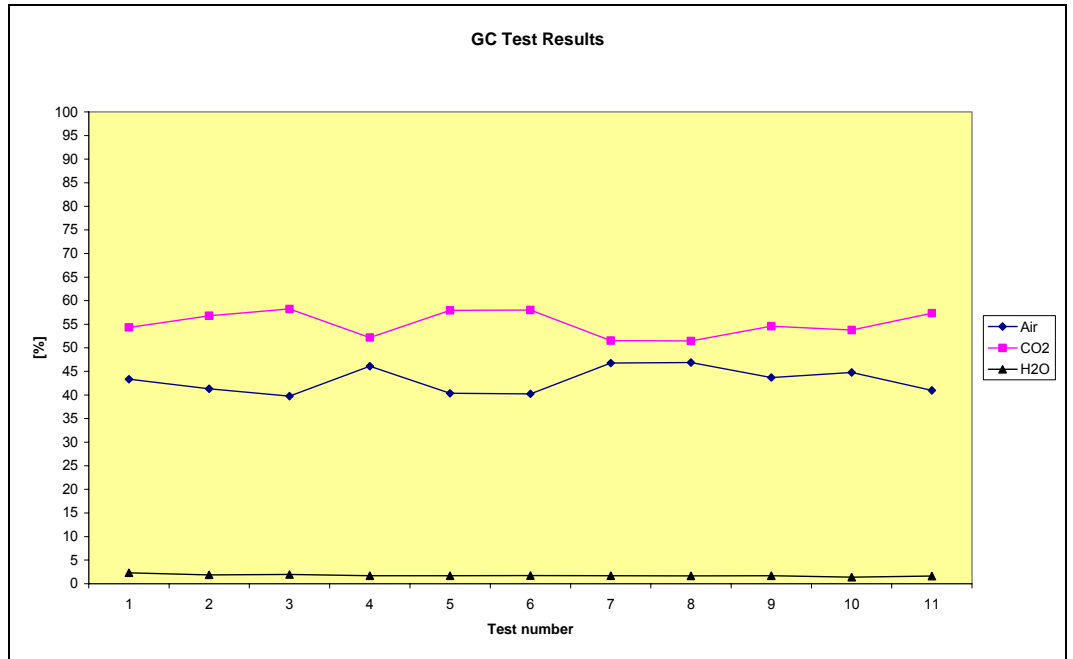
Figure 9: The test results for foam nr 1 containing no cyclopentane
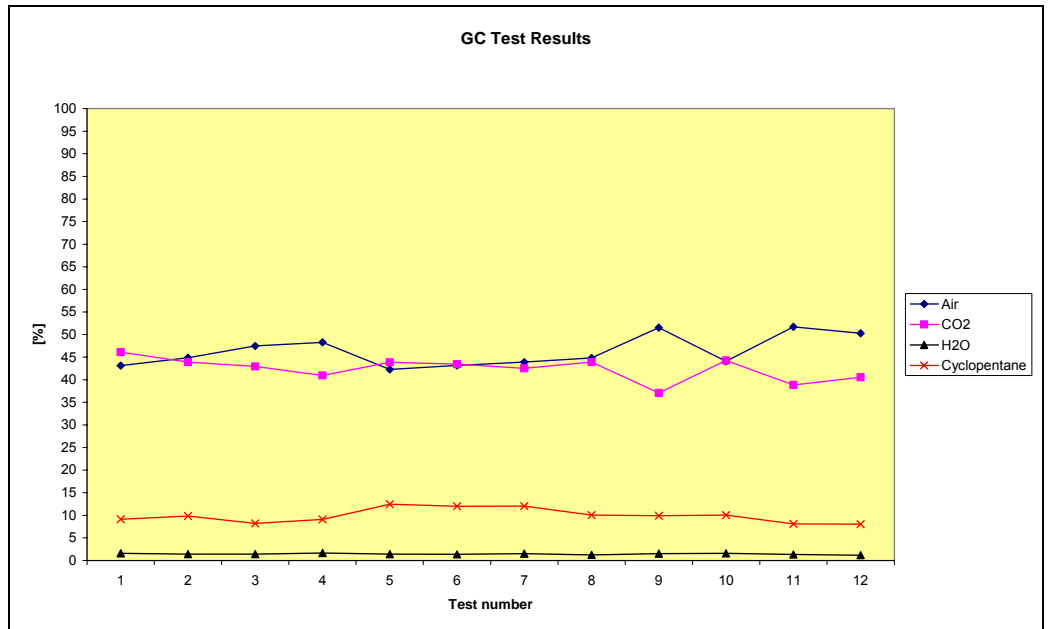
Figure 10: The test results for foam nr 2 containing low amount of cyclopentane
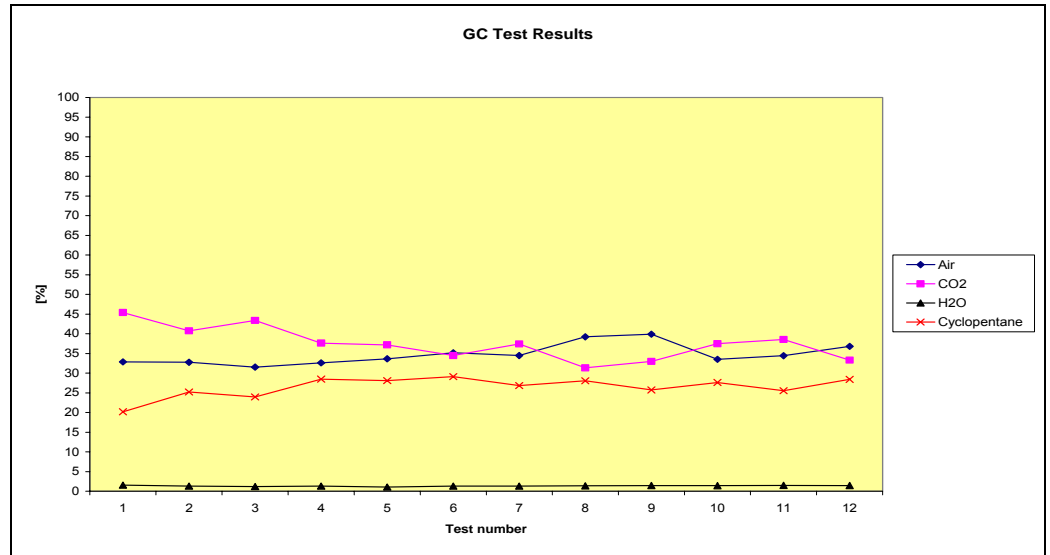
Figure 11: The test results for foam nr 3 containing high amount of cyclopentane

Issues to be considered in analysis

The time between sampling (cutting of the sample from a larger piece of foam) and crushing the sample should be as short as possible to avoid changes in the gas composition due to diffusion.

The analysis has to be performed as soon as the gas sample is collected, because air will diffuse into the glass syringe, and the cell gases will diffuse out.

Not all the cell gases can be transferred to the syringe: some uncrushed foam remains, also traces of cell gases stay in the transport tube between the cylinder and the syringe. How to account for this?

When determining the volume of the sample, the destroyed surface layer should be taken into account.
The "true" volume of the sample = Geometrical volume of the foam sample – destroyed surface layer.

Gas losses and air contamination, during the seconds in, which the cell gas-filled sampling needle is transported from the crushing device to the gas chromatograph injection port, must be accounted for. Connecting the glass syringe to the GC injection port does this, also, a precaution adopted by Lohmeyer is to eject part of the sample cell-gas from the needle just before injection into the GC.

Estimation of the heat loss

The initial heat loss

Cellular plastics consist of polyurethane, manufactured from isocyanate and polyole, using a blowing agent (gas and/or water) to create the desired cell structure. The cells are performed of pentagonal windows with frames called stocks. Each cell is formed of 12 windows to dodecahedrons. The size of the cells is typically 0.1 – 0.3 mm in the foams of the district heating pipes. In the European product standard EN 253, certain requirements are stated to the foam e. g. cell size shall be 0.5 mm or less.

With this structure energy transport through cellular plastics can take place by conduction through PUR cellular plastics, radiations through the cells and convections and conduction through the gas in the cells. Energy transport can therefore be described as a sum of individual transport mechanisms.

$$\lambda_{TOT} = \lambda_{SOLID} + \lambda_{RAD} + \lambda_{CONV} + \lambda_{COND}$$

where λ_{TOT} is the total energy transport, λ_{SOLID} is the conductions through the solid polyurethane, λ_{RAD} is the radiations through the cells, and λ_{CONV} and λ_{COND} is the convection and the conduction through the gas in the cells.

Thermal conductivity changes can only occur if there is a change in one of the elements.

Conductivity of the solid

The PUR structure of cellular plastics consists of solid windows frames - struts, which create the strength structure in cellular plastics and the membranes - windows, fill out the hollows between the struts and support them.

Thermal conductivity of the solid polyurethane is depending on the temperature. In recent years the thermal conductivity of the solid polyurethane used in district heating pipes is determinated to (Nielsen 1998)

$$\lambda_{PU} = 0.207 \times 10^{-3} \times T + 0.2183 \quad \text{W/(m K)}$$

At 50°C, which is the temperature where the thermal conductivity of the PUR-foam in district heating pipes is determinated, the thermal conductivity of the solid polyurethane can be calculated to $\lambda_{PU} = 0.229$ W/(m K)

Another equation is developed on foam used for district heating pipes and is simpler (Arduini-Schuster)

$$\lambda_{PU} = 0.197 \times (1 + 0.001 \times T),$$

At 50 °C this equation gives a $\lambda_{PU} = 0.214$ W/(m K).

In the literature results for the thermal conductivity for solid polyurethane up to 0.264 W/(m K) are found.

Ageing causes changes in the material structure, and the mechanical strength is reduced as the polyurethane is decomposed, but measurements (Sinofsky) showed no differences in the thermal conductivity of new and aged samples. Therefore, possible thermal conductivity changes resulting from material structure changes are disregarded in the following.

The thermal conductivity of cellular plastics is affected by the cellular structure. Experiments have shown that the relation – f_s - between the amount of polyurethane in the struts and windows together with the density of the foam and solid polyurethane controls the thermal conductivity of the solid foam. Through measurements performed on ridged foams for district heating pipes the following equation is developed (Nielsen 1998):

$$\lambda_{sol} := \left[0.48 \cdot f_s + 0.66 \cdot (1 - f_s) \right] \cdot \frac{\rho_f}{\rho_{PU}} \cdot \lambda_{PU}(T)$$

Experiments showed that f_s could be determined to 0.95 for foam with a density of 60 kg pr. m^3. The density of the solid in polyurethane was app. 1,225 kg per m^3. Under these conditions the thermal conductivity through the foam can be calculated to

$$\lambda_{sol} = 0.0055 \, \frac{watt}{m \cdot K}$$

Based upon the available measurements this value is considered constant over the entire lifetime of cellular plastics.

Radiation through the cells
Various expressions can be used to calculate the radiation effect in the cells. Radiation is dependent on the size of the cells, the density and the temperature (Jones). The radiation effect in PUR cellular plastics can be calculated by using 8 different calculation models (Collishaw). For cellular plastics with a density of 30-40 kg/m^3 the average was 0.0023 W/mK for the results varying between 0.001 and 0.003 W/mK.

One of the more simple equations to calculate the thermal conductivity from radiation is by the equation (Rosseland)

$$\lambda_{rad} := \frac{16 \cdot \sigma \cdot T^3}{3 \cdot E \cdot \rho_f}$$

where the extinction coefficient E can be determinated on thin slices of foam using infrared spectrophotometer in the wave period of 1400-2500 m^{-1}. The Extinction coefficient can be calculated as $I/I_o = c \exp(-K1)$, where I/I_o is the average light transmission and l the thickness of the slice (Glicksman).

Radiation is particularly dependent on the colour and the gloss of the surface. A dark and rough surface absorbs more radiation energy than a bright and shiny surface. It is a well-known fact that the colour of cellular plastics changes into a darker shade as it ages. Therefore, it must be expected that heat conduction during radiation will increase as cellular plastics change into a darker colour.

In practice, PUR cellular plastics become darker - most visible in the layer closest to the service pipe. The remaining part of the material is darkened very slowly. After a number of years it will still be cream-coloured, though darker than originally. In the major part of the foam only a limited change occurs in the colour and in the surface quality of cellular plastics.

The effect on the extinction coefficient of the discolouring is further reduced by the exponential relation between discolouring and the extinction value. Finally, radiation contribution is small compared to the total thermal conductivity. That means that even a relatively substantial increase in the surface properties of cellular plastics will only have a very limited effect on total thermal conductivity. Therefore, the change contribution will be disregarded in the following formulas, and the radiation contribution is considered constant over the entire lifetime of the cellular plastics.

The extinction coefficient is determinated to

$$E = 98.2 \, \frac{m^2}{kg}$$

and the for $\sigma = 5.7 \cdot 10^{-8}$ W/(m^2 K^4) and at a temperature of 50 °C the following is obtained:

$$\lambda_{rad} = 0.0019 \, \frac{watt}{m \cdot K}$$

As mentioned above it is presumed that this figure is constant during the lifetime of the pipe system.

Convection of cellular gas
By flow of cellular gases the individual cells can transport energy by convection. The driving force is the temperature difference between the cell walls. In practice it appears that there has to be a certain difference of temperature and a certain distance between the cell walls before the flow occurs. It is shown by Jones that a cell diameter larger than 5 mm is necessary before a flow can

occur at the temperature differences in this type of foam. The standard EN 253 prescribes that the average cell diameter must be max. 0.5 mm. In practice the average diameter is 0.1mm to 0.3 mm.

Therefore, the effect of the flow of the cell gas can be omitted in calculating the thermal conductivity. Consequently:

λ_{CONV} = 0.000 W/mK

Conductivity of cell gas
It is a well-known fact that the various gases conduct heat and that their ability to do so varies. It is also an experience that the thermal conductivity of the gases is depending on the temperature and increase when the temperature rises. At 50 °C the thermal conductivity of typical gases in polyurethane foams is calculated so: Carbon dioxide 0.019 W/(m K), Oxygen 0.029W/(m K), Nitrogen 0.032 W/(m K), Cyclo-pentane 0.014 W/(m K) and R11 0.009 W/(m K).

Normally the gases in the cells do not occur as pure gases, but as mixed gases. It is an experience that in gas-mixture an error is induced if the thermal conductivity is calculated as a summation of the single gases. This error can be reduced if the thermal conductivity is calculated by the Wassiljewa equations (Wassiljewa 1904). The equation has later been modified (Mason and Saxena 1958).

An assumption of contribution to the thermal conductivity of the interactions between the single gases can be made when the summations of the single gases contribution is compared to the results from the modified model. The contribution is negative and vary between – 0.001 and – 0.005 W/(m K).

Estimation of the future heat loss

The integrated model
Paper name: Thermal insulation: CFC alternatives and Vacuum Insulation.
Doctorial thesis.
Author: K. H. Brodt
Year: 1995
Technical University of Delft, The Netherlands.

The diffusion in a system of polyurethane, with some resistance against diffusion and a semi-permeable membrane has been examined by Broth (Broth 1995). The conclusion of this investigation was that the most effective way to estimate the future properties of the foam was to determine the resistance in the two materials separately and calculate the final gas diffusion by using the Biot number.

In an pre-insulated pipe the PUR-foam is closed to the one side of an impermeable steel pipe and to the one side covered with a semi-permeable membrane of polyethylene. In such a construction the partial pressure of the cellular gas can be estimated in the equation below.

$$\frac{p(x,t) - p_2}{p_0 - p_2} = \frac{2 \cdot \sin \beta_n}{\beta_n + \sin \beta_n \cdot \cos \beta_n} * \cos \frac{\beta_n \cdot x}{L_{foam}} * exp \frac{- \beta_n^2 \cdot D_{eff} \cdot t}{L_{foam}^2}$$

where p_0 partial pressure in foam at t = 0

L_{foam} Thickness of the foam

p_2 Partial pressure outside the casing

and the Bi number is the solution of the equations $\beta_n \cdot \tan \beta_n = Bi$ for n = 1, 2, ...

The Bi number can be understood as the ratio between the diffusion resistance in the foam and the casing

$$Bi = \frac{L_{foam} \cdot P_{casing}}{P_{foam} \cdot L_{casing}}, \text{ where } L_{casing} \text{ is the thickness of the casing}$$

The foam and casing model
Paper name: Celleplasts langtidsisoleringsevne (Long Term Insulation Properties of Cellular Plastic (Report in Danish).
Author: H. D. Smidt
Year: 1996
ISBN: 87-7756-440-5
Danish Technological Institute

The thermal conductivity of cellular gas is associated to the partial pressure of the individual gases that are included in cellular plastics. This means that when the partial pressure of the individual gases changes, the thermal conductivity of PUR-foam changes. Because of differences in the partial pressures of the gases in the cellular plastics and the external atmospheric air the partial pressure is changed currently. Thus the thermal conductivity is also changed.

The velocity depends on the partial pressure difference between the cellular gas and the atmospheric air and is controlled by the permeability of the pipe casing and the diffusion rate through the cellular plastics of the individual gases.

The partial pressure difference is the motive power, while the permeability coefficient and the diffusion coefficient is an expression of a decelerating effect. Some typical coefficients are shown in the table below.

	Permeability coefficients	Effective diffusion coefficients
Material	**PE-HD (20°C)** $P \cdot 10^{-16}$	**PUR (20°C)** $D \cdot 10^{-13}$
Gas	**mol/ (m s Pa)**	**m²/s**
O_2	1,9	150
N_2	0,65	25
CO_2	8,6	500
C-P	23 [3]	4
R11	62 [2]	1 [1]

1)Svanstrøm 1997 2) Jarfelt 1998 3) supplier

Table6 :The table shows the permeability and diffusion through HD-PE and PUR.

From the table it is seen that the permeability of the insoluble gases oxygen, nitrogen and carbon dioxide is mainly controlled by the HDPE casing as the permeability figures are lower than the figures through the PUR.

The opposite is the case for the diffusion coefficients. Here the diffusion of the cyclo-pentane is much lower.

With these assumptions it seems possible to develop a dynamic model for calculation. The model should be divided in two parts. One part is based on permeability of the casing and shall describe how the partial pressure of oxygen, nitrogen and carbon dioxide changes during time. The second part shall describe how the partial pressure of cyclopentane changes during time and that model is based on diffusion of the gas through the foam.

The insoluble gases and the casing
When there are different partial pressures on two sides of a permeable membrane, the molecules diffuse through the membrane until the same partial pressure is obtained on both sides. The mathematic equation for calculation of this type of diffusion is Fick's 1st law.

$$F = D \cdot \frac{(c_t - c_0)}{l}$$

where
F = Flux mol/(m^2 s)
c_t = concentration to the time t [mol/m^3]
c_0 = concentration to the time 0 (initial concentration) [mol/m^3]
l = thickness of the membrane [m]
D = diffusion coefficient [m^2/s]

When used on the casing it ends up with two equations, one for in-diffusion of oxygen and nitrogen and one with out-diffusion of carbon dioxide.

In-diffusion of nitrogen and oxygen

$$p_2 = p_1 \cdot e^{-\left[\frac{T_1}{273,15} \cdot \frac{p_1 \cdot P \cdot t \cdot 8}{V_{Gas} \cdot (D^2 - d^2) \cdot ln\frac{D}{d}}\right]}$$

Out-diffusion of carbon dioxide

$$p_2 = p_1 \cdot \left(1 - e^{-\left[\frac{T_1}{273,15} \cdot \frac{p_1 \cdot P \cdot t \cdot 8}{V_{Gas} \cdot (D^2 - d^2) \cdot ln\frac{D}{d}}\right]}\right)$$

t = time [s]
p_1 = the initial partial pressure [kPa]
p_2 = the actual partial pressure [kPa]
D = inside diameter of the casing [m]
d = diameter of the media pipe [m]
V_{gas} = gas volume inside the casing [m^3]
P = permeability coefficient [m^3 /(m s Pa)]
T_1 = temperature [K]

The actual partial pressure depends on the initial partial pressure as well as on the temperature and the geometry and the permeability of the material.

The soluble gases and the PUR-foam
The diffusion of the cyclopentane is not a static condition, because the diffusion is one in one direction and is a summation of diffusions through many small cells.
On this system Fick's second equation can be used resulting in the following differential equation

$$\frac{\partial u}{\partial t} = \frac{D}{\rho} \frac{\partial}{\partial \rho}\left(\rho \frac{\partial u}{\partial \rho}\right)$$

The boundary conditions are: Diffusion is 0 over internal radius, i.e. $\frac{\partial u}{\partial \rho}(r;t) = 0$ and the

concentration at external radius is 0, i.e. $u(R;t) = 0$

The relevant equation for a district heating pipe with a diffusion tight service pipe is:

$$\frac{\partial u}{\partial t} = \frac{D}{\rho} \frac{\partial}{\partial \rho}\left(\rho \frac{\partial u}{\partial \rho}\right); r \le \rho \le R; \frac{\partial u}{\partial \rho}(r;t) = 0; u(R;t) = 0$$

If variables with no dimensions are inserted $t = x\frac{r^2}{D}; \rho = yr; R = ar$ you get

$$\frac{\partial u}{\partial t} = \frac{1}{y} \frac{\partial}{\partial y}\left(y \frac{\partial u}{\partial y}\right); r \le y \le a; \frac{\partial u}{\partial y}(1;x) = 0; u(a;x) = 0$$

The initial state with homogeneous concentration is contained in $u(y;0) = 1$

The differential equation $\dfrac{\partial u}{\partial t} = \dfrac{1}{y}\dfrac{\partial}{\partial y}\left(y\dfrac{\partial u}{\partial y}\right)$ is solved by means of Bessel functions, resulting in

the concentration $u(y;x) = \sum_j c_j v_j(y)e^{-xk_j^2}$

Where k_j is the root of the equation $J_1(k)Y_0(ka) - Y_1(k)J_0(ka) = 0$

and c_j is given at $c_j = \dfrac{\int_1^a yv_j(y)dy}{\int_1^a yv_j^2(y)dy}$

Where v_j is given at $v_j(y) = J_0(k_j y)Y_0(k_j a) - Y_0(k_j y)J_0(k_j a)$

When the initial concentration of the diffusion gas and the time are known, the concentration can at any time be calculated.

Diffusion in cellular foams

Introduction
Closed cell foams consist of gas bubbles separated from another by a thin membrane of a continuous condensed phase. The condensed phase can be liquid or solid. Among foams having solid membrane, the polymeric foams are the most commonly used (Pilon, Fedorow and Viskanta 2000). Rigid closed cell foams are commonly used as thermal insulation material for district heating networks. The good insulation performance is based on the properties of the blowing agents used during the manufacturing process. Due to diffusion, some of the cell gases are replaced by air and therefore the insulation properties of the foam are worsened due to the higher thermal conductivity of air.

Generally, the techniques for measuring the diffusion of gases in foams can be divided into three general classes: 1. Gas transmission methods, where a pressure gradient is imposed across a foam sample and the quantity of the gas passing through the foam is measured. 2. Quantitative analysis of cell gas compositions present in the foam at a known foam age. 3. Measurement of out-gassing rates from foam samples as a function of time (Shankland 1990).

Diffusion
Very soon after the manufacture of a polyurethane insulated district heating pipe, a diffusion process starts which strives to equalise differences in partial pressures between the cells of the pipe insulation and the surroundings. As the diffusion rate for some gas components is quite slow, the total time until the partial pressures are equalised can be up to 25 years.

In a carbon dioxide blown pipe the partial pressure of the carbon dioxide inside the cells of the insulation will decrease due to the carbon dioxide leaving the pipe through the polyethylene casing pipe. At the same time, the concentration of atmospheric air in the foam will increase. Atmospheric air, which mainly consists of nitrogen and oxygen, enters the foam through the casing pipe. The mass transfer rate for gases in a specific district heating pipe is determined by the temperature and the partial pressure differences (Svanström et al. 1999).

Normally the diffusion of carbon dioxide outwards is quite fast, just a few weeks, while the inward diffusion of air is relatively slower and can take up to one year.

Models for determining the diffusion coefficient
During the last 30 years there has been published many studies of forecasting thermal conductivity ageing curves from foam diffusion characteristics. The so-called "continuum model" was first introduced by Norton and Cuddihy in 1967. The model treats the foam as a homogenous medium, that can be characterized by a constant effective diffusion coefficient D_{eff}.

The "continuum model" is usually based on the four following assumptions introduced by Norton 1967(du Cauze de Nazalle 1995).

A1: The effective diffusion coefficient D_{eff} of the different gases or vapours does not depend on their concentration in the polymer. It is therefore assumed that a linear gradient of concentration exists in the cell membrane at steady-state.

A2: The diffusion process of different gas components is independent.

A3: No pores exist in the cell walls.

A4: The mass storage capacity of the foam is modelled as the storage capacity of the voids only.

Averaging local field characteristics to effective properties such as effective diffusion coefficients requires that the actual geometric foam dimensions are large compared to the mean cell size and/or to the product heterogeneities. On the other hand, once averaged over a sufficiently large foam domain, will also be described as "continuum", those models in which:

A1$_{new}$: The effective diffusion coefficients are time or concentration dependent.

A4$_{new}$: The mass storage capacity of the foam is modelled as the sum of the cellular void and polymer storage capacity, assuming that the dissolved gas is in equilibrium with its cellular pressure.

Under these assumptions, the effective diffusion coefficient D_{eff} can be measured and determined. When used in the transient one-dimensional Fick's diffusion equation, the change of the gas composition and hence of foam thermal conductivity value can be forecasted (du Cauze de Nazalle 1995).

Fick's Law can be written as

$$\frac{\partial c}{\partial t} = D_{eff} \frac{\partial^2 c}{\partial x^2} \qquad (1)$$

where c is the gas concentration as function of time (t) and place (x) in the foam.

If we assume the partial pressure to be proportional to the concentration, as it is with ideal gases, Fick's law can be written as

$$\frac{\partial p}{\partial t} = D_{eff} \frac{\partial^2 p}{\partial x^2} \qquad (2)$$

Permeation

Next to the effective diffusion model a more detailed model describes the gas diffusion as a permeation process through the cellular structure. The foam is seen as a number of individual cells, and the cell-to-cell gas diffusion is assumed to be governed by Fick's first law. Permeation of gas through a cell wall occurs through two processes: the absorption of the gas in the wall due to a solubility S and diffusion through the wall given by an intrinsic diffusion coefficient D. The latter is a material property and differs from the effective value D_{eff} which is a continuum model property only. Permeation through a membrane at stationary conditions is given by a permeability factor P defined by:

$$J = P \frac{\Delta p}{\delta} \qquad (3)$$

where J is the mass flux of the permeating component of the gas, δ the membrane wall thickness and Δp the partial pressure difference over the cell wall for the component.(Hoogendoorn 1992)

Now the mass flux is also related to the diffusion by Fick's law

$$J = -D_{pol} \frac{dc_{pol}}{dx} \qquad (4)$$

The concentration of the gas in the polymer c_{pol} at the cell wall boundaries is related to the partial pressure by Henry's law, with the solubility S,

$$c_{pol} = Sp \qquad (5)$$

Hence it can be shown that

$$P = SD_{pol} \qquad (6)$$

The value of P in SI units has the dimension (mol/m* s* Pa). In practice, one uses often the unit of measurement 10^{-10}ml (STP) cm/s cm^2 cmHg, giving the mass flux as standard volume per cm^2 and per second over a thickness of 1 cm and for a partial pressure difference of 1cmHg or 13.33 mbar. Typical permeability coefficients P for different gases are for a PUR-laminate given in the table1. Also given are the values for D_{eff}, S and D_{pol}. P is a material property and varies with the composition of the polymeric material (C.J. Hoogendoorn 1992).

Gas	D_{eff}	S	D_{pol}	P
	$10^{-10}m^2/s$	cm^3(STP)/cm^3bar	$10^{-14}m^2/s$	$10^{-10}cm^3$(STP)/cmsbar.
CO_2	1,4	2,2	8,0	17,6
O_2	0,35	0,15	28,0	4,3
N_2	0,55	0,10	6,5	0,65

Table 7: Typical values for D_{eff}, S, D_{pol} and P for a PUR laminate at 25°C. (C.J.Hoogendoorn 1992).

Collected values
Values for effective diffusion coefficients (D_{eff}) were collected from the literature. These values are presented in appendices in Annex 1.

How to measure permeability coefficients for casing
The permeability of a material is typically measured on a membrane made of the material and placed as a wall between two chambers. On the one side of the membrane the selected gas is induced in the chamber. On the other side an inert or indifferent gas is normally induced for keeping the total pressure constant and hereby avoiding contaminations from outside coming gases. From this side samples are taken out.

The chambers can either be closed and mounted with valves for removing samples discontinuously or fitted with pipes connected directly to a detector for the gases for continuously measuring.

The system with valves is simple to establish, but care must be taken to avoid leakiness in the system. The gas mixture is induced in a gas chromatograph equipped with a detector system for the gases in the mixture. Most laboratories that have gas chromatographs and experience with measuring gas composition can do this work. The rest of the work is curve fit to the equation

$$\frac{p_t - p_1}{p_0 - p_1} = e^{-\frac{t}{t_c}}$$

where

$$t_c = \frac{L \cdot V}{P \cdot A \cdot R \cdot T}$$

t = time [s]
p_t = partial pressure to the time t [kPa]
p_0 = partial pressure to the time 0 (initial partial pressure) [kPa]
p_1 = partial pressure outside the casing [kPa]
A = area of the casing [m^2]
V = gas volume in the casing [m^3]
P = permeability coefficient [mol/(m s Pa)]
T = temperature [K]
L = thickness of the membrane
R = gas constant [(Pa m^3)/(mol K)]

The continuous system is the most commonly used method. It is developed for measuring oxygen permeability in food packaging material, as oxygen is the most important gas for controlling shelf life of food. This method is standardised in ASTM F1307-02 Standard Test Method for Oxygen Transmission Rate Through Dry Packages Using a Coulometric Sensor.

From the value of oxygen the values for nitrogen and carbon dioxide are calculated. The experience is that the permeability of nitrogen is app. 25% that of oxygen and carbon dioxide is app. 400% of the permeability of oxygen.

Estimation of cellular gas content in CFC blown pipes in year 1985

With the aim of calculating the heat loss from old R11 blown pipes it is necessary to estimate the cellular gas composition in preinsulated pipes produced in a time where cellular gas was not measured. The basic for this calculation are recipes from that time, and comparisons between the expected cellular gas content based on calculations and the content in pipes lifted in the recent year are made.

The polyurethane foams are made from polyole and isocyanate. The polyole often includes additives such as catalysers, surface active chemicals, water and a physical blowing agent such as R11 and cyclopentane in old days.

The two components are stored separately and are induced in a mixing device when used. In the traditional production of district heating pipes the mixture is pumped into the space between the media pipe and the casing pipe. The pipe ends are then closed with the aim to build a pressure in and density of the foam.

Recipes

To ensure that all the polyole will react to polyurethane, isocyanate is included, typical app. 25%. The relation between the isocyanate and polyole is named an index e.g. 1.25. The additives are added as a percentage of the polyole.

Typical recipes from about 1985 are found in a report (Bronnum 1986 and received from a supplier (Elastogran) of raw materials. From an internal report (Svanum 1987) it is shown that the index was typically about 135 with the limits of 125 to 145.

Recipe/source	Bronnum A	Bronnum B	Elastogran 83	Ealstogran 87
Index	1.25	1.05	1.10	1.4
Water	1.5	3.75	0.9	1.5
R11	40.7	16.0	28	*28*

Table 8: The table shows typical recipes from the mid 1980'ies.

The above mentioned recipes give the composition of the polyole/isocyanate mixture shown below.

Recipe/source	Unit	Bronnum A	Bronnum D	Elastogran 1983	Elastogran 1987
Isocyante	%	46.8	46.7	46.0	51.9
Polyole	%	37.4	44.5	41.9	37.1
Water	%	0.6	1.7	0.4	0.6
R11	%	15.2	7.1	11.7	10.4

Table 9: The table shows the composition of the mixture producing the PUR-foam.

From the composition of the mixture prepared for the PUR foam the cellular gas composition can be calculated under the consideration that all water will react to carbon dioxide and all the R11 will evaporate. There are some assumptions in this prediction. It is known that not all the water will react and some of the R11 will be absorbed in the polyurethane matrix and some will condensate to droplets.

In the report 41 (Svanum 1987) it is seen that the overall density at that time was app. 85 kg/m^3. When a density of the polyole/isocyanate mixture is assumed to 1000 kg/m3, app. 85 kg of the mixture is induced into the space between the media pipe and casing pipe per m^3 space. Depending on the recipe this 85 kg mixture will produce 2200 - 2900 l cellular gas at standard conditions (STP).

The calculated composition of the cellular gas content when all the gases are evaporated is shown table 9.

Recipe	Unit	Bronnum A	Bronnum D	Elastogran 1983	Elastogran 1987
R11	%	78	36	80	71
Carbon dioxide	%	22	64	20	29
Pressure (STP)	kPa	3.2	3.2	2.4	2.4

Table 10: The table shown the calculated cellular gas composition in preinsulated pipes made in 1985.

All the recipes were well functioning and form polyurethanes with sufficient thermal stability and mechanical properties, but there seems to be some variations in the calculated cellular gas composition and pressure. Which recipe was selected was more or less a question of machine ability and price.

As the isocyanate is the most expensive part of the recipe, a recipe with high content of low content of this component would be preferred, if possible. Even that the first and the third of the four recipes are used the calculation of the cellgascontent as the two recipes are very similar, but from different sources.

A theoretical cellular gas composition of 75% R11 and 25 % C02 with a theoretical cellular gas pressure of 2.8 kPa is probably a qualified guess for a typical recipe from 1985. In practice the gas pressure was much lower.

Cellular gas content in lifted pipes
Several old pipes have been lifted and the PUR foam analysed for cellular gas content. The thermal conductivity of the foam has been made, when possible. The pipes are all of the bonded type. Some of them have had LDPE casing. This means that the permeability of the casing was higher than for HDPE casings as low density polyethylene is more open for diffusion because of the low crystallinity. In some cases a thicker casing reduces the increased permeability.

We have not found test reports from 1985, but from an internal report from 1982 and 83 (Guntoft 1983) the following results are obtained. The results are measured on 9 pipes with dimension from 57/110 to 162/220 and from 5 different suppliers. The average value is 0.0247 W/(m K) going from 0.021 to 0.0266 W/(m K).

In another report (Svanum 1987) the thermal conductivity of the PUR-foam in 3 preinsulated pipe casings, size 110, 200 and 450mm from 5 different suppliers have been measured. Values from 0.021 to 0.027 W/(m K) are found with an average of 0.025 W/(m K).

The old Danish Standard concerning PUR-foam in district heating pipes DS 2178:1982 requires that the thermal conductivity shall not exceed 0.027 W/(m K).

Measured thermal conductivity	W/ (m K)	-	0.0323 [1]	-	0.0285	-
In use	Year	31	31	26	30	28
TI-Mark		220404-1	220404-2	030902-2	060203-1	151003-1
Dimension Pipe	Mm	122/200 Return	122/200 Flow	57,4/125 Flow	60,3/125 Return	160/250 Flow
In use [year]	Year	1973	1973	App. 1976	App. 1973	1975
Lifted	Town Year	Fredericia 2004	Fredericia 2004	Vaerloese 2002	Saeby 2003	Hundige 2003
Casing		LDPE	LDPE	HDPE	HDPE	HDPE
Casing	mm	202.3/6.3	202.3/6.3	125.7/3.2	126.3/3.5	250/6.5
Media	mm	133.2/4.2	133.2/4.2	57.2/2.7	60.2/3.0	160/4.5
Density	kg/m3	54	49	81	86	81
Cell size	mm	0.8	0.8	0.8	0.3	0.8
Casing thickness	mm	6.3	6.3	3.5	3.0	6
Measured Cellular gas content						
CFC – R11	%	35	40	23	46	28
Atmospheric air	%	64	60	75	51	71
Carbon dioxide	%	1	0	0.3	1	0.3
Total pressure	kPa	116	111	100	115	90
Measured thermal conductivity	W/ (m K)	-	0.0323 [1]	-	0.0285	-
In use	Year	31	31	26	30	28

[1] Joint included.

Table 11: The table shows cellular gas composition and thermal conductivity in lifted pipes

By these findings it is reasonable to conclude that the lambda value in the middle of the 80ties was 0.025 W/(m K).

Initial conditions for preinsulated pipes produced in 1985
The old pipes show some variety in composition, resulting in variations in density, cell size and cellular gas composition
Combining this information with recipes used in the middle of the eighties it is assumed, that the cell gas composition in new pipes at that time was close to 1.2 bar R11, 0.60 bar CO_2 and 0.03 bar atm. air.
This cellular gas composition, together with a cell size of 0.5 mm and a core density of 75 kg/m^3 (Svanum 1987), will be used in the calculation of the long-term properties of the thermal conductivity of the PUR-foams in district heating pipes.
In recent years cellular gas measurements in preinsulated pipes used for years have shown remarkably low oxygen content. At the same time some degradation of PUR-foam has been seen. This can explain the low oxygen content in old pipes.
Comparing all the observations on old pipes and the figures measured at that time, a reasonable initial cellular gas content for the calculation has been found to be carbon dioxide 0.60 kPa; R11 0.70 kPa; oxygen 0.01 kPa; nitrogen 0.04 kPa.
To compensate for the low oxygen content the foam the permeability coefficient is reduced by a factor of 0.01. With these approximations the thermal conductivity for a preinsulated pipe 60/125 is calculated to 0.025 W/(m K) for new pipes increasing to 0.029 W/(m K) during 30 years.

Typical cellular gas composition in traditional and micro cellular PUR-foams
Traditional PUR-foams have been on the market since CFDC was phased out in the middle of the 90'ies, and micro cellular PUR-foams have been on the marked since 2003. The principle difference is the cell size. The micro cellular foam is, as the name says, characterized by very small cells, typically 0.10 - 0.015 mm, which is app. 1/3 of the cell size in traditional foams. This reduces the cell size, decreasing the radiations through the foam, which is the main reason for better insulation properties.

A typical recipe and the calculated cellular gas content are shown below

Recipe		Microcellular	Traditional
- Index	-	1.6	1.5-1.6
- Water	%	2.0	1.8-2.3
- Cyclopentane	%	13	11-15
Cellular gas content			
- Cyclopentane	kPa	0.6	
- Carbon dioxide	kPa	1.1	
- Pressure (STP)	kPa	1.7	

Table 12: The table show a standard recipe for modern PUR foam.

Cellular gas analyses on different products produced with this type of PUR-foam show a cellular gas contribution as shown below.

Dimension	Mm	60/140	60/140
Laboratory		1	2
Density		62	62
Cellular gas content Cyclo-Pentane Atmospheric air Carbon dioxide Total pressure	 kPa kPa kPa kPa	 23 3 48 75	 29 7 66 102
Calculated thermal conductivity	W/(m K)	0.0237	0.0240
Measured thermal conductivity	W/(m K)	0.0240	

Table 13: Cellular gas content in new microcellular PUR foam measured at 2 laboratories.

As is seen from table 8 there are a good correlations between the measured and the calculated values of the foam. There is a surprisingly low pressure in the pipes measured at laboratory 1 but on the other side the content of atmospheric air in the sample measured at laboratory 2 is probably too high.

Based on these observations there will in the calculation of the change in the future thermal conductivity of micro cellular foams be used a cellular gas composition of 29 kPa C-P, 66 kPa CO_2 and 3 kPa atm. Air, a density of 62 kg/m^3 and a cell size of 0.1 mm.

Estimation of the future heat loss

When the future annual change in thermal conductivity is estimated the value of the actual heat loss can be calculated. If a qualified guess of the future interest rate and increase in energy price is made, the value of the future heat loss can be expressed as the capital that is needed today to pay the future heat loss. By such estimation it is possible to compare two different pipe systems with different insulation properties.

As the lambda value of the foam increases with every year the usual annuity calculation cannot be applied as this presumes a constant annual energy loss. The value of the energy loss must thus be calculated year by year, and must subsequently be calculated back to year 0, which is today. Now the value of the annual loss can be summed up to the total energy loss of the piping system.

Is the capital available the money is banked at deposit rate, but the energy price increases in the period and this increase must be included.

If the money shall be borrowed from the bank the lending rate shall be considered.

Definitions:
E Energy price today [€/MJ]
t_n Heat loss in year "n" per meter [MJ/m]
i_i Nominal deposit rate of interest [%]
i_e Expected price rising rent on energy [%]
k_n The necessary capital that shall be placed in the bank today to pay the heat
     loss in year n [€] .
n Index: Year 1, 2, 3, …..

The transmission loss is paid in advance – next year's heat loss is paid at the beginning of the year.

n' year: n' year's transmission loss shall be paid in n-1 year. The general equation for year n will be:

$$k_n = E \; x \; t_n \; x \; [(1 + i_e)/(1 + i_i)]^{n-1}$$

The total heat loss for all 30 years is the sum of $k_1 \ldots k_{30}$.

Comparison of old CFC network with new C-P network
The purpose of the project is to give the users a tool by which they can compare the value of the old CFC blown pipes with the new network made of microcellular C-P blown pipes. As the production of the old pipes has ceased within the EU the starting point is CFC-networks installed 20 years ago compared with new C-P networks. The value of the 30 heat losses is then calculated. The temperatures, the interest rate and increase of energy must be selected as it differs from country to country and from period to period.

Value of heat loss

Information about prices can be found at e.g. www.bp.com,
www.iea.org/dbtw-wpd/Textbase/nppdf/free/2004/keyworld2004.pdf or
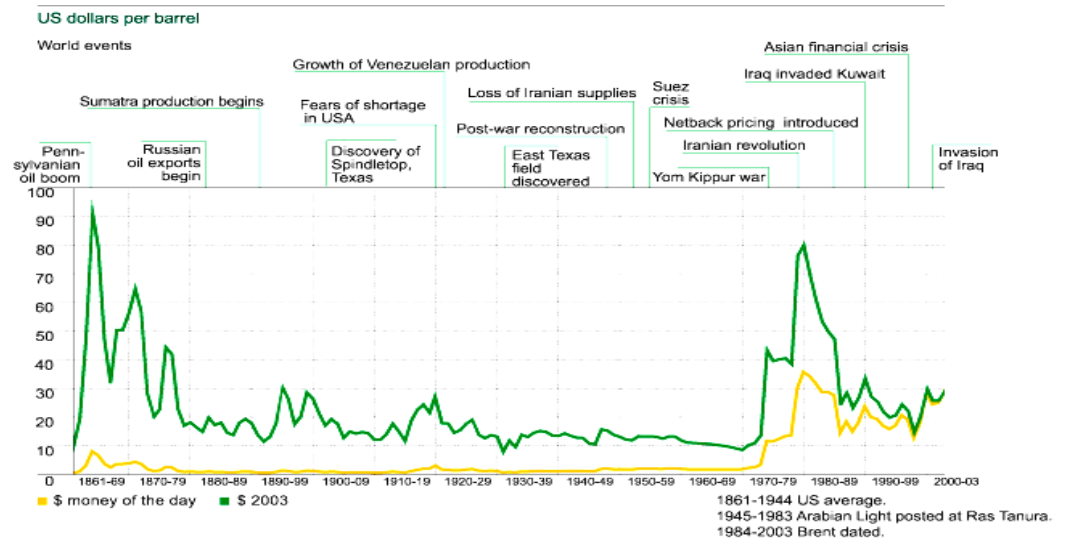www.iea.org/textbase/papers/2004/high_oil_prices.pdf-

Figure 12: The figure is an example of how the oil price has fluctuated.

The figure shows that the oil price has increased by app. 30% during the last 30 years inflations included, nut the oil price explained in fixed prices is reduced during the last 30 years.

In some countries energy is subject to taxes, environmental duties and VAT, for such costs a best guess for the future must be given. The calculation program must include taxes in the price increase.

Inflation seems at least in Europe to be under control, in most countries it is at a level of app. 2 %.

The interest is more or less related to the inflation. The deposit rate is often app. 1 % more than the inflation. The lending rate varies a lot, but it is difficult to obtain loans cheaper than 3-4 % above the deposit rate e.g. 3 and 7.

For the estimation of the value of the future heat loss in fixed prices based on historical data, a starting point could be -1% of the increase in the energy price, 4 % in interest. If the prices shall be in current value, 1-2 % for the energy price increase and 6-7 % in interest rate should be calculated.

Results
For the calculated values below the initial conditions are: $T_{forward}$ 100 °C; T_{return} 40 °C; T_{soil} 8 °C; energy price 20 EUR/MWh , interest of loan 7%; energy price increase 2%, soil covering 0.6m and distance between pipes 0.2m.

Tables 13 and 14 show results from a CFC blown pipe installed in 1985, the heat loss is calculated from 2005- 2035. The figures are compared to 30 years' heat loss from new pipes installed in 2005.

Dimension	CFC –20 years old	Traditional foam	Microcellular foam
mm/mm	MWh/m	MWh/m	MWh/m
28/90	5,4	5,7	5,4
48/110	7,7	8,2	7,7
89/160	10,5	11,0	10,4
168/250	14,8	15,5	14,6
323/450	17,1	18,0	16,8

Table 14: The table shows the accumulated heat loss from one metre preinsulated pipe during 30 years. Energy price 20 EUR/MWh.

The traditional foam will during the first 30 years in use have a heat loss which is app. 10% higher than the CFC-blown pipes in use from year 20 to year 50. This means that the environmental effect of a traditionally blown pipe will be app. 10 % higher than from an old CFC blown pipe. The microcellular foam will reduce the heat loss by app. 10% compared to traditionally blown preinsulated pipes. Compared to the CFC blown pipes the heat loss from the smaller dimensions will be at the same level as old CFC blown pipes and from larger dimensions the heat loss will be in favour of microcellular foam.

Dimension	CFC –20 years old	Traditional foam new	Microcelllular foam new
mm/mm	EUR/m	EUR/m	EUR/m
28/90	57	60	56
48/110	82	86	80
89/160	111	115	108
168/250	157	162	153
323/450	181	189	177

Table 15: The table shows today's value of the heat loss from one metre of preinsulated pipe accumulated for 30 years in use. Energy price 20 EUR/MWh.

The value of the heat loss for traditional blown pipes is app 5% higher than that of old CFC-blown pipes after 30 years in use. The value of the heat loss from microcellular foam is app. 6% lower than it is from traditionally blown foam. This is a bit better than for the old CFC blown pipes after 20 years in use.

Dimension	Heat loss in 30 years	To-day value of 30 years heat loss
mm/mm	MWh/m	EUR/m
28/90	5,4	56
28/110	4,5	47
28/125	4,1	43
48/110	7,7	80
48/125	6,6	69
48/140	5,8	61
89/160	10,4	108
89/180	8,6	89
89/200	7,4	77
168/250	14,8	153
168/280	11,3	119
168/315	9,1	96
323/450	17,7	177
323/500	12,7	134
323/550	10,7	107

Table 16: The long term effect of insulation thickness on heat loss and today's value of heat loss for one metre pipe. Lambda 0.025 W/(m K). Energy price 20 EUR/MWh.

The reduction in heat loss and the value of it increases with the thickness of the insulation. The rule of thumb is that the reduction is app 15% both on heat loss and the accumulated energy costs even though the variations are large.

With the foreseen future low energy buildings, carbon dioxide quotations and probably increasing duties is worth considering when calculating the economy of a new pipe system.

Questionnaire

The questionnaire survey was conducted to find out how the district heating plants in the various countries evaluate transmission loss. The object was further to investigate whether there was a connection between taxation and transmission loss. Finally, it was desired to know whether the plants had made comparisons between CFC-blown pipes and other pipe types.

The questionnaire was distributed to the app. 20 member organisations of EuroHeat & Power, who should further distribute to their sub-organisations. Some problems were foreseen in this process as the member organisations are often reluctant to complete questionnaires from institutes and further the questionnaire was in English. A few of the organisations put much effort in the process and even translated it to their own language. But the number of answers was nevertheless disappointing – 25 returned questionnaires. However, it was positive that most of the answers were uniform and represented 6 countries and 10,000 km trench, thus the answers were representative for a major part of the district heating plants in Europe. The main results are summarised in table 16.

Countries	AU; CZ; DE; FI; NO; RO	Total	Unit
Power Plant		18/6	Yes/No
District Heating distributor		23/1	Yes/No
Total length of pipetrench		9921	km
Total length of CFC blown pipes		3892	km
How many years has the oldest preinsulated pipesystem been in use?		7-38	Year
Economical lifetime of your pipe system		15-70	Years
Energy delivered to the network		112416	TJ/ Year
Sold energy		97175	TJ/Year
Normal temperature in the forward pipe		65-120	°C
Maximum temperature in the forward pipe		70-130	°C
Local tax per cent on energy (% of the actual energy price)?		8-200	%
Local VAT on district heating (% on top of the receipt to the customer)?		5-25	%
Calculated values			
Energy to network per year and km		13,4	TJ/km Year
Heat loss		14	%

Table 17: Participant representation

As can be seen almost 40% of the distribution system includes CFC blown. The energy density is relatively high with 13.4 TJ per km per year.

As the biggest suppliers changed to cyclopentane in the mid 1990'ies these pipes will not be more than 10 years old. The results show that the pipes with CFC must be between 10 and 38 years old. The forward temperatures vary from 65 to 120 °C. These figures will of course be reflected in the heat loss, which is 14% as an average.

In all the participating countries heat is taxed from 8 to 200% of the actual energy costs. To this comes VAT, which is varying from 5 to
25 %. This means that also heat loss is heavily taxed in certain countries. All data are collected in encl. 2.

Country	Total	
Question	**Mainly**	
	Yes	**No**
Does the company use preinsulated pipes?	24	0
Do you prefer low lamdba value to extra insulation thickness?	15	9
Are the longterm insulation properties important?	22	2
Do you control the insulation properties by measuring the lambda value for new pipes?	6	18
Do you prioritise carbon-dioxide blown pipes?	3	19
Do you prioritise cyclo-pentane blown pipes?	19	5
Have you made comparisons between heat loss on CFC blown pipes and CP/CO_2 blown pipes?	5	19
Are you of the opinion that the lifetime of the CFC blown pipes are longer than originally estimated?	13	8
Does the company use twin pipes (forward and return pipe in same insulation)?	10	13
Is the heat loss from the pipes important for the economy of the districht heating system.	23	1

Table 18: Summation of the answers.

As can be seen all participants use preinsulated pipes. Approx. 2 out of 3 plants, especially the Danish and Austrian plants, prefer low thermal conductivity to extra insulation thickness. In the other countries there is no clear preference but there is a general agreement that long-term insulation properties are important.
1 out of 4 plants state that they check the insulation power in new pipes, once again Denmark and Austria differ from the rest.
There is a general preference of preinsulated pipes with cyclopentane insulation. A small number prefers preinsulated pipes with carbon dioxide.
Only few have made comparisons between the transmission loss from CFC blown pipes and other pipes but the opinion is that CFC blown pipes have longer lifetimes than originally assumed. Twin pipes are especially known in Finland.
Finally, it is generally agreed that the transmission loss is vital for the district heating economy.

It can be concluded that the 25 plants participating in the investigations represent only a small part of the world's district heating, i.e. 5%. But the answers have generally been uniform with a high degree of consensys, which means that there is reason to believe that the answers are representative for many of the plants.

Many plants are of the opinion that CFC blown pipes have longer lifetimes but without having made an actual comparison with new pipes, perhaps in lack of a suitable tool.
In some countries, i.e. Sweden and Denmark, there are tools for making such comparison, however, only with foam types which have been in the market up till now.

With the new microcellular PUR-foams a comparison may prove different and therefore there has been reason to develop a programme for comparing the transmission loss of 20 years old CFC blow preinsulated pipes and new pipes insulated with microcellular PUR foam.

Foundations of vacuum and pre insulated pipe insulation

Physical foundations thermal insulation

The definition of temperature and warmth
The Temperature T is a measurement for the thermal condition of a body. The temperature of a material states how strongly the microscopic components of the body move. The possible movements depend very much on the respective body and the so-called internal degree of freedom of the respective body. In principle the degrees of freedom determine the "motion possibilities" of the microscopic components of a body or a gas. For example the atoms in a solid body are able to swing against each other. In a conductor the electrons can move freely such as atoms in a gas. Within a gas, atoms and molecules can move into the three directions in space, but - depending upon structure - they are also able to perform oscillations or rotations.

The warmth Q is a form of energy. In order to warm up a body the kinetic energy of its molecules and thus the temperature of the body must be increased. The warmth is always transferred by the warm material to the colder material. That means that a heat exchange between two bodies is only possible if a potential gradient, in this case the temperature gradient, is there.

The connection between the temperature of a body and the absorbed warmth, thus energy, is determined by the specific thermal capacity of a body C. The specific thermal capacity gives information on the number of the degrees of freedom. Without going into detail of the theoretical description of the specific thermal capacity, the values of the specific thermal capacity for some materials at ambient temperature are compared in the following table:

| Material	Density ρ in kg/m³	Specific thermal capacity in J/(kg K)	Heat conductivity λ in W/(m K)
Aerated concrete	600	400	0,14
Glass	2500	814	1,16
Plywood	600	2100	0,14
Air	1,20	988,1	0,0246
Polystyrene	15-30	120	0,03

Table 19: Density, spec. thermal capacity and heat conductivity for different materials

If a body is being heated by the temperature dT, then the absorbed energy is the value dW:

$$dW = c \cdot dT \qquad\qquad \text{to} \quad \frac{J}{kg\ K} K = \frac{J}{kg} = \frac{Ws}{kg} \qquad (1)$$

Heat transport
In the following chapter the different forms of heat transport will be briefly outlined. In reality, however, the 3 heat transport phenomena "thermal conduction, convection and radiation" will not be found separately from each other but normally go together (see fig. 13).
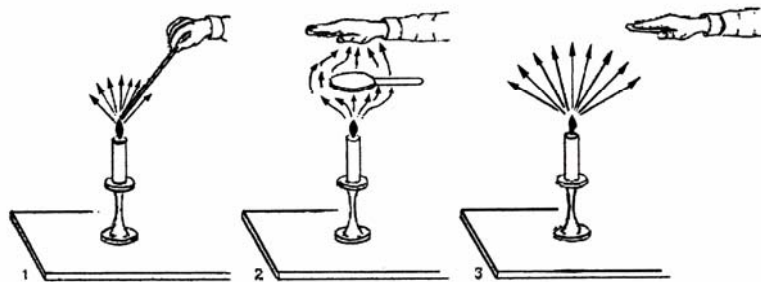
1 By thermal conduction the warmth moves from the candle via the metal bar to the hand.
2 By convection the heat energy moves from the candle via the air flow to the hand.
3 By radiation one transfers the heat energy of the candle to the hand.

Figure 13: Heat transport by thermal conduction, convection and radiation by the example of a candle (Hausladen 1998)

Thermal conductivity

It takes some time for the top of a clay brick on a hot plate to become hot when heated from below. The process which transfers the heat of the plate through the brick to the top of the brick is called thermal conduction.

There are multiple small oscillators in a solid body (oscillators are systems, which can swing like a pendulum, a spring or also a swing). A solid body can be seen as large number of small weights, which are connected by springs. If the weights are shaken- but only on one side of the body-and are thus set in motion then this is exactly what happens when a body is heated up. So the above mentioned weights start to swing first but since all the weights are somehow connected to each other all the weights will slowly start moving. That is exactly what happens in reality. By an increase of kinetic energy the warmth is transferred from one molecule to another. Thus the warmth is transferred from one side to the other. (University of Augsburg 2004)

Depending on how strongly the individual molecules (oscillators) are connected, the thermal conduction will be better or worse.

A good thermal insulation is the vacuum, because in a vacuum there are no oscillators, except maybe a few remaining atoms. Nevertheless warmth can be transported in a vacuum by means of the radiant heat.

Radiant heat

Each body, which is warmer than the absolute zero, delivers electromagnetic radiation. The spectrum and the intensity of the radiation depend strongly on the temperature of the body. Good examples are glowing iron and the sun, where a large part of the "radiant heat" is in the visible range. The entire radiation rises with the fourth power of the temperature.

Physically, radiant heat is similar to visible light. Therefore surfaces can only exchange radiant heat if they are in direct visual contact. Even air is optically not completely pure so that heat transport is most effective in the empty area (vacuum).

The radiant heat per solid angle as function of the wavelength λ is described mathematically by the Planck radiation law (Merker et al 1999):

$$I_S(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \qquad (2)$$

The formula expresses that a black body with the temperature T the unit area and the energy $I_S(\lambda,T)$ in the wavelength coverage λ per time unit radiates perpendicularly to the surface into the solid angle unit. If the function is integrated over all wavelengths and the solid angle, you will get the Stefan Boltzmann law, the eradiated power per unit area: (University Augsburg 2004)

$$P = \sigma T^4 \qquad (3)$$

Heat balance is a result of the sum of irradiated and eradiated power. But in reality most bodies are not black bodies. That means that in this case the above equations must be corrected by the emissivity ε. Furthermore the irradiated power is only absorbed by the body according to the absorption factor α. Both values ε and α depend on the wavelength. Hereunder applies generally $\varepsilon(\lambda) = \alpha(\lambda)$.

Then the balance results in the simplest case to: (University Augsburg 2004)

$$\frac{dp}{d\lambda\, d\omega\, dA} = \varepsilon\, B(\lambda, T_K) - \alpha\, B(\lambda, T_U) \qquad (4)$$

T_K is the temperature of the body and T_U the ambient temperature. You will get the total output by using the appropriate integration.

Convection
Convection is the transport of warmth by transport through matter. It only takes place within liquid or gaseous materials. So there are the following differently cases:
free or natural convection, produced by density variations with the heating up (e.g. the ascend of warmed up air at heating elements)
forced convection (e.g. fan ventilation; water in central heating by pump)
mixed convection (e.g. draft)

A good example of heat transport by convection is the heating up of water in a pot. Since water is a bad heat conductor there is no thermal conduction of the bottom of the pot to the water surface. The density of the water which has been heated at the bottom of the pot decreases and thus the warm water ascends to the surface, cools down and sinks back to the bottom. As can be seen in the example - warmth is bound to material transfer.

Heat transfer
Heat transfer takes place in the borderline area between firm subject and a fluid or a gas. It is a mixture of thermal conduction and convection.

Convective heat transfers play a substantial role e.g. in the distribution of warmth in a house and in the transition of warmth from external walls to the ambient air.

Vacuum insulation
The fact that warming and/or cooling losses of some materials can be improved in an evacuated area has been well-known for a long time. Not only convection and line losses can be prevented in the evacuated area, but, provided there is an appropriate surface, radiation losses can also be prevented. For this reason the vacuum insulation is being used in private households, in the industry and/or in the handicraft. One of the most well-known uses of vacuum insulation is the thermos bottle and/or the Dewar vessel.

Function of a Dewar vessel
Dewar vessels are double-walled vacuum-dammed containers made of glass or metal. The area between interior and external pistons is vacuum-dammed. Since there are practically no gas molecules in the gap, there is no heat transfer by thermal conduction or convection. In addition to that, the Dewar vessels made of glass are produced of reflective material as to minimize the radiant heat. The result is extremely small heat conductivity: 0.000576 W/mK (R 250). (Porextherm 2003)

Apart for the vacuum insulation there is another decisive factor for the insulation achievement of a Dewar vessel – the thermal insulation of the material the vessel is made of. The higher the thermal conduction of the material is, the larger the heat entry into the Dewar vessel.

Most calorific losses are due to the surface of the Dewar vessel, a surface which is not vacuum-dammed. In general a Dewar vessel has an opening on the upper side. By means of this opening the most part of the heat entry into the Dewar vessel takes place. The better the Dewar vessel is dammed at that opening, e.g. by means of a cover or a plug, the longer the service life of the product stored therein. A good example of a better dammed opening range is the thermos bottle.

Structure and function of a thermos bottle
As seen in fig. 2, the thermos bottle also consists of double-walled container with a vacuum-dammed interior. That means it functions exactly like a Dewar vessel. Contrary to a Dewar vessel the thermal bottle may possess a dammed opening range so that it can be used for cold and for hot liquids.
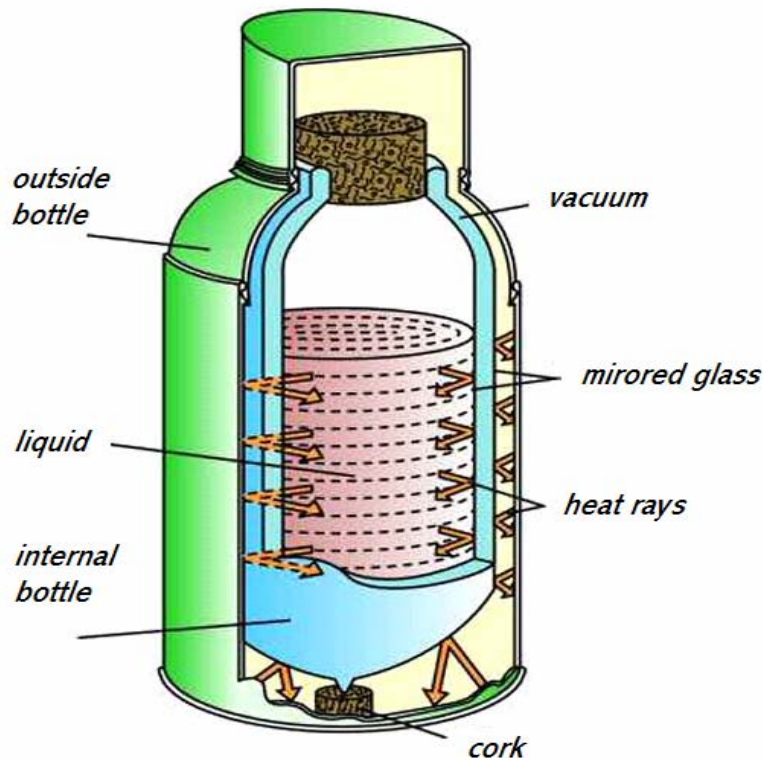
Figure 14: Cross section of a thermos bottle

Problems with vacuum-dammed containers

The maintenance of a pressure gradient between the outside and the inside of a container always pose a mechanical difficulty. The load of the air pressure that amounts to approx. 10000 kg/m² can be balanced in a thermos bottle. But at laminar applications there is a need for a supporting material which can carry the load and which has a thermal conductivity as low as possible. But there are limits as to the planning of such containers and as to the suitable materials. There is also the problem that the walls of the cylinder have to be absolutely resistant to gas and humidity because even a small number of gas molecules destroys the insulating ability. Since jets in the vacuum, in which they encounter no obstacle, spread best, the only material which can be used for these container walls is glass or metal which has been specially treated. These two materials, however, show a significantly heat conductivity at the junction points of the container walls (Porextherm 2003). In order to reduce and improve the mechanical stability the calorific losses, there is one example for a material of container walls - borosilicate glass.

Insulation with PUR

Economical potential

For years polyurethane foam (PUR) has proven to be suitable in the heat insulation of long distance heating pipelines. By means of a special procedure the polyurethane foam is being inserted into the gap of the core pipe made of steel and the jacket pipe made of plastic. Up into the 90´s CFC's, chloroflourocarbons, such as CFC 11, and HCFC´s, hydrochloroflourocarbons, such as HCFC 141b has been used as blowing agents for the foaming of PUR. All CFC and the HCFC´s are materials which may seem predestined with respect to its thermal characteristics but they are harmful to the environment. Both groups now phased out due to their high ozone depletion potential (ODP) and high global warming potential (GWP) and replaced mainly by hydrocarbons, primarily cyclopentane, and in few cases, fully waterblown systems using carbon dioxide from the water isocyanate reaction as the blowing agent.

That means that the problem is the withdrawal of propulsion gas in order to improve the thermal characteristics of the final product PUR-foam. The following estimate shows that high economic

goals play a considerable role (BASF 1996). Each year 1000 km of plastic coated pipes used as long-distance heating pipeline are being laid in Germany and 4600 km in Europe. A lowering of the heat conductivity k as a minimizing value by e.g. the value

$$\Delta k = 0{,}010 \ W/(m \ K)$$

in contrast to the PUR-foam which is used at the moment, means a saving potential of 30 GWh in Germany and 137 GWh in Europe per year. Taking the value 20 € per MWh there is an annual saving of 0.6 million Euro for Germany and 2.7 million Euro for Europe, with respect to the kilometres of long-distance heating pipes laid per year.

The estimated saving potential of primary energy does not only mean a saving in the area of primary energy carriers (mainly coal), but also an accompanying decrease of the carbon dioxide (CO_2) emission (greenhouse effect).

Heat transport in the PUR

The value which determines the calorific loss in long-distance heating pipes is the heat conductivity of the insulation system. That means the heat conductivities of the conduit (steel) and the jacket pipe (polyethylene) can be regarded in good approximation as infinite, so that practically only the foam material lying between them works as thermal isolation. The heat conductivity of this foam material is therefore the value which can be minimized.

According to Glicksman (Glicksman 1994) the heat conductivity of foam materials can be described as additive value of three addends:

$$k_{foam} = k_{gas} + k_{matrix} + k_{radiation}$$

k_{gas} means the heat conductivity of the propulsion gas in the foam pores, k_{matrix} is the portion , that is reducible on the lattice vibrations in the foam substance and $k_{radiation}$ corresponds to the radiation portion according to the Stefan-Boltzmann law.

Since, apart from the temperature T, the heat conductivity of a gas (Recknagel 1994) in accordance with

$$k_{Gas} = A \ r^{-2} \ k \ (kT/\mu)$$

The following abbreviations mean:
    A: number factor
    r: molecule radius
    k: Boltzmann constant
    T: absolute temperature
    μ: molecule mass

only dependent on the radius r of the gas molecules (here supposed to be balls) and on the molecule mass μ it had been found out the heavy gas R 11 is a particularly suitable propulsion gas for the foaming process. Each substitution by a gas of smaller mol mass had increased the heat conductivity of the insulating matter. But if a sufficient vacuum in the PUR is reached, then the component k_{gas} is almost completely void.
The optimization of the thermal insulation characteristics of PUR-foam has been advanced in recent years by decreasing the thermal conduction portions of the k_{matrix} and $k_{radiation}$.

According to Glicksman (Glicksman 1994) the relationship for the matrix heat conductivity can be deduced

$$k_{matrix} = k_p(1 - \delta)(1/3)(2 - f_s) \qquad .$$

The following abbreviations mean:
Kp : heat conductivity of the not foamed PUR-material
δ: factor of porosity ($\delta = 1 - (P_{foam} \ 1 \ (P_{PUR}))$
f_s: factor of mass distribution: f_s = (mass in cell barriers / PUR-total volume)
P: mass density

The relation above shows that matrix heat conductivity is directly proportional to the quotient made of mass density of the foam and mass density of the PUR raw material. Therefore a decrease of the PUR-foam mass density (enlargement of the factor for porosity) will always improve the technical isolation characteristics of the foam. For the foams used at present the number factor $(1 - \delta)$ has the value of about 0.065. And in addition k_{matrix} becomes smaller, if f_s rises: In the border line case (all PUR-mass concentrated in the bars of the foam) $f_s = 1$.

The radiation portion of the heat transport through the insulating material is (Glicksman 1994):

$$k_{Radiation} \ 4 \ \varepsilon \ (2-\varepsilon) \ \sigma T^3 d$$

The following abbreviations mean:
ε : radiating power of the PUR-walls
σ : Stefan-Boltzmann-factor
T : absolute temperature
d : middle diameter of the foam material cells

The radiation portion of the heat transport at a given temperature can be affected by the cell size and by the radiating power ε. The facts, which have been presented so far, can be summarized as follows:

- The gas thermal conduction portion becomes minimal, if the propulsion gas molecules are heavy and large (large mol mass) or are completely void.
- The matrix thermal conduction portion becomes minimal, if the porous coefficient is as close as possible to the ideal value 1 and if as much as possible of the PUR mass is concentrated in the bars of the foam material.
- The radiation portion (at given temperature) becomes small, if the average diameter of the foam material cells and the radiating power of the cell walls are as small as possible.

That means that the best insulating qualities can be found in a fine pored PUR-foam with a high porous factor, which has the following features-

- there is a gas of small heat conductivity or even better a vacuum in its cells
- the cell walls are characterised by small radiating power
- as much as possible of the PUR material is concentrated in the bars.

Heat transport through PUR-foam material reduces by 50 % the gas heat conductivity, the remainder is equally due to the matrix line and/or radiation. Because of the higher temperature of the heat distribution medium the relationship shifts somewhat towards the radiation conductivity. (Tempel et al 2000)

Statements of PUR manufacturers
Currently foams (also called XPS) are being used in the area of cooling devices; the life span is about 10-12 years. There is an in-liner made of ABS respectively polystyrene and a diffusion-close metal jacket on the outside. Panels are another example of an application, with the help of a foil they can be implemented very diffusion-close. (Dedecker 2004)

Heat-conductances (Grieser-Schmitz 2004):

- PUR-foam not flexible, up-to-date (only foam)   18 -19 mW/m K
- PUR evacuated   8 mW/m K
- PUR- foam not flexible (ventilated)   33..34 mW/m K
- Silicon Dioxide   4,5 mW/m K (evacuated)
- Based on Silicon manufactured insulations   18..19 mW/m K (ventilated)

A small price comparison:

- PUR-foam not flexible costs: 2 €/kg a 30 times higher volume can be produced
- Panels: 12,- € 0,7 x 0,5 m² (approx. 10 litres contents)

Thus the manufacturing costs for dammed panels are manifold when compared to the usual PUR applications

Some foam manufacturers in the chemical industry were actively researching in the range of vacuum insulations but have stopped by now. The company DOW Chemical had researched in the area of polystyrene (XPS) and had produced a vacuum foam. But the production of an adequately foam for vacuum uses was stopped.

The company Huntsman and others were active in the range of PUR. The following statements have been made by the above mentioned company on the topic PUR (Grieser-Schmitz 2004):

- It is possible to manufacture an open-cellular polyurethane foam. It is necessary to use a set of catalysts.

- It is substantially more difficult to manufacture an open-cellular surface of the PUR product. That is only possible by using further technical "tricks".

An even larger problem is the production of a very good vacuum.

The normal PE coating of a KMR is normally not sufficient to function as a diffusion obstacle against penetrating molecules and atoms. Thus an additional diffusion barrier must be created.

In general the use of vacuum-evacuated PUR foams is a very big idea and challenge. So in theory it would be possible to reduce the heat conductance of 25 mW/(m K) by approximately half (50 %) to 10-15 mW/(m K). This corresponds to the portion, which the insulation gas holds as "convection gas" during the heat transfer in the system.

To be able to use this effect in a classical KMR system, pumps would have to be installed about every other meter. The costs would be so high that this is a solution which is absolutely uneconomical. If you wanted to install a system without pumps, appropriate barriers would have to be created to prevent the penetration of molecules. This could only be achieves by using a very thick aluminium foil or similar materials.

In the past years there was a vacuum project at Huntsman Company. Foams in blocks were manufactured, encased with aluminium and tested. They were already used as parts of the insulation for refrigerators. They represented a material mix with a foam core. This core was encased by yet another material. A technical application, which is economically feasible, is not realistic at the moment. In future an application, however, would be conceivable.

Superinsulations
Superinsulations are thermal insulations, whose total heat permeability is clearly smaller than that of the surrounding resting air. This condition is reached among other things by the evacuation of fine-grained fill. Even smaller heat flows are reached by using evacuating highly reflecting metal foils (fig. 3). They rank among the intermittent assembled superinsulations, which also include Dewar vessels (thermos bottles) and partially supported insulations. (VDI-Wärmeatlas 1994)
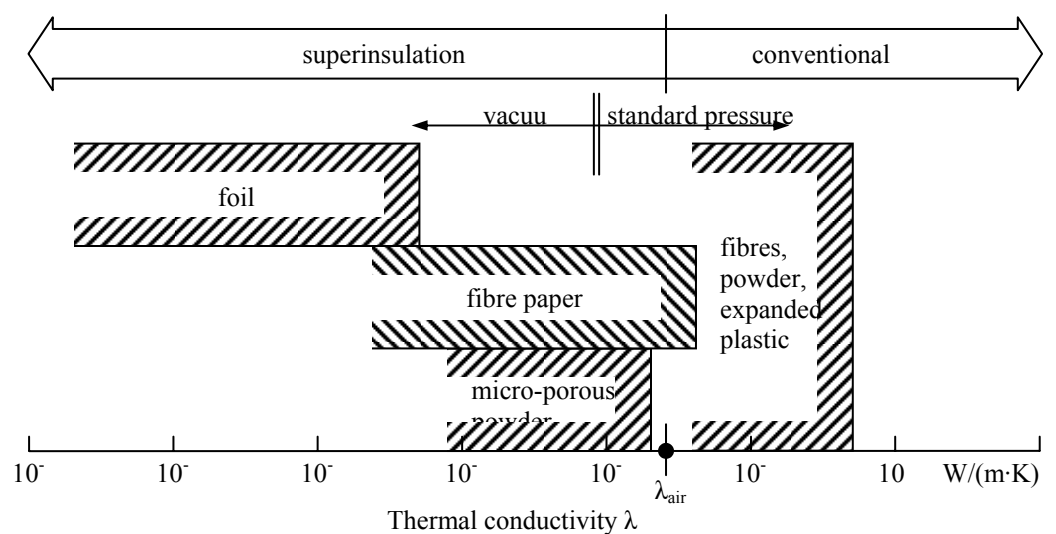

Table 20: Overview on the heat conductivities which can be reached by using superinsulations at low temperatures (VDI-Wärmeatlas 1994)

Discontinuously constructed superinsulations
The aim of these insulations is to reduce the total loss of the heat flow Q_{total} by minimization of its components Q_{gas}, Q_{FK}, Q_{Rad} , which means

- preventing the arising dissipated heat stream Q_{gas} through existing gases or ambient air. This is achieved by evacuation of the insulation area of the remaining gas pressures under 0.01mbar (1 Pa).
- avoiding solid cold bridges (e.g. contacts of radiation foils among themselves, supports etc.) and thus solid contacts Q_{FK} as far as possible,
- avoiding radiation losses Q_{Rad} by using reflective material on the inner walls (Dewar vessels) or by installation of highly inflecting metal foils (foil superinsulations).

If these measures are made at the same time, the total loss of heat flow at all temperatures can be brought to smallest technically possible values.
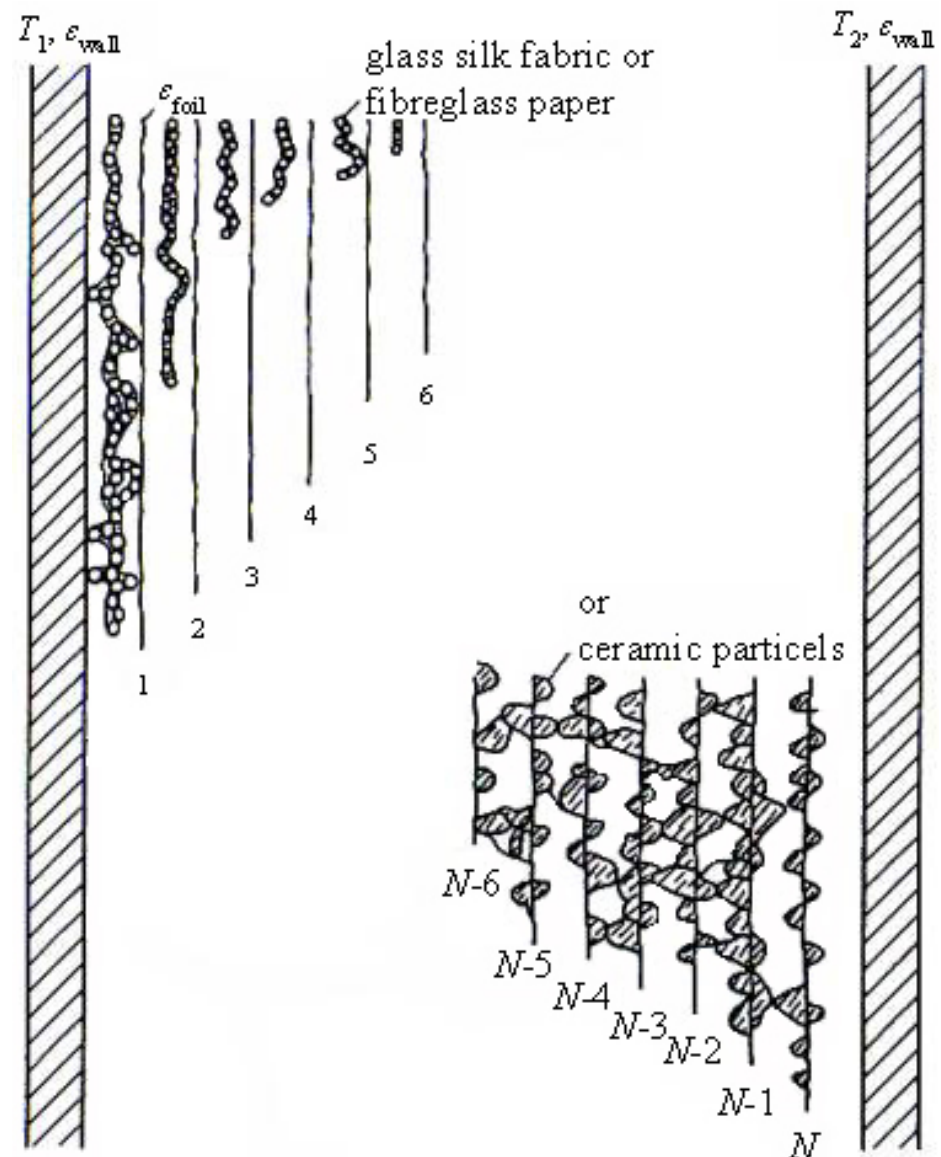
Figure 15: Structure (not full-scale) of foil superinsulation with different spacers (VDI-Wärmeatlas 1994)

Discontinuously constructed superisolations
In this case the heat transport by finely granulated media is to be examined. This includes also evacuated powder and fibre insulations (but not foam structures).

Improvement of heat insulation
You will achieve the smallest λ_{total} - values (total heat conductance) among other things through

– Noble gas fillings (evacuating and reduction of the pore diameters)
– Use of particle basic substances with small solid conductivities and large elasticity modules-pressure loads are to be avoided.

Experience with vacuum insulations/- applications

Studies in the field of vacuum insulations for heat accumulators
At the beginning of the 90´s, respectively in the mid-90s, studies in the field of vacuum insulation for heat accumulators were conducted. (BINE 1995)

In fig. 5 the heat conductivity of different insulating materials at ambient temperature and normal pressure is shown. As can be seen, the smaller heat conductivities exhibit evacuated thermal insulations. Fibre insulating materials and diatomite as well as aero gels are also particularly suitable for the deployment in an evacuated state.

heat conductivity (mW/m K)
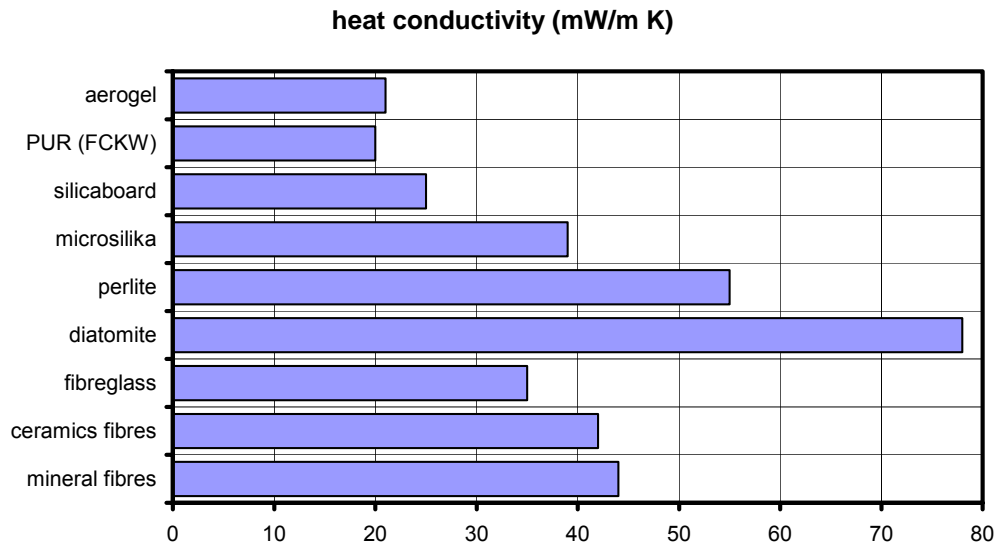
Figure 16: Heat conductivity of different insulating materials at room temperature and normal pressure

For the practical application, in particular for an economical series production, it is crucial to know up to which remainder gas pressure the thermal insulation must be evacuated in order to substantially reduce the heat conductivity. The measurements show that with most insulating material the remainder gas pressure must be smaller than 1 mbar (100 Pa) in order to reach an advantage over not-evacuated insulating materials. Only with micro-porous insulating materials it is possible to reach very small heat conductivity at normal pressure (fig. 17 and fig. 18).

Figure 17: Heat conductivity of different insulating materials dependent on gas pressure (BINE 1995)

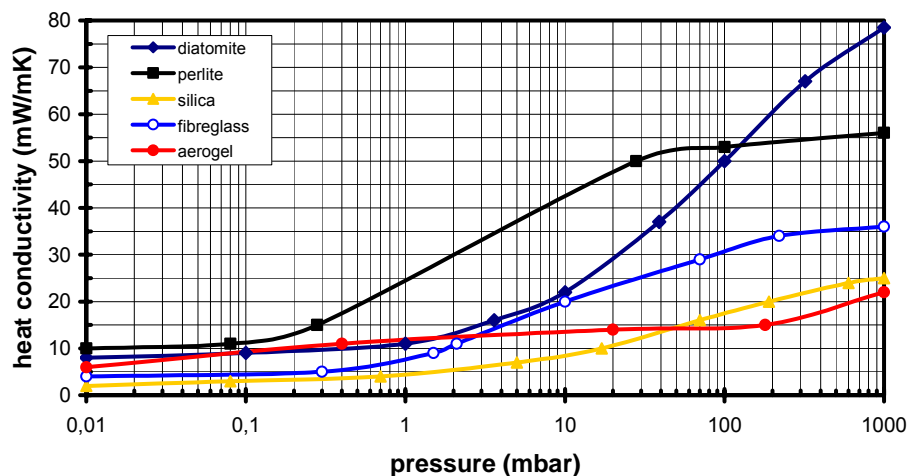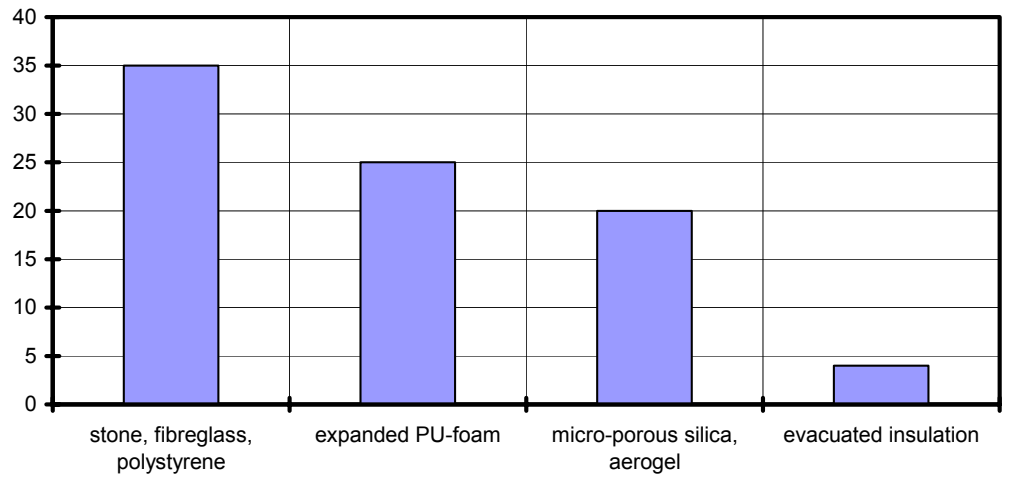**heat conductivity of different heat insulation materials (W/mK)**

Figure 18: Comparison of the heat conductivity of different heat insulation materials with an insulation on the basis of nano-particles, which are integrated into evacuated panels (ZAE Würzburg 2002) also (BINE 2001)

For the production costs of an evacuated insulation the decisive point is not only the necessary negative pressure but also the time for exhausting until reaching this residual pressure. Degassing of the material and in particular of air humidity stretch these times to a maximum. When falling below the vapour pressure, the water leaves slowly, whereby the exhausting curve runs asymptotic against a limit value. Baking is a proven method to shorten degassing times. Furthermore the time for exhausting depends on the diffusion resistance of the insulating material. The resistance is larger, the further the way of the gas molecules through the thermal insulation is. By use of degassing channels, which are arranged on the surface of the thermal insulation, this resistance can be reduced, without considerably affecting the heat insulation characteristics.

The results of these tests are shown in fig. 20 and fig. 21: The pumping out curves in fig. 20 prove that by heating the thermal insulation a partial substantially smaller residual stress can be achieved. The effect of suitable degassing channels is shown in fig. 21. Sufficient degassing channels are necessary to achieve short, justifiable evacuation times.
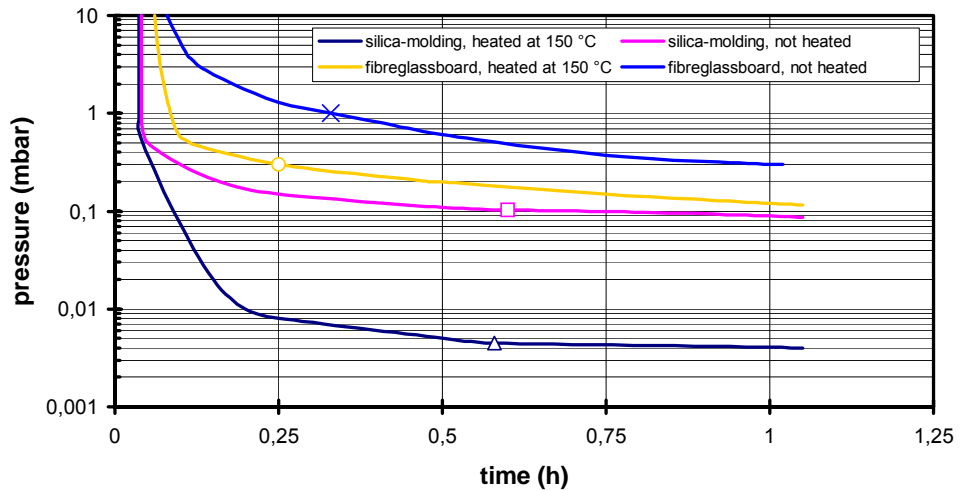

Figure 19: Pumping out curves of test specimens with and without heating (BINE 1995)
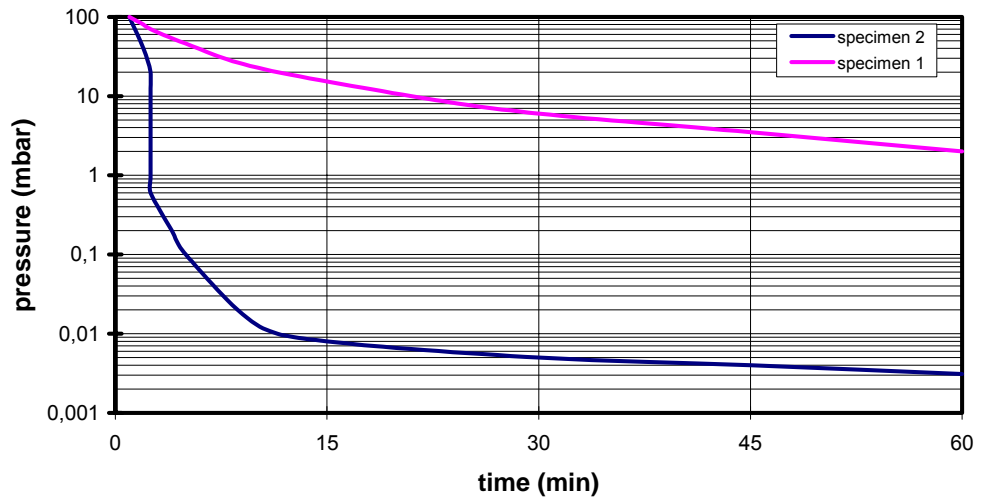
Figure 20: Pumping out curves of sample test specimens with (2) and without (1) degassing channels (BINE 1995)

Panels with high-grade steel casing

The company Thyssen-Vakuumtechnik (vacuum engineering) offers panels with a high-grade steel sheet metal casing. These casing are supposed to guarantee a long-term stable vacuum. (time for the penetration of atoms and molecules from the environment). The life-span is supposed to reach 25 years.

	Mechanically loadable VIP	Adjustable VIP	Foil VIP for building insulation	Foil VIP in logistics
Gas density casing	High-grade steel sheet metal	High-grade steel sheet metal	PE-aluminium-PET-laminated film Metallized high barrier foil	PE-aluminium-PET-laminated film Metallized high barrier foil
Insulating core	Micro-porous silicic acid, Polystyrene foam, open-cellular PUR foams	Glass fibre	Micro-porous silicic acid	Micro-porous silicic acid, Polystyrene foam, open-cellular PUR foams

Table 21: Material combinations for different operational areas of vacuum insulations (BINE 2001

Foil-coated vacuum insulation panels (VIP)

(BINE 2001) and (Porextherm 2003)

Foil-coated vacuum insulation panels named vacuum insulation panels (VIP) represent at present the largest new area of application, respectively the largest potential of application. The majority of current research projects take place in the above mentioned field. Typical applications can already be seen in refrigerators, freezers, transportation boxes, thermal insulation, cooling containers.
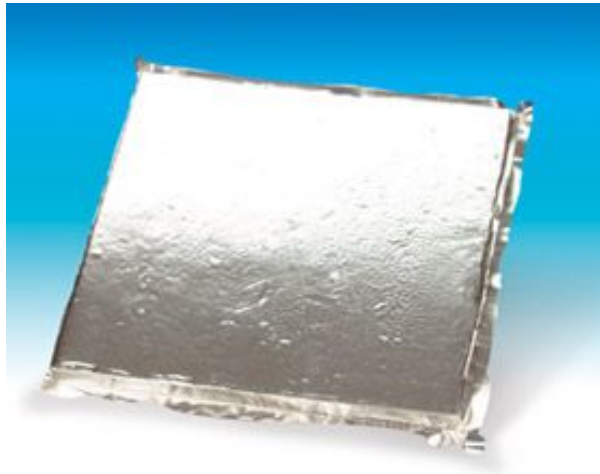
Figure 21: Vakuum-Isolations-Paneel - Vacuum isolation panel (Porextherm 2003)

A VIP (Vacuum Insulation Panel) consists of a filler which is called the "core" and which is covered by a protective plastic film. After bringing it into the casing, the system is evacuated to a vacuum between 0.001 mbar and 1.5 mbar (0.001 and 1.5 torr or 0.1 and 150 Pa) (according to manufacturer data) and then sealed. (Porextherm 2003)   That means that a foil VIP resembles in structure and appearance a package of vacuum-packed coffee powder.

The core material has three tasks (Porextherm 2003):

1. It serves the support of the panel walls. The atmospheric pressure exerts a pressure on the evacuated plate of 1 bar. Therefore a pressure of approximately 10 tons rests on a area with size of 1 square meter.

2. The core material restrains the movement of gas molecules which might still be in the panel. The smaller the size of the pores of the core material, the larger is the probability that the gas olecules do not collide with one another, but with the extended net of the filler.

3. The core materials offer a barrier layer against heat transfer by radiation. They contain a material for hazing which absorb or reflect the infrared radiation.

Insulation ability and life span of VIPs
The insulation ability and the life span of vacuum insulation panels depend on a whole set of factors (Porextherm 2003):

1. Characteristics of the core material
2. Vacuum at the beginning of the service life
3. Permeability degree of barrier foil and sealing
4. Quantity and effectiveness of getter materials and drying agents
5. Degassing of core material and foil
6. Size and thickness of the panels
7. Cold bridges
8. Application conditions
9. Operational areas
10. Mechanical stress

Core materials
The VIP materials which are on the market today are open-cellular polystyrene and PUR foam as well as fine dispersoid silicon dioxide, the so-called silica acid. At all vacuum insulation panels, a small thermal conduction is reached by means of a high vacuum. The silica acid, however, has a smaller thermal conduction as well as higher resistance for mechanical pressures than all the other fillers. If the vacuum in the casing weakens, the heat conductivity increases. The relationship between the rise of the internal pressure and the increase of the heat conductivity depends strongly on the kind of the filler. The following illustration shows a comparison of the effects of rising

internal pressure on vacuum insulation panels with different core materials. It is to be noted that all fillers exhibit a very good insulating ability in the highest vacuum. But even at a small rise of the internal pressure there are drastic differences. The most notable decrease of effectiveness can be seen in foams, so that they are often only suitable for applications where a shorter life span (<5 years) is sufficient. (Porextherm 2003)
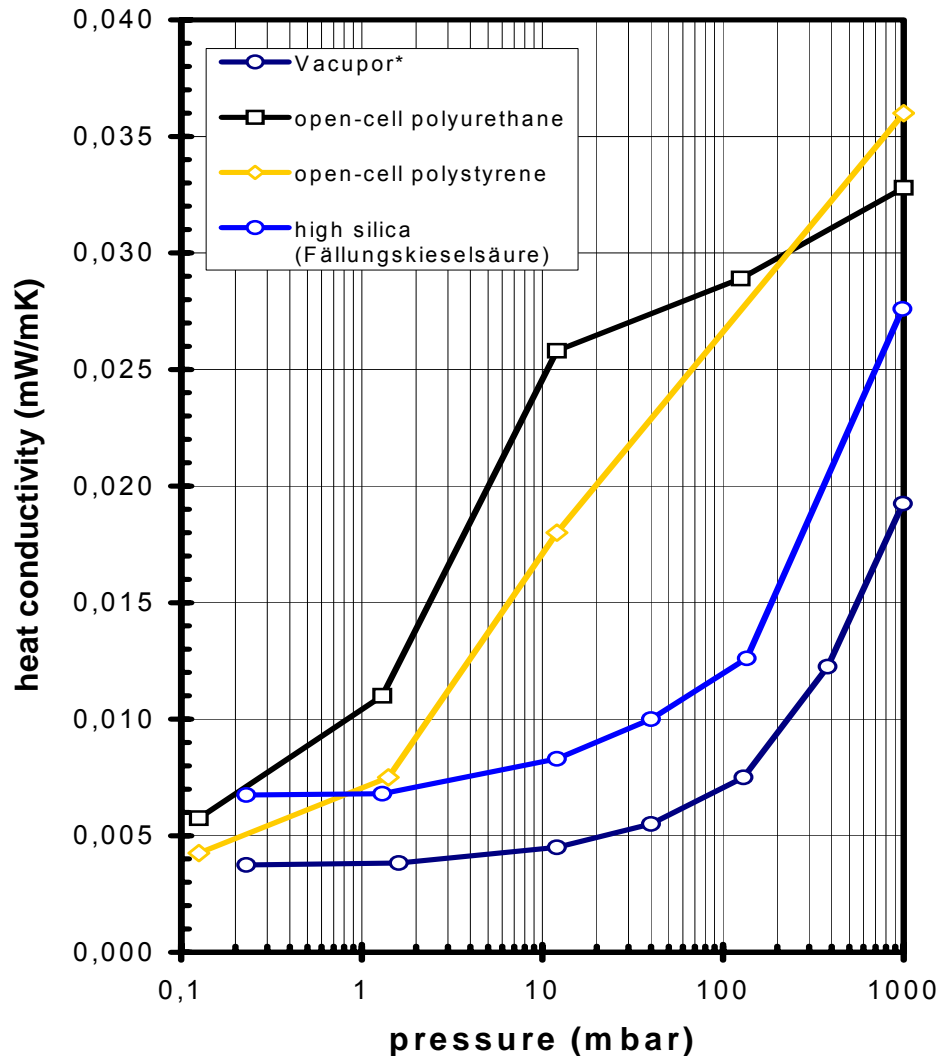
*Vacupor from Porextherm filled with silicon dioxide
Figure 22: Effect of the increase of pressure on the heat conductivity (Porextherm 2003)

Vacuum at the beginning of the service life
From the outset there is no "perfect vacuum" in vacuum insulation panels. A complete evacuation of the panels would entail a substantial increase of the manufacturing costs. This way a financial limit is set to the evacuation process.

Thus the goal at the production of vacuum-dammed construction units should not be the production of one „perfect vacuum ", but the stability of the existing vacuum. That means that high quality in the production of individual walls, in the evacuation of the finished construction units and in the process of sealing is enormously important.

Permeation rates of barrier foils - edge effects
The barrier foil is the material the walls of the VIPs are made of. In the course of time some gas molecules and a certain amount of moisture penetrate all barrier foils. The permeability of a certain foil depends on the material used and on the loss of quality when applied in the production process. In some foils a very thin metallic film (in earlier years usually made of aluminium) is strengthened by reciprocal coating with a plastic foil.

In recent years metal-vaporized foils, to be used as cladding foils, were developed. In contrast to aluminium foils they form reduced cold bridges at the edges. It is easy to limit the gas pressure rises in the VIPs manufactured with metal-vaporized foils. However, there are no long-term studies but only aging experiments (va-Q-tec 2004).

Such foils or metal constructions possess outstanding barrier characteristics but due to their strong intrinsic conductivity they also have the disadvantage of a strong edge bypass. Such "edge effects" may lead to a substantial restriction of the insulating efficiency of a VIP.
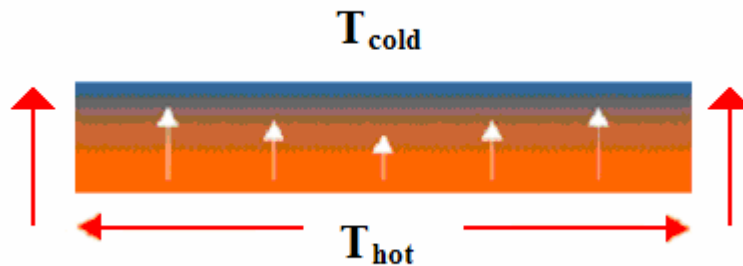

Figure 23: Thermal edge effect (Porextherm 2003)

The figure 24 shows the effective thermal conductivity as a function of the side length of the quadratic VIP for the case when the inner core has a thermal conductivity of 0.0036 W/(m K) Calculations have been performed for four different barrier material using typical thickness for the different layers. The 50 micron plastic exhibits negligible effects for all practical VIP sizes. However, for some VIP inserts/fillers which require extreme vacuum levels, plastic only barrier materials offer inadequate barrier performance. Using a relatively large amount of aluminium metallization on the plastic, edge effects still disappear for panels larger than 150 mm on a side. Depending upon the desired VIP lifetime, the critical pressure of the VIP filler material and the number and type of metallization layers, metallized films may not provide sufficient barrier performance. However, for VIP inserts which operate at higher pressure levels, relatively inexpensive metallized barriers offer more than adequate VIP lifetimes. If better barrier performance is required for materials which must be maintained below several mbar for the lifetime of the panel, foils are used. The thinnest available foil-based barrier has a foil thickness of approximately 7.5 microns. As shown in the fig. 13, for a 300 x 300 x 25 mm³ VIP using that type of barrier, the effective performance only would be 1/3 of that if there were no edge effects. For a 500 x 500 x 25 mm³ VIP, the performance would only be 1/2 of the performance with no edge effects.

Due to the high cost of producing these very thin aluminium foil based laminates with a minimum of pinholes, thicker foils can be used which are actually cheaper. 25 microns is typically taken as the thinnest foil which has no pinholes. However, as shown below, the edge effects associated with these thicker barriers practically preclude their use. Based on these results, it is clear that unless the panels being used are extremely large, the thermal performance of VIP's can only offer dramatic improvement over conventional insulation in the end-use application if the plastic or metallized plastic barriers are used. The quantitative results would be slightly different for different boundary conditions or for VIP insert materials with different intrinsic thermal conductivity. However, the same general trends would be observed. Therefore, when selecting a VIP insert material and the barrier material, it is important to balance the effects of the barrier on thermal performance, on VIP lifetime, and on overall cost of the VIP. (Porextherm 2003)
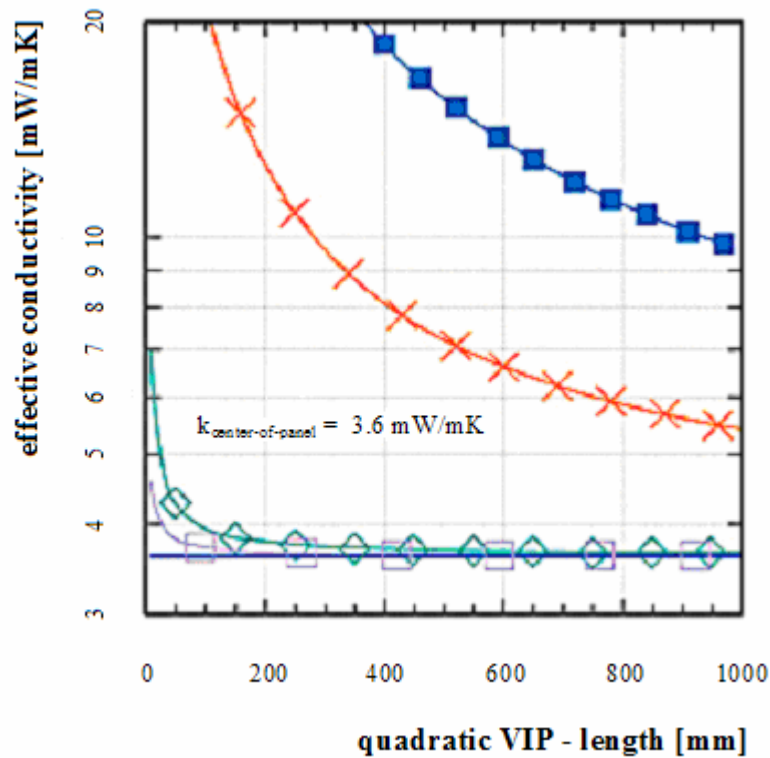
Figure 24: Modelling of thermal edge effect, quadrate with thickness of 25 mm (Porextherm 2003)

In order to avoid these edge effects, metallized sandwich foils are used, which exhibit a very high barrier effect and at the same time a very small thermal conductivity. For producing a cover for the core material the barrier foils are welded at the edges. On its inside a thin layer of very low-temperature plastic is applied, so that they can be sealed with the help of heat and pressure. Such layers of heat-sealingable plastic are more permeable to gas and humidity than the rest of the foil. In order to limit the negative effect of the permeability of the sealing layer to a minimum, a film as thin as possible (30 - 70 mm LDPE) is used in the production process. A seal seam width between 8 -15 mm procures the optimum firmness and tightness of the seal seam (particular for products of the company Porextherm).

The inexpensive aluminium sandwich foil (PE // 6-10 μm aluminium // PET) or metallized high barrier foil is often used as a casing. The high barrier foil is a plastic composite which is vaporized thinly with aluminium. At its impact edges there is a substantial reduction of the cold bridges – when compared to aluminium sandwich foil. That means that a two-layered VIP transfer displaced against each other is not necessary. (BINE 2001)

Aluminium improves the gas density of plastic foils. But nevertheless a slight amount of air and water vapour always diffuses into the panel even though the high barrier foil may be intact. That means that an annual increase of pressure of up to 1-2 mbar (100-200 Pa) is to be expected.

The area of application for these high barrier foils is usually (also due to the high plastic portion) limited to very low-temperature to standard temperature purposes. The diffusion resistances are partly exponentially reduced at further increasing temperature. (Heinemann 2004).

The standard foil contains in 2004 round about 4 up to 8 different layers.

Only casings made of certain metals, high-grade steel and glass guarantee a long-term good diffusion resistance.
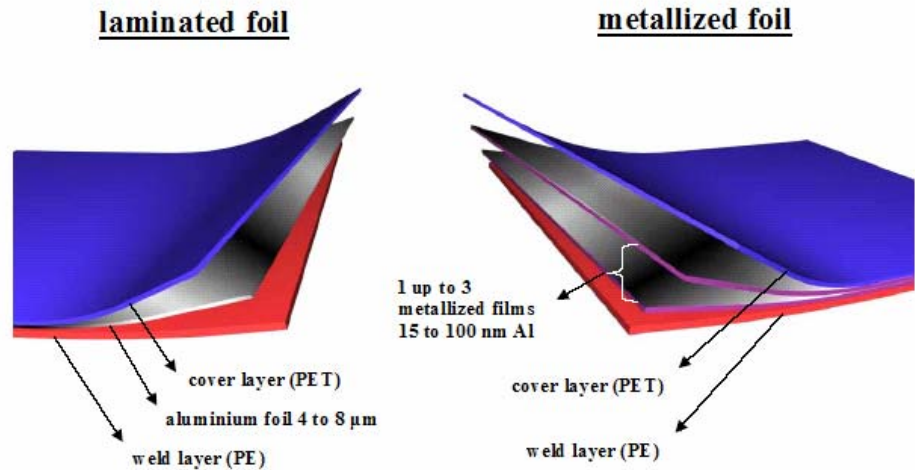
Figure 25: Multi-layer types in European market (Reto Bundi VIA Symposium 2003)

Getter materials and drying agents

Getters are chemicals which absorb gases. Drying agents (desiccants) are chemicals which absorb moisture. Getters and drying agents are supposed to extend the life span of the VIP by absorption of gas molecules and moisture, both of which promote the heat transfer in the evacuated area. They are only effective if they are carefully co-ordinated with the kind and quantity of the gas molecules/moisture which are to be absorbed. They must be able to effectively absorb and bind gases, also in the situation of low pressures in the vacuum insulation panels. For this reason the following conditions must be considered when choosing the quality and the sort of getter materials and drying agents- the used core material, the respective barrier foil and the necessary life span. The core material in vacuum insulation panels on foam basis has no absorptive capacity. Therefore getters and drying agents must be brought additionally into the casing. Silica acid represents a natural desiccant. If silica acids are used as core material, getters are not necessary also for a longer life span (10 - 20 years), if suitable barrier foils are used. (Porextherm 2003)

The getter materials can be chemically „adapted "and/or within certain framework „designed" They can be selected for special applications. Naturally, this can take place only within a small framework, but with good product tuning and good basic conditions (core material, barriers, atoms and molecules to be caught) the product can be improved. (Celik 2004)

Degassing

Most materials give off gas under the influence of low pressures (degassing). The kind and quantity of the gases which are set free, as well as duration of the degassing, are different from material to material. The gases which are set free may contribute substantially to an increase of the internal pressure of the VIP (thus to an attenuation of the vacuum). The quantity of gas set free by the core material and the membrane in some cases is higher than the quantity of gas which penetrates into the VIP through the membrane. The effects of this procedure on the life span of the VIP are dependent on the core and barrier materials used by the manufacturing firm. (Porextherm 2003).

Size and thickness

Gas molecules may penetrate through the barrier foil and the sealing material, which interconnects the individual film layers. The larger the VIP is the larger the relationship "foil-surface to welded surface". The smaller the VIP, the larger the relationship "welded surface/foil surface". When choosing a barrier material you have to make sure that both the foil for blocking out and the sealing are suitable for the kind and size of the VIP concerned.

The thickness of the VIP has a much larger influence on its efficiency. With half thickness also its life span halves itself, because the foil surface and the welded surface remain nearly alike, while the isolating volume is only half as large. Thus the gas pressure doubles itself because of the

smaller volume, although there is nearly no change in the permeability of the sealing and the foil. (Porextherm 2003)

Cold bridge problem
A project of the IEA dating from the year approx. 2000 concerns itself with the problem of disk joints, internal insulation at heat insulation systems at construction sites.

Application conditions
The application conditions play an important role for the usefulness and life span of vacuum insulation panels. By usefulness the suitability of the panel for a certain operational field is to be understood.

Foams are plastics and therefore find a use only in a limited temperature range. Outside this range it can come to decrease and deformations, so that the panels become practically useless. The upper temperature limit for e.g. polystyrene foams amounts to 88°C (190°F) (depending upon interpretation 60-100°C). Therefore such materials cannot be considered being used by hot water producers, for devices distributing hot food or for the direct contact with district heating medium pipes. Core materials can be used with suitable check foils (e.g. high-grade steel foils) for temperatures up to 950°C.

The life span of vacuum insulation panels is affected by the respective operating conditions because the permeability to water vapour and gases of the check foil and the sealing is temperature-dependent Higher temperatures promote the penetration of water vapour and gases, while low temperatures slow permeation through the foil. Furthermore the concentration of a gas in the VIP rises proportionally to the concentration of gas in the surroundings of the panel. Thus the effect of the gas on the heat transfer also increases. As a general rule- the smaller the gas molecule, the more rapidly it penetrates the panel and the larger its influence on their heat conductivity.

If a vacuum insulation panels is foamed with polyurethane-foam- the usual method at present in the field of household coolers- then the life span of the VIPs is extended because of the fact that only large volume gas molecules of the propellant surround the panel and that it is very difficult for them, due to their size, to penetrate the casing. If a molecule of this size should have penetrated nevertheless into the panel, an energy transfer through such molecules is clearly smaller in a micro-porous system, since the size of the pores is much smaller in the micro-porous system than the average free path length. That means that such molecules are restricted in their freedom of movement and thus it is nearly impossible for them to transfer any energy.

Water vapour, in contrast, behaves totally different. The larger the humidity in the surroundings of the panel, the more humidity penetrates the VIP. Due to the high absorptive power of the core material for humidity (gettering action) the penetrating humidity is absorbed (bind) by the micro-porous core material until a balance has been created. Thanks to the high gettering action of the core material the humidity that has penetrated does not cause an increase in pressure in the panels, provided it is no more than 7 % of weight (Porextherm 2003)

Operational areas
When buildings are renovated, the vacuum insulation panels achieve a high insulation and small insulation strength at the same time. Thus e.g. deep window frames can be avoided. It is very difficult to thermally insulate many old buildings with conventional materials, in particular old buildings next to public sidewalks.

Flat roofs, where substantial adjustment work on the roof end would be necessary are a further example, as well as roof terraces with a window front reaching to the floor and door entrances on almost same height. Yet another example is protected houses with interior insulation where the loss of space is to be minimized. (Bine 2001)

VIPs are also a recognized technical procedure when it comes to temperature-controlled transportation packing as well as trade- and household refrigerators. VIPs, however, are suitable for all applications, where the aim is volume gain, better temperature control, much longer dispatch times, decrease of the freight volume and dispatch weight or where an increase of the energetic efficiency is being sought. Vacuum insulation panels are available in different forms

(flat, curved, round) and thus a large flexibility is possible when it comes to the design of the product. But they usually represent no ready-made solution anyway, so that certain changes in the system may be necessary in order to obtain a maximum effect. (Porextherm 2003)

Figure 26: Installation of vacuum panels in the southern facade of the new ZAE building.

System integration
In principle VIPs can be produced in any form and size. But if the variety is limited to a few standard sizes, the costs can be lowered crucially. At geometrically irregular wall zones, cutable conventional EPS panels can be used, small cold bridges are thereby tolerated.

For internal insulation, VIPs can be fastened to the wall by means of sticking mortar or a rail system. Only the joints must be sealed with a vapour barrier tape before the finery panels are applied. Since a house front can be exposed to large wind suction forces, the more stable rail system, possibly into combination with gluing, should be used at the external insulation. Since up to now only a few VIP insulation systems have been scientifically examined regarding their practice fitness, permission and/or building recommendations are still pending. Of course VIPs may not be drilled. In order to secure unlimited use of the inner walls it is necessary to put a construction with plasterboard and stators in front of the vacuum insulating layer. These constructions are from 2 to 5 cm thick. In order to avoid panel destruction at the construction site foam material should be used as protection coating. When VIPs are put into prefabricated elements such as door leaves and roller-shutter cabinets, no special protection is necessary. (BINE 2001)

Mechanically loadable vacuum insulation systems
In order to be able to carry also heavy goods in vacuum-dammed containers, the insulating core must be protected against a large compressive load in case of point pressure. In order to ensure stability, high-grade steel sheet metals are used for the casing of the insulating core. Since this material is much more insensitive to damage and since it is very gas-tight when compared to foil coverings, not only silica acid insulating cores are being used but also more inexpensive, lighter foam materials.

The structure of a mechanically loadable VIP is to be presented with the basis of the floor of a refrigerating chamber as an example- it consists e.g. of a high-grade steel base plate (0.8 mm) and of a „watered "high-grade steel cover plate (3mm). Floor and cover plate are separated by a 30 mm supporting core. In order to reduce cold bridges, the two panels are welded with one another at their edges by means of a very thin profile frames made of high-grade steel (0.3 mm). In a load

test, which took several months, a four-wheeled car, weighing 1.200 kg, (point loading 300 kg) was driving over this metal sheet without causing any damage.

Many users are not only interested in the simple installation (e.g. in refrigerating chambers), optimized utilizable volumes and the external dimensions of containers (e.g. in cooling vehicles). When it comes to the transport of food, pharmaceuticals and medical-biotechnological products, product security, to be ensured by hygiene and stable temperatures, has highest priority, regardless of the higher costs for the mechanically loadable vacuum insulation systems. Thus the temperature of a test substance, when put into a vacuum-dammed transportation box (utilizable volume 15 l) and when 4 kg of dry ice is added, could be held at - 20°C for the period of 140 hours.(BINE 2001).

Costs of vacuum insulation systems
The price per square meter for foil-coated vacuum insulation panels- dependent on material, size and number of items – was between 25, - up to 100, - euro in the year 2001. In many cases vacuum insulation becomes already economical at this point, in particular when considering the saving in heating energy and dwelling gain and/or avoided property costs, which can reach some thousand euro in densely populated areas.

The cost for industrially manufactured SWD panels are around 250, - Euro per square meter. They could be a real alternative to tra The price per square meter for foil-coated vacuum insulation panels- dependent on material, size and number of items – was between 25, - up to 100, - euro in the year 2001. In many cases vacuum insulation becomes already economical at this point, in particular when considering the saving in heating energy and dwelling gain and/or avoided property costs, which can reach some thousand euro in densely populated areas.

The cost for industrially manufactured SWD panels are around 250, - Euro per square meter. They could be a real alternative to transparent thermally insulated fronts, particularly since they need a weatherproof mechanical sun protection. (BINE 2001)

Outlook
If the outer hull of a silica acid insulation plate is damaged and thus ventilated, then it still insulates clearly better than mineral wool or polystyrene insulation panels. Because compared to other materials their heat conductivity rises only very slowly with increasing internal pressure; only at 100 mbar (10^4 Pa) it doubles itself (S. fig. 11).

Moreover, micro-porous silica acid is not subject to a noticeable material aging, has few requirements as to the necessary evacuating pressure (fig. 11) and is heatproof. Due to a desired life span as long as possible, VIP insulating cores made of silica acid material are the ones which are usually used in construction, particularly since the weight is not crucial here. (BINE 2001)

Refrigerators
In particular in the field of refrigerators there has been a tendency towards an optimization of the utilizable volume in the past years. On the part of the federations in Germany there existed and still exist the regulations to achieve an improved insulation of 10-15%. This way the energy efficiency classes can be kept. Japan deserves special mentioning-there vacuum engineering in the field of refrigerators has already found a substantially stronger application than in other countries. 2 million refrigerators with vacuum insulating technology are sold there per year.

Vacuum-superinsulated district heating pipes (VSI)
At the beginning of the 90's a so-called VSI was applied in the BEWAG in Berlin.

In this practical research project stainless pipes were used for the medium pipe and for the external pipe. A product of the "Wacker-Chemie Company" (WDS) was used as a vacuum insulation. This insulation consists of a reddish powder, which was welded into aluminium foil and then crisp up on the internal pipes in a thin layer. This material reaches its main efficiency with very low pressures of approx. 0.1 mbar (10 Pa). It is, however, very difficult to reach this vacuum. The used material in the aluminium packings at that time could be produced up to the format 40 x 30 cm or similar and it was possible to create some elementary other forms. That meant that also the medium pipes could be encased with this material. (Dräger 2004)

In the long term test the fitting failed at some pipes. The damage analysis showed that a constructional revision of the pipe was necessary. Despite this, there are efforts trying to make the project a success. (PTJ-annual report 1996)

Superconductor technology – outlook
Currently the electrical company "Siemens" is building a 4-MW-system, which is supposed to serve as a power pack and to guarantee the power supply on board a ship. These power packs use High Temperature Superconductor Systems (HTS) and are on their way to be marketed. HTS work with so- called „warm "superconductors, which already show a superconducting effect starting from 35 °K. Liquid neon or liquid nitrogen are used as cooling agents. The advantage over conventional copper cables- the electrical resistance is void and the current density is higher up to 50 times higher. This kind of technology has only been made possible by the use of vacuum-dammed systems. This application would not have been conceivable some years ago. Constant development and improvement of the components of the system finally lead to the development of new systems. (VDI-nachrichten 2004)

High temperature vacuum insulations
These have existed for some years. Their uses are e.g. in the field of automobile manufacturing (protection of catalysts, turbochargers) and engine technology. This is where metal-coated carrier material with several reflecting foils is developed.

Vacuum technology

First experiences with vacuum were made at the beginning of 17.century. The attempts were first steps in an unknown area and only moderate final impressions were reached. Nevertheless Otto von Guericke could point with its hemisphere attempt in Magdeburg 1657, to which among other things vacuum is able.

Only in the middle of 19.century a progress was obtained by the avoidance of a harmful area in the pump. The break-through finally succeeded with the development of the vane-type pump, at the beginning of 20. century, which is to be regarded as forerunners of the rotation vacuum pumps used today.

The vacuum technology is not to be excluded in our daily life anymore. Within all ranges technologies come across, which take up and use the advantages of the vacuum technology. That does not only concern the industry and research, but also the private households, which profit from the advantages of the vacuum technology. Begin by the thermal can over lamps, over the tube of the television up to the foil-welded fresh meat from the deep-freezer.

Pressure ranges
In the vacuum technology it is usual to divide the large pressure range as follows:

Pressure ranges	Flow	Recommended vacuum pump	Example of use
rough vacuum (1013 mbar - 1 mbar $= 10^5$-100 Pa)	Viscose or continuum flow: laminar and turbulent	multi-vane pumps water ring pumps	drying process, distillation, steel degassing
rough- und Highvacuum (1 mbar - 10^{-3} mbar $= 100$-0.1 Pa)	Transition laminar-molecularly (Knudsen flow)	oil-sealed vacuum pumps roots pumps vapor-jet vacuum pumps	molecular distillation, freezing drying process, impregnating, bloom and casting furnaces, arcs furnace vacuum generation
high vacuum (10^{-3} mbar - 10^{-7} bar $= 0.1$-10^{-5} Pa)	molecular range (Molekylert flow)	diffusion pumps multi-stage roots pumps	evaporate, crystal pulling, mass spectrometers, tube production, electron microscopy, electron beam plants, particle accelerators
high- and ultrahigh vacuum ($< 10^{-7}$ mbar $= < 10^{-5}$ Pa)	molecular range (Molekylert flow)	turbomolecular pumpsion sputter pumps cryopumps	nuclear fusion, memory rings with accelerators, surface physics, space research

Table 22: Organization vacuum pumps recommended by vacuum and (Wutz et al 1997) as well as sample applications (Leybold 03/04)

Pump types
For the vacuum insulation pressure in the ranges from fine to high vacuum are mostly produced. A higher vacuum would not be appropriate, because it is economically not portable according to experience.

The positive displacement pumps are the most important pumps in the vacuum technology. The simplest positive displacement pumps are the oscillating displacement pumps, which play only a subordinated role today. Nowadays in most vacuum plants rotation or rotary vane pumps are used, which can produce everything from rough to medium-high vacuum range.

The simplest positive displacement pump is the piston pump like von Guericke has introduced. With each stroke the volume of the enclosed gas increased and accordingly the pressure becomes smaller after the law of Boyle and Mariotte.

Also rotary pumps function like this. These pumps possess corrugated drawing and densely populated areas, which are sealed against each other. Every time in use the corrugated drawing area in the recurring sequence of functions forms is outgoing from the volume zero again. Because thus no harmful volume is present, (supported by the oil seal as well as by the oil overlay of the exhaust valve) a high suction property far into the medium-high vacuum range area is reached. (Wutz et al 1997)

Rotary vane pumps are used everywhere, where a pressure range must be surely achieved from some mbar to 10^{-3} mbar (some 100 to 0.1 Pa). In almost all cases the variety of the available models makes an appropriate and economic choice for the optimal vacuum pump possible. Rotary vane pumps are single- or two-step oil-sealed pumps with integrated oil pump and gas ballast for high steam compatibility. The particularly powerful and compact rotary vane pumps are suitable for a far area of application in laboratory and concern with their flexible accessories. (VAK 2003).

Rotary vane pumps
Rotary vane pumps consist of a cylindrical housing (pumping ring) in which an eccentrically suspended and slotted rotor turns in the direction of the arrow. The rotor has vanes which are forced outwards usually by centrifugal force but also by springs so that the vanes slide inside the housing. Gas entering through the intake is pushed along by the vanes and is finally ejected from the pump by the oil sealed exhaust valve.
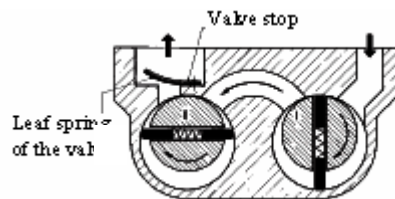
II: Second fore vacuum stage   I: High vacuum stage

Figure 27: Cross section of two-stage rotary vane pump, schematic

The oil reservoir of the rotary vane pump and also that of the other oil sealed displacement pumps serves the purpose of lubrication and sealing, and also to fill dead spaces and slots. It removes the heat of gas compression, i.e. for cooling purposes. The oil provides a seal between rotor and pump ring. These parts are "almost" in contact along a straight line (cylinder jacket line). In order to increase the oil sealed surface area a so-called sealing passage is integrated into the pumping ring. This provides a better seal and allows a higher compression ratio or a lower ultimate pressure.

With the two-stage oil sealed pumps it is possible to attain lower operating and ultimate pressures compared to the corresponding single-stage pumps. The reason for this is that in the case of single-stage pumps, oil is unavoidably in contact with the atmosphere outside, from where gas is taken up which partially escapes to the vacuum side thereby restricting the attainable ultimate pressure. In the oil sealed two-stage displacement pumps, oil which has already been degassed is supplied to the stage on the side of the vacuum. The ultimate pressure lies almost in the high vacuum range, the lowest operating pressures lie in the range between medium vacuum / high vacuum.

Pumping process
Generally, the pumping operation for these processes can be divided into two categories – dry- and wet – vacuum procedures, that is, into processes in which no significant amounts of vapour have to be pumped and those in which vapours (mostly water or organic) arise. Distinctions between the two categories are described briefly:

Dry processes work primarily in a narrow and limited pressure region. The system is usually evacuated to a suitable characteristic pressure before the actual working process begins. This happens, for example, in plants for evaporative coating, electron-beam welding, and crystal pulling; in particle accelerators, mass spectrometers, electron microscopes.

Further, there are dry processes in which degassing in vacuum is the actual technical process. These include work in induction- and arc furnaces, steel degassing plants, and plants for the manufacture of pure metals and electron tubes.

Wet processes are undertaken primarily in a prescribed working operation that covers a wider pressure region. This is especially important in the drying of solid materials. If, for instance, work is undertaken prematurely at too low a pressure, the outer surfaces dry out too quickly. As a result, the thermal contact to the moisture to be evaporated is impaired and the drying time is considerably increased.

Pumping of gases

Rough vacuum ($1013 – 1$ mbar $= 10^5$-100 Pa)
The usual working region of the rotary pumps lies below 80 mbar (8000 Pa). At higher pressures these pumps have a very high power consumption and a high oil consumption. Therefore, if gases are to be pumped above 80 mbar over long periods, one should use, particularly on economic grounds, jet pumps, water ring pumps or dry running, multi-vane pumps.

Rotary vane and rotary piston pumps are especially suitable for pumping down vessels from atmospheric pressure to pressures below 80 mbar, so that they can work continuously at low pressures. If large quantities of gas arise at inlet pressures below 40 mbar (4000 Pa), the connection in series of a Roots pump is recommended. Then, for the backing pump speed required for the process concerned, a much smaller rotary vane or piston pump can be used.

Medium vacuum ($1 – 10^{-3}$ mbar $= 100$-0.1 Pa)
If a vacuum vessel is merely to be evacuated to pressures in the medium vacuum region, perhaps to that of the required backing pressure for diffusion or sputtering pumps, single- and two-stage rotary pumps are adequate for pressures down to 10^{-1} and 10^{-3} mbar (10 Pa and 0.1 Pa), respectively. It is essentially more difficult to select the suitable type of pump if medium vacuum processes are concerned in which gases or vapours are evolved continuously and must be pumped away. An important hint may be given at this point. Close to the attainable ultimate pressure, the pumping speed of all rotary pumps falls off rapidly. Therefore, the lowest limit for the normal working pressure region of these pumps should be that at which the pumping speed still amounts to about 50 % of the nominal pumping speed.

Practical experiences
For the evacuation of steel jacket pipelines single-step rotary vane pumps are usually used. These have suction powers of e.g. 100 m³/h. The employment is possible for the stationary and the mobile employment with the same pump type. The durability, i.e. life span and assignment essentially depend on regular maintenance and the actually reached running times of the pump. Such a pump should run for e.g. 10-15 min. every week, in order to remove appropriate condensates from the oil of the pump.

For the evacuation of panels 2-step rotary vane pumps are usually used. Here e.g. a volume of 16 m³/h could be sufficient. Particularly with the evacuation of VIP's the aspects guarantee and leakage detection are important. Also acceptable pumping times must be achieved for the production process. Because the panels are produced in numbers of items, fast evacuating is necessary here. In contrast to this a long pumping process is less of importance by a steel jacket pipeline with very few ranges which can be evacuated. Usually there it is necessary to evacuate for days or weeks.

The production of a vacuum < 0.1 mbar (10 Pa) in panels is a fundamental problem. It is to be noted that, every material in particular materials with a porous or micro-porous structure also exhibit appropriate resistance values when evacuating. These resistance values against evacuating can be very high. Accordingly large beginning to cut surfaces must be present, from which the material can degas and deliver volatile atoms respectively. Success further depends on long pumping times.

Beyond that many manufacturer data to vacuum pressures in the product are to be regarded with caution. Like that it is of great importance, on which place the vacuum is measured. Measuring directly behind the pump, following resistances against evacuating are not considered then. Therefore a panel - over the entire range of its body measured – can exhibit very different vacuum values. However the problem is that one cannot measure on all points, without destroying the vacuum.

Making clear by an example, that it is difficult to produce a vacuum from 1 mbar (100 Pa): Evacuating of a commercial gas bottle (for oxygen or nitrogen) to a value of e.g. 0.1 mbar (10 Pa) is actually possible at very much expenditure only. Even in such a container, in which no obstructive resistances (porous materials) for the current exist, the vacuum only can be attained under expenditure. Thereby a completely special role plays the cross section of sucking in. But how does the vacuum within the bottle in comparison to the measuring range at the neck of the bottle really look?

Any internals in a vacuum permit in the gas or fluid contained molecules to hold on. Crucially for the evacuation is the attainable difference of pressure between pump and all body places to evacuate. Thereby stream resistances increase significantly with increasing material density and distance. The stream conditions are to be considered. Thus laminar-arranged streams are trained by differences of pressure up to approx. 5, 4 or 3 mbar (500, 400 or 300 Pa), if necessary also up to 1 mbar. These laminar-arranged streams permit a good evacuation effect. On change of the current, i.e. the transition to a difference of pressure up to 10^{-3} mbar (0.1 Pa), partially one has only a laminar-arranged stream and a molecular range to be present. This transient area is already substantially more difficult to evacuate. Below 10^{-3} mbar mentioned difference of pressure a purely molecular range is present. Evacuating within this range corresponds to one "catching the molecules" according to the search of space deaf in the universe.

Further it is to be noted that in particular plastics of any kind are inclined to out gassings and/or after gassings. An expert of a pump manufacturer proceeds from a real attainable vacuum with approx. 5-10 mbar (500-1000 Pa) by internals in panels. Measuring in the panel centre would result more real values than thus with measuring close to the pump, before the actual valve or at the surface before welding. Our expert thinks reaching a vacuum of less than 1 mbar is possible, but with relatively much expenditure of time (approx. 1 day). Therefore a value of 0.7-0.8 mbar (70-80 Pa) might represent the border.

A further example is mentioned: When evacuating tank isolations there are substantial differences regarding the attainable vacuum between the front and rear ranges of the isolation. Appropriate thermo technical examinations via thermal image camera confirm this.

Evacuating from porous ingredients like plastics and micro-porous silicates can only function within the range of few centimetres in the material. In principle a manufacturer should submit corresponding measurements for the proof. The theoretical computations do not show the technical gaps and changes of the theoretically ideal beginning, but should also point out the errors and the practical circumstances of production. Further appropriate panels possess different ingredients, which can hold on to molecules in various way or still fumigate and/or out-steam (water vapour). Here it gives many unknown quantity, which often finds no consideration in the theoretical view.

Actually there is no real replacement for the 2-step rotary vane pumps. Even with the employment of a single- step pump only a small amount would be saved of approximately 1000, - €, but the necessary vacuum would not be achieved.

A great help and support of the evacuation procedure is the fundamental warming up of the manor which can be evacuated. Thus the still existing molecules are activated and if necessary transferred more easily to the environment. As it were the molecules are made „legs". Naturally with heating up the limit temperatures must be considered e.g. for the further processing. In principle plastics as well as injected fibres and similar materials dispose of a very large surface, to which more molecules or other volatile components can hold on.

The pump manufacturer considers data of vacuum conditions around 0.1 mbar (10 Pa) to be very precarious. In principle it would be favourable in application and/or in the view to proceed from an ingredient with usually small heat conductance. With additional evacuation, e.g. under the range of 10 mbar the thermal resistance will surely increase and/or the heat conductivity will

reduce. From this view a practically feasible and/or realizable evacuation over years to a value below only 50 mbar (5000 Pa) is realistic.

In contrast to this the steel jacket pipeline still stands, in which the realization of a vacuum of 1-3 mbar (100-300 Pa) is practicable. This particularly applies under the aspect that the factor time has no or only a small influence here because it can be evacuated durably and over large periods before the employment.

The following may be used as a rule of thumb for dimensioning vacuum lines: The lines should be as short and as wide as possible. They must exhibit at least the same cross-section as the intake port at the pump. If particular circumstances prevent shortening the suction line, then it is advisable, whenever this is justifiable from the engineering and economic points of view, to include a roots pump in the suction line. This then acts as a gas entrainment pump which reduces line impedance.

Unobstructed stream when evacuating:

- Laminar stream
- Short lanes of evacuating
- Fundamental very small heat conductance already with ventilated material (also without evacuation of the material)
- Warm up the material when evacuating
- Optimal proves enveloping of the material with high-grade steel

The aspect of the amortization should not be neglected. So it must be noted that the additional expenditure for production finally should be amortized within a realistic time. Savings are to be confronted to the additional capital outlays.

- Unobstructed stream when evacuating - Laminar stream - Short lanes of evacuating - Fundamental very small heat conductance already with ventilated material (also without evacuation of the material) - Warm up the material when evacuating - Optimal proves enveloping of the material with high-grade steel - The aspect of the amortization should not be neglected. So it must be noted that the additional expenditure for production finally should be amortized within a realistic time. Savings are to be confronted to the additional capital outlays.

Table 23: Fundamental interpretation criteria for pump and vacuum insulation

District heating pipes - requirements

In Denmark, Finland, Sweden and in many other European countries, district heating is commonly used for household heating. "District heating" includes both the production and distribution of heat, either as hot water or steam. It involves components, such as production plants, distribution pipes, substations and in-house heating systems (radiator and hot water systems).

The history of district heating in Europe is some 100 years old, beginning with small local systems supplying heat for a limited group of buildings in Germany. In the post-war period, large-scale housing programs were built in many of the European countries, which provided means for district heating as an option for heat supply. Especially in the Eastern European countries, district heating became extensively used. In the OS, systems for the distribution of steam were built as early as the end of the 19th century. The use of district heating as a heat source, however, has not become large. Like in some other parts of the world, e.g. in Asia, systems for district cooling have become almost as big as the share of district heating.

In Europe, today, approximately 56 million people are supported by district heating. In Iceland, where the geothermal sources are used, district heating is the absolutely dominating heat source and Denmark is the second most district heating dense country here. (Olsson 2001)

The heat carrier in the European district heating network is water, with a few exceptions for steam. The heated water is distributed in a pipe system, which contains supply and return pipes for the distribution to consumers and back to the heating plant. The district heating pipes are usually buried in the ground. At each building (or group of buildings) there is a heat exchanger, which separates the district heating water from the internal heating system of the building(s), see fig. 17.
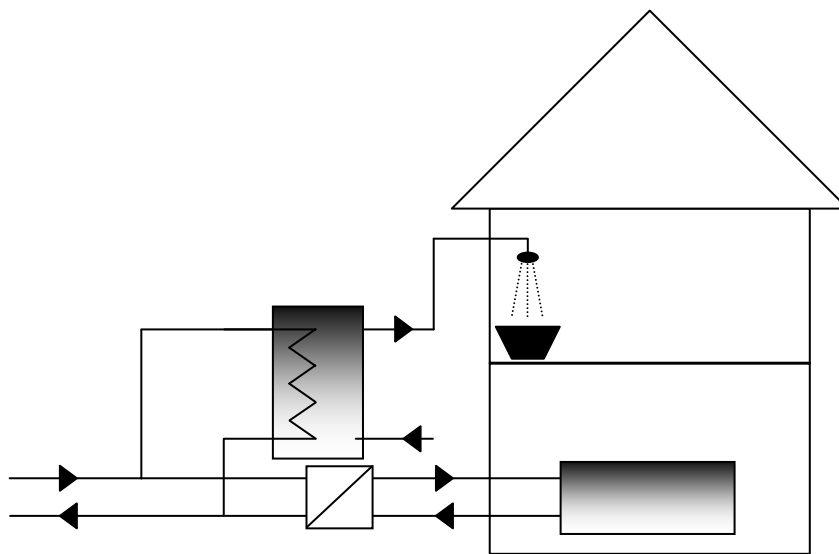
Figure 26: District heating system and internal heating system of the building

Denmark	23,000 km
Germany	18,500 km
Poland	16,000 km
Sweden	11,000 km
Finland	8,000 km
Belarus	5,000 km

Table 24: Total route length of district heating systems in 1998 in some European countries (Euroheat & Power 2001)

Pre insulated pipe systems

Pre insulated bonded pipe systems are today by far the most commonly used system both for new district heating and cooling systems and for the renovation of existing systems.

Since the first pre insulated pipes for district heating were laid in the 1960s the pipes have gone through continuous development. Today the pre insulated bonded pipes and components, as described in European standards EN 253, 448, 488 and 489, make up a complete system for the cost-effective distribution of hot water for district heating or chilled water for district cooling.

The share of the market of pre insulated pipes amounts to 80...90 %.

Pipes and components are described in the so-called product standards from CEN:

EN 253: Pre insulated bonded pipe systems for underground hot water networks – **Pipe assembly** of steel pipes, polyurethane thermal insulation and outer casing of high density polyethylene.

EN 448: Pre insulated bonded pipe systems for underground hot water networks – **Fittings assemblies** of steel service pipes, polyurethane thermal insulation and outer casing of high density polyethylene.

EN 488: Pre insulated bonded pipe systems for underground hot water networks – Steel valve **assembly** for steel service pipes, polyurethane thermal insulation and outer casing of high density polyethylene.

EN 489: Pre insulated bonded pipe systems for underground hot water networks – **Joint assembly** for steel pipes, polyurethane thermal insulation and outer casing of high density polyethylene.

Scope

A pre insulated bonded pipe for district heating is a sandwich construction consisting of a service pipe of mild steel, an insulation of polyurethane foam (referred to as PUR) and an outer casing of high density polyethylene (referred to as PE, HDPE or PEH).

Due to the bond between steel/PUR and PUR/PE, the pipe function as one integrated assembly and, understanding how pre insulated pipes work, is therefore basically to understand as the interaction between the pipe assembly and the soil.

PE casing

PUR foam

steal pipe
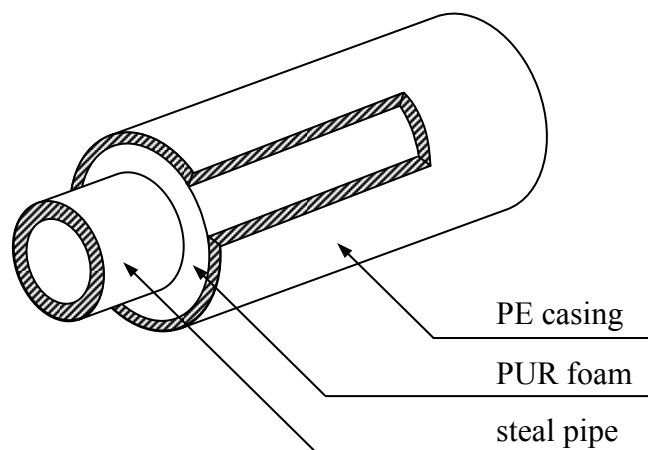
*Figure 28: Pre insulated bonded pipe (**Randløv 1997**)*

The bond between the PUR insulation and the steel pipe and the PE casing respectively is crucial for the function of the pipe system, these properties are especially discussed in the product standards. Sufficient bond – or shear strength – is assured during production among other things by cleaning the steel pipes through shot blasting and corona treatment of the inner surface of the PE casing.

Interaction with the soil
We are considering a bonded system, meaning that steel pipe, PUR insulation and PE casing are bonded together in a sandwich construction which acts as one whole.

When the steel pipe is subject to temperature variations - heating or cooling - the whole assembly will expand or contract.

Friction between the surrounding soil and the PE casing will counteract the movement thus reducing expansion. This means that movements in buried bonded pipe systems are smaller than movements in freely expanding pipes systems.

The forces from thermal extraction of medium pipe of buried bonded pipe systems have to be translated about insulation to the ground.

PUR
The most common pipe construction of today is the polyurethane-insulated steel pipe with a high-density polyethylene casing (fig. 30). This pipe construction has dominated the market for the last 20 years. However, several other pipe assemblies exist.

The media pipe can be made of steel, plastic or copper and the insulation is either made out of mineral wool (fibre material), polyurethane or PEX foam. In order to protect the insulation from water and to serve as a force-heating layer, a casing made of high-density polyethylene is the most common. Hot pipe assemblies with a steel casing do also exist and casings made out of asbestos cement were manufactured earlier and are still in use.

In same cases, a district heating pipe contains two (or in exceptional cases three or four) media pipes in the same assembly. The construction with several media pipes is used to simplify laying the pipes and may reduce heat losses. A more resource demanding construction constitutes concrete ducts. The pipes are placed onto supports within the duct and the duct itself forms the outer protecting layer. This is, however, less common today.

The temperature of the supply water is typically between 70 and 120°C and the returning water has a temperature of about 50 to 70°C. The soil temperature close to the pipes varies on the average between 10 and 30°C. Due to the temperature difference between the hot water and the soil, a heat transfer from the pipes to the ground is induced.

It is of fundamental interest to limit the temperature loss of the water on its way from the plant to the consumer in order to increase the capacity of the network and to bring economic means for running it. Reduced heat losses provide means for a stable supply of heat. The amount of effort exerted to minimise heat loss is, in the end, a balance between economic and environmental concerns.

The heat losses from a modern network are of the magnitude of 5 to 10 % of the supplied heat. In dense areas, the losses are less than 5 %, while in some residential areas, heat losses of more than 20 % have been observed (Werner 1982).

District heating pipes are produced for a technical lifetime of at least 30 years according to the European Standard EN 253. The insulation capacity will determine the heat losses during their time of operation. The more insulation, the better, however, the conditions for an extensive insulation thickness are considered limited for economic and practical reasons.

Polyurethane foam is a highly efficient insulating material. Besides the excellent thermal insulating capacity, it resists water penetration, has good mechanical properties and possesses good production properties, such as its flow pattern. This is the reason why polyurethane foam has become the prevailing thermal insulation of district heating pipes (Olsson 2001).

Polyurethane foam is manufactured by mixing two liquids, an isocyanates and a polyol. Added to the polyol is a blowing agent in liquid or dispersed phase. The foam formulation also contains water and other additives. The blowing agent expands due to an exothermic reaction between the isocyanates and the polyol and gas bubbles are formed, making the mixture rise. This process is known as "foaming". It is aided by a release of carbon dioxide, which is due to a chemical reaction between water and isocyanates. The ability of the mixture to adhere to surfaces and to fill out any cavities during foaming is characteristic.

If the gas pressure in the bubbles keeps below the strength of the contemporary solidifying polymer during foaming, the final foam structure will contain gas-filled closed cells, see fig. 31.
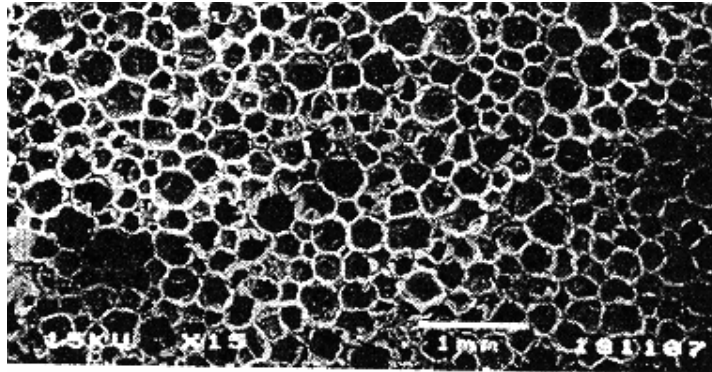

Figure 29: Cellular structure of a closed-cell rigid polyurethane foam

The foam "honeycomb" structure is characterised by a framework skeleton interconnected by thin membranes. Three elements of polymer can be differentiated; the thin membranes, which are termed windows; the thick intersections between the windows, which are termed struts and, finally, the even thicker strut joints. The cells are shaped as polyhedral and are often characterised as pentagonal dodecahedrons, more or less elongated due to the conditions during foaming, as summarised in Halyard and Cunningham, 1994. Adhesion to surfaces and the degree of over packing are factors that influence the elongation.

Cellular materials are generally well suited for thermal insulation. With less solid material, heat transfer due to conduction is minimised. Polyurethane foams normally have a porosity of 94-98 %, varying with density. Closed-cell rigid foams normally provide an even better means for low thermal conductivity. The closed cells encapsulate the low-conducting blowing agents, prevent heat transfer due to convection and reduce radiation, and due to its rigidity, the porous structure remains even though the material is subjected to mechanical loads.

The amount of closed cells in rigid polyurethane foam is around 90 %. At elevated temperatures, however, a rupture of the cellular structure occurs (see e.g. Brandreth and Ingersol, 1980, Dementyev et al., 1999), (Olsson 2001)

Using polyurethane foam for vacuum insulation, it has to be open celled (see chapter 2).

Mechanical requirement at insulating material for pre insulated bonded pipe systems
The thermal insulation shall comply with the requirements of EN 253 (here stand of 2000).

- Foam density: The density of the foam at any position shall be not less than 60 kg/m3 when measured in accordance with EN 253, 5.3.3. No specimen may have a density below 60 kg/m3.

- Compressive strength: The compressive strength or the compressive stress at 10 % relative deformation as defined in ISO 844 shall be not less than 0.3 Mpa in a radial direction when tested in accordance with EN 253, 5.3.4.

- General remarks: For normal applications, the pipe assembly should have a life of at least 30 years at a continuous operating temperature of 120 °C, at least 50 years at a continuous operating temperature of 115 °C and over 50 years at a continuous operating temperature below 115 °C.

Higher continuous operating temperatures can be stated. In this case, the calculated continuous operating temperature (CCOT) shall be established in accordance with annex C.

- Shear strength: The shear strength shall be tested in either the axial or tangential direction. The shear strength shall fulfil the minimum requirements of table 6 in both unaged and aged condition in accordance with 5.4.4.

Test temperature [°C]	Test clause	τax [Mpa]	Test clause	τtan [Mpa]
23 ± 2	5.4.2.1	0,12	5.4.3	0,20
140 ± 2	5.4.2.2	0,08	—	—

Table 25: Shear strength

Creep behaviour: The total radial displacement at 100 hours, ΔS100, and 1000 hours, ΔS1000, between the PE-casing and the service pipe measured along the force line shall be measured in accordance with EN 253, 5.4.7. A line drawn between ΔS100 and ΔS1000 shall be extrapolated to 30 years in a double logarithmic diagram, and may at that point not exceed 20 mm (see fig. F1, EN 253, Annex F). The radial displacement ΔS100 may not exceed 2.5 mm.

- Thermal conductivity for PUR: According to EN 253 the thermal conductivity shall be $\lambda \leq 0.033$ W/(mK). Test conditions are described in EN 253.

- Typically E-modulus for PUR (not in EN 253): For short term actions the elastic modulus can be evaluated at $E_{PUR} = 10$ N/mm². For long term actions $E_{PUR} = 6.5$ N/mm².

Advantages of the current manufacture technology of pre insulated bonded pipes
In comparison to many other district heating pipe work systems the production can happen faster and more economically. By intermittent manufacturing the two components, isocyanates and polyol, will be squirted into the space between the medium pipe and the jacket pipe. Within a few minutes the foam ascends, develops and strengthens. In this way several pipes with lengths up to 16 m can be manufactured at the same time. A high production rate is possible in this way.

In an intermittent process the foam is coated on the rotating medium pipe. The coat of PE-HD is up-extruded in the same way. The quality of these pipes is uniform.

Depending on the diameter and the flexibility, pipes up to 100 m and even more can be manufactured and rolled up. The manufacturing takes place via foaming into the partial opened jacket pipe, which is led underneath the medium pipe in the same speed as this. After filling in the foam, the jacket pipe will be closed and sealed to a pre insulated bonded pipe. The foam solidifies itself. After a cool down strain the system is rolled up. In this way it is possible to produce relatively large lengths of pre insulated bonded pipes.

The shifting and handling of pre insulated bonded pipes systems are well known. Appropriate standards and training courses are possible for all.

Steal jacket (bonded) pipe (steel-in-steel-pipe)
Just as pre insulated bonded pipes, steal jacket pipes must transfer the thermal expansions (forces resulting from the expanding of the centre pipe) to the environment. The system contains fixed and floating bearings (the heat losses are higher in these places) between the medium- and jacket pipe. The forces are delivered into sufficiently dimensioned bearings or diminished over stretch elbows. The employment is possible for very high medium temperatures up to 400°C (even 600°C).

Task of the vacuum is:

- prevention of the heat losses

- corrosion protection (drying of the interior and/or the insulation) in the ring interior between internal and outside steel tube and

- leakage monitoring.

After the laying steel-in-steel pipes should have a vacuum of less than 1 mbar (100 Pa). The maximum is 3 mbar (300 Pa). After completing the line it is necessary to carry out the leakage detection. In this way the errors of the line design can be detected and the quality guaranteed. The leakage rate is depending upon the examined volume (length of the line), this unit is indicated in "mbar x 1/s" (alternative 100 Pa/s or N/(m² s)). It is to be noted that the inserted heating insulations will degas or will emit of humidity. Individual leakages in the form of micro pores are possible.

The „tracing" of the vacuum is specified from a technical view. In this way it is conceivable to start the tracing of a new vacuum again up a total internal pressure of e.g. 10 mbar (1000 Pa). In addition there are 2 possibilities.

- First the application of a mobile vacuum pump is possible. With this pump also drying of the ring interior can be accomplished (e.g. after manufacturing, leakages or other).

- The second possibility is the application of a stationary vacuum pump in conjunction with an electronic system, that constantly measures the pressure in the ring interior and at a pressure of e.g. 3 mbar (300 Pa) automatically starts up the vacuum pump, until an adjusted pressure value is reached. Further a regular starting of the pumps (e.g. every 14 days) can be accomplished to protect the pump, to grease the bearings and to anticipate condensate of the engine oil.

The cost of a mobile pump inclusive condensate separator varies between a value of € 4.000 up to € 5.000. This pump would have a power rating close to 60 m³/h. On the other way a stationary pump, inclusive PC and data acquisition, will cost about € 20.000 (2004).

Two-step pump systems are generally used for evacuating. With them it is possible to receive pressures below 1 mbar (100 Pa). Principally it is possible to use 1-step pump systems, but they would work at their power limit

For the evacuating of a completely filled annular space (foam system), the employment of smaller pumps is necessary. Hereby it is to be noted that the resistance on the suction is significantly higher, because the SMR have to be evacuated over large distances and out off the cell fabrics.

Consequence: Only small limited ranges of pre insulated bonded pipes systems can be evacuated or little ring bodies. Only if they are durably evacuated, they will be applied.

Steel used in the processing for piping systems is not diffusion sealed against hydrogen (H_2). Particular during the practical processing (welding) special arrangements had to be carried out, in order to prevent the penetration of hydrogen. That is why generally, after welding, heat mats are dropped over the welded ranges up to 24 hours. In this way it is made possible for the penetrated H_2-molecules to step out the material (through the welding seams). The penetrated H_2-molecule can cause cracks in the material at a later time (cracks hydrogen-induced). The heat mats enable the hydrogen to diffuse out.

High grade steel pipes permit diffusion tightness.

Prospect: The steal jacket pipe offers in principle a high resistance against diffusion. It needs to evaluate if and how many hydrogen molecules can diffuse into the ring interior. And to evaluate if they will reach a critical increase of pressure (heat, explosion danger) and if a steadily or periodic post-evacuation is possible.

Flexible pipe systems
Flexible pipes show a large variety in the choice of materials and system design, and therefore no attempts have been made to standardise them before now. A working group under TC 107 has started to look at flexible pipes, and it is to be expected that they will propose a standard based on functional requirements.

Presently flexible pipes are produced with service pipes of
- thin-walled mild steel
- soft annealed copper
- cross-linked polyethylene (PEX) with oxygen restrainer
- polyuthylene
- aluminium and PEX.

The insulation is normally PUR and the casing PE (HDPE or LDPE).

The non-metal systems were made for the smaller dimensions (d ≤ 80 mm; house-connections). But dimensions up to 140 mm are on the market.

An advantage of flexible pipes is that, for example, a house connection can easily be made without much preliminary planning, since obstacles can be bypassed by bending the pipes. Installation is easy because problems with expansion are reduced, and house connections can be made without any intermediate joints.

For systems where plastic is used for service pipe there is a lower limit for temperature (< 80°C operating temperature), pressure and flow speed. For systems with copper there is a limit for flow speed. (Randløv 1997)

By flexible tubing systems is it necessary to make a further distinction. A large part of these systems are constructed in composites, i.e. in non-positive and positive fittings composites constructions between medium pipe and insulation up to the jacket pipe. In addition there exist systems, which show neither non-positive nor positive fittings, but they are nevertheless flexible. The insulation consists of patented polyurethane rigid foam bodies, which are interlocked as insulation. Or they consist of rolled up (in longitudinal direction) and included insulation stripes of polyethylene foam.

Thus it is possible to build flexible PUR insulation systems pipes by lining up single bodies.

Prospect 1: In a certain way flexible tubing systems are able to compensate automatically (inner) forces (regarding their expansion behaviour), therefore an application in the vacuum engineering, e.g. in the form of many, individual vacuum torus (ring bodies), would be favourable.

Prospect 2: The existing example of individual polystyrene rigid foam bodies in row shows that heat insulation is conceivable as flexible pipe with vacuum insulated single bodies.

Discussion

Technical barriers for production of well working systems

Characteristics of current PUR foam especially made for vacuum application
Normally the production of PUR foam is simple and economical. For the special application of PUR foam as core material there is at present PUR foam with the following characteristics-

- It is a 100% open celled PUR-foam (important for evacuating cells).

- The foam exhibits a high pressure resistance of 0.45 N/mm². That is necessary for the static construction of the bonded pipe system (design and construction of the system up to now) and the accompanying longitudinal and radial forces (= shear and compression forces).

- The heat conductivity amounts to approx. 8 mW/mK, with an evacuation on a pressure < 0.1 mbar (10 Pa)

- In the ventilated state the heat conductivity amounts to approx. 34 mW/mK

- The life span is considered 5-15 years (when using panels).

- Beforehand the PUR foam must be evacuated at a proper temperature of approx. 100°C. This is the only way to pull out humidity and remainder gases of the material. The supplied warmth "activates" the molecules otherwise remaining at ambient temperature, so that they are more mobile and sucked into the "suction".

- The application of this material is possible at a constant temperature of 100°C. The highest temperature is supposed to be 150°C.

General problems with PUR-foam
There are some physical and technical obstacles to achieve a very good evacuation of PUR-foam pieces:

- The first problem is the fact that the foaming process goes hand in hand with the formation of a skin on the outside of each PUR-foam core which is closed cellular. The open cell structure of this skin can be attained only by special production steps.

- A large problem is the necessary evacuation of a whole pipe and of a large surface. It is technically only possible to attain a sufficient evacuation on an area of 3-4 cm below the point of evacuation. The physical flow conditions when evacuating do not make better results possible with the PUR foam. The pressure loss, however, when evacuating over e.g. 2 m length would be much too large in order to achieve the necessary 0.1 mbar (10 Pa). It would have to be evacuated in very short distances (within the cm range). Evacuation channels would have to be inserted. Therefore it would have to be evacuated over the entire surface and not only over one point. The material may not be too thick, which it does not need to be, due to the later high insulating efficiency. But specially shaped parts would pose problems due to its thickness.

- An alternative solution is the full surface evacuation of the material and the welding and/or sealing under a vacuum. But here there are large evacuation units and extra large vacuum pumps needed. The realization of the necessary vacuum will become questionable with increasing plant size and/or it requires much time to reach the necessary vacuum.

- After the production air or other environmental medium diffuses into the insulation through the casing. The life span is expected to be 5-15 years at normal ambient temperature e.g. with house walls or with cooling applications.

- Later diffusion processes (after gassing) in the core material (here PUR foam) further destroy the vacuum. If necessary, getters must be brought in.

- The diffusing gases and humidity which diffuse through the seal seams are also absorbed by the getters.

- The relative rough porosity of the PUR leads to disadvantages when compared to other core materials (higher heat conductivity). In the 90´s of last century the PUR foams became increasingly more fine- pored. A substantial step, also when it comes to cell gases with low heat conductivity, was carried out. Other core materials, however, are still substantially more fine -pored.

- The application of common foil casings, the so-called high barrier foils, poses problems when the temperature is above ambient temperature. At higher temperature the foils become increasingly more permeable to atoms and gas molecules. Aluminium foils, in contrast, are good heat conductors (the above mentioned edge effect). In the refrigeration technology the foil employment would be conceivable. One alternative, up to a certain point, would be metals (when using steel there is the above mentioned problem of hydrogen which develops from welding application, however.) and high-grade steel.

- An extremely good (very low) vacuum continues to be necessary for the achievement of a good insulating efficiency with PUR. This will be in the range of 0.01 mbar (1 Pa) and can be realized in the physical technical area only with extreme difficulties. In particular in the well-known VIPs (panels) this should have been realized for the application in cool and freezing devices. Here we have a contradiction between manufacturer data and the data of pumping experts and vacuum experts.

- The area of application is limited to 100 °C, due to the material properties of PUR foams (and, depending upon the used casing, even to 60°C).

Application examples for PUR-foam
In Italy there is a small company, which manufactures comparable components by means of form construction units. A getter, however, is used, in order to bind penetrating humidity. Therefore it will be PUR or polystyrene.

Foam cores are already applied in refrigerators and/or cooling applications in Europe. The technically planned life span of the insulation corresponds approximately to the planned life span of the devices (5-15 years).

In Japan approx. 2 million refrigerators with vacuum insulation (VIP foam cores with casing) are manufactured per year. Here the economical production and form variability with foam cores are to be mentioned.

XPS-foam
The employment of polystyrene forbids itself because the polystyrene is deforming itself when used at temperatures above 70-100°C. Polystyrene can be produced open cellular. For the application in buried district heating pipelines the mechanical characteristics (pressure strength and heat resistance as well as diffusion behaviour at higher temperature) are not sufficient.

Micro-porous silicon dioxide
As a better possibility for the application in long-distance heating pipelines the material silicon dioxide can be used because of its mechanical characteristics (pressure strength). But both the base material and the production are more cost-intensive when compared to PUR or XPS. More appropriate for these kinds of applications are micro-porous silicon dioxides, which supply a good heat insulating efficiency up to 10 mbar 1000 Pa). The maintenance of the very small necessary vacuum with PUR foam would be substantially more difficult to realize, than e.g. with a 10 mbar vacuum, which is necessary for micro-porous silicon dioxide. Regarding the shearing strengths in the material, necessary under these circumstances, there are still developments to be accomplished respectively tests have do be done or solutions have to be found alternative to the systems with necessary force composite.

Nano-gel
Newly developments there are in the field of the so-called nano-gels which offer very good thermal insulation values even at a 50-100 mbar (10^4 Pa) vacuum. Regarding the shearing strengths in the material, necessary under these circumstances, there are still developments to be

accomplished respectively tests have do be done or solutions have to be found alternative to the systems with necessary force composite.

Physical barriers for production of well working systems
Physical barriers are:

- Flow losses when evacuating (vacuum channel): vacuum channels reduce the insulating efficiency, respectively the mechanical firmness. They must be held short.

- Turbulent streams (suction ranges > 2 cm). That means that the entire surface had to be widely sucked off. The thickness of the construction units which can be evacuated must remain under 2 cm. Thus it can be sucked off in the range of the laminar current (here with 0 to 1mbar (100 Pa) with PUR foam).

- To long ways of evacuating (large construction units) particularly within the technical suction ranges in the production. That is, that for large construction units several vacuum pumps are favourable. The ways of evacuating must be kept short. Otherwise the pumping time for a quantity production becomes too long.

- Cold core material. By warming up the material when evacuating to the maximally possible temperatures the gas molecule are activated. They move faster and separate themselves from other materials of the core material. That makes it easier to suck them off.

Bases for a good insulation are:

- The cladding of the material with high-grade steel, steel, aluminium or multi-layer sandwich foils of the newest generation.

- A very small heat conductance of the material in ventilated state (meaning also without evacuation of the material).

The requirements to mechanical properties
Aspects for the current application at warmth leading pipes:

- It is possible to produce in principle foil-coated vacuum insulation plates in round form!

- There must be a sufficient mechanical protection (against damage from the outside, for subterranean laying etc.). This can be obtained e.g. in form of a normal PUR insulating layer coat with an additional protective layer (HDPE or steel sheet) or in the form of a steel casing tube.

- The open cell structure of the core material must be ensured. That is possible by using the especially technology.

- The pressure strength of the core material for applications (earth thrust, forces due to medium pipe expansion at length, water pressure at deep sea application) must be given. PUR foam offers all these possibilities.

- The shear strength for the classical application in the form of a composite pipe must be given. With a flexible pipe system this is void. Both applications are possible.

Estimation of technical lifetime
The main difficulty is to reach a sufficient life span, i.e. the guarantee of the insulation characteristics for a period of 30 years.

The temperature resistance of all materials must be given. In particular the foil casings encounter their limits fast when the application temperatures are higher than ambient temperature. At temperatures higher than 60°C the diffusion tightness of many materials (foils) drops rapidly.

A better (higher) temperature resistance would result to a higher life span. The developments of new foil barriers in the past years give a positive outlook for the future.

The use of high-grade steel foils, steel, or aluminium foils would be conceivable, in order to be able to ensure a "durable" vacuum at higher temperatures.

In the current situation only assignments of 15-20 years at standard temperature are conceivable, due to the feasible foil thicknesses and/or diffusion barriers. According to the manufacturer Elastogran it is 5-15 years (especially PUR-core). According to Heinemann it will be 20-30 years, when using nano-porous materials. Only then a lesser evacuation level as with PUR foam would be necessary.

At current that means, that probably only solutions for special applications will be realized. Versions in high-grade steel sheet metal offer a relatively long life span. According to the data of manufacturers these are expected to be within the range of 15 to 25 years.

Long-term stability of the vacuum

The aim must surely be to develop a more robust cladding foil, which is gas tight and nevertheless economical. This must be considered in particular regarding e.g. employment within the district heating range (warmth and life span). Otherwise this is only possible when using steel or aluminium.

Future developments

Substantial progress has been made in the area of getter materials and foil barriers. Ever better core materials are being developed. If the components are being tuned to each other, then its application in heating will be easier and more economical within the next few years.

Discussion of solutions for different types of district heating technologies
1. Flexible piping systems: Because the flexible tubing systems are "self-compensating" (regarding their expansion behaviour and up to certain point), their application for the vacuum engineering would be favourable e.g. in the form of many, underline individual vacuum tories (ring bodies). Thus no shear stresses would need to be transferred and many small bodies could be manufactured industrially. These bodies could be manufactured also with a less diffusion-susceptible carrier material and thus its employment could be ensured for a long time. PUR-foams would also become interesting when diffusion brakes were improved. Regular evacuating does not seem to be feasible for technical and economical reasons.

2. Flexible pipe systems (plastic tubes) adjusted in a straight line could be encased with a few flexible large vacuum elements or PUR-foaming. After the full surface evacuation an aluminium foil welding could be made under vacuum. If necessary, several transferred layers are thus manufactured. The remaining problem is the diffusion barriers which are not quite sufficient.

3. Pre insulated bonded pipe systems with laminate-wise evacuation and foil or better-said aluminium casing- The individual insulation bodies are prefabricated and put one above the other in each layer. An outer casing made of classical PUR can be applied as protection as well as with the well-known PEHP coat. The problem, however, that remains, is how the mono layers with foil casing can transfer sufficient forces.

4. Pre insulated bonded pipe systems as compound systems with a PUR-layer: With this conceivable variant vacuum channels in the PUR foam would be necessary. Furthermore this system would have to be constantly and regularly evacuated afterwards for the entire duration of the process. The costs for that kind of evacuation would be probably inadequate high.

5. Steel jacket pipe with complete filling made of PUR foam: This system would be considered also as a compound system. Vacuum channels would be necessary. An evacuation over the term or a very long evacuation together with a lateral very good diffusion barrier (in tubing direction to the next section) would probably be necessary. One problem could result from hydrogen atoms, which could diffuse from the steel through the area of the welding seams. This could be solved by evacuation over the term or with special getter materials. The vacuum engineering functions are otherwise as with the classical steel jacket pipe transfer. The transfer would be similar as with the pre insulated pipe system.

Vacuum for lifetime - short summary

The vacuum for lifetime of e.g. 30 years appears solvable in the classical SMR technology. Due to the high costs only an application for special operation purposes appears feasible.

Future, but not yet conceived diffusion barriers, for the use in PUR applications at higher temperatures would make the above mentioned solutions much more realistic.

With other substrates (nano-gel, micro-porous silicon dioxide) the solutions which have duration of over 30 years are technically possible. The temperature range, however, might be somewhat reduced.

A further aspect is that the vacuum engineering is relatively cost-intensive. That means that for optimizing the utilizable volume and/or with a limited insulation area the application of the vacuum engineering can be worthwhile. Expressed in other terms this would mean that in the case of maximum necessity for insulation in limited space an application of the vacuum engineering is conceivable.

The topic "evacuation" does not represent a problem from the technical point of view. The typical procedure corresponds to the well-known evacuating in the vacuum chamber. One example would be the evacuating of food products into an appropriate foil casing. When evacuating PUR and/or from large surfaces, a gap could be planned, over which the vacuum in the material can be drawn ("reduced evacuation resistance").

It is, however, obviously a problem to pump from the ambient pressure up to 1 mbar (100 Pa) in the entire body which is to be evacuated. Flow resistances will permit realistic evacuations < 10 mbar (1000 Pa) in an appropriate period of time.

From a production-technical point of view there is rather a problem at fast evacuating in particular when it comes to larger articles (flow resistance and necessary difference of pressure).

Evaluation / Outlook
The technical circumstances were described in detail. The application will be determined by the costs. The aspect of the amortization should not be neglected. So it must be noted that the additional expenditure for production should finally be amortized within a realistic time. Savings are to be compared with the additional costs. For special operational purposes (short length of application and high necessary efficiency) its application may sometimes appear appropriate. With increasing technical development the employment in general becomes - perhaps in some years- more realistic.

How high is the need to thermally insulate very well?
Is there little space and/or is the place very valuable and/or expensive?
Would there be /or are there constructional problems when using a thick thermal insulation?
Can the thermal insulation be attached in such a way that there are few and/or no cold bridges?
Can the evacuated thermal insulation be brought in as a panel or as a small curved surface?
Are there (in the foreseeable future) regulations, which require a better thermal insulation when it comes to my project/product?
Can I attach the vacuum panels in such a way that they are protected from mechanical injuries?
Are the temperatures at the application under 50 degrees Celsius?
Could the volume be indicated so precisely that an adjustment at installing the prefabricated evacuated elements (VIP or similar) is not necessary?
Am I prepared to pay a higher price for the advantages of VIP, the prefabricated elements, which lead to a higher production cost per square meter insulation than conventional insulation?

Table 26: Decision making aids considering the current technical limit

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Further links and references

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Current research projects of neighbouring fields

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Technisches Datenblatt
Vakuumisolationspaneele va-Q-*vip*

Kennzeichen

Va-Q-*vip* ist eine evakuierte Dämmplatte mit sehr geringer Wärmeleitfähigkeit. Der Kern der Dämmplatte besteht aus einem gepressten Pulver, dessen Hauptbestandteil mikroporöse Kieselsäure ist mit Zusätzen von Infrarottrübungsmitteln zur Minimierung des Wärmestrahlungsdurchgangs. Hinzu kommt ein geringer Anteil organischer Cellulosefasern zur Verbesserung der mechanischen Stabilität. Aufgrund niedriger Dichte sowie der speziell entwickelten Infrarot-Trübungsmittel ist die Wärmeleitfähigkeit der va-Q-vip-Elemente extrem niedrig. Der Plattenkern ist nicht brennbar und in die Brandschutzklasse A2 oder A1 je nach Ausführung eingestuft

Der Pulverkern wird von va-Q-tec in einem speziellen Verfahren mit einer gas- und wasserdampfdichten Kunststofffolie umhüllt, evakuiert und verschlossen. Im allgemeinen werden rechteckförmige Platten hergestellt. Andere Plattenformen sind auf Anfrage möglich. va-Q-vip-Elemente zeichnen sich aufgrund ihrer besonderen Folienfalttechnik durch glatte Kanten aus. Einzelne Elemente lassen sich daher praktisch fugenlos aneinander setzen.

Anwendung

Überall wo mit wenig Platz sehr gut thermisch gedämmt werden soll, haben va-Q-*vip*-Systeme sehr gute Einsatzmöglichkeiten. Die drastische Verringerung der Dämmstärke mit va-Q-*vip* führt zu Dämmlösungen, die vorher technisch nicht möglich waren: bei Renovierungen geringste Fußbodenaufbauten bei gleichzeitiger Erfüllung der Dämmvorschriften, Steigerung des Nutzvolumens bei Transport- und Lagerbehältern von temperaturgeführten Gütern, Ersetzen von Kühlmitteln wie Trockeneis durch preiswerte Eutektika bei gleichzeitiger Verlängerung der Transport- und Kühlzeit. va-Q-*vip* Elemente können eingesetzt werden in Gebäuden (Dämmung von Fußböden, Dachgauben, schlanke Fassadenelemente), Logistik (Kühlboxen, Kühlzellen) und Hausgeräten (Kühl- und Gefrierschränke).

Eigenschaften

Farbe	Folie			silbrig
Äußeres Erscheinen	kein Folienüberstand, glatte Kanten *			
Dichte (Rohplatte)			kg/m³	150-180
Wärmeleitfähigkeit	bei 10 °C und Dichte 165 kg/m³ Gasdruck < 5 mbar Gasdruck 100 mbar	DIN 52612	W/m*K	0,0042 < 0,008
Temperaturbeständigkeit	bedingt durch die Folie		°C	- 30 ... + 60
Feuchtebeständigkeit	rel. Feuchte bei Raumtemperatur		%	0 ... 60
rechnerischer Anstieg des Gasdrucks	bei Raumtemperatur und 20 mm Stärke	je nach Folie	mbar / Jahr	< 1 ... 4
Innendruck	bei Auslieferung		mbar	1 ... 5
spez. Wärmekapazität Pulverplatte	bei Raumtemperatur		kJ/kg*K	0,8
maximale Plattenabmessungen	Länge Breite Stärke		mm	1000 650 30
Längentoleranzen	0 bis 500 mm 501 bis 1000 mm		mm	+ 2 /- 4 + 2 /- 5
Stärkentoleranzen (ohne Siegelnaht)			mm	+/- 1
Druckbelastbarkeit	10 % Stauchung		kPa	ca. 160
Temperaturwechselbeständigkeit	unempfindlich gegen Wärme- und Kälteschocks im angegebenen Temperaturbereich			

* bei 10 mm und 15 mm starken Paneelen liegt ein Teil der Randlasche auf der Paneelfläche

Alle Angaben stellen Richtwerte dar und sind nicht zur Erstellung von Spezifikationen bestimmt.

Lagerbeständigkeit
va-Q-vip-Elemente sind unter trockenen Bedingungen (relative Luftfeuchtigkeit < 60 %) und Temperaturen unterhalb 30 °C nahezu unbegrenzt lagerfähig. Der Gasdruckanstieg beträgt unter den angegebenen normalen Lagerbedingungen je nach Folientyp maximal 1-4 mbar pro Jahr.

Anwendungseinschränkungen
Die Kunststofffolie der va-Q-*vip* darf nicht durch Bohren, Schneiden, Fräsen, Nageln, Stoßen an scharfen Kanten etc. beschädigt werden, da ansonsten sich die Paneele belüften. Die Wärmeleitfähigkeit im belüfteten Zustand beträgt 0,020 W/mK.

Chemische Analyse Pulverkern laut Hersteller
Siliziumdioxid SiO_2 ca. 80 %
Siliziumcarbid SiC ca. 15 %
andere ca. 5%
Der gepresste Pulverkern der va-Q-*vip* ist mit einem Polyester-Vlies umhüllt.

Folienaufbau (Beispiel, prinzipiell):
Siegelschicht (innenliegend): PE, ca. 40 µm
Metallbedampfung: Al, ca. 0,04 µm
Außenschicht: PET, ca. 60 µm
Zur Verbindung mit anderen Materialien ist bei den va-Q-*vip* die außenliegende PET-Schicht maßgebend. Weitere mögliche Materialien für die Außenschicht sind: PE, PA, PP

Verarbeitung
Bitte beachten Sie auch die Verarbeitungshinweise, die dem Produkt beiliegen.

Sicherheitstechnischer Hinweis
Laut Hersteller ist der Pulverkern kein Gefahrstoff nach Richtlinie 91/155/EEC. Er setzt keine gefährlichen Zersetzungsprodukte frei und verursacht nach derzeitigem Wissensstand keine gesundheitliche Gefährdung beim Menschen.

Lieferformen:
1. Standardstärken: 10 mm, 15 mm, 20 mm, 25 mm, 30 mm
2. Standardgrößen: 1000 mm x 500 mm, 500 mm x 500 mm, 1000 mm x 650 mm, 500 mm x 650 mm
3. Sonderformate auf Anfrage möglich

Die in diesemMerkblatt mitgeteilten Daten entsprechen dem derzeitigen Stand. Änderungen der Produktkennzahlen sind vorbehalten. Die angegebenen Empfehlungen erfordern wegen der durch uns nicht beeinflussbaren Faktoren während der Verarbeitung eigene Prüfungen und Versuche. Verwendungsvorschläge begründen keine Zusicherung der Eignung für den empfohlenen Einsatzzweck.

Stand10/2002

Elastogran

Elastocool ™ plus

BASF Gruppe

Höhere Energieeffizienzklassen durch
Elastocool **PUR-Hartschaumstoff** *plus* **PUR-Vakuumpaneele**

Kennzeichen:

Elastocool plus ist die Kombination aus einem Hartschaumstoff der Elastocool-Serie und Polyurethan (PUR) Vakuum-Isolations-Paneelen (VIP). Die PUR-VIPs (s. Abb. 1) sind Hochleistungsdämmelemente mit äußerst niedriger Wärmeleitfähigkeit und besitzen einen offenzelligen PUR-Hartschaumstoff als Kernmaterial. Durch Umschäumung der PUR-VIPs mit einem Elastocool-Hartschaum entsteht ein PUR-Verbundsystem mit besonders effizienter Dämmleistung:
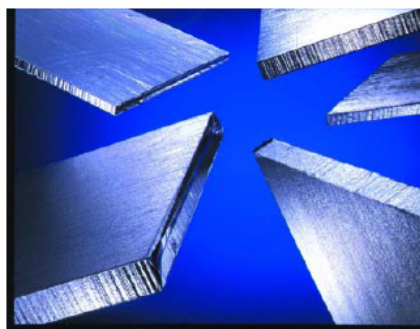

Abb. 1: PUR Vakuum-Isolations-Paneele (VIP)

Herstellung PUR-VIP:

Der offenzellige PUR-Hartschaumstoff (vgl. Abb.2) wird auf einer Doppelbandanlage kontinuierlich hergestellt und anschließend auf das gewünschte Maß zugeschnitten. Da eine gewisse Restfeuchte im Schaum vorhanden ist, die eine Evakuierung wesentlich erschwert, muss der Schaumstoff zunächst bei über 100 °C getrocknet werden. Im nächsten Verarbeitungsschritt wird der offenzellige Hartschaum in einem speziellen Verfahren in eine diffusionsdichte Mehrschichtverbundfolie eingehüllt und die Nähte verschweißt, wobei eine Seite für die Evakuierung geöffnet bleibt. In der Vakuumkammer wird der Hartschaum schließlich bis auf einen Druck <0,1 hPa evakuiert, um das gewünschte Wärmeleitfähigkeitsniveau zu erreichen (vgl. Abb. 3). Außerdem wird die noch offene Seite dieser Folienhülle in der Kammer versiegelt. Für Langzeitanwendungen mit Lebensdauern von mehreren Jahren, muss in die Elemente zusätzlich noch ein sogenannter Getter eingebracht werden, der durch die Siegelnähte eindiffundierende Gase und Feuchtigkeit absorbiert. So kann die konstante Dämmleistung über einen Zeitraum von mehr als 10 Jahren sichergestellt werden.
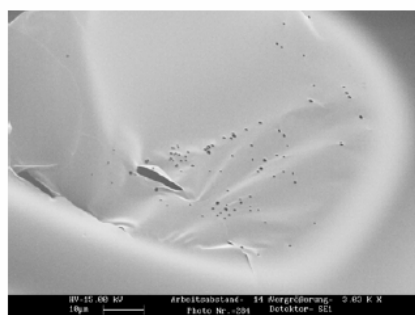

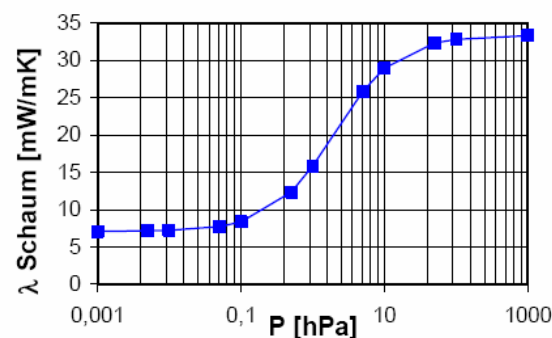Abb. 2: REM-Aufnahme einer Zelle; Mikroporen in der Zellwand

Abb. 3: Abh. der WLF vom Zellinnendruck beim offenzelligen PUR-Schaum

Technisches Merkblatt

Anwendung:

Das PUR Dämmsystem *Elastocool plus* wird zur Reduzierung des Wärmetransports in Kühlgeräten (vgl. Abb. 4) eingesetzt. Dadurch lassen sich die Energieverbräuche der Geräte drastisch reduzieren. **Elastocool plus ist prinzipiell überall dort nutzbar, wo es um maximale Dämmung bei begrenzter Dämmdicke geht.**
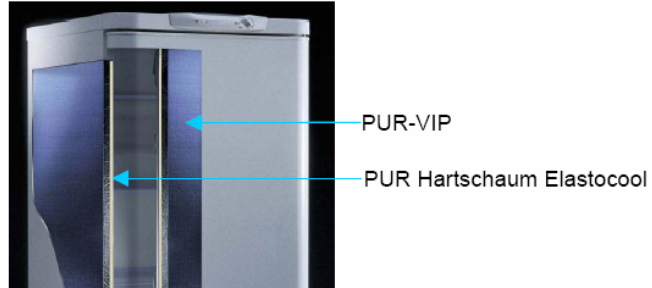

PUR-VIP

PUR Hartschaum Elastocool

Abb. 4: Schnittdarstellung eines Kühlschranks mit Elastocool plus

In der Regel werden die PUR-VIPs mit Hilfe von adhesiven Klebern (z.B. doppelseitiges Klebeband), die möglichst vollflächig auf einer Seite des Paneels aufgebracht werden, an den Innenseiten der Außendeckschichten fixiert. Anschließend werden die Paneele mit einem geschlossenzelligen PUR-Hartschaum der *Elastocool-Serie* umschäumt. Auf diese Weise ergibt sich ein konstruktiver Dämmverbund, der sowohl für die Stabilität des Gerätes als auch für eine besonders effiziente Wärmedämmung sorgt. Die beim Umschäumen der Vakuumpaneele auftretende Reaktionswärme beeinträchtigt nicht die thermischen und mechanischen Eigenschaften der Paneele.

Beim Einbau und beim Handling der Paneele ist immer darauf zu achten, dass die Folienhülle nicht durch mechanische Belastungen oder extreme Temperaturen beschädigt wird. Durch Beschädigung belüftete Paneele weisen entsprechend dem Diagramm in Abb. 3 Wärmeleitfähigkeiten von ca. 34 mW/mK auf. Außerdem findet durch die Belüftung eine Delaminierung der Folienhülle vom PUR-Kern statt, so dass der konstruktive Gesamtverbund damit nicht mehr gegeben ist.

Lieferformen der PUR-VIPs:

Für *Elastocool plus* sind PUR-VIPs in den nachstehenden Dimensionen lieferbar:

- Standardstärken: 20mm, 25mm, 30mm, 40mm, 50mm, 60mm
- Größen: Länge max. 1300mm, Breite max. 600mm
- Sonderformate auf Anfrage möglich
- Paneele mit Klebefilm für den direkten Einbau lieferbar
- Paneele mit Chip-Einsatz zur Qualitätskontrolle lieferbar, nur bei Einsatz des va-Q-check Systems der va-Q-tec AG nutzbar

Produktion und Vertrieb der Paneele wird von Firma **va-Q-tec AG** mit Sitz in Würzburg durchgeführt (Informationen unter www.va-Q-tec.com).

Va-Q-tec AG   Tel.: +49-(0)931/35942-0
Karl-Ferdinand-Braun-Str. 7   Fax: +49-(0)931/35942-10
97080 Würzburg - Germany   Mail: info@va-q-tec.com

Genauere Angaben zu den Paneelen sind den speziellen Datenblättern der va-Q-tec AG zu entnehmen.

Verarbeitung der PUR-VIPs:

Sprechen Sie die Anwendung und Verarbeitung mit den technischen Beratern der va-Q-tec AG ab. Von Ihnen erhalten Sie spezielle Verarbeitungshinweise.

Lagerung der PUR-VIPs:

PUR-VIPs (mit Getter) sind unter geeigneten Bedingungen (normale Luftfeuchte, niedrige Temperatur) mehrere Jahre lagerfähig. Genauere Informationen sind den Angaben der va-Q-tec AG zu entnehmen.

Eigenschaften:

Physikalische Eigenschaften des offenzelligen PUR-Hartschaums für die VIPs			
Merkmal	Einheit	Messwert	Vorschrift
Prüfkörper wurden unter Verwendung einer Hochdruckanlage (P=150 bar) hergestellt.			
Rohdichte	Kg/m³	62	DIN EN ISO 845
Druckfestigkeit	N/mm²	0,45	DIN 53421
Offenzelligkeit	%	100	ISO 4590
Wärmeleitfähigkeit (Normalbedingungen)	mW/mK	34	Gerät der Fa. Hesto
Temperatur-Beständigkeit	°C	> 100°C	

Eigenschaften der PUR-VIPs			
Merkmal	Einheit	Messwert	Vorschrift
Rohdichte	Kg/m³	62	DIN EN ISO 845
Thermischer Einsatzbereich	°C	-50 - +50	
Kurzzeitige (<15 min) Temperaturbest.	°C	150	
Innendruck bei Auslieferung	hPa	< 0,1	
Wärmeleitfähigkeit (23 °C Mitteltemp.)	mW/mK	8	Gerät der Fa. Fox
Lebensdauer typenabhängig	Jahre	5-15	

Eigenschaften *Elastocool plus*			
Die Angaben beziehen sich auf eine Kühlschrankdämmung ohne VIPs.			
Dämmvariante	Flächenbelegung mit PUR-VIPs	Reduzierung KxA-Wert	Reduzierung Energieverbrauch
PUR-VIPs im Gehäuse und Türen	Ca. 75 %	Ca. 35 %	Ca. 25 %
PUR-VIPs nur in den Türen	Ca. 20 %	Ca. 8 %	Ca. 8 %

Die Angaben in dieser Druckschrift basieren auf unseren derzeitigen Kenntnissen und Erfahrungen. Die aufgeführten Werte sind Richtwerte und stellen keine Spezifikation bzw. zugesicherte Eigenschaft dar. Sie befreien den Anwender wegen der Fülle möglicher Einflüsse bei Verarbeitung und Anwendung nicht von eigenen Prüfungen und Versuchen. Eine rechtlich verbindliche Zusicherung bestimmter Eigenschaften oder der Eignung für einen bestimmten Einsatzzweck kann aus unseren Angaben nicht abgeleitet werden. Etwaige Schutzrechte sowie bestehende Gesetze und Bestimmungen sind vom Empfänger unserer Produkte in eigener Verantwortung zu beachten.

Annex 1: Diffusion coefficients.

Publication &Year	Author	Method	Substances & Temperature	D_{eff} [cm2/s]	
European journal of cellular plastics 1980	D.A Brandreth H.G. Ingersoll	Sample sealed in a chamber, Evacuated and purged with propane as reference gas. Frozen and crushed. Analyzed by GC.	**CFC-11** 25°C 60°C 90°C **N_2** long term ageing accelerated aging **O_2** long term ageing accelerated aging	0,40 2,7 10 2,2 2,7 5,3 1,1	$*10^{-9}$ $*10^{-9}$ $*10^{-9}$ $*10^{-8}$ $*10^{-8}$ $*10^{-8}$ $*10^{-7}$
Journal of cellular plastics 1995	H.Fleurent S Thijis	Cell analysis by GC	**n-pentane** 23 °C 70 °C **Cyclopentane** 23 °C 70 °C	3,5 1,5 5,0 1,0	$*10^{-14}$ $*10^{-13}$ $*10^{-14}$ $*10^{-13}$
Journal of cellular plastics January 1967	Francis J. Norton	Polyethorol sample sealed in a chamber with a metal ball, cooled with nitrogen and shaken. Gas analysis by GC, residual components analysed by mass spectrometry.	**$CFCl_3$** 25°C -18° C **N_2** 25 °C -18 °C **O_2** 25 °C -18 °C	2,25 1,5 6,27 2,6 1,12 1,5	$*10^{-9}$ $*10^{-10}$ $*10^{-8}$ $*10^{-9}$ $*10^{-7}$ $*10^{-8}$
Journal of thermal insulation and building environments October 1995	K.H.Brodt, R.R.H.Brood and G.C.J.Bart	Gases released by crushing the sample and analyzed in GC.	**CO_2** 23°C 70°C	1,5 9,4	$*10^{-10}$ $*10^{-10}$
32nd annual polyurethane technical/marketing conference October 1989	A.Cunningham, D.J.Sparrow, I.D.Rosbotham and G.M.R.du Cauze de Nazelle.	Gases released by crushing the sample and analyzed in GC.	**CFC-11** 70 °C **HFA-123** 70 °C **HFA-141b** 70 °C	3,2 3,5 5,0	$*10^{-9}$ $*10^{-9}$ $*10^{-9}$
Publication &Year	Author	Method	Substances & Temperature	D_{eff} [cm2/s]	

Publication &Year	Author	Method	Substances & Temperature	D_{eff} [cm2/s]

Euroheat & Power 4-5 1997	Henning D. Smidt and Jorgen Daugaard	Values collected from literature	**O_2**
			  25 °C
			N_2
			  25 °C
			CO_2
			  25°C
			Cyclopentane
			  25°C
				1,1 *10^{-7}
				
				0,63 *10^{-7}
				
				36 *10^{-7}
				
				0,005 *10^{-7}

32nd Annual Polyurethane Technical/Marketing conference October 1989	T.R.Brehm & L.R. Glicksman	Constant volume sorption technique	**CO_2**
			  40°C
			  60°C
			  80°C
			O_2
			  40°C
			  60°C
			  80°C
			N_2
			  40°C
			  60°C
			  80°C
			R11
			  40°C
			  60°C
			  80°C
				
				193 *10^{-8}
				351 *10^{-8}
				609 *10^{-8}
				
				46,4 *10^{-8}
				88,8 *10^{-8}
				211 *10^{-8}
				
				6,84 *10^{-8}
				12,3 *10^{-8}
				21,1 *10^{-8}
				
				0,326 *10^{-8}
				0,959 *10^{-8}
				2,34 *10^{-8}

Polyurethanes world congress 1993	D. Bhattacharjee, J.R. Booth	Thin slice accelerated desorption of gases using a gravimetric methodology used to determine effective diffusion coefficients of both carbon dioxide and HCFC-22.	**HCFC-11** **CO_2** *Sample A:* Polyurethane modified PUIR foam blown with CFC-11. *Sample B:* Polyurethane foam blown with reduced CFC-11. *Sample C:* A polyurethane foam coblown with HCFC-22 and CO_2. *Sample D:* A polyurethane foam blown with 100% CO_2.	 **3,46** *10^{-8} **13,3** *10^{-7} **1,09** *10^{-8} **4,23** *10^{-7} **0,655** *10^{-8} **0,70** *10^{-7} **4,53** *10^{-8} **2,98** *10^{-7}
Publication &Year	**Author**	**Method**	**Substances & Temperature**	**D_{eff}** [cm2/s]

| Journal of Heat Transfer 1988 | A.G. Ostrogorsky, L.R. Glicksman | A rapid steady-state technique where sample is kept for 90 to 180 days at 60°C. This was used for determining the diffusion coefficients for O_2, N_2 and R11.
The long term steady state technique was used for determining the diffusion coefficients of CO_2 and N_2(II) | CO_2
25°C
50°C
O_2
25°C
50°C
N_2
25°C
50°C
75°C
90°C
N_2(II)
25°C
50°C
R11
25°C
50°C
75°C
90°C |
$202 \quad *10^{-8}$
$529 \quad *10^{-8}$

$46,8 \quad *10^{-8}$
$145 \quad *10^{-8}$

$7,6 \quad *10^{-8}$
$26,3 \quad *10^{-8}$
$82,7 \quad *10^{-8}$
$202 \quad *10^{-8}$

$6,0 \quad *10^{-8}$
$20,6 \quad *10^{-8}$

$0,23\text{-}0,57*10^{-8}$
$1,7 \quad *10^{-8}$
$11,2 \quad *10^{-8}$
$29,6 \quad *10^{-8}$ |

Annex 2:

Countries	Austria	Czeck Rep.	Denmark	Finland	Norway	Romania	Total	Unit
Power Plant	5/0	4/0	2/3	7/1	0/1	0/1	18/6	Yes/No
District Heating distributor	5/0	3/1	5/0	8	1/0	1/0	23/1	Yes/No
Total length of pipetrench	714	674	4314	2820	700	700	9921	km
Total length of CFC blown pipes	151	44	1925	1372	200	200	3892	km
How many years has the oldest preinsulated pipesystem been in use?	15-35	7-15	24/38	20-30	25	25	7-38	Year
Economical lifetime of your pipe system	30-50	30-50	30/45	15-70	40	40	15-70	Years
Energy delivered to the network	6640	18136	21541	51499	7300	7300	112416	TJ/ Year
Sold energy	6293	15512	17745	48225	4700	4700	97175	TJ/Year
Normal temperature in the forward pipe	80-120	65-80	75-95	75-95	100	100	65-120	°C
Maximum temperature in the forward pipe	130	70-130	95	120	120	120	70-130	°C
Local tax per cent on energy (% of the actual energy price)?	7,8-15	-	38-200	-	30	30	8-200	%
Local VAT on district heating (% on top of the receipt to the customer)?	20	5	25	22	19	19	5-25	%
Calculated values								
Energy to network per year and km	9,3	26,9	5,0	18,3	10,4	10,4	13,4	TJ/km Year
Heat loss	5	14	18	6	-	-	14	%
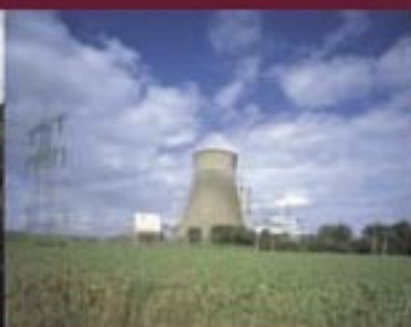
IEA DHC|CHP

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