History of Heat Pumps
Swiss Contributions and International Milestones

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Abstract: 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. Its pioneering role in the development of vertical 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 dwellings 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. This paper is a summary of a detailed report with many references on the subject prepared on behalf of the Swiss Federal Office of Energy [Zogg 2008].

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

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 the first pioneers invented refrigeration machines. The same machines can be used in heating as heat pumps. The huge demand for cooling led to the rapid development of this newly discovered technique and to a triumphal dissemination around the globe. In properly designed residential buildings of **central and northern Europe** only heating is needed in order to keep rooms comfortable during the cold season of the year. This is why in these regions for residential building appliances **heating only** is of particular interest. In contrary to cold, heat can be produced by cheap natural gas and oil boilers. Heating only heat pumps therefore have to meet high requirements in terms of efficiency and total costs in order to compete against the less complex boilers. It is still a challenge to win this competition in the interest of higher primary energy efficiency.

Why heat pumps for heating only? A boiler always has some losses. Therefore a boiler produces less than 100% utilizable heat from 100% primary energy input. Its primary energy ratio (PER) is below 1. This means an indefensible waste of exergy. This Stone Age principle has to be replaced by a **combination of cogeneration units or modern combined cycle power plants with heat pumps**. Due to the utilization of ambient heat, this arrangement leads with 100% fuel input to 150 % and up to 200% with present-day equipment and even more in the future.

The following will **focus on the development of heat pumps which produce heat as their main benefit**. Taking additional advantage of the cold side of the cycle is also mentioned in relevant applications. Swiss contributions to international developments will be highlighted and placed in the context of relevant international milestones in heat pump and refrigeration technology. The latter has strongly pushed the development of heat pumps. Heat pumps for heating only (or mainly) benefit from cheap components of air conditioning and refrigeration origin, which are produced in huge quantities.

1 SCIENTIFIC APPROACHES – HEAT PUMP FUNDAMENTALS

Robert Mayer established the principle of equivalence between work and heat in 1842, which was proven experimentally by James Prescott in 1843. In 1847, Hermann von Helmholtz established the principle of conservation of energy (**1st law of thermodynamics**).

Nicolas Léonard Sadi Carnot was the first to establish a precise relationship between heat and work in 1824. His privately published paper was rediscovered by Benoît Paul Emile Clapeyron and reformulated to the now widely used Carnot's cycle by Rudolf Julius Emanuel Clausius (1855-1867 professor at the ETH Zurich). Clausius first stated the basic ideas of the **2nd law of thermodynamics** and introduced the concept of **entropy** by 1850. In 1851, independently of Clausius, but recognising his priority, William Thomson, the later Lord Kelvin, gave a more general formula for the 2nd law of thermodynamics and introduced the thermodynamic scale of temperature (1852). In 1866, Ludwig Eduard Boltzmann gave new significance to the 2nd law by linking the concept of entropy to the concept of probability in statistical physics. Entropy thus represents the degree of disorder. In 1878, Josiah Willard Gibbs introduced the value of **enthalpy**, Richard Mollier brought it into applied thermodynamics by 1902. From ideas put forward by G. Zeugner (1859) and Hans Lorenz (1896) arose the idea of **exergy**, the useful maximum work done by a system changing from a given initial state to a given final state by means of constant temperature source and sink. 1870 Carl von Linde established a rigorous **thermodynamic approach to refrigeration**. Frederic Swarts was conducting fundamental work on **organofluorine chemistry** in the 1890s already.

2 THE PIONEERS BEFORE 1875

In this period, heat pumps for heating purposes were pushed for vapour recompression with its obvious advantage in wood and coal savings alone. But the later development based mainly on inventions to cover the huge demand for cooling particularly in the food industry. J. Perkins built the **first practical vapour compression machine** for producing ice in 1834. Only one machine was built. In 1855, A. C. Twining presented the first commercial **ice making plant** using vapour compression refrigeration. J. Harrison developed the **first compressor** ready for practical operation in 1856. Several **refrigerants** were introduced: Ammonia for absorption systems by F. Carré, for compression systems by J. Beath (1868) and D. Boyle (1873), methyl ether by Ch. Tellier (1863), carbon dioxide by Thaddeus S.C. Lowe (1866), and sulphur dioxide by the Swiss R. Pictet (1874). P. Van der Weyde invented the **thermostatically controlled refrigeration system** as early as 1870.

Concentration and crystallisation by evaporation is applied worldwide on a large scale. In the open **vapour recompression cycle** the exhaust vapour of such systems is compressed to a higher pressure in order to condensate it for heat recovery around 10 K above the boiling temperature of the brine solution to ensure a good heat transfer. This small temperature lift is of course optimal for a heat pump process. COP values of 15 to 30 are state of the art nowadays. That is why the mechanical vapour recompression was realized much earlier than heat pumps for space heating and other low temperature appliances. P. von Rittinger was the first, trying to realize this idea on a 14 kW pilot scale plant in the Austrian salt works at at Ebensee. Beside the somewhat strange closed cycle idea, a number of process problems arose. The pilot plant never worked successfully.

In 1851, the Frenchman F. Carré, designed the first commercially successful **ammonia absorption cooling system**. It was the first refrigeration machine to achieve general industrial importance. The developments were mostly empirical - the theory of absorption machine came much later by E. Altenkirch in the 1910s.

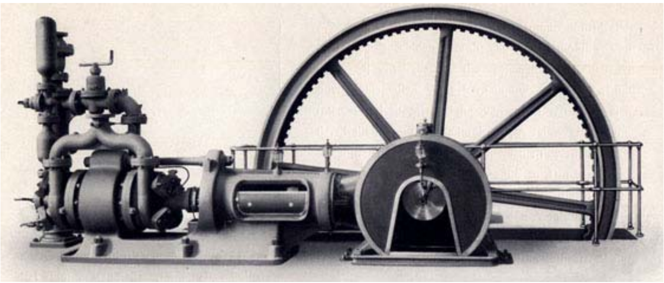
3 INDUSTRIALISATION 1876-1918

In this period the functional models of the pioneers were replaced by more reliable and optimised industrial products on the basis of a rapidly advancing scientific knowledge and industrial manufacturing ability. The refrigeration systems began to be manufactured on an industrial scale. The German, C. von Linde, was the most important person to bring about the change. He was a talented engineer and entrepreneur, but an outstanding academic researcher and teacher as well. As early as 1875, the Polytechnic Society of Munich undertook the first comparative tests on refrigeration machines. Around 1900, most fundamental inventions had been made. By 1918, ammonia was the dominant refrigerant and there were many compressor manufacturers in the U.S.A. and in Europe. In Switzerland these were Escher Wyss in Zurich, Sulzer in Winterthur and the Société Genevoise in Geneva.

3.1 Swiss Contributions: Compressors, Refrigeration, Vapour Recompression

In 1878, Sulzer - one of the leading manufacturers of steam engines - started with the construction of refrigeration compressors and plants as a logical expansion of its "steam engine" and "compressor" divisions. Sulzer became one of the most important manufacturers for Linde. **Refrigeration compressors** (Figure 1) were huge and heavy at that time. In 1878, Sulzer's 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 1898, Sulzer made the first two stage ammonia compound compressor, followed by a 1.45 MW refrigeration compressor in 1909 and an air conditioning plant for a hotel in Buenos Aires in 1914. At that time the steam engine was the dominant means of driving compressors.

Figure 1:
Piston compressor around 1905
[Archive Sulzer,
CH-8404 Winterthur]



In 1876, Raoul Pictet constructed a horizontal, unlubricated **SO_2 compressor**. The successful machine was manufactured by the "Société Genevoise" in Switzerland and in some other countries. Raoul Pictet also put forward a mixture of SO_2 and CO_2 as a refrigerant. From 1913, Escher Wyss made a 70 kW **chloromethane compressor** under licence from Douane. The Swiss turbine engineer Heinrich Zoelly was the first to propose an electrically driven **ground source heat pump** for the production of low temperature heat. He obtained a Swiss patent in 1912. But he was ahead of his time.

Probably stimulated by the experiments of Rittinger in Ebensee, the **first truly functioning vapour recompression salt plant** was developed in Switzerland by P. Piccard of the University of Lausanne and the engineer J.H. Weibel 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 prototype and produced around 175 kg/h of salt in continuous operation. Piccard's system was a great success. In 1881, a similar plant was realized in Ebensee. Four of Piccard's systems were applied in the Salies du Salat in France and one in Schönbeck, Germany. A smaller scale vapour recompression plant was realized at the **Jenny dye works** in Aarau. This world **first electric driven vapour recompression plant** registered a COP of 11.7. The plant was built by the Swiss company, Kummler & Matter. Based on the encouraging results, several other vapour recompression plants were built in Switzerland in the years that followed.

3.2 Relevant International Milestones

The real break through for **ammonia compressors** was achieved by C. von Linde. His piston compressor with a horizontal double acting cylinder of 1877 was made under licence in Europe and in the U.S.A. In 1885 (W.G. Lock, Australia → Sulzer) and 1892 (S. Saint Clar, USA → York) two-stage ammonia compressors were introduced. In 1880, F. Windhausen designed a **CO_2** refrigeration plant and in 1886 an operational CO_2 refrigeration compressor. **Methyl chloride** was introduced as a refrigerant in 1878, **chloroethane** in 1883 and **ethyl chloride** in 1884. The principle of the **screw compressor** was first patented by H. Krigar in 1878, but manufacturing was not yet possible. The principle of the modern **sliding vane compressor** dates back to the early 1900s, but it was not possible to put it to practical use until 1920. From 1911, W. Carrier first worked seriously on **radial turbo compressors** for air conditioning. The principle of the **scroll compressor** was patented in 1905 by L.Creux. But the precision machining of these uniquely shaped parts was not possible at that time.

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 was introduced in 1895 already, and the principle of the diffusion-absorption cycle was established as early as 1899 by H. Geppert. 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. In 1902, Vilter installed a **liquid separator** in the suction line, and an **automatic expansion valve** was patented by A. Marshall.

4 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. The increase in speed of rotation of compressors was accentuated and resulted in a reduction of bulk and weight. After 1918 the electric motor became the first choice for driving the compressors. About 1920 the synchronous electric motor, directly attached to the compressor became popular.

4.1 Swiss Contributions: Compressors, Refrigeration, Pioneer Heat Pumps

From 1920, **Sulzer** expanded its larger volume production of compressors for NH_3, CO_2 and methyl chloride. From 1922, Sulzer also made compact refrigeration units. 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. In the early 1930s, Sulzer introduced the oil-free "**dry labyrinth piston compressor**" which was first used for compressing air and, after modifications, was also used as a refrigeration compressor from around 1955. Sulzer began making **turbo compressors** as early as 1909 and entered the refrigeration market in 1927 with a multistage ammonia turbo compressor with steam turbine drive. Brown Boveri 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, its "Frigobloc", a water or brine cooler, was equipped with compressors with a capacity of 23 kW to 1.4 MW. Prior to 1940, 5 to 6 wheels needed for radial turbo compressors, then 2 to 3 ones. 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 (Figure 3).

HEAT PUMPS FOR SPACE HEATING AND DOMESTIC HOT WATER HEATING. Switzerland suffered from a fuel supply shortage during and after the First World War. On the other hand, it had reached a leading position in energy engineering and there was a 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. In his comprehensive book, Thevenot wrote: "*It was Switzerland, a land poor in fossil fuel reserves but rich in hydroelectric power, which gave the impetus to this method of heating*..."

At the eve und during the Second World War Switzerland again experienced a severe coal shortage. Heating by taking profit of waste heat from refrigeration cycles at skating rinks and breweries was practiced in the 1930s already. In Switzerland, 35 heat pumps for heating were installed from 1938-1945, mainly by the two constructors Sulzer and Escher Wyss. Brown Boveri in Baden took an active part as well. The main heat sources were lake water, river water, ground water and waste heat. In 1944, after five years of successful heat pump operation, pleasing results were reported. In 1955, there were about 60 heat pumps in Switzerland; the largest of them attained 5.86 MW. The **historic heat pumps of Zurich** along with several further heat pumps for space heating and industrial appliances of particular interest installed between 1941 and 1950 are presented in detail with all references in [Zogg 2008]. In this paper only a few impressions of them can be given: Table 1.

Table 1: Key data on Zurich's historic heat pumps

	City Hall	Indoor Swimming Pool City	Walche Plant District Heating	City Administration
Year of Start up	1938	1941	1942	1943
Total Heating Power [kW]	100	1025	5860	1750
Heating Power 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	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	R11 / Ammonia	Ammonia
Heat Pump Manufacturer	Escher-Wyss	Escher-Wyss	Brown-Boveri / Sulzer	Escher-Wyss

A worldwide milestone was the installation of a heat pump in 1937/38 to replace single room wood stoves in **Zurich City Hall**: Figure 2. To prevent excessive noise and vibration Escher Wyss implemented its patented rolling piston compressor, the so-called "Rotasco": Figure 3. It was 2001, following 63 years of operation, when the historic heat pump was replaced by a new one. Since 2001 this heat pump, which is the oldest still operational example, is put into operation for one hour every week to keep it alive. The **Zurich City indoor swimming pool** had got a 1 MW heat pump in 1941. It used waste heat from the pool outlet and a nearby transformer station and also used lake water as a heat source. The 5.8 MW heat pump of the **Walche plant** on the banks of the river Limmat for the district heating system in the university area started up in 1942. It consisted of two Brown Boveri (BBC) 2 MW "Thermoblock" heat pumps with five stage radial compressors (Figure 4) and one Sulzer 1.86 MW heat pump with 3 three stage piston compressors (Figure 5). 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. In 1943, a 1.75 MW heat pump to heat the **city's administration buildings** with 4 two stage compressors went into service.

Figure 2: City Hall of Zurich with River Limmat as heat source [www.picswiss.ch]

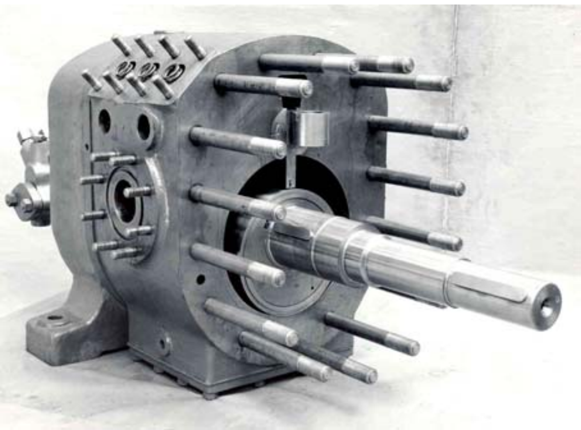


Figure 3: Rotasco Compressor of the City Hall heat pump [Hochbauamt, CH-8090 Zürich]

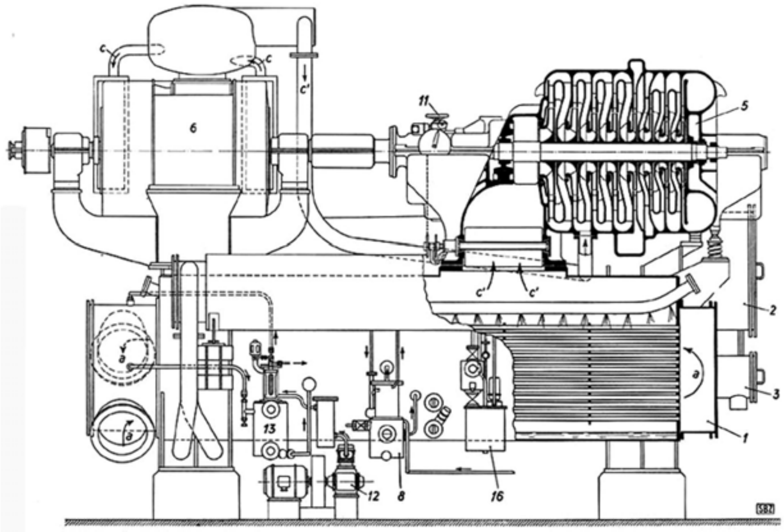


Figure 4: Walche plant, Brown Boveri « Thermoblock » with radial compressors
[Brochure 1988, Amt für Bundesbauten, CH-3001 Bern]

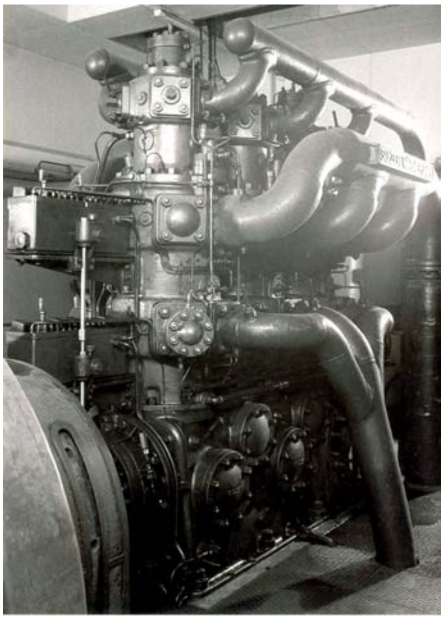


Figure 5: Walche plant, three stage Sulzer piston compressors
[Immobilien ETH, CH- 8093 Zürich]

VAPOUR RECOMPRESSION. The real beginning of mechanical vapour recompression was in the 1920s. After a problem solving period with a pilot plant in the German **salt works at Reichenhall,** the first industrial scale vapour recompression plant was built by Escher Wyss in cooperation with the Bavarian saltworks and the Swiss Kummler & Matter in 1926. It had a radial compressor of 344 kW. In 1941 Escher Wyss realized a vapour recompression plant in the Swiss **salt works at Riburg** (Rheinsalinen) for a salt production of 40'000 tons per year: Figure 6. In 1943, the Swiss **salt works at Schweizerhalle** was converted to a vapour recompression process as well. Both plants were rebuilt and enlarged. Today **Switzerland's largest heat pump systems** are operating in the salt works at Riburg and Schweizerhalle with a total evaporation power of around **80 MW**.

Figure 6: Salt works Riburg 1941 [Rheinsalinen Schweizerhalle, CH-4133 Pratteln]

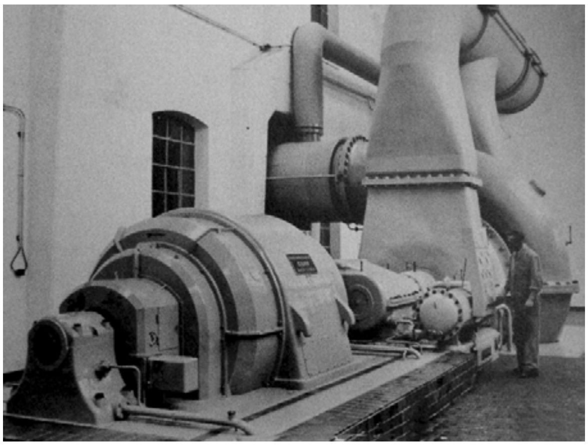


Figure 7: Sugar Plant Aarberg 1945 [Zuckerfabrik, CH-3270 Aarberg]

Escher Wyss built two vapour compression systems for the **Swiss sugar plant at Aarberg** in 1945. The sugar solution concentration plant was driven by a 2.9 MW radial compressor unit: Figure 7. This world first combination with a multi stage evaporation system resulted in a superb **COP of 26.8**! The second 3.3 MW unit served for the evaporative crystallisation.

ABSORPTION-DIFFUSION CYCLE. In 1944, Hans Stierlin started the successful production of a **diffusion-absorption refrigerator** in his company **SIBIR**. Stierlin improved the efficiency of the Munters-Platen-process significantly by 1967. But competition with the vapour compression technique became harder, when cheaper, quieter and more efficient hermetic compressors with the new synthetic refrigerants penetrated the market.

4.2 Relevant International Milestones

In 1928, **chlorofluorocarbon refrigerants** were synthesized in the U.S.A. for the first time. The CFCs **R-11** and **R-12** as substitutes for ammonia, sulphur dioxide and methyl chloride were announced publicly in 1930. This was a great step forward – at least before the environmental problems were discovered much later. In 1936, the HFC **R-134a** was synthesized. In 1919, H. Corblin patented the **diaphragm compressor**. In 1920, W.S.E. Rolaff introduced the **rolling piston rotary compressor**. The first **hermetic compressor** was made by D. Stokes in 1920 and soon after, General Electric began with mass production for household refrigerators. The **sliding vane compressor**, formerly used for air, was used for refrigerants from 1920. In 1923, W. Carrier built a prototype **radial turbo compressor chiller**. The CFCs R-11, R-12 and R-113 gave another boost to radial compressors. Long after the original patents had expired, A. Lysholm of Ljungstroms Angturbin made the first **screw compressor** ready for compressing air in 1934/1935. In the 1930s capacitor starting of the motor became common and the **small hermetic compressor** unit was perfected. In 1923, the **plate heat exchanger** (PHE) was invented by R. Seligman of the Aluminium Plant & Vessel Company (APV) and the first **thermostatic expansion valve** by E. Diffinger. In 1925, R. Bernat filed a patent on a first type of a **floating valve** for refrigerant control. By 1927, T. Carpenter invented the **capillary tube refrigerant control**. In the late 1940s, cork as a thermal insulation material faced superior competition from **insulating foams**.

In the **U.S.A.** the first **heat pumps** in the early 1930s were for air conditioning. They offered in addition to the summer cooling a low efficiency winter heating. There was an early boom for **unitary window air conditioners** (43’000 units sold in 1947). Around 1945 R. C. Webber built the **first ground coupled** 2.2 kW **heat pump**. He evaporated the CFC refrigerant in underground copper tubes. In **Germany** there were made some absorption heat pumps from 1947 onwards.

In 1920, two decades after the invention of the **diffusion-absorption** cycle, C. Munters and B. von Platen succeeded in employing hydrogen as an inert gas instead of air. Electrolux bought their patents and started production of the **absorption refrigerator** by 1926. It became a worldwide success. H. Stierlin and A. Lenning improved the process significantly between 1967 and 1971. Some installations of **larger absorption refrigeration** plants were in use in the U.S.A., Germany and France before 1935 already. In 1932, G. Maiuri introduced the **multi stage** ammonia absorption machine. Studies by Servel and Carrier introduced water – lithium bromide absorption refrigeration machines around 1940.

5 THE PERIOD OF LOW OIL PRICES 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, which in turn resulted in a certain stagnation in their development and market penetration. 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 heat pump know how and developed it further.

5.1 Swiss Contributions: Oil Free Compressors, on-line-Monitoring

Through enormous efforts in material science, fluid dynamics and machining accuracy, it was possible to increase the impeller revolution speed of **turbo compressors** to a tangential speed around sonic speed. For radial compressors this made it possible to achieve a one stage pressure ratio of 8. In close cooperation with the ETH Zurich, Escher Wyss, Sulzer and Brown Boveri (BBC) played a major role in this research and development. In 1956, Sulzer made the **first oil free labyrinth piston compressor**, and installed the first **high-speed radial turbo compressor** in a British air conditioning system in 1958. In the early 1970s, with “ULMA” BBC introduced the world’s **first commercial on-line inspection system**.

In this period a reasonable return on investment for ordinary **heat pumps** was not possible until the oil embargo in 1973. New installations were restricted to special cases. Taking advantage of special electricity tariffs, a new **350 kW ammonia heat pump** was built by Escher Wyss for a hospital in Altdorf in 1961. It achieved a respectable Lorenz efficiency of 52.3%. The **vapour recompression** business was still successful. In the 1960s and 1970s, Escher Wyss hold a world market share of about 30%.

5.2 Relevant International Milestones

In the U.S.A. the mass production of **hermetic compressors** for refrigerators began in the 1950s. In 1958, a significant rise in the pressure ratio **of screw compressors** became possible (Ljungstroms Angturbin → Svenska Rotor Maskiner) by oil injection. In the late 1950s, halogenated hydrocarbons had supplanted practically all the old **refrigerants** except ammonia. In the late 1960s and early 1970s, the **computer** provoked a tremendous change first in design calculation and optimization, and then in control. A huge market was developing for small air conditioners in residential homes and automotive cooling in the **U.S.A.** and in **Japan**. In the U.S.A. heat pump installations using ground water as the heat source were realized around 1952, and the first combustion engine driven heat pumps were introduced. Japan was increasing its air conditioning installations considerably, and was also interested in larger units providing cooling and heating. The air-conditioning units from the U.S.A. and Japan in year round use had very little acceptance in **Central Europe** (unpleasant air flow and noise, moderate efficiency, mostly with lack of a defrosting facility). In France and Germany heat pumps were used only sporadically, namely for simultaneous utilization of cold and heat. In 1969, the first ground coupled heat pump was realized in Germany. There was still a lot of activity in the vapour recompression business.

6 ENTHUSIASM AND DISILLUSIONMENT 1973-1989

1973 marked one of the most important turning points in the history of the twentieth century. The Arab members of the Organization of Petroleum Exporting Countries (OPEC) decided to cut back on their exports of petroleum to Western nations. This **oil embargo** had a devastating effect on the national economies with a global recession and high inflation. By the end of the embargo in March 1974, oil prices had risen by over 300%. This was the time, when alternative energies and the rational use of energy became a high public priority. The IEA was founded and recognised the importance of heat pumping technology. This tendency was accelerated by the **second oil crisis in 1979** and accentuated in 1980 when war broke out between Iran and Iraq. Alternative energies became more popular and there was a lot of optimism about replacing fossil fuels with nuclear energy. Both were in favour of heating by heat pumps. But the rapid growth of the heat pump business brought too many competitors with insufficient know-how. This and the next oil price collapse after 1981 were the reasons for the collapse of the European market by the end of the 1980s. Worldwide, the **number of heat pumps** was estimated in 1979 at about 800’000 without, and 4’000’000 with the reversible air conditioners. But there was little dissemination of heat pumps for space heating in Germany, Austria and France before the second oil crisis.

6.1 Swiss Contributions: Heat Pumps from Small to District Heating Systems

HEAT PUMPS**.** After more than two decades of stagnation heat pumps experienced a rebirth with the oil embargo of 1973. That is, when the development of the **second generation of heat pumps** for central water heating systems for dwellings and semi detached houses began. There was a lack of conform **small (10 – 50 kW) heat pump systems** with air or ground as heat source. This motivated **several pioneers** to develop a suitable device for this size of equipment (Figure 8). They were mostly skilled technicians from the refrigeration, air conditioning and electric utility business. These pioneers produced heat pumps on a small business basis. 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 was the combination of horizontal ground heat exchangers with unglazed solar roof collectors. Treated and untreated sewage, lake and river water were used as heat sources as well. The seasonal performance factor of the small units (10-50 kW) was only about 1.9 to 2.3 for air as heat source and not much higher when using horizontal ground heat exchangers. The first boom ended with deterioration in image due to the high number of unserious competitors.

The **third generation of small heat pumps** after 1979/1980 was less voluminous and had a lower refrigerant content. The heat sources were competed by thermo active building elements with integrated piping systems. The market of small heat pumps 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 the **medium size range (50-1000 kW)** three companies were active. Hoval Herzog, which built heat pumps on the basis of Carrier water chillers, was realising a 620 kW heat pump using the **drain of a sewage plant as a heat source** as early as 1975. Autofrigor / Scheco pushed solutions for a **combined use of heat and cold** wherever possible and played a leading role in replacing CFCs. Sulzer-Escher-Wyss was building plants in this range as well. In the 1980s, **gas engine and diesel engine driven heat pumps** with a heating power range of 200 kW to 1’000 kW emerged. But the maintenance costs proofed to be too high.

Figure 8: “Grimm Machine” around 1980 [H. Grimm, CH-3047 Bremgarten]

Figure 9: One of the four 440 kW heat pumps of the Lucerne railway station (1984) [Axima, CH-6010 Kriens]

Based on decades of experience and knowledge Sulzer-Escher-Wyss built up a leading position in the **large heat pump** business (> 1 MW). One of the first realizations of the modern concept of the **combinations of electric heat pumps with cogeneration units** was the total energy system built in 1984 by Sulzer-Escher-Wyss at **Lucerne railway station**. Four heat pump units with a heating power of 440 kW each (Figure 9) and water from Lake Lucerne as a heat source were driven by three gas engine cogeneration units with 374 kW_{el} each. In summertime the heat pumps are able to operate as chillers. The system is optimally operated by a computer system taking into account current heat demand and current electricity tariffs. After the replacement of R-12 by ammonia in 1990, the total heating power was increased to **7.2 MW** with a primary energy ratio around 2.

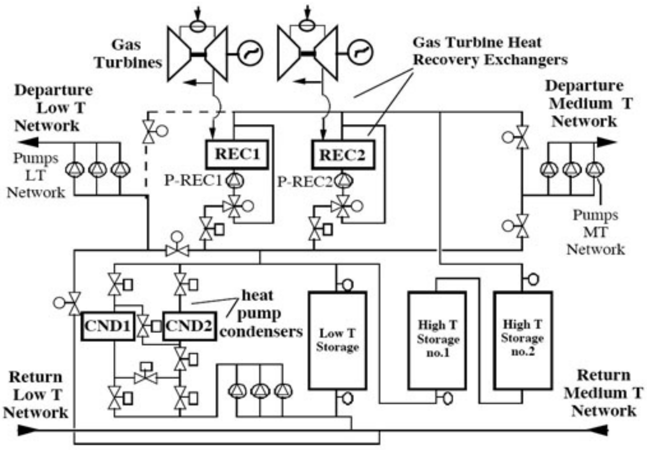


Figure 10: 23 MW Sulzer-Escher-Wyss/Silberring total energy plant at the EPFL, Lausanne (1986) [Pelet/Favrat/Voegli LENI-EPFL, CH-1015 Lausanne]

Figure 11: One of six 30 MW Sulzer heat pumps at the Stockholm district heating (1985) [www.friotherm.ch]

In 1979, based on a proposal by Lucien Borel, the engineering consultant Ludwig Silberring designed a path breaking **23 MW total energy plant** for heating the Swiss Federal Institute of Technology in Lausanne (EPFL). It had been realized by the incorporated Sulzer-Escher-Wyss (Figure 10) and consists of **two gas turbines** with 3 MW electricity and 5.7 MW heat each. The **two** identical electrically driven **ammonia heat pumps** with an economizer port have oil-injected screw compressors. The heat pumps, with a heating power of 3.9 MW each, are using ammonia as a working fluid and water from Lake Geneva as a heat source. With a total heating power of 7.8 MW this closed loop heat pump system became the largest in Switzerland so far. After the start up in 1986 the PER was 1.7. As Switzerland only has very limited district heating systems, the really big heat pumps had to be exported. With a heating power of **180 MW** Sulzer-Escher-Wyss installed **the world's biggest sea water heat pump** with six 30 MW-units (Figure 11) for Stockholm in 1984/1985. In Algeria Brown Boveri – Sulzer had installed machines with about 80 MW on one shaft.

THE PIONEERS OF VERTICAL GROUND HEAT EXCHANGERS. The Swiss gave an important impetus to this technology - which had just been flirted with until about 1980. Jürg Rechsteiner (Multi-Energie, Aadorf) was the Swiss pioneer in replacing horizontal ground heat exchangers with vertical borehole heat exchangers. As early as 1974, Rechsteiner rammed his first **coaxial steel probes** into the sandy ground of Lustenau (Austria). From 1974 until 1980 several others followed. It was a costly first trial and the frequent leakage between the 2.5 m long probe elements ruined the reputation of vertical borehole heat exchangers. Therefore Rechsteiner developed **the first double-U-tube probes made of polyethylene**. He presented his innovation to Ernst Rohner of the hydraulic-circulation drilling company Grundag and shortly afterwards Rechsteiner arranged initial tests with plastic U-tube probes. In 1980, the first installation for a dwelling in Arbon was realized. Rechsteiner's innovation was copied in thousands of installations in Switzerland and abroad. Other drilling companies followed Grundag (KWT 1987, Frutiger 1987, 2001 HASTAG, successor of Grundag). The depth of the boreholes was 50 m in 1980. By 1985 it went to over 100 m.

THE PIONEERS OF HEAT RECOVERY FROM RAW SEWAGE. Heinz Grimm was the first to use raw sewage as heat source. But the problems with the solid fraction were not solved before Felix Kalberer found a solution in separating the solid fraction by sedimentation and sieving around 1980. Since then more than 180 installations have been realized and his "**FEKA-tank**" has been improved continuously.

QUALITY CONTROL FOR SMALL HEAT PUMPS. Lucien Borel of the EPFL built up a heat pump testing facility for **commercial heat pumps** around 1980. The systematic long time field tests on complete small **heat pump space heating systems** were introduced by Peter Hubacher (Enfog in Gossau) with his colleague Bruno Dürr and the scientific advisor Max Ehrbar of the University of Applied Science in Buchs in 1981, and then continued for some years. While the heat pumps already had a reasonable COP, the efficiency of complete heat pump systems was still rather poor.

SCIENTIFIC ASSISTANCE. There were several important government funded scientific assistances. Comprehensive **fundamentals** on heat pump systems had been worked out by the Swiss Federal Institute for Reactor Research in the early 1980s. At the same time **guidelines and maximum values for extracting heat from rivers and lakes** of Switzerland were worked out by Dieter Imboden of the EAWAG in Dübendorf in order to avoid any harm to the sensitive ecosystems. A comprehensive research study was carried out on the behaviour and the design of **vertical borehole heat exchangers** by Robert J. Hopkirk from Polydynamics and later by 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 Switzerland's leading position in the design and realization of vertical borehole heat exchangers as a heat source or as a heat sink for combined usage of cold and heat, and for passive air conditioning. **Annual conferences** have at last been organized for knowledge and experience transfer.

SUPPORTING MEASURES BY ASSOCIATIONS AND POLITICS. Since 1980 the **Swiss Working Committee of Heat Pump Manufacturers and Distributors AWP** is engaged in a unification and simplification of the approval procedures, common planning guidelines, exchange of experience and professional training. The **Swiss Federal Office of Energy** supported research activities and acted as a catalyst for the associations and the cantons. In the middle of the 1980s, there was a breakthrough in the media presence of heat pumps.

6.2 Relevant International Milestones

Thanks to high precision, computer-controlled milling technology, the industrial manufacturing of **scroll compressors** and screw compressors became possible in the 1980s. For very large capacities the **axial compressor** entered the refrigeration scene. In 1974, S. Rowland and M. Molina suspected that the chlorine released might attack the **ozone layer**. The fear became certainty by 1978. In 1985, the "ozone hole" over the Antarctic had been discovered. A worldwide concerted action for a **phasing out of CFCs** was launched as a result of the Toronto Protocol (1984) and the **Montreal Protocol** (1987) with rigorous phase out agreements. This led to worldwide emergency programs, and a **renaissance of ammonia** as refrigerant. Within the space of only four years the HFC refrigerant **R-134a** was developed. Unfortunately, **HFCs** are persistent substances as well, and their greenhouse effect is very high. Consequently **hydrocarbons,** such as propane and isobutene, have been 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.

The **plate heat exchanger** definitively entered into the refrigeration and heat pumping scene in the 1970s. For synthetic refrigerants the elastomer gaskets were replaced by copper soldered connections in the 1980s. Laser welded seams were introduced in the 1990s. A determining milestone of the 1980s was the introduction of the **microprocessor**. Better control strategies became possible using far more sensors. As early as 1989 Carrier introduced a microprocessor controlled **electronic expansion valve**.

In 1980, six years after Jürg Rechsteiner in Switzerland, the first coaxial vertical borehole heat exchangers had been installed in **Germany**. From 1981 to 1983, Volkswagen and Ruhrgas developed the “Thermodiesel”, a heat pump driven by a 1.6 litre car diesel engine. But the maintenance costs were far too high and the lifetime of the engine was too short. Between 1980-1985, a heat pump testing facility was set up in Karlsruhe. From 1982, there was a boom in demand for large heat pumps in **Scandinavia.** Fundamental contributions on the thermal analysis of vertical borehole heat exchangers were given by P. Eskilson of Lund University. In 1989, the Nordic Council of Ministers introduced a voluntary and neutral approval certification program for heat pumps. In the **U.S.A.** a rapid expansion of unitary heat pumps began, and by 1976 there were 1.6 million units in service.

In the 1980s, there were many attempts to develop an **absorption heat pump** with heating powers below 50 kW. Depending on the complexity of the absorption process PER values of 1.15 to 1.4 were attained. The cost–benefit ratio was not inspiring and the additional problems with the solution pumps did not convince the market. The situation was different for **large absorption chillers**. **Japanese** companies continued to perfect their double-effect absorption chillers. Benefitting also from tax incentives, these developments enjoyed a market success. Large water-lithium bromide units with cooling PERs up to 1.2 and capacities up to 31.6 MW were built.

7 THE SUCCESS STORY 1990 – PRESENT

Cheaper, more efficient and more reliable heat pumps became available. The growing environmental problems made the idea of saving primary energy by heat pump heating more and more popular. These arguments were strengthened by national and international efforts in R&D and quality control. In some countries there were some additional financial incentives. Vapour compression cycles became a mature technique already in the years before. But the urgent refrigerant change was a 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

7.1 Swiss Contributions: Innovative Systems and Quality Control

After getting over the “once-burned” effect, from 1990 a **definitive take off of heat pumping technology** for heating only purposes began. This 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. After 1998 the take off of heat pumps was accelerated to a market share today of 75% for space heating and domestic hot water heating in new dwellings. Heat pumps are now slowly penetrating the retrofit market as well. Within the last 15 years, the average COP of the tested air (2°C) / water (35°C) heat pumps (2.5-30 kW) increased by 30% from 2.6 to 3.4 and the COP of the brine (0°C) / water (35°C) heat pumps (5-80 kW) increased by 17% from 3.8 to 4.45. After a standard deduction of the pumping energy used to circulate the “brine” in the vertical borehole heat exchanger the values for brine/water systems reduce to 3.5 - 4.1. At present **vertical borehole heat exchangers** are being brought in to a maximum length of 350 m. The most frequent drilling depth varies from 150 m (important passive summer cooling) to 250 m (heating only). The largest field of vertical borehole heat exchangers was realized in 2005 for the Dolder Hotel Zurich with 72 probes (Figure 12). As there is also a lot of summer cooling, the field is operating as a geothermal heat storage.

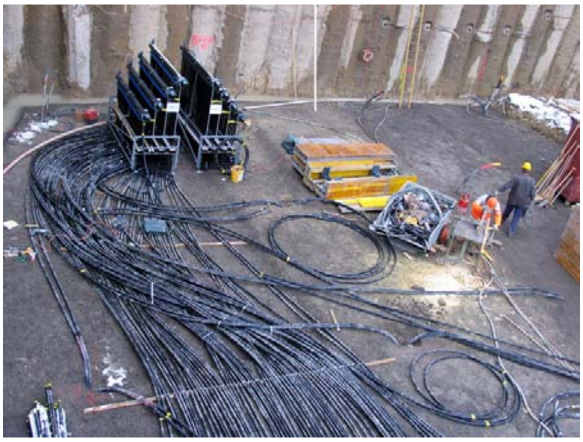


Figure 12: Geothermal heat storage under construction at Hotel Dolder Zurich [GEOWATT AG, CH-8050 Zürich]

Figure 13: FEKA-tank for the heat recovery from raw sewage [Kalberer, FEKA-Energiesysteme, CH-7310 Bad-Ragaz]

Besides heat pump installations for dwellings and heat pump laundry dryers, many **innovative larger heat pump systems** were built in this period. Among them, heat pumps using unconventional heat sources, such as drainage water from new train tunnels trough the Alps, low temperature district networks with no thermal insulation supplied by the effluent of sewage treatment plants, raw sewage and mountain lakes. Many combinations of cogeneration with heat pump units have been realized as well. Several large turbo heat pumps with heating powers up to 90 MW and cooling powers up to 60 MW have been exported by Friotherm. These installations are presented in [Zogg 2008]. With the **“zero energy” residential area Eulachhof** in Winterthur with 132 apartments, a vision became reality in 2006/2007. The buildings with an insulation thickness of 38 cm significantly surpass the Swiss passive house standard. 1’240 m^2 of photovoltaic panels with 176 kW_p provide all the electricity needed for two heat pumps and the blowers of the controlled aeration on an annual mean value basis. Heat recovery from the controlled aeration 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 mentioned in 6.1 (Figure 13). The backup space heating of about 8.5% of the total heat demand is provided by a district waste incineration plant heating system. It corresponds roughly to the energy content of the solid waste delivered by the residents.

SCIENTIFIC ASSISTANCE. Again in this period, Swiss **research and pilot installation activities** were focused on scientific and technological assistance. Besides the highest priority of developing a retrofit heat pump for covering the total heat demand (space and domestic hot water) of dwellings at air (-12°C) / water (60°C) conditions with high efficiency the following topics have been covered by federal funding (detailed description in [Zogg 2008]):

- Handbooks for better heat pump installations and
- Guidelines for standardized hydraulic schemes
- COP enhancement of air/water heat pumps by optimized defrosting and ground registers
- Silent air/water heat pumps
- Modelling and environmental impact of vertical borehole heat exchangers
- Combined cooling, refrigeration and heating using ground heat storage
- Environmental benefit of natural refrigerants and practical conclusions
- Heat transfer with HFC and natural refrigerants
- Ammonia heat pumps for dwellings and small semi hermetic oil free CO_2 compressor
- Small diffusion absorption heat pump without solution pump
- Unconventional heat pumps (Stirling engine with a Stirling heat pump, magnetic)
- Pulse width modulation and advanced fault detection and diagnosis methods
- Dynamic heat pump testing and testing with integrated domestic hot water heating

ASSISTANCE BY ASSOCIATIONS AND POLITICS. The political answer to a 10-year **moratorium on nuclear energy**, decided by Swiss voters in 1990, took the form of “Energy 2000” and “SwissEnergy” **action plans**. By classifying heat pumps in the renewable energy section, heat pumps were favoured in both aspects; CO_2 reduction and increasing the share of renewable energies. In 1993, the **Swiss Heat Pump Promotion Group** (FWS) was founded by the federal government, the cantons and important private associations of electricity utilities, relevant manufacturers, distributors and installers. Its main goal is the promotion of efficient heat pump heating systems of high quality at an affordable price.

QUALITY MANAGEMENT. There was an obvious demand for independent heat pump testing, pushed by the utilities, political actors and forward thinking manufacturers. In 1993, the Swiss **Heat Pump Test and Training Centre** was put into operation in order to test air/water (with a complete defrosting cycle), brine/water and later air/air heat pumps in accordance with European Standard EN 255, succeeded by EN 14511, introduced in 2004. Altogether, 118 air/water, 200 brine/water, 122 water/water commercial heat pumps were tested by 2007. The test results can be downloaded by the public from www.wpz.ch. In order to make it easier for the consumer to choose an efficient and high quality heat pump from a supplier with strong after sales support, the **DACH Quality Label for heat pumps** was introduced in 1998 by Germany (D), Austria (A) and Switzerland (CH). Negotiations are currently ongoing within the European Heat Pump Association EHPA in order to implement the DACH Label at a European level. The **DACH Label for vertical borehole heat exchangers** assesses and labels the drilling companies. An important goal is the prevention of any kind of ground water contamination. A high quality heat pump is one thing – a highly efficient complete heat pump system is another one. That is why in 1995, the Swiss Federal Office of Energy started comprehensive **field testing of complete heat pump systems (FAWA)** in order to analyse and tackle system problems. A total of 236 heat pump systems in the heat power range up to 20 kW have been measured and analysed so far. The class winners attained a seasonal performance factor of 3.1 for air/water systems (with a maximum of 3.4) and of 5.0 for vertical borehole heat exchanger/water systems (with a maximum of 5.6). A further important pillar of quality control is the appropriate **training of the installers**. At last a "**Heat Pump Doctor**" has been introduced. He can be called if any problem would arise between the customer and the installer.

In Switzerland all common salt and sugar is produced by **vapour recompression**. Evaporation plants using the Escher Wyss technology have been built for more than 80 years worldwide 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. But the Escher Wyss technology is also continued by the engineering company EVATHERM in Othmarsingen, Switzerland. **Distillation** is among the biggest energy consumers. The "Chemtech" division of Sulzer introduced the world's first distillation plant with vapour recompression and has carried out a lot of pioneering work. Large plants have been built around the globe.

7.2 Relevant International Milestones

From the beginning of the 1990s, the **hermetic scroll compressor** became more and more common for smaller heat pumps. The efficiency of small compressors has been improved significantly. New developments have started for **CO_2 compressors** worlwide. In the future new permanent magnetic electric motors will bring further improvements in efficiency. At the beginning of the 1990s, the **plate heat exchanger** became the definitive common heat exchanger type, and led to lower refrigerant volumes, lower temperature differences and space saving heat pumps. **Microcomputers** made it possible to use more sophisticated control strategies with more sensors and fully automatic operation. Not long after, the era **of remote monitoring and control** began. That lifted man-machine communication to a new level and led to an increase in reliability and efficiency and a fall in maintenance costs. New **diagnosis methods** allow periodic service intervals to be limited to a targeted maintenance when it is really required.

The **refrigerant topics** were dictated by the challenges in responding to environmental concerns. In 1992, the Montreal Protocol was revised to advance the **CFC phase out** to the end of 1995, with HCFCs to be phased out in stages by 2030. In many countries the **HCFC phase out** was scheduled much earlier (i.e. Germany by 2000, Austria and Switzerland by 2002). Worldwide the **environmental relevance** and the heat transfer characteristics of natural and HFC refrigerants have been studied many times. The new **HFC fluids** perform well, but because of their remaining global warming potential and persistent decomposition products they are still under international scrutiny and may be eliminated in the future. **Natural refrigerants** might be the final solution. The primary candidates are ammonia, carbon dioxide and hydrocarbons. Ammonia is widely used in large refrigeration plants, although it is toxic and flammable. Carbon dioxide requires a transcritical cycle, which reduces its efficiency for most space heating applications. Propane performs very well, but it is flammable and thus considered to be a safety hazard especially in the U.S.A. and in Japan. Guidelines for vapour compression cycles with natural refrigerants have been worked out within Annex 22 of the IEA Heat Pump Programme. A new effort for the application of natural refrigerants was taken in Europe by the **SHERHPA project** (Sustainable Heat and Energy Research for Heat Pump Applications).

From 1990, a definitive **take off of heat pumping technology for heating only** began in Europe as well. **Ground source heat pumps** became more popular, notably in Austria, Canada, Germany, Sweden, Switzerland und the U.S.A. Several personal computer programmes for a more precise design of single and fields of vertical borehole heat exchangers became available. In **Austria** direct expansion ground coil systems are quite successful, and there is an official test institution in Vienna. In 2001, K. Mittermayr introduced a vertical borehole heat exchanger working with evaporating CO_2. From 1997 on, in cooperation with Austria and Switzerland, the design know-how of ground coupled heat pumps has been concentrated in the German **Guideline VDI 4640**. In 1993, Stiebel Eltron presented its first propane heat pump. The company has developed a heat pump with integrated heat recovery from the exhaust and an integrated hot water tank particularly for low energy houses with controlled aeration. In 2006, Stiebel Eltron has built Europe’s largest heat pump manufacturing factory with a capacity of 25’000 heat pumps per year. AEG commercialized the first heat pump laundry dryers in 1998. In **Sweden,** at the Lund Institute of Technology the mathematical modelling of vertical borehole heat exchangers, started by P. Eskilson, was expanded to a groundbreaking thermal analysis of ground heat storage systems by G. Hellström. Many large heat pump systems were built in Sweden and **Norway**. The **Danish** firm Sabroe introduced an ammonia high temperature heat pump compressor in 1990. In 1997, Sabroe bought the refrigeration division of ABB (former BBC).

The small **diffusion absorption heat pump** DAWP by the Swiss Hans Stierlin was further tested by Buderus in **Germany** in 1994. In 1997, the project was continued at the **Dutch** subsidiary Nefit Fasto. Extensive field-testing with additional peak boilers for bivalent operation followed. In 2000, the Nefit Prototype (now “Buderus Loganova”) won the award of the German gas utilities. However it is not yet commercially available. In 1999, there was one manufacturer of unitary absorption air conditioners and heat pumps in the U.S.A. Despite other extensive research activities on absorption heat pumps worldwide, absorption heat pumps have not yet become competitive in the space and domestic hot water heating market.

8 SPECIAL PRINCIPLES

A lot of research has been carried out on **adsorption** machines, but only a few solar thermal applications have been realized. The **thermoelectric effect** with its low efficiency found only a few very special applications, such as thermoelectric cooling in medicine and radio-electronics. The **Stirling cycle** was successful only for cooling in deep temperature applications such as liquefying gases. As a result of the near room temperature “giant effect” demonstrated by K. A. Gschneidner Jr. and V. K. Pecharsky at the Iowa State University, the vision of heat pumps based on the **magnetocaloric effect** found a worldwide revival. In Switzerland a functional model for a temperature lift of 35 K is under construction. The **vortex effect**, or swirl effect occurs by a tangential injection of air into a cylindrical tube. It induces a gyratory expansion with simultaneous production of an escape of hot air and an escape of cold air. But its efficiency is very low.

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REFERENCE

Zogg M. 2008. “History of Heat Pumps - Swiss Contributions and International Milestones”, final report, Swiss Federal Office of Energy, Berne; with 285 references, downloadable from www.zogg-engineering.ch/publi/HistoryHP.pdf