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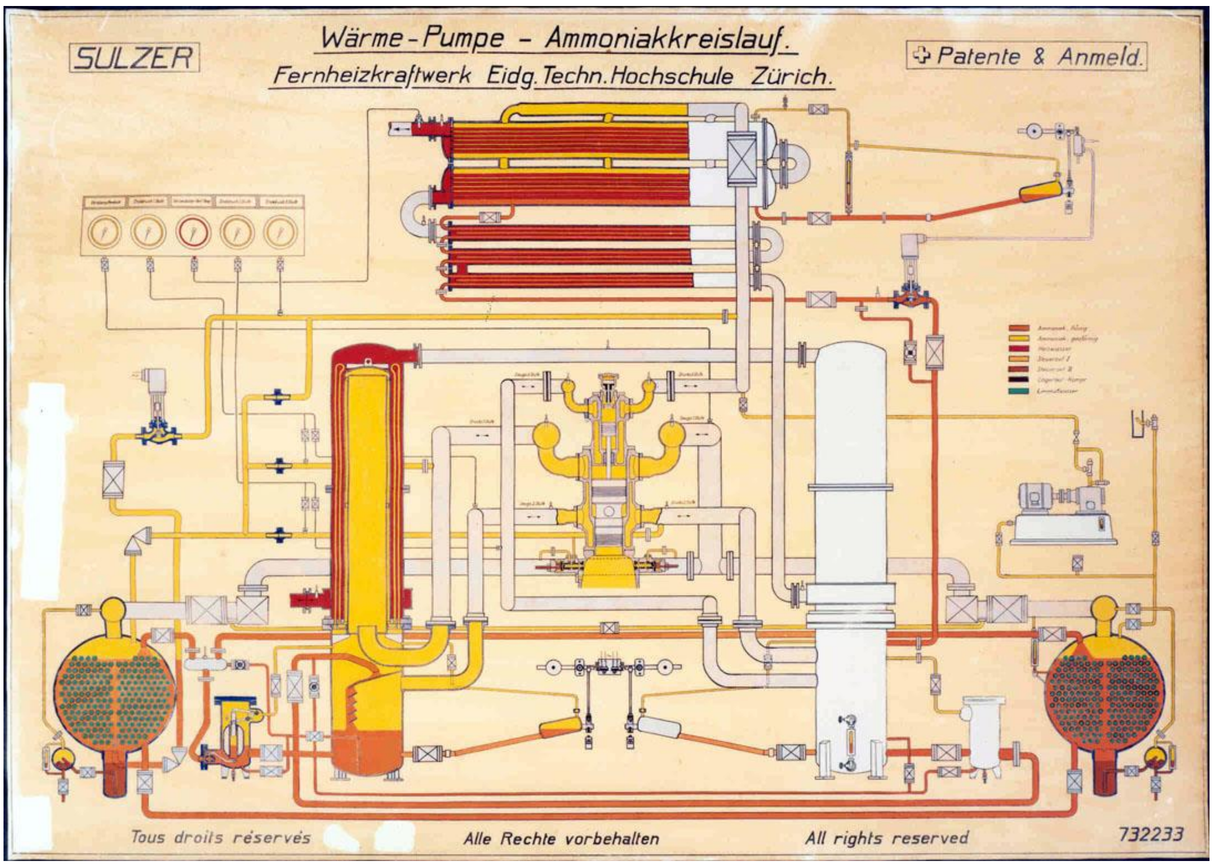
Section Energy Efficiency and Renewable Energies

History of Heat Pumps

Swiss Contributions and International Milestones



Martin Zogg

Process and Energy Engineering
CH-3414 Oberburg, Switzerland

mazo@zogg-engineering.ch

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Preface

This report emerged from the desire of the Swiss Federal Office of Energy for a comprehensive history of the heat pump development focussing on the Swiss pioneers' substantial contributions and to present it at the 9th International Energy Agency Heat Pump Conference on May 20-22, 2008 in Zurich. As regards the Swiss activities, many personal interviews were arranged. The report is based on the best knowledge of the author; but there is no claim for completeness and infallibility.

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Abstract

Compared to conventional boilers heating by heat pumps cuts down fuel consumption and CO_2 emissions to about 50%. Compared to electric resistance heating, the energy consumption is even reduced up to 80%. Therefore the impressive market penetration growth of heat pumps will continue. Swiss pioneers were the first to realize functioning vapour recompression plants. The first European heat pumps were realized in Switzerland. To date it remains one of the heat pump champions. Swiss pioneering work in the development of borehole heat exchangers, sewage heat recovery, oil free piston compressors and turbo compressors is well known. The biggest heat pump ever built comes from Switzerland. Although there is a fairly comprehensive natural gas distribution grid, 75% of the new single-family homes built in Switzerland are currently heated by heat pumps. This paper presents some of the highlights of this success story focusing on Swiss developments and relating them to the international milestones. In order to indicate the direction in which the future development might go to, some recent Swiss research projects are presented as well.

An English summary is available [Zogg 2008a].

Zusammenfassung

Mit Heizen durch Wärmepumpen kann der Brennstoffverbrauch und damit die CO_2 Emission im Vergleich zu einer konventionellen Kesselheizung auf rund die Hälfte gesenkt werden. Gegenüber einer elektrischen Widerstandsheizung ergibt die Wärmepumpenheizung sogar eine Reduktion des Energiebedarfs um bis zu 80%. Die Wärmepumpenheizung wird sich deshalb künftig noch vermehrt durchsetzen. Schweizer Pioniere haben als erste funktionierende Brüdenkompressionsanlagen gebaut. Die ersten Wärmepumpen in Europa wurden in der Schweiz realisiert. Die Schweiz ist in der Wärmepumpentechnik bis heute bei den führenden Ländern geblieben. Ihre Pionierarbeiten in der Entwicklung von Erdwärmesonden, der Nutzung von Abwasser als Wärmequelle, der Entwicklung ölfreier Kolbenkompressoren sowie von Turbokompressoren sind allgemein bekannt. Die grösste je gebaute Wärmepumpe stammt aus der Schweiz. Obwohl ein umfassendes Gasverteilnetz besteht, werden heute rund 75% der neuen Einfamilienhäuser mit Wärmepumpen beheizt. Dieser Bericht präsentiert einige „Highlights“ aus dieser Erfolgsgeschichte. Dabei werden die Schweizer Entwicklungen ins Zentrum gerückt und ihre Beziehungen zu den internationalen Meilensteinen aufgezeigt. Um anzudeuten, in welcher Richtung die künftigen Entwicklungen gehen könnten, werden auch einige neuere Arbeiten aus der Schweizer Wärmepumpenforschung vorgestellt.

Der vollständige Bericht erschien auch in deutscher Sprache [Zogg 2008b].

Instead of a **Glossary** use
http://en.wikipedia.org/wiki/Main_Page

Key Words: *heat pump, history, pioneer, vapour compression cycle, absorption cycle, vapour recompression, Switzerland*

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INTRODUCTION

Ever since the Stone Age mankind has been able to produce heat by artificially sparked fires. But the problem of artificial cooling was much more complex and was not solved before about 1850 when pioneers invented the first refrigeration machines. The same machines can be used as heat pumps for heating. But it was the huge demand for cooling, which led to the rapid development of this newly discovered technique and to a triumphal dissemination around the globe. By 2005, more than 130 million unitary heat pumps for cooling and heating were operating worldwide, and the annual sales attained 15 millions in Asia, 2 millions in North America and several hundred thousands in Europe [Groff 2005]. This illustrates the importance of the heat pump technology.

In Europe there is a main demand for cooling in the southern regions only. In northern climate heating only and heating of domestic hot water by heat pumps are the standard applications for properly designed buildings. The number of heating only heat pumps is much smaller than the rates mentioned above. The reason is, that (in contrary to cold) heat can also be produced by cheap natural gas and oil boilers or even by an open fire as in the Stone Age. Heating only heat pumps therefore have to meet high requirements in terms of efficiency and total costs in order to compete against these less complex devices. It is still a challenge to win this competition in the interest of higher primary energy efficiency. **This report will focus on the development of heat pumps which produce heat as their main benefit**. Taking additional advantage of using the cold side of the cycle as well is mentioned in relevant applications. Swiss contributions to international developments will be highlighted and will be placed in the context of international milestones in heat pump and refrigeration technology. The latter has strongly pushed the development of heat pumping technology. Heat pumps for heating only (or mainly) profit by cheap components of air conditioning and refrigeration origin produced in huge quantities. Therefore some highlights of the development of the refrigeration technology will also be covered as far as they are related to the history of heating only heat pumps.

There are already many detailed and abbreviated publications on refrigeration. The most comprehensive one was written by [Thevenot 1979]. In this report the main focus will be on vapour compression systems (reverse Rankine cycle). Selected topics of the absorption systems will be covered in the background only. The reverse Stirling cycle, the magnetocaloric effect and the thermoelectric effect will be touched only marginally in chapter 9. The report will not cover other refrigeration principles such as gas cycle refrigeration[1] (Joule-Thomson effect), evaporative cooling and heat of mixing effect.

1 WHY HEATING ONLY BY HEAT PUMPS?

If heating is based on electricity from hydropower, nuclear power ore photovoltaics, the advantages of heat pumps with electricity savings up to 80% are obvious. But if heating is based on combustion of fuels there are still sceptics left.

Fire is a discovery by chance rather than an invention. Prehistoric men introduced controlled fire some 1.5 million years ago. To our ancestors, the discovery of controlled fire was a great step forward comparable to the introduction of steam engines or electricity had been to us. From the prehistoric open fire the principle of artificial heating had been improved gradually to-

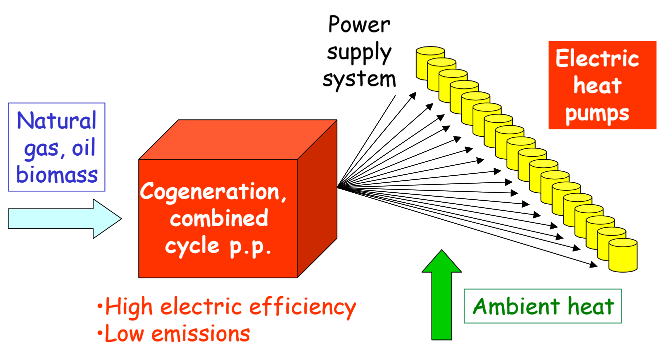
[1] It is generally known that the gas cycle or Brayton cycle is less efficient than the vapour compression cycle. This was demonstrated again by the development of an air-cycle heat pump water Heater in 1979. It ended up with a coefficient of performance of only 1.29.

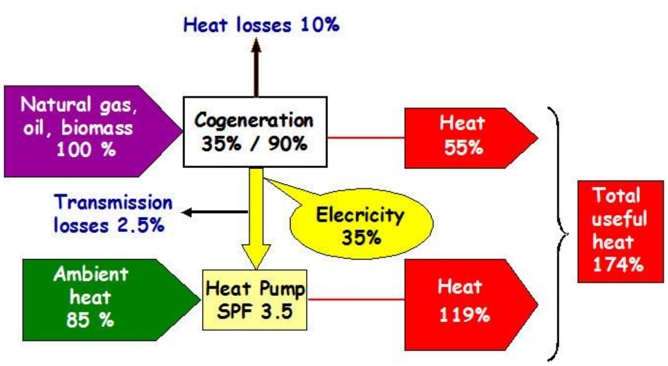
wards a modern condensing boiler. As long as there was no fuel supply problem mankind felt comfortable with heating by burning all types of fuel. But even a modern boiler still has some losses, and the simple combustion principle is limited by a primary energy ratio of 1. In other words a boiler produces less than 100% utilizable heat from 100% fuel energy input (oil, gas or biomass). This conventional solution of producing heat by boilers is a waste of exergy[2]. In the flame of a boiler with a temperature of 1800 °C and with an assumed room temperature of 20°C the exergy rate is 85.9%. A boiler does not take benefit from this high quality flame energy. If the supply temperature of a boiler is 40 °C the used rate of exergy is only 6.4%. The boiler destroys 92.5% of exergy!

The Basic Concept for an Efficient Production of Low Temperature Heat

The "stone age" principle described above has to be replaced with a combination of cogeneration units (or efficient combined cycle power plants) with heat pumps: Figure 1-1. The cogeneration unit is usually more efficient and more economic if it is installed in larger buildings, such as schools, office buildings or hospitals. There the produced heat is used for space heating and domestic hot water heating. The electricity, produced by the cogeneration, units is transported by the public electric power grid to smaller residential buildings in the vicinity. There it drives heat pumps, which have to work at the same time. These heat pumps produce the heat for space heating and domestic hot water heating by using a large part of ambient heat.

Figure 1-1 Basic concept of an efficient space heating system





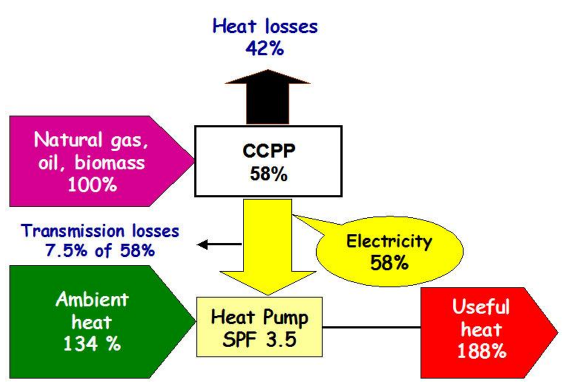


Figure 1-2 Example for high efficiency heating by the combination of cogeneration units with heat pumps, PER = 1.74

Figure 1-3 Example for high efficiency heating by the combination of combined cycle power plants with heat pumps, PER = 1.88

With the same input of oil, natural gas or biomass, this arrangement leads to a much higher heat output than a conventional boiler, due to the utilization of ambient heat. With a fuel energy input of 100% and today's technology it produces between 150% and up to 200% of utilizable

2 Exergy is the maximum work obtainable from heat. For details see textbooks on engineering thermodynamics such as [Baehr 2005] or [Moran and Shapiro 2007].

heat (primary energy ratio PER of 1.5 - 2.0). In Figure 1-2 this is illustrated by a numeric example with the following conservative assumptions: Cogeneration with an electric efficiency of 35% and a total efficiency of 90%, transmission losses 2.5% of the electric energy, seasonal performance factor of the heat pump 3.5. In the future a PER > 2 will become standard. Of course in the future conventional cogeneration units with combustion engines can be replaced with fuel cell modules. About the same efficiency is reached by producing the electricity with modern combined cycle power plants, even without utilizing the waste heat: Figure 1-3 [Zogg 2002b].

2 SCIENTIFIC APPROACHES - HEAT PUMP FUNDAMENTALS

The Frenchman Nicolas Léonard Sadi Carnot was the first to establish a precise **relationship between heat and work**. His manuscript notes were not found by his brother until 1871. Carnot died at the age of 36 in an epidemic. His little book of 1824 remained unknown until his death 1832. It was privately published only. The decisive contribution of Carnots „Reflections“ is that mechanical energy may be transformed completely into heat energy, but that heat energy may be only partially transformed into mechanical energy. The Frenchman Benoît Paul Émile Clapeyron took Carnots „Reflections“ from obscurity and analysed it in a memoir 1834. Carnots ideas were reformulated by Clausius in 1850.

The German Robert Julius von Mayer established the principle of **equivalence between work and heat** in 1842. In 1843, the Englishman James Prescott Joule gave the experimental proof of Mayers statement. In 1847, the German Hermann von Helmholtz published a paper in which the **principle of conservation of energy** was expressed in general terms. The **1st law of thermodynamics** was thus firmly established. Rudolf Julius Emanuel Clausius was a German physicist and mathematician and is considered one of the central founders of the science of thermodynamics [Cardwell 1971]. By his restatement of Sadi Carnot's principle known as the Carnot cycle, he put the theory of heat on a truer and sounder basis. His most important paper, on the mechanical theory of heat, published in 1850, first stated the **basic ideas of the second law of thermodynamics**. His paper contained the **concept of entropy** but he did not use the term until 1865 when he introduced it [Clausius 1865]. By the way in 1855 he became professor at the ETH Zurich, the Swiss Federal Institute of Technology in Zurich, where he stayed until 1867 [Thevenot 1979], [Carnot et al. 2003].

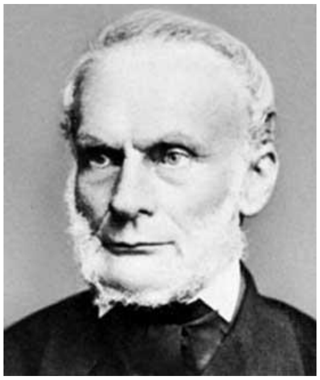
Carnot[3]

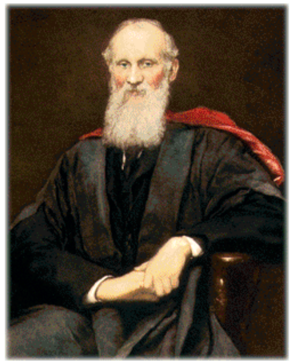
Mayer

Joule

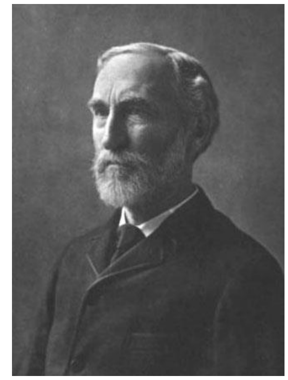
Helmholtz

3 All portraits taken from *Wikipedia*


Clausius


Thomson/Kelvin


Boltzmann


Gibbs

In 1851, independently of Clausius, but recognising his priority, William Thomson (the later Lord Kelvin) found a more general formula for the 2nd Principle. In 1852 he introduced the **thermodynamic scale of temperature**. In 1866, the Austrian physicist Ludwig Eduard Boltzmann gave new significance to the 2nd Principle by linking the concept of entropy to the concept of probability in statistical physics. **Entropy** thus represents the **degree of disorder**, and the Carnot principle becomes clearer.

1873 to 1878 the American Josiah Willard Gibbs introduced **enthalpy** into theoretical thermodynamics. Richard Mollier brought it into applied thermodynamics (1902) and used it as one coordinate of his thermodynamic diagrams (the other was entropy or pressure) for ammonia and CO_2 from 1904. Through diagrams he gave a graphic visualisation and an easily understandable method of calculation for the vapour compression cycle.

From ideas put forward by G. Zeugner (1859) and Hans Lorenz (1896) arose the concept of **exergy**, the maximum useful work produced by a system changing from a given initial state to a given final state by means of constant temperature source and sink. This was taken up again by Fran Bosnjakovic (1935), and then by Peter Grassmann and Kurt Nesselmann after 1950.

In 1870, Carl von Linde[4] was lecturing the theory of refrigeration machines at the "Königliche Polytechnische Schule" in Munich. He published a paper using a **rigorous thermodynamic approach to refrigeration**: “The Extraction of Heat at Low Temperature by Mechanical Means.” On the basis of a thermodynamic comparison Linde pointed out that the compression system is more efficient than systems based on the (at that time dominant) absorption system and other principles.

It was the Belgian chemist Frederic Swarts’ work between 1890 and 1893 on aliphatic fluorocarbons, which is widely considered as establishing the **foundations of organofluorine chemistry**. He published his first papers on the subject in 1892. Edmund Altenkirch carried out a comprehensive thermodynamic study of binary mixtures for **absorption refrigeration machines** in the 1910s. His two-stage machine had a very good output.

[Thevenot 1979]. [Burget et al. 1999], [Nagengast et al. 2006].

From the findings of the mentioned scientists, the following definitions will be used for this report:

The coefficient of performance of an **ideal Carnot heat pump cycle** COP_{rev} (maximum therоretical COP) with the absolute temperatures T_H of the hot side (heat sink) and T_C of the cold side (heat source) is

[4] von Linde studied from 1861 until 1863 at the ETH Zurich (at that time called “Polytechnikum”) and Clausisus was one of his professors.

$$COP_{rev} = \frac{T_H}{T_H - T_C} \quad (1)$$

The **coefficient of performance** (COP) of a real electric heat pump

$$COP = \frac{useful\_heat\_output}{electric\_energy\_input} \quad (2)$$

is much lower. In heat pump processes the temperatures of the heat sink and the heat source would remain constant in the case of infinite flow rates on both sides only. For benchmarking of heat pumps it is convenient to take the outlet temperature of the heat sink T_{Hout} and the inlet temperature of the heat source T_{Cin} as reference. This leads to an approximate exergetic efficiency, the **Lorenz efficiency** of

$$\eta_{Lorenz} = \frac{COP}{\frac{T_{Hout}}{T_{Hout} - T_{Cin}}} \quad (3)$$

For the **comparison of complete systems**, including the production of electric energy, the primary energy ratio

$$PER = \frac{useful\_heat\_output}{primary\_energy\_input} \quad (4)$$

allows a comparison of electric driven heat pumps with absorption heat pumps and boilers. For fuel driven systems the primary energy input is equal to the fuel energy input.

3 THE PIONEERS BEFORE 1875

As observed in many other technologies, inventions and first technical developments are pushed by smart, skilled practitioners and visionaries. The scientific approaches covered in chapter 2 arrived on the scene later. This was until about 1875.

As early as 1852, Lord Kelvin had an intuition regarding the heat pump, in remarking, that a „**reverse heat engine**“ could be used not only for cooling but also for heating. He pointed out, that such a heating device would need less primary energy due to the extraction of heat from the environment [Thomson 1852], [Ostertag 1946]. But for space heating it should take about 85 years until the first commercial heat pumps were started up for the purpose of heating only. In the period before 1875 heat pumps for heating purposes were pursued for **vapour recompression** in salt works with its obvious advantage in wood and coal savings alone. As a preparatory development for the later heat pumps for space heating the introduction of the water central heating is of interest. At that time the common type of central heating was the steam heating system. In 1867 the Sulzer Company in Winterthur (Switzerland) installed the **first water central heating** in a private house in Oberuzwil, **Switzerland**. Aside from smaller, cheaper tubes and higher comfort this new system had the important heat pump relevant advantage of lower supply temperatures. But temperatures did not yet match the requirements of heat pump heating. These first hot water systems were driven by natural convection. They were operating properly only above feed temperatures of about 50°C [Brügger et al. 1991].

Completely contrary to the production of heat by combustion, known for more than a million of years, was the situation for artificial cooling. With the only exception of the evaporative cooling, employed already by the Indian and Egyptian civilizations, there was no possibility for artificial cooling until the invention of refrigeration machines some 150 years ago. Natural ice was transported on an international and even an intercontinental scale. Still in 1890, there was a natural ice shortage problem reported. That's why the **development priority was on the refrigeration side**, with the exception of vapour recompression due to its enormous efficiency improvement. Heat pumps for heating and domestic hot water purposes were not attractive at that time because of the low efficiency of the steam engine drive. But the later development of the heat pump is based on inventions to cover the huge demand for cooling, particularly in the food industry.

3.1 Components and Refrigeration

With regard to the development of heat pumps the vapour compression cycle is by far more important than the absorption cycle. This is why the absorption cycle is covered only marginally.

3.1.1 Vapour Compression Cycle

Jacob Perkins, an American inventor living in England, built the **first vapour compression machine** for producing ice in **1834**. Perkins' invention is thought to be the first patent for mechanical refrigeration. Although his achievement was not mentioned in print for nearly 50 years, Perkins' machine, charged with **ether**, utilized the four principal components used in modern compression installations: a compressor, a condenser, an expansion valve, and an evaporator. Perkins had wide-ranging interests including steam machines, making improvements in banknote engraving, mass production of nails, and the invention of an early bathometer. But at this time there was no demand for artificial refrigeration in London. Only one machine was built, and there was no immediate follow up.

In 1849, the American Alexander C. Twining began experiments with vapour compression refrigeration and ice making. In 1855, he presented the **first commercial ice making plant**. In Australia James Harrison began experimenting with vapour compression for ice making in 1854. He developed the first compressor ready for practical operation in 1856 and introduced vapour compression refrigeration to the brewing and meatpacking industries. By 1861 a dozen of his machines were in operation.

Methyl ether as a refrigerant was introduced and patented by Charles Tellier in 1863. The first machine constructed by the German Linde in 1875 used methyl ether as a refrigerant. 1877 it was installed in a brewery in Italy [Linde 2004]. In 1866**, carbon dioxide CO_2** was introduced as a refrigerant by the American Thaddeus S.C. Lowe by inventing a functioning CO_2 compressor. He patented his carbon dioxide refrigeration system in 1867. Only later did it achieve a great success, especially on ships after 1890, where it replaced the air machines. In America, an **Ammonia** vapour compression ice making plant was constructed by John Beath in 1868, and a **double acting ammonia compressor** in 1869 by Francis DeCoppet. The American David Boyle (born in Scotland) made the first ammonia compressor in 1873 at the age of 23 years! Boyles machines were those of a skilled mechanic. The Swiss Raoul Pictet was a professor in **Geneva**, who worked on the liquefaction of gases. He introduced sulphur dioxide **SO_2** as a refrigerant in 1874. This fluid has the advantage of being an auto-lubricant and it does not burn. On the other hand, in contact with moisture it produces sulphurous and then sulphuric acid and is very corrosive.

Noteworthy is the invention of the **thermostatically controlled refrigeration** system by Peter Van der Weyde in 1870.

[Thevenot 1979], [Nagengast et al. 2006], [Cleveland and Saundry 2007].

3.1.2 Absorption Cycle

In 1851, the French Ferdinand Carré designed the **first** commercially successful ammonia **absorption cooling system** and introduced **ammonia as a refrigerant**. A **small batch domestic apparatus** for the production of 0.5 to 2 kg of ice at each operation was manufactured. However, the cost, size, and complexity of refrigeration systems of the time, coupled with the toxicity of their ammonia coolants, prevented the general use of mechanical refrigerators in homes. But the **continuous version** was more promising for the future. It was patented in 1859 and 1860 in France, in Great Britain and in the U.S.A. Carré's machine had all elements of modern ones including a boiler with a rectifier. This machine was made as early as 1860 by Mignon&Rouart in Paris. They first made 5 models, producing 12 to 100 kg of ice per hour. Carré's machine was soon imported to, and manufactured in, several countries. It was thus the **first refrigeration machine to achieve a general industrial importance**. Different improvements of this successful machine followed. Brewing was the first activity in the northern U.S.A. to use artificial refrigeration extensively, beginning with an absorption machine used by S. Liebmann's Sons Brewing Company in Brooklyn, New York in 1870. The developments were mostly empirical. The theory of absorption machine came much later – especially due to Altenkirch in 1913 [Thevenot 1979].

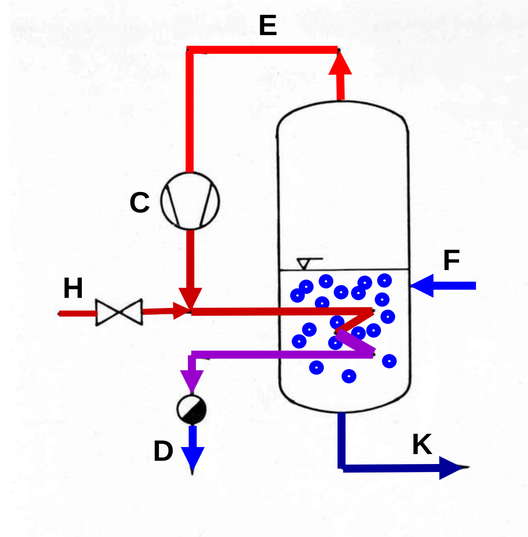
3.2 Mechanical Vapour Recompression

Concentration and crystallisation by evaporation is an important process with world wide large scale applications. In the open vapour recompression cycle the exhaust vapour is compressed to a higher pressure level. Thus its condensation temperature can be lifted above the boiling temperature of the brine solution to be evaporated. Thus the heat of condensation of the compressed exhaust vapour can be used to heat the liquid solution to be evaporated: Figure 3-1. Even though the enhancement of the boiling temperature according the Raoult's law[5] has to be taken into account, frequently only a modest temperature difference has to be reached in order to ensure a sufficient heat transfer from the exhaust vapour to the brine solution. This small temperature lift is of course ideal for a heat pump process. COP values of 15 and more are state of the art nowadays. That is why the mechanical vapour recompression was realised much earlier than heat pumps for heating homes and other low temperature appliances.

One of the main applications is the **salt production from salt brine**. In order to get 1 kg of salt there have to be evaporated about 3 kg of water, which illustrates the enormous energy demand of such processes. Whole forests had been cleared for this purpose.

[5] Raoult's law for ideal solutions: The partial pressure p_i of a component i is proportional to its mole fraction x_i (< 1) and the vapour pressure p_{bi} of the pure component: $p_i = p_{bi} * x_i$. If there is only one volatile component (e.g. water) in a solution, the total pressure is equal to the partial pressure of this component ($p = p_i$). Then the vapour pressure of this component is $p_{bi} = p / x_i$. It is higher compared to the evaporation of the pure component. Therefore the boiling temperature of a solution is higher than the one of a pure substance. Example in [Zogg 1983].

Figure 3-1 Simplified principle of mechanical vapour recompression without the extra heat recovery by preheating the feed.
C compressor, D condensate, E exhaust vapour, F feed, H heating steam, K concentrate



Peter von Rittinger, an Austrian engineer was the first to try the realisation of this idea on a pilot scale. His theoretical considerations in 1855 showed possible energy savings of as much as 80% by the use of the heat pump technology in comparison with direct wood firing. He designed and installed the **first known pilot heat pump for heating only** with a capacity of 14 kW, for the salt works in the village of Ebensee in Upper Austria. The start-up of Rittinger's "steam pump" was in **1857.** But his closed cycle remained an experiment. Technical maturity was not yet reached. Beside the somewhat strange closed cycle idea, many process problems (such as the not suitable batch boiler with to many interruptions in order to remove the salt and fouling of the heating surfaces due to gypsum and lime) arose [Wirth 1955, 1995], [Lieberherr 2007].

4 INDUSTRIALISATION 1876-1918

In this period the functional demonstrators of the pioneers were replaced with **more reliable and optimised machines** on the basis of a rapidly advancing scientific knowledge and industrial manufacturing ability. The refrigeration systems began to become industrial products manufactured on an industrial scale. The German Carl von Linde was the most important person to bring about the change. He was not only a talented engineer and entrepreneur, but an outstanding academic researcher and teacher as well. The activities at his Munich institute were dedicated to practical applications. As early as 1875, the Polytechnic Society of Munich (directed by M.Schröter) undertook the first comparative tests on refrigeration machines.

Around 1900 most fundamental inventions had been made. By 1918 there were many compressor manufacturers in the U.S.A. and in Europe. In Switzerland it were Escher Wyss in Zurich, Sulzer in Winterthur and the Société Genevoise in Geneva [Thevenot 1979].

Heat pumps for space heating remained visions of some engineers at that time. The Swiss turbine engineer Heinrich Zoelly[6] was the first to propose an electrically driven **ground source heat pump** for the production of low temperature heat. He obtained the Swiss patent 59350 in 1912. But the technology was not yet ready for his ideas [Wirth 1955].

[6] Heinrich Zoelly of Escher Wyss designed the world's first impulse steam turbine in 1903.

4.1 Components and Refrigeration

Little by little, **the speed of rotation of** the **compressors** was increased. Around 1890, in the U.S.A. for a compressor of 350 kW the mean speed was 40 rpm and went up to 220 rpm in 1916. The heavy refrigeration compressors took up much space. And their efficiency was rather low. But most of them were surprisingly long-living. Machines were known which have not been in service for three quarters of a century. At that time the **steam engine** was the dominant means of driving compressors: Figure 4-1. The electric motor was still in its infancy. The development in the U.S.A. is characteristic: In 1914, 90% of the motive power was produced by the steam engine. But after 1920, this share droped rapidly.

By the end of this period ammonia was the dominant **refrigerant**. Carbon dioxide (CO_2) was still the British choice for maritime installations. Sulphur dioxide (SO_2) ceased to be used in industrial, but on the contrary it was largely used in smaller compressors. Methyl chloride (CH_3Cl) was mostly used in France for small and medium applications. More fluids had been used to a limited extent, for example the hydrocarbons propane (C_3H_8) and isobutane (C_4H_{10}) [Thevenot 1979], [Fischer 2004].

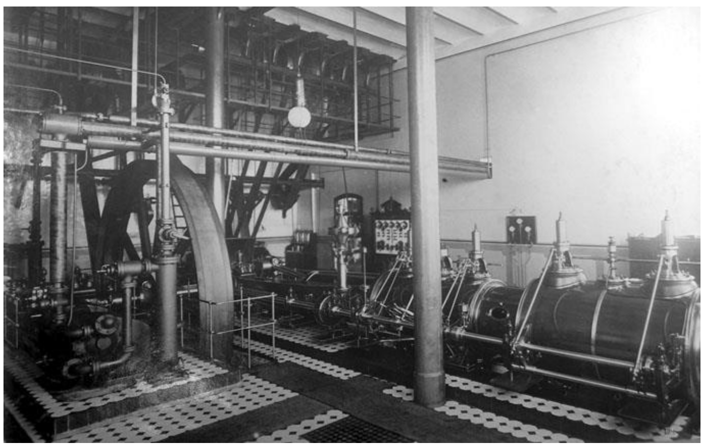


Figure 4-1 Impression of a Sulzer piston compressor (left) driven by a Sulzer steam engine (right), around 1905 [Archive Sulzer, CH-8401 Winterthur]

4.1.1 Vapour Compression Cycle

AMMONIA

The real break-through for **ammonia compressors** was achieved by the German. In contrast to his predecessors **Linde** based his machines **on a scientific approach** and a high quality of manufacturing. Linde's new ammonia compressor was installed in a brewery in Trieste in 1877, and worked there until 1908. In 1877, Linde made an improved type, with a horizontal double acting cylinder. This type of machine was at once very successful. It was taken as a prototype by many constructors and was the subject of many patents. It was made under licence from Linde in Germany by Augsburg (later MAN), in Switzerland by Sulzer, in Belgium by Carels, in Great Britain by Morton & Burton, and in the U.S.A. by Fred Wolf. Thus NH_3 became the most important refrigerant soon.

In 1867 and 1885, the two-stage compound compressor for ammonia was patented by the Australian W.G.Lock. But the first industrial application was in 1889, when the Swiss company **Sulzer** made a **two-stage compressor for ammonia**. In 1892, another two-stage ammonia compressor designed by Stuart Saint Clar was made by York in the U.S.A.

Around 1900 the horizontal two-stage ammonia compressor by Carl von Linde was the traditional design for major refrigeration units: Figure 4-2. One of the most important manufacturers for Linde was Sulzer Bros. in Winterthur. In 1878, **Sulzer** started with the construction of refrigeration compressors and plants as a logical expansion of the company's activities of its "steam engines"[7] and "compressors" divisions. Refrigeration machines were huge and heavy at that time. Nevertheless, in 1878 export of refrigeration plants commenced for an ice making company in Bombay, India. Its two Sulzer piston compressors were driven by two Sulzer steam engines with 37 kW each. The first refrigeration plant in Switzerland was installed in 1879 for the Hürlimann brewery in Zurich. In 1909, Sulzer built a 1.45 MW refrigeration compressor and in 1914 an air conditioning plant for a hotel in Buenos Aires [Thevenot 1979], [Kläy 1994], [Nagengast et al. 2006], [Friotherm 2008].

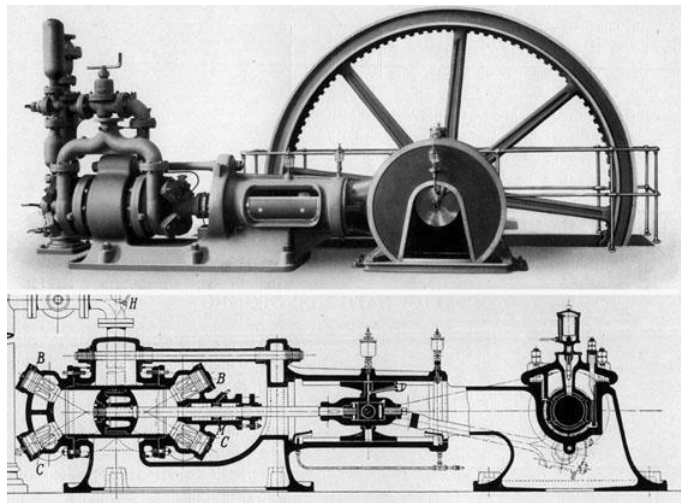


Figure 4-2 Sulzer piston compressor, licence Linde, around 1905 [Archive Sulzer, CH-8401 Winterthur]

OTHER REFRIGERANTS

In 1880, Franz Windhausen designed a **CO_2 refrigeration plant** and 1886 he constructed an operational CO_2 refrigeration compressor. In 1889 J. & E. Hall developed a very successful **two-stage CO_2 machine** for industrial application**.**

Raoul Pictet's new (1876) **SO_2 compressor** was horizontal and not lubricated. The **Pictet machine** was at once built in **Geneva** (by the Geneva company for physical instruments "Société Genevoise") and in Paris and then afterwards in some other countries. It was an instant success and the Pictet machine became rather popular in Europe. But for large installations, ammonia progressively replaced SO_2

Methyl chloride (CH_3Cl, chloromethane) was introduced as a refrigerant in 1878 by Vincent. The methyl chloride compressor was made from 1884 by the Parisian company Crespin & Marteau, which became Douane later. In 1900, Douane constructed a new compressor of 70 kW. It was made under Douane licence by **Escher Wyss** in Switzerland from 1913, and in the U.S.A. from 1920. In 1883, Cassius Palmer introduced **ethyl chloride** (C_2H_5Cl, chloroethane) as a refrigerant and in 1884, Pictet put forward a **mixture of SO_2 and CO_2**, the so called "**Pictet's liquid**".

[Thevenot 1979], [Nagengast et al. 2006].

COMPRESSORS

The principle of the **screw compressor** was patented by Heinrich Krigar in Germany in 1878. He improved his design later that year and lodged a second patent. Both of these patents are amongst the earliest on record, as the German Patent Office had only been formed just one

7 Sulzer started its steam engine business as early as 1851 and built the first horizontal steam engine with valves in 1867 [Kläy 1994].

year earlier. At that time it was not possible to develop the idea any further because of the lack of manufacturing technology. The practical realization had to wait for about fifty years.

One of the first **vane type machines** was the **Lemielle exhauster**, invented in France during the early 1880s, and widely used in Belgium to provide ventilation for collieries. The vanes were mechanically controlled to ensure semi-contact with the outer casing. It was then only a single step to replace the hinged vanes with sliding vanes. The principle of the modern **sliding vane compressor** dates back to the early 1900s when an American by the name of Robert Blackmer invented the first rotary vane pump. In 1909, derived from already existing pumps a refrigeration compressor with sliding vanes, using methyl chloride, on the American ship "Carnegie" was developed. But the positive displacement rotary compressor was not possible to put to practical use until 1920.

The **first turbo compressors** were manufactured at the turn of the 1900s. They were originally developed by steam turbine manufacturers and were widely used for ventilation purposes in deep shaft mining, in particular the coal industry. At that time, the possibilities of producing an impeller were rather limited by the manufacturing technology available. It would be decades before technology allowed highly efficient turbo compressors to be made. It was the American Willis Carrier (1876-1950) who first worked seriously on **radial turbo compressors** from 1911 for air conditioning. Piston compressors were then slow and bulky, and Carrier was looking for a more compact machine. In about 1919, he first tried a German radial compressor with dichloroethylene ($C_2H_2Cl_2$), and then a compressor made by Eastman Kodak in the U.S.A. with dichloromethane (CH_2Cl_2).

In small machines the stuffing box consumed an exaggerated share of the drive energy. In order to tackle these problems, the inventors began thinking of a **hermetic compressor** with drive and compressor in the same casing. The Frenchman Marcel Audiffren came up with a first rather curious technical solution in 1905. But the electric motor of that epoch, with brushes and commutator and also rudimentary electrical insulation, did not lend itself to the realization of the idea, which did not become a commercial proposition until after the First World War. The **first hermetic motor-compressor** was made by the Australian Douglas Stokes in 1920.

The principle of the **scroll compressor** was patented in 1905 by the Frenchman Leon Creux but it did not become commercial until the early 1980s. It waited for manufacturing to develop cost effective methods for high-volume precision machining of these uniquely shaped parts. In 1919, the French engineer Henri Corblin patented the **diaphragm compressor**.

[Thevenot 1979], [Cashflo 2007], [Nagengast et al. 2006].

MISCELLANEOUS

The **first diesel engine** to drive a compressor seems to have been used by De la Verne, in the U.S.A. in 1895. Also of note is the introduction of **cork** as an insulating material by Grünzweig in 1880. Toward 1900, the shell condenser appeared on the scene (after submerged types, double-pipe and multi tubular types). In the new shell condenser water circulated in the tube, the refrigerant condensed outside. In 1902, Vilter in the U.S.A. installed a **liquid separator** in the suction line, to ensure operation of the compressor in the dry state.

[Thevenot 1979], [Nagengast et al. 2006].

4.1.2 Absorption Cycle

One of the main reasons for the dominance of the absorption systems until about 1890 was the direct use of steam. At that time electricity was produced by steam engines with a very low efficiency. The absorption-compression **hybrid system** (combining the absorption and the compression system) was introduced in Australia and Germany 1895, later 1900 in Paris and 1916 in the U.S.A.

The **diffusion-absorption cycle** was established as early as 1899, when H. Geppert obtained a patent for a continuous absorption system, which did not require a solution pump. However his use of air as an inert gas did not succeed.

[Thevenot 1979], [Burget et al. 1999].

4.2 Vapour Recompression – Swiss Pioneering Work

Probably stimulated by the experiments of Rittinger at Ebensee, the **first truly functioning vapour recompression salt plant was developed in Switzerland** by Antoine-Paul Piccard[8] of the University of Lausanne and the engineer J.H. Weibel of the company Weibel-Briquet of Geneva in 1876. In **1877,** this **first heat pump in Switzerland** was installed at the **salt works at Bex**. It was on a larger scale than Rittinger's apparatus (Figure 4-3) and produced around 175 kg/h of salt in continuous operation: Figure 4-4.There was now a really open vapour compression cycle with a two-stage piston compressor: Figure 4-5. In order to prevent the fouling of the heat transfer surfaces the new crystalliser was equipped with a mechanical scraper. After the start up, some severe process problems arose. They were overcome in the following by the talent and impressive engagement of Piccard. The continuous operation was started in 1878. Even though the production capacity after several further improvements turned out to be only about 70% of the expected value, Piccard's systems were a great success. In 1881, a similar plant was built at Ebensee. Four of Piccard's systems were applied in the Salines du Salat in France and one in Schönbeck, Germany. In 1917, a second, bigger plant started up at Bex [Winkler 1995].

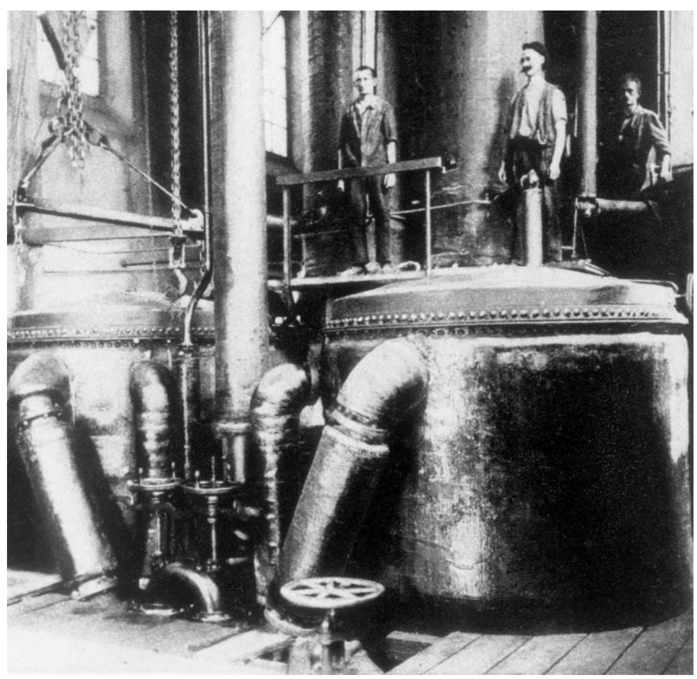


Figure 4-3 Evaporator of Piccard's vapour compression system at the Saline Bex [Kemm 2008]

[8] Antoine-Paul Piccard was born at Lausanne in 1844. He was a professor of the technical faculty of the academy of Lausanne from 1869 until 1881. His innovations covered hydraulic turbine construction as well (Niagara and others). As an entrepreneur he founded the company "Piccard et Pictet" in Geneva – a predecessor of the later "Atelier des Charmilles". Piccard died in 1929 [Kemm 2008].

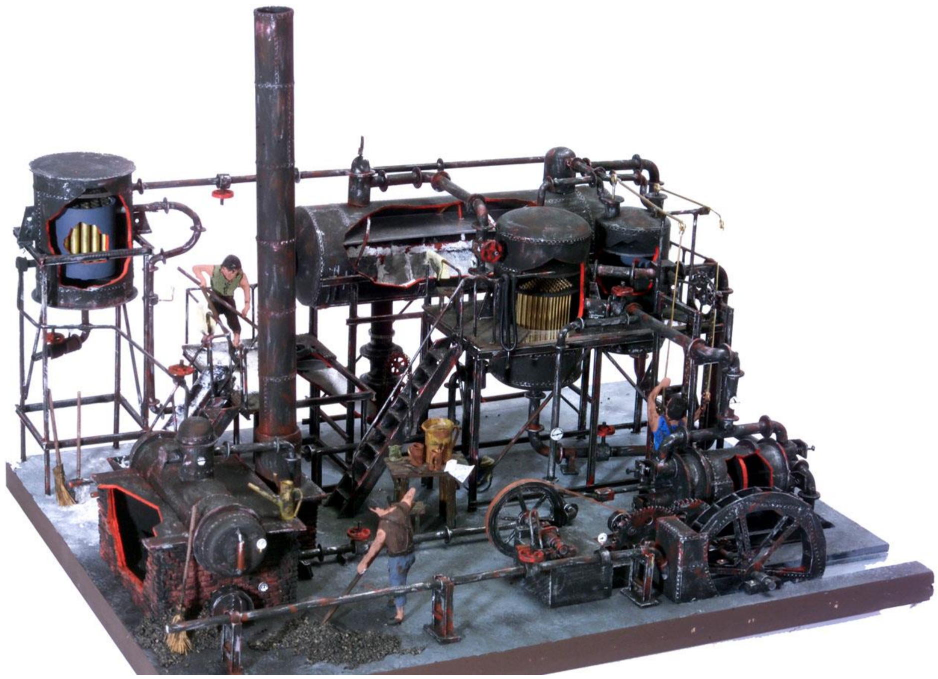


Figure 4-4 Model of Piccard's salt works system of 1878 at the Saline Bex [Made by Jürg Lieberherr, CEO Schweizerische Rhein-salinen Schweizerhalle, CH-4133 Pratteln]

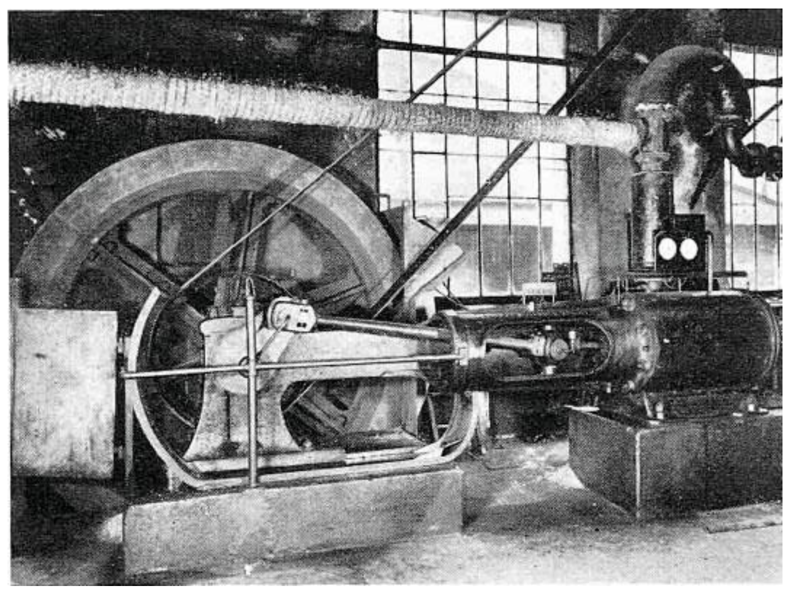


Figure 4-5 Compressor installed at the Saline Bex in 1878 [Wirth 1955]

Astonishingly one year after the works of Piccard his system was slightly modified and patented by the Germans Schäffer and Budenberg in 1877 (Deutsches Reichspatent 191). But they failed to make it working [Winkler 1995].

In the times of the First World War Switzerland suffered from exorbitant fuel prices. But there was sufficient hydroelectric energy available. Under these circumstances 1917 a small industrial scale vapour recompression plant was built at the Jenny dye works in Aarau. This world first **electric driven vapour recompression plant** the exhaust vapours of around 100°C were compressed to a condensation temperature of 114°C. The plant was built by the Swiss company **Kummler & Matter**. A COP value of 11.7 was measured. By the way the acceptance testing of the plant was supervised by the famous Aurel Boreslav Stodola, a world wide known steam turbine and gas turbine expert of the Swiss Federal Institute of Technology in Zurich. Based on these encouraging results, several other vapour recompression plants were built in Switzerland in the years that followed [Wirth 1936, 1955].

5 HEAT PUMP HEATING BECOMING COMPETITIVE 1919-1950

In this period, heat pumps for space heating and domestic hot water heating were developing from rare first prototypes to a reliable, efficient and - depending on the individual boundary conditions - even economically viable heating device.

5.1 Components and Refrigeration

5.1.1 Vapour Compression Cycle

The **increase in the speed of rotation** of compressors was accentuated. The old horizontal compressor often double acting, turned at 40 to 60 rpm. About 1920 “rapid” compressors arrived at 500 rpm. The changes in the shape and speed of compressors resulted in a reduction of bulk and weight: Table 5-1.

Table 5-1 Piston compressor evolution illustrated by a YORK 350 kW compressor [Thevenot 1979]

Year	Speed of Rotation rpm	Number of Cylinders	Specific Power W/kg	Refrigerant
1910	70	2	7.6	NH_3
1940	400	4	49	NH_3
1975	1750	16	233	R-22

After 1918, the **electric motor** became the first choice for driving the compressors. In 1925, an American enquiry showed for refrigeration compressors that they were driven 36% by steam engines, 58% by electric motors, 4% by diesel engines and 2% by gas engines. About 1920, the synchronous **electric motor, directly attached to the compressor**, without belt drive became popular [Thevenot 1979].

REFRIGERANTS

Despite the obvious advantages, refrigeration had its problems. Refrigerants like **sulphur dioxide** and **methyl chloride** were causing people to die. **Ammonia** had an equally serious toxic effect if it leaked. Refrigeration engineers searched for acceptable substitutes until the late 1920s, when a number of **synthetic refrigerants** were developed. In **1928**, **chlorofluorocarbon refrigerants** were synthesized by the General Motors Research Lab team of Thomas Midgley, Albert Henne and Robert McNary for Frigidaire. The development of the CFCs R-11 and R-12 as substitutes for ammonia, sulphur dioxide and methyl chloride was announced publicly in 1930. The best known of these substances were patented under DuPonts brand name of Freon. Fluorinated, chlorinated and sometimes brominated hydrocarbons are inflammable, odourless, compatible with lubricants, relatively cheap to produce, toxic only in extremely large concentrations and they have favourable thermodynamic properties as well. This was a great step forward – at least before the environmental problems of the CFCs were discovered long after. It was mainly after 1945 that the use of halogenated hydrocarbons expanded outside the U.S.A. as well. At the same time their variety increased, to meet all the different needs.

In **1936**, Albert Henne, co-inventor of chlorofluorocarbon refrigerants, synthesizes the **HFC refrigerant R-134a.** This refrigerant was acclaimed in the 1980s as the best non-ozone depleting replacement for the most commonly used chlorofluorocarbons. Nevertheless especially in Europe NH_3, SO_2 and CH_3Cl remained the most important refrigerants in the time between the two world wars.

[Thevenot 1979], [Nagengast et al. 2006].

COMPRESSORS

In 1920, W.S.E. Rolaff introduced the **rolling piston rotary compressor**, first manufactured by Norge in Detroit as "Rollator" and using sulphur dioxide as a refrigerant. Around 1920, General Electric began with mass production of **hermetic compressors** for household refrigerators.

In 1920, Sulzer began the larger volume production of the **two cylinder refrigeration compressor**. The serial production of vertical refrigeration compressors for NH_3 and CO_2 followed in 1925. In 1927, Sulzer built **the world's largest reciprocating refrigeration compressor** with a capacity of 9.4 MW. In 1937, this was followed by an even larger version of 11.6 MW (Figure 5-1). In the early 1930s, Sulzer introduced the "**dry labyrinth piston compressor"** for compressing air, which needed no lubricant: Figure 5-2 (1: labyrinth piston, 2: cylinder wall, 3: throttling point, 4: volume chamber, 5: vortex). From around 1955, it was modified for the use as a refrigeration compressor. Nowadays it is made and exported world wide in an advanced version under the trade name "Laby" by Burckhardt Compression in Winterthur mainly for the petrochemical industry with up to more than 25 MW.

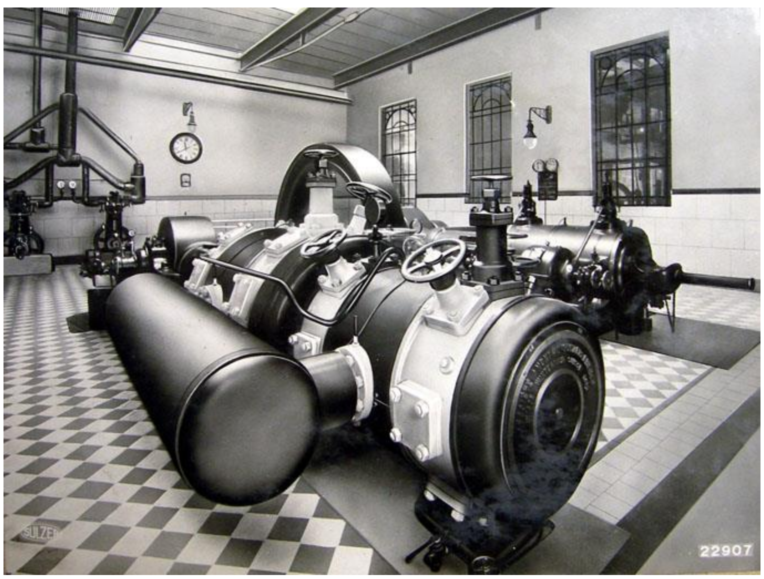


Figure 5-1 Large Sulzer compressor with steam engine in the background around 1925
[Archiv Sulzer, CH-8404 Winterthur]

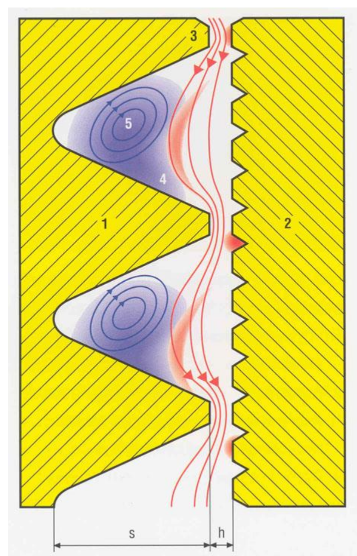


Figure 5-2 Flow within the sealing labyrinth of a dry labyrinth piston compressor [Burckhardt Compression, CH-8404 Winterthur]

The **sliding vane compressor**, formerly used for air, was used for refrigerants from 1920, for the first time in Germany, the U.S.A. and in **Switzerland**. From 1922, Sulzer made the "**Frigorotor**" and the larger types "**Frigocentrale**". "Frigorotor" was a compact refrigeration unit with a refrigeration capacity of 1.2 – 11.6 kW and methyl chloride as a refrigerant.

Sulzer began making turbo compressors as early as 1909 and entered the refrigeration market in **1927** with a multistage **turbo compressor** for NH_3 **with steam turbine drive**. Brown Boveri[9] (BBC) focused on turbo compressors, and in **1926** it produced **an ammonia machine of 9.3 MW**, followed by one of 17.4 MW in 1927. Later BBC used ethyl chloride and ethyl bromide, and then CFCs. In 1935 their “**Frigobloc**”, a water or brine cooler, was equipped with compressors with a capacity of 23 kW to 1.4 MW. Prior to 1940, for radial turbo compressors 5 to 6 wheels were needed. The development went to faster and faster peripheral speeds. From 1940 to 1960 most radial turbo compressors had 2 to 3 wheels. After 1960, more and more single wheel compressors with peripheral speeds close to sonic were made.

Escher Wyss made a **rolling piston compressor**, the so called “**Rotasco**” in 1936. This compressor type was chosen for the first European heat pump in Zurich City Hall; Figure 5-3, Figure 5-4.

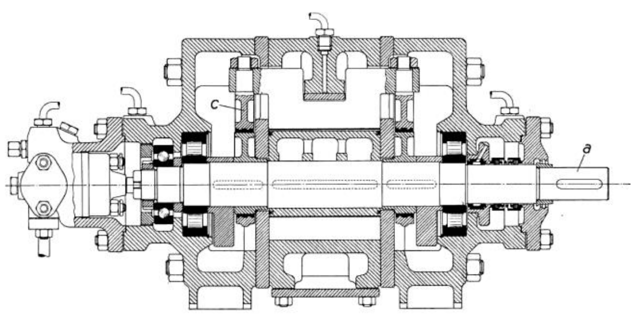


Figure 5-3 Cross section of an Escher Wyss Rotasco compressor [Egli 1940]

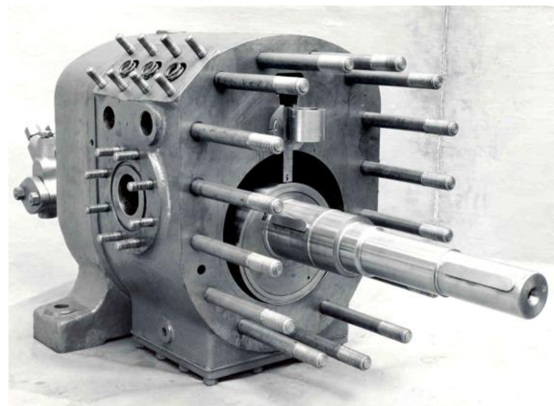


Figure 5-4 Rotasco compressor, City Hall of Zurich, 1938 [Hochbauamt, CH-8090 Zürich]

In 1923, Willis Carrier built a prototype **radial turbo compressor** chiller using carbon tetrachloride and dichloroethylene. In 1927, 50 of his radial turbo compressors were at work with dichloroethylene. Later dichloroethylene was replaced with CFCs (R-11, followed by R-12), which are most suitable for radial compressors. The Trane Company, in the U.S.A. used R-113 for its radial compressors in air conditioning. **Axial turbo compressors** did not appear in refrigeration until after the Second World War, and then mainly in large installations for liquefying natural gas.

1934 Alf Lysholm of the Swedish steam turbine manufacturer Ljungstroms Angturbin was looking into light weight compressors for gas and steam turbine use. By this time the original **screw compressor** patent rights had expired. Lysholm developed a practicable profile of the screw compressor and tested various configurations and rotor lobe combinations. He solved the problem of the shape of the rotors, but he also cared for the manufacturing and patented a method for accurately machining the rotors. The 1935 patent shows his asymmetric 5 female - 4 male lobe rotor design, although the shapes had been 'fine tuned' over the years, this became the basis of the later screw compressors. The application was limited to air compression purposes yet. For refrigeration purposes the accessible pressure ratio was too low. Another four decades passed until the screw compressor became a competitive refrigeration compressor.

Small compressors for household use came about as late as 50 to 60 years after the industrial compressors. They could not be realised before less energy consuming rotary shaft seals and an exact and reliable automatic control were developed. In the 1930s, capacitor starting of

9 The relevant activities of the former Brown Boveri Company went to Asea-Brown-Boveri (ABB) in 1988.

the motor became common and the hermetic unit was perfected. After 1940, the equipment was reduced in size namely by new electric motor types.

[Thevenot 1979], [Kläy 1994], [Nagengast et al. 2006], [Burckhardt Compression 2007], [Cashflo 2007], [Friotherm 2008], [Steiner 2007].

MISCELLANEOUS

The **plate heat exchanger** was invented by Richard Seligman of the Aluminium Plant & Vessel Company Limited (APV) in 1923. By the large surface, the short heat transport distances, the perfectly guided flow by corrugations in the plates, and the freedom in flow splitting arrangements, it brought a revolutionary size reduction and a much lower refrigerant content of the heat exchangers. In addition plate heat exchangers can be aggrandized retroactively. At the beginning it needed well sealing gaskets to prevent the fluids from escaping.

Probably the first **thermostatic expansion valve** was invented by E. Diffinger of the Etablissement P. Colombier Fils in Paris in 1923. Three years later H. Thompson invented a modern type thermostatic expansion valve and got an U.S.A. patent in 1927. In 1925, R. Bernat filed a patent on a first type of a **floating valve** for refrigerant control. 1927, the **capillary tube refrigerant control** was invented by T. Carpenter. In the late 1940s, cork as a thermal insulation material faced superior competition from **insulating foams**.

[Thevenot 1979], [Nagengast et al. 2006].

5.1.2 Absorption Cycle

Two decades after the invention of the **diffusion-absorption cycle** by H. Geppert the Swedish Carl Munters and Baltazar von Platen succeeded in employing hydrogen as an inert gas instead of air. They were granted a patent in 1920, samples of **refrigerators** were produced in the late 1920s [Theveonot 1979], [Burget et al. 1999]. Their noiseless ammonia-water refrigerator cycle worked without any moving parts and was able to operate by gas, kerosene and electricity. An additional advantage of this technical revolution was low price compared to the existing compression cycles. In 1925, the Swedish **Electrolux** bought the patents of Munters and Platen and started production in 1926. Later the absorption refrigerator became a worldwide success. After 1927, the manufacturing was expanded by several companies in the U.S.A.

The patent rights of Electrolux first expired in Switzerland (in consequence of the Second World War they were extended for 6 more years in the rest of Europe). Hans Stierlin – a later honorary doctor of the Swiss Federal Institute of Technology – took the chance, improved the cycle and began manufacturing refrigerators in his **SIBIR** company in Schlieren from 1944 on. Compared to the compressor refrigerators available at that time his refrigerators were sensationally cheap and the demand grew enormously. In the 1960s, SIBIR became a synonymous with refrigerator. In Europe 1962 around 50% of the domestic refrigerators were of the absorption type. Stierlin improved the efficiency of the process significantly by recovering the heat of the gaseous ammonia coming from the rectifier (about 1/3 of the process input heat!). He has applied for the patent in 1967 and it was approved in 1969 [Stierlin 1969]. A comparable improvement of the rectification process was reported by A. Lenning [Lenning 1971], [Wassermann 2007]. Competition with the vapour compression technique became harder when cheaper, quieter and more efficient hermetic compressors with the new synthetic refrigerants penetrated the market. The sales volume of SIBIR broke down by the end of the 1980s. Around 1990, SIBIR was sold to Electrolux [Wassermann 2007].

By the way the famous Albert Einstein was also interested in the absorption cycle. Stimulated by accidents with vapour compression refrigerators the Hungarian assistant Leo Szilard motivated Albert Einstein for the development of an absorption refrigerator. Szilard and Einstein filed a patent application, granted in 1930, for an absorption system to cool an icebox, but for whatever reason the device did not function as envisioned.

Around 1930, there was interest in the **use of industrial waste heat** for absorption refrigeration. Already some installations were in use in the U.S.A., Germany and France before 1935. In 1932, G. Maiuri introduced the **multi-stage ammonia absorption machine** in Great Britain.

A gradual transition from the dominant use of the ammonia water pair began in the 1930s. In about 1937, Kathaber used **lithium chloride and water** in an open absorption system. The most marked change in absorption refrigeration machines was the development of the **lithium bromide / water systems** which began around 1940. A study by Servel, Carrier and others showed this system to be very convenient for producing a cold temperature around +5°C at lower heating temperatures compared to ammonia / water systems. As the main barriers for these systems crystallisation and corrosion were identified. **Carrier** conducted serious studies on the system from 1938, and made the first 430 kW steam heated machine in 1945. The Golden Age of Absorption began. By 1960, Carrier had already delivered 1’500 large lithium bromide machines. In the U.S.A. 30% of the refrigeration machines were of the absorption type in 1965. [Thevenot 1979], [Burget et al. 1999], [Nagengast et al. 2006].

5.2 Heat Pumps for Heating – Swiss Pioneering Work

Switzerland suffered from a fuel supply shortage during and after the First World War and there was great potential for the extension of hydroelectric power. Hardship makes people creative. A serious discussion on the chances of heating using heat pumps began around 1918 [Wirth 1955]. It was stimulated by the **first paper on heating using heat pumps** published in one of the most important Swiss engineering journals [Hottinger 1920]. It concluded as follows: *“Taking into account the unstable market prices it does not make sense to establish generally accepted cost estimations. But it is worth while to assess the prospects of the realization of heat pumps case by case. Especially in Switzerland there is a need for paying more attention to the issue of electric driven heat pumps”.*

In his comprehensive book, Thevenot wrote [Thevenot 1979]: “*The heat pump is a refrigeration system used to produce heat. There is a temptation to regard this system as one which needs a world crisis before it is developed…*” and elsewhere “*It was **Switzerland**, a land poor in fossil fuel reserves but rich in hydroelectric power, which **gave the impetus to this method of heating**, from 1939, after having made some experiments around 1930*.”

Prior to und during the Second World War Switzerland again experienced a severe coal supply shortage. Figure 5-5 illustrates the precarious situation of Switzerland at that time. These arising problems were on the horizon years before. It firmly stipulated the construction of more hydroelectric power plants before and during the Second World War and a rational use of the hydroelectricity, the so called “Swiss White Coal” [Wirth 1941]. A further reason for Switzerland to become a **heat pump pioneering country** was the high level of its mechanical and thermal engineering. It had reached a leading position in energy engineering as is illustrated by the world’s first industrial scale gas turbine power generation plant constructed by the Brown Boveri Company in Baden and started up in the Swiss town of Neuchâtel in 1939[10].

[10] This 4.4 MW gas turbine plant had an efficiency of 17.4% and was in operation from 1939 until 2002. It had got the Landmark Award of the ASME in 1988 and it is now exposed as an industrial memorial at the ALSTOM site in

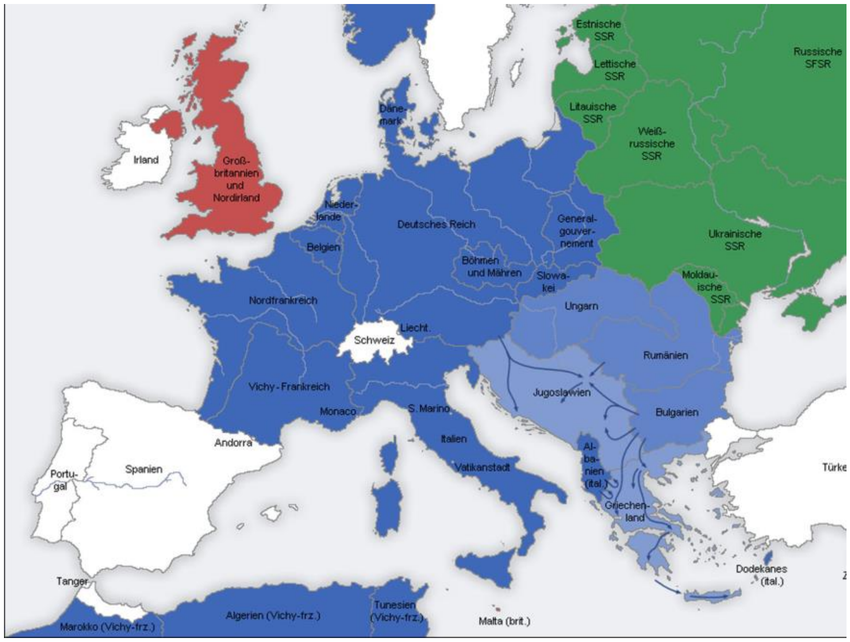


Figure 5-5 Switzerland in 1941 – completely surrounded by fascistic controlled countries (blue) [wikimedia.org]

Heating by making the most of waste heat from refrigeration cycles at skating rinks and breweries was practiced in the middle of the 1930s already. In Switzerland 35 heat pumps were manufactured and installed between 1938 and 1945 mainly by the two constructors **Sulzer** in Winterthur and **Escher Wyss** in Zurich. **Brown Boveri** in Baden took an active part as well. These heat pumps were used for space heating, but also for other low temperature heating purposes (e.g. domestic hot water, water in a public swimming bath). The main heat sources were lake water, river water, ground water and waste heat [Thevenot 1979], [Bauer 1944].

Another important motive to realise these first heat pumps was to **gather experience** with this new heating system and to **assess its potential** to serve the future Swiss heating demands. The key data of the historic heat pump systems installed between 1938 and 1943 in Zurich City are listed in Table 5-2. After five years of successful heat pump operation pleasing results were reported in 1944 [Egli 1944]. It put on record that the heat pump was working without any problems and that heat pumps do not need more attention to operate than conventional heating systems.

After the Second World War heat pumps remained an important issue in Switzerland. The start-up of many heat pumps brought the Swiss Federal Council (Swiss federal government) to a circular letter addressed at all Swiss cantons in which was asked for the necessity of a special law, regulating the heat withdrawal from rivers. The circular called on the cantons for reporting the federal government about heat pump systems with river water as a heat source and to set up usage zoning plans. In the interest of being less dependent of fuel imports the Federal Council recommended not to charge any fees for the heat withdrawal [Bundesrat 1949]. In **1955**, in Switzerland there were **about 60 heat pumps**, the largest of them attained 5.86 MW.

5.2.1 Historic Heat Pumps of Zurich

1938 ZURICH CITY HALL (100 KW)
(House of the City Council and of the Canton Council – Rathaus Zürich)

A worldwide milestone was the installation of the first heat pump in the Zurich City Hall (Figure 5-9) by the **Escher Wyss** company. This heat pump system was planned by the engineering

Birr. For comparison, it may be noted that a modern ALSTOM gas turbine is achieving 288 MW with an efficiency of 37.8% [GWA 2007].

company Heinrich Lier in Zurich. It had to replace single room wood stoves. There was too little room for solid fuels such as wood or coal. Therefore the choice was only between light fuel oil, coal gas and electricity. With regard to the supply shortage for coal and oil becoming more and more critical (see Figure 5-5) and also the hurting experiences during the First World War heating by electricity was decided. In 1937, Escher Wyss designed an energy efficient heat pump solution (Figure 5-8) and offered it for 27'850 Swiss francs. Worth to mention, the system was accounted finally for only 24'090 Swiss francs. The river Limmat with an average temperature around 7°C during the heating period gave an ideal heat source. It was cooled down for about 1.5 K in average load conditions. The nominal heating capacity of the heat pump was 100 kW. The feed temperature was around 60°C. In order to cover peak load

Figure 5-6 Zurich City Hall with the river Limmat as a heat source today [GNU Free Document]

Figure 5-7 The historic "Rotoasco" compressor today [Friotherm 2008]

situations a boiler with a 65 kW electric resistance heater was installed. As a novelty for Europe the heat pump was able to cool in the summertime (this is not the case for the heat pumps to follow in that period). The switch over was done by manually moving four three-way valves. The rest of the operation was **fully automatic** already. To prevent excessive noise and vibration Escher Wyss implemented its patented "Rotasco" rolling piston compressor described above: Figure 5-4, Figure 5-7. It completely satisfied the expectations in volumetric efficiency, low noise and vibration levels. The 42 kW electric motor drove not only the compressor but also the 8 l/s river water pump and the 3.6 l/s circulation pump of the central water heating: Figure 5-9. The refrigerant was R-12. Evaporator and condenser were of the horizontal shell and tube type: Figure 5-10. The system was built and installed in 1937-1938. The start up was in 1938.

Detailed measurements were taken during the heating season 1938-1939. With taking into account all auxiliary equipments a seasonal performance factor of 2.16 was measured. The Lorenz efficiency varied between 22% and 28%. The placement of the heat pump into a former office demanded a break through a wall. This historic heat pump is the oldest still operational example. In 1964, the compressor needed a complete revision and in 1983-1984 the heat pump system was worked over and the ventilation system was replaced [Egli 1938, 1940], [Dürr 1996]. It was as late as 2001, following 63 years of operation when the historic Escher Wyss heat pump was replaced with a new one made by Scheco, Winterthur. The new R-134a heat pump with a maximum heating capacity of 134 kW attains at a river temperature of 3.5°C and a feed temperature of 55°C a COP value of 3.27 or a Lorenz efficiency of 51% (without auxiliary equipment). But the historic heat pump is still in operation for 1 hour every week to keep it alive (Figure 5-7). Since 2001 it is operating with R-134a instead of R-12 [Fluri 2007].

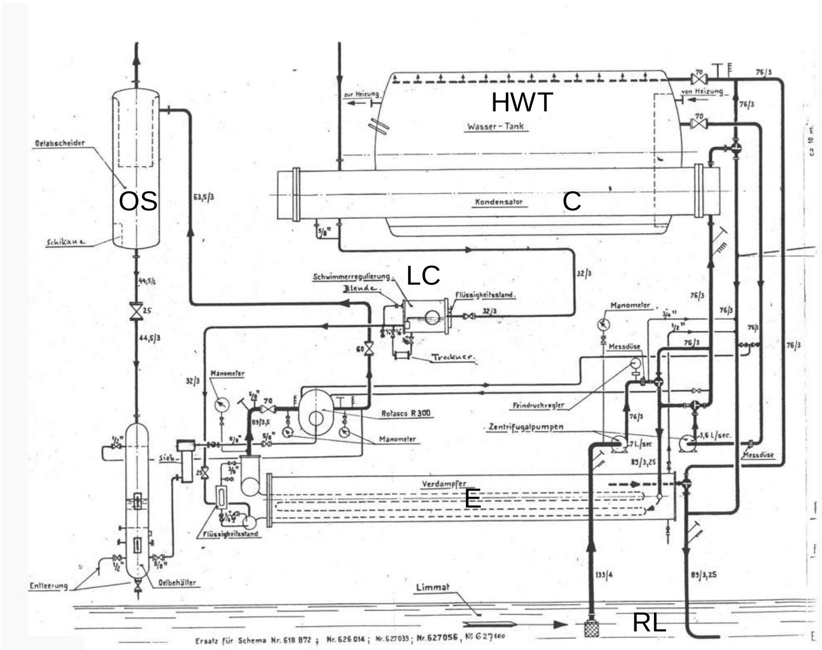


Figure 5-8 Flow sheet of the historic City Hall heat pump, 1938

HWT heating water tank,
C condenser,
OS oil separator,
LC level control,
E evaporator,
RL river Limmat

[Fluri 2007]

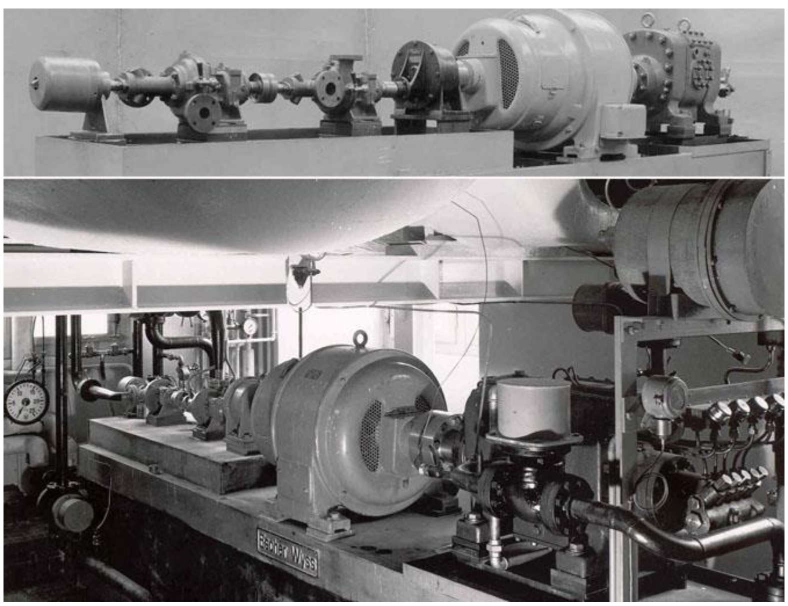


Figure 5-9 Heat pump subsystem on the test bench (upper) and installed in the City Hall, 1938 (lower) [Fluri 2007]

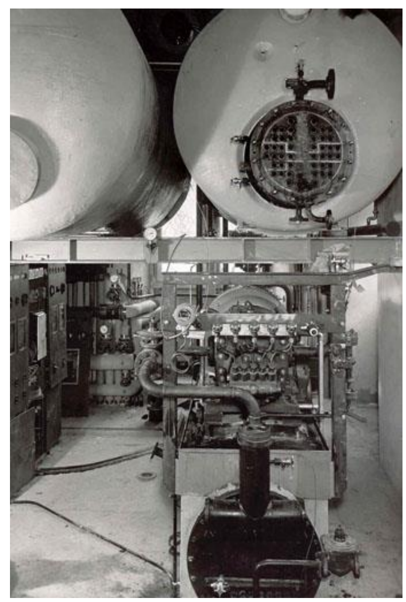


Figure 5-10 Heat pump in the City Hall with opened condenser and water tank (upper) and evaporator (l.)

1941 ZURICH-CITY INDOOR SWIMMING POOL (**1'025 KW**, HALLENBAD ZÜRICH-CITY)

The newly-built indoor swimming pool in the centre of Zurich City (Figure 5-11) had an annual heating requirement of around 5500 MWh. That meant 90 former railway wagons with 10 tonnes of coal per year - in the shortage of the war years an enormous quantity! Hydro electricity was still available to a limited extent. But it had to be used more rational than just by an electric resistance heating. Encouraged by the impressive achievements in the city hall the city council decided in favour of a heat pump solution. The indoor pool, with its relatively low temperatures promised an even more efficient operation of a heat pump. Moreover, there was an excellent heat source available. The fresh water feed for the pool was heated up to the requested temperature of 23 °C (nowadays standard is 28 °C…) by the waist heat of a nearby transformer station. But this was not sufficient to keep the temperature of the pool at 23 °C. In order to take advantage of the low night-time electricity tariff **Escher Wyss,** who planed and constructed the ammonia heat pump system, built the heating up of a partial volume of the pool with a heating power input of 325 kW to a temperature of 45 °C on night time. In **a first heat pump system** with the outflow of the pool as a heat source two of the total five compressors (Figure 5-13)

Figure 5-11 Zurich-City Indoor swimming pool today (left)

Figure 5-12 Compressors today [Scheco]

served for that purpose. A **second heat pump system** with three further compressors heated floor, ceiling, walls, piers and deck benches. This space heating system had a maximum feed temperature of 50 °C and a maximum heating capacity of 700 kW. By this way thermo-active elements were realised at that time already! Lake water from the ancient moat "Schanzengraben" was used as a heat source for this heat pump heating system: Figure 5-14. An electric supplemental electric resistance heater of 2000 kW served for heating up the pool after a complete replacement of the water once a month [Hochbauamt 1941].

In 1979/1980, as a part of a revision of the indoor pool the original second heat pump system with the three piston compressors was replaced with a Sulzer turbo heat pump with 1.2 MW heating capacity and R-12 as a refrigerant [Hochbauamt 1980]. It proved to be largely over dimensioned. Also in order to replace R-12 as a refrigerant all previous heat pumps were replaced with a new heat pump system in 1996. Its heating capacity was drastically reduced to

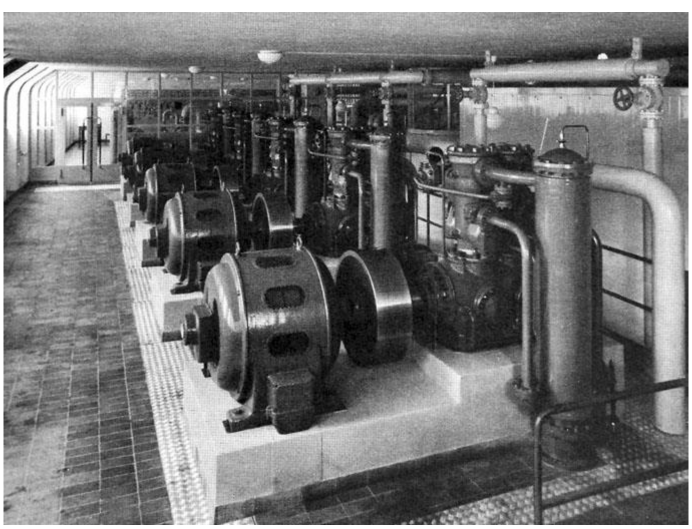


Figure 5-13 Escher Wyss piston compressors , 1941 [Hochbauamt 1941]

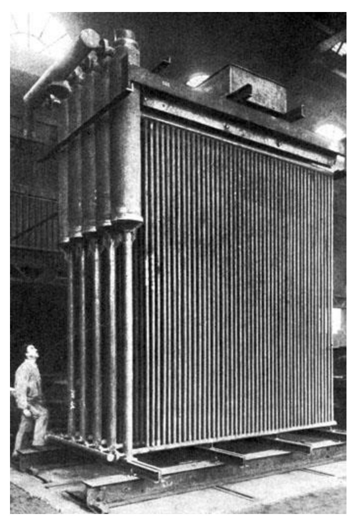


Figure 5-14 Submerged Escher Wyss evaporator, 1941 [Hochbauamt 1941]

100 kW for the first (pool water heating) and to 325 kW for the second heat pump system (space heating). The peak load is covered by an oil boiler with a maximum power of 550 kW. With heat recovery from the out flowing pool water and the dehumidification, lake water and ground wateras aheat source the new R-134a heat pump system is attaining a Seasonal performance factor of 3.2. While the historic heat pump compressors in Figure 5-13 were filling out a whole machine hall, the machines of 1996 found enough space in a cabinet: Figure 5-12. Even if taking into account the reduction in heating capacity from 1'025 kW of the historic machine to 425 kW of the modern one the comparison of the volumes remains impressive. Due to a complete modernization of the busiest Swiss indoor pool the replacement of this third generation heat pump system is already emerging on the planning horizon [Huwyler 2007].

1942 WALCHE PLANT FOR THE UNIVERSITY AREA DISTRICT HEATING (5'860 KW)

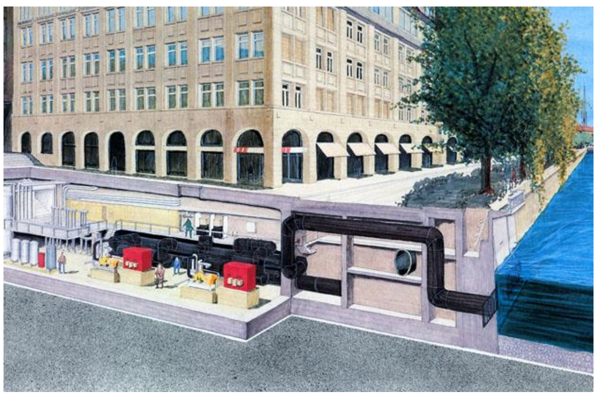


Figure 5-15 Walche plant today [Friotherm 2008]

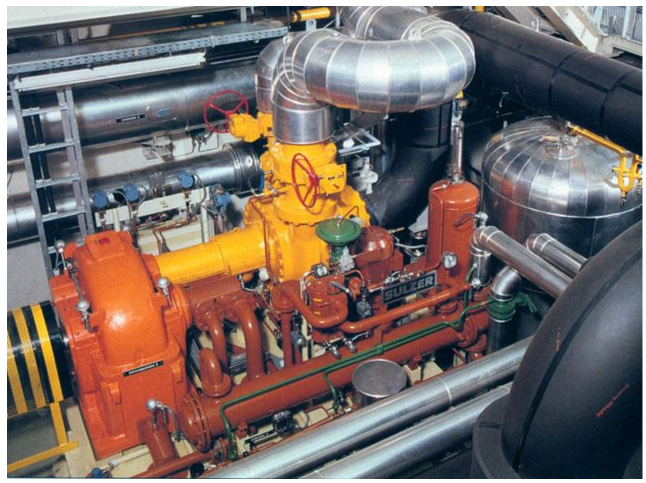


Figure 5-16 Heat pump unit since 1988 [Friotherm 2008]

The increase in the coal price an the insecure fuel supply for the mall Swiss island in the middle of fascist-governed countries, the willingness to keep and strengthen the leading position of the domestic industry and the Swiss Federal Institute of Technology (ETH-Zürich) in the area of thermal engineering and last but not least the clear will to Swiss independence were the main motivations for the construction of a third major heat pump system in Zurich. Under these circumstances the Swiss Federal Council (Bundesrat) approved in 1942 a large heat pump plant at the Walche site on the banks of the river Limmat: Figure 5-17.

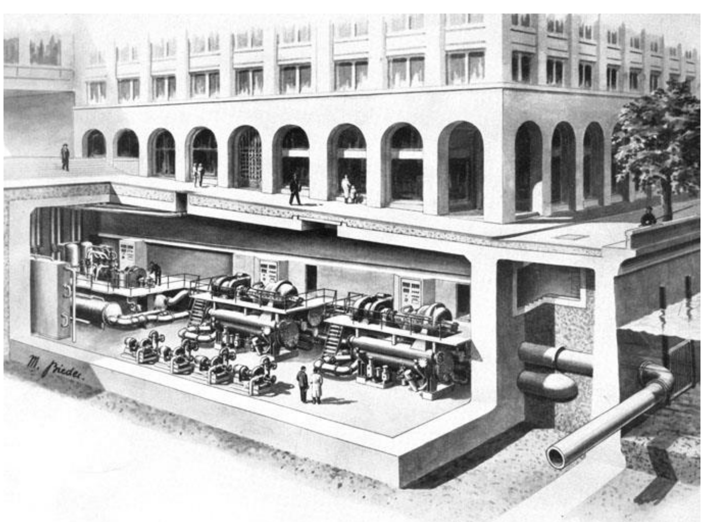


Figure 5-17 5.86 MW heat pump plant at Walche, 1942 [Riesen 2007]

Figure 5-18 Underground machine room under construction, 1942 [Riesen 2007]

The goal of the project was to save 45% of the coal consumption of the district heating system of Zurich built in 1930/32 (Fernwärmenetz der Stadt Zürich). But it should also become a prime example for the new heating system and contribute to research and development. The large heat pump system was built in an extraordinary short period of time. In the same year 1942 an underground machine room was prepared (Figure 5-18), and a heat pump system with three heat pumps with a nominal total heat output of 5’860 kW was built.

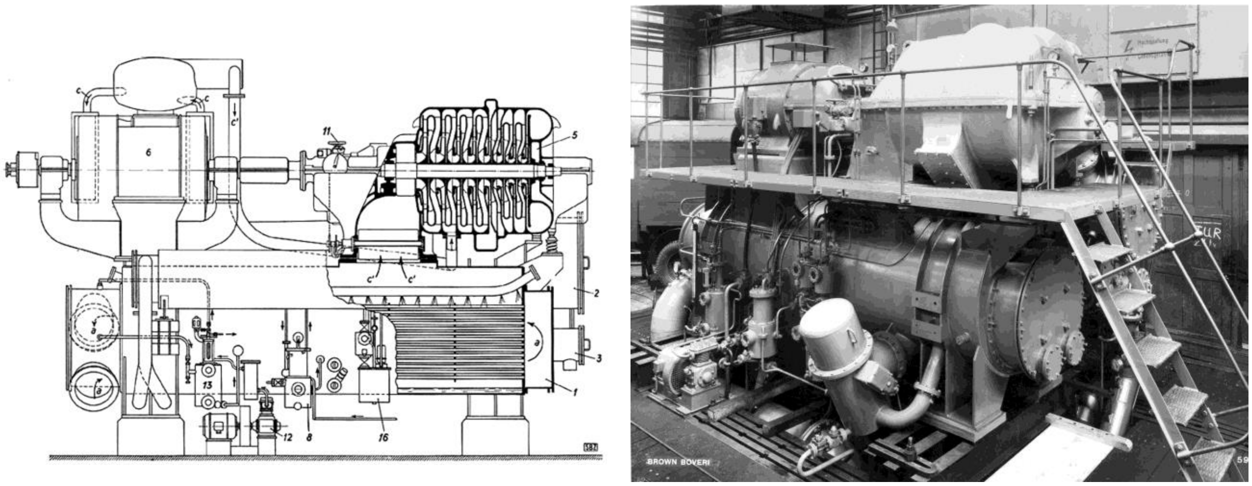


Figure 5-19 Walche plant, 1942: 2 MW BBC heat pump with eight-stage radial compressors [Riesen 2007]

The heat pump system consisted of **three heat pumps**. Two of them were identical heat pumps, called “Thermoblock”, with eight-stage **radial compressors** and 3’200 kg CFC R-11 as a refrigerant of the **Brown Boveri Company** in Baden with heating capacity of 2’000 kW each: Figure 5-19 The third heat pump (Figure 5-20) with a heating capacity of 1’860 kW of **Sulzer** in Winterthur had a three-stage **piston compressor** (Figure 5-21) and used 6’000 kg ammonia as a refrigerant. This astonishing combination was chosen in order to simultaneously collect experiences for turbo and piston compressor heat pumps. The three heat pumps were operated in parallel. The **world’s first integration of heat pumps in a district heating network** with a required feed temperature of 70°C was not an easy task. It was managed surprisingly well. At 9 °C / 71 °C the turbo heat pumps attained a COP of 2.58 and the piston compressor heat pump a COP of 2.73 [Schindler-Fässler and Schindler 1944]. This means **very high Lorenz efficiencies** of 46.5% or 49.2% respectively. However it remains unclear how the auxiliary energies were balanced. The cooling down of the river water by only around 0.6 °C (in 10 meters distance from the re-entry of the water into the river complied with the requirements. More details in [Bauer 1944]. In 1972, following 30 years of operation the plant was shut down due to too high maintenance costs and low fuel oil prices.

As a consequence of the commissioning of a waste incineration plant and the rapidly disintegrating oil price after the oil crisis the heat pump operation paused for 13 years. In 1985/1986, a new turbo heat pump with a heating capacity of 6.5 MW was built and started up by Sulzer. This plant was destroyed by a fire and followed in 1987/1988 by two **new Sulzer Unitop heat pumps** with two-stage radial compressors and R-12 as a refrigerant: Figure 5-16. The total heating capacity of this heat pump system is **13 MW** at 15 °C river and 72 °C feed temperature. It is reduced to 10 MW in cold winter conditions (3.5 °C / 72 °C). The new heat pump system with more than doubled heating capacity was realised in the same room as in 1942. Equipped with an intermediate pressure vessel and supercooling of the condensate an average COP of 3.4 was reached. Of special interest is the filtering of the river water by self-cleaning spherical filters and the continuous cleaning of the evaporator tubes by circulating balls.

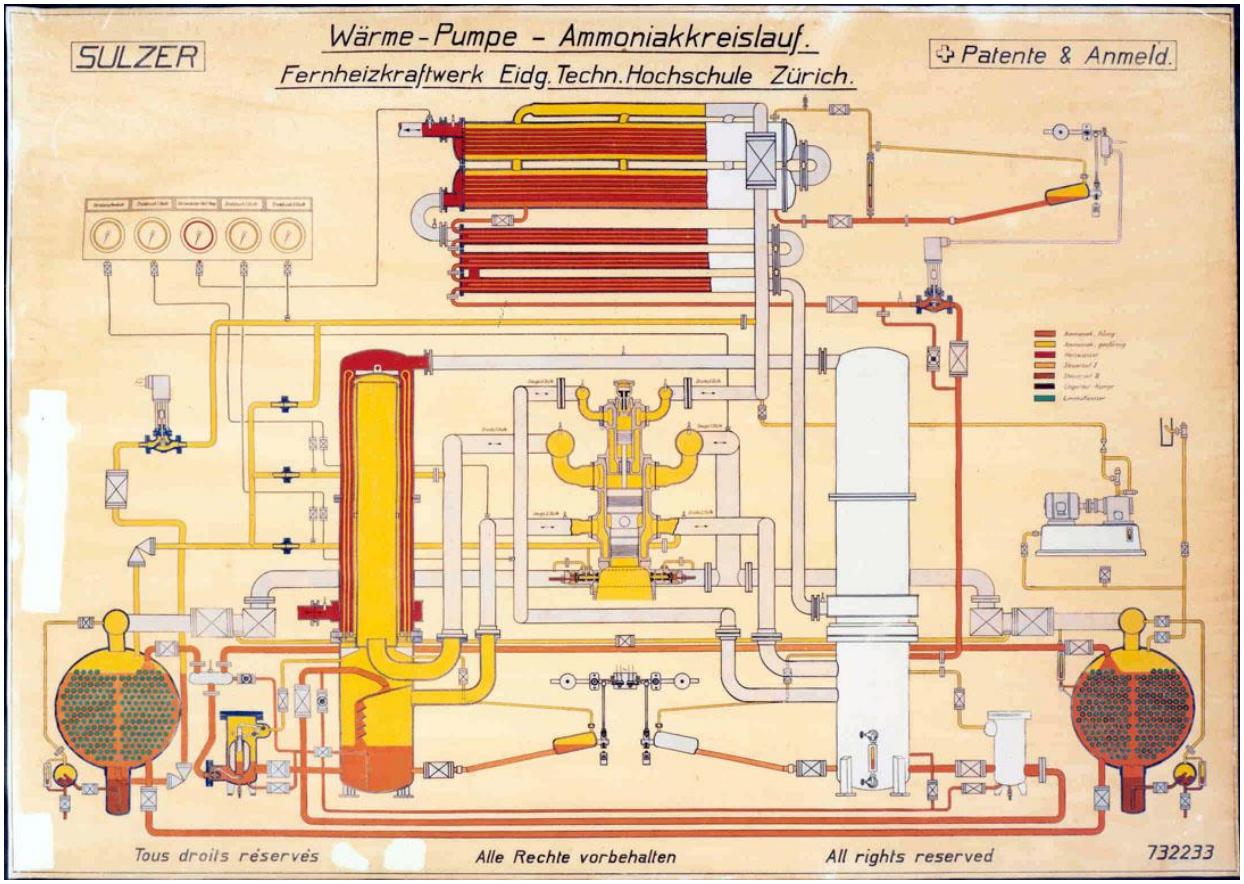


Figure 5-20 1.86 MW Sulzer heat pump with 3 three-stage piston compressors, 1942 [AFB 1988]

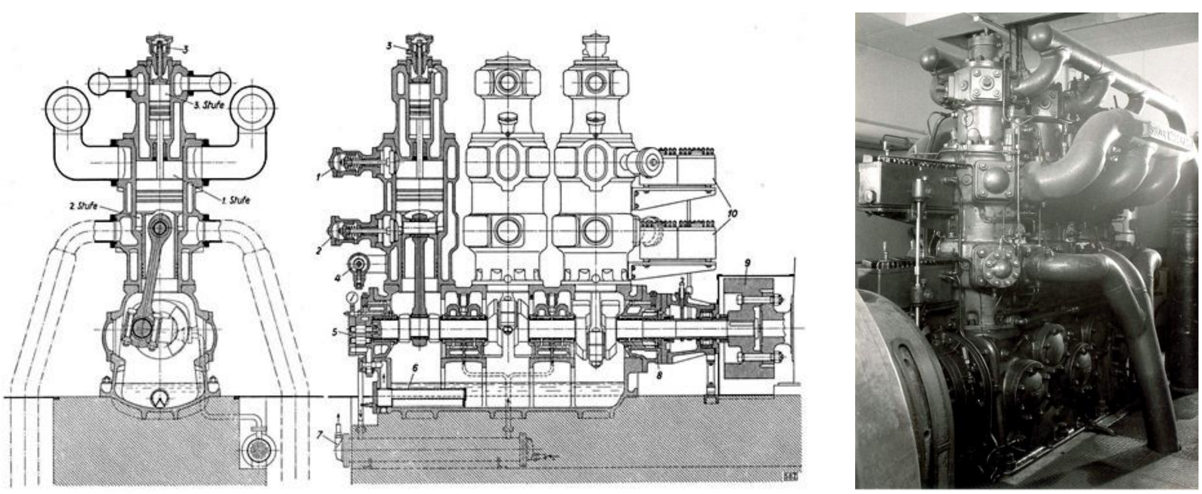


Figure 5-21 3 three-stage Sulzer piston compressors, 1942, [Riesen 2007]

Due to the absence of larger district heating systems in Switzerland this heat pump system remained the biggest one until today. It covered 50% of the heat demand and reduces the consumption of fuel oil by 4'500 t/year and the SO_2 and NO_x emissions by 67% In 1998, the installation had to be modified in order to replace the CFC-Refrigerant R-12 with the HFC R-134a [AFB 1988].

1943 CITY'S ADMINISTRATION BUILDINGS (1'750 KW, AMTSHÄUSER ZÜRICH)

In view of the alarming shortage of the coal supplies the City Council of Zurich approved an offer of **Escher Wyss** for a large heat pump system for the five city's administration buildings in the Werdmühle-Beatenplatz district in June 1943. The **ammonia heat pump** with four two-stage piston compressors (Figure 5-22) used the river Limmat as a heat source again and was installed in one of the administration buildings (Amtshaus 4). At a feed temperature of the water heating system of 50 °C the heat pump had a heating capacity of 1'750 kW. This covered 80% of the total heat demand. The peak load was supplied by a coal boiler. At that time the heat pump system cost was 560'000 Swiss Francs and the extra amount for the constructional costs was 260'000 Swiss Francs. Despite the chaos of the wartime the plant was built in a very

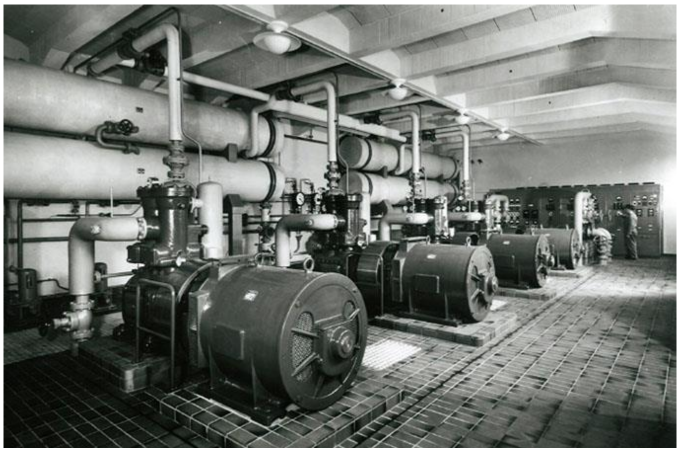


Figure 5-22 Machine hall with heat pumps and condensers, 1943 [Eberhard 2007]

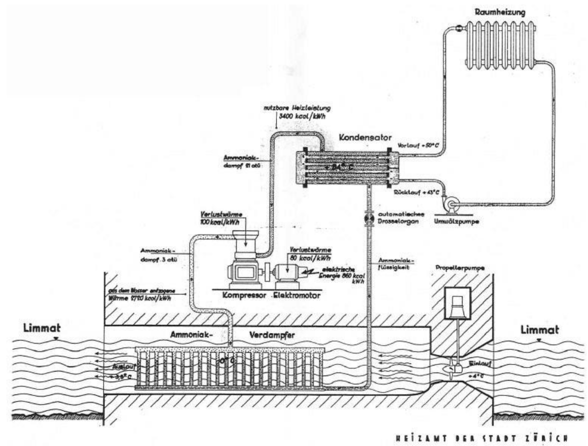


Figure 5-23 Principle of the administration buildings heating, 1943 [Eberhard 2007]

Table 5-2 Key data on Zurich's historic heat pumps

	City Hal	**Indoor Swimming Pool City**	**Walche Plant District Heating**	**City Administration**
Year of Start up	1938	1941	1942	1943
Total Heating capacity [kW]	100	1025	5860	1750
Heating capacity per Unit [kW]	100	325 / 700	2*2000 / 1860	1750
Mode of Operation	Heating (Cooling)	Heating	Heating	Heating
Type of Heat Source	River	Waste Heat / Lake Water	River	River
Temperature Heat Source [°C]	7	23 / 7	9 / 9	7
Temperature Heat Sink [°C]	60	45 / 50	71 / 71	50
COP		8.0 / 3.5	2.58 / 2.73	4.0
Seasonal performance factor SPF	2.16			
Lorenz efficiency	22..28%	55% / 47%	47% / 49%	53%
Number of Compressors	1	2 / 3	2 / 1	4
Type of Compressor	Rolling Piston	Piston	Radial Compressor / Piston	Piston
Refrigerant	R-12	Ammonia	R-11/Ammonia	Ammonia
Heat Pump Manufacturer	Escher Wyss	Escher Wyss	Brown-Boveri/ Sulzer	Escher Wyss

short time. It started up already by the end of 1943. The vertical tube evaporator (Figure 5-23) was placed directly in the river Limmat at the Bahnhofquai north of the Urania bridge. At 7 °C / 50 °C the heat pump system attained a high COP of about 4 or a Lorenz efficiency of very high

53%[11]. Again making up the balance with the auxiliary energies remains unclear [SBZ 1944], [Baumann M. et al 2007], [Eberhard 2007], [Mendler 2007]. Table 5-2 gives an overview on the historic heat pumps of Zurich City.

1943 CANTONAL HOSPITAL – A NON-ENDED PROJECT (KANTONSSPITAL ZÜRICH)

In connection with the Swiss pioneering achievements a non-ended project for the heating of the Hospital of the Canton Zurich is noteworthy. The unusual concept envisaged a central evaporator in the river Limmat and 750 m long ammonia pipes connection to the heat pump in the Hospital 77 m above the Limmat [Egli 1943]. The evaporator in the Limmat had been built already. But after the war the priority for the finalization of the project fell rapidly and it was stopped. As a consequence the evaporator was deconstructed.

5.2.2 Other Heat Pumps of Special Interest

Outside the town of Zurich there were also built many heat pumps. Out of these some of particular interest will be described in the following.

In 1941, Escher Wyss installed a heat pump in the **Baumberger brewery** in Langenthal with **simultaneous use of heat** (flushing and space heating) **and cold** (production of ice and cellar cooling). Sulzer made refrigeration plants with simultaneous use of heat as well. Examples were the systems installed at an artificial **silk manufacturer in Widnau** or in an **industrial butchery in Basel**. By these double benefit systems total COP values up to 5.5 were achieved [Ostertag 1946].

On the initiative of the proprietor an exceptional **ammonia heat pump** with a capacity of only around 10 kW, **driven by a nearby rivulet,** was installed 1943 in the **Truninger** company in Solothurn. The mechanical energy of the small Francis turbine was directly transmitted to the heat pump by a belt transmission. The same rivulet was used as a heat source as well. The condenser was placed in the coiling room to be heated. The operation in cold winter time lead to a time-consuming manual defrosting of the evaporator placed in the rivulet directly. This heat pump system was in operation until 1963. In 1982, the Truninger Company installed a heat pump in its new building in Langendorf again [Truninger et al. 2007].

The heat pump power modulation by **regulation of rotary speed** was realised as early as 1944 in an 128 kW Escher Wyss ammonia heat pump installed in the **electric power station of the Swiss Federal Railways** at the “Etzelwerke” in Altendorf. It used exhaust air of the transformer stations as a heat source. Thanks to a heat source temperature between of 20°C and 30 °C and a heating system feed temperature of (at that time) only 48°C it came up with a very high COP between 6 and 11. The heat pump covered 75% of the total heat demand.

An interesting example of the appetite for new solutions is also the ammonia heat pump system built in 1946 for the **leather goods factory in Schaffhausen** (Lederwarenfabrik Schaffhausen). It consisted of two piston compressors and a steep tube evaporator directly placed in the river Rhine. As a venturesome feature the rooms on the six floors were directly heated by separate **ammonia plate condensers situated in each room**. From them the heat was distributed into the rooms by a forced convection air heating system. **After 62 years** the original heat pump is **still in operation** with modified peripherals (corroded evaporator replaced, number of heated rooms reduced from 9 to 6). And this not for demonstration purposes only [Bosshart 2008]!

[11] Another information to be found is a heating capacity of 1.86 MW with a COP of 4.28 at 4° C / 50 °C. This would result in a Lorenz efficiency of astonishing 61%.

Between 1945 and 1950 Sulzer built several heat pumps as well. Instead of radiators Sulzer introduced very early low temperature radiation heating systems. For the use with heat pumps these were particularly suitable [Ostertag 1947]. A good example for Sulzer's heat pump activities in this period is the administrative building of the **Selve** company in Thun with **groundwater** as a heat source. It covered the total maximum heating capacity demand of 440 kW by 92%. With a maximum supply temperature of 40 °C the water heating system was a low temperature one at that time. Consequently the system had a high a seasonal performance factor of 4.5. In a heat pump system at the **brick factory Frick** (Ziegelwerk Frick) using **humid exhaust air** even a COP of 5.2 was achieved [Brügger et al. 1991].

Therma in Schwanden[12], a manufacturer of electric resistance heating systems planed and built an own heat pump for its house of personal in 1948. This building was at that time well insulated and 70% of the heating demand was covered by a floor heating system already. The rest of the rooms had well dimensioned radiators. The heat pump with ground water from around 7 °C as a heat source was operated with R-12 as a refrigerant and had also to provide hot water of 45 °C. With two eight cylinder compressor units driven by v-belts, the heat pump achieved a Lorenz efficiency of 35% [Ostertag 1949]. However, again it remains unclear if the results of the measurements do include the auxiliary energies or not.

5.3 Heat Pumps for Heating - International Milestones

U.S.A. AND CANADA

In 1930, a house in Tucson (Arizona, U.S.A.) was equipped with a heat pump. There were several **other larger heat pump installations** in the **U.S.A**: 1932 an office building of the Southern California Edison Company in Los Angeles was equipped with a 420 kW air conditioning installation, intended to **cool the rooms**, but a quarter of the power of the turbo system being used for **heating**. The COP for heating was at 9 °C / 23.5 °C as low as 2 [Ostertag 1946] which corresponds to a Lorenz efficiency of only 9.8%. In 1932, Willis Carrier installed his first heat pump at the main office of the Uji utility in **Japan.** In 1933, **Frigidaire** demonstrated the year–round air conditioning of homes at the Chicago World's Fair "Century of Progress" [Nagengast et al. 2006]. Until 1940 there were installed another about 40 heat pumps in the power range of 25 kW to 1'200 kW in the U.S.A. In addition to summer cooling they offered a low efficiency winter heating alternative. But heat pumps remained a curiosity before 1938. Efficiency comparisons of the two compressor air conditioning systems of the Ohio Power Company in office buildings at Portsmouth (air/air) and Coshocton (water/air) showed around 1940 still rather poor efficiencies [Ostertag 1946], [Thevenot 1979], [Groff 2005].

Around 1945, Robert C. Webber, an employee of the „Indianapolis Power & Light Co", was experimenting with his deep freezer. He dropped the temperature in the freezer, touched a heat sink pipe and almost burned his hand. He observed, that heat was lost and realised its recovery by heating up the feed of his water boiler. Thus he provided his family with more hot water than they could use! There was still wasted heat left, so he piped hot water through a coil and used a small fan to distribute heat through the house to save coal. Webber was so pleased with the results that he decided to build a full size heat pump to generate heat for the entire home. Webber also came up with the idea to **pump heat from underground**, where the temperature doesn't vary much throughout the year. 152 m of copper tubing were buried up to 2 meters deep into the ground and a CFC refrigerant was evaporated in the tubing to gather the ground heat. The **ground coupled heat pump** was born and the **direct expansion system** as well. The heat output of the heat pump with an electric power consumption of 2.2 kW was dis-

12 Therma AG in Schwanden was transferred to Electrolux in 1978. It became one of Europe's most modern manufacturing sites for larger domestic appliances.

tributed into the home by a hot air heating system. The next year, Webber sold his old coal furnace. In 1949, the first ground coupled heat pump was installed in **Canada** [Sanner 1992], [IGSHPA 2007].

There was an early boom in demand for **unitary window air conditioners** for cooling and flameless heating in the U.S.A. By 1947 43'000 units were sold already [Nagengast et al. 2006]. But as mentioned above, there were larger installations such as the heat pumps for heating and cooling of the Equitable Building (an office building with 14 floors), initiated in 1948 [ASME 80].

GREAT BRITAIN

The first residential heat pump air conditioner was made by T.G.N. Haldane in 1927-28, to heat his London office and his Scottish home. There were some heat pump prototypes installed from 1946 (a dozen in 1948). As a matter of interest the Festival Hall, in London, built as part of the Festival of Britain after the war, was heated by drawing heat from the river Themes, activated by a compressor driven by a jet engine running on town gas [Thevenot 1979].

GERMANY

The Germans, notably K.Nesselmann and W.Niebergall, were interested in absorption refrigeration machines working as heat pumps, and there were some installed from 1947 onward in several countries to heat process liquids and for air conditioning as well [Thevenot 1979].

5.4 Mechanical Vapour Recompression - a Swiss Success Story

The real beginning of salt production by mechanical vapour recompression was in the 1920s when there was found a solution to avoid the encrusting of the heat exchanger surfaces by removing the critical minerals causing the hardness, and when the corrosion problems were handled. In 1920, a **first pilot plant** with **radial turbo compressors** was installed in the German **salt works at Reichenhall**. The plant was built in cooperation with the Swiss company

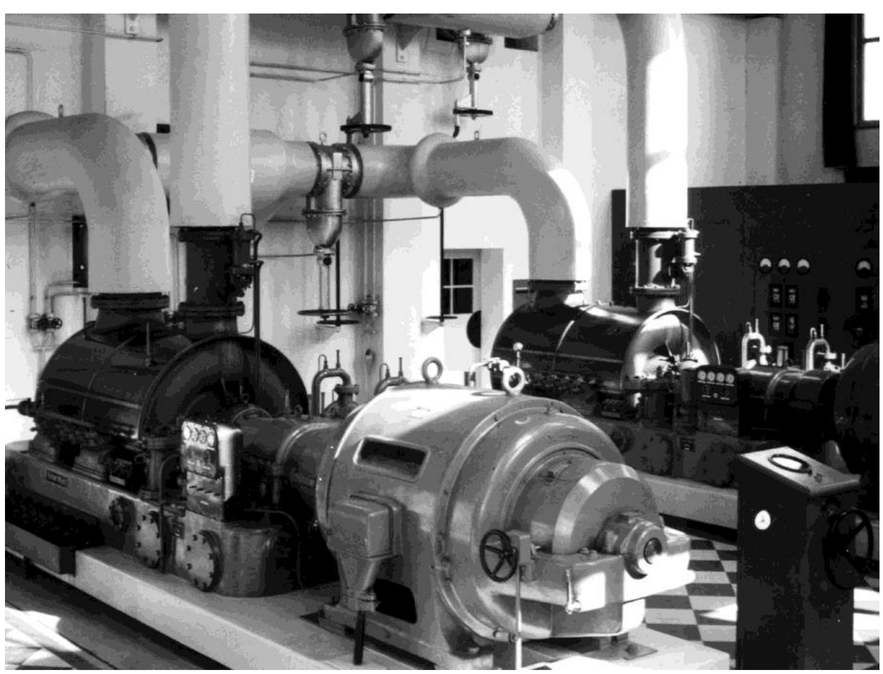


Figure 5-24
Compressor station,
Swiss Saline Riburg, 1941
[Lieberherr 2007]

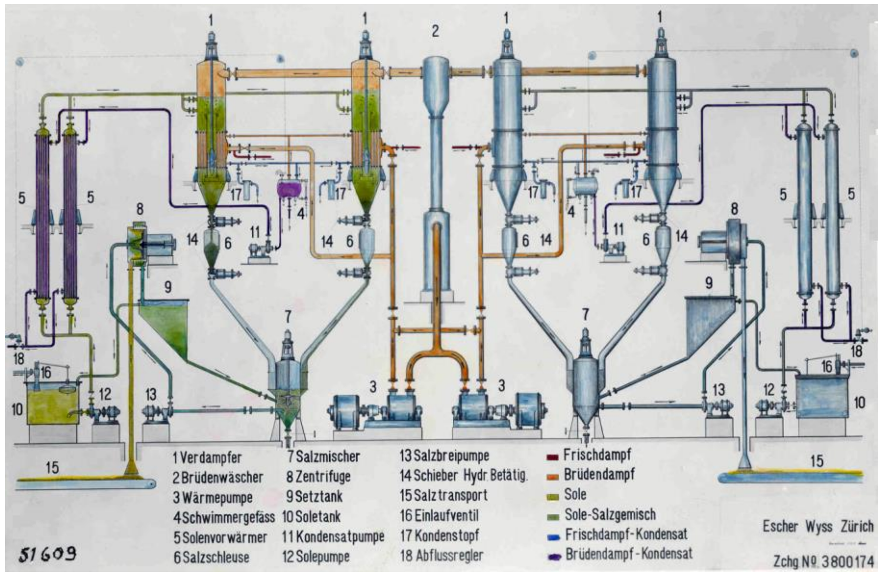


Figure 5-25 Flow sheet of the Saline Riburg, 1941 [Lieberherr 2007]

Kummler & Matter. First there were serious compressor corrosion problems and then the process proved to be more complex than expected. As a consequence the process was transferred to the responsibility of **Escher Wyss** in 1923. In **1926,** the **first industrial scale vapour recompression plant** with turbo compressor (344 kW) was started up. The fructuous team work with the Bavarian salt works gave Escher Wyss an important input to the development their later heat pump business [Wirth 1955, 1995].

In 1941, **Escher Wyss** built a vapour recompression plant in the Swiss **Saline at Riburg** (Rheinsalinen) for a salt production of 40’000 tonnes per year: Figure 5-24 und Figure 5-25. An enlargement by one more compressor followed in 1959. In 1973, a new plant with a capacity of 250'000 tonnes per year was built by Escher Wyss: Figure 5-26. It replaced the historic plant of 1941 and remained Europe’s largest plant for many years. In 1943, the Swiss **Saline Schweizerhalle** was converted to a vapour recompression process as well. 1964 this plant was reconstructed and had got an enhanced evaporation system with a four-stage radial compressor: Figure 5-27. It came up with COP values of 13.5.

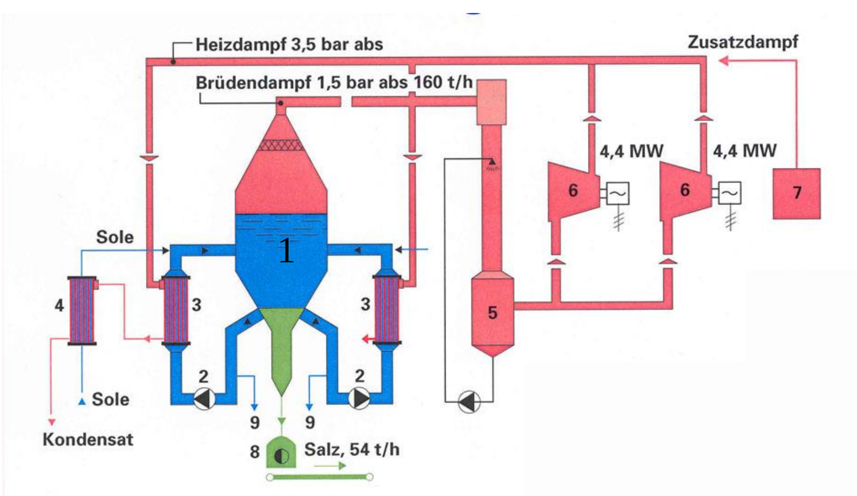


Figure 5-26 Flow sheet of the Saline Riburg after 1973
1 Evaporator,
2 Circulation Pumps,
3 Condensers,
4 Preheater, 5 Scrubber,
6 Compressors, 7 Boiler,
8 Centrifuge,
9 Mother liquor.
[Lieberherr 2007]

Today **Switzerland’s largest heat pump systems** are operating in the vapour recompression plants at Riburg and Schweizerhalle with a total evaporation capacity of around **80 MW**: Figure 5-28 [Winkler 1995], [Lieberherr 2007].

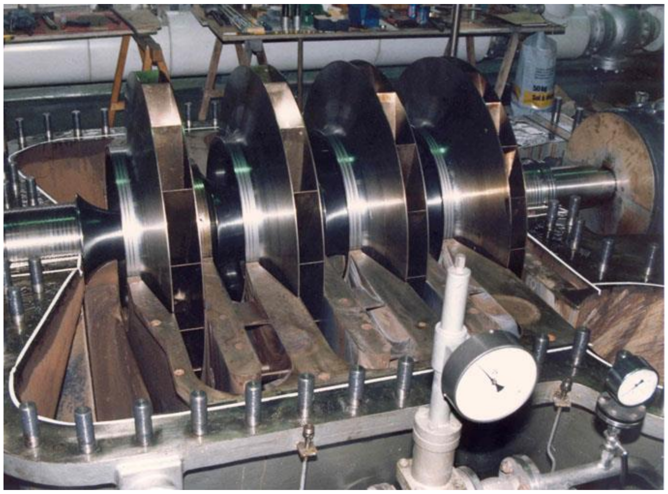


Figure 5-27 New compressor Saline Schweizerhalle, 1964 [Lieberherr 2007]

Figure 5-28 Salt stock of the United Swiss Rhine Saline today [Lieberherr 2007]

In Switzerland there is a sugar production from domestic sugar beets with a sugar content around 17% in the sugar plant at Aarberg and Frauenfeld. Together they produce some 230'000 t/year of refined sugar. **Escher Wyss** built another mechanical vapour recompression system in the **Swiss sugar plant at Aarberg** (Zuckerfabrik Aarberg) by the end of 1945. The multi-stage evaporation plant for the **sugar solution concentration** was driven by a 2.9 MW two-pass **radial compressor** which compressed 125 t/h steam of the first stage from 0.9 bar to 1.3 bar: Figure 5-29.This world first **combination with a multi-stage evaporation system** resulted in a superb **COP** of **26.8**! It was in operation until 1984. Then the plant was expanded and updated. The new radial compressor also made by Atlas Copco (Figure 5-30) has to compress only 60 t/h steam from 1.1 to 1.57 bar and the power consumption of the electric motor could by reduced to 1.84 MW.

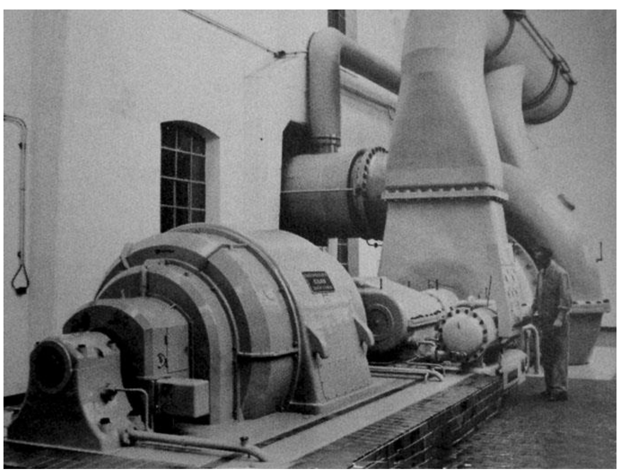


Figure 5-29 First radial compressor for the sugar solution concentration at Aarberg, 1945 [Zuckerfabrik, CH-3270 Aarberg]

Figure 5-30 Second radial compressor for the sugar solution concentration at Aarberg, 1984 [Zuckerfabrik, CH-3270 Aarberg]

A second vapour recompression system was serving the **evaporative crystallisation**. For that purpose a 3.3 MW **axial compressor** made by Escher Wyss (Figure 5-31) compressed 25 t/h of steam from 0.25 bar to 1.5 bar and attained a COP of about 5.3 [Brunner 1981]. This second heat pump at Aarberg was in operation for 46 years until 1991! Then on the occasion of a

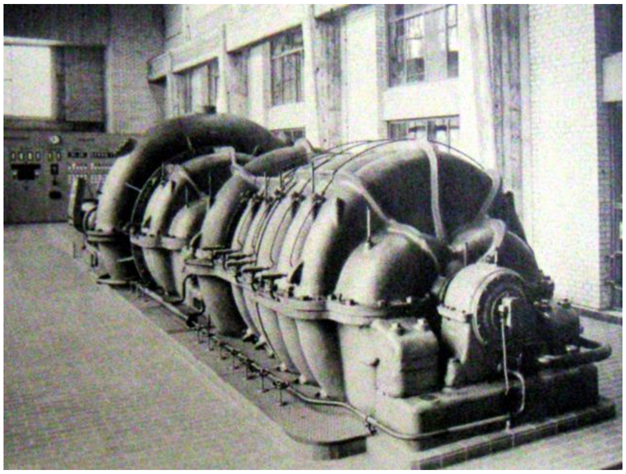


Figure 5-31 Axial compressor for the evaporation crystallisation at Aarberg, 1945 [Zuckerfabrik, CH-3270 Aarberg]

Figure 5-32 New radial compressor for the evaporation crystallisation at Aarberg, 1991 [Zuckerfabrik, CH-3270 Aarberg]

complete revision of the evaporation crystallisation the historic compressor was replaced with a new radial compressor for the compression of 25 t/h of steam from 0.23 bar to 0.73 bar by Sulzer – Escher Wyss[13]: Figure 5-32. Thus a reduction of the power consumption of the electric motor down to 2.0 MW was attained [Brunner et al. 1981, 1992], [Brunner 1992], [Fankhauser 2007].

6 THE PERIOD OF LOW OIL PRICE 1951-1972

The 1950s and 1960s were characterised by a continuously falling oil price. This had the effect of dramatically slowing down all heating only heat pump activities in colder climates, which in turn resulted in a certain stagnation in their development and market penetration. In this period a reasonable return on investment for heating only heat pumps was not possible until the oil embargo in 1973. New installations were restricted to special cases.

But in warmer climates there was an associated need for both cooling and heating. In these regions, heat pumps continued their success. Air conditioning systems safeguarded the heat pump know-how and developed it further. Europe – namely Swiss companies - took the lead on the ventilation side [Scholten 2004]. Especially in the U.S.A. and in Japan there was a take off of small unitary air conditioners. A huge market was developing for small air conditioners in homes and automotive cooling.

6.1 Components and Refrigeration

The developments in this period were characterised by the introduction of screw compressors, by significant improvements of other compressor types, by the continuation of the triumphant success of the halogenated hydrocarbons and by the advent of computers.

[13] In 1970 Escher Wyss was incorporated into the Sulzer group. Sulzer was engaged in a large number of industrial activities including energy, textile machinery, chemical & medical engineering etc.

6.1.1 Vapour Compression Cycle

COMPRESSORS

In this period there was only one really new machine, the **screw compressor.** Ljungstroms Angturbin AB changed its name to Svenska Rotor Maskiner AB in 1951. This company has issued manufacturing licences to almost every screw compressor manufacturer [Cashflo 2007]. By oil injection a significant rise in the pressure ratio of screw compressors became possible. As a result screw compressors entered into the refrigeration scene in 1958. For the time being these machines found no general dissemination due to low efficiency and constructively limited pressure ratios. In the 1970s Bernhard Zimmern from Paris developed the „Mono-Screw“ with one main shaft and two barricading wheels. A single rotor compressor was also introduced in 1974 by Grasso (the Netherlands). But only from around 1980, screw compressors reached significant quantities. They were mainly produced in the U.S.A., Sweden, Germany, the Netherlands and Japan. The long lasting competition between the piston and the screw compressor was removed by the insight, that the two are complementing one another at the end of the 1980s. The advantages of piston compressors are outbalancing at lower and those of the screw compressor at higher power [Frommann 2004], [Thevenot 1979].

With regard to the mass production of consumer goods the U.S.A. was far ahead of Western Europe. In the 1950s, the mass production of **hermetic compressors** for refrigerators started. **Brown Boveri (BBC)** developed and produced not only large turbo compressors. Around 1960, with 25’000 units per year, BBC Mannheim was Europe’s biggest manufacturer of open and semi-hermetic compressors for refrigerants up to 10 kW. At that time BBC produced refrigerators as well [Stenzel 2004]. In 1956, **Sulzer** made the first oil free labyrinth piston compressor for refrigerants and the Danish Sabroe introduced a W-type ammonia piston compressor with 1’200 revolutions per minute.

In the early 1950s in one stage **radial turbo compressors** reached a pressure ratio of only about 1.5. Through enormous efforts in material science, fluid dynamics and machining accuracy it was possible to increase the impeller revolution speed to a tangential speed around sonic speed. A one-stage pressure ratio of 8 became possible for radial compressors. In close cooperation with the **Swiss Federal Institute of Technology in Zurich** (ETH Zürich) the Swiss companies **Escher Wyss, Sulzer** and **Brown Boveri** played an outstanding role in this research and development process. Sulzer installed the first **high speed radial turbo compressor** in a British air conditioning system in 1958. In order to attain an evaporation temperature of –55°C two Sulzer turbo compressors were connected in series in 1967 [Friotherm 2008].

REFRIGERANTS

By the end of the 1950s **halogenated hydrocarbons** got ahead of practically all the old refrigerants except ammonia, which was still used in larger industrial plants. From 1968 R-22 became the standard refrigerant for unitary air conditioners and heat pumps [Nagengast et al. 2006].

COMPUTERS

In the late 1960s and early 1970s computers appeared on the scene. They **provoked a tremendous technological change**. Initially the voluminous computers operating in air-conditioned rooms revolutionized the design calculations by replacing slide-rules, tables of logarithms and slow mechanical calculating machines. They were used to find optimum solutions for components and complete systems much more precisely in a very short time. Soon after, computers entered into the operational level. In the early 1970s with "ULMA" **Brown Boveri**[14] introduced the first commercial on-line inspection system in the world. Early ULMA generations were based on patented phototransistor technology. Some of these installations are still on duty in paper mills today [ABB 2008].

6.1.2 Absorption Cycle

Though vapour compression became more efficient and cheaper the **absorption refrigerator** kept its market for applications in noise sensitive areas such as hotel rooms and camping cars. In the latter case the additional advantage of functioning with different energy supplies was another reason for the absorption system. Around 1950 there were the first prototype absorption refrigeration machines heated by solar energy, notably by G. Lof [Nagengast et al. 2006].

The Golden Age of Absorption continued in the **U.S.A.** and in **Japan**. Trane introduced the first hermetic design in 1959. In 1960, units of 3.5 MW were built by Carrier. There were many other US companies building absorption chillers. Around 1965 cooling COPs around 0.6 - 0.7 were reached. Because oil and steam costs were low, the market for absorption units grew rapidly and reached its peak in the U.S.A. around 1970 with 25% of the chiller market. In Japan higher efficiencies were aimed at. A **double-effect**, indirect fired unit was built by Kawasaki Thermal Engineering in 1964. Mitsubishi and Ebara built their first units in 1965. Sanyo and Hitachi also introduced new equipment during the 1960s. In the late 1960s in the U.S.A. several manufacturers began to investigate higher efficiency cycles. Carrier and Trane built a double-effect, indirect-fired unit in their laboratories around 1970-1971. Trane commercialized the product in 1972 [Burget et al. 1999].

6.2 Heat Pumps in Switzerland

In contrary to the stagnation in the standard heat pump business there were interesting new vapour compression installations in this period.

6.2.1 Rare Closed Loop Systems

Heat pumps for heating only could not follow the impressive Swiss market penetration in the 1940s. The reasons were not technical problems but the continuously falling oil price with rising prices of electricity in parallel. For heating only heat pumps this period was the first "valley of tears".

Surprisingly in the 1950s there were already research activities on **horizontal ground heat exchangers** going on. They led to the first guideline values for overall heat transfer coefficients, length and diameter of the tubes and distance between them. COP-values around 3 were attained. Even regenerating in summertime and latent heat storage tanks were covered at that time [Ostertag 1955], [Baumann et al 2007].

In larger department stores arose a demand for summer cooling. This leads to a sporadic application of the chillers for heating in winter time. Such systems were built by **Dreyer-Hanson**. The so called "**Air-Topio**" had a refrigeration power in the range of 10 to 50 kW. Around 1967,

[14] In the meantime ABB (Asea Brown Boveri) has become one of the market leaders in automation technology and variable frequency drives also for larger heat pump installations. ABB was the result of a merger between the Swedish ASEA AB with the Swiss Brown Boveri Ltd. of Baden in 1988.

Kurt Trüssel[15], the later founder of **KWT** (Kälte-Wärmetechnik) in Belp, built a small refrigeration plant with a cooling capacity of 5 kW and a simultaneous using of the rejected condenser heat at 45 °C in the **cheese diary** at Mamishaus. After 40 years it is still operating [Trüssel 2007].

As a result of special electricity price conditions due to the construction of the new hydraulic power plant at Göscheneralp (Zentralschweizerische Kraftwerke) it came to a new 350 kW ammonia heat pump system for space heating and heating of the domestic water in the **hospital of Altdorf**. It was built and installed by **Escher Wyss.** In order to get a higher COP the radiators surface area of the old central heat distribution system with maximum water temperatures of 90°C / 70 °C was increased by 40%. The result was a still high maximum feed temperature of 77°C. The heat pump system with three heat pump units and ground water as a heat source was started up in 1961. At an average temperature lift from 4°C to 44 °C, and taking into account the electricity needed for the ground water pump, the first heat pump unit made a COP of 4.15 which corresponds to a respectable Lorenz efficiency of 52.3%. The two further heat pump units were functioning in parallel and served the ceiling heating system. At 4°C / 42.5°C the COP of these units attained 4.4 or a Lorenz efficiency of 53.7%. At these temperature conditions the heating capacity of the three units was 116 kW each. One unit was used for summer ceiling cooling for one single room [Mustoe 1977].

6.2.2 Success in Mechanical Vapour Recompression

Still successful was the vapour recompression business. In the 1960s and 1970s **Escher Wyss** held a world market share of about 30%. Main competitors were Standard Messo (Germany), Wiegand (Germany) and Swenson Evaporator (U.S.A.). Excellent overviews on the development of the vapour recompression technology are given by [Austmeyer et al. 1987, 1993].

6.3 Heat Pumps – International Milestones

CENTRAL EUROPE

Not only as a result of the perceived unpleasant air flow and noise the **year round air conditioning units** from the U.S.A. had little acceptance in Central Europe. The **lack of a defrosting facility** in most units was an even more serious drawback. By the end of the 1950s radiator water heating systems with maximum temperatures of 80 °C / 60 °C were common in Central Europe. This was not in favour of heat pumps. Large surface area radiant heating systems with 50 °C / 40 °C were still considered exotic and were manufactured particularly as ceiling heating systems with the possibility of summer cooling [Ostertag 1958].

FRANCE

Among other applications a heat pump heating of a factory and an office next to a cold store in Chalon-sur-Saône (1950) and the heating of sports centres and swimming pools in the vicinity of ice rinks are noteworthy. France had about 200 heat pumps in 1973.

GERMANY

In Germany heat pumps were used only sporadically. Compared to the low costs for boilers and fossil fuels the investment costs were too high for heating only heat pumps. This situation

[15] At that time Kurt Trüssel was an employee of Therma at Zurich.

changed little until 1973. But for simultaneous use of cold and heat there were realised some examples in diaries and in heat recovery from department stores air conditioning. These pilot systems were funded by the electricity utilities and the Ministry of Agriculture [Ostertag 1955], [Adolph 2004], [Dienel 2004]. In 1969, the first ground coupled heat pump was realised in Germany. It was a brine-water system with a horizontal ground heat exchanger [Sanner 1992].

AUSTRIA

In 1951, there was the beginning of the changing over of the **Austrian salt works** from direct heating to vapour recompression [Matl 1984].

U.S.A.

In the U.S.A. there was a slow, gradual development of the heat pump, especially in **medium capacities**, packaged of 12 to 35 kW. In the 1950s **heat pumps for domestic hot water boilers** of approximately 300 litres with hot water temperatures up to 65°C penetrated the market. They had a rather poor COP of about 2.2 only and they chilled the rooms in which they were installed. This was a severe disadvantage when space heating was needed in wintertime [Ostertag 1955].

As mentioned in 5.3, small **air conditioners** in the drive power range of 250 W to 1 kW were often installed in the windows. They did not only summer cooling but made it possible to utilise the heat given off by the condenser during the winter. These “all-electric year round air conditioning units” gave an additional comfort and expanded in the south, from 1951. The curve of growth shows at first a rapid increase (2000 units made in 1954, 10’000 in 1957, 76’000 in 1963). But then followed a stagnation, due to a high unreliability of the equipment. In this context ARI[16] has initiated the first product rating performance certification program for unitary air conditioners, and hat introduced an ARI certification “seal” in 1958 [Nagengast et al. 2006].

Before 1955 **General Electric** and the **Marveyer Corporation** commercialized air/air heat pumps for heating and cooling with an electric input in the range of 2.2 kW to 3.7 kW. These were equipped with a defrosting device and made a COP in the range of 2 to 3. Some of them were sold in Switzerland as well. J. Donald Kroeker realised heat pump installations on office buildings and shopping centres using **ground water** as a heat source around 1952 [Nagengast et al. 2006]. In the U.S.A. some heat pumps were **driven by combustion engines** in the early 1950s already. In some cases the exhaust heat was being used [Ostertag 1955].

JAPAN

From around 1950, Japan was increasing its **air conditioning** installations considerably and was also much interested in the heat pumps providing cooling and heating. During 1957, heat pumps with a total of 11.6 MW were started up.

7 ENTHUSIASM AND DISILLUSIONMENT 1973-1989

1973 marked one of the most important turning points in the history of the twentieth century. Prior to 1973, the world had become accustomed to a plentiful supply of inexpensive fossil fuels such as coal, petroleum and natural gas. The world economy completely based on these low cost fuels. However in 1973, a number of factors changed this picture dramatically. The

[16] Air-conditioning and refrigeration institute.

turning point was triggered by a decision of the Arab members of the Organization of Petroleum Exporting Countries (OPEC) to cut back on their exports of petroleum to Western nations as an answer for their backing Israel in the Yom Kippur war with Syria and Egypt in October **1973**. This **oil embargo** had a devastating effect on the national economies with a global recession and high inflation.

The so called developed nations had to learn how to live with less energy in general and to rethink their dependence on fossil fuels. The oil embargo entailed immediate measures. In Switzerland for example, as urgent measures car driving was completely stopped on Sundays, room temperatures had to be reduced to 20°C, the street lightning was turned off during night time etc. By the time the embargo ended in March 1974, oil prices had risen by over 300%. A much greater effect than the physical reduction of the oil supply and the price step-up of around 100% by some OPEC members had the oil companies by taking the opportunity for which they had been looking for to increase profits for many years.

This was the time when alternative energies and the rational use of energy were no longer the affair of a few idealists but became a high public priority. Worldwide new energy strategies gave a chance not only to solar energy, wind energy, biomass and geothermal energy but to the **use of ambient heat by heat pumps** as well. A **renascence of heat pumps** began. In this situation the **International Energy Agency IEA** was established by the OECD countries to find answers to the now scarce energy supply. The IEA soon identified heat pumping technologies as one of the key strategies for building energy conservation. This was the beginning of the IEA Heat Pumping Technologies Implementing Agreement [Groff 2005].

The tendency for a more rational use of energy was accelerated by the **second oil crisis in 1979** and accentuated in **1980** when **war** broke out **between Iran and Iraq**. With regard to the again doubled oil price **alternative energies** became more popular. But the main hope was for replacing oil with **nuclear energy**. The topics were nuclear high temperature reactors and fast breeder reactors. And there were dreams of realising the nuclear fusion by the turn of the millennium. At the same time **severe pollution concerns** which manifested in acid rain and forest dieback arose. This all was in favour of heating using heat pumps and led to a second heat pump boom.

But the rapid growth of the heat pump business brought to many competitors with insufficient know-how. This was one of the reasons for the **collapse of the European heat pump boom** by the end of the 1980s. The other reason was an oil price decline after 1982. Therefore the 1980s had been characterised as the second “valley of tears”.

7.1 Components and Refrigeration

The main developments in this period were the break trough of scroll and screw compressors, the phasing out of CFC, the definitive break trough of plate heat exchangers and the microprocessor control.

7.1.1 Vapour Compression Cycle

COMPRESSORS

In 1972, 67 years after the invention by Leon Creux, the Arthur D. Little Co. in Cambridge, Mass., began research on scroll technology for air conditioning compressors. Realizing the significance of its research, the company partnered with Trane who continued to fund the scroll research. Thanks to high precision, computer-controlled milling technology the industrial manufacturing of **scroll compressors** and screw compressors became possible in the 1980s. The first mass production of **scroll compressors** by **Copeland** for unitary air conditioner application was in 1986. In 1992 the 3rd scroll compressor generation of Copeland attained an annual production of one million units. The production was globalised (in Europe since 1995) and attained 10 million units by the end of 1997. In 2001 followed a scroll compressor with vapour injection – a very interesting step for retrofit heat pumps[17]. In 2003 a two-stage scroll compressor was introduced. **Bristol Compressors** became another important U.S.A. scroll compressor manufacturer. **Maneurop** (a subsidiary of Danfoss) in Lyon, France, became the main European competitor for scroll compressors. In Germany the mass production **of screw compressors** began by the end of the 1980s [Frommann 2004].

The lower power limit for **radial compressors** was in the order of 200 kW. In 1975, the maximum value for one compressor was 25 MW. The **axial compressors** came on the refrigeration scene later than the radial compressors[18]. They were used only for very large capacities, especially in the compression of natural gas before liquefaction. In Skikda, Algeria BST (Brown Boveri Sulzer Turbo Machines) had installed machines with about 80 MW on one shaft [Thevenot 1979]. The German Borsig made an **axial turbo compressor** for an ammonia refrigeration plant with a refrigeration capacity of 12 MW. In 1973, Sulzer launched a new generation of high speed radial turbo compressors, the so called “UNITURBO” [Friotherm 2008].

REFRIGERANTS

In 1973, James Lovelock reported finding trace amounts of refrigerant gases in the atmosphere. In 1974, Sherwood Rowland and Mario Molina predicted that **chlorofluorocarbon** refrigerant gases would reach the high stratosphere. They suspected that the chlorine released by partial dissociation of the compounds in the atmosphere might **attack the ozone layer**, which is found some 25 to 35 km above the earth, and which protects us from the high-energy ultraviolet radiation. The fear became certainty by 1978. In 1985, the "**ozone hole**" over the Antarctic had been discovered. By 1990 Rowland’s and Molina's prediction was proven to be correct [Thevenot 1979].

With the **Toronto Protocol** a draft for a **step by step reduction of CFCs** was adopted 1984. It was followed by the Vienna Convention on the ozone layer protection. In September 1987 the **Montreal Protocol** with rigorous phasing out agreements was signed. This might be the first time, mankind was willing for a strict action in order to avert a environmental catastrophe.

This led to **worldwide emergency programs** for a quick phasing out of CFCs. This was the renaissance of ammonia as a refrigerant. Within the only four years the **HFC** refrigerant R-134a was developed. Unfortunately R-134a and other HFCs are persistent substances, and their greenhouse effect is very high. Consequently **hydrocarbon**s such as propane and isobutene were pushed especially in Europe. In the U.S.A. and Japan this alternative was not well received due to the fear of legal recourse in case of accidents. In 1993, the mass production of refrigerators with hydrocarbons as a refrigerant began in Europe [Kunis et al. 2004], [Frommann 2004].

Non **azeotropic mixtures** of refrigerants enter the scene around 1984. With ammonia-water significantly higher COPs are attained for heating up domestic water (or in general heat sinks with largely changing temperature) by the Joule instead of the Ranking cycle [Mucic and Schermann 1984].

[17] Today this compressor type is available within a capacity range of 5 to 45 kW: www.ecopeland.com.
[18] But for vapour recompression, Escher Wyss used an axial compressor in 1945 already (Figure 5-31)

HEAT EXCHANGERS

The **plate heat exchanger** definitively entered into the refrigeration and heat pumping scene in the 1970s. For synthetic refrigerants the replacement of the elastomer gaskets by soldered connections took place in the middle of the 1980s already. This technique had an impressive growth rate. Between 1987 and 2001 there was a worldwide production of around three millions of soldered plate heat exchangers with corrugated plates. Laser welded seams were introduced at the beginning of the 1990s [Frommann 2004].

ELECTRONIC CONTROL

A crucial milestone of the 1980s was the introduction of **microprocessors**[19]. These made it possible not only to change from mechanic P-controllers to PID-controllers but to use far more sensors and actors. This resulted in a significantly enhanced temperature control of the heat source and the heat sink, which is especially favourable for heat pumps with ambient air as a heat source. As early as 1989, **Carrier** introduced an **electronic expansion valve** controlled by a microprocessor with sensors in the evaporator, the compressor and the condenser. The system was called “Flotronic” [Szokody 2007].

REFRIGERATION

In the 1980s, the big players in the industrial refrigeration business in Europe were **BBC-York**, Stahl Refrigeration, Sabroe, Linde and **Sulzer** [Frommann 2004].

7.1.2 Absorption Cycle

SMALL ABSORPTION HEAT PUMPS

In the 1980s, there were many attempts to develop an absorption heat pump with heating capacities **below 50 kW** [Loewer 1981], [Murphy and Phillips 1984], [Schäfer and Stephan 1984]. Depending on the complexity of the absorption process for heating PER of 1.15 to 1.4 were attained. However, the cost–benefit ratio was not inspiring and the problems with the solution pumps did not convince the market. Batch absorption cycles had been studied in particular for solar energy drive [Peters et al. 1986]. At least in the heat pump application small absorption heat pumps were no commercial success.

U.S.A.

The impact of the 1973 oil embargo favoured the vapour compression systems with their higher efficiency. By 1978 the share for absorption fell to less than 10 percent of the **large tonnage water chiller** market in North America.

JAPAN

There was a different situation in **Japan**. The Japanese companies continued to perfect their double-effect absorption chillers. By 1975, **absorption chillers** in Japan surpassed electric chillers for the first time. In 1980, the Ministry of Finance offered tax incentives to end-users who employed gas-fired absorption. By the mid 1980s the large tonnage water-lithium bromide units exceeded cooling PERs of 1.2. Units up to 31.6 MW capacities were built in Japan.

[19] Intel began with the development of its first microprocessor for the pocket calculator of a Japanese manufacturer in 1969. Today in industrialised countries there are around 50 microprocessors in a household (www.intel.com).

7.2 Heat Pumps for Heating - Swiss Contributions

Following more than two decades of stagnation heat pumps had a **new birth** by the oil embargo in 1973 and the second oil shock in 1979. Adolf Ostertag, the head of the refrigeration and heat pump design engineering department of Escher Wyss before and during the Second World War, gave a recall of fundamentals and particularities of heat pumps for space heating, domestic water heating and the implementation in district heating systems [Ostertag 1974].

The development of the **second generation of heat pumps** for central water heating systems for single-family homes and larger residential buildings began straight after the oil embargo of 1973. By 1980, the seasonal performance factor of correct functioning small units (10 - 25 kW) was only about 1.9 to 2.3 for air as a heat source and not much higher when using horizontal ground heat exchangers [Hubacher 2007]. Rumours about bad systems with a seasonal performance factor not far above 1 were published in the daily press [Blattmann 1981]. The boom ended with deterioration in image due to the high number of unserious competitors with technically poorly conceived and insufficient planned installations.

After the second oil shock in 1979/1980, the **third generation** of heat pumps for homes was less voluminous and had a lower refrigerant content. The main heat source remained, apart from air, horizontal ground heat exchangers, often combined with unglazed roof collectors. Thermo active building elements with integrated tubing (walls and roofs of prefabricated garages, façade elements and special roof bricks) were used as well. The preferred refrigerant for heat pumps became R-502 but R-22 and R-12 were still used. Besides heating of homes larger heat pump applications were public buildings, shopping centres, public swimming pools (most indoor), and industrial processes (especially food and metal) etc.

In the 1980s **gas engine** and **diesel engine** driven heat pumps with a heating capacity range of 200 kW to 1’000 kW came up [Bitterli 1986]. After a few years of operation they proved to have too frequent breakdowns and too high maintenance costs. Furthermore they were not as flexible as the combinations of heat pumps with cogeneration units. This combination is far more reliable and despite the losses of the energy conversion and transmission by the electric grid it attains a primary energy ratio of 1.5 and more [Zogg 1995].

The heat pump market needed a certain amount of self cleaning and concerted accompanying measures for quality assurance, before a successful restart with competent suppliers by the end of the 1980s became possible In 1993, there was one trial for a fruitful cooperation of the manufacturers SHF Ostermundigen (brine/water and water/water heat pumps) and Schweizer Hedingen (air/water heat pumps) with the (for “home size” heat pumps) distribution and market oriented CTC Wärmetechnik Zürich and Scheco Winterthur. But the consortium “Integral Wärmepumpen” survived for a few years only.

7.2.1 Pioneers of Central Heat Pumps for Homes (10-50 kW)

In this power range a lot had been done right after the 1973 oil embargo but there exist almost no documents on theses activities. The concerned pioneers were realizing all types of heat pump systems, sometimes day and night. But they did not care for publishing. That is why most of the following is based on personal interviews with them.

For **heating homes** the most frequent power demand was in the range of 15 kW to 25 kW for the coldest days of the year. Semi detached houses required some more. There was a lack of conform heat pump systems with air or ground as a heat source and a central heat distribution system. This motivated several pioneers to develop suitable systems for this demand. They were mostly skilled technicians from the refrigeration, air conditioning and electricity utilities business. These pioneers produced heat pumps on a small business basis in

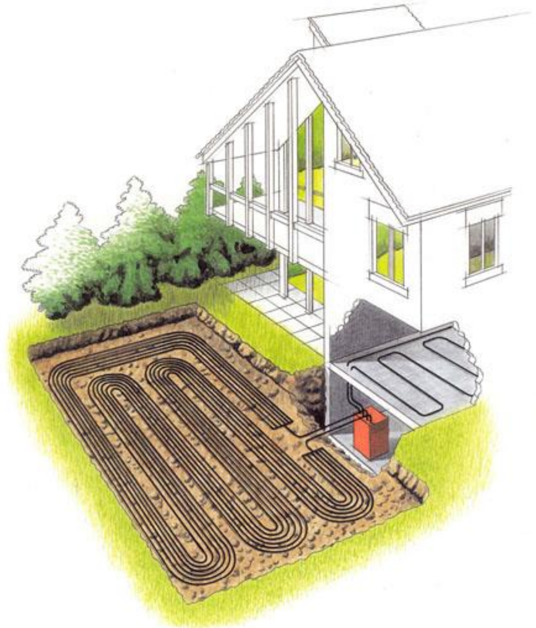


Figure 7-1 Heat pump system with horizontal ground heat exchanger, Neucalora, around 1980

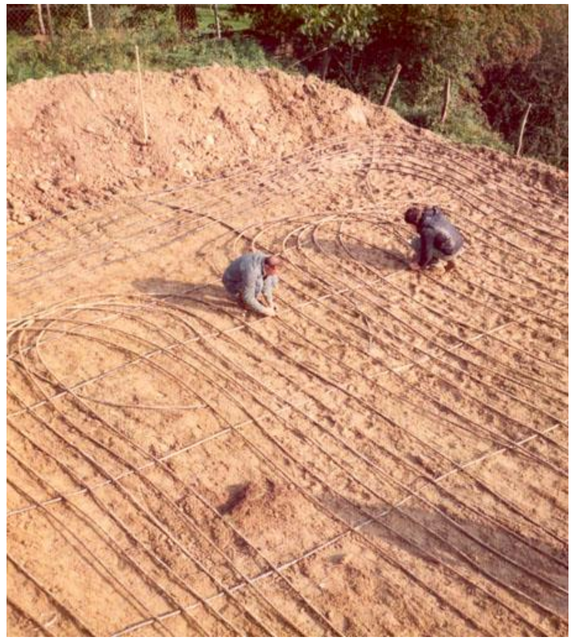


Figure 7-2 Horizontal ground heat exchanger under construction, 1978 [Grimm 2007]

general for the Swiss market. All of them used R-12 and later R-22 as a refrigerant, hermetic piston compressors and other refrigeration components from the world market. By 1978 the most common heat source were **horizontal ground heat exchangers** (Figure 7-1,Figure 7-2) often in **combination with unglazed solar roof collectors**:(Figure 7-3, Figure 7-4). This latter system for homes is detailed in [Promatec 1978] and was occasionally used for apartment buildings as well [Baumann and Züllig 1983]. But there were also rather exotic solutions such as the one with roof collectors and domestic sewage heat recovery (without toilet) combined with a gas engine driven heat pump: Figure 7-5.

Figure 7-3 Roof collector with polyethylene tubing on the roof, 1978 [Grimm 2007]

Figure 7-4 Roof collector below tiles installed between rafters, 1978 [Grimm 2007]

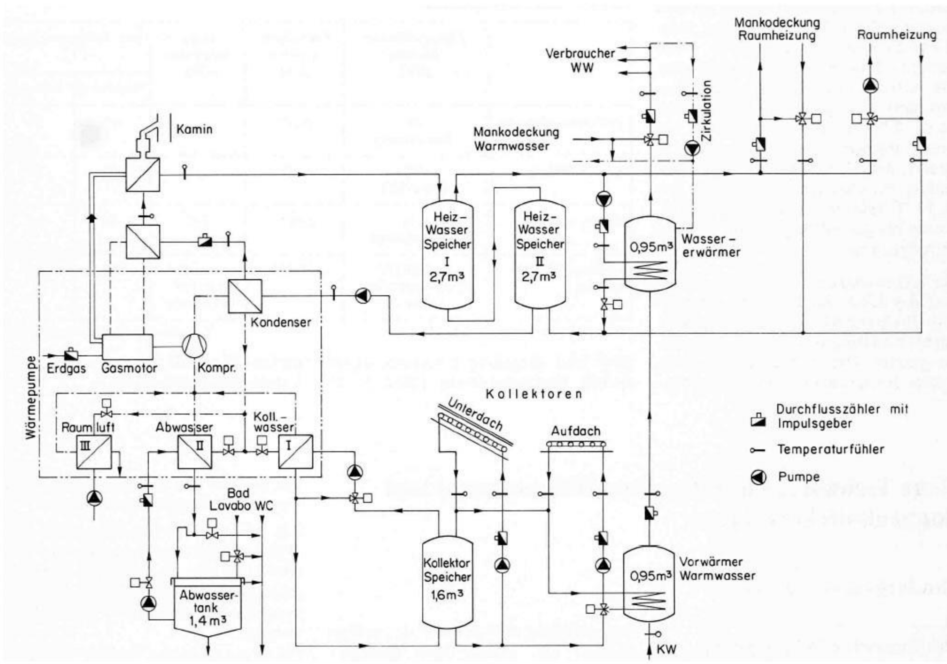


Figure 7-5
Example of an exotic system: Gas engine ("Gasmotor") driven heat pump with both types of roof collectors showed in Figure 7-3 ("Aufdach") and Figure 7-4 ("Unterdach) and heat recovery from domestic sewage ("Abwasser") [Gass 1984]

The widely criticized electric resistance heating was an important precursor for the heat pumps. Its relatively high energy costs motivated for a **good thermal insulation** of the buildings, sufficient electricity grids and in case of central heat storage the needed heating water distribution systems in the buildings. The heat pump pioneers, frequently coming from the resistance heating side, took the chance for a far more efficient use of electricity.

GRIMM / NEUCALORA

One of the first heat pump pioneers was Heinz Grimm (born in 1928). Following a vocational training as a toolmaker he had broad activities reaching from electric overhead lines to air conditioning. In the 1960s he went into business for himself and was manufacturing central electric resistance heaters with heat accumulators for the utility BKW-FMB Energy in Berne. His first functional demonstrator was running in 1973 already. The first trial was functioning just during one night. But this was no hinder for showing his new prototype in collaboration with BKW-FMB at the exhibition OHA in Thun (Oberländer Herbstausstellung) by the end of 1973. One year later Grimm built his first heat pump for a home in Wynigen. Initially Grimm's heat pumps – they were called "Grimm machines" – used **horizontal ground heat exchangers** made from polyethylene tubes: Figure 7-1. Later he combined them with **roof collectors** for regeneration in summertime. They consisted of polyethylene tubes as well. The tubes were mounted either on the roof (Figure 7-3), – or where the view of a place did not allow it under the roof tiles between the rafters (Figure 7-4). Later Grimm used **air, ground and lake water** as a heat source as well. For using air as heat source he also experimented with energy fences (Figure 7-6) as a noiseless device. He did further experiments with latent heat storage tanks and variable compressor speed. Evaporation and condensation took place in self manufactured helical double wall copper tubes: Figure 7-7. As early as 1975, Grimm reported on measured temperature profiles in his heat sources mentioned above [Kunckler 1975]. Heinz Grimm always built **complete systems** including heat source and heat distribution system in the building. In this aspect his opinion differed from his competitors. Due to high costs for all the experiments going on the companies budget Grimm went bankrupt. 1977 Grimm joined the new company **Neucalora** in Berne[20]. In 1981, 1'000 Grimm machines were installed, by 1989 the number increased to 2'000 units. There was cooperation with the University of Applied Science in Biel and the Swiss

[20] 1992 Neucalora moved from Berne to Ostermundigen.

Federal Institute of Technology in Lausanne (EPFL, Lucien Borel). 1990 Neucalora changed to plate heat exchangers, 1993 the heat pump manufacturer SHF mentioned bellow was incorporated. Under the name **Integral Wärmepumpen** followed in 1993 a production of

Figure 7-6 Energy fence evaporator type around 1980, Neucalora [Grimm 2007]

Figure 7-7 "Grimm Machine" around 1980, Neucalora [Grimm 2007]

small heat pumps for CTC[21] in Zurich and Scheco in Winterthur. In 1995, Neucalora was taken over by the heat pump manufacturer **Grünewald[22]** in Affoltern a.A. [Grimm 2007], [Giger 2007].

SHF / STEINMANN

In 1973, Albert **S**teinmann (mechanic, main investor), Karl **H**ess (refrigeration engineer) and Norbert **F**elber (sales) founded the company **SHF** in Zollikofen. Soon SHF had a good reputation for building reliable heat pumps, also for heating capacities exceeding 100 kW. Some of the SHF heat pumps are still in operation today. In 1976, SHF incorporated the refrigeration company AirCold in Worblaufen. By this takeover Manfred Beerhalter joined SHF. In 1982, Steinmann left SHF and built up the **Steinmann** company in Kirchlindach which became a subsidiary of **Danfoss** in 2007 (www.danfoss-steinmann.ch). SHF was sold to Grünewald, later to Frutiger[23] and in 1993 to Neucalora [Beerhalter 2007], [Grimm 2007].

GRÜNIGER / SOLTHERM

Emil Grüniger, a former technician of Escher Wyss, had got a worldwide practical experience in refrigeration and heat pumping technologies. He was engaged in building a small heat pump since 1973. In 1975, he started with his own company **Soltherm** in Altendorf. His first heat pump system in the power range of 10 kW had a direct expansion horizontal ground heat exchanger with copper tubes and epoxy resin connections. The installation in Altendorf revealed the later well known oil recirculation problems already. Thereupon he changed to indirect evaporation using the "normal" horizontal ground heat exchanger with a liquid heat carrier. Soltherm built about 500 of such heat pump systems with hermetic Maneurope piston compressors. Emil Grüniger was with Kurt Trüssel of KWT among the first to use refrigerant desu-

[21] Today CTC Giersch in CH-8112 Otelfingen.
[22] Today Grünewald in CH-8112 Otelfingen.
[23] Frutiger, Tiefbohrungen, CH-3661 Uetendorf.

perheating for heating rooms in the basement in winter and for the final domestic hot water heating in summertime [Grüniger 2007], [Szokody 2007].

HUBACHER / KAUFMANN

In this context, Peter **Hubacher** as one of the first planners of small heat pump systems should be mentioned. In 1976, he installed a heat pump of the company **Kaufmann** in Netstal with open Bitzer piston compressor. Very little is known of the Kaufmann company, except that it was manufacturing good quality heat pumps, but went bankrupt [Hubacher 2007].

7.2.2 Medium Size Heat Pump Systems (50-1000 kW)

SZOKODY / HOVAL HERZOG / HOVAL / CARRIER

Gyula Szokody was the one among the pioneers with an exceptional influence on the professional community of the Swiss small heat pump manufacturers. He has not only an extraordinary personal history (three years of studies in theology, fleeing from the communist ruled Hungary, then engineering studies) but an important impact on the Swiss heat pump scene as well. In 1974, he joined **Hoval** Herzog (www.hoval.ch) in Feldmeilen as a product manager for heat pumps and solar energy and was from the beginning in 1980 until 1995 chairman of the technical committee of the Swiss Working Committee of Heat Pump Manufacturers and Distributors AWP (see 7.2.8).

For **larger heat demands** Hoval Herzog was pushing modified **Carrier water chillers** as heat pumps. These air cooled machines were designed for warm climate zones. For the application of the chillers as heat pumps special condensers were constructed. In 1974, Hoval was realising a heat pump system for central space heating and domestic hot water heating for **40 homes** in a residential area in Balzers (Principality of Liechtenstein). Three Carrier water chillers built in France with four compressors each had been equipped with a special condenser in order to attain condensation temperatures of 60°C. The nearby river Rhein served as a heat source. The system with a total heating capacity of **1.18 MW** came up with a COP of 3.64 at 9°C/60°C (Lorenz efficiency 46.2%). In order to provide the domestic hot water heating one unit made a feed temperature of 55°C. Extraordinary at that time the heat pump system was operating **fully automatically** with a patented **electronic multi step power control** starting up the needed units according to the outside temperature [Szokody 1975, 2007].

An epoch making heat pump system was realised by Hoval Herzog at the municipal sewage treatment plant at Obermeilen on the bank of the lake of Zurich in 1975. It was Switzerland's first heat pump **using the drain of a sewage plant as a heat source**. The drain of around 0.1 m^3/s had a temperature of 8°C - 22°C. Two carrier heat pumps with 310 kW at 7°C / 55°C each provided the heat supply for the fouling tower of the sewage plant and a nearby residential area for the aged (Alterssiedlung Dollikon). A constant feed water temperature of 50 °C was required in order to heat up the fresh sludge[24] to a temperature of 37°C. In order to cope with the same feed temperature of 50°C the surface area of the radiators of the central heating system of the residential area had to be augmented. This system was operating with the same automatic multi step power control mentioned above [Gubser 1975, 1976], [Szokody 2007]. Around 1975 Hoval Herzog brought the heat pump **"WW-Automat**" to market: Figure 7-8. This was no longer an adapted chiller but a fully automatic heat pump system with integrated domestic hot water heating and only two on/off switches for space heating and domestic hot water heating. The first of them was installed in a building in Surava near Tiefencastel. Instead of the simple temperature-time method Hoval Herzog realised a new defrosting concept by introducing a microprocessor controller in 1985: Figure 7-9 [Szokody 2007].

[24] The digester gas was used by a nearby industrial company.

Figure 7-8 Hoval-Carrier heat pump brine/water, around 1980 [Szokody 2007]

Figure 7-9 Hoval heat pump air/water, 1985 [Szokody 2007]

WERMELINGER / AUTOFRIGOR / SCHECO / SULZER

In the pioneering days it was necessary to convince the heating business, the architects, the building owners and the authorization authorities. The beginnings of heat pumps after the oil embargo were marked by lengthy approval procedures and refusals due to ignorance of the authorities and the utilities: “no” if in doubt… That was when the young engineer Bruno Wermelinger at **Autofrigor** in Winterthur was highly engaged in realizing heat pumping technologies [Wermelinger 1977]. Wermelinger did not get rid of and even had a phone call on the **insufficiencies of the approval procedures** with Minister Willi Ritschard, a member of the Swiss Federal Council. Along with Max Ehrbar of the University of Applied Science in Buchs and Gyula Szokody he organized working groups on the heat pump issues. This led to a first **SVK[25] guideline on heat pumping technology**. From 1975 the refrigeration company Autofrigor made many water/water and air/water heat pumps in the power region of 10-150 kW. Among the about 50 heat pumps by the end of 1977 there were also **combustion engine (**natural gas and diesel) driven ones, **high temperature** heat pumps up to 120°C, systems for a **combined use of heat and cold** and plate heat exchangers. Wermelinger was among the founder members of AWP (see 7.2.8) and took the lead in establishing guidelines for the **quick replacement of chlorofluorocarbons** by Fluorocarbons in a research project of the Swiss Federal Office of Energy [Wermelinger 1992]. Between 1981 and 1999 he was the CEO of **Scheco** in Winterthur (www.scheco.ch), which became a subsidiary company of Sulzer in 1989. At Scheco the share of heat pumps attained about 25% of the company’s turnover in 1990. As a town councillor of Bülach Wermelinger was engaged in a sustainable energy policy. After his retirement in 1999 he is leading the OptiCasa company (www.opticasa.ch) which is realizing passive houses not needing an active heating system any more. The solution of OptiCasa was awarded as the future building shell at the opening ceremony of the Swissbau exhibition in 2007. On this topic, Wermelinger notes: “Again the same problems as they were arising at the heat pump pioneer period – everybody is sceptical – **people can only been convinced by showing them that it works**." [Wermelinger 2007].

[25] Schweizerischer Verein für Kältetechnik (Swiss Association for Refrigeration).

SULZER SOLSET / BRUGNOLI / STREBEL / CRYOTHERM

Based on decades of experience, **Sulzer** built many medium and large size heat pump systems. From 1978 Carlo Brugnoli developed a small air/water heat pump with combined domestic hot water heating. It was called "**Solset**". Thanks to a bivalent-parallel operation with a seasonal heat power share of the heat pump of about 75% it provided a feed temperature of 65°C. At lower heat demands the back-up heating was performed by a continuous flow electric heater. At higher heat demands the back-up heating was done by an oil boiler. In order to avoid a too frequent on-off operation a special heat pump storage tank had been developed and patented by R. Huber. This solution had been tested in 1978/1979 in the laboratory and at the same time field tests were carried out. The first Solset heat pumps with heating capacities up to 30 kW were sold to installers from 1979 on. But consumer goods did not fit the concepts of Sulzer and were sold to the boiler manufacturer Strebel in Rothrist. In further developments of this company the heating capacity was enhanced to 120 kW. Sulzer was continuing its efforts for a small heat pump. But in the early 1980s there was a rapidly loosing of the momentum in the heat pump business due to circumstances described above. In 1984, Sulzer abandoned the small heat pump business definitively. It was Brugnoli who saved the technical know-how. He built up his own company **Cryotherm** in Toffen. Strebel was involved in Cryotherm as well. The Solset system was advanced by a heat pump boiler and up to four semi hermetic compressors. It came on the market with a heating capacity up to 300 kW. Following takeovers by the "Verzinkerei Zug" and an Austrian group, Brugnoli decided in 1996 to go into business for himself. Until his retirement in 1998 there were some more Solset heat pumps sold, among them also systems for bivalent-alternative operation and borehole heat exchangers. Brugnoli was a member of the technical committee of the AWP (see 7.2.8) (www.awpschweiz.ch) for many years as well [Bula and Bachofner 1979], [Brugnoli 2007].

7.2.3 Large Heat Pump Systems (> 1 MW)

As presented above, the Swiss pioneers of large heat pump systems were acting before 1950 already. The cumulated knowledge led to a leading position of **Sulzer**[26] in the large heat pump business. There were many systems built. In the following only a few examples will be mentioned.

4.7 MW TOTAL ENERGY UNIT AT LUCERNE RAILWAY STATION 1984

Compared to the combustion engine driven heat pumps the combination of cogeneration units with electric heat pumps, as mentioned in chapter 1, is a more reliable und more flexible total energy system. One of the first realizations of this modern concept was the system built by **Sulzer** for the Swiss Railway and the Swiss Mail in the railway station area. Six[27] heat pump units (Figure 7-10) with a heating capacity of 440 kW each and the water from the Lake Lucerne as a heat source were installed. The electric energy for these heat pumps was provided by three gas engine cogeneration units (Figure 7-11) with a heating capacity of 678 kW and an electricity production of 374 kW each. The heat supply temperature levels are 55°C - 60°C / 40°C[28] for the heat pumps and 75°C / 60°C for the cogeneration units. In summertime the heat pumps can be operated as chillers with a cooling capacity of 320 kW each. The primary energy ratio of the cogeneration - heat pump system was 1.7. Wood chips are used for the 3.2 MW backing boiler for peak shaving. The alternative heating system resulted in a light fuel oil saving of 1'300 tonnes. It was optimally operated by a computer taking into account the current

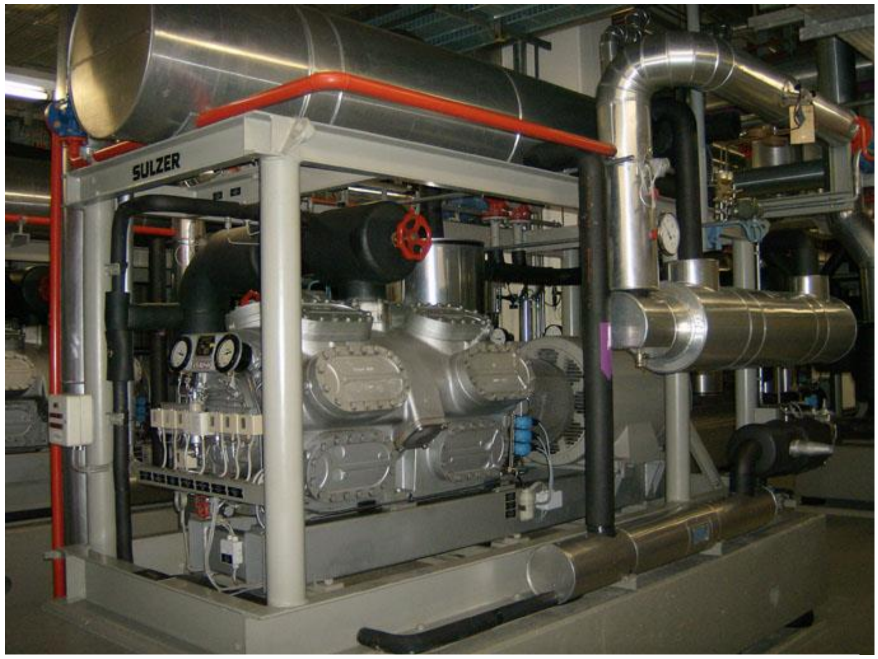
[26] In 1970, Escher Wyss was incorporated into the Sulzer group. After selling its hydraulic division to the Austrian VA Tech in 1999 and its turbo compressor division to the German MAN in 2001, the brand "Escher Wyss" disappeared.

[27] In 1984, four units were installed, two additional ones followed in 1986.

[28] Supply temperature / return temperature.

heat demand and the currant electricity tariffs [Etterlin 1985]. In 1990, the heat pump units had to be modified in order to replace R-12 with ammonia [Brügger et al. 1991]. In 2007 the original cogeneration units were replaced with new ones, built by **AVESCO**[29] in Langenthal and the total heating capacity of the system was increased to 7.2 MW.

Figure 7-10 One of the heat pump units at the Lucerne railway station area, installed in 1984 and modified in 1990 by Sulzer [Axima, CH-6010 Kriens]



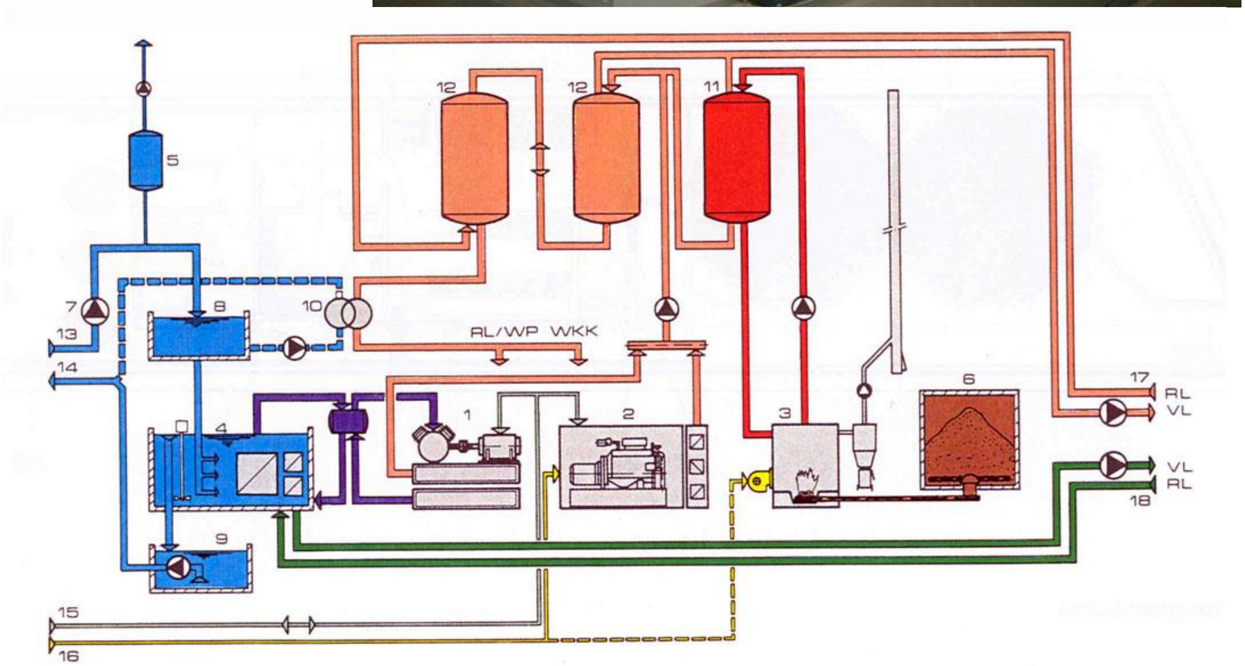


Figure 7-11 Principle of the combined cogeneration – heat pump plant at the Lucerne railway station area, 1984. 1 heat pumps, 2 cogeneration units, 3 wood chip boiler, 4 ice slurry basins, 5 vacuum vessel, 6 wood chips storage, 7 lake water pumps, 8, 9 lake water basins, 10 summer cooling system, 11 high temperature storage tank, 12 low temperature storage tank, 13 lake water supply, 14 lake water return, 15 electricity grid, 16 natural gas, 17 heat distribution, 18 cooling system. [Etterlin 1985]

29 AVESCO is manufacturing big cogeneration units with Caterpillar engines for natural gas and biogas in Langenthal. They have electric efficiencies up to 43%. Smaller high efficiency cogeneration units with the new exhaust gas recirculation SwissMotor of Liebherr in Bulle are being manufactured in Bubendorf [Hauptmann 2008].

19.2 MW TOTAL ENERGY PLANT AT THE EPFL IN LAUSANNE 1986

In 1979, based on a proposal by Lucien Borel the engineering consultant Ludwig Silberring[30] planned a path breaking heating plant [Silberring 1986]. It was realised by **Sulzer** at the Swiss Federal Institute of Technology in Lausanne (EPFL): Figure 7-12. The plant was started up in 1986. It is including two **gas turbine cogeneration units** with 3 MW electricity (electric efficiency 28.1%) and 5.7 MW heat (heat recovery efficiency 53.4%) each. The operation of the cogeneration is decoupled from the heat pumps. It is using light fuel oil. The two identical **electrically driven heat pumps** with an economizer port have oil-injected screw compressors: Figure 7-13. The heat pumps with a heating capacity of 3.9 MW each use ammonia as a working fluid and water from Lake Geneva (average temperature in the heating season 6°C) as a heat source. The water is taken from 65 m depth some 700 m offshore. The water, cooled down by about 3K in the evaporator, is then released into a nearby river. The two heat pumps with separate ammonia loops can either be operated in series (two-stage heat pump) or in parallel (then one heat pump is on stand-by mostly) depending on the heating conditions. Ammonia was chosen mainly with regard to its excellent thermodynamic properties. With a total **heat pump system** heating capacity of **7.8 MW** it became one of the largest ones in Switzerland. Measurements gave the following average Lorenz efficiencies of the heat pumps: 58.1% at 5°C/50°C, 59.7% at 6°C/ 45°C and 45.4% at 7°C/30°C. After ten years of operation the COP of the heat pumps declined as a result of the fouling in the evaporator, the presence of inert gases an a reduction of the compressor performance. Initially the plant achieved a primary energy ratio of 170% [Tastavi 1994], [Favrat and Tastavi 1995], [Pelet et al. 1997], [Favrat 2007].

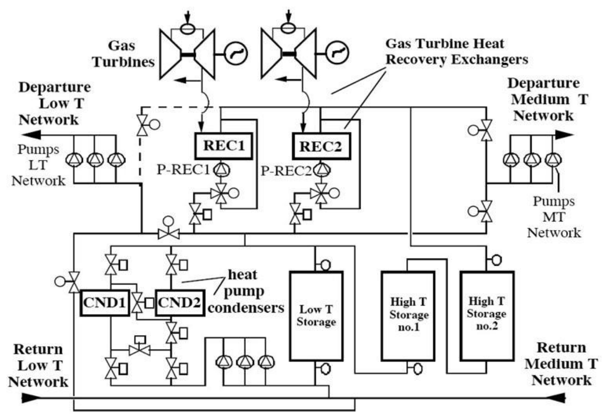


Figure 7-12 Simplified flow sheet of the EPFL total energy plant, 1986 [Pelet et al. 1997]

Figure 7-13 3.9 MW ammonia heat pumps at EPFL, 1986 [Friotherm 2008]

30 The engineering office „**Dr. Ludwig Silberring**" in Zurich has existed until 2005.

180 MW HEAT PUMP SYSTEM FOR THE STOCKHOLM DISTRICT HEATING SYSTEM

As Switzerland has only very limited district heating systems, the really big heat pumps had (and still have) to be exported. Only one of them will be mentioned here. In 1984-1986, the **world's largest heat pump system with sea water as a heat source** had been built and installed by **Sulzer** for **Stockholm's district heating system** (Värtan Ropsten). It has a total **heating capacity of 180 MW.** With a sea water temperature of 2.5 °C / 0.5 °C and a heating water temperature of 57 °C / 80 °C it is achieving a COP of 3.75. The system consists of 6 radial compressor heat pumps: Figure 7-14. The heating capacity is adjustable within the range of 10% to 100%. The system was retrofitted in 2003 in order to replace R-22 by R-134a [Friotherm 2008].

Figure 7-14 One of the six 30 MW radial compressor heat pump units of the Värtan Ropsten district heating system of Stockholm [Friotherm 2008]

SWISS DISTRICT HEATING SYSTEM - A NEVER REALISED FARSIGHTED CONCEPT

Independently from the activities and fundings of the Swiss Federal Heat Recovery Commission Peter Steiger, Conrad. U. Brunner, Heinz-Horst Becker, Werner Stoos and Bruno Wick developed an interesting concept on a **cold distance heating system (40 °C – 50 °C)** for a large part of the Swiss Midland with the rejected heat of the three nuclear power plants Mühleberg, Beznau I and Beznau II and industrial waste heat as heat sources. The main idea of the "**plenary system**" was to lift the temperature to the required temperature levels at the heat consumer side by heat pumps and thermal solar energy. The vision of the proposal was a cost equivalence with conventional oil boiler heating. The authors of the proposal estimated a realization time of 15 years and total costs of 11.7 billion Swiss Francs. This farsighted concept had never been realised. But in times of fast rising energy prices and growing CO_2 emissions it is worth while to rethink about it [Steiger et. al 1977], [Schärer 2007].

7.2.4 Pioneers of Borehole Heat Exchangers

The Swiss gave an important impetus to this technology – which had just been flirted with until about 1980.

RECHSTEINER / MULTI-ENERGIE - FIRST BOREHOLE HEAT EXCHANGERS

The high price of land in Switzerland misled to a sub-sizing of the horizontal ground heat exchanger which resulted in later vegetation growth or even ground frost damages. This motivated Jürg Rechsteiner to try to replace them with vertical **borehole heat exchangers**. He was the Swiss pioneer for this system. As early as **1974** Rechsteiner rammed his first borehole heat exchanger of a total length of 70 m into the sandy ground of Lustenau (Vorarlberg, Austria). It consisted of **coaxial steel ram probes** with 60 mm outer diameter, a wall thickness of 5 mm and a length of the bolted elements of 2.5 m each. The ramming of the first probe was successful. The second ramming ended up with an unpleasant surprise. The top of the probe arrived just a few meters from the ramming machine. There was no alternative at that time than a borehole heat exchanger design by rough plausibility assumptions. Nevertheless a heat pump system was built by the German Schäfer Heiztechnik, which went bankrupt in the 1980s. Between 1974 and 1977 Rechsteiner's company **Multi-Energie** (www.multienergie.ch) made 12 more heat pump systems with steel probes. But there were a lot of problems with leakage from damaged gaskets between the probe elements. This was a costly first trial and it ruined the reputation of borehole heat exchangers. By the way, one steel probe is still in operation today!

Because of the bad experiences with the steel probes Rechsteiner developed the **first double-U-tube probes made of polyethylene** (duplex probes, outer diameter of the tubes 25 mm, wall thickness 2.4 mm, length 50 m). He presented his innovation to Ernst Rohner of the drilling company Grundag (see below). Shortly afterwards Multi-Energie arranged initial tests with plastic u-tube probes near St.Gallen. As early as **1980 the first installation** for a home in Arbon with a Multi-Energie heat pump was built and started up on December 18, 1980. As shown by later long time measurements it was well working – even though a back filling of the probe was lacking yet. After 30 years of operation it is still functioning to the full satisfaction of the owner.

Since 1980, many new installations all over Switzerland followed. By 1983 the double-u-tube probe made of plastic had demonstrated its usefulness and reliability. The Swiss Patent 649623 for this new solution was granted in 1985. But soon after, it turned out that there existed a German Patent for a likewise solution with a direction change box at the bottom of the probe instead of a u-bend. This German patent has never been utilised, but it prevented a protection of Rechsteiner's innovation. In consequence it was copied in thousands of installations in Switzerland and abroad. Rechsteiner took comfort in saying “Only good things are being copied thousandfold” [Rechsteiner 2007].

ROHNER / GRUNDAG / HASTAG

As mentioned above Ernst Rohner's **Grundag** did the first drilling for U-tube probes in 1980. But Grundag started earlier and carried out drillings for other purposes manly in the ground water business for drinking water and hot springs. Its technique was hydraulic-circulation drilling which is much cheaper than core hole drilling. From 1980, Grundag was a dependable partner of the whole Swiss heat pump community. It did its job with experienced and competent drill-masters all over Switzerland and was active in the neighbouring Germany and Austria as well. Ernst Rohner was able to get a patent on special clamps for leading the drill. He retired in 2001 and handed over his business to HASTAG in St.Gallen (www.hastag.ch). The depth of the boreholes was 50 m in 1980. By 1985 it went to over 100 m and has reached more than 300 m today. The main reason for this development is not the inclining temperature in deeper regions (about 1 K per 30 m) but the shortage of land [Rohner 2007], [Ottinger 2007].

TRÜSSEL / KWT

In about 1980, Kurt Trüssel, the founder of the **KWT**[31] company in Belp wanted to realise borehole heat exchangers as well. Apparently independent from Jürg Rechsteiner he carried out a first experiment. He let drilling a 50 m deep borehole in his own garden, inserted a coaxial probe and connected it with a refrigeration unit. By monitoring the thermal behaviour of the probe he got first design information for this device. Around 1981, Trüssel was installing his first commercial ground coupled heat pump for a home in Hettiswil. But by this occasion the German drilling company, used to sandy soil, run into problems with the rocks some 30 m below Hettiswil. Although the heat pump system with two coaxial probes of 50 m each was finished and it is still in operation! From then on until 1987 KWT engaged the drilling company Grundag for its further borehole heat exchangers. Then KWT began its own drilling business. By the way, in 1985, Trüssel introduced heat pumps with **integrated domestic hot water heating** by using the desuperheater for the final temperature lift. At that time he also came up with his famous separate **desuperheater for laundry drying** [Trüssel 2007].

BURREN / WA-TEC / FRUTIGER

In 1980, the brothers Erwin and Jürg Burren tried it with 2 inch coaxial steel probes of 50 m length, backfilled by bentonite. Probably they acted without knowing Rechsteiner's experiences. Inside the steel probes, called "Zonatherm", there was a polyurethane hose. The first drilling had been made in summer 1980 by a subsidiary of **Dicht** in St.Gallen. The company **WA-TEC** in Thun broke down on too many children's diseases of their first heat pumps and the too costly cathodic protection against corrosion for the steel probes.

Later, in 1988, **Frutiger** in Uetendorf began drilling for borehole heat exchangers as well [Beck 2007], [Ottinger 2007].

7.2.5 Pioneers of Heat Recovery from Raw Sewage

As mentioned above the first heat recovery from raw sewage as a heat source was built by Heinz Grimm. But Grimm's solution suffered from problems with the solid fraction.

Figure 7-15 Latest version (2007) of the FEKA tank for the heat recovery from raw domestic sewage. Left: heat exchanger tubes, right: solid separation zone. Photos Eulachhof Winterthur [Kalberer 2007]

This problem was talked by Felix Kalberer by the end of the 1970s. In 1981, he patented a new system for the heat recovery from raw sewage with a separation of the solid fraction by sedimentation and sieving [Kalberer 1981]. The first larger of the so called "**FEKA"** tanks was a re-

[31] KWT Kälte-Wärmetechnik, CH-3123 Belp, founded in 1979 by Kurt Trüssel, www.kwt.ch

gional stadium in Sargans. This tank is still in operation. Until now it was followed by about 180 more ones with a continuous improvement of the system. Figure 7-15 shows a modern version installed at the residential estate Eulachhof in Winterthur in 2007 (Eulachhof is presented in the next chapter).

If the solid content is extremely high an annual cleaning of the FEKA tank is necessary. For a normal raw sewage a cleaning every four years is sufficient. The cleaning can be done by the local raw sewage system cleaners. In new systems a remote monitoring of the COP of the heat pump is indicating a demand for cleaning [Kalberer 2007].

7.2.6 Quality Control for Small Heat Pumps

BOREL / FIRST HEAT PUMP TESTING

In the French speaking part of Switzerland Lucien Borel[32] of the Swiss Federal Institute of Technology in Lausanne **EPFL** (Ecole Polytechnique Fédérale de Lausanne) built up **a heat pump testing** facility around **1980**. "EPFL tested" became an important quality label years before the Swiss Heat Pump Test Centre in Winterthur-Töss opened. Borel was among the francophone pioneers of exergetic analysis. He applied it also on heat pump systems in order to identify the weak spots of the process [Borel 1980]. The testing of commercial heat pumps was funded by the Swiss Federal Office of Business Activities (Bundesamt für Konjunkturfragen). The best Lorenz efficiencies of the heat pumps tested in 1986 were close to 40% for air/water and 45% for water/water heat pumps: Figure 7-16. Compared to the later measurements at Töss the values seem to be too high for that time. Probably the test conditions (such as defrosting) were not in accordance with EN 255 (see 8.2.5). Borel was also concerned with the cost effectiveness of heat pumps and the potential of different heat pump applications [Borel et. al 1981].

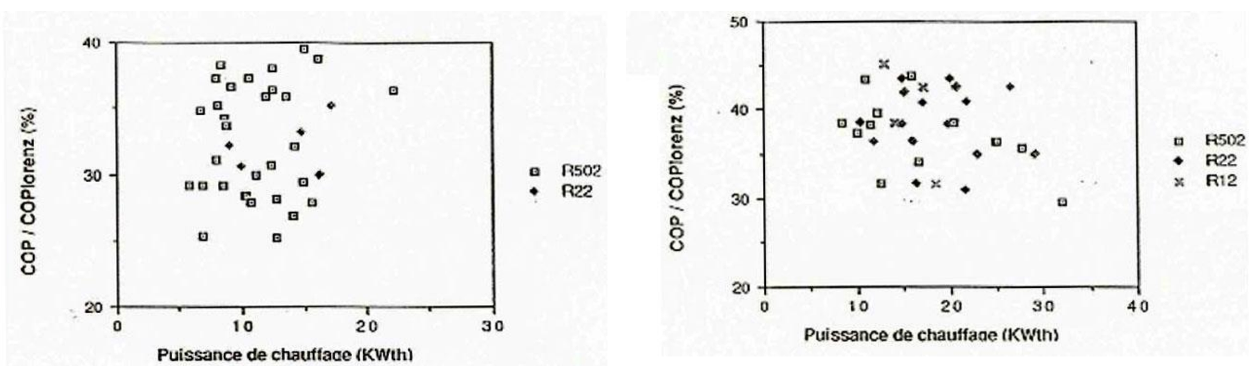


Figure 7-16 Lorenz efficiency calculated from the test results at the EPFL for commercial air/water (left) and brine/water[33] (right) heat pumps in 1986 [Favrat 1989]

HUBACHER, DÜRR, EHRBAR / FIRST HEAT PUMP SYSTEM TESTING

It is important to know the efficiency of a heat pump. But finally consumers and planners want to know the efficiency of the heat pump heating system as a whole, consisting of heat source, heat pump, control, piping and heat distribution. The **systematic long time field tests on**

[32] Lucien Borel was a professor and the head of the laboratory for thermodynamics and energy (Laboratoire de thermodynamique et d'énergétique de l'EPFL) from 1954 until his retirement in 1988.

[33] On the original diagram this was referred to water/water – but the tests had been done under today's brine/water conditions [Favrat 2007].

complete heat pump space heating systems were introduced by Peter Hubacher (owner of the Enfog company in Gossau) with his colleague Bruno Dürr and the scientific advisor Max Ehrbar of the University of Applied Science in Buchs (Neutechnikum Buchs NTB) in the heating season 1981/1982 and then continued for some years. The tests were supported by the private national energy research fund NEFF and the Swiss Federal Office of Energy. Some of the results give an interesting impression of the poor efficiency of air/water heat pump systems in the early 1980s: Table 7-1. Later systems with vertical borehole exchangers for homes had been tested as well. A system at Rorschacherberg, checked between 1984 and 1989, achieved a seasonal performance factor of 2.3. Another one at Frauenfeld, checked between 1985 and 1989, attained a seasonal performance factor of 2.9. The measurements had been taken every two minutes and were used by Hopkirk, Rybach and his collaborators for the validation of their computer simulations [Hubacher 1987, 1990].

Table 7-1 Measured efficiency of air/water heat pump central heating systems in the early 1980s

Net Heated Area m^2	Heat Pump Type	Heat Source	Heat Pump Heating Power kW	Seasonal Performance Factor SPF[34]	Primary Energy Ratio PER	Reference
1426	electric electric electric resistance backup	ambient air sewage	32 22 bivalent 20	1.91		[Dürr and Hubacher 1984]
253	electric	ambient air	25	2.21		[Dürr and Hubacher 1985]
7700	gas engine	ambient air	300		1.2[35]	[Brechbühl et al.1983]

7.2.7 Support by Public R & D

STUDIES ON HEAT PUMPS

By the end of the 1970s the **Swiss Federal Heat Recovery Commission** (Eidgenössische Abwärmekommission) – the precursor of the later Ambient Heat Section of the **Swiss Federal Office of Energy SFOE** (Bereich Umgebungswärmenutzung des Bundesamts für Energie BFE) – got involved with heat pumps. Hans Ulrich Schärer (SFOE) was its secretary. In 1977, on behalf of this commission there were carried out extensive theoretical studies on heat pump heating by the **Swiss Federal Institute for Reactor Research** (**EIR**, Eidgenössisches Institut für Reaktorforschung)[36]. Using ground water, surface water, ground and air as a heat source were among the topics. Concerning the ground as a heat source, only horizontal ground heat exchangers were taken into account at that time. The deficits in designing ground heat exchangers were obvious and further research on this issue was stipulated. Also the costs for this system were assessed to be too high [Mustoe 1977]. The studies were extended in 1982 and complemented by an investigation of non azeotropic mixtures (adaptation to the temperature change of the outside heat carrier – Lorenz process), absorption processes and unusual processes such as steam jet compression, thermoelectric and magnetic effects. Direct driving

[34] M. Ehrbar and P.Hubacher used the term “MALZ (mittlere Anlagenleistungszahl)“ which means the seasonal mean value of the COP.
[35] The expected value was 1.5. The reasons for the low value of 1.2 were several breakdowns, to short operation periods and defrosting problems.
[36] Today Paul Scherrer Institute (PSI), www.psi.ch

of heat pumps by gas, Diesel and Stirling engines were studied as well. There was predicted a brilliant future of the direct coupled combustion engine heat pump – which due to problems not foreseen did not prove to be so. Another part of the study was covering the optimal integration of heat pumps in different heating systems and the depletion of the ozone layer by CFCs [Leuenberger et. al 1982].

GUIDELINES FOR SURFACE WATER AS A HEAT SOURCE

On the basis of computer simulations Dieter Imboden[37] of the EAWAG[38] in Dübendorf worked out **guidelines and extreme values for extracting heat from rivers and lakes** of Switzerland in order to avoid any harm to the sensitive ecosystems. This study - prepared on behalf of the Swiss Federal Heat Recovery Commission – illustrated, that in principle the surface water heat source potential would be sufficient for covering the whole heating demand of Switzerland without any damage to the water ecosystems. Assumed a correct keeping of the conditions formulated in the report the limits are not the water ecosystems but the distances to overcome in terms of costs for the piping systems and the pump energy demand [Imboden et. al. 1981].

MODELLING OF BOREHOLE HEAT EXCHANGERS

Science came after practical pioneering developments, as it is often the case. After the preparation of the field by the mentioned pioneers borehole heat exchangers gained popularity quickly. Following the fighting against and the laughing at the practitioners the matter became serious and a **scientifically based design and optimisation** of the installations for an optimum long time operation became important. Following horror stories about cooling the ground down to permafrost in less than ten years there were arranged long time field tests by the SFOE and the NEFF[39] in order to get a better understanding of the theoretic fundamentals.

At the beginning of the 1980s, in Switzerland it was Robert J. Hopkirk from Polydynamics (www.polydynamics.ch) who began the **modelling and computer simulation** for the first time. Later followed Ladislaus Rybach of the ETH Zurich and his collaborators (in particular Walter J. Eugster), notably motivated by Ernst Rohner Sr. The theoretical and experimental studies by these individuals together with the practical experience of the drilling and heat pump pioneers led to significant international contributions and to the leading position of some Swiss companies in designing and realising of borehole heat exchangers as heat source for heat pumps, as ground storage for an optimal jear round operation of combined heating and cooling plants and as heat sink for passive air conditioning [Schwanner et al. 1983], [Hopkirk et al. 1985], [Rybach 1987].

CONFERENCES ON KNOWLEDGE AND EXPERIENCE TRANSFER

The first Swiss conferences on heat pumping technology were organized in 1980 and 1981. 12 papers covered all Swiss fields of activities such as heat sources, refrigerants, compressors, noise insulation and complete systems [SVG 1981]. Since then these conference have been continued annually. They are dedicated to pilot installations and research issues alternatively and have been organised by Hans Ulrich Schärer, Martin Zogg, Fabrice Rognon, Thomas Kopp and Max Ehrbar on behalf of the SFOE.

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[37] Dieter Imboden became later a Professor at the ETH (Institut für Biogeochemie und Schadstoffdynamik, CH-8092 Zürich).
[38] Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz, today Swiss Federal Institute of Aquatic Science and Technology, www.eawag.ch.
[39] Nationaler Energieforschungs Fonds NEFF – a private national energy research fund, sponsored by oil, gas and electricity utilities.

7.2.8 Support by Associations, Federal Administration and Media

SWISS WORKING COMMITTEE OF HEAT PUMP MANUFACTURERS AND DISTRIBUTORS

On the initiative of Ernst Lüthi (CEO of CTC Wärmetechnik[40]) the **Swiss Working Committee of Heat Pump Manufacturers and Distributors AWP** (www.awpschweiz.ch, Arbeitsgemeinschaft Wärmepumpen) was founded as an association of manufacturers and distributors of heat pumps, drilling companies and component suppliers in 1980. The objectives of the AWP were a common language of all providers, a unification and simplification of the approval procedures, common planning guidelines, an exchange of experience and a professional training. Members of the **technical commission** were G.Szokody (chairman), C. Brugnoli, E. Grüniger, K. Hess, H. Reiner and P. Schneiter. Under the lead of G. Szokody the commission elaborated groundbreaking **heat pump guidelines** in a very short period of time und published them in 1981 already [SVK 1981]. The commission was involved in the preparation of the **decree** of the Swiss Federal Office for the Environment (Bundesamt für Umwelt, at that time BUWAL) **on heat withdrawal** from surface water, ground water and solid ground implemented in 1982.

Of great importance for the elimination of previous uncertainties, and thus significant hurdles for the dissemination of heat pumps were also the **recommendations for the electrical connection** of heat pump systems worked out in cooperation with the utilities [VSE 1983], [Schär 1983]. Also organized by the Swiss Federal Office of Energy there was a meeting with the energy departments of the cantons in order to unify and simplify the approval procedure of the authorities in 1983. A number of other **recommendations and guidelines** followed, which found international attention as well [Szokody 1984]. In 1990, the retrofit market had been addressed by a checklist for the collection of data necessary for a serious planning [Szokody 1990]. The generous dedication of Gyula Szokody for the heat pump community is illustrated by the example of preparing a draft of the AWP planning recommendations of some 120 pages during the days off on Christmas and New Year. As mentioned above Szokody was AWP's technical commission chairman between 1980 and 1995. AWP is still active and is continuously updating and extending its **technical bulletins** reaching from heat sources to CO_2 heat pumps [AWP 2007].

SWISS FEDERAL OFFICE OF ENERGY SFOE

Besides supporting research activities the Swiss Federal Office of Energy acted as a catalyst for the associations and the cantons. It arranged a study on the potential of heat pump heating in Switzerland in case of a further oil embargo [BFE 1983].

PROMOTION

A first retrofit heat pump with several borehole heat exchangers for a apartment building in Münchenstein replaced an aging oil boiler in 1985. That became a breakthrough in the media

[40] Today CTC Giersch, CH-8112 Otelfingen, www.ctc-giersch.ch.

presence of heat pumps. That event was presented not only in the daily newspapers[41] but on the television in a detailed broadcast[42] as well [Beck 2007].

7.3 Heat Pumps for Heating - International Milestones

Worldwide, the number of heat pumps in 1979 was estimated at about 800’000 without, and 4’000’000 with the reversible air conditioners. Among the heating only heat pumps the U.S.A. had a share of about 90%, Europe only about 6.5%. Including heat pump boilers there were reported 6’600 heat pumps in Switzerland, 30’000 (without heat pump boilers only around 500) in Germany, 13’000 in France, 2’000 in Austria and 100 in Italia at that time [Barclay J.A. et al 1978], [IEA 1980].

AUSTRIA

The 1973 oil embargo did not move much in Austria and the referendum in Austria on November 5, 1978 was not a favourable signal for heat pumps: 50.5% of the Austrians voted against the start up of the already built nuclear power plant in Zwentendorf.

GERMANY

There was only a minor effect of the 1973 oil embargo on Germany’s heat pump scene. Until **1979 only some 500 heat pumps** for space heating were sold. The first generation of heat pumps for homes had many children’s diseases. They used to be bulky and had a problematic high volume of refrigerants, mostly R-22, R-12 and R-502. For the defrosting of the evaporators of air source machines up to 8 magnetic valves were needed. The growing interest is demonstrated by a first three days heat pump conference (Wärmepumpentagung) in Essen in 1977 organized by Horst Kruse and Fritz Steimle [Joachim 1980]. In 1978, the first comprehensive text book on heat pump technology in German appeared. Already one year later, it was followed by a second one. Both books appeared later in several revisions and new editions [Cube and Steimle 1978], [Cube et al 1997], [Kirn and Hadenfeldt 1979].

But only the second energy crisis in 1979/1980 changed the situation in favour of heat pumps. In 1981 there were about 12’000 heat pumps installed in homes – most of them restricted to domestic hot water heating [Dienel 2004]. The technical development went along the same lines as described for Switzerland above. Thermoactive building elements such as walls and roofs of prefabricated garages or façade elements as a heat source became more popular than in Switzerland [Jochheim, Bracke 1985]. In 1980, six years after Jürg Rechsteiner in Switzerland, the first **borehole heat exchangers** had been installed in Germany. There were 8 **coaxial** probes, 50 m long each. Others followed soon [Sanner 1992].

From 1981 to 1983 **Volkswagen** and **Ruhrgas** developed the so called “**Thermodiesel**”, a heat pump driven by a 1.6 litre car diesel engine: Figure 7-17. All technical finesses such as heat recovery from the exhaust gas, rotary speed modulation and even a ceramic carbon-particulate filter had been built in. Pilot marketing and sales were carried over to **Hoval Herzog** in Feldmeilen, Switzerland. Some units were field tested by Hoval in 1985 until 1986. Unfortunately the failure of the costly project became clear rather soon. The time between services proved to be much to short (in some cases not even a heating season) and the lubricating oil consumption of 17 litres per year was expensive as well. The running time for one single heating season corresponds to a car driving performance of more than 200’000 kilometres. For a minimum heat pump lifetime of 15 years this would correspond to 3’000’000 kilometres. This is

[41] For instance in the “Berner Zeitung” from March 21, 1985.

[42] Within the popular serial program “Mensch-Technik-Wissenschaft” (human being – technology – science).

simply too much – even for a German quality car engine. Aside the too short lifetime of the engine and the high lubrication oil consumption there arouse further problems such as the direct coupling of engine and compressor (that meant a too high rotational speed for the compressors available) and to too high noise level [Adolph 2004], [Szokody 2007].

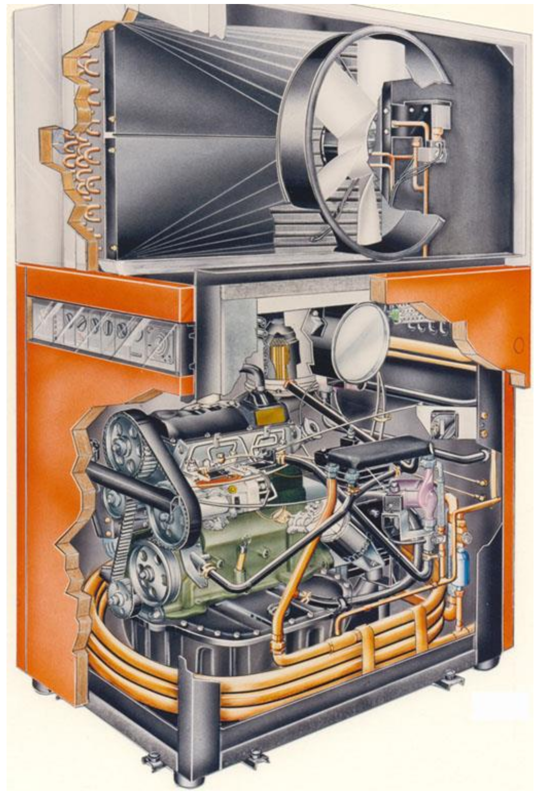


Figure 7-17 Hoval thermodiesel, 1986 [Szokody 2007]

In the period of 1980 to 1985, a **heat pump testing facility** was set up at the University of Applied Science in **Karlsruhe** (Fachhochschule Karlsruhe). About 45 space heating and 45 domestic hot water heating heat pumps had been tested in accordance with DIN standards. The tested heat pumps were of German, Austrian, Danish and Swiss origin. By 1985 the demand broke down and the testing was stopped [Adolph 2004].

HOLLAND

In Holland an experimental variable speed heat pump **driven by a Stirling engine** for a semi-detached house was built in 1978. The Stirling engine of the crank drive type attained a mechanical efficiency of 25% and a thermal efficiency of 55%. The heat pump used groundwater as a heat source and the heat distribution was provided by a floor heating system. This unconventional total energy unit as a combination of Stirling engine and heat pump had a total heating capacity in the range of 8 kW to 25 kW and a primary energy ratio of 1.4 [Philips – OGEM 1978].

SCANDINAVIA

Since 1982 there was boom in demand for large heat pumps in Scandinavia as discussed in section 7.2.3.

The thermal analysis of **borehole heat exchangers** began in the early 1980s (compare with the Swiss activities in 7.2.4). At the Department of Mathematical Physics of Lund University Per Eskilson gave fundamental contributions to this topic [Eskilson 1987].

In 1989, the Nordic Council of Ministers introduced a **voluntary and neutral approval certification program,** the **Nordic Swan**. The program was introduced in an attempt to unify the emerging ecolabeling programs that were appearing throughout the Nordic countries. The participating national organizations propose new product categories, assist in establishing award criteria, grant licenses, and market the program. The Nordic environmental label is an independent label, which guarantees a **good environmental standard**. Only products, which satisfy its requirements on the basis of objective assessments will be allowed to display the environmental label. The label is intended to provide consumers with guidance in choosing products least hazardous to the environment, to stimulate manufacturers to develop products and processes that are better for the environment, and to use market forces as a complement to environmental legislation. The green swan symbol, covering over 60 product groups, is enjoying high consumer recognition to date. The label is usually valid for three years, after which the producers must reapply and then have to meet the actual requirements. Currently, Norway, Sweden, Finland, Iceland, and Denmark are participating in the program.

U.S.A.

As mentioned in 6.2 there was stagnation in the heating only heat pump market before the oil embargo of 1973. But soon afterwards a rapid expansion began. In 1976 were 1.6 million unitary heat pumps for cooling and heating operating in the U.S.A. and 300’000 new units were manufactured.

7.4 Vapour Recompression – Swiss Pioneering Work in Distillation

Distillation is among the biggest energy consumers. The “Chemtech” division of **Sulzer**[43] introduced the **world’s first distillation plant with vapour recompression** around 1985 and has carried out a lot of pioneering work [Meili 1990]. The plant shown in Figure 7-18 for the separation of fine chemicals[44] with an evaporation power of about 2 MW was started up in 1986 at a chemical company in the U.S.A. In 1987 a distillation plant for the separation of 1,2-dichloroethane was installed. It had a pressure ratio of 2.2 and an electric drive power of 1.3 MW [Dummer and Schmidhammer 1991]. A further vapour recompression distillation plant was built for the separation of styrene/ethylbenzene in 1987. Later, there were many more of these systems, for example in a propylene plant with an annual production of 125’000 t [Meszaros 2007]. In case of corrosion and risk of explosion close loop heat pumps are replacing vapour recompression: Figure 7-19.

[43] Sulzer Chemtech, CH-8404 Winterthur, www.sulzerchemtech.com.

[44] Separation of chlorobenzene isomers.

Figure 7-18 One of the first distillation plants with vapour recompression [Sulzer Chemtech, CH-8404 Winterthur]

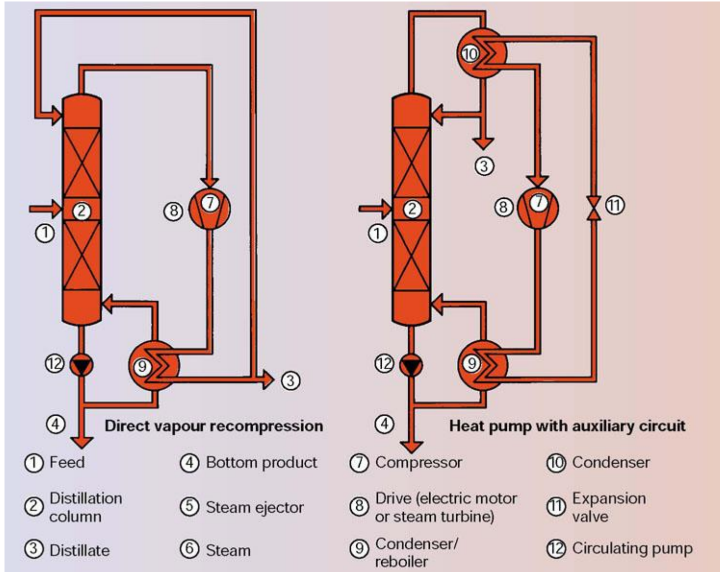


Figure 7-19 Principles of vapour recompression and heat pump integration into heat pumps [Sulzer Chemtech, CH-8404 Winterthur]

8 THE SUCCESS STORY 1990 – TODAY

Cheaper, more efficient and more reliable heat pumps became available. The growing environmental problems are favouring the idea of saving primary energy by heat pump heating. In a time with rapidly growing oil prices this means saving more and more money as well. Further heat pump heating is backed up by national and international efforts in R&D and quality control. In some countries there were and still are some additional financial incentives.

8.1 Components and Refrigeration

Vapour compression cycles became a mature technique already in the years before. But the urgent phasing out of the chlorinated synthetic refrigerants (CFCs, HCFCs) was a great challenge. The focal point of the development went from component innovations to system optimisation and to cheaper mass production. This was highly favoured by the impressive progress of the information technology. There is a tendency towards natural refrigerants, mainly ammonia, and higher efficiencies due to low temperature floor heating systems. Energy contracting is taking the risk from the customer and has become very popular for larger installations.

COMPRESSORS

From the early 1990s **hermetic scroll compressors** were outrunning hermetic piston compressors and became the common choice for smaller heat pumps. The efficiency of small compressors was improved significantly. New permanent magnetic electric motors will bring further improvements. New developments have started for **CO_2 compressors** worldwide. A Swiss contribution for a small oil free CO_2 compressor within the framework of the IEA Annex 27 is referred to in 8.2.3.

REFRIGERANTS

The refrigerant topics were dictated by the challenges in responding to environmental concerns. In 1990, the parties to the Montreal Protocol agreed in London two amendments to eliminate the CFC use and production by the year 2000 [Nagengast et al. 2006]. In 1992, the Montreal Protocol was revised to advance **CFCs phase out by the end of 1995**, with HCFCs to be phased out in stages by 2030. In many countries the HCFC phasing out was scheduled much earlier (i.e. Germany by 2000, Austria and Switzerland by 2002).

As a consequence of the phase out scenarios a new generation of refrigerants had been introduced. In 2001 the **Global Refrigerants Environmental Evaluation Network (GREEN) program** was inaugurated in order to obtain objective performance data on new and existing refrigerants in a variety of refrigeration, air conditioning, and heat pump applications. The testing program was accompanied by a communications effort to disseminate performance information as well as other comparisons of HFC and alternative refrigerants (HFC, such as R134a), hydrocarbons and carbon dioxide.

The new **HFC** fluids perform well as an adequate replacement of the CFCs and HCFCs. But because of their high global warming potential GWP and above all their persistent decomposition products (trifluoroacetic acid) they are still under international scrutiny and may be eliminated in the future. **Natural refrigerants** were discussed as the final solution to the quest for the ultimate refrigerant [IIR 1998]. The primary candidates are **ammonia, carbon dioxide** and **hydrocarbons,** such as propane or isobutene. Each fluid comes with its own set of challenges. Ammonia is widely used in large refrigeration plants, although it is toxic and flammable. But its stinging odour warns of any leaks long before any dangerous concentrations are obtained. Carbon dioxide requires a transcritical cycle, which reduces its efficiency for most space heating applications (in contrary to hot water heating). On the other hand, in refrigeration it may provide new secondary uses due to its high temperature level waste heat. Carbon dioxide hot water heat pumps were introduced in the market around 2000. Propane performs very well, but it is flammable and thus considered a safety hazard especially in the U.S.A. and in Japan.

Many comparative studies on global warming effect issues of different refrigerants have been done. The **GWP** (global warming potential) of a refrigerant is an indicator for the greenhouse gas effect of a refrigerant compared to the equivalent effect of CO_2. More relevant to the greenhouse gas effect of a refrigerant is the **Total Equivalent Warming Impact (TEWI)**. It is defined as the sum of the **direct global warming potential** through refrigerant leakage during the lifetime of the plant and at its disposal and the **indirect global warming potential** through the CO_2 emissions of the electric energy generation for operating the plant. Therefore the TEWI is strongly dependent on the efficiency of the heat pump process and of course of the primary energy source used. Higher energy efficiency by the use of some refrigerants can reduce the indirect effect and compensate higher GWPs to a certain extent.

However, the environmental impact is not restricted to the greenhouse gas effect. Therefore more comprehensive answers on the harm of refrigerants to the environment can only be given by complete **Life Cycle Assessment (LCA)**. Worldwide the **environmental relevance and the heat transfer characteristics of natural and HFC refrigerants** have been studied many times. The Swiss contributions are described in 8.2.3. By about 2005 the worldwide efforts led to a stop of the ozone layer cutback [Baumann M. et al 2007].

HEAT EXCHANGERS

At the beginning of the 1990s **the plate heat exchanger** became the common heat exchanger type definitely. This led to lower refrigerant volumes, lower temperature differences (and hence lower losses of exergy) and space saving heat pumps.

DIGITAL CONTROL

Around 1990 the digital control entered the scene. **Microcomputers** made it possible to program controllers for more sophisticated strategies, such as model based control and complete automation of processes. Not long after, the era of **data communication** on longer distance began. Controllers had got a connection to a data bus. That lifted man machine-communication to a new level. The remote monitoring and the remote control by modems became possible. New diagnose methods allow to reduce periodic service intervals to a well directed maintenance at the time when really required. This led to an increase in the reliability and efficiency and a fall in maintenance costs. After all, the easy worldwide communication by the Internet accelerated this development enormously. By the way, the **Internet** had its origin at the international nuclear research centre CERN in Geneva, Switzerland [Segal 1995].

8.2 Heat Pumps for Heating - Swiss Contributions

After getting over the “once-burned” effect, from 1990 a definitive take off of heat pumping technology for heating only purposes began. It had technical reasons such as greater reliability, quieter compressors with higher efficiency and sophisticated microcomputer control. But less prejudice due to a broader understanding of the advantages of heat pumping technology, better trained planners, more competent installers, quality labelling and last but not least falling prices by a factor of 2 within 25 years were decisive as well.

It had technical reasons such as greater reliability, quieter hermetic piston or scroll compressors with higher efficiency and sophisticated microcomputer control. But less prejudice due to a broader understanding of the advantages of heat pumping technology, better trained planners, more competent installers, quality labelling and last but not least falling prices by a factor of 2 within 25 years were decisive as well.

In 1991, in Switzerland there were about 30’000 heat pumps with an average thermal power of 25 kW in operation. About 2/3 of them used ambient air as a heat source but the share of borehole heat exchangers was increasing rapidly [BFE 1993]. At that time the seasonal performance factor was around 2.4 for air/water systems and with 2.5 not much higher for brine/water systems [Hubacher 2007]. The reason for this minor difference was circulation pump energy losses due to too high flow rates and the lack in dependable design fundamentals. After 1998 the take off of heat pumps accelerated to a market share today of 75% for space heating and domestic hot water heating in new homes: Figure 8-1.

Heat pumps are now slowly penetrating the retrofit market as well. By 2006 the total market share of heat pumps below 20 kW for new and old buildings has attained 33% (Figure 8-2) and there were about 3000 retrofit heat pumps und about 100’000 heat pumps in new buildings in operation (www.fws.ch). For capacities exceeding 50 kW heat pump heating on an **energy contracting basis**[45] is becoming more and more popular. The biggest energy contractors in Switzerland are the utilities of the canton of Zurich (EKZ) and of Zurich City (EWZ). Together they have delivered more than 50 GWh of heat in 2006.

[45] The client is not buying a heat pump system and does not care for the maintenance; he is just paying for the heat consumed.

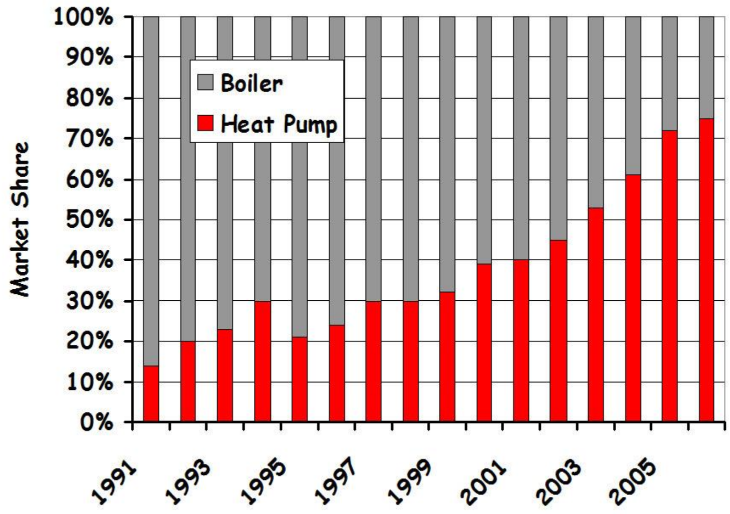


Figure 8-1 Market share of heat pumps with heating capacity up to 20 kW in new homes. Values from www.fws.ch

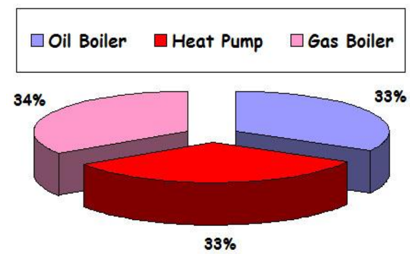


Figure 8-2 Total market shares of new installed heating systems in 2006. Values from www.fws.ch

Most basic innovations happened before 1990. But there was a huge optimisation potential to tackle. And this had been done successfully as is demonstrated by the **results of the Swiss Heat Pump Test Centre** (it is presented in the section "Quality Management"). Within 15 years, from 1992 to 2007, the tested heat pumps for central water space heating with ambient air as a heat source show an increase in the average COP by 30% from 2.6 to 3.4: Figure 8-3. This is equivalent to an only moderate Lorenz efficiency of 28% to 36%. The tested air/water heat pumps were in a heating capacity range of 2.5 kW to 30 kW with an average of about 8 kW.

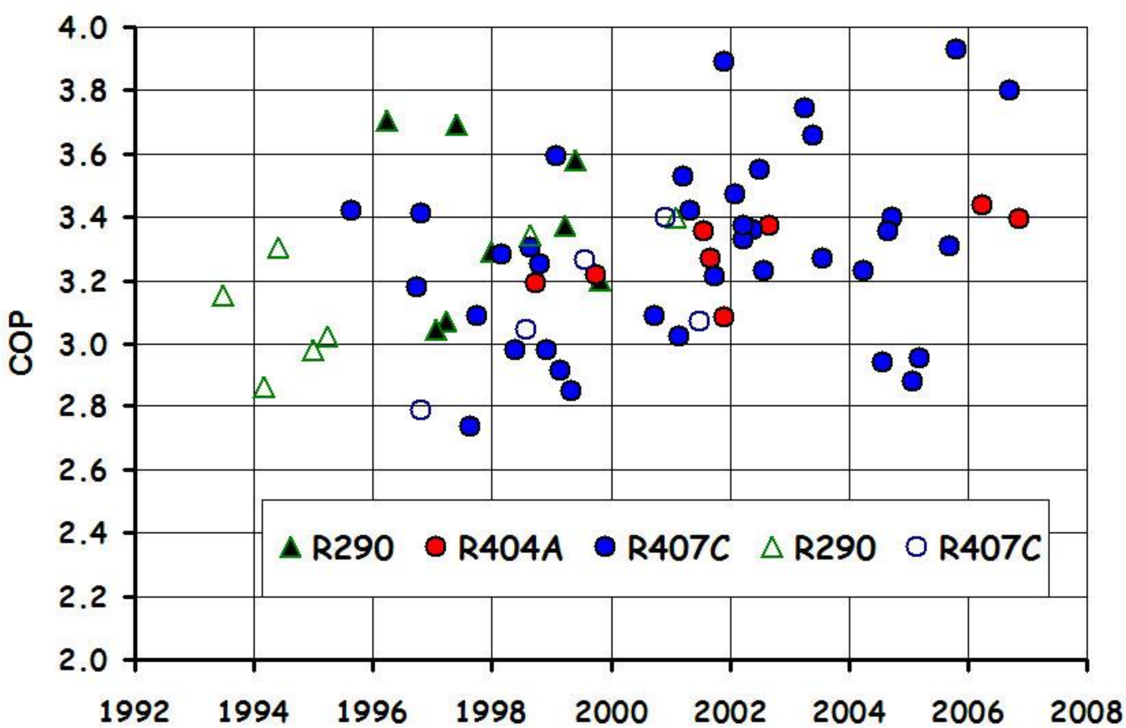


Figure 8-3 Efficiency of commercial air (2°C) / water (35°C) heat pumps at a maximum heat sink temperature difference of 10 K, measured with complete defrosting cycles at the Swiss Heat Pump Test Centre. Separated by refrigerant and compressor type. Filled out symbols: scroll compressors; void sym-

bols: piston compressors. Values from [Nani et. al 2005] with additional results from [Nani 2008]

Within the same period of time for brine[46] as a heat source there is an increase of the average COP by 17% from 3.8 to 4.45 or an improvement of the Lorenz efficiency from 43% to 50%: Figure 8-4. However the best machines did not improve significantly within the last 15 years. The tested brine/water heat pumps were in a heating capacity range of 5 kW to 80 kW with an average of about 12 kW. The significantly higher values for the brine/water units do not tell the whole truth, because they do not include the pumping energy used to circulate the "brine" in the borehole heat exchanger. In order to get a faire comparison with the air/water units this pumping energy has to be taken into account. According the approach in [Nani 2005] this reduces the test results from 3.8 to 3.5 and from 4.5 to 4.1, which is equivalent to an average Lorenz efficiency ranging from 40% to 47%.

The temperatures of the heat sources (air 2°C, brine 0°C) and of the heat sink (water 35°C) give a first rough impression on the **seasonal performance factor to be expected** for Swiss conditions. But there are many influencing variables. The results of systematic field tests with complete heat pump heating systems will be discussed in the section "Field test of complete heat pump systems". As will be shown there, nowadays seasonal performance factors up to maximum values of 3.4 for air/water and 5.6 for borehole heat exchanger/water systems were measured.

Although there is not a sufficient number of samples available, suspicion is arising, that there is no more progress since the beginning of an even stronger heat pump boom around 2005. Is a booming market suppressing the efforts for efficiency improvements?

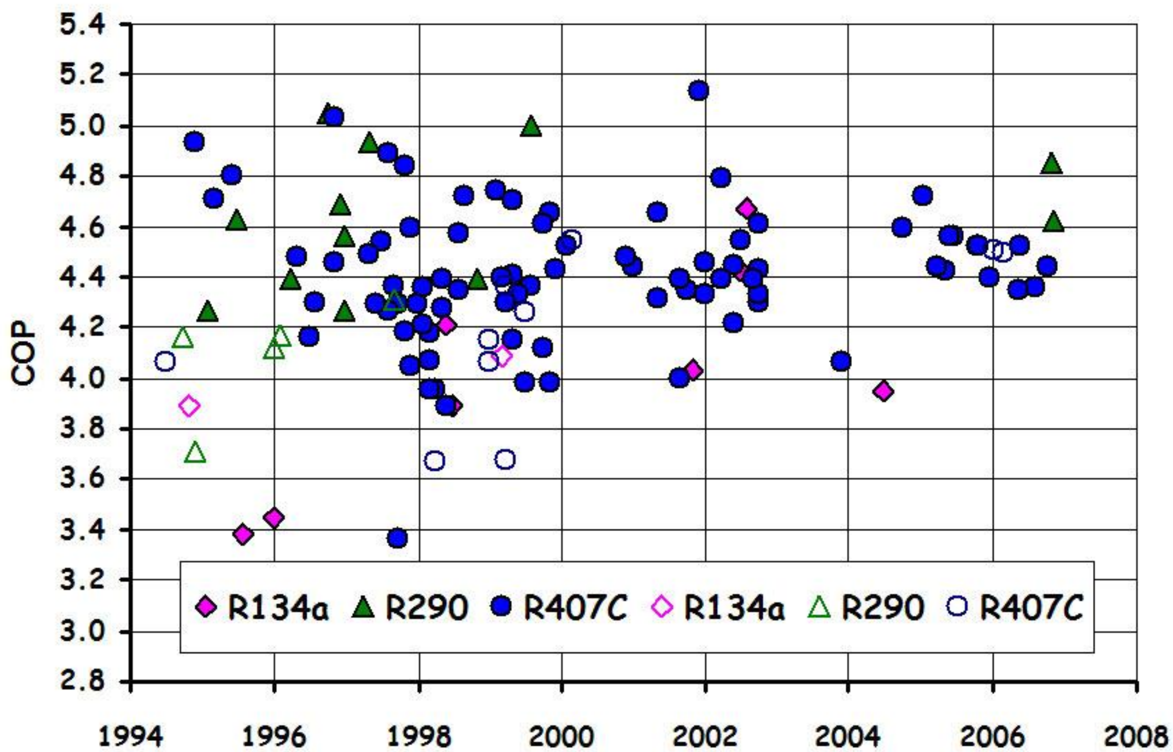


Figure 8-4 Efficiency of commercial brine (0°C) / water (35°C) heat pumps at a maximum heat sink temperature difference of 10 K, measured without circulation pump energy for the borehole heat exchangers at the Swiss Heat Pump Test Centre. Separated by refrigerant and compressor type.

46 „Brine" unfortunately is the common term; but as a matter of fact for ground heat exchangers mixtures of water and organic antifreeze (mostly ethylene-glycol) are used as heat carrier.

Filled out symbols: scroll compressors; void symbols: piston compressors.
Values from [Nani et. al 2005] with additional results from [Nani 2008]

Figure 8-3 and Figure 8-4 illustrate the triumphal take over of the **scroll compressors** for this type of heat pumps. Further it shows a certain pull back of propane as a **refrigerant** in air/water systems following a period of enthusiasm. The champion for air/water and brine/water heat pumps is R-407C, followed by R-404A for air/water and R-134a or propane for brine/water units.

Swiss research and development activities were favoured by pioneering spirit and a good cooperation between universities and practice. They were focused on replacing chlorofluorocarbons (CFC) and HCFCs by hydrofluorocarbons (HFC) and natural refrigerants, the development of validated design tools for borehole heat exchangers, the enhancement of one and two phase heat transfer operations, the reduction of the refrigerant volume, the investigation of new compressor types, computer simulations for an improved heat pump heating system design and the development of a diffusion-absorption heat pump. The Stirling cycle – mainly the free piston type - was investigated as well. The development of retrofit heat pumps with higher supply temperatures (Swiss Retrofit Heat Pump) and the optimization of complete heat pump heating systems by an optimal integration of the heat pumps, new control methods and automatic diagnosis systems were the main priorities. Also new test methods for covering the dynamic behaviour of heat pumps and the combined space heating and domestic hot water heating were established.

8.2.1 Selected Installations and Developments

TOTAL ENERGY PLANTS – COMBINATION COGENERATION - HEAT PUMPS

Many larger **total energy plants** with cogeneration and heat pump units according to Figure 1-1 have been realised in this period. River water, lake water, groundwater, sewage, ground but also cold stores and skating rinks were used as heat sources.

High primary energy ratios of the total energy plants can only be attained by high efficient cogeneration plants. On the basis of a SFOE research project, a new type of gas engine for natural gas and biogas with a patented controlled exhaust gas recirculation was developed in cooperation with Liebherr Machines Bulle and the ETH Zurich [Nellen and Boulouchos 2000], [Nellen et al. 2000]. Today this so called "**Swissmotor**" is being produced in Switzerland by Liebherr Machines at Bulle. It is characterised by extremely low emissions and a high mechanical efficiency. Cogeneration units with Swissmotors are available in the electricity power range between 140 kW and 280 kW. Figure 8-5 shows an example built by AVESCO.

Figure 8-5
Cogeneration unit with a 8-cylinder “Swissmotor”. Electric efficiency 38%, electricity generation 280 kW, heating capacity 389 kW, NOx < 50 mg/Nm^3 [Avesco, CH-4901 Langenthal]

LOW TEMPERATURE DISTRICT NETWORK

Instead transporting useful heat by a conventional district heating system with an expensive thermal insulation and still considerable thermal losses, transporting low temperature water in a **low temperature district network** with no thermal insulation can be advantageous. The low temperature water is then used as a heat source for local heat pumps at the heat consumer’s site. In 1995, such a system (in German called “kalter Wärmeverbund”) with cheap plastic tubes was realised in Muri. The purified **water from a sewage treatment plant** was circulated in the district network. The connected heat pumps have a total heating capacity of 2.4 MW and an over-all seasonal performance factor of 3.1 was attained [Stohler 1995]. In the meantime about 50 more sewage heat pump systems were built and the low temperature district network systems became a competitive technology. Seasonal performance factors up to 5 were measured. The sewages have the **potential** of being an excellent heat source for the heat pump heating of about **15% of the buildings** connected to the sewage network [Müller 2005].

SWISS MAIL CENTRE – SEWAGE TREATMENT PLANT AS A HEAT SOURCE

The automatic postal sorting office of Muelligen/Schlieren of the Swiss Mail – the largest building in the Zurich area - and the Werdhoelzli **sewage treatment plant at** the Zurich City are around one kilometre away from each other. The postal centre is a large user of heat and cold. Ideal conditions to use **treated effluent** as a heat source/heat sink for a 5.5 MW ammonia heat pumps system for heating (9'500 MWh per year, maximum temperature 65°C) and cooling (8'500 MWh per year, 8°C-12°C). The heat pump system has been installed on an energy contracting basis by the utility EWZ (www.ewz.ch) in 2006 [Deiss 2007].

HEAT RECOVERY FROM UNTREATED SEWAGE

The FEKA tank (Figure 7-15), a local heat recovery solution from raw sewage, was presented in section 7.2.5 already.

In the 1990s, Urs Studer introduced his “Rabtherm” system for the heat recovery from untreated sewage by integrating gutter type **heat exchangers in the bottom zone of sewers**: Figure 8-6. In Switzerland it was applied in several sewer systems as pilot installations. In the stadium Basel-Bachgraben it is working without any problems since 25 years [Müller 2005]. So far no fouling problems have been reported for the system in Binningen, installed in 2001 [Dietler 2003]. At Zurich-Wipkingen 200 m of Rabtherm elements were installed in 1999 as a heat source for the bivalent heat pump heating of 900 apartments. There some fouling problems by the formation of a biofilm had been observed. These were then analysed in a project of the Swiss Federal Office of Energy. The results were practical measures concerning the flow velocity and the surface treatment [Wanner 2004]. In 2007, Studer has filed several patents on the material of construction in order to avoid biofilm problems.

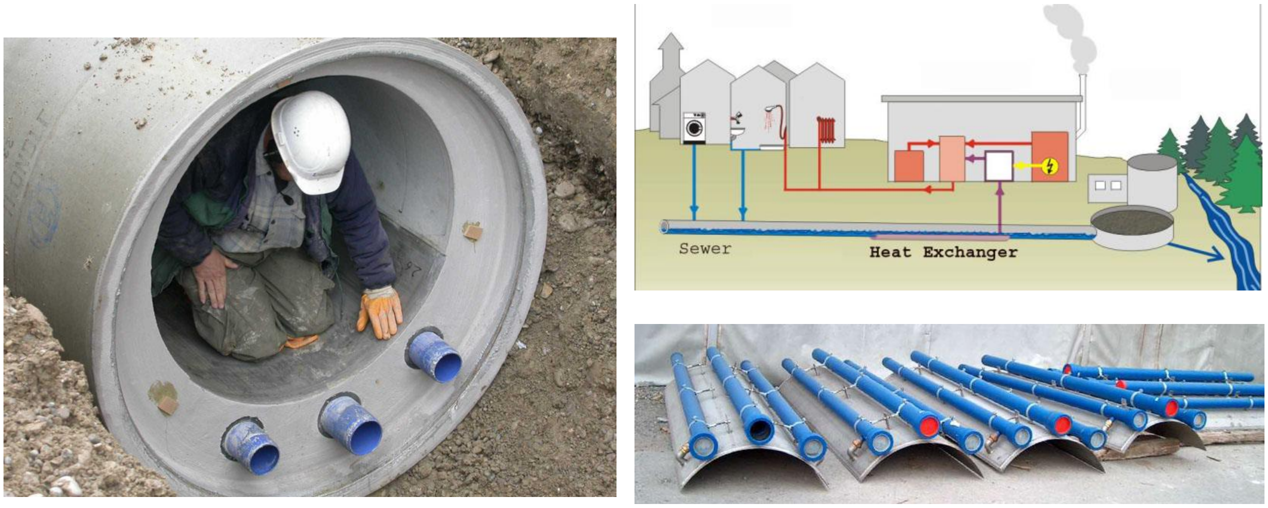


Figure 8-6 Rabtherm sewer element (left), Rabtherm principle and elements (right) [Müller 2005]

BOREHOLE HEAT EXCHANGER ARRAY

A lot of heat pump installations with borehole heat exchangers ranging from single probes for homes to large arrays of probes has been realised in this period. Until 1990 the drilling depth of **borehole heat exchangers** was below 150 m. Today they are being brought in to a maximum length of 350 m, limited by the strength of the probe material. The optimum drilling depth depends on many influencing variables such as geothermal properties and temperature gradient of the ground, the flow velocity and the pressure drop of the heat carrier (→ pumping power). Today in Switzerland the most frequent drilling depth varies from 150 m (if passive summer cooling is important) to 250 m (in the heating only case). In Switzerland the **largest borehole heat exchanger array** was built in 2005 for "The Dolder Grand" hotel in Zurich with 72 probes and a total probe length of 10'600 m. In this top class hotel summer cooling is as important as heating in wintertime. Therefore the field is operating as a **geothermal heat storage** and its depth is 152 m only. Figure 8-7 shows the drilling of the boreholes (left) and the preparation of the u-bend probes (right) for this vertical borehole heat exchanger array [Rohner et al. 2005], [Signorelli 2008].

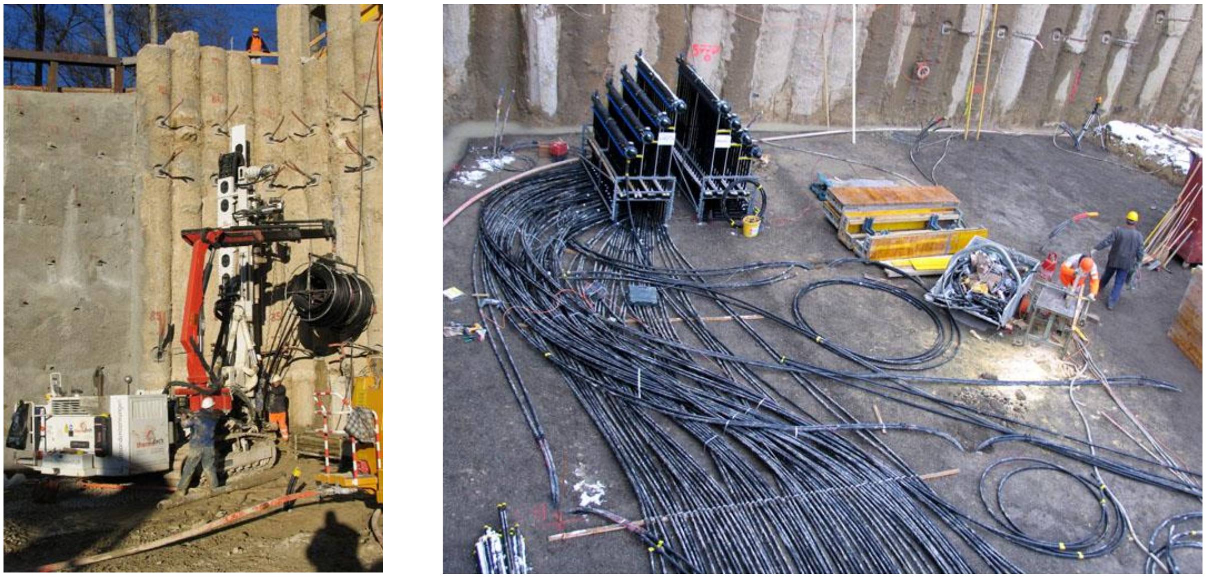


Figure 8-7 Geothermal heat storage at "The Dolder Grand" hotel in Zurich under construction [Signorelli 2008]

TUNNEL DRAINAGE WATER AS A HEAT SOURCE

In 1993, a heat pump installation with warm **drainage water from the Furka tunnel** as a heat source was installed for space heating in Oberwald (Goms) [Arnold 1993]. The drainage water from the new Lötschberg base tunnel has a temperature of about 20°C and will be used as a heat source for a district heating system in the area of Frutigen by the "Nahwärmeverbund Frutigen". The start up is planned by the heating season 2008/2009[47].

Figure 8-8 Hotel Palace in St.Moritz with ice covered lake (to the right) as a heat source [Dubacher 2007]

MOUNTAIN LAKE AT 1750 M ABOVE SEA LEVEL AS A HEAT SOURCE

[47] http://www.bkw-fmb.ch/de/unternehmen/medien/2007/august/nahwaermeverbund.html

The mountain valley Engadin belongs to the Swiss regions with the lowest winter temperatures. The average temperature at St.Moritz is around – 10°C in January. Therefore efficient space heating is a must. In 2006, the **Palace Hotel** (Figure 8-8) and the school building "Grevas" in **St.Moritz** have got a heat pump heating system with the Lake of St.Moritz as a heat source. With an annual heat output of 4'000 MWh the ammonia heat pump is covering 80% of the heat demand of the Palace Hotel and 70% of the heat demand of the school. The average temperature of the lake during the heating season is only around 4°C (with an ice cover thickness up to 75 cm) and the maximum supply temperature of the water heating systems is 70°C. Nevertheless the seasonal performance factor is around 3. The system was built by the Zurich City utility EWZ on an energy contracting basis. It is fully remote monitored and controlled from the Zurich headquarter [Dubacher 2007].

"ZERO ENERGY" RESIDENTIAL AREA - A VISION BECAME REALITY

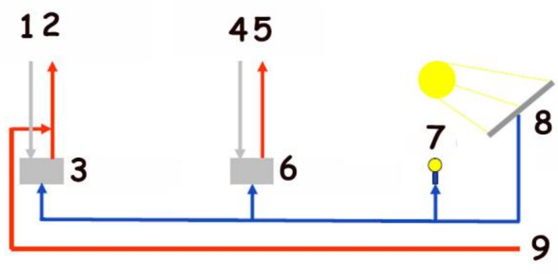
Today 15% of the new houses are built according the low heating energy standard "Minergie", which is explained in section 8.2.4. Some forward-looking constructors go further. Such an example is the **residential estate** Eulachhof in Winterthur **with 132 apartments** built in 2006 / 2007. It goes significantly below the passive house standard "Minergie-P-Eco". Among other features the thermal insulation thickness of 38 cm is noteworthy. On the roof of the buildings 1'240 m^2 of photovoltaic panels with 176 kW_p are installed: Figure 8-9. They provide all the electricity needed for the blowers of the controlled aeration and the two heat pumps on a mean value basis[48]. In cases of an overproduction, electricity is delivered to the electricity grid – in cases of a shortage, electricity is drawn from the grid: Figure 8-10.

The controlled aeration is equipped with a central plate heat exchanger for heat recovery. This is the heat source of the high efficiency heat pump for space heating with supply temperatures below 30°C. The heat source of the second heat pump for the domestic hot water is the heat recovery from raw sewage by a FEKA tank as described in section 7.2.5 and shown in Figure 7-15. The backup space heating of about 8.5% of the total heat demand is provided by a waste incineration plant's district heating system. The amount of heat drawn from this district heating system corresponds roughly to the energy content of the solid waste, delivered by the residents of the Eulachhof themselves [Eulachhof 2006], [Weber 2007], [Kalberer 2007].

Figure 8-9 Eulachhof, Winterthur. Photovoltaic panels to drive the heat pumps and aeration. [Allreal, CH-8050 Zürich]

48 The remaining electricity demand of the residents is covered by the grid of the town utility.

Figure 8-10 Principle of the Eulachhof heat pump system. 1 exhaust air, 2 supply air, 3 heat pump for heating, 4 sewage, 5 domestic hot water, 6 hot water heat pump, 7 electricity grid, 8 photovoltaic panels, 9 backup district heating from incineration plant [Allreal, CH-8050 Zürich]



LARGE FRIOTHERM HEAT PUMPS

Scandinavia with its large district heating systems always was an important market for **Sulzer** and still is today for **Friotherm**. The relevant activities of Sulzer were regrouped as **Sulzer Friotherm** in 1996. Together with Sulzer Infra it was sold to the French Suez group in 2001 and operating under the name Axima Refrigeration until it finally became independent in a management buyout in 2005. Today, Friotherm is a Swiss company again and the only European manufacturer of large turbo compressor heat pumps. Mentioned below are some selected installations of large heat pumps built by Friotherm in Scandinavian countries. A more complete overview on the radial compressor heat pumps of the UNITOP type is given in [Friotherm 2008].

One single Friotherm heat pump with a heating capacity of **18.4 MW** and a COP of 2.8 installed in 2002 in **Oslo** (N) is upgrading the heat of **untreated sewage** from 9.6°C to temperature levels of 60°C and 90°C for use in the town's district heating system: Figure 8-11 [Friotherm 2003].

Figure 8-11 18.4 MW heat pump of the Viken Fjernvarme of the district heating system of Oslo [Friotherm 2008]

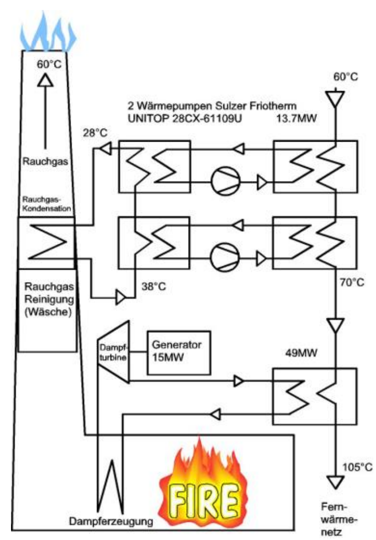


Figure 8-12 Power plant flue gas heat recovery at Umea, Sweden [Friotherm 2008]

At **Umea**, Sweden, the **waste heat from a flue gas cleaning process** of a power plant is upgraded from 38°C/28°C for use in a district heating system with 60°C/70-75°C with a heating capacity of 13.7 MW and a COP of 4.1: Figure 8-12. The heating capacity is adjustable within the range of 10%-100%. Another "waste-to-energy plant" was built for a power plant in **Malmö**, Sweden (19 MW and a COP of 5.43 at 34.2°C/24.3°C – 50°C/60-70°C) [Pietrucha 2008].

In **Helsinki**, Finland, Friotherm has installed the **world's largest combined heating and cooling plant** for district heating and cooling recently. With **60 MW cooling capacity** and a **heating capacity of 90.5 MW** at 45°C/88°C in summertime and of **83.8 MW** at 40°C/62°C in wintertime. In winter operation mode the heating COP is 3.5, and the combined heating and cooling COP in summer operation mode is 6.0. The heat source in wintertime is sewage of 12°C/5°C (indirect system) [Pietrucha 2008].

INNOVATION TO INCREASE THE COP WITH ZOETROPE REFRIGERANTS

In 1997, SATAG Thermotechnik[49] in Arbon patented a special arrangement of an internal heat exchanger for decreasing the evaporator pressure in heat pumps and/or refrigeration machines with zoetrope refrigerants. The special features of the invention are the combination of the placing of the temperature sensor at the outlet of the heat exchanger (not at the inlet as is common), an angular momentum droplet separator and the use of a zoetrope refrigerant. By moving the final evaporation into the internal heat exchanger it enables for a given evaporation temperature a lower pressure and as a consequence a lower power demand. This is increasing the COP [Kuratli et al 1997], [Hohl 2008].

HEAT PUMP LAUNDRY DRYER

In 2002[50], heat pump laundry dryers (tumblers) are brought on the market by Schulthess[51] and V-Zug[52]. These dryers cut the electricity consumption by 50% compared to conventional electric laundry dryers [Schwarzwald 2002].

SINGLE ROOM AIR-TO-AIR HEAT PUMP

In 1995, there were about 200'000 homes with electric resistance heating in Switzerland. About 80% of them were single room systems with a share of the total Swiss electricity consumption of around 8%. Initiated by Hans Ulrich Schärer and Fabrice Rognon of the Swiss Federal Office of Energy the development of **a single room air-to-air heat pump to replace the resistance heaters** was started in 1995. After a market study Emil Grüniger, the owner of **Soltherm** in Altendorf, developed in cooperation with the experts Winfrid Seidinger and Max Ehrbar a radiator type single room heat pump including a drilling device for the air inlet and air outlet opening in the wall. This development reached the pilot plant level. The radiator heat pump (Heizkörperwärmepumpe) with a concrete heat storage device was produced with heating capacities of 600 W, 900 W and 1200 W by Hegner at Galgenen. In order to keep the noise level as low as possible only free convection for the heat distribution was accepted. That is the main reason why the seasonal performance factor was only around 2.3. The technical problems were solved – but with a pay back time of 15 years there was no successful market penetration [Humm 1996]. There were similar ideas abroad. They were covered by the Annex 23 of the IEA Heat Pump Programme which ran between 1996 and 1998. Participating countries were Canada (Operating Agent), France, Sweden, Switzerland, and the U.S.A. [Annex 23 1999].

SMALL DIFFUSION ABSORPTION HEAT PUMPS

Hans Stierlin was convinced of a market for an absorption heat pump with a device following the cycle of his refrigerator, described in section 5.1.2. He was thinking of a system with about 3.5 kW heating capacity and as silent as to be installed in a living room (in this case some

[49] 1998 Incorporated into the Viessmann Group, now Viessmann (Schweiz), SATAG Thermotechnik, CH-9320 Arbon; http://www.satagthermotechnik.ch.

[50] In Germany AEG introduced a similar product in 1988 already.

[51] Schulthess Maschinen, CH-8633 Wolfhausen; www.schulthess.ch.

[52] V-ZUG AG, CH-6301 Zug; www.vzug.ch.

more 150 W might be used which otherwise would be a useless heat loss). For higher power demands Stierlin envisioned to use several of his modules in parallel. He started realising his idea with his little company “Creatherm” in 1988 when he was 72 (!) years old. He was working in close cooperation with Carl Ulrich Wassermann of Entex (see below), a former employee of Stierlin’s company SIBIR: Figure 8-13. The new device was working on the same principle as his famous SIBIR refrigerator: Figure 8-14. In 1992, Stierlin had already an **ammonia-water diffusion absorption heat pump** ready for neutral testing. He called it “**DAWP**” (**D**iffusions-**A**bsorptions-**W**ärme**p**umpe). Compared to the functional demonstrator in Figure 8-13 it was reduced in overall height. On behalf of the Swiss Federal Office of Energy **field tests** were carried out in an older home with radiators and in a new home with floor heating system during the heating period 1992/1993. The tests were carried out in bivalent operation with a gas boiler. In both cases air as a heat source was used. Both diffusion absorption heat pumps worked perfect. With taking into account the electric auxiliary energy (fan, control) the seasonal average primary energy ratio PER was 1.37.

Figure 8-13 First functional sample of the DAWP

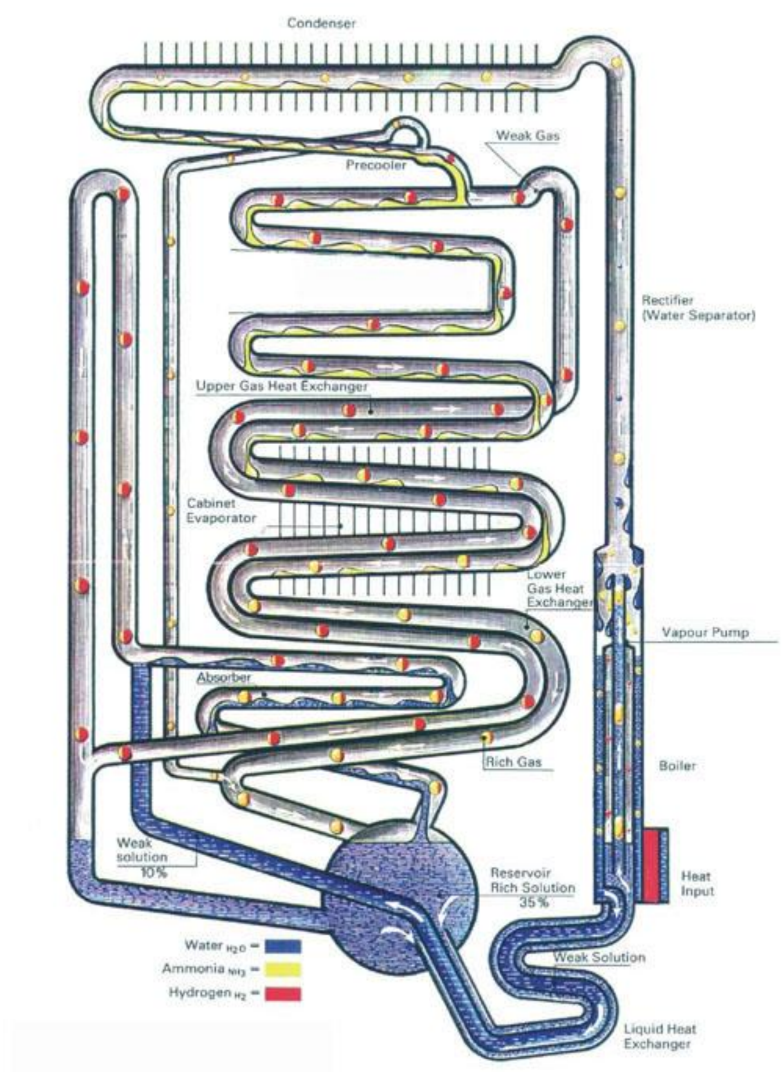


Figure 8-14 Functional principle of the diffusion absorption heat pump DAWP [Wassermann 2007]

Figure 8-15 Laboratory test of the DAWP at the ETH Zurich, 1993

The test demonstrated the only minor dependence of the efficiency on the evaporation temperature compared to compression systems. The requirement of a preferably steady state operation of the system was confirmed.

A third prototype was **tested** in detail un**der laboratory conditions** in accordance with the German standards DIN 8900 and 33830: Figure 8-15. The laboratory test resulted with similar encouraging results. At 0°C/35°C a PER of 1.43 and at 0°C/50°C a PER of 1.35 was measured. In the case of installing the DAWP in living rooms, these values would incline to 1.5 or 1.42 respectively. By a simple interchange of the connections, the DAWP proved to be suitable for room conditioning as well. Problematic was the separate heating of domestic hot water [Stierlin et. al 1993], [Stierlin and Wassermann 1996].

In a further step a concept for a combination of the diffusion absorption heat pump with a conventional peak load gas boiler was worked out. This combination was called "**AWP-Kessel**" (absorption heat pump boiler) and was supposed to reach an over all PER of 1.25 to 1.3. It was characterised by an intelligent control and connections as simple as installers were used from conventional boilers. In order to motivate Swiss boiler manufacturers a market study and a detailed list of requirements was elaborated. However none of the small Swiss boiler manufacturers was finally willing to take the risk and the further development went to Germany (see section 8.3).

After SIBIR was sold to Electrolux, Carl Ulrich Wassermann (earlier head of the engineering departement of SIBIR for four years) founded the **ENTEX** Energy[53] company in 1990. Since that time ENTEX is developing diffusion absorption systems for different appliances such as hotel room refrigerators, refrigerators and gas driven air conditioners. In the late 1990s Wassermann developed a **second generation of diffusion absorption heat pumps**. It is characterised by no vessels under pressure, ammonia-water solution only inside the tubes and a simpler manufacturing. The heating capacity of the three to four modules is 1.9 kW each and the PER is predicted to be around 1.5. By the end of this report negotiations for a production in a European company were going on.

ABSORPTION HEAT PUMP IN HOUSING ESTATE

Around 1995 in the district "Im Bilander" at Brugg, a **commercial 870 kW lithium-bromide/ water-absorption heat pump** with ground water (10°C-13°C) as a heat source was installed in a housing estate with 342 apartments as a pilot project. It covers about 40% of the heating capacity demand. This absorption heat pump delivers a medium temperature network with 50°C/40°C. From this temperature level the remaining temperature lift for domestic hot water heating is done at the user's site by electric heat pumps. Taking into account the auxiliary energies, the PER proofed to be about 1.3 [Krüsi 1996]. This is clearly below what a modern combination of a cogeneration unit with an electric heat pump might attain. The system was not built any more.

8.2.2 Swiss Retrofit Heat Pump Programme for Homes

As a result of coordinated efforts of manufacturers, installers, associations, public suport and customers, today 75% of the heating systems installed in new single-family homes are heat pump heating systems (Figure 8-1). However, in the much larger retrofit market the share of heat pumps represents about 3% only. In other countries of Western Europe the retrofit heat pump share is even much lower. This indicates a **very large potential in the retrofit market**. Every new domestic boiler that is installed to replace an old one represents a missed opportunity. In Western Europe alone, this happens a million times a year. Consequently higher CO_2 emissions are accepted than the state-of-the-art technology would produce.

[53] ENTEX Energy, CH-5445, www.entex-energy.ch.

What are the obstacles? The older central water heating systems are characterised by high supply temperatures. Conventional heat pumps reach their limits if they have to provide the **high temperature lifts and the high supply temperatures** required in the retrofit market. On the initiative of Hans Ulrich Schärer, Fabrice Rognon and Martin Zogg the programme "Swiss Retrofit Heat Pump" was started in 1998. The objective was the development of a retrofit heat pump, which meets the requirements of an older hydronic heat distribution system at a competitive price and a high efficiency. This programme became the **main priority of the Swiss Federal Office of Energy's heat pump research programme** on the utilisation of ambient heat between 1998 and 2003.

While larger retrofit heat pumps are already available on the market (for example with economizer and screw compressors), optimal solutions do not yet exist for **heating capacities below 25 kW**. In order to change this situation the Swiss Federal Office of Energy launched a **competition "Swiss retrofit heat pump"** in 1998 to develop a new type of retrofit heat pumps. This has to integrate the domestic hot water heating, and to provide an efficient heat pump operation up to the maximum temperature lift from –12°C to 60°C without any backup systems. The main requirements were for ambient air as a heat source a Lorenz efficiency (with all losses included) to be maintained above 37.5% under all operational conditions and above 42.5% for the test point at air 2°C to water 50°C. The other requirements of the competition are listed in [Zogg 2002a].

To assist Swiss manufacturers of heat pumps a number of research projects were initiated by the Swiss Federal Office of Energy. These were aimed at thermodynamic challenges and control issues. They had been elaborated in close cooperation with the manufacturers, several university institutes and the Swiss Heat Pump Test Centre.

The topics of the research projects were **new cycles for small heat pumps** with a heating capacity below 25 kW in order to fulfil the special requirements for retrofit heat pumps with a high temperature lift as mentioned above: smaller drop in heating capacity, lower compressor outlet temperature and higher efficiency. Figure 8-16 gives an overview on the cycles optimised by computer simulation, built, measured in the laboratory and finally – the most promising – tested in real installations. The main results of the comparison are listed in Table 8-1.

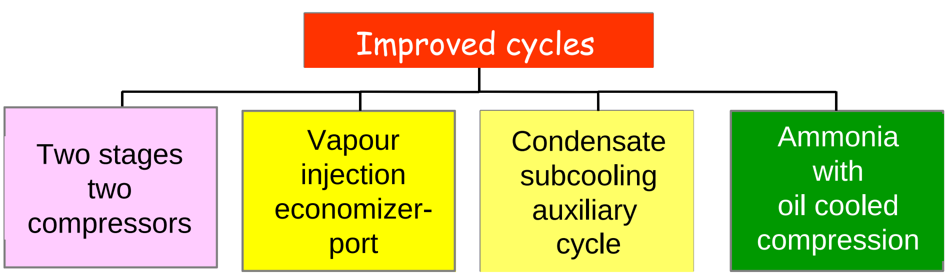


Figure 8-16 Heat pump cycles for small retrofit heat pumps investigated in the *Swiss Retrofit Heat Pump* programme

The thermodynamically most promising solution to the retrofit problem is a **two-stage heat pump with two compressors** as shown in Figure 8-17. This cycle was built and investigated [Zehnder et al. 1999]. Compared to a simple one-stage cycle it attained a 50% increase in heating capacity and a 14% increase of the COP at the highest temperature lifts. But it turned out that the oil migration in the circuit prevented a proper lubrication of both compressors after a few hours of operation. Furthermore a heat pump of this type is too complex to compete with the much simpler boiler, which a retrofit heat pump should replace.

The **cycle with economizer and vapour injection port** is a simpler and cheaper solution. It is well known from larger heat pumps with screw type compressors: a part stream of the condensate is expanded to a middle pressure level. The created liquid-vapour mixture is then evaporated to saturation by subcooling the rest of the condensate and is injected into the compressor. This cycle has the following advantages (discussion in [Zogg 2002a]):

1. Higher mass flow rate at the compressor outlet → higher heating capacity.

2. Reduction of the compressor outlet temperature → meeting the temperature limits of the compressor.

3. Subcooling the condensate → increasing the COP, if a suitable compressor is used.

Table 8-1 Comparison of the processes investigated for retrofit heat pumps. Heating capacity and COP improvements compared to conventional single stage heat pump circuits at high temperature lifts [Zogg 2002a]

	Two-stage with two Compressors	Economizer	Economizer and Suction Gas Heat Exchanger	Separate HP-loop for Condensate Subcooling
Principle	Figure 8-17		Figure 8-18	Figure 8-19
Refrigerant	R-407C	R-407C	R-407C	R-407C, R-417A (Isceon 59)
Compressor	1st stage reciprocating 2nd stage Scroll	Commercial scroll with liquid injection port	Prototype[54] scroll with vapour injection port	Scroll (main loop) reciprocating (aux. loop)
Heating capacity Improvement by	50%	15%	30%	20%
COP Improvement by	14%	Insignificant	15%	5%
Compressor Outlet Temperature	Unproblematic	Unproblematic	Unproblematic	To high with R-407C

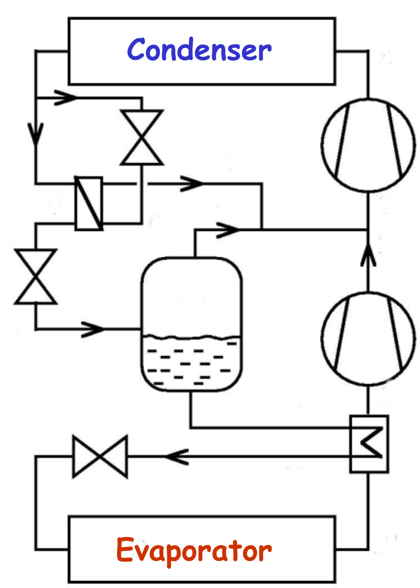


Figure 8-17 Heat pump cycle with two compressors, economizer and an intermediate injection. Reciprocating compressor in the first and scroll compressor in the second stage. R-407C as refrigerant [Zehnder et al. 1999]

A suitable compressor for heating capacities below 25 kW was not available when the first experimental studies were carried out. But the results with the best available scroll compressor with a liquid injection port showed promising results [Zehnder et al. 2000]. In a subsequent research project with a first prototype scroll compressor with an injection port optimised for the vapour injection was available from Copeland. Supplementary a suction gas heat exchanger

[54] Today commercially available.

was inserted (Figure 8-18). With this prototype heat pump and R-407C as a refrigerant the following improvements compared to a simple single-stage cycle were attained at high temperature lifts: **increase of the heating capacity by up to 30%**, **increase of the COP up to 15%** (measured at –7°C/60°C) [Brand et al. 2000]. **This development was a success**. Copeland started the mass production of the scroll compressor with vapour injection in 2002. The cycle was first used by SATAG/Viessmann [Guex et al. 2002], [Zehnder et al. 2002]. In the meantime cycles with vapour injection became common for home heat pumps with high temperature lifts.

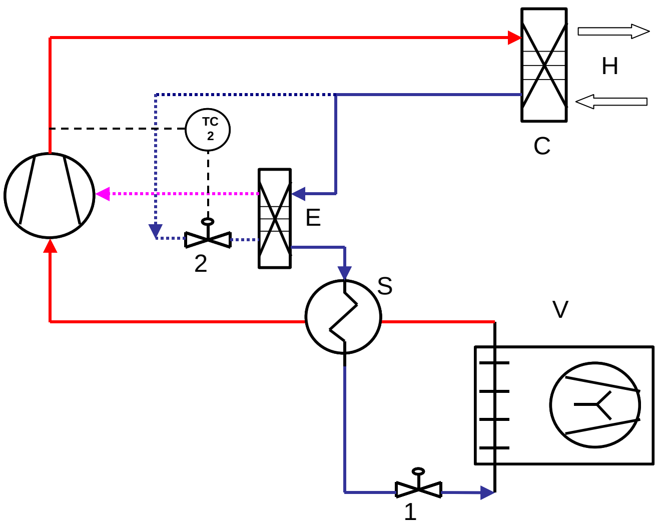


Figure 8-18 Heat pump cycle with economizer/vapour injection and suction gas heat exchanger. Scroll compressor with vapour injection port; R-407C as refrigerant.
C condenser,
E economizer,
S suction gas heat exchanger
H heating system,
V evaporator,
1 main expansion valve,
2 auxiliary expansion valve

In a further approach [Reiner et al. 1998] investigated a **cycle with a separate auxiliary heat pump loop**. This uses the condensate subcooling as a heat source and delivers the heat at the loop of the hydronic system coming from the main heat pump (Figure 8-19). This prototype heat pump was tested with R-407C and R-417A (Isceon 59). For high temperature lifts an increase in heating capacity by up to 20% and of the COP by up to 5% compared to a simple one-stage cycle was achieved. With R-417A there were no problems with the compressor outlet temperature. R-407C lead to a too high compressor outlet temperature and is therefore not suitable for this cycle in retrofit applications. For a small heat pump this cycle is rather complex. But it should be taken into account for larger heat pumps.

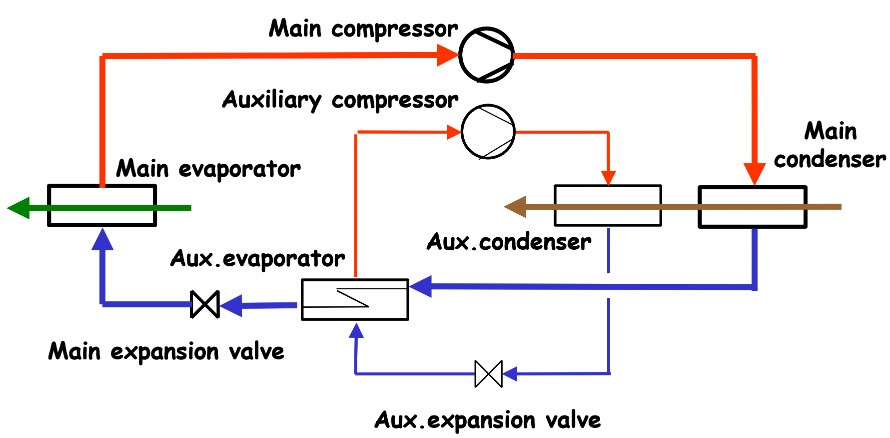


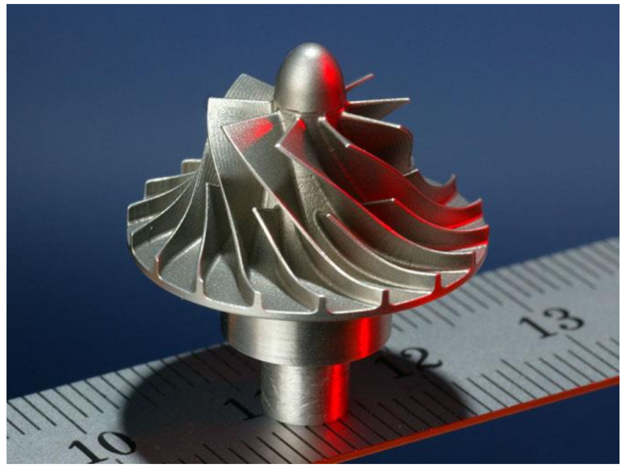
Figure 8-19 Heat pump with a separate auxiliary heat pump loop for subcooling the condensate of the main heat pump loop; main cycle with a scroll compressor, auxiliary cycle with a piston compressor

Winner of the Swiss Retrofit Heat Pump competition was **KWT in Belp.** KWT's proposal was an advanced split solution with integrated domestic hot water heating by a separate heat pump cycle and desuperheating [Trüssel et al. 2000], [Cizmar et al. 2001]. Its putting on the market was not yet successful. May be it was too complex. May be it was the heat pump boom which was a hinder for the further development (why develop if there is not enough capacity for the production?). Anyhow, the final stop came due to a selling out of the interested manufacturer to a big foreign company.

A NEW AND UNCONVENTIONAL APPROACH – NOT YET READY

As mentioned above, for a retrofit heat pump a real **two-stage cycle** would lead to the highest efficiency; but there are lubrication problems. Jürg Schiffmann proposed an **oil free miniature radial compressor** instead of conventional scroll or piston compressors with oil migration problems. The proposed solution is consisting of two radial compressors with mini rotors of less than 20 mm in diameter (Figure 8-20) on a single shaft, running at variable speeds up to 240’000 rpm. The precision bearings with clearances

Figure 8-20 Rotor of an oil free prototype miniature turbo compressor [Schiffmann et al. 2005]



between 5 and 10 micrometers are lubricated by the gaseous refrigerant itself. Investigations performed by ABB showed promising results for the feasibility of such compressors. They would be lighter and smaller than existing ones [Schiffmann and Molyneaux 2002]. In a second project phase a first single-stage compressor was built and tested as a proof of the new concept. The bearing unit ran to speeds up to 150'000 rpm without any problems with an air turbine. Driving the bearing unit with an electric motor has revealed to be trickier; the first motor has not allowed the bearings to run properly at low speeds. Only the second motor has worked well to speeds up to 104'000 rpm where the bearing have touched down and were destroyed [Schiffmann et al. 2005]. The project is continuing.

8.2.3 Further Support by Public R & D

The following projects had been coordinated and at least partially funded by the heat pump research programme of the Swiss Federal Office of Energy, headed by Hans Ulrich Schärer (until 1992), Martin Zogg (until 2002), and Thomas Kopp (do date). Fabrice Rognon and Max Ehrbar were responsible for the pilot and demonstration projects.

HANDBOOKS FOR BETTER HEAT PUMP INSTALLATIONS

Within the framework of the RAVEL Programme for an efficient use of electricity of the Swiss Federal Office of Business Activities[55] experienced professionals elaborated consolidated technical knowledge for a direct application in the heat pump business. In the years 1993 until 1996 three handbooks were published. The first on the planning, the construction and the operation of heat pumps [Baumgartner et al. 1993], the second on hydraulic schemes [Gabathuler et al. 1994] and the third on quality management [Gabathuler et al. 1996].

[55] Impulsprogramm „RAVEL (rationelle Verwendung von Elektrizität)“ des damaligen Bundesamts für Konjunkturfragen.

LOW COST HEAT PUMP HEATING SYSTEMS FOR LOW ENERGY HOMES

Low energy homes with an annual heat demand below 160 MJ/m^2a have a tight an well insulated building envelope, high solar gains, low temperature heat distribution systems and a high share of the heat demand for domestic hot water. The complete system of building and heat pump heating system had been investigated in order to find optimal control strategies and low cost central water heat distribution systems without heat storage and mixing valves. The results were condensed in a technical handbook for such systems [Afjei et al. 2000], [Afjei 2002].

STANDARDISED HYDRAULIC SCHEMES FOR SMALL SYSTEMS

On the basis of an evaluation of the most frequent hydraulic schemes of heat pumps for homes with heating capacity up to 25 kW seven hydraulic schemes were identified. They were chosen on the criteria high energy efficiency, high reliability and opportune for practical realization. This was done in close cooperation with the main heat pump suppliers. The seven hydraulic schemes (one of them for integration of thermal solar energy) cover air and ground as a heat source, different temperature levels of the heat distribution systems, combined space heating and domestic hot water heating. They were investigated and optimized by computer simulation. The results are summarized in a step by step planning guideline for the complete dimensioning of heat pumps for homes. The guideline brings a significant reduction of the confusing high number of hydraulic schemes. With a minimal planning effort energy and cost efficient heat pumps systems can be designed. This is favours a good quality management and makes it easier to compare offers of different competitors [Afjei et al. 2002], [Gabathuler et al. 2002b].

COP ENHANCEMENT OF AIR/WATER HEAT PUMPS BY OPTIMIZED DEFROSTING

The energy needed for defrosting the evaporators of heat pumps that use air as a heat source is considerable, amounting to approximately 10% of the total electricity consumption of the heat pump. A reduction down to 5% seems possible. First, the most important defrosting processes were analysed theoretically [Hubacher and Ehrbar 2000]. An energetic and economic comparison of the defrosting processes was then carried out in a second project phase [Bertsch et al. 2002]. The standard measurements carried out at the Heat Pump Test Centre in Toess (WPZ) were used and complemented by further laboratory and field measurements. On the basis of the WPZ test reports, 6 heat pumps with process reversal and 7 heat pumps with hot-gas defrosting were evaluated. Unconventional defrosting solutions, such as using heat from the heat distribution system or using on-site room air for heat pumps with small thermal capacities (air-defrosting), were investigated as well. Surprisingly enough, hot-gas defrosting, for instance, exhibits approximately the same total costs over 15 years of operation as process reversal. Air-defrosting does quite well – but is indeed combined with the disadvantage of a considerable influence on room climate.

COP ENHANCEMENT OF AIR/WATER HEAT PUMPS BY GROUND REGISTERS

There were several **monovalent air/water heat pump systems** built with conduction of the incoming ambient air through ground registers, consisting of a **system of tubes** (100-250 mm in diameter, 20-60 m in length, flow speed 3 – 10 m/s) in the garden or around the buildings. The idea behind is preheating the air in cold nights or even in longer periods with deep temperatures. An investigation showed an improvement of the seasonal performance factor by 5% up to 10%. Compared to borehole heat exchanger solutions this is not overwhelming. But an additional benefit can be taken in summertime by passive cooling, and this is decisive in many cases [Huber et al. 1995].

SILENT AIR/WATER HEAT PUMPS

Over half of the new small heat pumps with thermal powers up to 25 kW use ambient air as a heat source. Especially in heavily built-up areas, these air/water heat pumps have occasionally led to complaints about noise emissions. Within the framework of a the research program, sources of noise from air/water heat pump systems were analysed and guidelines for designers and manufacturers on the low-noise constructional design of such installations were developed and include a large number of specific measures that can be taken [Graf 2002]. The results have been successfully implemented into commercial heat pumps already [Beerhalter 2007].

MODELLING OF BOREHOLE HEAT EXCHANGERS

Under the lead of Ladislaus Rybach the studies on borehole heat exchangers at the ETH Zurich were continued [Rybach et al. 1990, 1992, 1998], [Rybach 2001, 2004]. Computer simulations are only helpful, if the needed geothermal input data are sufficiently known. Therefore a computer tool for estimating them for the molasses of the Swiss midland was elaborated by Werner Leu and collaborators in 1998/1999 and complemented in 2006 [Leu 1998], [Leu et al. 1999, 2006].

For the use as tool for computer simulations of complete heat pump heating systems, a **new dynamic calculation module** – named **EWS** (Erdwärmesonden) - for the determination of the outlet temperature of borehole heat exchangers was developed by Arthur Huber[56]. First (1997) it was established for single double u-bend probes [Huber 1997] and then (1999) extended for fields with several probes [Huber and Pahud 1999]. The short calculation time of EWS[57] is empowering the program to be used as a module for dynamic computer simulation of ground coupled heat pumps on personal computers. It was later implemented in the Swiss heat pump design program WpCalc [Stalder et al. 2001] and validated by Sarah Signorelli and Thomas Kohl, the successor of Ladislaus Rybach at the Institute of Geophysics at the ETH Zurich [Signorelli and Kohl 2002].

ENVIRONMENTAL IMPACT OF BOREHOLE HEAT EXCHANGERS

Within the **Swiss Federal Office for the Environment** SFOEN the **impact of borehole heat exchangers on soil and groundwater** was studied in detail. In 1994, the SFOEN published guidelines for such installations. This was another **Swiss pioneering work** and had also an important impact on the later German guideline VDI 4640 (see section 8.3). In the corresponding commission it was not that easy for Switzerland to bring in its restrictive attitude. A Swiss National Standard SN 565 384/6 (Erdwärmesonden / Sondes géothermiques / Sonde geotermiche) is in preparation.

For lubricated heat pumps direct expansion systems have never been accepted in Switzerland for environmental reasons. If there is an alternative – and there is always one – direct expansion systems are not allowed. The only exception would be an oil free CO_2 cycle [Beck 2007], [Rognon 2007].

REGENERATION OF BOREHOLE HEAT EXCHANGERS - SUSTAINABILITY

A detailed assessment of the usefulness of a **summer regeneration** of single and groups of borehole heat exchangers by thermal solar energy showed, that in most cases the benefit from the summer regeneration does not even compensate the needed circulation pump energy. Just

[56] Arthur Huber, Huber Energietechnik, Zürich, www.hetag.ch.

[57] This was achieved by a combination of a numerical calculation in the close-up range and an analytical solution for the outside area.

for highly loaded groups of borehole heat exchangers solar summer regeneration might be of interest [Hässig et al. 1998]. A comprehensive answer on the **sustainability** of borehole heat exchangers is given in [Signorelli et al. 2005].

COMBINED COOLING AND HEATING USING GROUND HEAT STORAGE

The use of the "waste" heat from refrigeration and air conditioning plants for space heating and hot water production offers a substantial potential for saving energy; this in comparison to separate cooling and heating systems. For refrigeration (cold storage rooms and cooling cabinets), the year round cooling requirement often is approximately constant. Roughly this is the case for the domestic hot water demand as well. In contrary, the cooling requirement for air conditioning only occurs in summer, and that for space heating during the heating season only. These quantities are also dependent on the ambient temperature, which varies during the day. Thus, in general, the requirements for cooling and heating correspond neither on a daily nor on a seasonal basis.

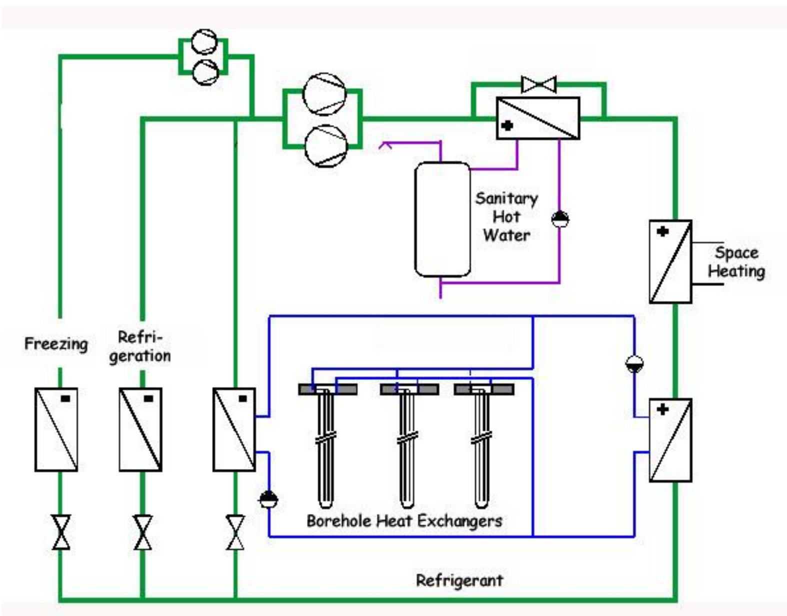


Figure 8-21 Simplified flow diagram of the plant built by KWT, for a restaurant[58] with combined heating and cooling, and a small borehole heat exchanger array [Good et al. 2001]

Figure 8-22: Compressors of the investigated plant example [KWT, CH-3123 Belp]

While daily differences may be compensated by water storage tanks, **the seasonal imbalance may be equalized by ground storage with borehole heat exchanger arrays**. At low heating demand the excess heat from the condensers of the cooling devices can be deposited in the ground (typical of summer operation). In typical winter operation, the heating requirement will dominate. Then the ground is as a supplementary heat source. Figure 8-21 shows the principle of such a plant (Figure 8-22) for combined heating and cooling for a situation that often occurs in smaller **commercial refrigeration** installations, with refrigeration and deep-freezing units combined with hot water and space heating systems.

For such systems for combined heating and cooling a **planning handbook** was prepared on behalf of the Swiss Federal Office of Energy. The design procedure is explained in five main steps and is illustrated by a practical example [Good 2000], [Good et al. 2001]. The design of large groups of borehole heat exchangers operating as ground heat storage by a detailed numerical simulation is covered by [Rohner et al. 2005].

ENVIRONMENTAL BENEFIT OF NATURAL REFRIGERANTS

58 Highway restaurant Grauholz close to Berne.

As a Swiss contribution to Annex 22 (Compression Systems with Natural Working Fluids) of the IEA Heat Pump Programme a first Life Cycle Assessment was performed in 1996 [Weibel 1996]. A second one was extended to a comparison of all relevant environmental impacts related to the use of natural and synthetic refrigerants for Swiss electricity production conditions. This new **Swiss study** contains a **Life Cycle Assessment (LCA)** of heat pump heating, air conditioning and refrigeration. The systems analysed use **ammonia**, **propane**, **carbon dioxide**, the **hydrofluorocarbons HFCs** R-134a, R-404A, R-407C, R-410A, Isceon 59 (the later R-417A) and the Chlorodifluoromethane R-22 as a reference. In the LCA the following environmental impacts were studied: non renewable primary energy demand, global warming, ozone depletion, acidification, photochemical ozone creation, aquatic and terrestrial ecotoxicity and carcinogenic and hereditary effects due to ionising radiation.

The results showed that the **energy efficiency plays a key role**. Systems using natural refrigerants with similar or better energy efficiency compared to others using HFCs show lower environmental impact scores except for photochemical ozone creation (propane systems). When comparing systems using synthetic refrigerants to systems using natural ones with lower energy efficiency the situation is not as clear, and value judgements are indispensable. A trade-off between non renewable primary energy demand, acidification, photochemical ozone creation, aquatic ecotoxicity, and carcinogenic and hereditary effects due to ionising radiation on the one hand, and global warming, ozone depletion, and terrestrial ecotoxicity on the other hand is necessary in order to identify the overall environmental benefit of natural or synthetic refrigerants. The **main conclusion** of the study was that HFCs can still be used if there is no natural alternative. But only on the condition of a **strict lifetime tightness control** and a **proper refrigerant recycling** at the plant disposal. At the same time the production processes for HFC should be improved [Frischknecht 1999, 2000], [Zogg 2000b].

In 2003, there was established a **reasonable compromise for the practical use of HFC**- refrigerants, regulated in the Federal decree for the risk reduction of chemicals ChemRRV[59]. New plants with a filling of more than 3 kg need an official authorization and the tightness of the system has to be checked annually.

HEAT TRANSFER WITH HFC AND NATURAL REFRIGERANTS

Supported by the Swiss Federal Office of Energy a comprehensive study on flow boiling heat transfer characteristics of alternative refrigerants in smooth and enhanced tubes with and without lubricants was carried out at the EPFL. For the experimental part a special test facility with inclinable tubes was installed [Thome 1994, 1996], [Kattan et al. 1995], [Thome et al. 1997]. The investigations were expanded to the natural refrigerant **ammonia** [Zürcher et al. 1997]. At the ETH Zurich the heat transfer of overcritical **CO_2** was investigated [Trepp Ch. 1997].

AMMONIA HEAT PUMPS FOR HOMES

Ammonia's excellent thermodynamic properties are well known. Therefore for large heat pumps ammonia is widely used. But this is not yet the case for small heat pumps. Within the framework of the heat pump research programme of the Swiss Federal Office of Energy first there was started a theoretical study about the advantages of ammonia versus propane or R-407C for small heat pumps. The results were motivating to go on, especially for small temperature lifts as occurring with floor heating systems. With ammonia a pressure ratio around 15 is needed for such systems. With a single compressor without intermediate cooling this leads to a too high discharge temperature. A small compressor with an intermediate cooling possibility is

[59] Chemikalien-Risikoreduktions-Verordnung (ChemRRV).

not available and a two-stage cycle is to complex. Therefore a screw type or a rotary vane compressor with a high oil circulation rate for cooling was proposed [Boyman et al. 1997].

Figure 8-23 Functional demonstrator of a brine/water heat pump with ammonia as a refrigerant and an open rotary vane compressor [Kopp 2001]

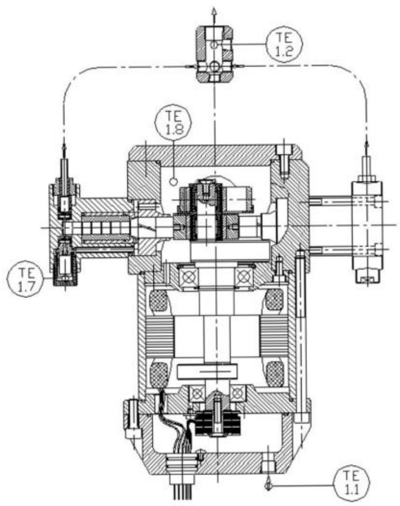
In the second phase of the project a functional demonstrator of a brine/water heat pump with an open rotary vane compressor was designed, built and after many setbacks finally started up: Figure 8-23 [Kopp 2001]. Extensive tests were carried out in the third project phase with a rotary vane compressor and a screw compressor. The following COP values were achieved: 2.4 at –7°C/50°C and 2.7 at 2°C/50°C. The reason for the modest COP values is the high oil flow rate. The heat pump was able to overcome a maximum temperature lift from a brine temperature of –20°C to a sink water temperature of 60°C. The effect of the economizer was an increase in the COP by 6% and of the heating capacity by 12%. Some tests were also carried out with the small screw compressor without an economizer port. The compressors used for the tests did not convince. A commercialisation of ammonia heat pump for single-family homes would strongly depend on a more suitable compressor [Geisser and Kopp 2003].

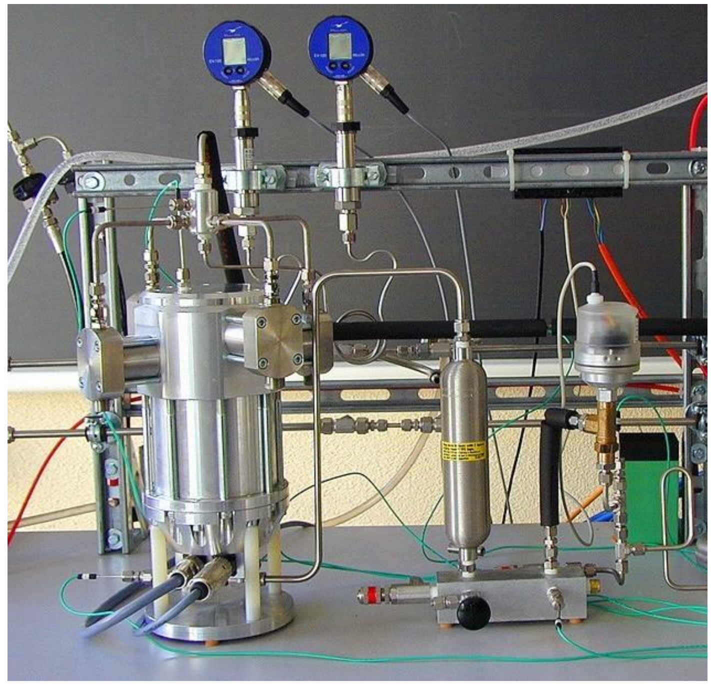
SMALL SEMI HERMETIC OIL FREE CO_2 COMPRESSOR

For overcritical CO_2 processes the problems in connection with the lubrication oil are still topical. The goal of a SFOE and an IEA[60] project was to prove the feasibility of a small **oil free semi hermetic piston type CO_2 compressor** for supercritical heat pump applications with large temperaturespans. These processes are characterised by high pressures with around 35 bar suction pressure and 80 to 150 bar delivery pressure. A functional compressor model with four cylinders, speeds from 750 to 2'900 RPM and an electrical power consumption between 150 and 950 W was designed and manufactured: Figure 8-24. Its performance was tested over the full range of speed and pressure and showed promising results [Baumann 2001], [Baumann and Conzett 2002].

[60] Swiss contribution within the scope of the **Annex 27** (Selected Issues on CO_2 as a Working Fluid in Compression Systems) of the Implementing Agreement for a Programme of Research, Development, Demonstration and Promotion of Heat Pumping Technologies of the International Energy Agency.

Figure 8-24 Functional demonstrator of a small oil free CO_2 compressor [Baumann 2001]





PULSE WIDTH MODULATION - AN ADVANCED APPROACH

The common outside temperature on-off control of heat pumps for homes often leads to a too frequent switch-on and switch-off of the heat pump with too short periods of operation. This leads not only to a lower efficiency but also to a reduced lifetime of the heat pump. Therefore the pulse width modulation had been introduced. The **basic idea of this new concept** is to make full use of the thermal inertia of the building and the heat distribution system in order to get periods of operation as long as possible without a noticeable comfort loss. A further goal is to optimise the heat consumption over the day in order to exploit low-tariff electricity. The pulse width modulation concept was realised by three different approaches. They differ in the methods used to determine the quantity of heat required and the optimum timing of the heating periods during the day.

For the two simpler control strategies, the heat requirement is determined either **from the heating capacity demand characteristic as a function of ambient temperature**, or from the **running time characteristic** (heat requirement as given by the heating capacity demand characteristic divided by the heating capacity as given by the heat pump characteristic). The third control strategy, called **model predictive control**, which is considerably more complex, accounts for the thermal inertia of the building and the heat distribution system by a physical model. The method also estimates the ambient temperatures in the hours to come based on the temperatures measured during the previous 24 hours. In optimising the heat supply, the coefficient of performance of the heat pump, as well as the tariff structure and cut off times of the electricity utilities are considered. The room temperature is followed indirectly by the water return temperature of the heat distribution system. The controller may be operated in one of two modes: minimum energy consumption or minimum electricity costs.

The controllers were tested in a single-family home of typical construction type for the retrofit case with an air-to-water heat pump: Figure 8-26. The hydraulic heat distribution system was equipped with a storage tank installed in series. Heat distribution was via floor heating (FLH) and radiators (RAD). The relative heating power shares were changeable from 33% FLH / 67% RAD to 33% RAD / 67% FLH.

Figure 8-26 Home used for testing the three control procedures based on pulse width modulation [Gabathuler et al. 2002a]

Figure 8-25 Dynamic heat pump test rig for comparative tests under defined conditions [Zogg and Shafai 2001]

Using pulse width modulation, a comparable level of comfort was achieved in the rooms as compared to a conventional controller based on the ambient temperature and the return temperature. Further advantages were [Gabathuler et al. 1998, 2002a], [Shafai et al. 1999, 2002]:

- The proportion of low-tariff electricity was between 60% and 70% in comparison to 43% for conventional controller.
- Longer heat pump running times of 0.5-1.5 hours were achieved at part load.
- With the heat pump switched off, the circulation pump did not need to come into operation, resulting in lower auxiliary energy consumption.
- Simple adjustment, i.e. no heating characteristic curve required, and no coupling of heating characteristic curve to time schedule or to domestic hot water preparation system needed.
- Optimum exploitation of low-tariff electricity without the necessity to oversize the heat pump.

In phase 3 and 4, comparative studies of the mentioned control strategies under identical operating conditions on a dynamic heat pump test rig were carried out at the ETHZ (Figure 8-25) in cooperation with industrial partners [Zogg and Shafai 2001], [Gabathuler et al. 2003]. In phase 4 of the project the **model-based predictive controller** was **extended to an adaptive controller** by utilizing an algorithm for the on-line identification of the parameters of the house model. The controller is now able also to access and **use the weather forecast data** of SwissMeteo for the prediction of the outdoor temperature as well as the solar radiation. Moreover, the controller was extended to handle the domestic hot water conditioning. With the new controller there is no need any more to readjust the controller manually during the start-up operation or after the drying-out phase of a newly built house. This controller reduces the heating costs by approximately 10% without sacrificing comfort mainly by increasing the heating rate during the periods of lower electricity tariff [Bianchi et al. 2005].

ADVANCED FAULT DETECTION AND DIAGNOSIS METHODS

During the operation of heat pumps, faults like heat exchanger fouling, component failure, or refrigerant leakage can reduce the system performance. In order to recognise these faults early, a fault diagnosis system was developed and verified on a test bench. The parameters of a heat pump model are identified continuously and classified during operation. For this classification, several “hard” and “soft” clustering methods were investigated, while Fuzzy Inference Systems or Neural Networks are created automatically by new developed software. Choosing a simple black-box model structure, the number of sensors can be minimized, whereas a more advanced grey-box model yields better classification results. A software tool was developed for the **fully automated training process**. The new method can be implemented on a modern heat pump controller and is able to monitor the optimal operation of a heat pump permanently. This allows changing from periodic service intervals to a **targeted maintenance** when it is really required. It can also be applied for refrigeration machines of course [Zogg and Shafai 2001], [Zogg et al. 2001, 2005].

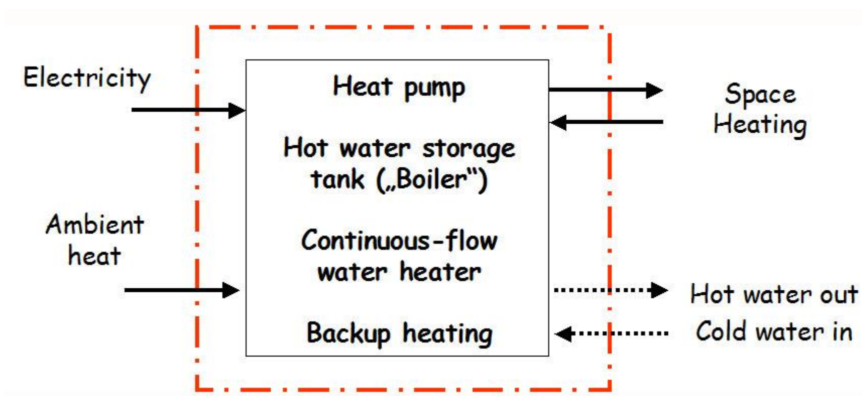
DYNAMIC HEAT PUMP TEST

The common heat pump test on the basis of the European Standard EN 14511 is a steady state test. But especially in the on-off operation mode the start-up and shut-down the heating capacity worsening is significant. Therefore the dynamic behaviour should be tested additionally. A first approach for a dynamic test procedure was elaborated [Shafai et al. 2000] and was successfully applied on a brine/water and an air/water heat pump [Ehrbar and Hubacher 2001].

TESTING FOR COMBINED SPACE HEATING AND DOMESTIC HOT WATER HEATING

The share of the heat demand for the heating of domestic hot water compared to the heat demand for space heating is growing continuously. Today it represents 10% to 50% of the total annual heating demand. Decisive for heat pump systems with combined space heating and heating of domestic hot water is the over-all efficiency for both tasks. Nevertheless, the existing test procedures are restricted to the separate space heating (or cooling) and the separate heating of domestic hot water. Therefore on the initiative of Martin Zogg, the Annex 28 "Test Procedure and Seasonal Performance Calculations for Residential Heat Pumps with Combined Space and Domestic Hot Water Heating" of the IEA Heat Pump Programme was started in 2002 with the participating countries Switzerland (operating agent), Austria, Canada, France, Germany, Great Britain, Japan, Norway, Sweden and the U.S.A. The aim of a new testing procedure is to get the necessary data in order to calculate the over-all seasonal performance factor of such heat pump systems. The systems to be investigated include the heat pump, the hot water storage (or one through water heater) and an optional supplemental backup heating: Figure 8-27.

Figure 8-27 System boundary for testing heat pumps with combined space heating and domestic hot water heating



The final results of Annex 28 were presented as the opening session of the 8th International Heat Pump Conference in Las Vegas in 2005. Parts of the results have already been implemented into standards. The calculation approach was adapted for the European Standard EN 14335 in the European framework of the Directive on the Energy Performance of Buildings (EPBD) and the German national standardisation committee (DIN) has implemented it into its national standard. The working groups of the European CEN standardisation committee will start work soon, so that the results of the testing will be implemented as well [Wemhöner and Afjei 2005]. Swiss Contributions to Annex 28 were the management of the Annex, a calculation method for the seasonal performance factor [Afjei and Wemhöner 2003] and an experimental approach based on the experience of the Heat Pump Test Centre in Töss [Montani 2003].

8.2.4 Support by Associations and the Federal Government

POLITICAL BOUNDARY CONDITIONS

In a **referendum** on October 23, 1990 the Swiss voters decided with a majority of 53.6% in favour of a 10-years **moratorium on nuclear energy**. That was after the catastrophe of Tschernobyl in 1986 and in a situation where about 40% of the Swiss electricity was produced by nuclear power (the rest was mainly hydro electricity), and the planning of a big new power plant in Kaiseraugst ongoing for many years. The political answer to that new situation was the **"Energy 2000" action plan** with the following goals to be reached by 2000: Use of fossil energy and CO_2 production not higher than in 1990, the use of renewable energies has to grow by 0.5% of the total energy demand and by 3% of the heat demand, the production of hydro electricity has to be augmented by 5% and the production of nuclear electricity by 10%. Heat pumps were one of the technical solutions in order to fulfil this action plan. "Energy 2000" is continued by "**SwissEnergy**" (**EnergieSchweiz**) with comparable goals and an annual budget of around 40 millions Swiss Francs or 0.1% of the Swiss Federal budget. Among other goals with "SwissEnergy" the Swiss Government set the target of a 10% reduction in CO_2 emissions by 2010. In order to tackle the problems in an efficient way five energy agencies had been founded. The heat pump technology is covered by the agency "Renewable Energies and Energy Efficiency" (Agentur für erneuerbare Energie und Energieeffizienz, AEE) in which the Swiss Heat Pump Promotion Group (Fördergemeinschaft Wärmepumpen Schweiz FWS) is an important member [Schmid 2001].

SWISS HEAT PUMP PROMOTION GROUP FWS

In 1992, Hans Ulrich Schärer of the Swiss Federal Office of Energy elaborated a **strategy paper** for the action programme "Energy 2000". He pointed out the high potential of heat pump heating. Heat pumps had at that time only a market share of about 7.5% in new buildings. In 1991, there were about 37'000 heat pumps in Switzerland. As a target Schärer postulated 100'000 additional heat pumps with a total heating capacity of 2'500 MW to be installed by the year 2000. The paper presented by which research and development, training, information and support actions the ambitious target could be reached. It did also include the providing of the necessary electric energy by replacing electric resistance heating and an additional production of electricity by the waste incineration plants with steam turbines and cogeneration. By the way Schärer always classified heat pumps in the renewable energy section, which later proofed to be very favourable in the rank of public priorities and fund rising [Schärer 1992, 2007].

On the basis of this strategy paper, Franz Beyeler worked out a plan for the detailed **marketing and communication** actions to be taken [Beyeler, Lehni 1992]. As a consequence of his action plan Beyeler proposed the launching of the Swiss Heat Pump Promotion Group [Beyeler 2007].

The head of the energy department staff unit of the Canton Zurich, Gabriella Brugger, had got the task of supporting the heat pump technology by creating an information and quality control centre from her supervisor Rudolf Kriesi, the founder of the Swiss Minergie concept[61]. Having

[61] In Switzerland the concept of **Minergie** has become a sustainability brand for new and refurbished buildings introduced by Rudolf Kriesi. It is registered in Switzerland and around the world. The aim of Minergie is to promote the use of construction strategies and techniques that make the reduction of energy dependence on non renewable sources possible in a cost efficient way. Furthermore, the standard sets other objectives such as healthiness of internal air, thermal comfort (winter and summer), and noise protection. Experience from new constructions shows that the additional costs compared to a traditional building are around 1 %, easily recoverable in a few years thanks

had very bad experiences with a lousy heat pump installation at her parent's house, she knew about the importance of this new task. With her extraordinary ability to communicate she managed to motivate the (at least at the beginning) distrustful heat pump business community and to bring the task not only within the canton Zurich but in the framework of a Swiss action to a successful end.

In 1993, on the basis of a close cooperation with Gabriella Brugger, Hans Ulrich Schärer (SFOE), Franz Beyeler (MKR Consulting), Ruedi Kriesi (Canton Zurich) and Hanspeter Eicher (SwissEnergy) the **Swiss Heat Pump Promotion Group** (FWS Fördergemeinschaft Wärmepumpen Schweiz) was founded. Responsible members of this association were from the beginning the federal government (represented by Fabrice Rognon of the SFOE), the cantons, the Association of Swiss Electricity Utilities VSE [62], the associations of the relevant installers VSHL and SSIV[63] and the members of AWP (Swiss Working Committee of Heat Pump Manufacturers and Distributors). Dieter Wittwer of INFEL[64] was the first FWS manager [Brugger and Eicher 1994], [Mariani-Brugger 2007], [Schärer 2007], [Szokody 2007].

The main goal of the Swiss Heat Pump Promotion Group is the promotion of **efficient heat pump heating systems of high quality at an affordable price** according the motto "happy heat pump owners prior to selling as many heat pumps as possible". In December 1993 already, the Swiss Heat Pump Promotion Group organised its first **open days** in Worblaufen where interested consumers and investors could visit an operating heat pump installation and get neutral information. The first public **heat pump exposition**, called "Wärmepumpen-Expo", happened under the lead of Franz Beyeler in November 1996 [Beyeler 2007].

Today the Swiss Heat Pump Promotion Group is an excellent **neutral information centre** for all persons interested in heat pump. A comprehensive documentation starting with introductions and going to design guidelines, check lists and maintenance instructions can be downloaded from www.fws.ch. Unfortunately they are available in the Swiss languages German, French and Italian only. An overview on the actual state of the Swiss Heat Pump Promotion Group in English is given in [Peterhans and Rognon 2005].

8.2.5 Quality Management

HEAT PUMP TEST AND TRAINING CENTRE – A EUROPEAN PIONEER INSTITUTION

On the way from pioneer's prototypes to reliable products with predictable performance a strict quality control is indispensable. There was an obvious demand for independent heat pump testing, pushed by the utilities, political actors and forward thinking manufacturers. But among many manufacturers there was a lot of resistance. It was Gabriella Brugger who broke the ice for an independent **Heat Pump Test and Training Centre** (Wärmepumpentest und Ausbildungszentrum WPZ) in **Winterthur-Töss**. In a kick-off meeting she, as a lawyer, faced around 100 engineers and technicians. Many of the heat pump manufacturers and distributors were very sceptical: "What, if nobody will come for testing?" But thanks the strong engagement and

to the savings from reduced heating costs. The Minergie concept has now spread widely in Switzerland, and in fact, many banks grant loans and financing at more favourable conditions for those buildings that have this mark. By applying the specific energy consumption criteria of Minergie on a large scale, it has the potential to halve CO_2 emissions for space heating. Details in www.minergie.ch.

62 Verband der Schweizerischen Elektrizitätswerke VSE, www.vse.ch.

63 „Verband der Schweizer Heizungs- und Lüftungsfirmen VSHL" and „Verband der Schweizerischen Spenglermeister- und Installateure SSIV; later united as „suissetec" (Schweizerisch-Liechtensteinischer Gebäudetechnikverband), www.suissetec.ch.

64 INFEL Informationsstelle für Elektrizitätsanwendung, Zürich.

leadership of Karl-Heinz Handl[65], Brugger and the excellent cooperation between the utilities NOK (Handl), EKZ[66] (Georgio Lehner) and EWZ[67], the Canton Zurich and last but not least the Swiss Federal Office of Energy the test centre was finally realised. NOK and EKZ were responsible for the operation of the centre and the Swiss Federal Office of Energy took the main share of the operating costs. Max Ehrbar was engaged as experienced technical expert and he did the conceptual planning. Later co-financing was granted by the research fund of the Swiss utilities PSEL[68] and later of AXPO[69]. The centre was inaugurated on January 26, 1993. The first tests were started in the late 1993's. The testing of air/water, water/water and brine/water units followed the former European Standard EN 255. For ambient air as a heat source a complete defrosting cycle was integrated into the test procedure. The manufacturers were charged by only 30% of the effective testing costs [Handl 1993], [Ochsner 1993], [Mariani 2007], [Schärer 2007].

In 1996, the tests were extended to air/air units and as an addendum to the EN 255 the temperature difference between feed and return temperature of the heat sink was restricted to a maximum of 10 K in order to avoid a COP tuning by wise guys. This problem was recognised by others as well. The new European Standard EN 14511 (replaced EN 255) is even more stringent and restricts this temperature difference to a maximum of 5 K.

Since 1998 the safety-related electric testing based on the European Standard EN 60 335-2-240 is done at the Heat Pump Test and Training Centre as well. In 2003 the Heat Pump Test and Training Centre was moved to the University of Applied Science in **Buchs** (formerly Neutechnikum Buchs NTB) where the testing based on the European Standard EN 14511 for heating capacities **up to 60 kW** is continued since 2004. In addition to the Töss programme the testing of heat pumps for heating domestic water according to EN 255-3 was implemented. Aside the conventional COP values the test results for brine/water and water/water heat pumps are represented by a modified COP value – called "**standard energy number**[70]". In contrast to the COP it takes into account a standard energy demand for the heat source circulation pump [Nani 2005].

The success of this institution may be illustrated by the number of heat pumps tested until November 2007: air/water 118, brine/water 200, water/water 122, water heater 7. From the beginning the test results were published in **bulletins**. Nowadays they can be downloaded from www.wpz.ch.

DACH LABEL FOR HEAT PUMPS

In order to make it easier for the consumer to choose an efficient high quality heat pump from a supplier with strong after sales support, the **DACH quality label** for heat pumps (DACH-Gütesiegel für Wärmepumpen) was introduced in 1998 by Germany (D), Austria (A) and Switzerland (CH). The first DACH Label was given in 1999. It is probably the most renown label for heat pumps in Europe today. Negotiations are currently ongoing within the European Heat Pump Association EHPA (http://ehpa.fiz-karlsruhe.de) in order to implement the DACH Label at a European level.

The **minimum requirements** of the DACH Label are the following:

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[65] Karl-Heinz Handl was at that time a vice director of the Power Plants of North East Switzerland (NOK, www.nok.ch). The test centre was built up in a substation of NOK,

[66] EKZ Elektrizitätswerke des Kantons Zürich (electric utility of the Canton of Zurich); www.ekz.ch.

[67] EWZ Elektrizitätswerk der Stadt Zürich (Zurich City electric utility), www.stadt-zuerich.ch/internet/ewz/home.html.

[68] Projekt und Studienfonds der Elektrizitätswirtschaft PSEL.

[69] The holding AXPO is a leading Swiss electric utility based in Baden, www.axpo.ch.

[70] Standard-Energiekennzahl SEKZ.

- Heat pumps with a heating capacity up to 60 kW manufactured in more than 20 units per year (no prototypes).
- Minimum efficiency requirements on the basis of measurements in accordance with the European Standard EN 14511: Table 8-2.
- Electric safety tests in order to meet the European CE safety mark and Swiss national SEV standards.
- Electric connections in accordance with the conditions of the utilities.
- Meeting the documentation requirements for planning and installation.
- Maintenance organisation available.
- Two years of full warranty and ten year spare part availability.

Table 8-2 Minimum COP requirements of the DACH Label

Type of Heat Pump	Heat Source Temperature	Minimum COP at a Heat Sink Temperature of 35 °C
Brine/Water	Brine = 0 °C	4
Air/Water	Air = 2°C	3
Water/Water	Water = 10 °C	4.5
Direct Evaporation	Ground = 4 °C	4

The label is valid for three years only and has to be reapplied for the following years. Within the FWS there is a quality label committee[71] responsible for the Swiss labelling affairs. Further details in www.fws.ch.

DACH LABEL FOR BOREHOLE HEAT EXCHANGERS

Contrary to the DACH Label for heat pumps the DACH Label for borehole heat exchangers (DACH Gütesiegel für Erdwärmesonden) assesses and labels the drilling companies. After training courses the implementation on the field is checked periodically and the personal involved in drilling has to be trained annually. An important goal is the prevention of any kind of ground water contamination. In Switzerland, the first DACH Labels for borehole heat exchangers were awarded in 2001 to Frutiger, Hastag, KWT and Geotherm. Exact requirements in www.fws.ch.

FIELD TEST OF HEAT PUMP SYSTEMS "FAWA"

A high efficient heat pump is one thing – a highly efficient complete heat pump system is another one. Even when using the best heat pump available, from the heat source to the heat distribution into the individual rooms of a building many things can go wrong. That is why in 1995, on the initiative of Fabrice Rognon the Swiss Federal Office of Energy started comprehensive **field testing of heat pump systems as a whole** (**FAWA** Feldanalyse Wärmepumpen) in order to analyse and tackle such problems and to find out the best systems. A total of 236 heat pump systems in the heat power range **up to 20 kW** were measured under the lead of Peter Hubacher from 1996 to 2003. Among these there are roughly 45% air/water, 45% brine/water and the rest (just as control samples) water/water and ground/water systems. A total of 1.3 millions hours or 740 years of operation were recorded by the measurements. The average seasonal performance factors seasonal performance factor emerged to be around 2.6

[71] The Swiss labelling committee has bean chaired until 2002 by Peter Suter, and from then Max Ehrbar is the chairman.

for air/water systems and 3.4 for borehole heat exchanger/water systems [Hubacher et al. 2004].

The 20 best systems (8.5% of the total number of systems tested) were further analysed. They attained seasonal performance factor of 3.1 for air/water systems (with a maximum of 3.4) and 5.0 for borehole heat exchanger/water systems (with a maximum of 5.6). The improvements compared to the mean values of all FAWA samples are high. These champion installations were not exotic but carefully designed according the guidelines well known to date. The main reason for the enormous improvement observed with the borehole heat exchanger / water systems was a carefully optimised flow rate in the probes and the replacement of "brines" by pure water (an improvement of 24% was observed in one case). The latter is possible without any risk if there is a proper design of the borehole heat exchanger for this purpose. Further propane as a refrigerant had a high share among the champion systems [Nani et. al 2005].

TRAINING OF THE INSTALLERS

From the beginning of FWS the training of the installers was an important pillar of its quality control. Hansueli Bruderer was the first head of the resort department. Since 2006 there is a regular three days training. The successful trainees get a certificate (www.fws.ch).

HEAT PUMP DOCTOR

The fourth pillar of the Swiss heat pump quality management is the "**Heat Pump Doctor**" for members of the Swiss Heat Pump Promotion Group. He can be called if any problem would arise between the customer and the installer. The first survey is free of charge. Fortunately it comes to such surveys only in 0.25% of the installed heat pump systems. Normally the first survey of the heat pump doctor results in an amicable settlement. The first heat pump doctors were Georgio Lehner from the utility EKZ and Gyula Szokody from Hoval Herzog [Mariani 2007], [Szokody 2007].

8.2.6 Vapour Recompression

In Switzerland all common salt and sugar is produced by vapour recompression. The several-stage compressors of the beginning had been replaced with single-stage high speed radial compressors[72]. The operation of the plants is fully automated [Hoyer 2007]. Evaporation plants using the **Escher Wyss system** have been built for more than 80 years. The worldwide implementation of this process technology occurred in the salt and sugar production, in the basic chemical industry, in the treatment of wastewater from flue gas scrubbers etc. It was designed and built under the following company names: 1924 – 1981 Escher Wyss; 1981 – 1991 Sulzer - Escher Wyss; 1992 – 1996 Sulzer Chemtech; 1996 – 1999 CT Environment ; 1999 – 2000 VA TECH WABAG; 2001 – 2004 Messo and since 2004 GEA Messo (www.geamesso.com). But the Escher Wyss technology is also continued by the engineering company EVATHERM in Othmarsingen[73].

8.3 Heat Pumps for Heating - International Milestones

In Europe since 1990 a **definitive take off** of heat pumping technology for heating only began. The reasons were more ore less similar to those described for Switzerland. Some countries

[72] Tangential speed up to 500 m/s, rotors made from titanium.

[73] EVATHERM AG, CH-5504 Othmarsingen (www.evatherm.com); CEO is the former design manager of Escher Wyss [Hoyer 2007].

like Germany with electric energy produced from coal to a large extent had it more difficult to achieve a significant CO_2 reduction compared to gas boilers. The quality problem was recognised and more emphasis on **quality management** came up as a consequence.

Ground source heat pumps became more popular. Several personal computer programmes for a more precise design of single and groups of borehole heat exchangers became available, among them the popular EED (Earth Energy Designer) [Hellström and Sanner 2000]. An excellent overview on the status of ground source heat pumps by leading scientists [Lund et al. 2003] mentions a worldwide installed thermal capacity of 9’500 MW produced by some 800’000 units. Leading countries using ground source heat pumps are Austria, Canada, Germany, Sweden, Switzerland und the U.S.A.

In Europe **natural refrigerants** were pushed early. The first propane heat pumps were introduced in 1993, and guidelines for vapour compression cycles with natural refrigerants had been worked out within the IEA Heat Pump Programme [Stene J. 1998], [IEA-HPC 1999], [Schiefelbein 1999]. Recently a new effort for the application of natural refrigerant was taken in Europe by the **SHERHPA** project (Sustainable Heat and Energy Research for Heat Pump Applications). This project of the European Union is dedicated to small and medium enterprises. It is dealing with the development, manufacturing and testing of cost-energy efficient **heat pumps using natural fluids (hydrocarbons, ammonia and carbon dioxide)** and is in compliance with Europe’s future environmental regulations. The project is coordinated by the two independent associations **Greth** (Heat Equipment Association) and **EHPA** (European Heat Pump Association). The core group is composed of 18 SMEs from 11 countries and the R&D work is performed by nine European centres of excellence. The natural refrigerants have different thermodynamic and chemical properties compared to existing refrigerants. This requires redesigning the principal components like heat exchangers and compressors. At the same time, appropriate control strategies have to be developed. Other challenges involve material compatibility and a minimising the amount of refrigerant in the system. After initial studies, in a next phase 10 prototype systems will be designed, manufactured and evaluated with capacities ranging from 2 to 100 kW [Thonon 2006].

GERMANY

TÜV (Technischer Überwachungs-Verein) is the German accredited test laboratory for the DACH Label. Since 1997 the design know-how of **ground coupled heat pumps** was concentrated in the German guideline VDI 4640[74] worked out in cooperation with Austria and Switzerland.

In 1993, Stiebel Eltron presented its **first propane heat pump** and reported on the market experiences a few years later [Schiefelbein 1999]. For **low energy houses** with controlled aeration the company has developed a heat pump with integrated exhaust air heat recovery and an integrated domestic water heating. The system is optionally available with an additional integration of solar energy. In 2006, Stiebel Eltron has built **Europe’s largest heat pump manufacturing** factory with a capacity of 25’000 heat pumps at Holzminden.

The first **heat pump laundry dryers** were tested in 1997 and commercialized in 1998 [AEG 1988]. Bitzer is manufacturing hermetic scroll compressor since 2003 [Frommann 2004].

Because of the lack of interest of potential Swiss manufacturers, the **diffusion absorption heat pump** pioneer, Hans Stierlin went with his innovation abroad. Further testing was started by **Buderus** in Germany in 1994 already. In 1997, the cooperation between Stierlin’s Crea-

[74] VDI-Richtlinie 4640; Thermal use of the underground. Vol. 1, Fundamentals, approvals, environmental aspects 2000-12; Vol. 2, Ground source heat pump systems 2001-09; Vol. 3, Underground thermal energy storage 2006-11; Vol. 4, Direct uses 2004-09. www.vdi.de/vdi/organisation/schnellauswahl/fgkf/get/richtlinien/.

therm and Buderus was contracted. The DAWP project was continued at the Dutch subsidiary **Nefit Fasto**. In 1999, extensive field-testing was carried out with additional peak boilers for bivalent operation – the “AWP-Kessel” Swiss researchers dreamed of in 1995. The project showed a high degree of satisfaction. The old results were confirmed: heating capacity of one modul 3.6 kW, heat ratio 1.5 in stand alone and 1.32 in combination with the peak load boiler [Blom 2000], [Laue and Heidelck 2000]. In 2000 the Nefit Prototype – now called “**Buderus Loganova**” – won the award of the German gas utilities. There was a lot of other publicity and announcements about bringing the system on the market. However it is not yet commercially available. Probably the mass production of the complicated tube in tube arrangement according to Figure 8-14 is the main problem.

The idea of a **borehole heat exchanger with CO_2 as a working fluid** arose from the European Project COHEPS. The CO_2 heat pipe solution was patented by the Research Centre on Refrigeration and Heat Pumps FKW in Hannover in 1988. In order to avoid corrosion problems a flexible stainless steel tube system is under investigation [Kruse et al. 2008].

AUSTRIA

In the U.S.A. first attempts for **direct expansion ground coil systems** go back to 1945 as described above. Such systems have advantages (no heat carrier circulation pump, high heat transfer coefficients) but handicaps as well (lubricant feed back in vertical arrangements, danger of liquid phase blow out, recommended factory refrigerant filling) and were never accepted in Switzerland for environmental reasons. But they are quite successful in Austria and there is an official test institution for direct expansion systems in Vienna[75]. Austria had a share of 66% of direct expansions systems in 1996 [Halozan 1997].

In 2001, Karl Mittermayr brought the **borehole heat exchanger working with evaporating CO_2** to practical operation. The some obvious advantages (no environmental problem if oil free, thermosyphon → no circulation pump, high heat transfer coefficient, most evaporation where warmest surrounding) stand vis-à-vis serious disadvantages (high pressure → expensive cooper tubes with corrosion protection by plastic material or flexible stainless steel tubes, restricted depth of less than about 75 m, no passive summer cooling without circulation pump, very high tightness requirements). By 2007 about 500 CO_2 probes had been installed [Ehrbar et al. 2004], [Rieberer et al. 2005], [Wenzel 2007]. This type of ground heat exchanger is not covered by the guidelines VDI 4640.

SCANDINAVIA (Norway, Sweden, Denmark, Finland)

Especially in **Sweden** a strong sentiment against nuclear power generation led to initiatives for reducing energy consumption. Heat pumps were identified as an **alternative to electric resistance heating**, saving electric energy by factors. At the Lund Institute of Technology the mathematical **modelling of borehole heat exchangers,** started by Per Eskilson, was expanded to a groundbreaking thermal analysis of ground heat storage systems by Göran Hellström [Hellström 1991].

The **labelling systems in Sweden**, the P-mark, which is a quality label and the Swan which is an eco-label has been maintained do date [Forsén 2005]. In the same direction as the presented Swiss single room radiator heat pump presented above, headed a Swedish development of a **single room heat pump** by Eufor of Härnösand. It was a direct expansion ground coupled system with a high seasonal performance factor [Falén 1995].

[75] arsenal research, Österreichisches Forschungs- und Prüfzentrum Arsenal G.m.b.H., A-1210 Wien; http://www.arsenal.ac.at/org/org_contacts_de.html.

The **Danish** firm **Sabroe** introduced **high temperature heat pump compressor** for **ammonia** in 1990. This extended the heat sink temperatures to up 70°C. Also in Switzerland many sport centres with skating rinks and indoor swimming pools as well as residential areas were equipped with this compressor [Reiner 2007]. In 1997, Sabroe bought the refrigeration division of ABB (former BBC) [Kunis et al. 2004].

There was a Norwegian attempt to build a **small ammonia heat pump** [Jonassen and Stene 1997]. Many **large heat pump systems** were built in Norway and Sweden. Those among them of Swiss origin are described in section 8.2.1. The reasons for the big plants are existing large district heating systems, a low electricity price, and in many cases the sea as a heat source.

U.S.A. AND CANADA

In the U.S.A. the expansion of **heat pumps and unitary air conditioners** based on vapour compression continued. In 1999, there was only one manufacturer of unitary absorption air conditioners and heat pumps in the U.S.A. There were extensive research activities on **absorption heat pumps** worldwide [Radermacher et al. 1994], [Ab-Sorption 1996]. But on the space heating and domestic hot water heating market absorption heat pumps could not compete to a significant share against the cheaper and more efficient vapour compression technology until to date. The available absorption heat pump equipment is based on single-effect ammonia – water cycles with PERs around 1.5. Experiments with the more complex GAX-cycle (Generator-Absorber heat exchanger) led to PERs signifigantly above this value [Burget 1999]. In 1990, Ontario Hydro (Canada) funded a program to install geothermal heat pumps in residences without connection to the natural gas grid (www.centreforenergy.com).

CHINA

In 2005 there were installed prototype devices to **use raw sewage as a heat source** for heating in wintertime and as a heat sink for cooling in summertime. They were successfully tested in a hotel and shopping centre in Harbin, a city in the Heilongjiang Province, northeast China, which is very cold in wintertime [Fangchao 2005].

VAPOUR RECOMPRESSION

Today there is an annual common **salt** (NaCl) production of some 2’300’000 t worldwide. A growing share is produced by vapour recompression. The European vapour recompression companies are mentioned in 8.2.6. Another vapour recompression company to be mentioned is HPD in the U.S.A.

9 SPECIAL PRINCIPLES

ADSORPTION

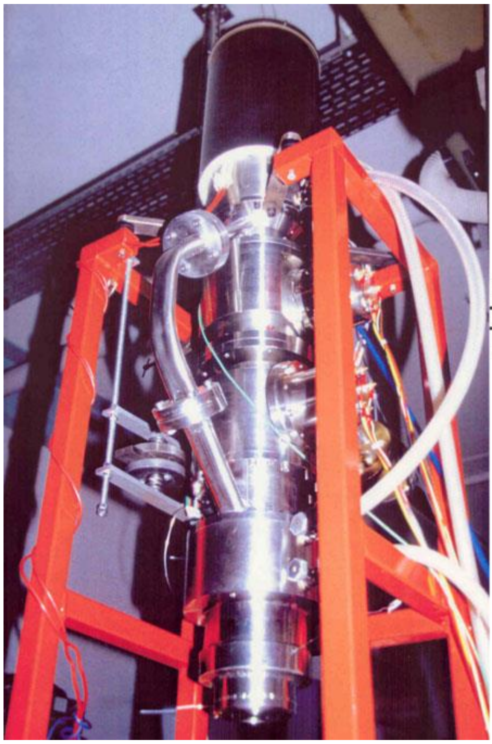
A lot of research has been carried out on **adsorption** machines, but only a few solar thermal refrigeration applications have been realized. In 1930, I. Amundsen built a domestic adsorption refrigerator with activated carbon and methyl alcohol. From 1950 new chemical compounds were used for adsorption units such as **silica gel** (gave only mediocre results) and **zeolites** (“molecular sieves”, gave better results). Nowadays there is a certain revival of adsorption devices for cooling, using solar thermal energy. But there are no adsorption units for heating purposes of any practical importance [Nagengast et al. 2006], [Thevenot 1979].

THERMOELECTRIC EFFECT

Thermoelectric cooling occurs when a current is passed through two dissimilar metals or semiconductors (n-type and p-type) that are connected to each other at two junctions (Peltier junctions): one junction cools off while the other heats up. Thus the electric current drives a transfer of heat from one junction to the other. This effect was observed in 1834 by the physicist Jean **Peltier**. In 1909 and 1912, Edmund Altenkirch presented two papers on thermoelectric cooling. But his phenomena remained in a laboratory curio until after 1945. In 1949, A.F. Loffe constructed the first thermoelectric refrigerator. In 1949/50, the use of semiconductors gave rise to hope, to produce an effect much stronger than with pure metals. Several thermoelectric household refrigerators were made in the U.S.S.R. But due to the still low efficiency of the thermoelectric effect only a few very special applications such as thermoelectric cooling in medicine and radio-electronics remained after 1960 [Thevenot 1979], [Nagengast et al. 2006].

STIRLING CYCLE

In 1834, John Herschel is said to be the first to use **Stirling's machine for refrigeration purposes**. From descriptions published in 1876 by Alexander Kirk, it seems that by then Stirling cycle cooling principle was well known in technical circles. Long after, beginning in 1946, the cycle was applied by Philips under the direction of J. W. L. Köhler for deep temperature use in order to generate liquefied gases. In 1957, machines based on this principle were able to obtain temperatures down to 12K [Global Cooling 2004].



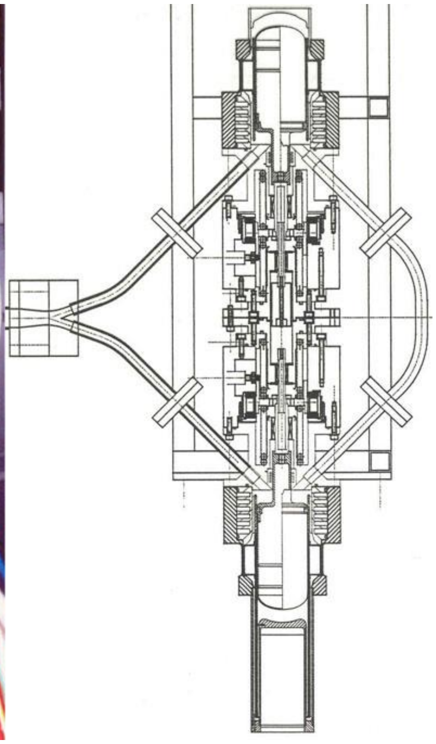


Figure 9-1 Vuilleumier Stirling heat pump with a resonating gas column in a resonance tube [Budliger 1995]

The combination of a Stirling engine with a Stirling heat pump is called **Vuilleumier heat pump**. In Switzerland Jean-Pierre Budliger began with the development of a new Technology for Vuilleumier heat pumps in 1986. It had been derived from the free piston duplex Stirling heat pump of W. Beale. In his new concept Budliger replaced the heavy power piston with its problematic piston seal by a **resonating gas column**. He carried out an intensive theoretical and experimental study on his arrangement with two pistons and resonance tubes in between: Figure 9-1. The primary energy ratio was calculated to be 1.5. On the basis of these studies Budliger built a functional demonstrator, which was operating already. But then the development had to be stopped due to financial problems and the predicted primary energy ratio of 1.5 could not be validated any more [Budliger 1987, 1993, 1995].

In the U.S.A. Sunpower developed a **free-piston Stirling cooling machine** with horizontally opposed piston arrangement (boxer) from 1989 until 1995. It was operating in the Space Shuttle [Global Cooling 2004].

MAGNETOCALORIC EFFECT

If a suitable material is placed in a strong magnetic field, the magnetic dipoles in the material become aligned with the magnetic field. This produces a reduction of magnetic entropy. As entropy cannot be reduced in total, there is a compensating warming the material. If afterwards the material is cooled whilst still being in the magnetic field, and then is removed from the field, it cools down further, producing a refrigeration effect. In 1881, the German physicist Emil Warburg was the first to discover this effect. He put a block of pure iron into a strong magnetic field and found that it increased very slightly in temperature. The **magnetocaloric effect** (MCE) varied between 0.5 to 2 K/T (T: tesla). Major advances first appeared in the late 1920s when cooling via adiabatic demagnetization was independently proposed by the Dutch physical chemist Peter Debye (1926) and the American chemist William F. Giauque (1927). The magnetocaloric effect was impressively demonstrated by Giauque (who won the Nobel Prize in Chemistry in 1949) and his colleague D.P. MacDougall in 1933 for cryogenic purposes when they reached 0.25 K.

In the U.S.A. there was a development of a magnetocaloric refrigerator in 1929. It was functioning but the researchers claimed further studies [Barclay 1978]. Between 1933 and 1997, a number of advances in utilization of MCE cooling occurred. In 1997, the first near room temperature “giant effect” with pseudobinary gadolinium alloys was demonstrated by Karl A. Gschneidner Jr. and Vitalij. K. Pecharsky at the Iowa State University. This event attracted interest from scientists and companies worldwide which started developing new kinds of materials and magnetic refrigerator designs. Refrigerators based on the magnetocaloric effect were demonstrated in laboratories, using magnetic fields from 0.6 T up to 10 T (1 tesla corresponds to about 20’000 times the Earth's magnetic field). Magnetic fields above 2 T are difficult to obtain with permanent magnets and therefore are produced by superconducting electromagnets. The rising interest in this technology is demonstrated by the founding of the IIR Working Party on Magnetic Refrigeration (www.mcwp.ch) and a first International Conference in 2005 in Switzerland [Egolf et al. 2005], [Gschneidner et al. 2005].

Recently Peter Egolf, Osman Sari, Andrej Kitanovski and their assistants of the University of Applied Sciences of Western Switzerland in Yverdon-les-Bains have developed and patented a **new rotary magnetic refrigerator/heat pump** [Kitanovski et al. 2004], [Egolf et al. 2006]. In their system the four thermomagnetic processes (adiabatic magnetization, isomagnetic enthalpic transfer, adiabatic demagnetization, isomagnetic entropic transfer) are realised in a simple continuous manner [Sari 2007], [Vuarnoz 2007]. In a theoretical feasibility study for a **magnetocaloric 8 kW heat pump** application they have got promising results for a heat pump with 0°C source and 35°C sink temperature [Egolf 2007]. As there is a one cascade element maximal temperature lift of only 8 K, the realistic overall maximal temperature lift is limited to the envisaged 35 K. The project will be continued experimentally by a functional heat pump model.

VORTEX TUBE

In 1933, the French Georges Ranque discovered the so called **vortex tube effect**. His vortex tube has been improved by the German Rudolf Hilsch in 1947. The tangential injection of air into a cylindrical tube induces a gyratory expansion with a simultaneous production of an escape of hot air and an escape of cold air. This system has the advantage of great simplicity but its efficiency is very low. Therefore it is not of any interest for heat pump applications. Its use is restricted to some special cases where a supply of compressed air is available, to obtain momentarily a fall in temperature [Thevenot 1979].

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The Author

Martin Zogg was born on August 30, 1942.

He ended his studies in Mechanical and Process Engineering at the Swiss Federal Institute of Technology in Zurich with a PhD thesis.

Martin Zogg has got his first industrial experience in aircraft construction (Flug- und Fahrzeugwerke, Altenrhein), power generation (Brown Boveri, Baden), cryogenics and process engineering (Sulzer Winterthur).

Then Martin Zogg acted

> 25 years as a professor on process engineering at the Bernese University of Applied Sciences;
>
> 10 years as head of the Research Program on Ambient Heat, Waste Heat and Cogeneration of the Swiss Federal Office of Energy and
>
> 7 years as an expert on energy and process engineering of the Swiss Innovation Promotion Agency KTI/CTI (assessment of research applications and expert monitoring of research projects).